EXPERT REPORT
OF
JAMES E. HANSEN, Ph.D.

Director of Climate Science, Awareness and Solutions Program
Earth Institute
Columbia University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

Prepared for Plaintiffs and Attorneys for Plaintiffs:

Julia A. Olson
JuliaAOlson@gmail.com
Wild Earth Advocates
1216 Lincoln Street
Eugene, OR 97401
Tel: (415) 786-4825

Philip L. Gregory
pgregory@gregorylawgroup.com
Gregory Law Group
1250 Godetia Drive
Redwood City, CA 94062
Tel: (650) 278-2957

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TABLE OF ACRONYMS AND ABBREVIATIONS

AGU:	American Geophysical Union
AMOC:	Atlantic Meridional Overturning Circulation
BAU:	business as usual
C:	Celsius
CH_4:	methane
CO_2:	carbon dioxide
EPA:	U.S. Environmental Protection Agency
F:	Fahrenheit
GCM:	global climate model
GISS:	Goddard Institute for Space Studies
GHG:	greenhouse gas
GNP:	gross national product
GtC:	gigatonnes of carbon
LDGO:	Lamont-Doherty Geophysical Observatory
IPCC:	United Nations Intergovernmental Panel on Climate Change
MBM:	mass budget method
NAS:	National Academy of Sciences
NASA:	National Aeronautics and Space Administration
NOAA:	National Oceanic and Atmospheric Administration
NRC:	National Research Council
N_2O:	nitrous oxide
PETM:	Paleocene-Eocene Thermal Maximum
ppm:	parts per million
SCEP:	The Study of Critical Environmental Problems
SLR:	sea level rise
SMIRC:	The Study of Man's Impact on Climate
SO_2:	sulfur dioxide
UNFCCC:	United Nations Framework Convention on Climate Change
W/m^2:	Watts per square meter

QUALIFICATIONS

I, James E. Hansen, am a party to this litigation, as a guardian in the above-captioned matter for both my beloved granddaughter Sophie, during the period of the case when she was a legal minor, and for future generations.

Regarding my qualifications: I was trained in the space science program of Prof. James Van Allen at the University of Iowa. I received a Bachelor of Sciences degree with highest distinction with double majors in physics and mathematics in 1963, a Master of Sciences degree in astronomy in 1965, and a Ph.D. in physics in 1967, all from the University of Iowa.

For 32 years, I directed NASA's Goddard Institute for Space Studies (GISS), with a total career at NASA of 46 years. I was the longest serving director in the Institute's history. NASA is one of two primary federal expert agencies tasked with studying the climate system and climate change today. The other is the National Oceanic and Atmospheric Administration (NOAA). Within the federal government today, NASA and NOAA house our federal government's best understanding of the science of climate change.

Since my retirement from NASA, I have worked as an adjunct professor at Columbia University's Earth Institute and Director of the Climate Science, Awareness and Solutions program at the Earth Institute, where I have continued my climate science research, writing and communications.

I received the Rossby Research medal, the highest award of the American Meteorological Society, and the Roger Revelle medal of the American Geophysical Union, the Leo Szilard award of the American Physical Society for Outstanding Promotion & Use of Physics for the Benefit of Society, the American Association for the Advancement of Science Award for Scientific Freedom and Responsibility, the American Association of Physics Teachers Klopsteg Memorial Award for communicating physics to the general public.

I am a member of the National Academy of Sciences.

A true and correct copy of my CV is attached as **Exhibit A** to my expert report in this action.

To the best of my recollection, I have not served as an expert at trial or by deposition in any case in the last four years.

A true and correct copy of a list of publications I authored within the last ten years is attached as **Exhibit B** to my expert report in this action.

Exhibit C contains three recent peer-reviewed papers of which I am the principal author whose analysis forms the basis of many of the expert opinions I express in this report, and I incorporate their analyses by reference. **Exhibit C.1** is *Assessing ''Dangerous Climate Change'': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature*. PLoS ONE (2013). **Exhibit C.2** is *Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous*, Atmos. Chem. Phys. (2016). **Exhibit C.3** is *Young people's burden: requirement* *of negative CO_2 emissions*, Earth Syst. Dynam. (2017). I also incorporate by reference my Declarations that have been filed in this litigation.

In preparing this expert report, in addition to relying upon my extensive experience and expertise, I have relied on a number of documents. My expert report contains a list of citations to the documents on which I relied in forming my opinions, listed in **Exhibit D** to my expert report in this action.

Attached hereto are **Exhibits E-U**, which include, in **Exhibits E-R**, maps and video simulations of sea-level rise in regions that are areas of special concern to several Youth Plaintiffs; in **Exhibit S**, early and recent curves depicting CO_2 in the post-industrial era; in **Exhibit T**, a dataset from NOAA of sea level rise projections through 2200; and in **Exhibit U**, an animation from NOAA depicting the record of atmospheric CO_2 over the last 800,000 years, with most recent levels rising nearly off the chart (minute 3:30 of **Exhibit U**). **Exhibit V** is a spreadsheet compiling **Exhibits E-U**. Also attached are **Exhibits W-KK**, which contain various reports or document evidence.

In preparing my expert report and testifying at trial, I am not receiving any compensation and am providing my expertise pro bono to Plaintiffs.

EXECUTIVE SUMMARY

This expert report conveys fundamental considerations that undergird my expert opinion as to the urgent nature of the climate crisis, the special responsibility of the Defendants (and their predecessors) in creating and exacerbating the climate crisis, and the increasingly grave danger faced by the Plaintiffs and future generations if present leadership of the Defendants continues to intensify, rather than solve, the climate crisis.

Dangerous anthropogenic climate change is on our doorstep. For decades, the long-approaching threat was well understood by both the Defendants and the scientific community. Averting carbon pollution's worst impacts and restoring a well-functioning climate system likely still remains within the Defendants' control, should our leaders within the Defendants serve the interests of the nation – including its young people. The present Defendants under the Trump Administration – building upon the actions of prior administrations in allowing, permitting, and subsidizing fossil fuel interests to exploit our reserves and treat the atmosphere as a dumping ground for waste carbon dioxide (CO_2) and other greenhouse gases (GHGs) – has floored the emissions accelerator and thus hurdles Plaintiffs, their progeny, and the natural world as we have come to know it, towards climate points of no return. Plaintiffs are now in jeopardy; their circumstance will not improve absent a major and timely redirection by the Defendants, utilizing their existing authority, of national energy decisions, plans, and policies of the federal government, as well as climate and carbon sequestration decisions, plans, and policies.

In my expert opinion, the Defendants' continuing knowing, elective imposition of untenable and unwarranted risks on Plaintiffs has created an extraordinarily dangerous situation. At this stage, this dangerous situation can be remedied, if at all, only by an order of this Court issued promptly requiring the Defendants to take immediate steps based on climate science.

Continued emissions of CO_2 and other GHGs place Plaintiffs in an unusually serious risk of harm that humanity has never previously faced. There is no time left for further delay in taking actions to address the atmospheric burden that endangers our climate system and threatens our children. The Defendants must commence to phase out our country's carbon emissions and replace these carbon emissions with carbon-free energy sources. For too long, our energy system has been powered by fossil fuels, such that our planet's atmospheric composition has already overshot the safe level of CO_2 and other GHGs, forcing consequences that are highly threatening and that will rise to an unbearable level unless action is taken by these Federal Defendants without delay. In my opinion, based on multiple lines of evidence in climate science, our country must phase out carbon emissions over the next several decades coupled with significant efforts to draw down CO_2 from the atmosphere, so that we can work successfully to return the atmospheric CO_2 concentration to no more than 350 parts per million by the end of the century, with continued work, if necessary, to further reduce CO_2 concentrations according to our best scientific understanding to protect Earth's climate system and its diversity of life, including humanity.

Accordingly, in my report I make the following expert opinions:

- Our government has long permitted, subsidized, allowed, and otherwise encouraged fossil fuel exploitation, processing, transport, and burning – with little or no control on ensuing emissions of CO_2 and other GHG emissions. At present, the Defendants are doubling down on that pattern and attempting to erase every vestige of even the nascent and insufficient efforts of the prior administration to reduce emissions.

- Over nearly four decades, colleagues and I developed increasingly compelling evidence that ensuing and unconstrained emissions markedly raised the atmospheric CO_2, CH_4, and N_2O concentrations in the atmosphere, enhancing the greenhouse effect and, accordingly, posing an increasingly dire threat to coastal cities, natural systems, essential human services, and human life.
- Based on simple climate models, temperature measurements at weather stations, and limited paleoclimate data, colleagues and I were able, as early as 1981, to anticipate discernible warming for the 1980s and 1990s, and 21st century shifts in climate zones, increasing climate extremes, eroding ice sheets, and accelerated sea level rise. We urged, as an appropriate strategy, a shift to low-carbon and non-carbon energy sources, coupled with conservation, with fossil fuels used only as necessary for a few decades more.
- Our work analyzing paleoclimate data corroborated earlier estimates of climate sensitivity for a doubling of atmospheric concentration of CO_2 and led us to conclude -- and warn the government -- that all fossil fuels could not be burned without untenable consequences for future generations. Those untenable consequences include the aforementioned sea level rise and loss of coastal cities (and present shorelines), species extinctions, increasingly severe heat waves and droughts alongside, at the times and places of rainfall, increasingly extreme flooding and more powerful storms.
- While there was more than enough scientifically-credible evidence to act on climate change in prior decades, by the early 2000s, the reality of global warming had become unequivocal. Progress of the scientific community, including our work estimating the efficacy of different climate forcing mechanisms, including aerosols, CH_4, and CO_2, and have fully established CO_2 as the largest human-made climate forcing.
- Our studies examining the potential impacts of climate change raised questions about the stability of the planet's major ice sheets. In addition, we drew attention to the threat that rapidly shifting isotherms (conceptual lines connecting areas of similar average temperatures) pose to the persistence of other species.
- The enormity of the potential consequences of these two matters, loss of coastal cities and extermination of countless species, demanded reassessment of what constituted "dangerous human-made interference with the climate system," which the global community sought to avoid by ratifying the United Nations Framework Convention on Climate Change in 1992. That reassessment led me and others to conclude in 2008 that the political guardrail of 2°C of warming (corresponding approximately to an atmospheric CO_2 concentration of ~450 ppm) is highly dangerous, and that an initial target of < 350 ppm CO_2 is justified by the relevant science.
- Particularly in light of approaching points of no return, it is, in my expert opinion, essential to commence serious and sustained action to return atmospheric CO_2 to < 350 ppm without further delay; essential, that is, to preserve coastal cities from rising seas and floods (caused in part by melting of Antarctic and Greenland ice) and superstorms, and otherwise to restore a viable climate system on which the life, liberty, and property

prospects of Plaintiffs, young citizens of America, and future generations so thoroughly depend.

- In my opinion, this salvation remains possible if we phase out GHG emissions within several decades and actively draw down excess atmospheric CO_2. Drawdown can be achieved largely via reforestation of marginal lands with improved forestry and agricultural practices, if rapid emission reductions are initiated without further delay.

EXPERT OPINION

1. Introduction

I agreed to serve as the guardian for Plaintiff future generations in this case because I have been working for almost four decades to use my scientific expertise to warn the federal government of the irreversible dangers from climate change caused by burning fossil fuels. Through my repeated recommendations to the Defendants (including their predecessors), I have been laboring to cause the swift decarbonization of our energy system to protect our country's children and future generations. Herein, I provide expert testimony regarding the Defendants' role in causing climate change and how human-caused CO_2 and other GHG emissions are harming Earth's natural systems, human communities, and Plaintiffs themselves.

The opinions expressed in this expert report are my own and are based on the data and facts available to me at the time of writing and my 46-year career in the federal government, and are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report.

My expert report focuses on development of relevant science during the past half century, which is the period in which human-caused global warming passed from being a validated scientific theory and government concern to full-blown global reality with life and death consequences for humans and many other species on the planet. I have been a witness during this period to the development of scientific understanding of climate change, including the role of humans in causing climate change. Indeed, I have been a participant in that scientific research process, as well as a participant in efforts to bring the increasing urgency of the situation to the attention of federal government officials, who retain authority to do something meaningful about the situation.

My goal in this expert report is to provide the Court with the fundamental bases for my concern as to the emergency nature of the climate situation, as well as an understanding of its continuing, but fading, tractability – including my considered view as to what must be done, and how quickly it must be done. The aims must be to both limit the damage and restore the functioning of the climate system on which Plaintiffs, young persons, and future generations depend.

In describing the development of climate science and general understanding of it, I will focus on the research carried out at NASA (GISS) (www.giss.nasa.gov), especially on work in which I was involved, which can be accessed at https://pubs.giss.nasa.gov/authors/jhansen.html and http://www.columbia.edu/~jeh1/.

Through a review of NASA's research, and my own personal experience working in the federal government, I am also able to address "what did they know and when did they know it," where "they" refers to both the Defendants and the fossil fuel industry because I participated in providing them this information. Although the fossil fuel representatives, the Intervenor Defendants, have withdrawn from this case, the issue of the long-standing knowledge of the fossil fuel industry and the Federal Defendants about the dangers of human-made climate change was often in concert, as was their joint efforts to perpetuate the danger rather than redress it.

In-depth understanding of climate change comes from using all the tools in the scientific tool kit. A common misconception is that our knowledge of ongoing climate change and projections for the future are a product of climate models. This misconception can lead to the conclusion that we have little understanding, because models are imperfect and incomplete representations of reality. This misconception is fostered by people who want to cast doubt on conclusions about climate change, even though those conclusions are clear to the scientific community.

In reality, understanding of ongoing climate change and expectations for the future depend to comparable degrees on three major sources of information and knowledge: (1) increasingly detailed reconstructions and analyses of Earth's long-term climate history, i.e., paleoclimate studies; (2) increasingly detailed and accurate measurements of modern climate change, climate forcings,[1] and climate processes; and (3) climate models, i.e., numerical simulations of climate change, including models of many contributing physical processes.

Over the past half-century I have witnessed advances in understanding of climate change, advances in understanding of the contribution that humans are making to climate change, and advances in understanding of the degree to which climate change may be harmful (or beneficial). In this expert report, I describe the development of my expert opinion on these topics, as a way to provide the Court with insight about how confidence was developed in the assessment of the climate situation by the scientific community.

This expert report does not include explicit review of all papers published by the research community, which are extensive. I am, however, familiar with the wealth of climate research and assessments carried out by the international research community, as summarized succinctly in references such as the treatises on climate change and human-induced global warming by Pierrehumbert (2010) and the National Research Council report (NRC, 2010) and in more detail by reports of the Intergovernmental Panel on Climate Change (IPCC).

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[1] A *climate forcing* is an imposed change in Earth's energy balance, measured in Watts per square meter (W/m^2). For example, Earth absorbs about 240 W/m^2 of solar energy, so if the Sun's brightness increases 1%, it is a forcing of +2.4 W/m^2. The Sun's brightness has been accurately monitored since the late 1970s, the total amplitude of its variations is about 0.1%, and the effect of this small variability is limited because it is oscillatory. In contrast the CO_2 climate forcing is much larger and steadily increasing. CO_2 is the principal climate forcing altering Earth's energy balance, as I will discuss.

The following discussion is organized chronologically.

2. Background Science: Studies Prior to 1981

2.1 Historical CO_2 Studies

It has long been understood that Earth's temperature is determined by the fact that the planet must be hot enough to radiate back to space as heat the same amount of energy that it absorbs from incoming sunlight. As a result, the fundamental processes that can change Earth's temperature are 1) changes in the amount of energy incident on Earth or the fraction of that energy absorbed by Earth; and 2) changes in the amount of heat radiated to space. Heat radiated to space is affected primarily by absorption of infrared radiation by CO_2 and other GHGs.

The scientific roots of understanding of climate change date to the early 19th century when scientists discovered that certain gases trap heat in the atmosphere and thus warm Earth's surface. Atmospheric CO_2 levels were just beginning to rise above 280 ppm at that time. In 1824, Joseph Fourier, a French mathematician and physicist, identified the greenhouse effect, writing: "The temperature [of Earth's surface] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in re-passing into the air when converted into non-luminous heat."

John Tyndall, an Irish physicist, realized the huge impact of atmospheric water vapor in keeping Earth's surface warmer than it otherwise would be, writing (Tyndall, 1872, p. 423) "This aqueous vapour is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapor from the air which overspreads this country, and you would assuredly destroy every plant capable of being destroyed by a freezing temperature. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost. The aqueous vapor constitutes a dam, by which the temperature at the earth's surface is deepened: the dam however, finally overflows, and we give to space all that we receive from the sun." Tyndall wrote with elegance, but also with the clarity of a physicist, about the importance of water vapor in keeping Earth's surface warmer than it would be without the presence of that gas, which acts as a "blanket." His other metaphor, that the dam must eventually overflow and "give back to space all that we receive from the sun," refers to the most fundamental concept, conservation of energy: Earth must radiate to space the same amount of energy that it receives from the sun.

Tyndall (1872) also measured in the laboratory the absorption of heat (infrared) radiation by gases. The strongest absorption of heat radiation is by water vapor. However, atmospheric water vapor amount is determined by atmospheric temperature, because the vapor condenses once humidity reaches 100%. Average relative humidity in Earth's lower atmosphere is less than saturation, about 60%, because of atmospheric circulation and weather variability. Water vapor is thus an amplifying climate feedback. For example, if climate forcing increases, say the Sun becomes brighter or the amount of a 'permanent' (i.e., noncondensing) atmospheric gas increases, this forcing causes global temperature to increase. The warmer atmosphere holds more water vapor, whose greenhouse effect amplifies the warming.

Among the gases other than water vapor, CO_2 is the strongest absorber of heat radiation, i.e., the strongest greenhouse gas. The amount of atmospheric CO_2 is naturally variable on long time scales, and Tyndall correctly inferred that climate changes on long time scales, the glacial to interglacial oscillations, are associated with changes of atmospheric CO_2. Indeed, subsequent research confirms that CO_2 acts as a strong 'control knob' on global temperature.

Svante Arrhenius, a Swedish scientist, was the first scientist to estimate quantitatively the impact of rising atmospheric CO_2 amount on Earth's temperature. Arrhenius (1896) used observations by Samuel Langley of heat transmission through Earth's atmosphere, which Langley obtained by measuring heat fluxes from the Moon. Via elaborate energy balance calculations, Arrhenius estimated that a doubling of Earth's atmosphere would cause a global warming between 4.9°C and 6.1°C, depending on latitude and season. This first estimate of 'climate sensitivity' (global mean warming in response to doubled CO_2) suffered from errors in Langley's measurement and other approximations in a complex calculation, with a resulting sensitivity that is somewhat larger than obtained in more realistic calculations and empirical studies today.

Arrhenius himself was able to improve upon his first analysis, providing his later estimate (Arrhenius, 1908) of 4°C for doubled CO_2 and 8°C for quadrupled CO_2. This improved estimate of Arrhenius turned out to be within the range predicted in later studies and today, as I discuss further below. The basic physics, understood for well over 100 years, is that more CO_2 molecules trap more radiation in the lower layers of the atmosphere. As Tyndall aptly stated, more greenhouse gases, are a thicker blanket that makes the surface warmer. By Arrhenius's time, CO_2 levels had risen from ~280 ppm to ~300 ppm.

In 1900 another Swedish scientist, Kunt Angstrom, disputed Arrhenius, arguing that CO_2 absorption bands are 'saturated', i.e., they absorb essentially all of the radiation within narrow spectral (wavelength) regions and negligible energy elsewhere. Therefore, he suggested, additional CO_2 would have little effect. This argument did not take account of the fact that the CO_2 bands become broader as the CO_2 amount increases, nor of the fact that the CO_2 bands are never saturated high in the atmosphere, where their increased absorption still blankets the planet effectively, reducing radiation to space. Angstrom's logic was faulty and it was rigorously and quantitatively disproven when computers made it practical to precisely calculate the transfer of radiation through the atmosphere.

Guy S. Callendar, a British engineer, used records from 147 weather stations around the world to show that the U.S. and the North Atlantic region had warmed significantly on the heels of the Industrial Revolution. The impact of rising CO_2 levels on global temperature was coined "the Callendar effect". In 1938, during FDR's administration and Callendar's early work, CO_2 levels had risen to ~310 ppm.

After World War II, the Office of Naval Research expanded climate science work as an offshoot of the Manhattan Project. By 1955, using a new generation of early computers, U.S. researcher Gilbert Plass analyzed in detail the infrared absorption of various GHGs. Plass explained that, although water vapor is the strongest greenhouse gas absorber, its amount falls off rapidly with height while CO_2 is uniformly mixed through the atmosphere. Thus CO_2 is especially effective in reducing heat radiated from the top of the atmosphere, affecting the planet's energy balance.

He concluded that doubling CO_2 amount would increase temperature by 3-4°C. By 1955, during Eisenhower's administration, CO_2 levels had risen to ~314 ppm.

Uncertainty persisted about exactly how much global temperature would increase in response to a given atmospheric CO_2 concentration. However, a crucial discovery was made in 1957 by U.S. oceanographer Roger Revelle. Until then, it had been thought that the ocean should rapidly take up most of the CO_2 from fossil fuel burning, so it was a bit puzzling why CO_2 seemed to be increasing substantially. During the International Geophysical Year, Revelle and chemist Hans Suess showed that there is a chemical resistance, characterized by what is now called the Revelle factor, that slows the uptake of CO_2 by sea water. Suddenly it was realized that the greenhouse problem was more immediate than had been thought. Revelle wrote: "Human beings are now carrying out a large scale geophysical experiment..." Revelle publicly speculated that in the 21st century the greenhouse effect might exert "a violent effect on the earth's climate" (as quoted by Time magazine in its 28 May 1956 issue). He thought the temperature rise might eventually melt the Greenland and Antarctic ice sheets, which would raise sea levels enough to flood coastlines. In 1957, Revelle told a congressional committee that the greenhouse effect might someday turn Southern California and Texas into real deserts. He also remarked that the Arctic Ocean might become ice free. By 1957, CO_2 levels had risen to almost 315 ppm.

By 1958, using equipment he developed himself, Charles David Keeling began systematic measurements of atmospheric CO_2 at Mauna Loa, Hawaii and in Antarctica, making measurements with a greater precision than prior data. Observations at Mauna Loa observatory revealed a beautifully precise curve for annual variations superimposed on a long-term increase, which would become known as the "Keeling Curve." Through his measurements, Keeling had unequivocal evidence that CO_2 concentrations were increasing and rising to levels not seen in over 20 million years. Based on data for carbon isotopes it was clear that CO_2 was increasing due to fossil fuel combustion. Within four years, the project - which continues today - provided undeniable proof that CO_2 concentrations were rising. The level of CO_2 in 1958 was 315 ppm.

By 1965, when CO_2 levels were 320 ppm, a White House Report signed by President Johnson warned that the greenhouse effect is a matter of "real concern." They reported: "by the year 2000 the increase in atmospheric CO_2 … may be sufficient to produce measurable and perhaps marked changes in climate." The Committee remarked that the resulting changes "could be deleterious from the point of view of human beings." At a meeting in Boulder, Colorado later that year on the causes of climate change, Edward Lorenz and others pointed out the chaotic nature of the climate system and the possibility that climate change could be accompanied by sudden shifts.

In 1967 the International Global Atmospheric Research Program was established, led by the World Meteorological Organization and the International Council of Scientific Unions. Although its objective was primarily to gather data needed to improve weather prediction, climate research was included and benefitted from important field experiments. These field experiments, including the GARP Atlantic Tropical Experiment in 1974 and the Alpine Experiment in 1982, spurred fundamental progress in meteorology, which allowed major improvements in global numerical modeling.

By 1969 Syukuro Manabe and his colleagues had made major advances in modeling and understanding the global ocean-atmosphere system. Manabe, Smagorinsky, and Strickler (1965) presented a comprehensive general circulation model of the atmosphere with a realistic hydrologic cycle. Manabe and Richard Wetherald (1967) used a one-dimensional climate model to explore important processes affecting climate change and climate sensitivity. Manabe and Kirk Bryan (1969) published the first results from a coupled ocean-atmosphere general circulation model.

By 1972 important conferences and studies occurred that are widely cited as the origin of public policy interest in anthropogenic climate change (Study of Critical Environmental Problems, 1970; Study of Man's Impact on Climate, 1971). The first United Nations environment conference (United Nations Conference on the Human Environment) was held in Stockholm in 1972. Although climate change hardly registered on the agenda, which focused on issues such as chemical pollution, atomic bomb testing, and whaling, two important studies were prepared in advance of the conference. "The Study of Critical Environmental Problems" (SCEP) focused on pollution-induced "changes in climate, ocean ecology, or in large terrestrial ecosystems." "The Study of Man's Impact on Climate" (SMIC) endorsed general circulation modeling. Both SCEP and SMIC recommended a major initiative in global data collection, new international measurement standards for environmental data, and the integration of existing programs to form a global monitoring network.

2.2 Planetary Comparisons of Mars, Venus, and Earth

In this section, I note some of the planetary and terrestrial studies of the 1960s and 1970s that provided a basis for understanding of climate systems. I focus on the NASA perspective, especially research in which NASA GISS was involved.

Instrumented exploration of the planets by the space science community in the 1960s and 1970s provided the opportunity to check our understanding for a broad range of planetary conditions, specifically a useful check on how the temperature of a planetary surface depends upon factors such as atmospheric composition and the distance from the sun.

The current conditions on Mars (too cold), Venus (too hot), and Earth (just right for life as we know it to exist) are well explained by the atmospheric compositions and the distance from the sun. The amount of GHGs making up the atmospheric composition, including gases that absorb infrared (heat) radiation and thus act as a blanket that warms the planetary surface, varies dramatically from one planet to another. Greenhouse warming as a global annual average temperature today is about 6°C on Mars, 35°C on Earth, and several hundred degrees on Venus, as a result of successively greater amounts of GHGs on each planet, providing a useful confirmation of understanding of the greenhouse effect (Kasting et al., 1988; Pierrehumbert, 2010).

There is still substantial uncertainty in the detailed history of the evolution of the atmospheric composition of the planets over their full history (Kasting et al., 1988; Pierrehumbert, 2010). However, we know, based on the relative abundances of different hydrogen isotopes in the Venus upper atmosphere, that Venus once had more water vapor and probably an ocean, but most of its water was lost via a runaway greenhouse effect (Ingersoll, 1969; Hansen, 2013).

2.3 Volcanoes Cause Natural Climate Change, Test Climate Models

In 1963, Mount Agung on the island of Bali exploded in a spectacular volcanic eruption, the largest in several decades. The eruption injected a large amount of particles suspended in gas, called *aerosols*, into Earth's stratosphere. My first scientific calculations (Hansen and Matsushima, 1966) were made to help understand the unusual lunar eclipse of 30 December 1963, when the moon became practically invisible as it passed into Earth's shadow. The explanation turned out to be upper atmospheric aerosols formed after a massive injection of SO_2 into the stratosphere by the Agung eruption.

Years later, colleagues and I at NASA GISS used this Agung eruption to test understanding of the global climate response to a short-lived event that temporarily changed the energy balance of the planet (Hansen et al., 1978). We found that the aerosols caused (1) a heating of the stratosphere, by absorbing heat radiation from the lower atmosphere and absorbing a small amount of sunlight; and (2) a cooling of the lower atmosphere and surface of Earth, because the stratospheric aerosols reflected a significant amount of incident sunlight, thus reducing solar heating of Earth's surface.

A simple climate model reproduced stratospheric warming and surface cooling in approximate agreement with observed climate in the few years following the Agung eruption. We concluded in our 1978 article in *Science* that a large volcanic eruption in the future could provide a more valuable test of understanding if observational capabilities were available for prompt measurements after future large volcanic eruptions. The NASA Administrator asked his sciences directorate to support such an instrumentation effort, which aided attainment of observations following eruptions of El Chichon in 1982 and Pinatubo in 1991, as discussed below.

2.4 Charney Study of Climate Sensitivity

Because the federal government was becoming increasingly concerned about the effect of CO_2 emissions on the global climate system, President Carter in 1979 requested the National Academy of Sciences (NAS) to report on the possible climate effect of increasing atmospheric CO_2. The NAS formed a committee chaired by Jule Charney of the Massachusetts Institute of Technology. Charney prepared the report for the Executive Office of Science and Technology Policy, attached here as **Exhibit EE**. Charney focused the study on a specific fundamental question: the eventual (equilibrium) global warming in response to a doubling[2] of atmospheric CO_2. Further, he emphasized study of this question using global climate models (GCMs) that included simulation of three-dimensional atmospheric dynamics using fundamental equations for atmospheric structure and motions.

GISS had conducted GCM simulations for doubled atmospheric CO_2 ($2\times CO_2$). Doubled CO_2 was chosen as a standard forcing because it was about the magnitude of CO_2 increase that could occur in a century if fossil fuel use continued to grow. Syukuro Manabe conducted simulations in 1979 that yielded a 2°C global warming for $2\times CO_2$, while our model produced 4°C warming.

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[2] CO_2 doubling refers to doubling the atmospheric CO_2 concentration from preindustrial CO_2 levels.

The models confirmed prior scientific understanding that an increase in CO_2 would increase Earth's temperatures. The large difference between results of the two models for the increase in temperature per CO_2 doubling spurred efforts to understand the physical processes leading to that difference. Charney visited our laboratory to talk about our modeling. One of his study members, Prof. Akio Arakawa, stayed at our laboratory for several days to analyze the climate model simulations. After further analysis, we concluded that the main differences between the models were in climate feedback processes; most likely the simulated changes of sea ice and clouds. Such feedbacks can either amplify or diminish the simulated climate response. For example, the equilibrium sea ice response to doubling atmospheric CO_2 is expected to be a reduction of sea ice area in the warmer world, which is an amplifying feedback because the dark ocean exposed by reduced sea ice absorbs more sunlight than an ice-covered ocean.

The Charney Report concluded that doubling atmospheric CO_2 would be expected to cause a large climate change, with eventual global warming of $3 \pm 1.5°C$. Narrowing the model's range of uncertainty about how much warming should be expected could be achieved via analysis of climate change in response to changing climate forcings during Earth's history, especially changes of atmospheric CO_2, as discussed below. Nonetheless, all of the models conclusively indicated significant warming from CO_2 forcing. In addition to reporting our results to the Charney committee, which was composed of the preeminent experts in climate sciences, I had numerous discussions with the leaders Charney and Arakawa; it was clear that none of these experts had any doubt that significant warming would occur.

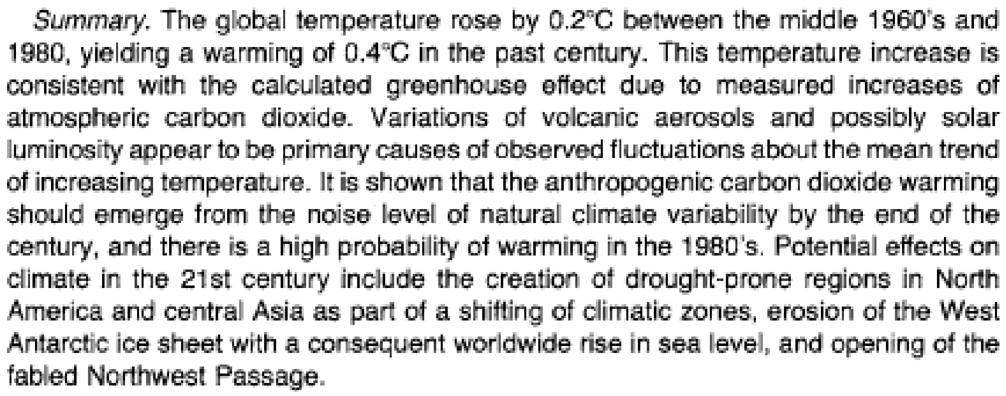
A factor about the Charney Report to bear in mind is that the idealized $2\times CO_2$ experiments kept important parts of the climate system fixed, e.g., ice sheets and vegetation. In reality, and as we are seeing today, as climate changes, these features will change. Some of these omitted feedbacks were thought to be important mainly on long time scales, i.e., they can be classified as "slow feedbacks"; but the main reasons these feedbacks were omitted in these early studies were the absence of good models for ice and vegetation processes and a desire to keep the initial assessment manageable.

Slow feedbacks can be either amplifying or diminishing, and some are very complex to simulate. Fortunately, Earth's history provides substantial information about how slow feedbacks have responded to prior climate change, as will be noted below.

Notwithstanding the uncertainty about how quickly temperatures would rise and the omission of certain feedback loops, Charney, et al. still reported to the Executive Office of the President in 1979 that future climate change would cause severe impacts on future generations in the 21st century, referring to their findings about inevitable warming as "disturbing to policymakers." Charney advised the Federal Defendant Executive Office of the President: "A wait-and-see policy may mean waiting until it is too late" and suggested their findings should be a guide to policy makers.

3. 1981 paper in Science: Climate Impact of Increasing Atmospheric CO_2

Beginning in 1978, NASA provided 3-year special project funding for GISS to study the climate effect of increasing CO_2. We published our first major paper on this topic in 1981 in *Science*.



Summary. The global temperature rose by 0.2°C between the middle 1960's and 1980, yielding a warming of 0.4°C in the past century. This temperature increase is consistent with the calculated greenhouse effect due to measured increases of atmospheric carbon dioxide. Variations of volcanic aerosols and possibly solar luminosity appear to be primary causes of observed fluctuations about the mean trend of increasing temperature. It is shown that the anthropogenic carbon dioxide warming should emerge from the noise level of natural climate variability by the end of the century, and there is a high probability of warming in the 1980's. Potential effects on climate in the 21st century include the creation of drought-prone regions in North America and central Asia as part of a shifting of climatic zones, erosion of the West Antarctic ice sheet with a consequent worldwide rise in sea level, and opening of the fabled Northwest Passage.

Chart 1. Abstract of "Climate Impact of Increasing Atmospheric Carbon Dioxide", by J. Hansen, D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, Science, 213, 957-966, 1981.

This study showed what we knew based on tools and data available almost 40 years ago; specifically simple climate models, temperatures measured at weather stations for about a century, and limited paleoclimate data.

We found that the weather station data was sufficient to yield reasonably accurate knowledge of global temperature change, despite limited coverage in the Southern Hemisphere. We showed that observed warming of 0.4°C from 1880 to 1980 was consistent with climate simulations for a *climate sensitivity* (the amount of change expected from any type of forcing) of about 3°C for doubled CO_2, a climate sensitivity in the middle of the range that the Charney Report had estimated.

We were able to make testable predictions: the 1980s were likely to exhibit warming and in the 1990s, the globe would warm beyond the range of natural variability. The 21st century would see shifting of climate zones, increasing climate extremes including stronger droughts, eroding of ice sheets with rising sea levels, and opening of the Northwest Passage. Observations have confirmed all of these predictions.

We calculated the implications for fossil energy use. We concluded, based on available fossil fuel reserves and paleoclimate evidence (for the sensitivity of sea level to global temperature change), that all coal could not be burned if we wished to preserve shorelines and coastal cities.

Specifically, we stated: "However, the degree of warming will depend strongly on the energy growth rate and choice of fuels for the next century. Thus CO_2 effects on climate may make full exploitation of coal resources undesirable. An appropriate strategy may be to encourage energy conservation and develop alternative energy sources while using fossil fuels as necessary during the next few decades."

This paper in Science received widespread attention, including, e.g., front page reporting in the New York Times and lead editorials in the Washington Post and New York Times. The paper also led to my first testimony to Congress, to a Joint Hearing on Carbon Dioxide and the Greenhouse Effect, of the House of Representatives Subcommittee on Natural Resources, Agriculture Research, and Environment, and Subcommittee on Investigations and Oversight of the Committee on Science and Technology, on 25 March 1982.

4. 1982 Ewing Symposium: Climate Sensitivity and Climate Feedbacks

Taro Takahashi and I organized a symposium on "Climate Processes and Climate Sensitivity" held at Lamont-Doherty Geophysical Observatory (LDGO) in Palisades, New York, on 25-27 October 1982.

4.1 Climate Sensitivity and Feedbacks

In one of the symposium papers (Hansen et al., 1984), my colleagues and I showed that the climate change between a glacial period and an interglacial (warm) period could be used to extract an estimate of climate sensitivity that is largely independent of climate models. I briefly describe that matter here, because of its relevance to issues discussed later in my expert report.

Large oscillations of Earth's climate between ice ages and warmer interglacial periods occur naturally, especially on time scales of 20,000 to 400,000 years. These climate changes are associated with (1) changes in the shape of Earth's orbit about the sun (which varies from nearly circular to elliptical with as much as 7% deviation from a perfect circle), and (2) changes of the tilt of Earth's spin axis relative to the orbital plane (the tilt varying by about one degree larger or smaller than the present tilt of about 23.5°) (Hays et al., 1976). These oscillations of Earth's orbit and spin-axis tilt are caused by neighboring planets, mainly Jupiter and Saturn, because they are so heavy, and Venus, because it passes so close to Earth (Berger, 1978).

Earth's slowly changing orbit and spin-axis tilt both alter the seasonal and geographical distribution of solar radiation striking Earth, spurring a transition (called *oscillations*) back and forth between glacial and interglacial conditions. The direct global climate forcing due to the changing *insolation* (the amount of solar exposure striking the Earth) is very small (Fig. S3, Hansen et al., 2008), but large global climate change is induced via two major "slow feedbacks": (1) changes in the amount of stable atmospheric greenhouse gases (CO_2, CH_4, and N_2O) and (2) changes in the size of ice sheets. As Earth becomes warmer: (1) more of these GHGs are released to the atmosphere by the ocean and continents, and (2) ice sheets become smaller. Thus, both of these feedbacks are *amplifying feedbacks* – meaning they are self-reinforcing and they amplify warming. For example, when (bright, reflective) ice sheets shrink, this exposes darker ground, thus causing more solar energy to be absorbed, increased warming, and further shrinking of the ice sheets.

Climate can be reasonably stable for thousands of years during glacial and interglacial periods. In such periods, Earth must be in near energy balance with space, i.e., Earth radiates an amount of infrared (heat) energy to space equal to the amount of solar energy absorbed by Earth. The "forcings" that keep the interglacial period warmer than the glacial period are the larger amount of GHGs and the darker planetary surface, even though these forcings in reality are slow feedbacks. Thus, the equilibrium climate sensitivity to a change of climate forcing, i.e., the eventual global temperature change after waiting long enough for the planet to return to energy balance, can be estimated by dividing the glacial-to-interglacial global temperature change by the GHG plus surface reflectivity forcing.

We compared the depths of the last ice age (about 20,000 years ago) to the current interglacial period (the Holocene) prior to substantial human influence, concluding that the planet will warm in the range 2.5-5°C for doubled CO_2. This compares to the range 1.5-4.5°C estimated by Charney using climate models. Accepting both of these as valid analyses suggested that climate sensitivity is in the range 2.5-4.5°C for doubled CO_2.

More recent modeling analyses are not able to tighten this range much; the range accounts for the uncertainty. The empirical approach based on Earth's climate history has potential for greater accuracy, but it requires more accurate reconstruction of past global temperatures.

However, even the low extreme in this range of climate sensitivity results in dangerous climate change, if fossil fuel emissions remain high, as discussed in Section 8.

4.2 Energy and CO_2

A keynote talk at the Ewing Symposium mentioned above was given by E.E. David, Jr., President of Exxon Research and Engineering Company on 25 October 1982. David's talk, reproduced in the Ewing volume (Hansen and Takahashi, 1984), includes a remarkably prescient statement: "faith in technologies, markets, and correcting feedback mechanisms is less than satisfying for a situation such as the one you are studying at this year's Ewing Symposium. The critical problem is that the environmental impacts of the CO_2 buildup may be so long delayed. A look at the theory of feedback systems shows that where there is such a long delay the system breaks down unless there is anticipation built into the loop. The question then becomes how to anticipate the future far enough in advance to prepare for it."

This ***delayed response of the climate system*** is the critical factor that gives rise to intergenerational inequities. David correctly concluded that this delayed response demands ***anticipation*** to avoid system breakdown, where, in the climate case, system breakdown would be catastrophic climate change for today's young people and future generations.

E. E. David's Summary and Conclusion begins: "To sum up, the world's best hope for inventing an acceptable energy transition is one that favors multiple technical approaches subject to correction - - feedback from markets, societies, and politics, and scientific feedback about external costs to health and the environment." (Emphasis in original.)

I discuss "the external costs to health and the environment" in detail below. For now, it suffices to say that our 1981 *Science* paper already made clear that all fossil fuels could not be burned without untenable consequences for future generations. Realization of this conclusion and understanding of the impacts of global warming spread rapidly in the following decade, leading to the 1992 United Nations Framework Convention on Climate Change (UNFCCC, 1992).

It was thus clear to 166 nations[3] across the globe by 1992, more than 25 years ago, that the "anticipation" David spoke about would require development of energy sources that did not produce CO_2 and were capable of replacing fossil fuels. Yet, instead, the "anticipation" chosen by the Federal Defendants like the Department of Energy (in collaboration with the fossil fuel industry) was extremely expensive investment in developing technologies such as hydraulic fracturing "fracking," an energy-, chemical-, water-, and resource-intensive process that allows extraction of more and more fossil fuels. The fossil energy approach chosen by Federal

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[3] Today there are 197 parties to the UNFCCC.

Defendants resulted in extraction operations in pristine regions such as the Arctic and the deep ocean, and still includes methods of extraction such as mountaintop removal for coal and forest destruction for increasingly low-grade energy resources like tar sands bitumen, that have detrimental effects on human health and the environment. This course was chosen - to double down on fossil fuels, including carbon-intensive, unconventional sources - even though it was scientifically clear by 1981 that existing fossil fuel reserves contained more than enough carbon to create climate change with dramatic and dangerous consequences, including significant sea level rise.

5. 1988/1989 Congressional Testimony: Advanced Modeling and Data

By 1988, when I testified to the United States Senate, it was clear that the 1980s had warmed as we had projected in our 1981 research paper, and it appeared that 1988 would be the warmest year in the period of instrumental data.

In my testimony (Hansen, 1988) to the U. S. Senate on 23 June 1988, I described three conclusions:

1. Earth was warmer in 1988 than at any time in the history of instrumental measurements.
2. Global warming was large enough that we could then ascribe, with a high degree of confidence, a cause and effect relationship between measured warming and human caused greenhouse gas emissions.
3. Our computer simulations indicated that the measured warming was already large enough to begin to affect the probability of extreme events, such as summer heat waves.

In 1989, I took the opportunity to testify to the Senate once more (Hansen, 1989), because of my concern that conclusion (3) of my 1988 testimony was incomplete, which could lead to public confusion. In my 1989 testimony, I wanted to make clear that, in addition to the more extreme heat waves and droughts caused by global warming, we must also expect more extreme heavy rainfall and thus greater flooding. This is because a warmer atmosphere holds more water vapor, leading to more extreme rainfall from moist convection. In times and places where it is dry, such as the Southwest United States and the Mediterranean region, global warming makes the warm seasons hotter and drier, but in the times and places of rainfall, the rainfall and floods can be more extreme. In most cases, the wet get wetter and the dry get drier.

My 1988 testimony to the United States Senate engendered extensive media coverage because of extreme climate anomalies, including strong heat waves and drought in the United States. My 1989 testimony before the United States Senate also resulted in extensive media coverage because of the revelation that my 1989 testimony had been altered by the White House.[4]

After that period in the public spotlight, I decided that other climate scientists could better communicate the issues to the public, and so for the next 15 years I avoided public testimony and the media.

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[4] I discuss the political censorship of climate science throughout Storms of My Grandchildren (2009).

6. 1989-2004: Research Progress

By 2004, our ability to understand the mechanisms driving global warming and predict the impacts more precisely had improved dramatically. Warming had risen beyond the range of natural variability and the reality of human-caused global warming had become unequivocal. The examples of GISS research that I show here, which contributed to these advances, are from papers available at https://pubs.giss.nasa.gov/authors/jhansen.html.

6.1 Pinatubo Volcanic Eruption

On 15 June 1991, nature launched a great climate experiment as the explosion of Mt. Pinatubo sent massive amounts of gas and dust into the atmosphere. Several colleagues and I used new NASA satellite data to predict the climate effect of the Pinatubo eruption (Hansen et al., 1992). We projected a temporary global cooling of about 0.4°C during the two years following the eruption and observations confirmed a cooling very close to our projections, thus increasing confidence in the ability of global models to simulate correctly the global response to a climate forcing.

Volcanic aerosols and greenhouse gases affect the climate in similar ways, but in the opposite direction. Volcanic aerosols directly cause planetary cooling by reflecting sunlight back into space. The resulting energy imbalance (less energy absorbed by Earth than emitted to space) causes a planetary cooling. In contrast, greenhouse gases reduce heat loss to space, causing the planet to have a positive energy balance, more energy coming in than going out, thus resulting in planetary warming.

Fortunately, a negative (cooling) forcing (like this volcanic eruption) tests our climate models just as well as a positive (warming) energy imbalance. Accordingly, the natural experiment provided by the Mt. Pinatubo eruption provided a valuable confirmation of scientific understanding and climate modeling capability.

6.2 Black Carbon

Increasing atmospheric CO_2 and volcanic aerosols are only two of many pollutants that act to change the Earth's energy balance, referred to as *forcings*. Understanding of climate forcings has advanced over the last few decades through the combination of field measurements, laboratory data, and theoretical studies. Black carbon is an example of a complex climate forcing, which is different than the forcing caused by sulfates, the predominate aerosols produced by volcanic eruptions. Sulfates are light-colored, reflecting most of the sunlight that strikes them, while black carbon absorbs most of the sunlight striking it.

Hansen and Nazarenko (2004) estimated a significant indirect climate forcing caused by black carbon. Black carbon falls out of the air and darkens snow and ice surfaces, absorbing solar energy and causing ice to melt more rapidly. Substantial black carbon is found in the Arctic (Clarke and Noone, 1985), much of which originates from pollution sources at lower latitudes.

Black carbon aerosols are produced from burning of biofuels as well as fossil fuels. Human-made aerosols affect more than climate: they are the largest component of both outdoor (ambient) and indoor air pollution. Outdoor air pollution causes three to four million deaths per year (Cohen et al., 2017; World Health Organization, 2016a). Indoor air pollution, mainly from open fires and simple stoves burning coal and biomass (wood, animal dung, and crop waste), causes more than four million deaths per year (World Health Organization, 2016b). Thus, instituting policies regarding fossil fuels that protect the climate system has the co-benefit of protecting human health from air pollution.

Analyzing the climate role of black carbon requires determination of its efficacy as a climate forcing, as discussed in the next section.

6.3 Efficacy of Climate Forcings

A systematic study of the effectiveness of different forcing mechanisms (Hansen et al., 2005a) defined an "efficacy" for each mechanism. We illustrated that CO_2 is easily the largest human-made climate forcing and CH_4 is the second largest (Hansen et al., 2005a, Figure 28b). The net forcing by "soot" aerosols, (soot being the sum of black carbon and the associated organic carbon aerosols) is smaller than CO_2 and CH_4 forcings (Hansen et al., 2005a).

6.4 Earth's Energy Imbalance

Another layer of quantitative verification of our understanding of global climate change came to fruition near the end of the period 1989-2004. It had long been understood that when greenhouse gases such as CO_2 increase, they would cause a planetary energy imbalance by reducing Earth's heat radiation to space: thus the energy in absorbed sunlight would temporarily exceed the energy returned to space. The planet must warm in response to this positive energy imbalance, but full response to the forcing could require a very long time, decades or even centuries, because of the great thermal inertia of the ocean. The question we undertook to study was the extent of such an energy imbalance and whether it was quantitatively consistent with estimates of climate sensitivity. Hansen et al. (1997) showed, on the basis of climate model simulations for the period 1979-1996 with several alternative representations of the ocean, that there should have been a planetary energy imbalance of about $+0.5\ W/m^2$ averaged over the entire planet in 1979, and this would grow to as much as $0.7\text{-}1\ W/m^2$ at the end of the 20th century.

It is the ocean's thermal inertia that slows the planet's response to changing climate forcing, so the planetary energy imbalance (the net incoming energy) is largely flowing into the ocean. Much smaller amounts of energy go into a net melting of ice and a warming of the ground and atmosphere. The energy going into the ocean can be measured by monitoring ocean temperature throughout the ocean. Despite limitations in the coverage of measurements, especially in the deeper parts of the ocean, and despite difficulties caused by changing technologies employed for ocean temperature measurements, it became clear by 2004 that the ocean was accumulating heat and the rate of energy gain was consistent with expectations (Hansen et al., 2005b).

Measurement of Earth's planetary energy imbalance did more than provide additional confirmation of the most fundamental prediction of greenhouse theory, it also proved that more global warming was already "in the pipeline." This is unavoidable warming that will occur in the coming decades, if atmospheric composition stays as it is today. These conclusions were based mainly on observational data, not climate models.

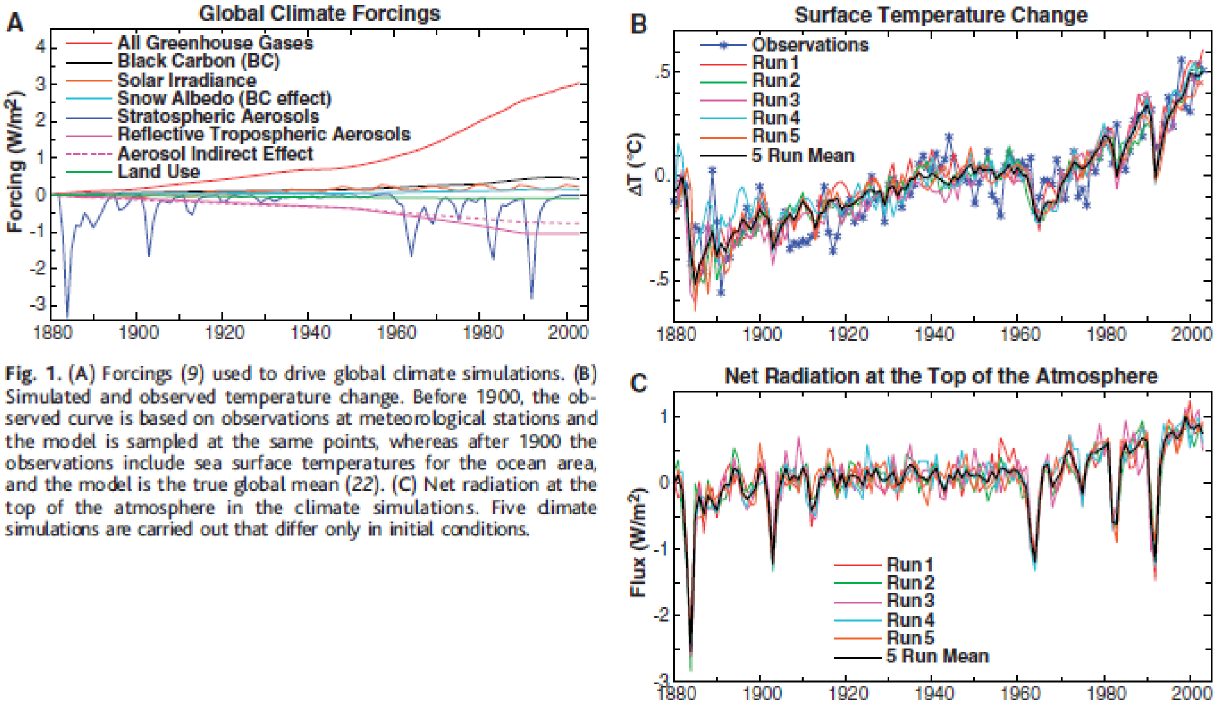

Fig. 1. (A) Forcings (9) used to drive global climate simulations. (B) Simulated and observed temperature change. Before 1900, the observed curve is based on observations at meteorological stations and the model is sampled at the same points, whereas after 1900 the observations include sea surface temperatures for the ocean area, and the model is the true global mean (22). (C) Net radiation at the top of the atmosphere in the climate simulations. Five climate simulations are carried out that differ only in initial conditions.

Chart 2. This is Fig. 1 in the paper by Hansen et al. (2005b). Global surface temperature (B) and Earth's energy imbalance (C) are computed with the GISS climate model using the climate forcings in (A).

Measurements of ocean heat gain, and smaller heat gains inferred from melting ice and warming land and atmosphere, meant that Earth was substantially out of energy balance by the year 2000, by 0.5 to 1 W/m^2. This large imbalance confirmed our understanding of climate sensitivity. If real world climate sensitivity were much smaller than our climate models suggested (2.7°C for 2×CO_2), the ocean surface temperature response would be much more rapid, and Earth's energy imbalance would be much less than the measured 0.5-1 W/m^2.

These fundamental confirmations of the physics of global warming [summarized in two papers submitted for publication in January 2005 (Hansen et al., 2005a, b)] were unsettling to me, and combined with the federal government's ongoing national energy policies promoting fossil fuels, I became concerned enough to bring this information to federal policymakers and to the public. As a federal government employee, I watched Federal Defendants support even the development of unconventional sources of fossil fuels despite the fact that these "unconventional" fossil fuels are even more carbon-intensive than conventional oil and gas and are thus more harmful to the climate.

7. 2004-2010: From Science to Policy Implications

President George W. Bush appointed a cabinet-level energy and climate task force in 2001. However, by late in his first term, if not sooner, it was obvious that the federal government was not taking actions needed to phase out fossil fuel emissions. While I was giving the (politically appointed) NASA Administrator the first climate science presentation that he heard as Administrator, he told me that I should not talk about "dangerous anthropogenic interference" with climate because, he claimed, we did not know how much humans were changing climate or that climate change is dangerous.

What he ignored was decades of scientific research and understanding that preceded his political appointment demonstrating a longstanding understanding that humans were causing dangerous anthropogenic climate interference. By the time he took office, we could even approximate the amount of warming attributable to human activities. The green band in **Figure 1** illustrates the global temperature change that would be expected when we model only natural factors like changes in solar radiation and volcanic eruptions. The purple band shows the results when models account for both natural and human-caused forcings. The black line of observed warming aligns with the results from the models that include human factors.

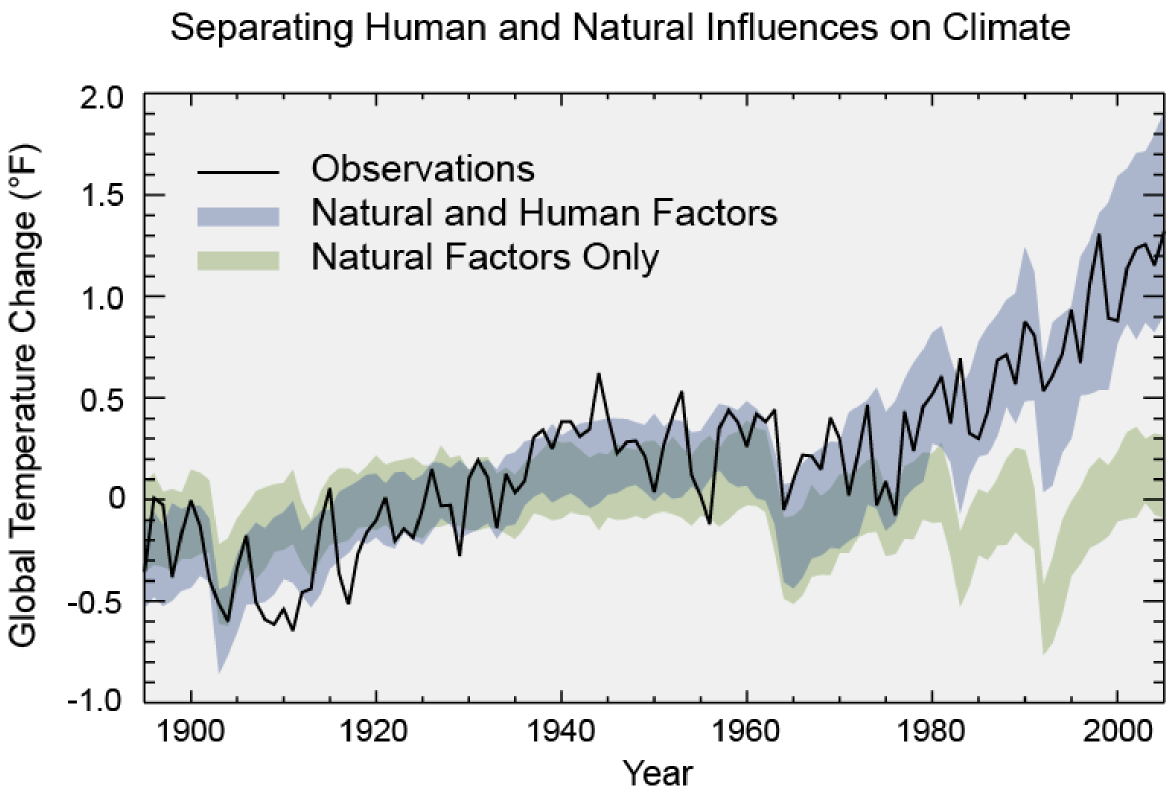

Fig. 1. Human and Natural Influences on Climate. Source: Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Unfortunately, top federal agency leaders gave these same admonitions to scientists in other relevant science agencies of the federal government (Bowen, 2008). Thus, the urgency of the climate situation, especially the danger of locking in large future sea level rise, was being kept from the public, in my opinion, and not reflected in energy policies of the federal government.

For that reason, I abandoned my 1989 decision to avoid the media. I believed that if I gave a well-prepared scientific talk it might help clarify the situation, especially because our new analyses of Earth's energy imbalance provided improved insight. I gave that talk (Hansen, 2004) at the University of Iowa in October 2004 and again a year later I gave an improved version of the talk (Hansen, 2005a) in honor of Charles David Keeling at the annual American Geophysical Union (AGU) meeting in San Francisco.

My talk at AGU resulted in multiple calls from the White House to NASA Headquarters (Bowen, 2008) and the assignment by NASA of a "minder" to monitor my schedule. This allowed NASA to restrict my communications. For example, the White House prevented me from appearing on the National Public Radio program On Point to discuss my AGU talk. After a few such instances, I objected publicly by informing Andy Revkin of the New York Times about the Bush Administration's attempts to silence my exposition on the science of climate change.

At about this time, the focus of my research changed. Instead of focusing only on trying to understand and predict climate change, I began thinking more about impacts of climate change – two potential climate impacts in particular.

The first is the danger that we could lock in large future sea level rise that young people and future generations would be unable to avoid. I described the bases for my concern in a paper: "A slippery slope" (Hansen, 2005b). At the time, the Intergovernmental Panel on Climate Change (IPCC) reports projected a viewpoint that ice sheets were quite stable – that sea level rise this century likely would be no more than a fraction of a meter, even with huge assumed increases of greenhouse gases.

My concern was in part based on paleoclimate evidence. Ice sheet models could reproduce only the long-term glacial-to-interglacial ice sheet changes inferred from sea level change. However, the slow millennial time scale of glacial-to-interglacial ice sheet changes was likely a result of the slow pace of changes of Earth's orbit, not a result of <u>inherently stiff</u> ice sheet physics. I concluded that the extreme forcing resulting from a very short time period of humans rapidly increasing greenhouse gas emissions is not likely to result in a slower glacial-to-interglacial melt. I also argued that the principal mechanism for ice sheet disintegration was probably the effect of a warming ocean on ice shelves, the tongues of ice that extend from the ice sheets into the ocean, a mechanism that was well known but not realistically included in ice sheet models.

I was also concerned about the threat that continued rapid climate change poses to other species. My research group (Hansen et al., 2006) made maps of the rate at which isotherms, lines of a given seasonal average temperature, were shifting in recent decades. Since 1975, isotherms over land have moved poleward at a rate that varies with location and season but is typically 3-6 miles per year (Fig. 6B, Hansen et al., 2006). If such rapid rates are maintained for a century or more it may be deadly for many species, because species must migrate to stay within physical conditions in which they can survive (Parmesan, 2006). The first article that I wrote about this, in New York Review of Books (Hansen, 2006), began: "Animals are on the run."

Climate is always changing, but species have never experienced rapid continuing change comparable to present human-caused climate change. The most rapid large change in the paleoclimate record, the Paleocene-Eocene Thermal Maximum (PETM) was a global warming of about 5°C that occurred in about 4000 years (Zeebe et al., 2016). The PETM warming[5] was driven by a carbon injection into the atmosphere of a magnitude comparable to the amount that would be injected by burning all available fossil fuels (Zachos et al., 2008), which will happen within another century or two with current rates of fossil fuel use. The current rate of carbon injection and the current rate of global warming are thus each about a factor of 10 larger than occurred during the PETM.

Some species can migrate easily, others are more restricted, and there is an interdependency among species (Parmesan, 2006). Migration today is also hindered by human-made barriers and human-caused stresses on species, such as overharvesting, land use changes, nitrogen fertilization, and introduction of exotic species. As a result, IPCC (2007) estimated that as much as a quarter to half of all species could be committed to extinction by 2100, if rapid CO_2 emissions and climate change continue.

The enormity of the potential consequences of these two matters – loss of coastal cities and loss of a huge number of species – demanded reassessment of what constituted “dangerous human-made interference” with climate. The “burning embers” diagram used by IPCC (2007) as a tool to illustrate risk left the mis-impression that serious risks began with global warming of 2-3°C.

The European Union, in 1996 and again in 2005, chose 2°C as a political guardrail and the United Nations, in the 2009 Copenhagen Agreement to the UNFCCC concurred (Randalls, 2010). The international political decisions to target 2°C as a guardrail did not have a strong scientific basis in 1996 nor in 2009, in contrast to our analyses based on changes of GHGs needed to restore Earth’s energy balance and assessment based on past association of sea level rise with warming.

By the early 2000s I was reasonably convinced, mainly on the basis of paleoclimate evidence, that 2°C global warming (equivalent to an atmospheric CO_2 concentration of approximately 450 ppm) would be highly dangerous. Our scientific understanding indicated an initial target of no more than 350 ppm CO_2 to avoid dangerous impacts, but the target must be continually evaluated as the world made progress in turning around CO_2 growth (CO_2 in 2007 was already 385 ppm).

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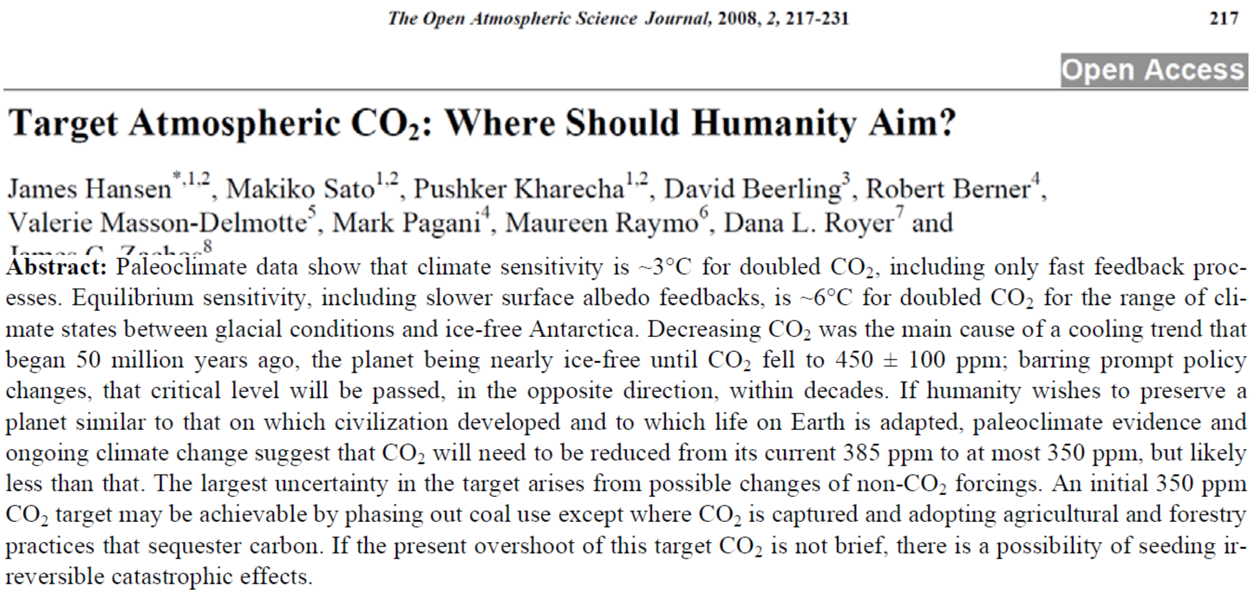
[5] The “sudden” PETM warming, which was a temporary ~4000 year spike in the geologic record, occurred 56 million years ago during a 10 million year-long warming period. The 10 million year warming trend was associated with increasing atmospheric CO_2 (Beerling and Royer, 2011), likely a result of increasing volcanic CO_2 injection into the atmosphere associated with increased rates of seafloor subduction beneath moving continental plates (“continental drift”) (Kent and Muttoni, 2008). The carbon source for the PETM spike likely was methane hydrates on continental shelves (Dickens et al., 1995), although a suggested alternative source is Antarctic permafrost and peat (DeConto et al., 2012).



The Open Atmospheric Science Journal, 2008, 2, 217-231 217

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Target Atmospheric CO_2: Where Should Humanity Aim?

James Hansen[*,1,2], Makiko Sato[1,2], Pushker Kharecha[1,2], David Beerling[3], Robert Berner[4], Valerie Masson-Delmotte[5], Mark Pagani[4], Maureen Raymo[6], Dana L. Royer[7] and James C. Zachos[8]

Abstract: Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica. Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.

Chart 3. Abstract of Target CO_2 paper published in *The Open Atmospheric Science Journal* in 2008.

In December 2007, I was fortunate to begin work with several of the top relevant paleoclimate researchers, including the godfather of carbon cycle modeling on long time scales, Yale Prof. Robert Berner, on a study ("Target CO_2: Where Should Humanity Aim?"). The study used long-term climate change (including CO_2 amounts much larger than today), glacial-interglacial climate oscillations of the past 800,000 years, Earth's modern energy imbalance, and climate modeling to complete a broad-based assessment. We concluded that 2°C and 450 ppm were extremely dangerous. Such warming would lock in eventual loss of coastal cities, including more than half of the world's large cities. In addition, the tropics in all seasons and subtropics in summer would become uncomfortably hot, limiting outdoor activity and likely causing large scale emigration from those regions. Economic and social effects of such displacements would challenge the ability of governments to maintain order. We concluded that an initial target of 350 ppm was appropriate, but the target must be fine-tuned as progress in reducing atmospheric CO_2 is achieved.

These conclusions, peer-reviewed and, more significantly, coming from some of the best climate scientists in the world, fundamentally altered the global picture for energy policies.

Many governments had been willing, and continue to be willing today, to accept a target to keep global warming from exceeding 2°C even though there was substantial scientific evidence showing such a target was highly dangerous to humanity. Why did they accept this target? I believe it is because they were comfortable with the limited immediate requirements for fossil fuel emissions reduction that a 2°C target placed on them and because the worst impacts would accrue in the future. It was easier to allow CO_2 levels to climb to 450 ppm, rather than restore them to a level that avoided or minimized climate danger. A 2°C target primarily required setting goals for emission reductions in future years, allowing business as usual to continue with minimal efforts to improve energy efficiency and subsidize clean energies (which, however, still remain a small piece of total energy). This 450 ppm CO_2 target avoided the need to face the task of confronting the powerful fossil fuel industry in the near term.

The Federal Defendants acted as if they could leave the task of confronting the fossil fuel industry to young people. Except that they couldn't--not unless they wanted to consign their children, grandchildren, and future generations to an unlivable planet. Our science-based assessment made crystal clear that the casualty in the convenient 2°C global warming target was the future of young people. The scientific community took notice of our paper, as shown by more than 1000 citations. No contradicting conclusions, that 2°C warming would be safe, have appeared in refereed scientific papers, to my knowledge, and certainly not by any of the scientific unions or academies of science. I was director NASA GISS at the time we published this paper. Its clear recommendations on a target were disseminated to the highest levels of the federal government and Federal Defendants, e.g., to the Science Adviser to the President.

Our conclusion that a target of no more than 350 ppm by the end of the century must be achieved raised a fundamental question: were we asking the Federal Defendants to do something that is possible? Can emissions be phased down substantially faster than in the 2°C scenarios?

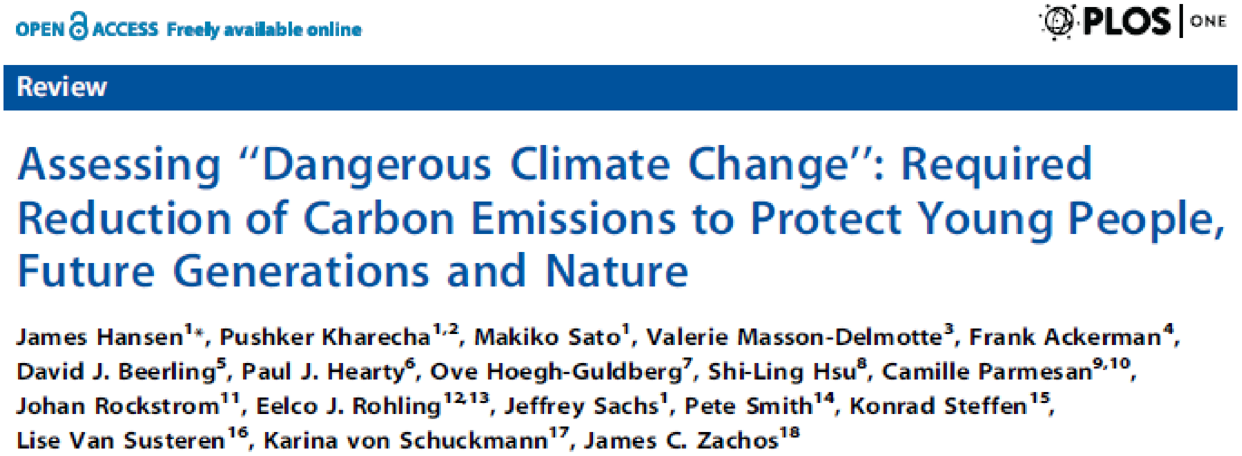
The answer to that question is crucial to young people. I suspect that answer is also helpful to the Court's considerations, because Plaintiffs are asking the Court to require the Federal Defendants to have an energy/climate recovery plan that no longer violates the Constitutional rights of the Plaintiffs. Specifically, Plaintiffs are asking the Court to require the Federal Defendants to develop and implement a plan to reduce fossil fuel emissions at a rapid rate, substantially faster than emission scenarios that would be required to achieve the 2°C target.

In addition to consistently drawing the government's attention to dangerous levels of warming and atmospheric CO_2, I have conducted studies presenting ample evidence that the ambitious, necessary target of 350 ppm is achievable (Hansen, 2008a, 2008b, 2009, 2013b). However, as long as fossil fuels are a cheap, federally-permitted and supported source of energy, the public and industry will continue to use them.

Fossil fuels are cheap in part because they receive significant federal public subsidies and because they are not required to pay their costs to society, including costs of air pollution, water pollution, and climate change. Many economists (Mankiw, 2009; Hsu, 2011; Ackerman and Stanton, 2012, to name a few) have written about this flaw in the energy market, offering such strategies as a steadily rising carbon fee or carbon tax, so that the price of fossil fuels reflects their cost. They note that such an approach is beneficial for the national economy, the general principle being that an economy is more efficient if prices are honest.

8. 2010-2017: Increasing Urgency and Need for Judicial Remedy

Despite the 1992 Framework Convention on Climate Change (UNFCCC, 1992) and the resulting 1997 Kyoto Protocol intended to reduce GHG emissions, global fossil fuel emissions actually increased at a faster rate after 1997 than they did in the two decades leading up to 1997 (an annually-updated graph of CO_2 emissions is available at http://www.columbia.edu/~mhs119/CO2Emissions/).



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Review

Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature

James Hansen[1]*, Pushker Kharecha[1,2], Makiko Sato[1], Valerie Masson-Delmotte[3], Frank Ackerman[4], David J. Beerling[5], Paul J. Hearty[6], Ove Hoegh-Guldberg[7], Shi-Ling Hsu[8], Camille Parmesan[9,10], Johan Rockstrom[11], Eelco J. Rohling[12,13], Jeffrey Sachs[1], Pete Smith[14], Konrad Steffen[15], Lise Van Susteren[16], Karina von Schuckmann[17], James C. Zachos[18]

Abstract: We assess climate impacts of global warming using ongoing observations and paleoclimate data. We use Earth's measured energy imbalance, paleoclimate data, and simple representations of the global carbon cycle and temperature to define emission reductions needed to stabilize climate and avoid potentially disastrous impacts on today's young people, future generations, and nature. A cumulative industrial-era limit of ~500 GtC fossil fuel emissions and 100 GtC storage in the biosphere and soil would keep climate close to the Holocene range to which humanity and other species are adapted. Cumulative emissions of ~1000 GtC, sometimes associated with 2 °C global warming, would spur "slow" feedbacks and eventual warming of 3-4 °C with disastrous consequences. Rapid emissions reduction is required to restore Earth's energy balance and avoid ocean heat uptake that would practically guarantee irreversible effects. Continuation of high fossil fuel emissions, given current knowledge of the consequences, would be an act of extraordinary witting intergenerational injustice. Responsible policymaking requires a rising price on carbon emissions that would preclude emissions from most remaining coal and unconventional fossil fuels and phase down emissions from conventional fossil fuels.

Chart 4. Abstract of Assessing "Dangerous Climate Change" paper published in *PLoS ONE* in 2013.

Following our 2008 "Target Atmospheric CO_2" paper, I undertook an analysis with my colleagues to specify the rate at which CO_2 emissions must decline to stabilize climate and return atmospheric CO_2 to 350 ppm by 2100. The "Target CO_2" paper had gone a long way toward achieving that objective, but I decided to do a deeper analysis with the help of international experts in the relevant disciplines.

Thus in late 2010 I contacted a number of experts to begin working on a substantive, quantitative paper (Assessing "Dangerous Climate Change") to define emission reduction requirements.

8.1 Assessing "Dangerous Climate Change": Required Emissions Reduction

Numerous scientists agreed to help produce the paper 'Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature' including experts in climate science and the carbon cycle, but also three economists and experts on the impacts of climate change on human health, species extinctions, and coral reefs.

Paul Epstein of Harvard University, who drafted the portions of the paper on human health and the environment while he was battling late stages of non-Hodgkin's lymphoma, did not live to see completion of the paper, which we dedicated to him. Lise Van Susteren, a psychiatrist, joined the team to help complete the health discussion, bringing attention to the psychological

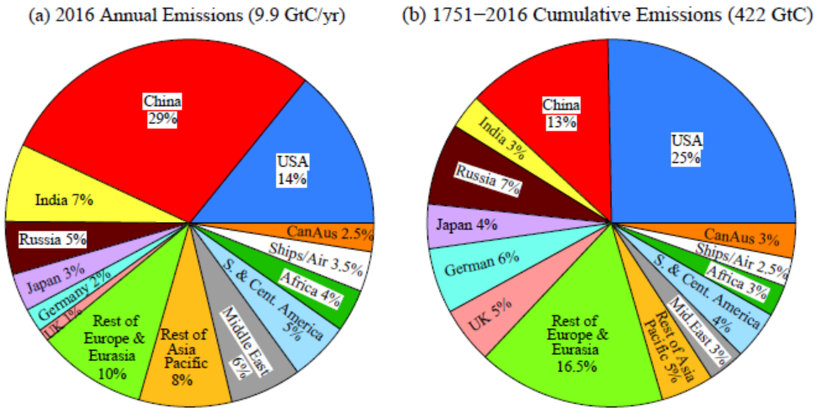

Fig. 2. Fossil fuel CO_2 emissions by source in 2016 and cumulative 1751-2016. Results are an update of Figure 10 of Hansen et al. (2013b) using data of Boden et al. (2017) and BP (2017).

impact of global warming on young people, an issue that will grow if these Federal Defendants do not undertake actions to stabilize climate.

Our paper describes the practical impacts of continued global warming. If ice sheets are allowed to become unstable, shorelines will not be stable at any time in the foreseeable future, instead experiencing continual sea level rise for centuries, a consequence of the slow response time of ocean temperature and ice sheet dynamics. Economic and social implications could be devastating. Because more than half of the largest cities in the world are located on coastlines and the population of coastal regions today continues to grow rapidly, the number of refugees would dwarf anything the world has ever experienced. It is not difficult to imagine a scenario in which the world could become nearly ungovernable.

Rapid shifting of climate zones, already well underway, will be a major contributor to species extinction if global warming continues. Coral reefs, the "rainforests of the ocean," harboring millions of species, are already threatened by the combination of a warming ocean, ocean acidification, rising sea level, and other human-caused stresses. The subtropics in summer and the tropics in all seasons will become dangerously hot, such that it will be difficult to work outdoors (Hansen and Sato, 2016). More than half of the jobs are outdoors (agriculture and construction), so there is a large economic impact that makes those parts of the world less desirable to live in.

Increasing CO_2 is now responsible for about 80 percent of the annual increase in climate forcing by greenhouse gases, the other 20 percent being from the combination of CH_4, N_2O, and other trace gases. China is now the largest source of CO_2 from fossil fuels and cement manufacture, with the United States second (**Fig. 2a**). However, we showed (Hansen et al., 2007) that climate change is proportional to cumulative CO_2 emissions, as discussed in more detail by Matthews et al. (2009). Thus, by contributing a disproportionately large share of cumulative global emissions, (**Fig. 2b**), the United States is, by far, the nation most responsible for the associated increase in global temperatures. Matthews et al. (2014) calculate the United States alone is responsible for a 0.15ºC increase in global temperature. "The United States is an unambiguous leader" in total contributions to global warming, "with a contribution of more than double that of

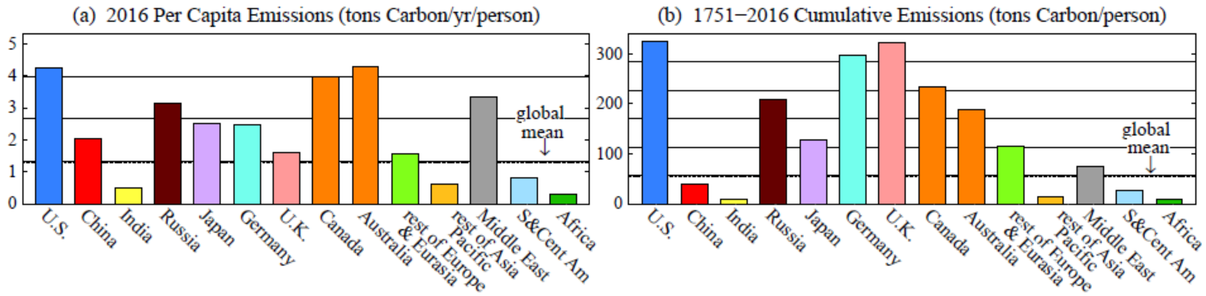

Fig. 3. Per capita fossil fuel CO_2 emissions in 2016 and cumulative 1751-2016. Data sources as in **Fig. 1**. Results for additional individual nations are available at www.columbia.edu/~mhs119/CO2Emissions/

China, which falls second in the ranking." (Matthews et al. 2014). On a per capita basis, the United States, the United Kingdom, and Germany are about equally responsible (**Fig. 3b**).

Nations in the tropics and subtropics, expected to suffer major climate impacts, have little responsibility for climate change. Such nations are located especially in South and Central America, in Africa (including the Mediterranean region), in Southeast Asia, and in Oceania.

Even though China's degree of responsibility will grow in coming years and decades, the outsize responsibility of the United States, and in particular these Federal Defendants, will be a burden for young people to bear if climate change is allowed to grow to the point that major populations are seriously impacted and even displaced. Continued support and authorization for current high fossil fuel emissions by the Federal Defendants, given existing knowledge of the consequences, would continue to exacerbate the danger they created and enhanced.

The measured energy imbalance of Earth indicates that atmospheric CO_2 must be reduced to a level below 350 ppm by the end of the century, which would be expected to restore energy balance and keep global temperature at or below +1°C relative to preindustrial temperature, assuming that the net of other human-made climate forcings remains at today's level. Specification now of a CO_2 target more precise than <350 ppm is difficult due to uncertain future changes of radiative forcing from other gases, aerosols and surface albedo, but greater precision should be feasible during the time that it takes to turn around CO_2 growth and approach the initial 350 ppm target. This warming limit keeps global temperature closer to the range that has existed during the past thousands of years in which civilization developed, but the warming limit too must be reassessed as progress is made in reducing atmospheric CO_2. It is my best expert opinion, based upon my decades of study and research, that these are the maximum levels of CO_2 and temperature increase that avoid dangerous consequences for young people and future generations. The precise limits may indeed be lower than I have specified here, but they surely are not higher.

The quantitative conclusion of the PLoS ONE paper (Hansen et al., 2013b) was that it would be possible to return atmospheric CO_2 to 350 ppm this century and restore Earth's energy balance, keep end-of-centurywarming at no more than 1°C of warming, and reasonably stabilize climate. Achieving that result required reducing fossil fuel emissions several percent per year and extracting some CO_2 from the air via reforestation of marginal lands and improved agricultural

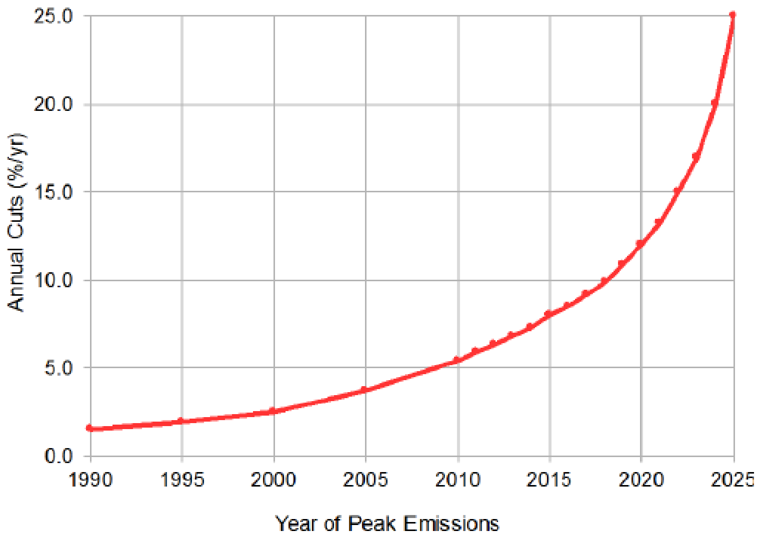

Fig. 4. Annual cut of emissions (in percent of emissions) required to achieve 350 ppm by 2100 as a function of the year at which emissions peak.

and forestry practices. This scenario assumed that emission reductions would begin in 2013 at a global average annual rate of ~6% (exponentially, i.e., the 6% applies to the fossil fuel emissions remaining at that time) per year through 2050 and 100 GtC sequestered globally through improved land management practices and reforestation through 2100.

Consistent with Hansen et al. (2013b), delay of the date at which emission reduction begins causes an increase in the required rate of emissions reduction to meet the requirement of restoring CO_2 to 350 ppm in 2100. **Figure 4** shows that the required rate increases very rapidly if emission reduction does not begin soon. Further, the implausibility of somehow sucking the excess CO_2 from the air, if high emissions are allowed to continue, has been demonstrated quantitatively (Hansen et al., 2017), the implied costs for young people running into the hundreds of trillions of dollars.

One focus of the PLoS ONE paper was on economics, because of the potential concern that actions to stabilize climate might be considered too costly by politicians. The economist co-authors have a comprehensive range of expertise and experience: Frank Ackerman on the social cost of carbon, integrated assessment models and their limitations, and involvement with the IPCC economic studies; Shi-Ling Hsu on the relative merits of cap-and-trade versus a carbon tax or fee and on international regulations and policies; Jeffrey Sachs on sustainable development, developing country issues and United Nations programs.

Those co-authors on the PLoS ONE paper concluded that one important potential underlying policy, albeit not sufficent alone, is for emissions of CO_2 to come with a price that allows these costs to be internalized within the economics of energy use. It was also concluded by these experts that inclusion of fossil fuel costs to society (caused by air pollution, water pollution and climate change) in the price of the fossil fuels would make the economy more efficient, and would thus be an overall benefit to the nation. Quantitative confirmation of this conclusion was obtained in a later economic study for the United States (Nystrom and Luckow, 2014), which showed that a steadily increasing carbon fee with all of the proceeds distributed uniformly to

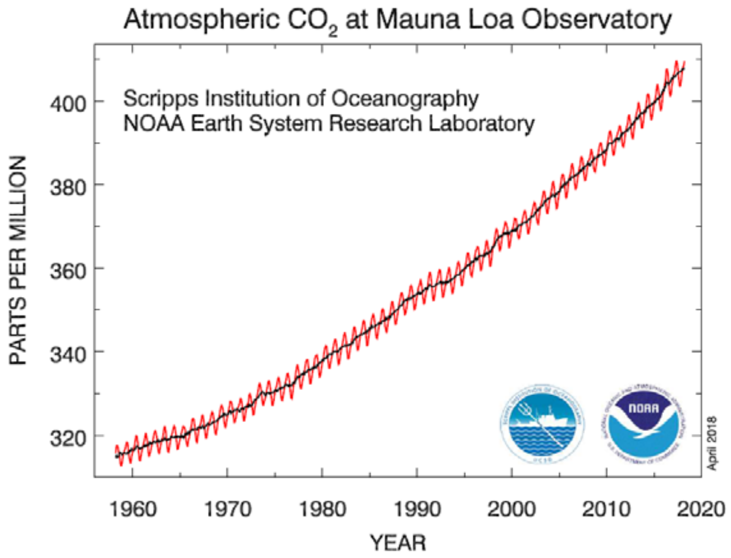

Fig. 5. Atmospheric CO_2 amount measured at Mauna Loa observatory in Hawaii. Measurements in the early decades were made by Charles David Keeling and in recent years by NOAA.

legal residents would increase GNP and create millions of jobs. The most directly relevant conclusion of this latter economic study is that a rising carbon fee would cause United States CO_2 emissions to fall at a significant rate.

The actions decribed above (rapid phasedown of CO_2 emissions and increased carbon storage in the soil and biosphere) are minimally needed to restore Earth's energy balance, preserve the planet's climate system, and avert irretrievable damage to human and natural systems – including agriculture, ocean fisheries, coastlines, and fresh water supply – on which human civilization depends. However, if rapid emissions reductions are delayed until 2030, for instance, then the global temperature will remain more than 1°C higher than preindustrial levels for about 400 years. Were the emissions cessation only to commence after 40 years, then the atmosphere would not return to 350 ppm CO_2 for nearly 1000 years at the earliest – and due to feedbacks described below, it is probable that returning to 350 ppm within that timeframe would become impossible. Overshooting the safe level of atmospheric CO_2 and the safe range of global ambient temperature for anything approaching these periods will consign Plaintiffs and succeeding generations to a vastly different, less hospitable Earth, including conditions in the United States.

8.2 Danger Grows for Young People

Global emission reductions did not begin in 2013. Dangers for young people continued to grow. Atmospheric CO_2 continued to grow. **Figure 5** is an update of the famous "Keeling curve," the amount of atmospheric CO_2 measured in pristine Pacific Ocean air at Mauna Loa, Hawaii. Not only is atmospheric CO_2 continuing to increase, it's annual rate of growth, which averaged less than 1 ppm per year when Keeling began his measurements in the late 1950s, now averages more than 2 ppm per year (**Figure 6**). **Exhibit S** extends the Keeling curve back to 1870 with the help of a curve created by G.S. Callendar in 1957.[6]

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[6] G.S. Callendar, *On the Amount of Carbon Dioxide in the Atmosphere*, Tellus X (1958) available at http://www.rescuethatfrog.com/wp-content/uploads/2017/01/Callendar-1958.pdf

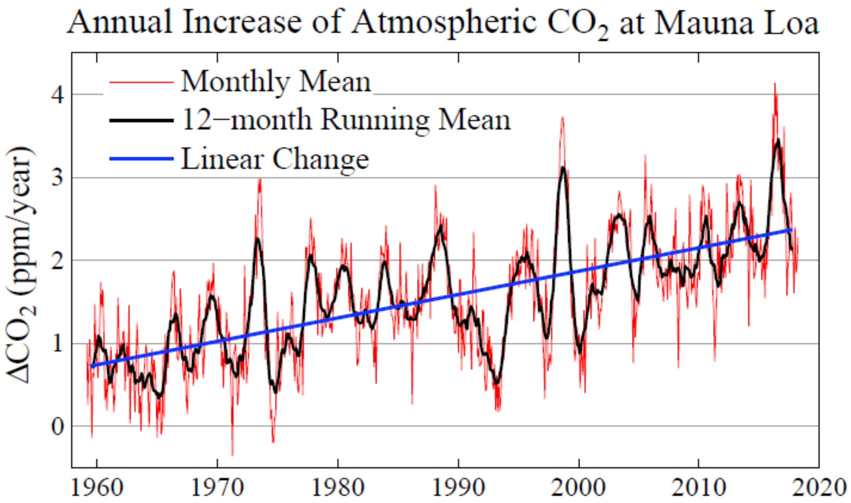

Fig. 6. Annual increase of monthly mean atmospheric CO_2 at Mauna Loa. CO_2 data obtained from P. Tans (www.esrl.noaa.gov/gmd/ccgg/trends) and R. Keeling (www.scrippsco2.ucsd.edu/).

Current high levels of long-lived atmospheric GHGs CO_2, CH_4, and N_2O will have consequences for young people and future generations. Well-understood and confirmed theory, climate models, and empirical data all concur that these GHG levels will cause substantial and highly dangerous global warming for humans and many other species if they are left in place for long.

Paleoclimate data for the past 140,000 years (**Fig. 7**) helps provide some perspective on what can be expected. **Figure 7** here is Fig. 27 from the paper "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous" (Hansen et al., 2016). This figure is a bit technical for the layperson. Here I briefly note key take-away points:

The period covered, from 140 ky ago (1 ky = 1000 years) to the present, includes two interglacial periods: the Eemian, from about 130 ky ago to 116 ky ago, and the Holocene, from about 11,700 years ago to the present. The quantity $\delta^{18}O$ is based on measurements of an oxygen isotope in ice cores from the Greenland (**Fig. 7b**) and Antarctic (**Fig. 7c**) ice sheets and provides a proxy measure of temperature change in the past. The amplitude (or maximum extent) of the glacial-to-interglacial temperature change, say between the depths of the ice age 20 ky ago and the mean Holocene temperature is around 10°C on both of these polar ice sheets (green and blue curves in 5b and 5c), but only about half that amount on global average.

Greenhouse gas amounts are shown in **Fig. 7c** for CO_2 and in **Fig. 7d** for CH_4 and N_2O. Sea level is shown in **Fig. 7f**. Much of this long-term climate change is spurred by insolation changes (changes in the amount of solar radiation reaching Earth's atmosphere) (**Fig. 7a**) associated with changes of Earth's orbit about the Sun and changes of the tilt of Earth's spin axis. However, the climate forcings that maintain the global temperature are changes of the GHGs, which yield a glacial-interglacial climate forcing of about 3 W/m^2 (**Fig. 7e**), and changes in the size of ice sheets. The size of ice sheets and the negative forcing that they cause by reflecting sunlight can be inferred from sea level (**Fig. 7f**). The size of ice sheets, and thus sea level, change almost synchronously with global temperature, but high resolution studies indicate

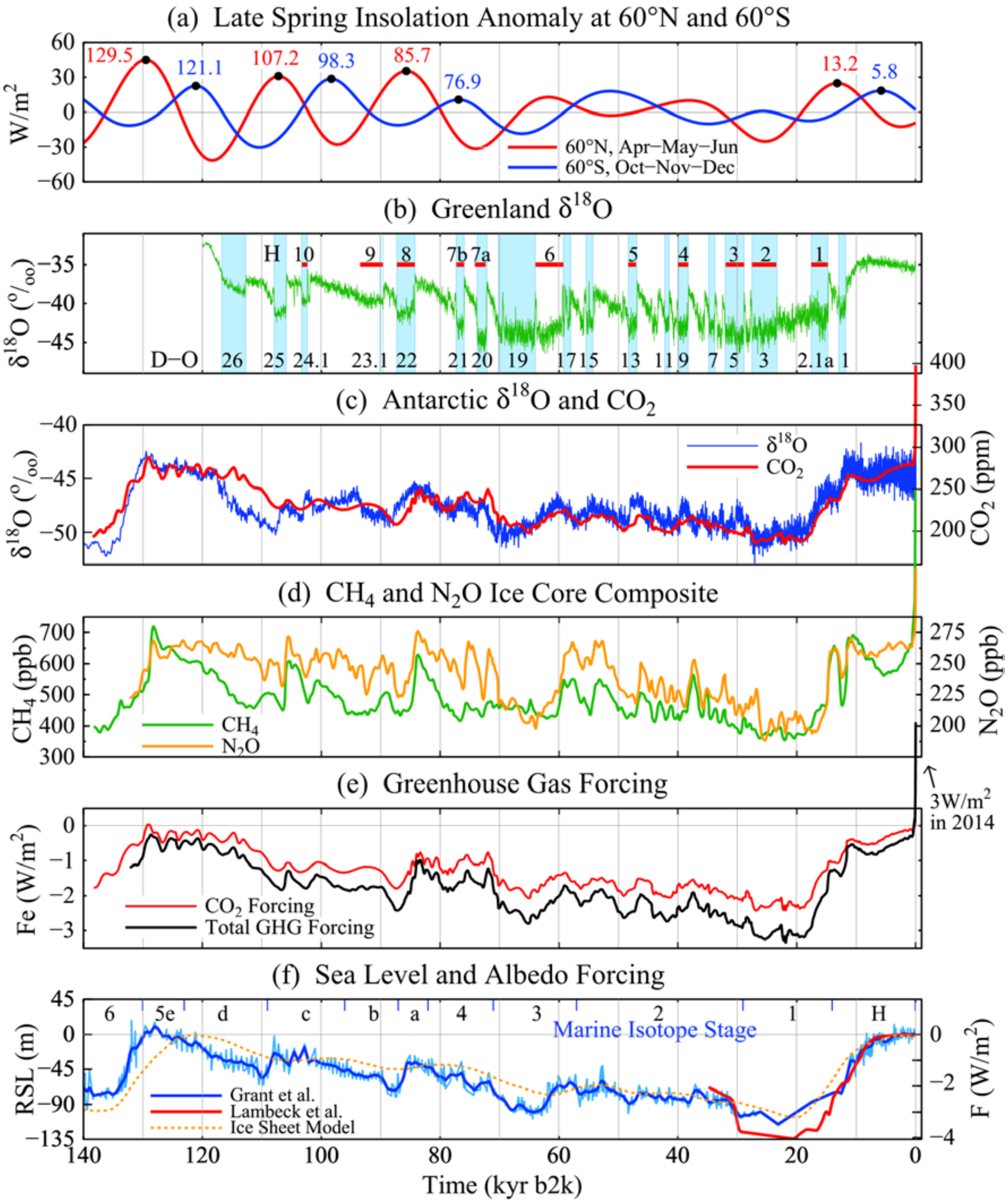

Fig. 7. (a) Late spring insolation anomalies relative to the mean for the past million years, (b) $\delta^{18}O_{ice}$ of composite Greenland ice cores (Rassmussen et al., 2014) with Heinrich events of Guillevic et al. (2014), (c, d) $\delta^{18}O_{ice}$ of EDML Antarctic ice core (Ruth et al., 2007), multi-ice core CO_2, CH_4, and N_2O based on spline fit with 1000-year cut-off (Schilt et al., 2010), scales are such that CO_2 and $\delta^{18}O$ means coincide and standard deviations have the same magnitude, (e) GHG forcings from equations in Table 1 of Hansen et al. (2000), but with the CO_2, CH_4, and N_2O forcings multiplied by factors 1.024, 1.60, and 1.074, to account for each forcing's "efficacy" (Hansen et al., 2005a), with CH_4 including factor 1.4 to account for indirect effect on ozone and stratospheric water vapor, (f) sea level data from Grant et al. (2012) and Lambeck et al. (2014) and ice sheet model results from de Boer et al. (2010). Marine isotope stage boundaries from Lisiecki and Raymo (2005). (b-e) are on AICC2012 time scale (Bazin et al., 2013).

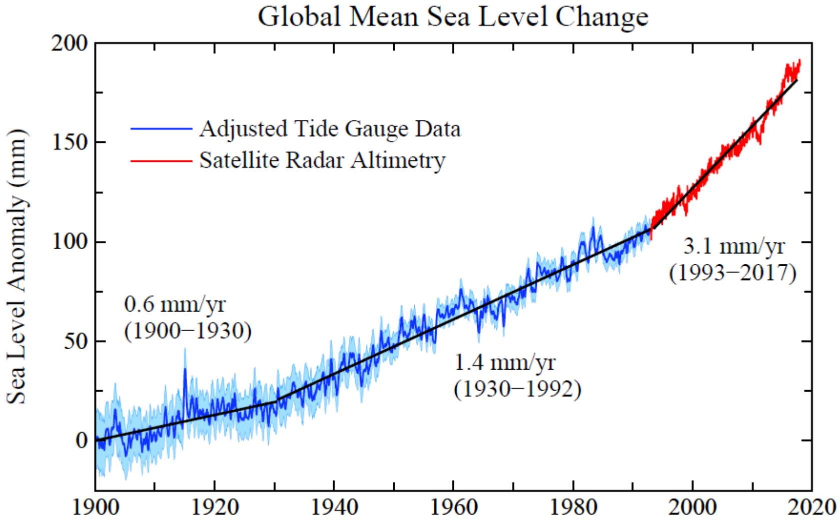

Fig. 8. Sea level change (Hansen et al., 2016) based on satellite altimetry (Cazenave and Le Cozannet https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/references.html) and tide gauge data (Church and White, 2011) with the latter change rate multiplied by 0.78, so as to yield a mean 1901-1990 change rate 1.2 mm/year (Hay et al., 2015).

that the sea level change lags (follows) the temperature change by 1-4 centuries (Grant et al., 2012). The relationship of gas amounts and temperature can be complex because changes of GHG amounts are induced by climate change, so temperature change sometimes precedes gas changes. However, global temperature responds to the planetary energy imbalance induced by change of GHG amount. Thus, the GHGs control global temperature, and the temperature controls ice sheet size with ice sheet size and sea level lagging 1-4 centuries after temperature change in the paleoclimate record.

CO_2 accounts for about 80 percent of the GHG climate forcing in the paleo climate changes. Indeed, CO_2 is the control knob that tightly controls global temperature as illustrated in Fig. 28 of Hansen et al. (2016) and discussed there and by Lacis et al. (2013).

The right-hand edge of **Fig. 7** shows the CO_2, CH_4, N_2O, and the GHG climate forcing shooting off the scale of the chart, unlike anything we have seen in the paleo record. Temperature change has not yet caught up to the forcing. Earth has not nearly reached its full response to the GHG changes that humans have made. The most rapid response (the fast-feedback response) is only partly complete, as shown by Earth's continuing energy imbalance. The slow-feedback response, the shrinking of ice sheets and release of GHGs by the soil, biosphere, and ocean, has barely begun, and could still be short-circuited if GHG amounts are reduced quickly and sufficiently to restore planetary energy imbalance or achieve a slightly negative imbalance. Indeed, such short-circuiting is what young people must require of their elders, if they wish to avoid continued global warming and climate impacts that are dangerously out of their control. To be clear, the effects of the CO_2 forcing humans have injected into the atmosphere and our climate system is far from being fully realized in terms of warming and sea level rise, *yet*. Because of the slow feedback loops of global warming, there is still a brief period of time today through century's end to reduce the concentrations of atmospheric CO_2, and slow and ultimately reverse global warming, if actions are commenced immediately, thereby avoiding the catastrophic and unprecedented warming that would occur in coming centuries.

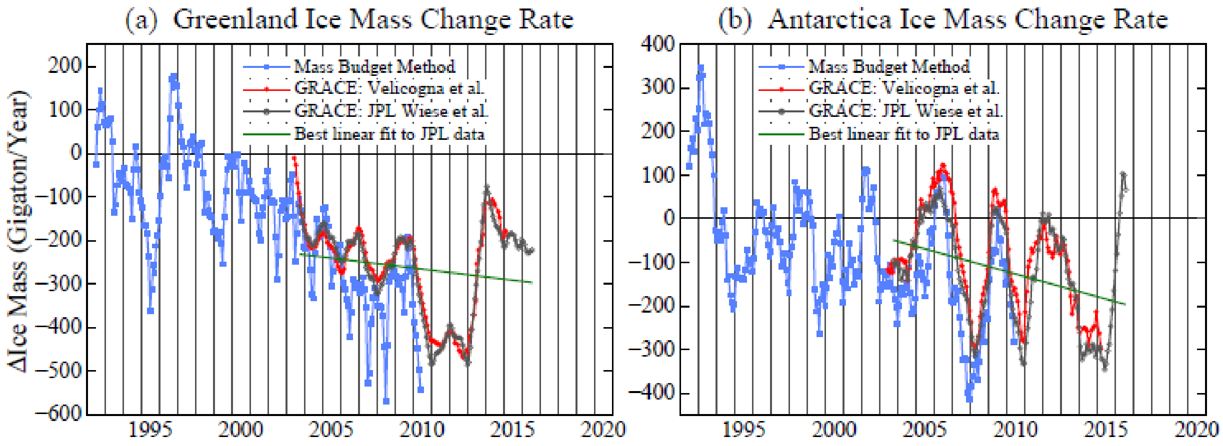

Fig. 9. Greenland and Antarctic ice mass change. GRACE data is extension of Velicogna et al. (2014) gravity data. MBM (mass budget method) data are from Rignot et al. (2011). Red curves are gravity data for Greenland and Antarctica only. This is an update of Fig. 30 of Hansen et al. (2016).

Sea level was reasonably stable for the past several thousand years, prior to the industrial era. Preindustrial sea level changes were less than one meter per millennium, which is less than 10 cm (4 inches) in a century. Even with satellite measurements today, it is difficult to measure the year-to-year change of global average sea level, but **Fig. 8**, from our "Ice Melt" paper, captures the acceleration of the rate of sea level rise. Recent improved analyses of the satellite data suggest that the rate has accelerated within the satellite era (Chen et al., 2017).

Sea level and temperature are highly correlated in the paleo record: as Earth warms, ice melts. Response of ice sheets to warming on the short term can be complex, as it depends on the local weather during the short summer melt season, which accounts for the change in mass loss rate of Greenland between 2012 and 2013 seen by a gravity-measuring satellite (red curve in **Fig. 9**, based on an update of Velicogna et al., 2014). However, the principal factor causing large sea level rise is expected to be ice dynamics and increased ice mass flux to the ocean. A warming ocean melts buttressing ice shelves, increasing the rate of ice sheet discharge to the ocean.

Antarctic ice sheet mass loss is the potential source of large sea level rise. In our "Ice Melt" paper, we present evidence, from modern observations, modeling, and paleoclimate analyses, that the Atlantic Meridional Overturning Circulation (AMOC) is slowing as a result of freshening of the ocean mixed layer in the North Atlantic. Resulting reduced northward heat transport in the ocean will tend to warm the Southern Ocean, increasing the threat of Antarctic ice mass loss. Our paper (Hansen et al., 2016) concludes that continued high fossil fuel emissions this century would produce nonlinearly growing sea level rise reaching multi-meter levels within a time scale of 50-150 years.

The climate system is out of equilibrium. In such a system, in which the ocean and ice sheets have great inertia but are beginning to change, the existence of amplifying feedbacks presents a situation of great concern. There is a real, imminent danger that we are handing young people and future generations a climate system that is practically out of their control.

To further illustrate the danger of a 2°C target, 2°C global warming implies eventual sea level rise of at least 6 meters (20 feet), in accord with recent expert assessment (Dutton et al., 2015).

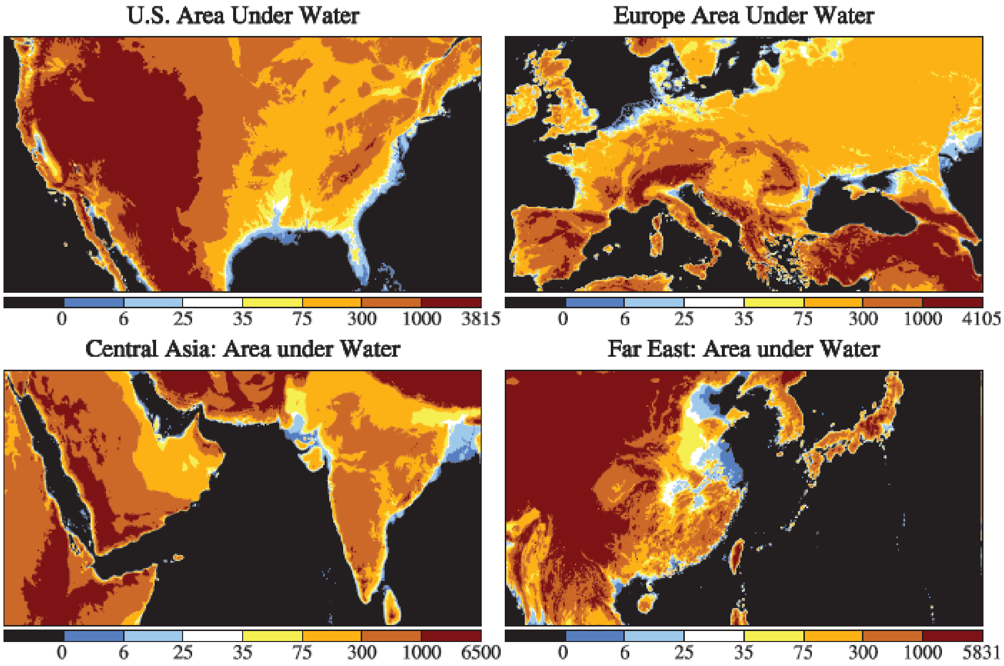

Fig. 10. Areas (light and dark blue) that nominally would be under water for 6 and 25 m sea level rise.

However, scenarios with 2°C warming based on assessments that include only fast feedbacks (as in most studies) imply eventual warming of 3-4°C from the added effects of slow feedbacks. That would make Earth at least as warm as in the Pliocene, suggesting a sea level rise of 15-25 m. **Figure 10** shows areas that would be under water for 6 and 25 m sea level rises. These areas include a majority of the world's largest cities and a total population of hundreds of millions of people (see higher resolution maps for areas affecting individual Plaintiffs in **Exhibits E-K**). Based upon all of this evidence, it is my expert opinion that it is imperative that we stabilize global temperatures at cooler temperatures than we have today and only allow for an overshoot above 1°C for a very short period of time, consistent with our 350 ppm prescription.

8.3 Young People's Burden: Requirement of Negative CO_2 Emissions

Continued actions by these Federal Defendants to perpetuate carbon pollution and not take immediate action to restore our climate system is endangering and limiting the prospects for young people. While our 2013 PLoS ONE paper concluded that the combination of rapid emissions reduction and storage of carbon in the soil and biosphere via reforestation and improved forestry and agricultural practices could keep global temperature close to the Holocene range, continued high emissions and continued global warming are altering that picture. Thus, the levels of required emissions reductions have changed since this case was first filed in 2015, and as stated in the First Amended Complaint.

Global temperature relative to preindustrial time now exceeds 1°C (**Fig. 11**), and fossil fuel emissions continued to increase after 2013, rather than decline. Global temperature is well above the range that has occurred in the Holocene, the last 11,700 years (**Fig. 12**). Note that the 1880-1920 mean temperature serves as our best estimate of the preindustrial level, because the small warming effect of human-made GHGs that had been added by 1880-1920 was approximately offset by greater than average volcanic activity in 1880-1920 (Hansen et al., 2017).

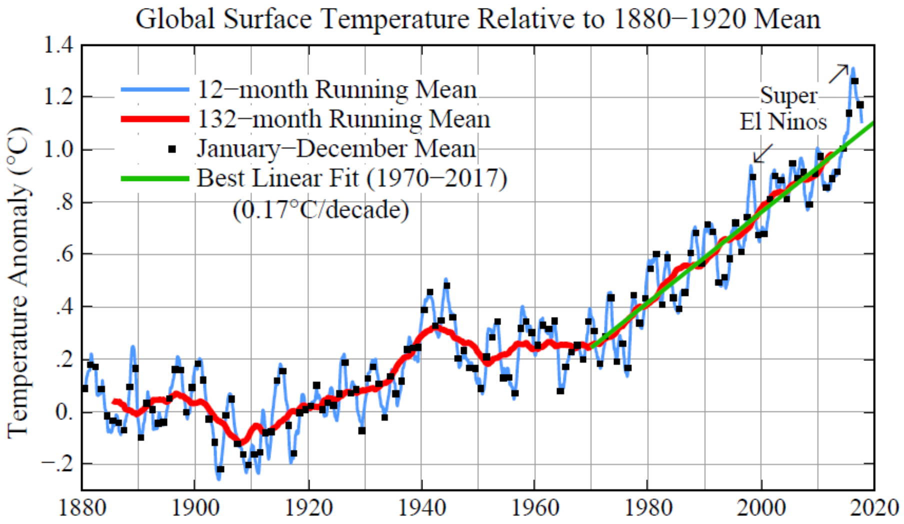

Fig. 11. Global surface temperature relative to 1880-1920, an update of Fig. 2 of Hansen et al. (2017) with the data here extending through June 2017. Black squares are calendar year (Jan-Dec) means.

In the "Young People's Burden" (Hansen et al., 2017) it is further shown that the rapid warming of the past four decades has raised global temperature to a level matching best estimates for the level of warmth in the Eemian period. The Eemian period, the most recent interglacial period prior to the Holocene, lasted from about 130,000 to 116,000 years before present. Global temperature in the Eemian, at about +1°C relative to 1880-1920, was moderately warmer than the Holocene and sea level reached heights as great as 6-9 meters (20-30 feet) above present.

During the past several thousand years during which civilization evolved, cities were built along coastlines at or just above sea level with enormous investment. This has been possible because of stable sea level. Similarly, agricultural regions and other settlements relate to relatively stable Holocene climate patterns. Our coastal cities, agricultural food production on which we depend, and other environment-dependent livelihoods are placed at risk if we allow warming to continue. Because of the inertia of ocean temperature, the long time required to cool once it has warmed, we stand to lock in highly undesirable consequences for young people and future generations if we let warming reach the extraordinary level +2°C, which would exceed Eemian warmth.

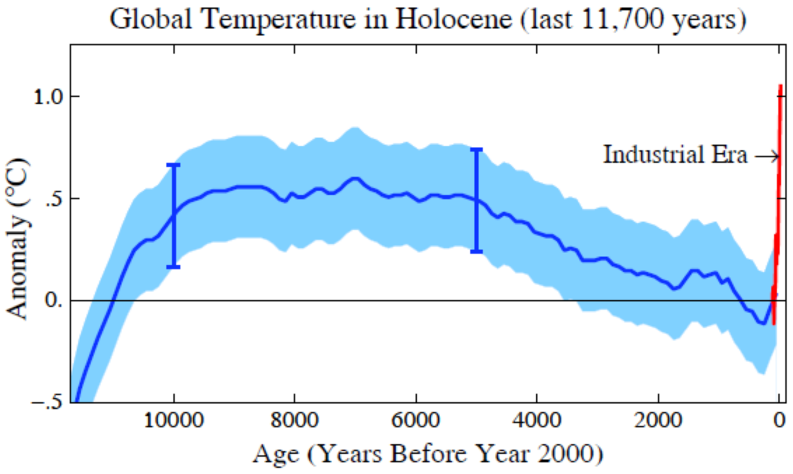

Fig. 12. Estimated centennially-smoothed global-mean Holocene temperature (Marcott et al., 2013) and 11-year mean of modern data (**Fig. 6**), as anomalies relative to 1880-1920 (Hansen et al., 2017).

It is the decades-long research culminating in the "Young People's Burden" paper that leads me to my expert opinion: **we must strive this century to keep global warming from exceeding about 1°C relative to the pre-industrial level. This is fully consistent with our prior conclusion that we must aim to reduce CO_2 to less than 350 ppm.** These conclusions were developed and reached by a cadre of some of the best scientists in the world in relevant disciplines. The appropriate limits for global temperature and atmospheric CO_2 may indeed be lower, but they certainly are not higher. A scientifically-defensible target to aim for this century should be no higher than CO_2 of 350 ppm and 1°C of warming relative to the pre-industrial level.

Achieving those levels now requires "negative emissions," i.e., extraction of CO_2 from the air. If phasedown of fossil fuel emissions begins soon, most, if not all, of this extraction can still be achieved via improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content. In that case, the magnitude and duration of global temperature excursion above the natural range of the current interglacial (Holocene) could be minimized. In contrast, continued high fossil fuel emissions would place a burden on young people to undertake massive technological CO_2 extraction if they are to limit climate change and its consequences. Estimated costs of such extraction are in the range of tens to hundreds of trillions of U.S. dollars this century, which raises severe questions about their feasibility. Continued high fossil fuel emissions unarguably sentences young people to a massive, implausible cleanup or growing deleterious climate impacts or both.

Figure 13 (from Hansen et al. 2017) illustrates the different emissions trajectories including the dangerous emissions scenarios evaluated by the IPCC and a trajectory of returning to 350 ppm by the end of the century (Hansen, et al. 2017). If emissions were reduced 6% per year beginning in 2013, 350 ppm in 2100 could be achieved with CO_2 sequestration/extraction of 100 GtC. Because of the failure to initiate reduced emissions, the 6% scenario in **Fig. 13** requires that the extraction of CO_2 be increased from 100 GtC (PgC) to 153 GtC (PgC).

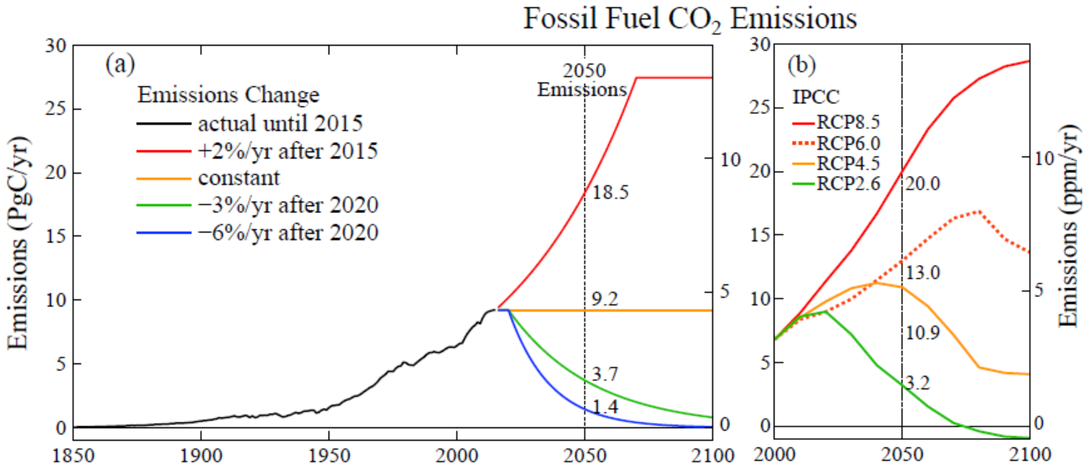

Fig. 13. Fossil fuel emissions scenarios. **(a)** Scenarios with simple specified rates of emission increase or decrease. **(b)** IPCC (2013) RCP scenarios. Note: 1 ppm atmospheric CO_2 is ~ 2.12 GtC.

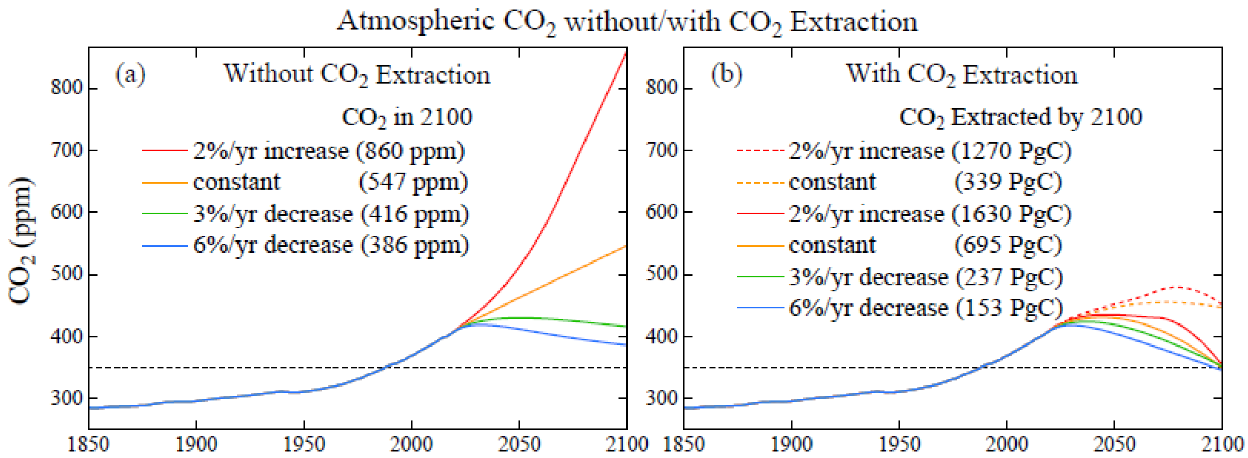

Fig. 14. Atmospheric CO_2 for Fig. 13a emission scenarios. **(a)** Atmospheric CO_2 including effect of CO_2 extraction that increases linearly after 2020 (after 2015 in +2% yr^{-1} case).

Finally, I note that my analysis is based on real-world data for temperature, planetary energy balance, and GHG changes. As such, it differs from the inaccurate (and congratulatory) perception of progress toward stabilizing climate emanating from some politicians. The hard reality of the physics emerges from the continually increasing global surface temperature (**Fig. 11**), the large planetary energy imbalance that guarantees additional warming (see Fig. 5 of Hansen et al., 2017), and from **Fig. 15**. **Figure 15** shows that the GHG climate forcing is not only continuing to grow, its annual growth rate is accelerating!

The accelerating growth of the GHG climate forcing is a result of increasing growth rates of CO_2 and CH_4. (**Fig. 15**, right side) in the atmosphere. Their recent growth may be partly climate feedback, but such feedback is fueled by the initial GHG source, which is primarily fossil fuels.

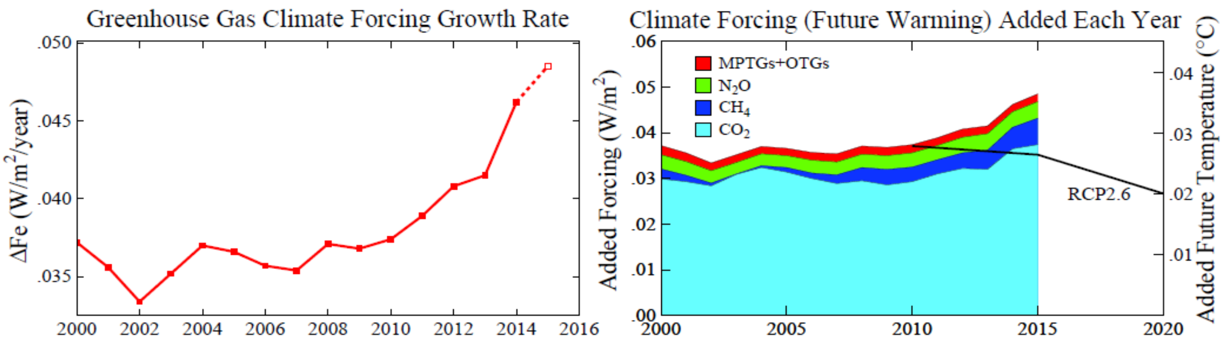

Fig. 15. (a) Recent growth rate of total GHG effective climate forcing; points are 5-year running means, except 2015 point is a 3-year mean. (b) Contribution of individual gases to GHG climate forcing growth rate. RCP2.6 is an IPCC scenario that would keep global warming less than 2°C, but it requires a declining growth rate of climate forcings, which are actually accelerating. The temperature scale on the right is the annual addition to equilibrium warming for climate sensitivity 3°C for doubled CO_2.

9. Summary

I have reviewed, and participated in the creation of, historical progress in the development of our understanding of human-caused climate change. Fossil fuel emissions are responsible for most of the increase in atmospheric CO_2, and increasing CO_2, in turn, is the main cause of Earth's energy imbalance and planetary warming. Accordingly, human decision-making and action are now in control of our planet's thermostat. The Federal Defendants have a heavy hand in how far that control knob is turned due to their historic and continuing support of fossil fuels and the size of U.S. emissions.

However, our ability to turn back the dial will not long persist. In particular, continued high emissions are now pressing the system towards a point of no return, beyond which consequences will proceed without any realistic opportunity for human control. Dialing back Earth's thermostat and stopping short of calamity requires concerted, thoughtful, and timely action.

I have reviewed, as well, the special responsibility of our federal government in creating our nation's present predicament, in light of the fact that the emissions from fossil fuel consumption that the Federal Defendants have authorized, permitted, and subsidized exceed, by far, those of any other nation. The inference that our nation bears a special responsibility to resolve the crisis is also supported by the fact that we retain the requisite expertise and capacity to do so, and that our young persons and our nation's future generations have nowhere else to turn.

9.1 High-level Government Knowledge

Our federal government has long known the fundamental features of this enveloping climate crisis. Beyond my own public attempts to bring the matter to its attention while a government employee, much of the evidence for that long-held knowledge resides in the federal government's own high-level reports.

Since my time working with the federal government, these reports include a 1977 Council on Environmental Quality study that warned that "[a] possible 2-3 degrees C average temperature increase must be looked upon as a major global environmental threat." [7] Similarly, a 1983 EPA report projected sea level rise between five and seven feet by 2100, with a higher than average rise along Atlantic and Gulf Coast states.[8] Another 1983 EPA report anticipated a "2 degree C (3.6 F) increase in temperature . . . by the middle of the next century and a 5 degree C (9 F) increase by 2100," with such temperature increases "likely to be accompanied by dramatic changes in precipitation and storm patterns" with agricultural conditions "significantly altered, environmental and economic systems potentially disrupted, and political institutions stressed."[9]

A 1985 Department of Energy report, moreover, observed that "[i]f increased concentrations of CO_2 and trace gases raise the global mean surface temperature by 1.5°C or more, the resultant

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[7] The 8th Annual Report of the Council on Environmental Quality available, as of July 15, 2017, at https://babel.hathitrust.org/cgi/pt?id=mdp.39015021811750;view=1up;seq=230, p. 190.

[8] Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs**,** available, as of July 19, 2017, at http://www.biodiversitylibrary.org/item/86886#page/3/mode/1up.

[9] EPA, Can We Delay a Greenhouse Warming? (1983), available, as of July 19, 2017, at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9101HEAX.TXT.

average global climatic conditions will be beyond the range of climates that have existed during the historical past and during recent geological times."[10]

These reports suffice to establish that enough was known even four decades ago for the federal government to have begun to act preventatively to arrest and limit the severity of climate change. This is consistent with my understanding of the federal government's knowledge during the years I worked in the federal government at NASA GISS. As discussed *supra* (Section 3) limitations on allowable fossil fuel use and implications for policy were already clear by at least 1981. The failure of the federal government to act to avert avoidable consequences, and indeed to facilitate and support the increased use of fossil fuels since 1981, will place a disproportionate burden on today's young people and future generations.

9.2 Sea Level Rise and Youth Plaintiffs

Earlier I provided graphics (*supra*, **Figure 10**) of several major land regions – the U.S., Europe, Central Asia, and the Far East – with blue highlighting over current land surfaces that would be submerged in events of truly extreme sea level rise ("SLR"). Specifically, I illustrated areas covered by water for sea level rises of 6 m and 25 m. Eventual SLR of those orders would be expected in response to, respectively, +1°C relative to preindustrial (Eemian level of warmth) and +4°C relative to preindustrial, where +4°C is typical of the magnitude of warming projected by IPCC to occur within a century if business-as-usual fossil fuel emissions continue. As discussed above (Section 8.2), the time scale on which such many-meter SLR can occur remains uncertain and is dependent on the speed at which greenhouse gases continue to increase.

These enormous amounts of sea level rise are possible in light of the forgoing discussion. However, I must note two things: first, the large scale of those graphics may not sufficiently convey the impact of anticipated sea level rise on Plaintiffs in the event of continuing high CO_2 emissions; and second, unacceptable impacts in the United States will be induced by far less extreme sea level rise than 25 m.

Accordingly, in **Exhibits E-R**, including accompanying video animations, I illustrate impacts on several U.S. coastal cities and communities from moderate to high SLR, with attention to locations that may be of particular continuing concern to some Youth Plaintiffs. The maps and animations are based on projections published in 2017 by NOAA, the key science agency within the federal Department of Commerce.[11] For my summary of these, see **Box 1**.

Box 1: Sea Level Rise and Impacts on the Homes of Youth Plaintiffs

NOAA's projections account for, among other things, changes in ocean circulation patterns, changes in Earth's gravitation field and rotation due to melting ice sheets, and ground subsidence

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[10] Projecting the climatic effects of increasing carbon dioxide, available, as of July 13, 2017, at http://archives.aaas.org/docs/Projecting_Climate_Effects_Increasing_CO2.pdf.

[11] *See* Global and Regional SLR Scenarios for the U.S. and Data: Global and Regional SLR Scenarios for the U.S., from NOAA Technical Report NOS CO-OPS 083, available as of July 20, 2017, from https://tidesandcurrents.noaa.gov/pub.html.

or uplift. Under certain sea level rise scenarios, this yields higher levels of SLR for nearly every state than NOAA's projected global mean sea level rise.[12]

The maps in **Exhibit E** indicate that the home of one Youth Plaintiff, presently situated at 8.6 meters elevation some 50 miles from the Gulf, may become coastal property – again, in the event that NOAA's extreme, but increasingly plausible, SLR scenario is realized for the year 2100. By 2200, under that scenario, this Plaintiff's home would be submerged. *See* also the animation illustrating impacts to Southern Louisiana at **Exhibit L**.

The maps in **Exhibit F** illustrate that under NOAA's projections, the family home of one of the Youth Plaintiffs in this case, situated at ~ 0.8m elevation in Satellite Beach, FL., may be lapped by the rising sea within several decades, fully inundated by 2100, and potentially overtopped by the year 2200, in the event of continued high emissions. *See* also **Exhibit M** for coastal Florida potential SLR animation. Those rising seas for calm waters do not include the already occurring flooding and from increasingly severe storm surges and hurricanes affecting that Youth Plaintiffs' home.

One Youth Plaintiff has expressed hope that her grandmother's home in Yachats, Oregon, at 8.5 m elevation, will remain safe and available for Plaintiff's own children and grandchildren. I too hope for her that will be true, but NOAA's projections include the possibility that rising seas may lap the family home by the year 2200 (again, in the event of business as usual emissions). *See* impacts to Yachats region at **Exhibits G and N**. For potential sea level projections relevant to another Oregon-based Youth Plaintiff's coastal home, namely in Manzanita, Oregon, *see* **Exhibits K and R**.

The homes of two Youth Plaintiffs living in Seattle, at 76-87 m elevation, may be situated above the reach of projected sea level rise. Still, Puget Sound will be substantially reshaped by eroding coastlines in the event of continued high emissions. *See* impacts to the Puget Sound shoreline at **Exhibits H and O**.

Several Plaintiffs have connections to New York City, as do I. Accordingly, I include, as **Exhibits J and Q**, maps and animation showing the potential impact of SLR on New York City, with the Hudson River overtopping its bank at least to 57th Street and the East River to 42nd Street under NOAA's extreme SLR scenario. Much of Battery Park, Tribeca, Soho, East Village, and the Bronx would be submerged. So too would much of Brooklyn and Jersey City be submerged.

I have no doubt that important and fundamental interests of Youth Plaintiffs may be damaged by sea level rise even when they do not presently live at sea level (or even near a coast). One Youth Plaintiff moved recently with his family inland to higher ground in the face of the rising sea on the north shore of Kauai, Hawaii. However, he continues to be adversely impacted by eroding beaches, dying reefs, sea water intrusion into local freshwater ecosystems, etc. Based on this Plaintiff's declaration, ECF 41-5, "[w]atching the beaches erode away and disappear brings me

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[12] Alaska's coastline being the sole exception.

deep emotional pain." We should all feel that pain. *See* **Exhibits I and P** indicating the prospective inundation of parts of Kauai's shoreline.

I conclude from these exhibits and other information that the family homes of several Youth Plaintiffs are directly threatened by projected or potential sea level rise due to global warming. These exhibits do not take into account the increased frequency and depth of flooding, storm surges and critical infrastructure failure that will likely precede the direct inundation of Youth Plaintiffs' homes. I understand, as well, that the fundamental interests of many, probably all, of the other Plaintiffs also are severely jeopardized by the likely inundation of coastal regions of the United States, particularly as we account for the lost functioning of major coastal cities and the ensuing economic and social disruption that may cut this nation to its knees.

9.3 Actions of the Government

This lawsuit seeks to establish that the aggregate actions and decisions not to act by our federal government have caused and exacerbated dangerous climate change in unconstitutional deprivation of Plaintiffs' fundamental rights. The Trump Administration's astounding recent efforts to accelerate fossil fuel CO_2 emissions are pressing the world more rapidly towards the climate precipice. However, in my view, the initial focus of Plaintiffs' First Amended Complaint on the continuous and aggregate nature of the Federal Defendants' acts of endangerment, that is, those across multiple administrations, remains proper – as the actions of the present Federal Defendants build upon earlier acts and acts of omission of the Federal Defendants' predecessors.

Thus, for example, in its final year, the Obama Administration imposed a moratorium on new coal leases on public lands, which is now in the process of being lifted.[13] Yet that long overdue move by the Obama Administration followed its 2011 decision to open up hundreds of millions of tons of coal on public lands to new lease sales.[14] Those sales, moreover, were at prices far below market, continuing an over three decade long practice of federal subsidization to coal titans amounting to, through those sales alone,[15] tens of billions of dollars.[16]

Moreover, the Obama Administration failed to follow up its partial moratorium in any substantial way, ignoring calls to end all public lands coal leasing – including a petition from several climate scientists based on the understanding that "the vast majority of known coal in the United States must stay in the ground . . . to be consistent with national climate objectives, public health, welfare, and biodiversity."[17] The Trump Administration's decision to roll back the 2016 Obama

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[13] *In Climate Move, Obama Halts New Coal Mining Leases on Public Lands*, New York Times, Jan. 14, 2016.
[14] *See Feds open 758 million tons of Powder River Basin coal to leasing*, Casper Star-Tribune, Mar. 22, 2011.
[15] That is, not accounting for public health costs and climate change costs imposed on the public from the unrestricted burning of the coal mined pursuant to leases secured at far below market price.
[16] *See Report- Almost $30 billion in revenues lost to taxpayers by "giveaway" of federally owned coal in Powder River Basin*, Institute for Energy Economics and Financial Analysis (June 25, 2012) available, on May 1, 2017, at http://ieefa.org/study-almost-30-billion-in-revenues-lost-to-taxpayers-by-giveaway-of-federally-owned-coal-in-powder-river-basin/.
[17] *Scientists Support Ending Coal Leasing on Public Lands to Protect the Climate, Public*

Administration's moratorium,[18] therefore, constitutes a major step down the same dangerous path trod by the Obama Administration, and other prior administrations, during the lion's share of its time in office. The harms caused to our climate system by the Defendants have long been non-partisan, systemic, and in contravention of its long-standing knowledge of the dangers of carbon pollution.

By deciding to abandon the Obama Administration's Clean Power Plan,[19] the Trump Administration is advancing the interests of the coal industry, a key sector of the fossil fuel industry and part of President Trump's campaign base. But in a similar fashion, by its Clean Power Plan, the Obama Administration sought to favor the natural gas sector – a growing and slightly different portion of the fossil fuel industry – while modestly bending down the curve of total power plant emissions. Critically, the Federal Defendants, through the Clean Power Plan, did not seek to commence a phase out of all fossil fuels, even though the need to achieve that objective was widely understood by the time of that Clean Power Plan's effective date[20] to be necessary to restore a viable climate system.[21] In fact, as discussed above, the need to phase out all fossil fuels was well understood long before the Clean Power Plan was developed.

Accordingly, the decision by the Trump Administration to kill or further weaken the Clean Power Plan builds upon the great deference to the fossil fuel industry that kept the Obama Administration from timely committing itself in the battle for a livable planet, and instead adopting an "all of the above" energy strategy, which largely included fossil fuels.[22]

I do not mean by this discussion to suggest an equivalency between the present administration and its predecessor, either as to climate or anything else. However, President Obama clearly recognized that there is "such a thing as being too late" on climate,[23] yet his actions to avert climate change were minimal and he missed opportunities for fundamental progress (see prior footnote). My central point is that the actions of the Federal Defendants in violation of Plaintiffs' underlying right to a viable climate system have not only just begun. The actions (and

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Health, and Biodiversity, available at https://www.biologicaldiversity.org/programs/public_lands/energy/dirty_energy_development/coal/pdfs/16_7_26_Scientist_sign-on_letter_Coal_PEIS.pdf. I was a signatory on this letter.

[18] Executive Order 3348, March 29, 2017, available as of July 1, 2017 at https://www.doi.gov/sites/doi.gov/files/uploads/so_3348_coal_moratorium.pdf.

[19] *See* Executive Order on Promoting Energy Independence and Economic Growth, March 28, 2017, available on June 15, 2017 at https://www.whitehouse.gov/the-press-office/2017/03/28/presidential-executive-order-promoting-energy-independence-and-economi-1.

[20] Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units; Final Rule (Oct. 23, 2015) available at https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf.

[21] Indeed, the government admits in its answer that the Plan would likely lead to an increase in the use of natural gas for electricity production, and that it did not directly address the extraction, production, and exportation of fossil fuels. ECF 98 at ¶127.

[22] *See also* an account by the Sierra Club's former chief climate counsel, David Bookbinder, *Obama had a chance to really fight climate change. He blew it*. Vox (April 29, 2017) available at https://www.vox.com/the-big-idea/2017/4/28/15472508/obama-climate-change-legacy-overrated-clean-power. *See also* my opinion piece of May 12, 2012, *Game Over for the Climate,* New York Times, available at http://www.nytimes.com/2012/05/10/opinion/game-over-for-the-climate.html.

[23] Obama in Alaska: 'There is such a thing as being too late' on climate change, Chicago Tribune (Sept. 1, 2015) available at http://www.chicagotribune.com/news/nationworld/ct-obama-alaska-20150831-story.html.

inactions) of the Obama Administration in the face of climate science show an intentional disregard for the dangers they created and exacerbated for these Youth Plaintiffs.

9.4 Well-Formed Government Admissions

By their Answer in this case, the Federal Defendants appear to me to have demonstrated a good grasp of the critical features of our present predicament. Thus:

- With respect to CO_2 emissions: the Federal Defendants admit CO_2 emissions are altering the atmospheric composition, Fed. Ans. ECF 98 ¶ 206, and driving it to > 400 ppm for the first time in millions of years, *Id*. at ¶ 208. The Federal Defendants admit that CO_2 emissions can persist in the atmosphere for at least a millennium, *Id*. at ¶206, and will continue to alter the climate for thousands of years. *Id.* The Federal Defendants also admit that other important GHGs, including methane and nitrous oxide, “are at unprecedentedly high levels compared to the past 800,000 years of historical data. *Id*. at ¶5.
- With respect to emissions-induced global warming: the Federal Defendants admit human activity leading to elevated GHG concentrations is likely “the dominant cause of observed warming since the mid-1990s,” *Id*. at ¶217; the planet has warmed ~ 0.9°C above pre-industrial temperatures, *Id*. at ¶210, a function of the greenhouse effect, *Id*. at ¶205, and consequential present energy imbalance, *Id*. at ¶202; and, depending on future emissions, global temperatures are projected to increase by 2.5 to 11°F by 2100, with “more warming [] expected on land and at higher latitudes.” *Id*. at ¶245.
- With respect to fossil fuels: the Federal Defendants admit the extraction, development and consumption (burning) of fossil fuel is the principle activity by which humans are driving up atmospheric GHG concentrations, including CO_2, *Id*. at ¶7, with the U.S. being responsible for one quarter of cumulative global CO_2 missions. *Id*.
- With respect to the U.S. role: the Federal Defendants admit that they permit, authorize, and subsidize fossil fuel extraction development, consumption, and exportation, *Id*. at ¶7, and that these activities produce CO_2 emissions that, in turn, increase atmospheric CO_2 concentrations, *Id*.; that many activities resulting in CO_2 emissions are undertaken on public lands pursuant to federal permits, *Id*. at ¶112; and that fossil fuel combustion accounting for greater than a third of all national CO_2 emissions derive from the electricity sector whose emission standards have been set by the federal government, *Id*. at ¶125.
- With respect to the ensuing threat: the Federal Defendants admit that current and projected GHG concentrations, driven higher by human activity, “threaten the public health and welfare of current and future generations, and this threat will mount over time as GHGs continue to accumulated in the atmosphere.” *Id*. at ¶213; that elevated atmospheric CO_2 has caused ocean acidity to increase at a rate 50 times faster than during the last 100,000 years, *Id*. at ¶231; and that the oceans likely have not experienced this rate of pH change for 100 million years. *Id*. at ¶232. The Federal Defendants have also admitted that elevated atmospheric CO_2 has caused ocean warming and sea level rise, and that sea levels will rise further depending on future emissions, *Id*. at ¶214, 215, presently resulting in increased erosion, *Id*. at ¶243, loss of wetlands, *Id*. at ¶219, inundation of

low-lying lands and beaches and increased salinity of near-coastal estuaries and aquifers, *Id.*, and increased flooding in many communities. *Id.* at ¶218.

- With respect to action required to preserve or restore a viable climate system: the Federal Defendants admit that "stabilizing atmospheric CO_2 concentrations will require deep reductions in CO_2 emissions, *Id.* at ¶208; that "current action by the United States will not achieve global atmospheric CO_2 levels of 350 ppm by the end of the century, *Id.* at ¶261; and that the Clean Power Plan is not intended to preserve a viable climate system nor is it "designed to provide a complete response to all climate change." *Id.* at ¶127.

Viewed in their entirety this set of admissions, it seems to me, quite clearly evince our government's knowing endangerment of Plaintiffs.

9.5 Urgency of Action: No Time for Further Delay

The teams of experts producing "Dangerous Climate Change" (Hansen et al., 2013b) and "Young People's Burden" (Hansen et al., 2017) prescribed fossil fuel emission pathways that would restore Earth's energy balance within a few decades, allowing Earth's surface later in the century to begin to cool back toward the Holocene temperature range (Fig. 9 in 2013 paper and Fig. 12 in 2017 paper). Such emission and temperature scenarios would allow the regional climate extremes and climate impacts, now beginning to emerge, to peak within several decades and then decline. These scenarios also maximize the likelihood that large sea level rise will be averted.

These scenarios define glide paths of steadily declining fossil fuel emissions, by at least several percent per year. In addition, it is assumed that emission reductions will be accompanied by programs to increase carbon storage in the soil and biosphere, especially in forests. It is estimated that as much as 100 GtC can be extracted from the air via improved agricultural and forestry practices, including reforestation of marginal lands not required for food production. Without this biogenic sequestration, even greater and swifter emission reductions would be necessary in order to maintain the glide path back to 350 ppm by 2100.

The two figures mentioned in the first paragraph of this section (9.5) quantitatively reveal the two crucial requirements on future emissions, if the hopes and rights of young people are to be achieved, i.e., if the human-made assault on their world is to be limited such that human-made global warming peaks in their lifetime, within decades, and begins to decline:

First, the emission reductions must begin promptly. In "Young People's Burden," it is shown that delay of initiation of emission reductions by eight years, from 2013 to 2021, places a burden on young people to find a way to extract an additional 53 GtC from the air or accelerate emission reductions in the short term (Figure 10 of Hansen, et al. 2017). Because of limitations on plausible storage in the soil and biosphere, added extraction above 100 GtC may require "technologic extraction," i.e., carbon capture and storage. Optimistic estimates of the cost of extracting and safely storing 53 GtC are in the range of $8 trillion to $18.5 trillion (Section 9.1 of the "Young People's Burden" paper), although the U.S. National Academy of Sciences estimates substantially higher costs.[24] The experts writing the "Young People's Burden" paper concluded: "if large fossil fuel emissions are allowed to continue, the scale and cost of technological CO_2 extraction, occurring in conjunction with a deteriorating climate and costly dislocations, may become unmanageable. Simply put, the burden placed on young people and future generations may become too heavy to bear." This burden highlights the need for the maximum rate of emission reductions as technically feasible in the coming decades.

Second, the emission reductions must occur at a significant rate on an annual basis, i.e., leisurely reductions of one or two percent per year will not suffice. This is illustrated by the large difference between 2% per year and 5% per year emissions reduction in Fig. 9b of the paper "Assessing 'Dangerous Climate Change'" (Hansen et al., 2013b). The glide path described in that paper had 6% per year emissions reduction. That glide path was appropriate if emissions reduction began in 2013 and was accompanied by large carbon extraction (~100 GtC) via reforestation of marginal lands and improved forestry and agricultural practices. With a delay of commencement of serious emissions reductions, the same glide path to climate safety will require increasingly costly and problematical technological CO_2 extraction. Under the 350 ppm by 2100 prescription, the rate of annual emissions reduction affects the required amount of CO_2 sequestration/extraction.

The critical point remains that a trajectory to restore Earth's energy balance and keep global temperature close to the Holocene, the climate in which civilization developed and is adjusted to, is possible *if plans to reduce emissions and drawdown excess atmospheric* CO_2 *are commenced without delay, and then adhered to.* As I have indicated, such action is *minimally* needed to restore earth's energy balance, preserve the planet's climate system, and avert *imminent and irretrievable damage* to human and natural systems – including agriculture, ocean fisheries, stable coastlines, and fresh water supply – on which civilization depends.

In contrast, the Defendants' continued permitting, leasing, and other support for fossil fuel exploitation and expansion projects, combined with the absence of any countervailing, coherent, effective government program to rapidly reduce atmospheric CO_2 to a safe level, will consign succeeding generations to a vastly different, less hospitable planet.

In the context of the present global climate crisis, which United States emissions to date have done so much to engender, the additional emissions stemming from fossil fuel projects going forward *right now* under the Trump administration will work only to further <u>increase</u> the atmospheric concentrations of CO_2. This will tend to further increase Earth's energy imbalance – *thereby driving our planet towards and potentially beyond irretrievable points of no return*.

Such a strong statement requires clarification by specific and general examples. As a specific example, let us consider the ocean temperature and the danger that a warming ocean poses to the stability of ice sheets and thus sea level. Evidence from paleoclimate records, from climate models, and from modern observations implies that the crucial process affecting ice sheet disintegration is a warming ocean, which melts the ice shelves, the tongues of ice extending from

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[24] NAS (National Academy of Sciences): Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration, Washington, D.C., 154 pp., https://doi.org/10.17226/18805, 2015.

the ice sheets into the ocean. As the ice shelves disappear, ice streams discharge ice to the ocean more and more rapidly, as described in the vast scientific literature compiled in the paper "Ice Melt, Sea Level Rise and Superstorms" (Hansen et al., 2016). Earth's energy imbalance is causing the ocean to warm, the ice sheets to begin to lose mass, and sea level to begin to rise, with the time scale for major sea level rise still substantially uncertain, and indeed very much dependent upon the magnitude and duration of excessive ocean warmth.

It is well agreed by the scientific community, and understandable to the lay person, that the great thermal inertia of the ocean works both ways. The ocean is slow to warm as we add CO_2 to the air. That warming is expected to continue as long as Earth's energy imbalance is positive, i.e., more energy coming in than going out. Today the imbalance is $+0.75 \pm 0.25$ W/m^2, i.e., that much more energy is coming in than going out, most of the excess energy going into the ocean. Such a global energy imbalance is large. For example, it is equal to the amount of energy released by exploding 500,000 Hiroshima atomic bombs per day every day of the year.

Restoration of planetary energy balance, at today's global temperature, requires reduction of atmospheric CO_2 from its present 405 ppm to about 350 ppm. The precise CO_2 reduction needed to restore energy balance depends also, to a lesser degree, on how other gases such as methane (CH_4) change. Once energy balance is restored, the ocean can begin to cool slightly, if CO_2 or other gases are reduced a bit further. However, because of the ocean's great thermal inertia, any cooling will proceed slowly. Thus, it is very dangerous to let ocean temperature rise substantially, because it could become implausible to prevent large sea level rise.

This specific concern applies more generally. By exacerbating and extending Earth's energy imbalance, government actions jeopardize many signal features of the relatively benign and favorable climate system that, over the last 10,000 years, enabled civilization to develop and nature to thrive, as I have discussed. These features included not only rather stable coastlines, but also moderate weather, fertile soils, and dependable hydrological systems – the natural capital on which the lives of Plaintiffs depend no less than did the lives of their parents and *their* forebears.

As well, present and future government action that exacerbates and extends Earth's energy imbalance risks economic collapse, social disintegration, and the loss of essential natural and human services, as I have discussed. The resulting diminution of Plaintiffs' life prospects – their compromised ability to earn a living, to meet their basic human needs, to safely raise families, to maintain property rights, to practice their religious and spiritual beliefs, and otherwise to lead dignified lives – is a predictable if not intended result of the government action.

In addition, where such government action exacerbates and extends Earth's energy imbalance that, in turn, predictably will lead to the climate change-driven inundation, burning, or other destruction of the value of property in which Plaintiffs hold interests. These will include the homes, farms, and other valuable property that their parents or grandparents own and that Plaintiffs will inherit.

Action by the Defendants that allows the continued increase of atmospheric CO_2 levels, and the consequential long-term impacts on Earth's climate system, will disproportionately impose harsh burdens on Plaintiffs and other children. If fossil fuel emissions are not systematically and rapidly abated, as I have discussed above – including in the materials that I have incorporated by reference – then Youth and Future Generations Plaintiffs will confront what reasonably only can be described as, at best, an inhospitable future. That future will be marked by rising seas, coastal city functionality loss, mass migrations, resource wars, food shortages, heat waves, mega-storms, soil depletion and desiccation, freshwater shortage, public health system collapse, and the extinction of increasing numbers of species. That is to mention only the start of it. While prior generations and, to a certain extent, some in our present generation have benefitted and, even, been enriched by the exploitation of fossil fuels, our children and their progeny will not similarly benefit. Indeed, the impact on Plaintiffs will be nearly completely to the contrary, as I have discussed.

Closely-related to the above, the Defendants' continued permitting and promotion of the fossil fuel enterprise now impairs and increasingly will dismantle the fundamental natural resources on which Plaintiffs will depend. Again, these are the fundamental resources on which the prior and present generations have relied, and on which Plaintiffs now and in the future must rely. They include the air, freshwater, the oceans and stable shores, the soil and its agronomic capacity, the forests and its wildlife, biodiversity on earth, and the planet's climate system in a form conducive to civilization, humanity, and nature as we know it.

Furthermore, it is clear to me that Plaintiffs' right to a government that retains any significant capacity to address the climate crisis adequately is violated by prior and present government actions that exacerbate and extend our planet's energy imbalance. Such action is irretrievably damaging our planet's favorable climate system. Once begun, for example, collapsing and disintegrating ice sheets will not readily be reformulated – certainly not within a timeframe relevant to present and foreseeable generations. The loss of species too is irretrievable. Many species are adapted to specific climate zones, so those species that have adapted to polar and alpine regions will have no place to run. Present and pending actions by our federal government now must be viewed in the context of a climate crisis that the Defendants to date have done so much to bring about. Imminent action is required to preserve and restore the climate system such as we have known it in order for the planet as we have known it to be able to continue adequately to support the lives and prospects of young people and future generations. But that cannot be done effectively by future governments, and other sovereigns, if the Defendants continue to exacerbate the planet's energy imbalance and press our planet towards irretrievable points from which there can be no practical opportunity to return. In short, the Defendants are actually perpetrating irreparable harm on the young and the unborn.

Simply put: The Defendants' persistent permitting and underwriting of fossil fuel projects serves now to further disrupt the favorable climate system that to date enabled human civilization to develop. In order to preserve a viable climate system, our use of fossil fuels must be phased out as rapidly as is feasible. Only government can ensure this will be done. Instead, these Defendants seek to approve permitting of fossil fuel projects that would slam shut the narrowing window of opportunity to stabilize climate and ensure a hospitable climate and planet for young people and future generations. The Defendants' permitting of additional, new, or renewed fossil fuel projects is entirely antithetical to their fundamental responsibility to our children and their posterity. These actions are happening right now and will continue to happen over coming 6 months as our attorneys prepare for trial. Every month of delay exacerbates this crisis and further endangers these Plaintiffs and all Future Generations. Their fundamental rights now hang in the balance.

Immediate, effective action to restore Earth's energy balance in time to avert wider disintegration of the major ice sheets would achieve multiple benefits, virtually at the same time. These benefits include slowing and eventually stopping sea level rise, averting further acidification of the oceans and consequential disruption of the marine food chain, slowing and in time stemming the loss of terrestrial species, preserving a viable agricultural system, stemming the growth in wildfires, securing essential water resources – the list goes on.[25]

What must be recognized is that atmospheric CO_2 functions now as the control knob for the planet's climate system. Within the remaining period prior to the full manifestation of slow feedbacks and the crossing of climate points of no return, it remains within the power of the Defendants to dial it back so as to secure a viable future for our children and their progeny. At this late stage an order from this federal court is manifestly necessary to turn this thing around. Further delay is nothing short of catastrophic.

10. Appraisal

My expert opinion and conclusion is that, at this late stage, further delay in the commencement of rigorous, systemic, comprehensive, and sustained action to phase out CO_2 emissions and draw down atmospheric CO_2 risks imminent catastrophe – a conclusion shared by most climate scientists.

The present circumstance appears to me to be far worse than grating. Given all that is known to a reasonable or higher level of scientific certainty; notwithstanding that the Defendants have, at their disposal, the relevant information and expertise as to the dangers and the reasonable alternatives to power our energy system in all sectors; and despite their own clearly-expressed understanding of the problem for half a century and its likely consequences: still, the Defendants proceed to expand fossil fuel extraction, development, exportation, and combustion efforts, and, thus, to lock in more CO_2 and other pollution to the detriment of the security and safety of present and future generations, including the Youth Plaintiffs in this case.

Through their actions and inactions, the Defendants have exposed Plaintiffs to a substantial (and unjustified) risk of serious harm that these Plaintiffs would not have otherwise faced. Even after the knowing exposure to this risk of serious harm, and the alternative courses of action, these Defendants have failed and continue to fail to treat what will, to a reasonable or higher scientific certainty, result in significant injury or unnecessary and unjustifiable infliction of pain. These risks are clear and present and obvious. As a result, in part based on my expert opinion, I must conclude that the deliberate indifference of the Defendants to health and safety rights of Plaintiffs is so egregious as to "shock the conscience."

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[25] Such action also should avert the feared shutdown of the Atlantic Meridional Overturning Circulation. *See* James Hansen and Makiko Sato, Predictions Implicit in "Ice Melt" Paper and Global Implications, Sept. 21, 2015, available at http://csas.ei.columbia.edu/2015/09/21/predictions-implicit-in-ice-melt-paper-and-global-implications/.

These Defendants should be shielding these young Plaintiffs from harm. Yet, the Defendants have acted in knowing disregard of the science available to policymakers for decades. This science put them on notice that the ongoing acts and omissions of the Defendants is substantially certain to result in serious harm to these Youth Plaintiffs, including increased risk of imminent injury, potentially life-threatening.

We are now, all of us, witness to this flagrant and sustained assault.

In my expert opinion, based on comprehensive analyses carried out by an international cadre of leaders in the relevant scientific fields, as described in the 2013 PLoS ONE and 2017 Earth Systems Dynamics papers discussed *supra*, there is still time to preserve Plaintiffs' rights.

From my standpoint as a climate scientist, a citizen and as guardian of future generations in this case, it is clear to me that these Youth have been handed an incredible burden no previous generation has ever faced, and as a result they are threatened with irreparable harm not known to humanity.

Although interpretation of the Constitution is a function that I leave to the Court, I would invoke the wisdom of Thomas Jefferson, who was a fellow scientist who kept a weather and climate diary, as well as a statesman and a farmer. On 6 September 1789, concerning the proposed Bill of Rights, Jefferson wrote to James Madison: "The question whether one generation of men has a right to bind another . . . is a question of such consequences as not only to merit decision, but place also among the fundamental principles of every government . . . I set out on this ground, which I suppose to be self-evident, 'that the Earth belongs in usufruct to the living'."

Jefferson, in saying that the present generation can enjoy the fruits of the land but with an obligation to leave Earth in as good condition as when we received it from our parents, was especially concerned about the fertility of the soil – it should be maintained for the next generation, not depleted. Today's youth in America face the threat of a depleted Earth, and more. A reasonably stable seashore, I believe our Nation's Founders would agree, is an asset that should not be stolen from young people and future generations.

These Youth Plaintiffs confront an imminent gathering storm. They have at their command considerable determination, a dog-eared copy of our beleaguered Constitution, and rigorously developed science. This Court can decide if that is enough.

Signed this 13th day of April, 2018 in New York, New York.

James E. Hansen

Dr. James E. Hansen

EXHIBIT A
James E. Hansen CV

James E. Hansen

Columbia University Earth Institute, Climate Science, Awareness and Solutions
Interchurch Building, 475 Riverside Drive, Room 520, New York, NY 10115 jimehansen@gmail.com

1-paragraph bio/introduction:

Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. Dr. Hansen is best known for his testimony on climate change in the 1980s that helped raise awareness of global warming. He is a member of the U.S. National Academy of Sciences and has received numerous awards including the Sophie and Blue Planet Prizes. Dr. Hansen is recognized for speaking truth to power and for outlining actions needed to protect the future of young people and all species on the planet.

1-long-paragraph bio:

Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. He was trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa. His early research on the clouds of Venus helped identify their composition as sulfuric acid. Since the late 1970s, he has focused his research on Earth's climate, especially human-made climate change. Dr. Hansen is best known for his testimony on climate change to congressional committees in the 1980s that helped raise broad awareness of the global warming issue. He was elected to the National Academy of Sciences in 1995 and was designated by Time Magazine in 2006 as one of the 100 most influential people on Earth. He has received numerous awards including the Carl-Gustaf Rossby and Roger Revelle Research Medals, the Sophie Prize and the Blue Planet Prize. Dr. Hansen is recognized for speaking truth to power, for identifying ineffectual policies as greenwash, and for outlining actions that the public must take to protect the future of young people and other life on our planet.

3-paragraph bio:

Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. He was trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa, receiving a bachelor's degree with highest distinction in physics and mathematics, master's degree in astronomy, and Ph. D. in physics in 1967. Dr. Hansen was a visiting student, at the Institute of Astrophysics, University of Kyoto and Dept. of Astronomy, Tokyo University, Japan from 1965-1966. He received his Ph.D. in physics from the University of Iowa in 1967. Except for 1969, when he was an NSF post-doctoral scientist at Leiden Observatory under Prof. H.C. van de Hulst, he has spent his post-doctoral career at NASA GISS.

In his early research Dr. Hansen used telescopic observations of Venus to extract detailed information on the physical properties of the cloud and haze particles that veil Venus. Since the mid-1970s, Dr. Hansen has focused on studies and computer simulations of the Earth's climate, for the purpose of understanding the human impact on global climate. He is best known for his testimony on climate change to Congress in the 1980s that helped raise broad awareness of the global warming issue. In recent years Dr. Hansen has drawn attention to the danger of passing climate tipping points, producing irreversible climate impacts that would yield a different planet from the one on which civilization developed. Dr. Hansen disputes the contention, of fossil fuel interests and governments that support them, that it is an almost god-given fact that all fossil fuels must be burned with their combustion products discharged into the atmosphere. Instead Dr. Hansen has outlined steps that are needed to stabilize climate, with a cleaner atmosphere and ocean, and he emphasizes the need for the public to influence government and industry policies.

Dr. Hansen was elected to the National Academy of Sciences in 1995 and, in 2001, received the Heinz Award for environment and the American Geophysical Union's Roger Revelle Medal. Dr. Hansen received the World Wildlife Federation's Conservation Medal from the Duke of Edinburgh in 2006 and was designated by Time Magazine as one of the world's 100 most influential people in 2006. In 2007 Dr. Hansen won the Dan David Prize in the field of Quest for Energy, the Leo Szilard Award of the American Physical Society for Use of Physics for the Benefit of Society, and the American Association for the Advancement of Science Award for Scientific Freedom and Responsibility. In 2008, he won the Common Wealth Award for Distinguished Service in Science and was also awarded both the Ohio State University's Bownocker Medal and the Desert Research Institute's Nevada Medal. In 2009, Dr. Hansen received the American Meteorological Society's Carl-Gustaf Rossby Research Medal. In 2010 he received the Sophie Prize and the Blue Planet Prize.

Additional Information:

Http://www.columbia.edu/~jeh1/
http://www.columbia.edu/~mhs119/
Photos: http://ww.mediafire.com/?8ecel33ccmg81

Education:

BA with highest distinction (Physics and Mathematics), University of Iowa, 1963
MS (Astronomy), University of Iowa, 1965
Visiting student, Inst. of Astrophysics, University of Kyoto & Dept. of Astronomy, Tokyo University, Japan, 1965-1966
Ph.D. (Physics), University of Iowa, 1967

Research Interests:

Analysis of the causes and consequences of global climate change using the Earth's paleoclimate history, ongoing global observations, and interpretive tools including climate models. Connecting the dots all the way from climate observations to the policies that are needed to stabilize climate and preserve our planet for young people and other species.

Professional Employment:

1967-1969	NAS-NRC Resident Research Associate: Goddard Institute for Space Studies (GISS), NY
1969	NSF Postdoctoral Fellow: Leiden Observatory, Netherlands
1969-1972	Research Associate: Columbia University, NY
1972-1981	Staff Member/Space Scientist: Goddard Institute for Space Studies (GISS), Manager of GISS Planetary and Climate Programs
1978-1985	Adjunct Associate Professor: Department of Geological Sciences, Columbia University
1981-2013	Director: NASA Goddard Institute for Space Studies
1985-2013	Adjunct Professor: Earth and Environmental Sciences, Columbia University
2013-present	Director: Program on Climate Science, Awareness and Solutions, Columbia University

Project Experience:

1971-1974	Co-Principal Investigator AEROPOL Project (airborne terrestrial infrared polarimeter)
1972-1985	Co-Investigator, Voyager Photopolarimeter Experiment
1974-1994	Principal Investigator (1974-8) and subsequently Co-Investigator, Pioneer Venus Orbiter Cloud-Photopolarimeter Experiment
1977-2000	Principal Investigator, Galileo (Jupiter Orbiter) Photopolarimeter Radiometer Experiment

Teaching Experience:

Atmospheric Radiation (graduate level): New York Univ., Dept. of Meteorology & Oceanography
Intro. to Planetary Atmospheres & Climate Change: Columbia Univ., Dept. of Geological Sciences

Awards:

1977	Goddard Special Achievement Award (Pioneer Venus)
1978	NASA Group Achievement Award (Voyager, Photopolarimeter)
1984	NASA Exceptional Service Medal (Radiative Transfer)
1989	National Wildlife Federation Conservation Achievement Award
1990	NASA Presidential Rank Award of Meritorious Executive
1991	University of Iowa Alumni Achievement Award
1992	American Geophysical Union Fellow
1993	NASA Group Achievement Award (Galileo, Polarimeter/Radiometer)
1996	Elected to National Academy of Sciences
1996	GSFC William Nordberg Achievement Medal
1996	Editors' Citation for Excellence in Refereeing for Geophysical Research Letters
1997	NASA Presidential Rank Award of Meritorious Executive
2000	University of Iowa Alumni Fellow
2000	GISS Best Scientific Publication (peer vote): "Global warming – alternative scenario"
2001	John Heinz Environment Award
2001	Roger Revelle Medal, American Geophysical Union
2004	GISS Best Scientific Publication (peer vote): 'Soot Climate Forcing'

2005	GISS Best Scientific Publication (peer vote): 'Earth's Energy Imbalance'
2006	Duke of Edinburgh Conservation Medal, World Wildlife Fund (WWF)
2006	GISS Best Scientific Publication (peer vote): 'Global Temperature Change'
2006	*Time Magazine* designation as one of World's 100 Most Influential People.
2007	Laureate, Dan David Prize for Outstanding Achievements & Impacts in Quest for Energy
2007	Leo Szilard Award, American Physical Society for Outstanding Promotion & Use of Physics for the Benefit of Society
2007	Haagen-Smit Clean Air Award
2008	American Association for the Advancement of Science Award for Scientific Freedom and Responsibility
2008	Nevada Medal, Desert Research Institute
2008	Common Wealth Award for Distinguished Service in Science
2008	Bownocker Medal, Ohio State University
2008	Rachel Carson Award for Integrity in Science, Center for Science in the Public Interest
2009	Carl-Gustaf Rossby Research Medal, American Meteorological Society
2009	Peter Berle Environmental Integrity Award
2010	Sophie Prize for Environmental and Sustainable Development
2010	Blue Planet Prize, Asahi Glass Foundation
2011	American Association of Physics Teachers Klopsteg Memorial Award for communicating physics to the general public
2011	Edinburgh Medal from City of Edinburgh, Edinburgh Science Festival
2012	Steve Schneider Climate Science Communications Award
2012	*Foreign Policy* designation as one of its Top 100 Global Thinkers
2013	Ridenhour Courage Prize
2013	NASA Distinguished Service Medal
2014	Center for International Environmental Law's Frederick R. Anderson Award for Outstanding Contributions to Addressing Climate Change
2014	Walker Prize, Museum of Science, Boston
2017	2017 AAG Honorary Geographer, American Association of Geographers
2017	BBVA Foundation Frontiers of Knowledge Award in Climate Change, Spain – shared with Suki Manabe

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EXHIBIT B

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EXHIBIT C

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Exhibit C.1

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Review

Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature

James Hansen[1]*, Pushker Kharecha[1,2], Makiko Sato[1], Valerie Masson-Delmotte[3], Frank Ackerman[4], David J. Beerling[5], Paul J. Hearty[6], Ove Hoegh-Guldberg[7], Shi-Ling Hsu[8], Camille Parmesan[9,10], Johan Rockstrom[11], Eelco J. Rohling[12,13], Jeffrey Sachs[1], Pete Smith[14], Konrad Steffen[15], Lise Van Susteren[16], Karina von Schuckmann[17], James C. Zachos[18]

1 Earth Institute, Columbia University, New York, New York, United States of America, **2** Goddard Institute for Space Studies, NASA, New York, New York, United States of America, **3** Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ), Gif-sur-Yvette, France, **4** Synapse Energy Economics, Cambridge, Massachusetts, United States of America, **5** Department of Animal and Plant Sciences, University of Sheffield, Sheffield, South Yorkshire, United Kingdom, **6** Department of Environmental Studies, University of North Carolina, Wilmington, North Carolina, United States of America, **7** Global Change Institute, University of Queensland, St. Lucia, Queensland, Australia, **8** College of Law, Florida State University, Tallahassee, Florida, United States of America, **9** Marine Institute, Plymouth University, Plymouth, Devon, United Kingdom, **10** Integrative Biology, University of Texas, Austin, Texas, United States of America, **11** Stockholm Resilience Center, Stockholm University, Stockholm, Sweden, **12** School of Ocean and Earth Science, University of Southampton, Southampton, Hampshire, United Kingdom, **13** Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia, **14** University of Aberdeen, Aberdeen, Scotland, United Kingdom, **15** Swiss Federal Institute of Technology, Swiss Federal Research Institute WSL, Zurich, Switzerland, **16** Center for Health and the Global Environment, Advisory Board, Harvard School of Public Health, Boston, Massachusetts, United States of America, **17** L'Institut Francais de Recherche pour l'Exploitation de la Mer, Ifremer, Toulon, France, **18** Earth and Planetary Science, University of California, Santa Cruz, CA, United States of America

Abstract: We assess climate impacts of global warming using ongoing observations and paleoclimate data. We use Earth's measured energy imbalance, paleoclimate data, and simple representations of the global carbon cycle and temperature to define emission reductions needed to stabilize climate and avoid potentially disastrous impacts on today's young people, future generations, and nature. A cumulative industrial-era limit of ~500 GtC fossil fuel emissions and 100 GtC storage in the biosphere and soil would keep climate close to the Holocene range to which humanity and other species are adapted. Cumulative emissions of ~1000 GtC, sometimes associated with 2°C global warming, would spur "slow" feedbacks and eventual warming of 3–4°C with disastrous consequences. Rapid emissions reduction is required to restore Earth's energy balance and avoid ocean heat uptake that would practically guarantee irreversible effects. Continuation of high fossil fuel emissions, given current knowledge of the consequences, would be an act of extraordinary witting intergenerational injustice. Responsible policymaking requires a rising price on carbon emissions that would preclude emissions from most remaining coal and unconventional fossil fuels and phase down emissions from conventional fossil fuels.

Introduction

Humans are now the main cause of changes of Earth's atmospheric composition and thus the drive for future climate change [1]. The principal climate forcing, defined as an imposed change of planetary energy balance [1–2], is increasing carbon dioxide (CO_2) from fossil fuel emissions, much of which will remain in the atmosphere for millennia [1,3]. The climate response to this forcing and society's response to climate change are complicated by the system's inertia, mainly due to the ocean and the ice sheets on Greenland and Antarctica together with the long residence time of fossil fuel carbon in the climate system. The inertia causes climate to appear to respond slowly to this human-made forcing, but further long-lasting responses can be locked in.

More than 170 nations have agreed on the need to limit fossil fuel emissions to avoid dangerous human-made climate change, as formalized in the 1992 Framework Convention on Climate Change [6]. However, the stark reality is that global emissions have accelerated (Fig. 1) and new efforts are underway to massively expand fossil fuel extraction [7–9] by drilling to increasing ocean depths and into the Arctic, squeezing oil from tar sands and tar shale, hydro-fracking to expand extraction of natural gas, developing exploitation of methane hydrates, and mining of coal via mountaintop removal and mechanized long-wall mining. The growth rate of fossil fuel emissions increased from 1.5%/year during 1980–2000 to 3%/year in 2000–2012, mainly because of increased coal use [4–5].

The Framework Convention [6] does not define a dangerous level for global warming or an emissions limit for fossil fuels. The

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* E-mail: jimehansen@gmail.com

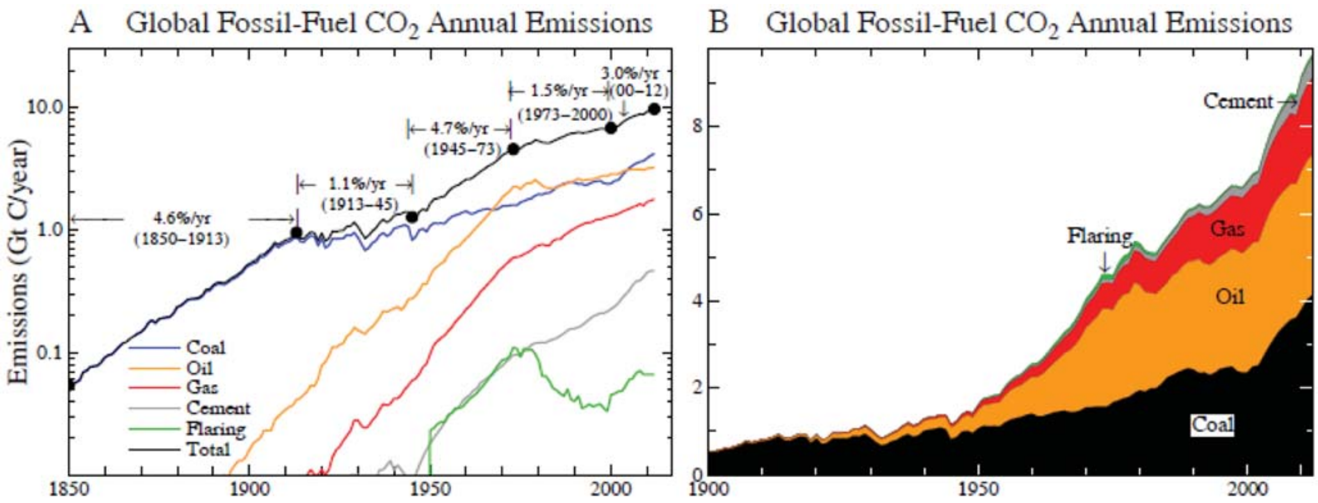

Figure 1. CO_2 annual emissions from fossil fuel use and cement manufacture, based on data of British Petroleum [4] concatenated with data of Boden et al. [5]. (A) is log scale and (B) is linear.
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European Union in 1996 proposed to limit global warming to 2°C relative to pre-industrial times [10], based partly on evidence that many ecosystems are at risk with larger climate change. The 2°C target was reaffirmed in the 2009 "Copenhagen Accord" emerging from the 15th Conference of the Parties of the Framework Convention [11], with specific language "We agree that deep cuts in global emissions are required according to science, as documented in the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius…".

A global warming target is converted to a fossil fuel emissions target with the help of global climate-carbon-cycle models, which reveal that eventual warming depends on cumulative carbon emissions, not on the temporal history of emissions [12]. The emission limit depends on climate sensitivity, but central estimates [12–13], including those in the upcoming Fifth Assessment of the Intergovernmental Panel on Climate Change [14], are that a 2°C global warming limit implies a cumulative carbon emissions limit of the order of 1000 GtC. In comparing carbon emissions, note that some authors emphasize the sum of fossil fuel and deforestation carbon. We bookkeep fossil fuel and deforestation carbon separately, because the larger fossil fuel term is known more accurately and this carbon stays in the climate system for hundreds of thousands of years. Thus fossil fuel carbon is the crucial human input that must be limited. Deforestation carbon is more uncertain and potentially can be offset on the century time scale by storage in the biosphere, including the soil, via reforestation and improved agricultural and forestry practices.

There are sufficient fossil fuel resources to readily supply 1000 GtC, as fossil fuel emissions to date (370 GtC) are only a small fraction of potential emissions from known reserves and potentially recoverable resources (Fig. 2). Although there are uncertainties in reserves and resources, ongoing fossil fuel subsidies and continuing technological advances ensure that more and more of these fuels will be economically recoverable. As we will show, Earth's paleoclimate record makes it clear that the CO_2 produced by burning all or most of these fossil fuels would lead to a very different planet than the one that humanity knows.

Our evaluation of a fossil fuel emissions limit is not based on climate models but rather on observational evidence of global climate change as a function of global temperature and on the fact that climate stabilization requires long-term planetary energy balance. We use measured global temperature and Earth's measured energy imbalance to determine the atmospheric CO_2 level required to stabilize climate at today's global temperature, which is near the upper end of the global temperature range in the current interglacial period (the Holocene). We then examine climate impacts during the past few decades of global warming and in paleoclimate records including the Eemian period, concluding that there are already clear indications of undesirable impacts at the current level of warming and that 2°C warming would have major deleterious consequences. We use simple representations of the carbon cycle and global temperature, consistent with observations, to simulate transient global temperature and assess carbon emission scenarios that could keep global climate near the Holocene range. Finally, we discuss likely overshooting of target emissions, the potential for carbon extraction from the atmosphere, and implications for energy and economic policies, as well as intergenerational justice.

Global Temperature and Earth's Energy Balance

Global temperature and Earth's energy imbalance provide our most useful measuring sticks for quantifying global climate change and the changes of global climate forcings that would be required to stabilize global climate. Thus we must first quantify knowledge of these quantities.

Temperature

Temperature change in the past century (Fig. 3; update of figures in [16]) includes unforced variability and forced climate change. The long-term global warming trend is predominantly a forced climate change caused by increased human-made atmospheric gases, mainly CO_2 [1]. Increase of "greenhouse" gases such as CO_2 has little effect on incoming sunlight but makes the atmosphere more opaque at infrared wavelengths, causing infrared (heat) radiation to space to emerge from higher, colder levels, which thus reduces infrared radiation to space. The resulting planetary energy imbalance, absorbed solar energy exceeding heat emitted to space, causes Earth to warm. Observations, discussed below, confirm that Earth is now substantially out of energy balance, so the long-term warming will continue.

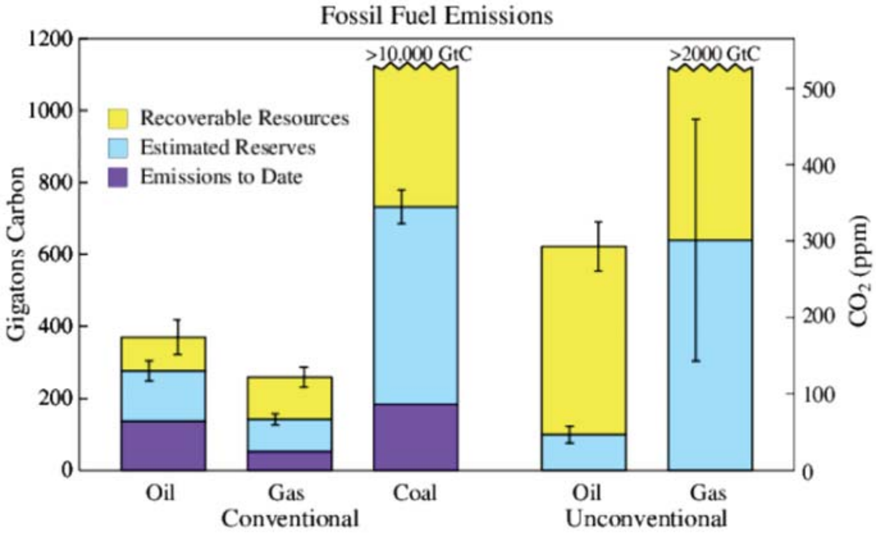

Figure 2. Fossil fuel CO$_2$ emissions and carbon content (1 ppm atmospheric CO$_2$ ~ 2.12 GtC). Estimates of reserves (profitable to extract at current prices) and resources (potentially recoverable with advanced technology and/or at higher prices) are the mean of estimates of Energy Information Administration (EIA) [7], German Advisory Council (GAC) [8], and Global Energy Assessment (GEA) [9]. GEA [9] suggests the possibility of >15,000 GtC unconventional gas. Error estimates (vertical lines) are from GEA and probably underestimate the total uncertainty. We convert energy content to carbon content using emission factors of Table 4.2 of [15] for coal, gas and conventional oil, and, also following [15], emission factor of unconventional oil is approximated as being the same as for coal. Total emissions through 2012, including gas flaring and cement manufacture, are 384 GtC; fossil fuel emissions alone are ~370 GtC.
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Global temperature appears to have leveled off since 1998 (Fig. 3a). That plateau is partly an illusion due to the 1998 global temperature spike caused by the El Niño of the century that year. The 11-year (132-month) running mean temperature (Fig. 3b) shows only a moderate decline of the warming rate. The 11-year averaging period minimizes the effect of variability due to the 10–12 year periodicity of solar irradiance as well as irregular El Niño/La Niña warming/cooling in the tropical Pacific Ocean. The current solar cycle has weaker irradiance than the several prior solar cycles, but the decreased irradiance can only partially account for the decreased warming rate [17]. Variability of the El Niño/La Niña cycle, described as a Pacific Decadal Oscillation, largely accounts for the temporary decrease of warming [18], as we discuss further below in conjunction with global temperature simulations.

Assessments of dangerous climate change have focused on estimating a permissible level of global warming. The Intergovernmental Panel on Climate Change [1,19] summarized broad-based assessments with a "burning embers" diagram, which indicated that major problems begin with global warming of 2–3°C. A probabilistic analysis [20], still partly subjective, found a median "dangerous" threshold of 2.8°C, with 95% confidence that the dangerous threshold was 1.5°C or higher. These assessments were relative to global temperature in year 1990, so add 0.6°C to these values to obtain the warming relative to 1880–1920, which is the base period we use in this paper for preindustrial time. The conclusion that humanity could tolerate global warming up to a few degrees Celsius meshed with common sense. After all, people readily tolerate much larger regional and seasonal climate variations.

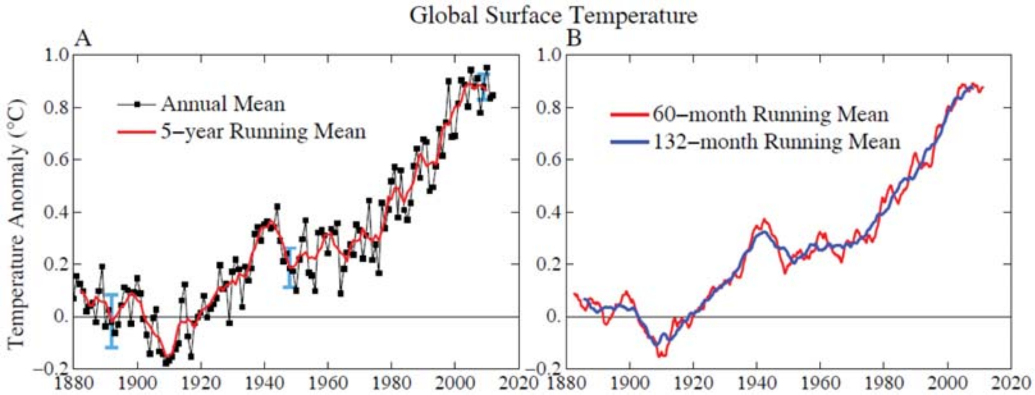

Figure 3. Global surface temperature relative to 1880–1920 mean. B shows the 5 and 11 year means. Figures are updates of [16] using data through August 2013.
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The fallacy of this logic emerged recently as numerous impacts of ongoing global warming emerged and as paleoclimate implications for climate sensitivity became apparent. Arctic sea ice end-of-summer minimum area, although variable from year to year, has plummeted by more than a third in the past few decades, at a faster rate than in most models [21], with the sea ice thickness declining a factor of four faster than simulated in IPCC climate models [22]. The Greenland and Antarctic ice sheets began to shed ice at a rate, now several hundred cubic kilometers per year, which is continuing to accelerate [23–25]. Mountain glaciers are receding rapidly all around the world [26–29] with effects on seasonal freshwater availability of major rivers [30–32]. The hot dry subtropical climate belts have expanded as the troposphere has warmed and the stratosphere cooled [33–36], contributing to increases in the area and intensity of drought [37] and wildfires [38]. The abundance of reef-building corals is decreasing at a rate of 0.5–2%/year, at least in part due to ocean warming and possibly ocean acidification caused by rising dissolved CO_2 [39–41]. More than half of all wild species have shown significant changes in where they live and in the timing of major life events [42–44]. Mega-heatwaves, such as those in Europe in 2003, the Moscow area in 2010, Texas and Oklahoma in 2011, Greenland in 2012, and Australia in 2013 have become more widespread with the increase demonstrably linked to global warming [45–47].

These growing climate impacts, many more rapid than anticipated and occurring while global warming is less than 1°C, imply that society should reassess what constitutes a "dangerous level" of global warming. Earth's paleoclimate history provides a valuable tool for that purpose.

Paleoclimate Temperature

Major progress in quantitative understanding of climate change has occurred recently by use of the combination of data from high resolution ice cores covering time scales of order several hundred thousand years [48–49] and ocean cores for time scales of order one hundred million years [50]. Quantitative insights on global temperature sensitivity to external forcings [51–52] and sea level sensitivity to global temperature [52–53] are crucial to our analyses. Paleoclimate data also provide quantitative information about how nominally slow feedback processes amplify climate sensitivity [51–52,54–56], which also is important to our analyses.

Earth's surface temperature prior to instrumental measurements is estimated via proxy data. We will refer to the surface temperature record in Fig. 4 of a recent paper [52]. Global mean temperature during the Eemian interglacial period (120,000 years ago) is constrained to be 2°C warmer than our pre-industrial (1880–1920) level based on several studies of Eemian climate [52]. The concatenation of modern and instrumental records [52] is based on an estimate that global temperature in the first decade of the 21st century (+0.8°C relative to 1880–1920) exceeded the Holocene mean by 0.25 ± 0.25°C. That estimate was based in part on the fact that sea level is now rising 3.2 mm/yr (3.2 m/millennium) [57], an order of magnitude faster than the rate during the prior several thousand years, with rapid change of ice sheet mass balance over the past few decades [23] and Greenland and Antarctica now losing mass at accelerating rates [23–24]. This concatenation, which has global temperature 13.9°C in the base period 1951–1980, has the first decade of the 21st century slightly (~0.1°C) warmer than the early Holocene maximum. A recent reconstruction from proxy temperature data [55] concluded that global temperature declined about 0.7°C between the Holocene maximum and a pre-industrial minimum before recent warming brought temperature back near the Holocene maximum, which is consistent with our analysis.

Climate oscillations evident in Fig. 4 of Hansen et al. [52] were instigated by perturbations of Earth's orbit and spin axis tilt relative to the orbital plane, which alter the geographical and seasonal distribution of sunlight on Earth [58]. These forcings change slowly, with periods between 20,000 and 400,000 years, and thus climate is able to stay in quasi-equilibrium with these forcings. Slow insolation changes initiated the climate oscillations, but the mechanisms that caused the climate changes to be so large were two powerful amplifying feedbacks: the planet's surface albedo (its reflectivity, literally its whiteness) and atmospheric CO_2 amount. As the planet warms, ice and snow melt, causing the surface to be darker, absorb more sunlight and warm further. As the ocean and soil become warmer they release CO_2 and other greenhouse gases, causing further warming. Together with fast feedbacks processes, via changes of water vapor, clouds, and the vertical temperature profile, these slow amplifying feedbacks were responsible for almost the entire glacial-to-interglacial temperature change [59–62].

The albedo and CO_2 feedbacks amplified weak orbital forcings, the feedbacks necessarily changing slowly over millennia, at the pace of orbital changes. Today, however, CO_2 is under the control of humans as fossil fuel emissions overwhelm natural changes. Atmospheric CO_2 has increased rapidly to a level not seen for at least 3 million years [56,63]. Global warming induced by increasing CO_2 will cause ice to melt and hence sea level to rise as the global volume of ice moves toward the quasi-equilibrium amount that exists for a given global temperature [53]. As ice melts and ice area decreases, the albedo feedback will amplify global warming.

Earth, because of the climate system's inertia, has not yet fully responded to human-made changes of atmospheric composition. The ocean's thermal inertia, which delays some global warming for decades and even centuries, is accounted for in global climate models and its effect is confirmed via measurements of Earth's energy balance (see next section). In addition there are slow climate feedbacks, such as changes of ice sheet size, that occur mainly over centuries and millennia. Slow feedbacks have little effect on the immediate planetary energy balance, instead coming into play in response to temperature change. The slow feedbacks are difficult to model, but paleoclimate data and observations of ongoing changes help provide quantification.

Earth's Energy Imbalance

At a time of climate stability, Earth radiates as much energy to space as it absorbs from sunlight. Today Earth is out of balance because increasing atmospheric gases such as CO_2 reduce Earth's heat radiation to space, thus causing an energy imbalance, as there is less energy going out than coming in. This imbalance causes Earth to warm and move back toward energy balance. The warming and restoration of energy balance take time, however, because of Earth's thermal inertia, which is due mainly to the global ocean.

Earth warmed about 0.8°C in the past century. That warming increased Earth's radiation to space, thus reducing Earth's energy imbalance. The remaining energy imbalance helps us assess how much additional warming is still "in the pipeline". Of course increasing CO_2 is only one of the factors affecting Earth's energy balance, even though it is the largest climate forcing. Other forcings include changes of aerosols, solar irradiance, and Earth's surface albedo.

Determination of the state of Earth's climate therefore requires measuring the energy imbalance. This is a challenge, because the imbalance is expected to be only about 1 W/m^2 or less, so accuracy approaching 0.1 W/m^2 is needed. The most promising

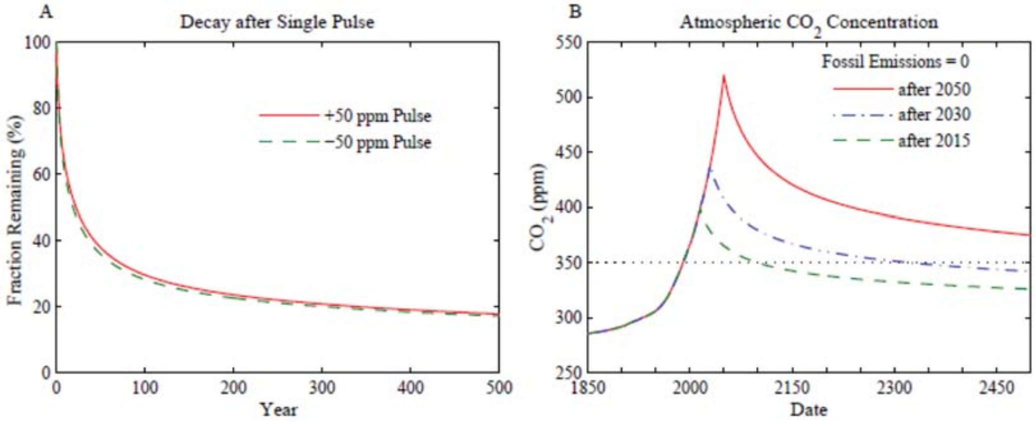

Figure 4. Decay of atmospheric CO_2 perturbations. (A) Instantaneous injection or extraction of CO_2 with initial conditions at equilibrium. (B) Fossil fuel emissions terminate at the end of 2015, 2030, or 2050 and land use emissions terminate after 2015 in all three cases, i.e., thereafter there is no net deforestation.
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approach is to measure the rate of changing heat content of the ocean, atmosphere, land, and ice [64]. Measurement of ocean heat content is the most critical observation, as nearly 90 percent of the energy surplus is stored in the ocean [64–65].

Observed Energy Imbalance

Nations of the world have launched a cooperative program to measure changing ocean heat content, distributing more than 3000 Argo floats around the world ocean, with each float repeatedly diving to a depth of 2 km and back [66]. Ocean coverage by floats reached 90% by 2005 [66], with the gaps mainly in sea ice regions, yielding the potential for an accurate energy balance assessment, provided that several systematic measurement biases exposed in the past decade are minimized [67–69].

Argo data reveal that in 2005–2010 the ocean's upper 2000 m gained heat at a rate equal to 0.41 W/m^2 averaged over Earth's surface [70]. Smaller contributions to planetary energy imbalance are from heat gain by the deeper ocean (+0.10 W/m^2), energy used in net melting of ice (+0.05 W/m^2), and energy taken up by warming continents (+0.02 W/m^2). Data sources for these estimates and uncertainties are provided elsewhere [64]. The resulting net planetary energy imbalance for the six years 2005–2010 is $+0.58\pm0.15$ W/m^2.

The positive energy imbalance in 2005–2010 confirms that the effect of solar variability on climate is much less than the effect of human-made greenhouse gases. If the sun were the dominant forcing, the planet would have a negative energy balance in 2005–2010, when solar irradiance was at its lowest level in the period of accurate data, i.e., since the 1970s [64,71]. Even though much of the greenhouse gas forcing has been expended in causing observed 0.8°C global warming, the residual positive forcing overwhelms the negative solar forcing. The full amplitude of solar cycle forcing is about 0.25 W/m^2 [64,71], but the reduction of solar forcing due to the present weak solar cycle is about half that magnitude as we illustrate below, so the energy imbalance measured during solar minimum (0.58 W/m^2) suggests an average imbalance over the solar cycle of about 0.7 W/m^2.

Earth's measured energy imbalance has been used to infer the climate forcing by aerosols, with two independent analyses yielding a forcing in the past decade of about -1.5 W/m^2 [64,72], including the direct aerosol forcing and indirect effects via induced cloud changes. Given this large (negative) aerosol forcing, precise monitoring of changing aerosols is needed [73]. Public reaction to increasingly bad air quality in developing regions [74] may lead to future aerosol reductions, at least on a regional basis. Increase of Earth's energy imbalance from reduction of particulate air pollution, which is needed for the sake of human health, can be minimized via an emphasis on reducing absorbing black soot [75], but the potential to constrain the net increase of climate forcing by focusing on black soot is limited [76].

Energy Imbalance Implications for CO_2 Target

Earth's energy imbalance is the most vital number characterizing the state of Earth's climate. It informs us about the global temperature change "in the pipeline" without further change of climate forcings and it defines how much greenhouse gases must be reduced to restore Earth's energy balance, which, at least to a good approximation, must be the requirement for stabilizing global climate. The measured energy imbalance accounts for all natural and human-made climate forcings, including changes of atmospheric aerosols and Earth's surface albedo.

If Earth's mean energy imbalance today is +0.5 W/m^2, CO_2 must be reduced from the current level of 395 ppm (global-mean annual-mean in mid-2013) to about 360 ppm to increase Earth's heat radiation to space by 0.5 W/m^2 and restore energy balance. If Earth's energy imbalance is 0.75 W/m^2, CO_2 must be reduced to about 345 ppm to restore energy balance [64,75].

The measured energy imbalance indicates that an initial CO_2 target "$<$350 ppm" would be appropriate, if the aim is to stabilize climate without further global warming. That target is consistent with an earlier analysis [54]. Additional support for that target is provided by our analyses of ongoing climate change and paleoclimate, in later parts of our paper. Specification now of a CO_2 target more precise than $<$350 ppm is difficult and unnecessary, because of uncertain future changes of forcings including other gases, aerosols and surface albedo. More precise assessments will become available during the time that it takes to turn around CO_2 growth and approach the initial 350 ppm target.

Below we find the decreasing emissions scenario that would achieve the 350 ppm target within the present century. Specifically, we want to know the annual percentage rate at which emissions must be reduced to reach this target, and the dependence of this rate upon the date at which reductions are initiated. This approach is complementary to the approach of estimating cumulative emissions allowed to achieve a given limit on global warming [12].

If the only human-made climate forcing were changes of atmospheric CO_2, the appropriate CO_2 target might be close to the pre-industrial CO_2 amount [53]. However, there are other human forcings, including aerosols, the effect of aerosols on clouds, non-CO_2 greenhouse gases, and changes of surface albedo that will not disappear even if fossil fuel burning is phased out. Aerosol forcings are substantially a result of fossil fuel burning [1,76], but the net aerosol forcing is a sensitive function of various aerosol sources [76]. The indirect aerosol effect on clouds is non-linear [1,76] such that it has been suggested that even the modest aerosol amounts added by pre-industrial humans to an otherwise pristine atmosphere may have caused a significant climate forcing [59]. Thus continued precise monitoring of Earth's radiation imbalance is probably the best way to assess and adjust the appropriate CO_2 target.

Ironically, future reductions of particulate air pollution may exacerbate global warming by reducing the cooling effect of reflective aerosols. However, a concerted effort to reduce non-CO_2 forcings by methane, tropospheric ozone, other trace gases, and black soot might counteract the warming from a decline in reflective aerosols [54,75]. Our calculations below of future global temperature assume such compensation, as a first approximation. To the extent that goal is not achieved, adjustments must be made in the CO_2 target or future warming may exceed calculated values.

Climate Impacts

Determination of the dangerous level of global warming inherently is partly subjective, but we must be as quantitative as possible. Early estimates for dangerous global warming based on the "burning embers" approach [1,19–20] have been recognized as probably being too conservative [77]. A target of limiting warming to 2°C has been widely adopted, as discussed above. We suspect, however, that this may be a case of inching toward a better answer. If our suspicion is correct, then that gradual approach is itself very dangerous, because of the climate system's inertia. It will become exceedingly difficult to keep warming below a target smaller than 2°C, if high emissions continue much longer.

We consider several important climate impacts and use evidence from current observations to assess the effect of 0.8°C warming and paleoclimate data for the effect of larger warming, especially the Eemian period, which had global mean temperature about +2°C relative to pre-industrial time. Impacts of special interest are sea level rise and species extermination, because they are practically irreversible, and others important to humankind.

Sea Level

The prior interglacial period, the Eemian, was at most ~2°C warmer than 1880–1920 (Fig. 3). Sea level reached heights several meters above today's level [78–80], probably with instances of sea level change of the order of 1 m/century [81–83]. Geologic shoreline evidence has been interpreted as indicating a rapid sea level rise of a few meters late in the Eemian to a peak about 9 meters above present, suggesting the possibility that a critical stability threshold was crossed that caused polar ice sheet collapse [84–85], although there remains debate within the research community about this specific history and interpretation. The large Eemian sea level excursions imply that substantial ice sheet melting occurred when the world was little warmer than today.

During the early Pliocene, which was only ~3°C warmer than the Holocene, sea level attained heights as much as 15–25 meters higher than today [53,86–89]. Such sea level rise suggests that parts of East Antarctica must be vulnerable to eventual melting with global temperature increase of a few degrees Celsius. Indeed, satellite gravity data and radar altimetry reveal that the Totten Glacier of East Antarctica, which fronts a large ice mass grounded below sea level, is now losing mass [90].

Greenland ice core data suggest that the Greenland ice sheet response to Eemian warmth was limited [91], but the fifth IPCC assessment [14] concludes that Greenland very likely contributed between 1.4 and 4.3 m to the higher sea level of the Eemian. The West Antarctic ice sheet is probably more susceptible to rapid change, because much of it rests on bedrock well below sea level [92–93]. Thus the entire 3–4 meters of global sea level contained in that ice sheet may be vulnerable to rapid disintegration, although arguments for stability of even this marine ice sheet have been made [94]. However, Earth's history reveals sea level changes of as much as a few meters per century, even though the natural climate forcings changed much more slowly than the present human-made forcing.

Expected human-caused sea level rise is controversial in part because predictions focus on sea level at a specific time, 2100. Sea level on a given date is inherently difficult to predict, as it depends on how rapidly non-linear ice sheet disintegration begins. Focus on a single date also encourages people to take the estimated result as an indication of what humanity faces, thus failing to emphasize that the likely rate of sea level rise immediately after 2100 will be much larger than within the 21st century, especially if CO_2 emissions continue to increase.

Recent estimates of sea level rise by 2100 have been of the order of 1 m [95–96], which is higher than earlier assessments [26], but these estimates still in part assume linear relations between warming and sea level rise. It has been argued [97–98] that continued business-as-usual CO_2 emissions are likely to spur a nonlinear response with multi-meter sea level rise this century. Greenland and Antarctica have been losing mass at rapidly increasing rates during the period of accurate satellite data [23]; the data are suggestive of exponential increase, but the records are too short to be conclusive. The area on Greenland with summer melt has increased markedly, with 97% of Greenland experiencing melt in 2012 [99].

The important point is that the uncertainty is not about whether continued rapid CO_2 emissions would cause large sea level rise, submerging global coastlines – it is about how soon the large changes would begin. The carbon from fossil fuel burning will remain in and affect the climate system for many millennia, ensuring that over time sea level rise of many meters will occur – tens of meters if most of the fossil fuels are burned [53]. That order of sea level rise would result in the loss of hundreds of historical coastal cities worldwide with incalculable economic consequences, create hundreds of millions of global warming refugees from highly-populated low-lying areas, and thus likely cause major international conflicts.

Shifting Climate Zones

Theory and climate models indicate that the tropical overturning (Hadley) atmospheric circulation expands poleward with global warming [33]. There is evidence in satellite and radiosonde data and in observational data for poleward expansion of the tropical circulation by as much as a few degrees of latitude since the 1970s [34–35], but natural variability may have contributed to that expansion [36]. Change in the overturning circulation likely contributes to expansion of subtropical conditions and increased aridity in the southern United States [30,100], the Mediterranean region, South America, southern Africa, Madagascar, and southern Australia. Increased aridity and temperature contribute to increased forest fires that burn hotter and are more destructive [38].

Exhibit C 7

Despite large year-to-year variability of temperature, decadal averages reveal isotherms (lines of a given average temperature) moving poleward at a typical rate of the order of 100 km/decade in the past three decades [101], although the range shifts for specific species follow more complex patterns [102]. This rapid shifting of climate zones far exceeds natural rates of change. Movement has been in the same direction (poleward, and upward in elevation) since about 1975. Wild species have responded to climate change, with three-quarters of marine species shifting their ranges poleward as much as 1000 km [44,103] and more than half of terrestrial species shifting ranges poleward as much as 600 km and upward as much as 400 m [104].

Humans may adapt to shifting climate zones better than many species. However, political borders can interfere with human migration, and indigenous ways of life already have been adversely affected [26]. Impacts are apparent in the Arctic, with melting tundra, reduced sea ice, and increased shoreline erosion. Effects of shifting climate zones also may be important for indigenous Americans who possess specific designated land areas, as well as other cultures with long-standing traditions in South America, Africa, Asia and Australia.

Human Extermination of Species

Biodiversity is affected by many agents including overharvesting, introduction of exotic species, land use changes, nitrogen fertilization, and direct effects of increased atmospheric CO_2 on plant ecophysiology [43]. However, an overriding role of climate change is exposed by diverse effects of rapid warming on animals, plants, and insects in the past three decades.

A sudden widespread decline of frogs, with extinction of entire mountain-restricted species attributed to global warming [105–106], provided a dramatic awakening. There are multiple causes of the detailed processes involved in global amphibian declines and extinctions [107–108], but global warming is a key contributor and portends a planetary-scale mass extinction in the making unless action is taken to stabilize climate while also fighting biodiversity's other threats [109].

Mountain-restricted and polar-restricted species are particularly vulnerable. As isotherms move up the mountainside and poleward, so does the climate zone in which a given species can survive. If global warming continues unabated, many of these species will be effectively pushed off the planet. There are already reductions in the population and health of Arctic species in the southern parts of the Arctic, Antarctic species in the northern parts of the Antarctic, and alpine species worldwide [43].

A critical factor for survival of some Arctic species is retention of all-year sea ice. Continued growth of fossil fuel emissions will cause loss of all Arctic summer sea ice within several decades. In contrast, the scenario in Fig. 5A, with global warming peaking just over 1°C and then declining slowly, should allow summer sea ice to survive and then gradually increase to levels representative of recent decades.

The threat to species survival is not limited to mountain and polar species. Plant and animal distributions reflect the regional climates to which they are adapted. Although species attempt to migrate in response to climate change, their paths may be blocked by human-constructed obstacles or natural barriers such as coast lines and mountain ranges. As the shift of climate zones [110] becomes comparable to the range of some species, less mobile species can be driven to extinction. Because of extensive species interdependencies, this can lead to mass extinctions.

Rising sea level poses a threat to a large number of uniquely evolved endemic fauna living on islands in marine-dominated ecosystems, with those living on low lying islands being especially vulnerable. Evolutionary history on Bermuda offers numerous examples of the direct and indirect impact of changing sea level on evolutionary processes [111–112], with a number of taxa being extirpated due to habitat changes, greater competition, and island inundation [113]. Similarly, on Aldahabra Island in the Indian Ocean, land tortoises were exterminated during sea level high stands [114]. Vulnerabilities would be magnified by the speed of human-made climate change and the potentially large sea level rise [115].

IPCC [26] reviewed studies relevant to estimating eventual extinctions. They estimate that if global warming exceeds 1.6°C above preindustrial, 9–31 percent of species will be committed to extinction. With global warming of 2.9°C, an estimated 21–52 percent of species will be committed to extinction. A comprehensive study of biodiversity indicators over the past decade [116] reveals that, despite some local success in increasing extent of protected areas, overall indicators of pressures on biodiversity including that due to climate change are continuing to increase and indicators of the state of biodiversity are continuing to decline.

Mass extinctions occurred several times in Earth's history [117–118], often in conjunction with rapid climate change. New species evolved over millions of years, but those time scales are almost beyond human comprehension. If we drive many species to extinction we will leave a more desolate, monotonous planet for our children, grandchildren, and more generations than we can imagine. We will also undermine ecosystem functions (e.g., pollination which is critical for food production) and ecosystem resilience (when losing keystone species in food chains), as well as reduce functional diversity (critical for the ability of ecosystems to respond to shocks and stress) and genetic diversity that plays an important role for development of new medicines, materials, and sources of energy.

Coral Reef Ecosystems

Coral reefs are the most biologically diverse marine ecosystem, often described as the rainforests of the ocean. Over a million species, most not yet described [119], are estimated to populate coral reef ecosystems generating crucial ecosystem services for at least 500 million people in tropical coastal areas. These ecosystems are highly vulnerable to the combined effects of ocean acidification and warming.

Acidification arises as the ocean absorbs CO_2, producing carbonic acid [120], thus making the ocean more corrosive to the calcium carbonate shells (exoskeletons) of many marine organisms. Geochemical records show that ocean pH is already outside its range of the past several million years [121–122]. Warming causes coral bleaching, as overheated coral expel symbiotic algae and become vulnerable to disease and mortality [123]. Coral bleaching and slowing of coral calcification already are causing mass mortalities, increased coral disease, and reduced reef carbonate accretion, thus disrupting coral reef ecosystem health [40,124].

Local human-made stresses add to the global warming and acidification effects, all of these driving a contraction of 1–2% per year in the abundance of reef-building corals [39]. Loss of the three-dimensional coral reef frameworks has consequences for all the species that depend on them. Loss of these frameworks also has consequences for the important roles that coral reefs play in supporting fisheries and protecting coastlines from wave stress. Consequences of lost coral reefs can be economically devastating for many nations, especially in combination with other impacts such as sea level rise and intensification of storms.

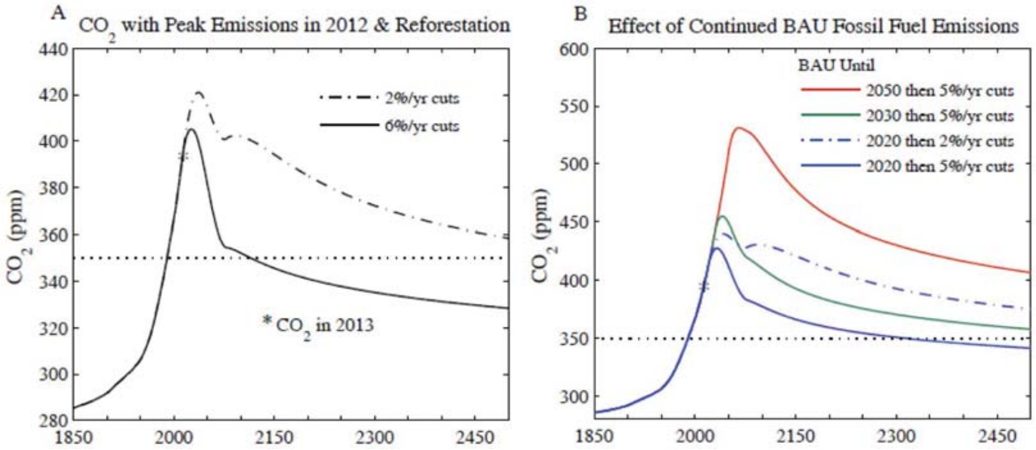

Figure 5. Atmospheric CO_2 if fossil fuel emissions reduced. (A) 6% or 2% annual cut begins in 2013 and 100 GtC reforestation drawdown occurs in 2031–2080, (B) effect of delaying onset of emission reduction.
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Climate Extremes

Changes in the frequency and magnitude of climate extremes, of both moisture and temperature, are affected by climate trends as well as changing variability. Extremes of the hydrologic cycle are expected to intensify in a warmer world. A warmer atmosphere holds more moisture, so precipitation can be heavier and cause more extreme flooding. Higher temperatures, on the other hand, increase evaporation and can intensify droughts when they occur, as can expansion of the subtropics, as discussed above. Global models for the 21st century find an increased variability of precipitation minus evaporation [P-E] in most of the world, especially near the equator and at high latitudes [125]. Some models also show an intensification of droughts in the Sahel, driven by increasing greenhouse gases [126].

Observations of ocean salinity patterns for the past 50 years reveal an intensification of [P-E] patterns as predicted by models, but at an even faster rate. Precipitation observations over land show the expected general increase of precipitation poleward of the subtropics and decrease at lower latitudes [1,26]. An increase of intense precipitation events has been found on much of the world's land area [127–129]. Evidence for widespread drought intensification is less clear and inherently difficult to confirm with available data because of the increase of time-integrated precipitation at most locations other than the subtropics. Data analyses have found an increase of drought intensity at many locations [130–131] The magnitude of change depends on the drought index employed [132], but soil moisture provides a good means to separate the effect of shifting seasonal precipitation and confirms an overall drought intensification [37].

Global warming of ~0.6°C since the 1970s (Fig. 3) has already caused a notable increase in the occurrence of extreme summer heat [46]. The likelihood of occurrence or the fractional area covered by 3-standard-deviation hot anomalies, relative to a base period (1951–1980) that was still within the range of Holocene climate, has increased by more than a factor of ten. Large areas around Moscow, the Mediterranean region, the United States and Australia have experienced such extreme anomalies in the past three years. Heat waves lasting for weeks have a devastating impact on human health: the European heat wave of summer 2003 caused over 70,000 excess deaths [133]. This heat record for Europe was surpassed already in 2010 [134]. The number of extreme heat waves has increased several-fold due to global warming [45–46,135] and will increase further if temperatures continue to rise.

Human Health

Impacts of climate change cause widespread harm to human health, with children often suffering the most. Food shortages, polluted air, contaminated or scarce supplies of water, an expanding area of vectors causing infectious diseases, and more intensely allergenic plants are among the harmful impacts [26]. More extreme weather events cause physical and psychological harm. World health experts have concluded with "very high confidence" that climate change already contributes to the global burden of disease and premature death [26].

IPCC [26] projects the following trends, if global warming continue to increase, where only trends assigned very high confidence or high confidence are included: (i) increased malnutrition and consequent disorders, including those related to child growth and development, (ii) increased death, disease and injuries from heat waves, floods, storms, fires and droughts, (iii) increased cardio-respiratory morbidity and mortality associated with ground-level ozone. While IPCC also projects fewer deaths from cold, this positive effect is far outweighed by the negative ones.

Growing awareness of the consequences of human-caused climate change triggers anxiety and feelings of helplessness [136–137]. Children, already susceptible to age-related insecurities, face additional destabilizing insecurities from questions about how they will cope with future climate change [138–139]. Exposure to media ensures that children cannot escape hearing that their future and that of other species is at stake, and that the window of opportunity to avoid dramatic climate impacts is closing. The psychological health of our children is a priority, but denial of the truth exposes our children to even greater risk.

Health impacts of climate change are in addition to direct effects of air and water pollution. A clear illustration of direct effects of fossil fuels on human health was provided by an inadvertent experiment in China during the 1950–1980 period of central planning, when free coal for winter heating was provided to North China but not to the rest of the country. Analysis of the impact was made [140] using the most comprehensive data file ever compiled on mortality and air pollution in any developing country. A principal conclusion was that the 500 million residents of North China experienced during the 1990s a loss of more than 2.5 billion life years owing to the added air pollution, and an average reduction in life expectancy of 5.5 years. The degree of air pollution in China exceeded that in most of the world, yet assessments of total health effects must also include other fossil fuel caused air and water pollutants, as discussed in the following section on ecology and the environment.

The Text S1 has further discussion of health impacts of climate change.

Ecology and the Environment

The ecological impact of fossil fuel mining increases as the largest, easiest to access, resources are depleted [141]. A constant fossil fuel production rate requires increasing energy input, but also use of more land, water, and diluents, with the production of more waste [142]. The increasing ecological and environmental impact of a given amount of useful fossil fuel energy is a relevant consideration in assessing alternative energy strategies.

Coal mining has progressively changed from predominantly underground mining to surface mining [143], including mountaintop removal with valley fill, which is now widespread in the Appalachian ecoregion in the United States. Forest cover and topsoil are removed, explosives are used to break up rocks to access coal, and the excess rock is pushed into adjacent valleys, where it buries existing streams. Burial of headwater streams causes loss of ecosystems that are important for nutrient cycling and production of organic matter for downstream food webs [144]. The surface alterations lead to greater storm runoff [145] with likely impact on downstream flooding. Water emerging from valley fills contain toxic solutes that have been linked to declines in watershed biodiversity [146]. Even with mine-site reclamation intended to restore pre-mined surface conditions, mine-derived chemical constituents are found in domestic well water [147]. Reclaimed areas, compared with unmined areas, are found to have increased soil density with decreased organic and nutrient content, and with reduced water infiltration rates [148]. Reclaimed areas have been found to produce little if any regrowth of woody vegetation even after 15 years [149], and, although this deficiency might be addressed via more effective reclamation methods, there remains a likely significant loss of carbon storage [149].

Oil mining has an increasing ecological footprint per unit delivered energy because of the decreasing size of new fields and their increased geographical dispersion; transit distances are greater and wells are deeper, thus requiring more energy input [145]. Useful quantitative measures of the increasing ecological impacts are provided by the history of oil development in Alberta, Canada for production of both conventional oil and tar sands development. The area of land required per barrel of produced oil increased by a factor of 12 between 1955 and 2006 [150] leading to ecosystem fragmentation by roads and pipelines needed to support the wells [151]. Additional escalation of the mining impact occurs as conventional oil mining is supplanted by tar sands development, with mining and land disturbance from the latter producing land use-related greenhouse gas emissions as much as 23 times greater than conventional oil production per unit area [152], but with substantial variability and uncertainty [152–153]. Much of the tar sands bitumen is extracted through surface mining that removes the "overburden" (i.e., boreal forest ecosystems) and tar sand from large areas to a depth up to 100 m, with ecological impacts downstream and in the mined area [154]. Although mined areas are supposed to be reclaimed, as in the case of mountaintop removal, there is no expectation that the ecological value of reclaimed areas will be equivalent to predevelopment condition [141,155]. Landscape changes due to tar sands mining and reclamation cause a large loss of peatland and stored carbon, while also significantly reducing carbon sequestration potential [156]. Lake sediment cores document increased chemical pollution of ecosystems during the past several decades traceable to tar sands development [157] and snow and water samples indicate that recent levels of numerous pollutants exceeded local and national criteria for protection of aquatic organisms [158].

Gas mining by unconventional means has rapidly expanded in recent years, without commensurate understanding of the ecological, environmental and human health consequences [159]. The predominant approach is hydraulic fracturing ("fracking") of deep shale formations via injection of millions of gallons of water, sand and toxic chemicals under pressure, thus liberating methane [155,160]. A large fraction of the injected water returns to the surface as wastewater containing high concentrations of heavy metals, oils, greases and soluble organic compounds [161]. Management of this wastewater is a major technical challenge, especially because the polluted waters can continue to backflow from the wells for many years [161]. Numerous instances of groundwater and river contamination have been cited [162]. High levels of methane leakage from fracking have been found [163], as well as nitrogen oxides and volatile organic compounds [159]. Methane leaks increase the climate impact of shale gas, but whether the leaks are sufficient to significantly alter the climate forcing by total natural gas development is uncertain [164]. Overall, environmental and ecologic threats posed by unconventional gas extraction are uncertain because of limited research, however evidence for groundwater pollution on both local and river basin scales is a major concern [165].

Today, with cumulative carbon emissions ~370 GtC from all fossil fuels, we are at a point of severely escalating ecological and environmental impacts from fossil fuel use and fossil fuel mining, as is apparent from the mountaintop removal for coal, tar sands extraction of oil, and fracking for gas. The ecological and environmental implications of scenarios with carbon emissions of 1000 GtC or greater, as discussed below, would be profound and should influence considerations of appropriate energy strategies.

Summary: Climate Impacts

Climate impacts accompanying global warming of 2°C or more would be highly deleterious. Already there are numerous indications of substantial effects in response to warming of the past few decades. That warming has brought global temperature close to if not slightly above the prior range of the Holocene. We conclude that an appropriate target would be to keep global temperature at a level within or close to the Holocene range. Global warming of 2°C would be well outside the Holocene range and far into the dangerous range.

Transient Climate Change

We must quantitatively relate fossil fuel emissions to global temperature in order to assess how rapidly fossil fuel emissions must be phased down to stay under a given temperature limit. Thus we must deal with both a transient carbon cycle and transient global climate change.

Global climate fluctuates stochastically and also responds to natural and human-made climate forcings [1,166]. Forcings, measured in W/m^2 averaged over the globe, are imposed perturbations of Earth's energy balance caused by changing forcing agents such as solar irradiance and human-made greenhouse gases (GHGs). CO_2 accounts for more than 80% of the added GHG forcing in the past 15 years [64,167] and, if fossil fuel emissions continue at a high level, CO_2 will be the dominant driver of future global temperature change.

We first define our method of calculating atmospheric CO_2 as a function of fossil fuel emissions. We then define our assumptions about the potential for drawing down atmospheric CO_2 via reforestation and increase of soil carbon, and we define fossil fuel emission reduction scenarios that we employ in our study. Finally we describe all forcings employed in our calculations of global temperature and the method used to simulate global temperature.

Carbon Cycle and Atmospheric CO_2

The carbon cycle defines the fate of CO_2 injected into the air by fossil fuel burning [1,168] as the additional CO_2 distributes itself over time among surface carbon reservoirs: the atmosphere, ocean, soil, and biosphere. We use the dynamic-sink pulse-response function version of the well-tested Bern carbon cycle model [169], as described elsewhere [54,170].

Specifically, we solve equations 3–6, 16–17, A.2.2, and A.3 of Joos et al. [169] using the same parameters and assumptions therein, except that initial (1850) atmospheric CO_2 is assumed to be 285.2 ppm [167]. Historical fossil fuel CO_2 emissions are from Boden et al. [5]. This Bern model incorporates non-linear ocean chemistry feedbacks and CO_2 fertilization of the terrestrial biosphere, but it omits climate-carbon feedbacks, e.g., assuming static global climate and ocean circulation. Therefore our results should be regarded as conservative, especially for scenarios with large emissions.

A pulse of CO_2 injected into the air decays by half in about 25 years as CO_2 is taken up by the ocean, biosphere and soil, but nearly one-fifth is still in the atmosphere after 500 years (Fig. 4A). Eventually, over hundreds of millennia, weathering of rocks will deposit all of this initial CO_2 pulse on the ocean floor as carbonate sediments [168].

Under equilibrium conditions a negative CO_2 pulse, i.e., artificial extraction and storage of some CO_2 amount, decays at about the same rate as a positive pulse (Fig. 4A). Thus if it is decided in the future that CO_2 must be extracted from the air and removed from the carbon cycle (e.g., by storing it underground or in carbonate bricks), the impact on atmospheric CO_2 amount will diminish in time. This occurs because carbon is exchanged among the surface carbon reservoirs as they move toward an equilibrium distribution, and thus, e.g., CO_2 out-gassing by the ocean can offset some of the artificial drawdown. The CO_2 extraction required to reach a given target atmospheric CO_2 level therefore depends on the prior emission history and target timeframe, but the amount that must be extracted substantially exceeds the net reduction of the atmospheric CO_2 level that will be achieved. We clarify this matter below by means of specific scenarios for capture of CO_2.

It is instructive to see how fast atmospheric CO_2 declines if fossil fuel emissions are instantly terminated (Fig. 4B). Halting emissions in 2015 causes CO_2 to decline to 350 ppm at century's end (Fig. 4B). A 20 year delay in halting emissions has CO_2 returning to 350 ppm at about 2300. With a 40 year delay, CO_2 does not return to 350 ppm until after 3000. These results show how difficult it is to get back to 350 ppm if emissions continue to grow for even a few decades.

These results emphasize the urgency of initiating emissions reduction [171]. As discussed above, keeping global climate close to the Holocene range requires a long-term atmospheric CO_2 level of about 350 ppm or less, with other climate forcings similar to today's levels. If emissions reduction had begun in 2005, reduction at 3.5%/year would have achieved 350 ppm at 2100. Now the requirement is at least 6%/year. Delay of emissions reductions until 2020 requires a reduction rate of 15%/year to achieve 350 ppm in 2100. If we assume only 50 GtC reforestation, and begin emissions reduction in 2013, the required reduction rate becomes about 9%/year.

Reforestation and Soil Carbon

Of course fossil fuel emissions will not suddenly terminate. Nevertheless, it is not impossible to return CO_2 to 350 ppm this century. Reforestation and increase of soil carbon can help draw down atmospheric CO_2. Fossil fuels account for ~80% of the CO_2 increase from preindustrial time, with land use/deforestation accounting for 20% [1,170,172–173]. Net deforestation to date is estimated to be 100 GtC (gigatons of carbon) with ±50% uncertainty [172].

Complete restoration of deforested areas is unrealistic, yet 100 GtC carbon drawdown is conceivable because: (1) the human-enhanced atmospheric CO_2 level increases carbon uptake by some vegetation and soils, (2) improved agricultural practices can convert agriculture from a CO_2 ource into a CO_2 sink [174], (3) biomass-burning power plants with CO_2 capture and storage can contribute to CO_2 drawdown.

Forest and soil storage of 100 GtC is challenging, but has other benefits. Reforestation has been successful in diverse places [175]. Minimum tillage with biological nutrient recycling, as opposed to plowing and chemical fertilizers, could sequester 0.4–1.2 GtC/year [176] while conserving water in soils, building agricultural resilience to climate change, and increasing productivity especially in smallholder rain-fed agriculture, thereby reducing expansion of agriculture into forested ecosystems [177–178]. Net tropical deforestation may have decreased in the past decade [179], but because of extensive deforestation in earlier decades [170,172–173,180–181] there is a large amount of land suitable for reforestation [182].

Use of bioenergy to draw down CO_2 should employ feedstocks from residues, wastes, and dedicated energy crops that do not compete with food crops, thus avoiding loss of natural ecosystems and cropland [183–185]. Reforestation competes with agricultural land use; land needs could decline by reducing use of animal products, as livestock now consume more than half of all crops [186].

Our reforestation scenarios assume that today's net deforestation rate (~1 GtC/year; see [54]) will stay constant until 2020, then linearly decrease to zero by 2030, followed by sinusoidal 100 GtC biospheric carbon storage over 2031–2080. Alternative timings do not alter conclusions about the potential to achieve a given CO_2 level such as 350 ppm.

Emission Reduction Scenarios

A 6%/year decrease of fossil fuel emissions beginning in 2013, with 100 GtC reforestation, achieves a CO_2 decline to 350 ppm near the end of this century (Fig. 5A). Cumulative fossil fuel emissions in this scenario are ~129 GtC from 2013 to 2050, with an additional 14 GtC by 2100. If our assumed land use changes occur a decade earlier, CO_2 returns to 350 ppm several years earlier; however that has negligible effect on the maximum global temperature calculated below.

Delaying fossil fuel emission cuts until 2020 (with 2%/year emissions growth in 2012–2020) causes CO_2 to remain above 350 ppm (with associated impacts on climate) until 2300 (Fig. 5B). If reductions are delayed until 2030 or 2050, CO_2 remains above 350 ppm or 400 ppm, respectively, until well after 2500.

We conclude that it is urgent that large, long-term emission reductions begin soon. Even if a 6%/year reduction rate and 500 GtC are not achieved, it makes a huge difference when reductions begin. There is no practical justification for why emissions necessarily must even approach 1000 GtC.

Climate Forcings

Atmospheric CO_2 and other GHGs have been well-measured for the past half century, allowing accurate calculation of their climate forcing. The growth rate of the GHG forcing has declined moderately since its peak values in the 1980s, as the growth rate of CH_4 and chlorofluorocarbons has slowed [187]. Annual changes of CO_2 are highly correlated with the El Niño cycle (Fig. 6). Two strong La Niñas in the past five years have depressed CO_2 growth as well as the global warming rate (Fig. 3). The CO_2 growth rate and warming rate can be expected to increase as we move into the next El Niño, with the CO_2 growth already reaching 3 ppm/year in mid-2013 [188]. The CO_2 climate forcing does not increase as rapidly as the CO_2 amount because of partial saturation of CO_2 absorption bands [75]. The GHG forcing is now increasing at a rate of almost 0.4 W/m^2 per decade [187].

Solar irradiance variations are sometimes assumed to be the most likely natural driver of climate change. Solar irradiance has been measured from satellites since the late 1970s (Fig. 7). These data are from a composite of several satellite-measured time series. Data through 28 February 2003 are from [189] and Physikalisch Meteorologisches Observatorium Davos, World Radiation Center. Subsequent update is from University of Colorado Solar Radiation & Climate Experiment (SORCE). Data sets are concatenated by matching the means over the first 12 months of SORCE data. Monthly sunspot numbers (Fig. 7) support the conclusion that the solar irradiance in the current solar cycle is significantly lower than in the three preceding solar cycles. Amplification of the direct solar forcing is conceivable, e.g., through effects on ozone or atmospheric condensation nuclei, but empirical data place a factor of two upper limit on the amplification, with the most likely forcing in the range 100–120% of the directly measured solar irradiance change [64].

Recent reduced solar irradiance (Fig. 7) may have decreased the forcing over the past decade by about half of the full amplitude of measured irradiance variability, thus yielding a negative forcing of, say, $-$ 0.12 W/m^2. This compares with a decadal increase of the GHG forcing that is positive and about three times larger in magnitude. Thus the solar forcing is not negligible and might partially account for the slowdown in global warming in the past decade [17]. However, we must (1) compare the solar forcing with the net of other forcings, which enhances the importance of solar change, because the net forcing is smaller than the GHG forcing, and (2) consider forcing changes on longer time scales, which greatly diminishes the importance of solar change, because solar variability is mainly oscillatory.

Human-made tropospheric aerosols, which arise largely from fossil fuel use, cause a substantial negative forcing. As noted above, two independent analyses [64,72] yield a total (direct plus indirect) aerosol forcing in the past decade of about -1.5 W/m^2, half the magnitude of the GHG forcing and opposite in sign. That empirical aerosol forcing assessment for the past decade is consistent with the climate forcings scenario (Fig. 8) that we use for the past century in the present and prior studies [64,190]. Supplementary Table S1 specifies the historical forcings and Table S2 gives several scenarios for future forcings.

Future Climate Forcings

Future global temperature change should depend mainly on atmospheric CO_2, at least if fossil fuel emissions remain high. Thus to provide the clearest picture of the CO_2 effect, we approximate the net future change of human-made non-CO_2 forcings as zero and we exclude future changes of natural climate forcings, such as solar irradiance and volcanic aerosols. Here we discuss possible effects of these approximations.

Uncertainties in non-CO_2 forcings concern principally solar, aerosol and other GHG forcings. Judging from the sunspot numbers (Fig. 7B and [191]) for the past four centuries, the current solar cycle is almost as weak as the Dalton Minimum of the late 18th century. Conceivably irradiance could decline further to the level of the Maunder Minimum of the late 17th century [192–193]. For our simulation we choose an intermediate path between recovery to the level before the current solar cycle and decline to a still lower level. Specifically, we keep solar irradiance fixed at the reduced level of 2010, which is probably not too far off in either direction. Irradiance in 2010 is about 0.1 W/m^2 less than the mean of the prior three solar cycles, a decrease of forcing that

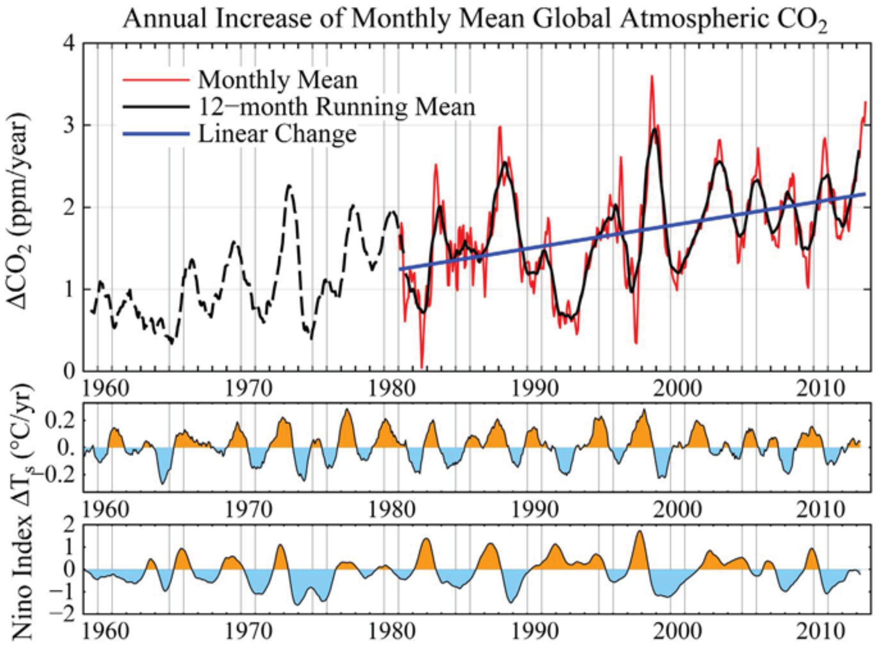

Figure 6. Annual increase of CO_2 based on data from the NOAA Earth System Research Laboratory [188]. Prior to 1981 the CO_2 change is based on only Mauna Loa, Hawaii. Temperature changes in lower diagram are 12-month running means for the globe and Niño3.4 area [16].
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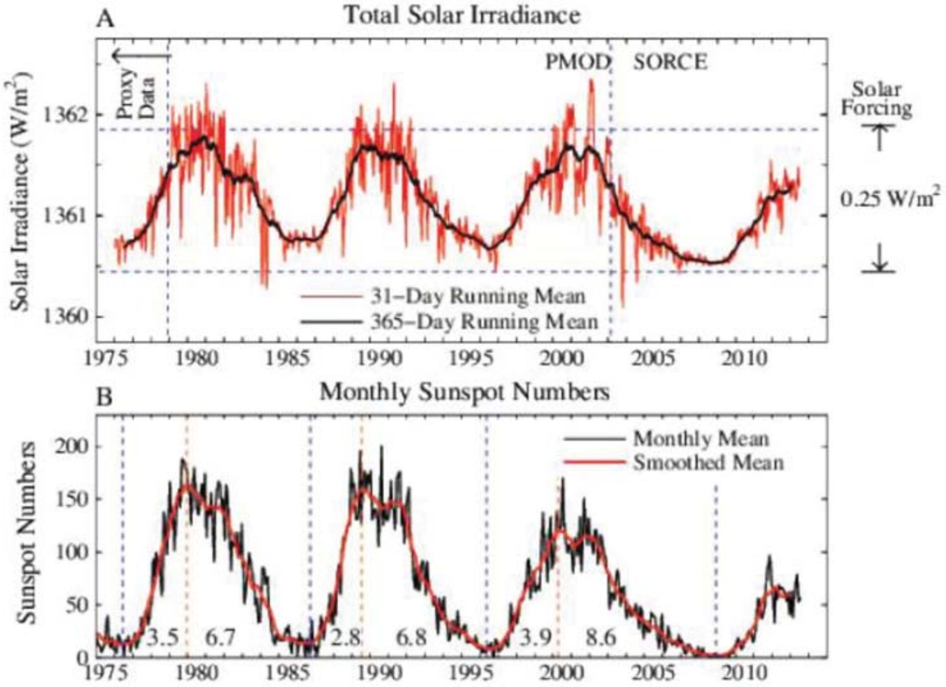

Figure 7. Solar irradiance and sunspot number in the era of satellite data (see text). Left scale is the energy passing through an area perpendicular to Sun-Earth line. Averaged over Earth's surface the absorbed solar energy is ~240 W/m^2, so the full amplitude of measured solar variability is ~0.25 W/m^2.
doi:10.1371/journal.pone.0081648.g007

would be restored by the CO_2 increase within 3–4 years at its current growth rate. Extensive simulations [17,194] confirm that the effect of solar variability is small compared with GHGs if CO_2 emissions continue at a high level. However, solar forcing can affect the magnitude and detection of near-term warming. Also, if rapidly declining GHG emissions are achieved, changes of solar forcing will become relatively more important.

Aerosols present a larger uncertainty. Expectations of decreases in large source regions such as China [195] may be counteracted by aerosol increases other places as global population continues to increase. Our assumption of unchanging human-made aerosols could be substantially off in either direction. For the sake of interpreting on-going and future climate change it is highly desirable to obtain precise monitoring of the global aerosol forcing [73].

Non-CO_2 GHG forcing has continued to increase at a slow rate since 1995 (Fig. 6 in [64]). A desire to constrain climate change may help reduce emissions of these gases in the future. However, it will be difficult to prevent or fully offset positive forcing from increasing N_2O, as its largest source is associated with food production and the world's population is continuing to rise.

On the other hand, we are also probably underestimating a negative aerosol forcing, e.g., because we have not included future volcanic aerosols. Given the absence of large volcanic eruptions in the past two decades (the last one being Mount Pinatubo in 1991), multiple volcanic eruptions would cause a cooling tendency [196] and reduce heat storage in the ocean [197].

Overall, we expect the errors due to our simple approximation of non-CO_2 forcings to be partially off-setting. Specifically, we have likely underestimated a positive forcing by non-CO_2 GHGs, while also likely underestimating a negative aerosol forcing.

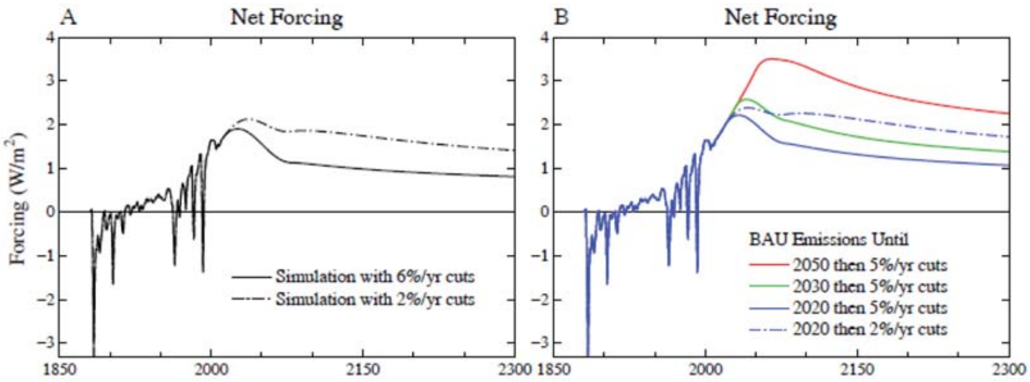

Figure 8. Climate forcings employed in our six main scenarios. Forcings through 2010 are as in [64].
doi:10.1371/journal.pone.0081648.g008

Note that uncertainty in forcings is partly obviated via the focus on Earth's energy imbalance in our analysis. The planet's energy imbalance is an integrative quantity that is especially useful for a case in which some of the forcings are uncertain or unmeasured. Earth's measured energy imbalance includes the effects of all forcings, whether they are measured or not.

Simulations of Future Global Temperature

We calculate global temperature change for a given CO_2 scenario using a climate response function (Table S3) that accurately replicates results from a global climate model with sensitivity 3°C for doubled CO_2 [64]. A best estimate of climate sensitivity close to 3°C for doubled CO_2 has been inferred from paleoclimate data [51–52]. This empirical climate sensitivity is generally consistent with that of global climate models [1], but the empirical approach makes the inferred high sensitivity more certain and the quantitative evaluation more precise. Because this climate sensitivity is derived from empirical data on how Earth responded to past changes of boundary conditions, including atmospheric composition, our conclusions about limits on fossil fuel emissions can be regarded as largely independent of climate models.

The detailed temporal and geographical response of the climate system to the rapid human-made change of climate forcings is not well-constrained by empirical data, because there is no faithful paleoclimate analog. Thus climate models necessarily play an important role in assessing practical implications of climate change. Nevertheless, it is possible to draw important conclusions with transparent computations. A simple response function (Green's function) calculation [64] yields an estimate of global mean temperature change in response to a specified time series for global climate forcing. This approach accounts for the delayed response of the climate system caused by the large thermal inertia of the ocean, yielding a global mean temporal response in close accord with that obtained from global climate models.

Tables S1 and S2 in Supporting Information give the forcings we employ and Table S3 gives the climate response function for our Green's function calculation, defined by equation 2 of [64]. The Green's function is driven by the net forcing, which, with the response function, is sufficient information for our results to be reproduced. However, we also include the individual forcings in Table S1, in case researchers wish to replace specific forcings or use them for other purposes.

Simulated global temperature (Fig. 9) is for CO_2 scenarios of Fig. 5. Peak global warming is ~1.1°C, declining to less than 1°C by mid-century, if CO_2 emissions are reduced 6%/year beginning in 2013. In contrast, warming reaches 1.5°C and stays above 1°C until after 2400 if emissions continue to increase until 2030, even though fossil fuel emissions are phased out rapidly (5%/year) after 2030 and 100 GtC reforestation occurs during 2030–2080. If emissions continue to increase until 2050, simulated warming exceeds 2°C well into the 22nd century.

Increased global temperature persists for many centuries after the climate forcing declines, because of the thermal inertia of the ocean [198]. Some temperature reduction is possible if the climate forcing is reduced rapidly, before heat has penetrated into the deeper ocean. Cooling by a few tenths of a degree in Fig. 9 is a result mainly of the 100 GtC biospheric uptake of CO_2 during 2030–2080. Note the longevity of the warming, especially if emissions reduction is as slow as 2%/year, which might be considered to be a rapid rate of reduction.

The temporal response of the real world to the human-made climate forcing could be more complex than suggested by a simple response function calculation, especially if rapid emissions growth continues, yielding an unprecedented climate forcing scenario. For example, if ice sheet mass loss becomes rapid, it is conceivable that the cold fresh water added to the ocean could cause regional surface cooling [199], perhaps even at a point when sea level rise has only reached a level of the order of a meter [200]. However, any uncertainty in the surface thermal response this century due to such phenomena has little effect on our estimate of the dangerous level of emissions. The long lifetime of the fossil fuel carbon in the climate system and the persistence of ocean warming for millennia [201] provide sufficient time for the climate system to achieve full response to the fast feedback processes included in the 3°C climate sensitivity.

Indeed, the long lifetime of fossil fuel carbon in the climate system and persistence of the ocean warming ensure that "slow" feedbacks, such as ice sheet disintegration, changes of the global vegetation distribution, melting of permafrost, and possible release of methane from methane hydrates on continental shelves, would also have time to come into play. Given the unprecedented rapidity of the human-made climate forcing, it is difficult to establish how soon slow feedbacks will become important, but clearly slow feedbacks should be considered in assessing the "dangerous" level of global warming, as discussed in the next section.

Danger of Initiating Uncontrollable Climate Change

Our calculated global warming as a function of CO_2 amount is based on equilibrium climate sensitivity 3°C for doubled CO_2. That is the central climate sensitivity estimate from climate models [1], and it is consistent with climate sensitivity inferred from Earth's climate history [51–52]. However, this climate sensitivity includes only the effects of fast feedbacks of the climate system, such as water vapor, clouds, aerosols, and sea ice. Slow feedbacks, such as change of ice sheet area and climate-driven changes of greenhouse gases, are not included.

Slow Climate Feedbacks and Irreversible Climate Change

Excluding slow feedbacks was appropriate for simulations of the past century, because we know the ice sheets were stable then and our climate simulations used observed greenhouse gas amounts that included any contribution from slow feedbacks. However, we must include slow feedbacks in projections of warming for the 21st century and beyond. Slow feedbacks are important because they affect climate sensitivity and because their instigation is related to the danger of passing "points of no return", beyond which irreversible consequences become inevitable, out of humanity's control.

Antarctic and Greenland ice sheets present the danger of change with consequences that are irreversible on time scales important to society [1]. These ice sheets required millennia to grow to their present sizes. If ice sheet disintegration reaches a point such that the dynamics and momentum of the process take over, at that point reducing greenhouse gases may be unable to prevent major ice sheet mass loss, sea level rise of many meters, and worldwide loss of coastal cities – a consequence that is irreversible for practical purposes. Interactions between the ocean and ice sheets are particularly important in determining ice sheet changes, as a warming ocean can melt the ice shelves, the tongues of ice that extend from the ice sheets into the ocean and buttress the large land-based ice sheets [92,202–203]. Paleoclimate data for sea level change indicate that sea level changed at rates of the order of a meter per century [81–83], even at times when the forcings driving climate change were far weaker than the human-

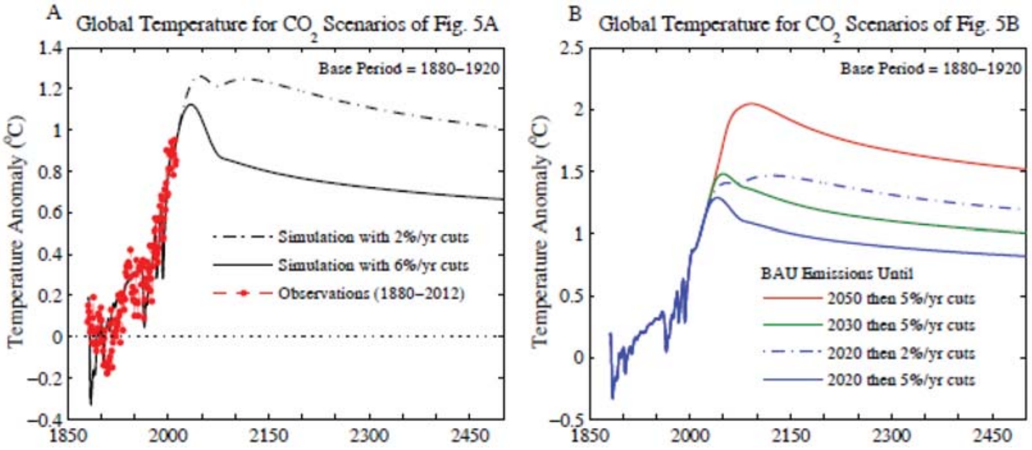

Figure 9. Simulated global temperature relative to 1880–1920 mean for CO_2 scenarios of Figure 5.
doi:10.1371/journal.pone.0081648.g009

made forcing. Thus, because ocean warming is persistent for centuries, there is a danger that large irreversible change could be initiated by excessive ocean warming.

Paleoclimate data are not as helpful for defining the likely rate of sea level rise in coming decades, because there is no known case of growth of a positive (warming) climate forcing as rapid as the anthropogenic change. The potential for unstable ice sheet disintegration is controversial, with opinion varying from likely stability of even the (marine) West Antarctic ice sheet [94] to likely rapid non-linear response extending up to multi-meter sea level rise [97–98]. Data for the modern rate of annual ice sheet mass changes indicate an accelerating rate of mass loss consistent with a mass loss doubling time of a decade or less (Fig. 10). However, we do not know the functional form of ice sheet response to a large persistent climate forcing. Longer records are needed for empirical assessment of this ostensibly nonlinear behavior.

Greenhouse gas amounts in the atmosphere, most importantly CO_2 and CH_4, change in response to climate change, i.e., as a feedback, in addition to the immediate gas changes from human-caused emissions. As the ocean warms, for example, it releases CO_2 to the atmosphere, with one principal mechanism being the simple fact that the solubility of CO_2 decreases as the water temperature rises [204]. We also include in the category of slow feedbacks the global warming spikes, or "hyperthermals", that have occurred a number of times in Earth's history during the course of slower global warming trends. The mechanisms behind these hyperthermals are poorly understood, as discussed below, but they are characterized by the injection into the surface climate system of a large amount of carbon in the form of CH_4 and/or CO_2 on the time scale of a millennium [205–207]. The average rate of injection of carbon into the climate system during these hyperthermals was slower than the present human-made injection of fossil fuel carbon, yet it was faster than the time scale for removal of carbon from the surface reservoirs via the weathering process [3,208], which is tens to hundreds of thousands of years.

Methane hydrates – methane molecules trapped in frozen water molecule cages in tundra and on continental shelves – and organic matter such as peat locked in frozen soils (permafrost) are likely mechanisms in the past hyperthermals, and they provide another climate feedback with the potential to amplify global warming if large scale thawing occurs [209–210]. Paleoclimate data reveal instances of rapid global warming, as much as 5–6°C, as a sudden additional warming spike during a longer period of gradual warming [see Text S1]. The candidates for the carbon injected into the climate system during those warmings are methane hydrates on continental shelves destabilized by sea floor warming [211] and carbon released from frozen soils [212]. As for the present, there are reports of methane release from thawing permafrost on land [213] and from sea-bed methane hydrate deposits [214], but amounts so far are small and the data are snapshots that do not prove that there is as yet a temporal increase of emissions.

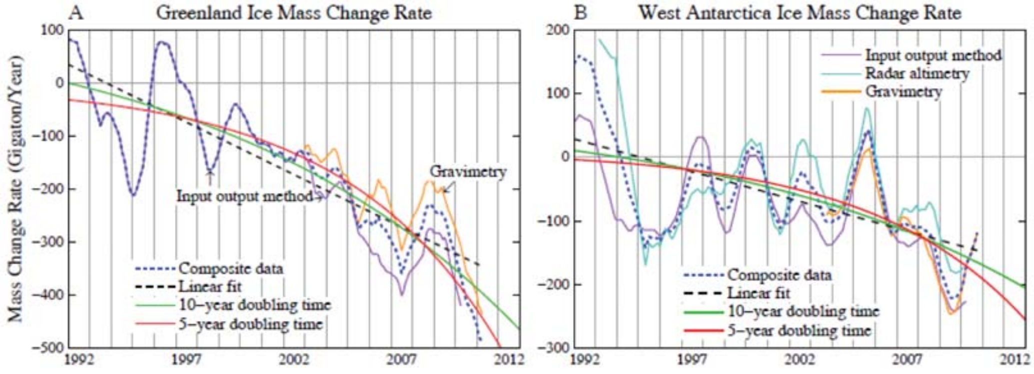

Figure 10. Annual Greenland and West Antarctic ice mass changes as estimated via alternative methods. Data were read from Figure 4 of Shepherd et al. [23] and averaged over the available records.
doi:10.1371/journal.pone.0081648.g010

There is a possibility of rapid methane hydrate or permafrost emissions in response to warming, but that risk is largely unquantified [215]. The time needed to destabilize large methane hydrate deposits in deep sediments is likely millennia [215]. Smaller but still large methane hydrate amounts below shallow waters as in the Arctic Ocean are more vulnerable; the methane may oxidize to CO_2 in the water, but it will still add to the long-term burden of CO_2 in the carbon cycle. Terrestrial permafrost emissions of CH_4 and CO_2 likely can occur on a time scale of a few decades to several centuries if global warming continues [215]. These time scales are within the lifetime of anthropogenic CO_2, and thus these feedbacks must be considered in estimating the dangerous level of global warming. Because human-made warming is more rapid than natural long-term warmings in the past, there is concern that methane hydrate or peat feedbacks could be more rapid than the feedbacks that exist in the paleoclimate record.

Climate model studies and empirical analyses of paleoclimate data can provide estimates of the amplification of climate sensitivity caused by slow feedbacks, excluding the singular mechanisms that caused the hyperthermal events. Model studies for climate change between the Holocene and the Pliocene, when Earth was about 3°C warmer, find that slow feedbacks due to changes of ice sheets and vegetation cover amplified the fast feedback climate response by 30–50% [216]. These same slow feedbacks are estimated to amplify climate sensitivity by almost a factor of two for the climate change between the Holocene and the nearly ice-free climate state that existed 35 million years ago [54].

Implication for Carbon Emissions Target

Evidence presented under Climate Impacts above makes clear that 2°C global warming would have consequences that can be described as disastrous. Multiple studies [12,198,201] show that the warming would be very long lasting. The paleoclimate record and changes underway in the Arctic and on the Greenland and Antarctic ice sheets with only today's warming imply that sea level rise of several meters could be expected. Increased climate extremes, already apparent at 0.8°C warming [46], would be more severe. Coral reefs and associated species, already stressed with current conditions [40], would be decimated by increased acidification, temperature and sea level rise. More generally, humanity and nature, the modern world as we know it, is adapted to the Holocene climate that has existed more than 10,000 years. Warming of 1°C relative to 1880–1920 keeps global temperature close to the Holocene range, but warming of 2°C, to at least the Eemian level, could cause major dislocations for civilization.

However, distinctions between pathways aimed at ~1°C and 2°C warming are much greater and more fundamental than the numbers 1°C and 2°C themselves might suggest. These fundamental distinctions make scenarios with 2°C or more global warming far more dangerous; so dangerous, we suggest, that aiming for the 2°C pathway would be foolhardy.

First, most climate simulations, including ours above and those of IPCC [1], do not include slow feedbacks such as reduction of ice sheet size with global warming or release of greenhouse gases from thawing tundra. These exclusions are reasonable for a ~1°C scenario, because global temperature barely rises out of the Holocene range and then begins to subside. In contrast, global warming of 2°C or more is likely to bring slow feedbacks into play. Indeed, it is slow feedbacks that cause long-term climate sensitivity to be high in the empirical paleoclimate record [51–52]. The lifetime of fossil fuel CO_2 in the climate system is so long that it must be assumed that these slow feedbacks will occur if temperature rises well above the Holocene range.

Second, scenarios with 2°C or more warming necessarily imply expansion of fossil fuels into sources that are harder to get at, requiring greater energy using extraction techniques that are increasingly invasive, destructive and polluting. Fossil fuel emissions through 2012 total ~370 GtC (Fig. 2). If subsequent emissions decrease 6%/year, additional emissions are ~130 GtC, for a total ~500 GtC fossil fuel emissions. This 130 GtC can be obtained mainly from the easily extracted conventional oil and gas reserves (Fig. 2), with coal use rapidly phased out and unconventional fossil fuels left in the ground. In contrast, 2°C scenarios have total emissions of the order of 1000 GtC. The required additional fossil fuels will involve exploitation of tar sands, tar shale, hydrofracking for oil and gas, coal mining, drilling in the Arctic, Amazon, deep ocean, and other remote regions, and possibly exploitation of methane hydrates. Thus 2°C scenarios result in more CO_2 per unit useable energy, release of substantial CH_4 via the mining process and gas transportation, and release of CO_2 and other gases via destruction of forest "overburden" to extract subterranean fossil fuels.

Third, with our ~1°C scenario it is more likely that the biosphere and soil will be able to sequester a substantial portion of the anthropogenic fossil fuel CO_2 carbon than in the case of 2°C or more global warming. Empirical data for the CO_2 "airborne fraction", the ratio of observed atmospheric CO_2 increase divided by fossil fuel CO_2 emissions, show that almost half of the emissions is being taken up by surface (terrestrial and ocean) carbon reservoirs [187], despite a substantial but poorly measured contribution of anthropogenic land use (deforestation and agriculture) to airborne CO_2 [179,216]. Indeed, uptake of CO_2 by surface reservoirs has at least kept pace with the rapid growth of emissions [187]. Increased uptake in the past decade may be a consequence of a reduced rate of deforestation [217] and fertilization of the biosphere by atmospheric CO_2 and nitrogen deposition [187]. With the stable climate of the ~1°C scenario it is plausible that major efforts in reforestation and improved agricultural practices [15,173,175–177], with appropriate support provided to developing countries, could take up an amount of carbon comparable to the 100 GtC in our ~1°C scenario. On the other hand, with warming of 2°C or more, carbon cycle feedbacks are expected to lead to substantial additional atmospheric CO_2 [218–219], perhaps even making the Amazon rainforest a source of CO_2 [219–220].

Fourth, a scenario that slows and then reverses global warming makes it possible to reduce other greenhouse gases by reducing their sources [75,221]. The most important of these gases is CH_4, whose reduction in turn reduces tropospheric O_3 and stratospheric H_2O. In contrast, chemistry modeling and paleoclimate records [222] show that trace gases increase with global warming, making it unlikely that overall atmospheric CH_4 will decrease even if a decrease is achieved in anthropogenic CH_4 sources. Reduction of the amount of atmospheric CH_4 and related gases is needed to counterbalance expected forcing from increasing N_2O and decreasing sulfate aerosols.

Now let us compare the 1°C (500 GtC fossil fuel emissions) and the 2°C (1000 GtC fossil fuel emissions) scenarios. Global temperature in 2100 would be close to 1°C in the 500 GtC scenario, and it is less than 1°C if 100 GtC uptake of carbon by the biosphere and soil is achieved via improved agricultural and forestry practices (Fig. 9). In contrast, the 1000 GtC scenario, although nominally designed to yield a fast-feedback climate response of ~ 2°C, would yield a larger eventual warming because of slow feedbacks, probably at least 3°C.

Danger of Uncontrollable Consequences

Inertia of the climate system reduces the near-term impact of human-made climate forcings, but that inertia is not necessarily our friend. One implication of the inertia is that climate impacts ''in the pipeline'' may be much greater than the impacts that we presently observe. Slow climate feedbacks add further danger of climate change running out of humanity's control. The response time of these slow feedbacks is uncertain, but there is evidence that some of these feedbacks already are underway, at least to a minor degree. Paleoclimate data show that on century and millennial time scales the slow feedbacks are predominately amplifying feedbacks.

The inertia of energy system infrastructure, i.e., the time required to replace fossil fuel energy systems, will make it exceedingly difficult to avoid a level of atmospheric CO_2 that would eventually have highly undesirable consequences. The danger of uncontrollable and irreversible consequences necessarily raises the question of whether it is feasible to extract CO_2 from the atmosphere on a large enough scale to affect climate change.

Carbon Extraction

We have shown that extraordinarily rapid emission reductions are needed to stay close to the 1°C scenario. In absence of extraordinary actions, it is likely that growing climate disruptions will lead to a surge of interest in ''geo-engineering'' designed to minimize human-made climate change [223]. Such efforts must remove atmospheric CO_2, if they are to address direct CO_2 effects such as ocean acidification as well as climate change. Schemes such as adding sulfuric acid aerosols to the stratosphere to reflect sunlight [224], an attempt to mask one pollutant with another, is a temporary band-aid for a problem that will last for millennia; besides it fails to address ocean acidification and may have other unintended consequences [225].

Potential for Carbon Extraction

At present there are no proven technologies capable of large-scale air capture of CO_2. It has been suggested that, with strong research and development support and industrial scale pilot projects sustained over decades, costs as low as ~\$500/tC may be achievable [226]. Thermodynamic constraints [227] suggest that this cost estimate may be low. An assessment by the American Physical Society [228] argues that the lowest currently achievable cost, using existing approaches, is much greater (\$600/tCO_2 or \$2200/tC).

The cost of capturing 50 ppm of CO_2, at \$500/tC (~\$135/tCO_2), is ~\$50 trillion (1 ppm CO_2 is ~2.12 GtC), but more than \$200 trillion for the price estimate of the American Physical Society study. Moreover, the resulting atmospheric CO_2 reduction will ultimately be less than 50 ppm for the reasons discussed above. For example, let us consider the scenario of Fig. 5B in which emissions continue to increase until 2030 before decreasing at 5%/year – this scenario yields atmospheric CO_2 of 410 ppm in 2100. Using our carbon cycle model we calculate that if we extract 100 ppm of CO_2 from the air over the period 2030–2100 (10/7 ppm per year), say storing that CO_2 in carbonate bricks, the atmospheric CO_2 amount in 2100 will be reduced 52 ppm to 358 ppm, i.e., the reduction of airborne CO_2 is about half of the amount extracted from the air and stored. The estimated cost of this 52 ppm CO_2 reduction is \$100–400 trillion.

The cost of CO_2 capture and storage conceivably may decline in the future. Yet the practicality of carrying out such a program with alacrity in response to a climate emergency is dubious. Thus it may be appropriate to add a CO_2 removal cost to the current price of fossil fuels, which would both reduce ongoing emissions and provide resources for future cleanup.

Responsibility for Carbon Extraction

We focus on fossil fuel carbon, because of its long lifetime in the carbon cycle. Reversing the effects of deforestation is also important and there will need to be incentives to achieve increased carbon storage in the biosphere and soil, but the crucial requirement now is to limit the amount of fossil fuel carbon in the air.

The high cost of carbon extraction naturally raises the question of responsibility for excess fossil fuel CO_2 in the air. China has the largest CO_2 emissions today (Fig. 11A), but the global warming effect is closely proportional to cumulative emissions [190]. The United States is responsible for about one-quarter of cumulative emissions, with China next at about 10% (Fig. 11B). Cumulative responsibilities change rather slowly (compare Fig. 10 of 190). Estimated per capita emissions (Fig. 12) are based on population estimates for 2009–2011.

Various formulae might be devised to assign costs of CO_2 air capture, should removal prove essential for maintaining acceptable climate. For the sake of estimating the potential cost, let us assume that it proves necessary to extract 100 ppm of CO_2 (yielding a reduction of airborne CO_2 of about 50 ppm) and let us assign each country the responsibility to clean up its fraction of cumulative emissions. Assuming a cost of \$500/tC (~\$135/tCO_2) yields a cost of \$28 trillion for the United States, about \$90,000 per individual. Costs would be slightly higher for a UK citizen, but less for other nations (Fig. 12B).

Cost of CO_2 capture might decline, but the cost estimate used is more than a factor of four smaller than estimated by the American Physical Society [228] and 50 ppm is only a moderate reduction. The cost should also include safe permanent disposal of the captured CO_2, which is a substantial mass. For the sake of scaling the task, note that one GtC, made into carbonate bricks, would produce the volume of ~3000 Empire State buildings or ~1200 Great Pyramids of Giza. Thus the 26 ppm assigned to the United States, if made into carbonate bricks, would be equivalent to the stone in 165,000 Empire State buildings or 66,000 Great Pyramids of Giza. This is not intended as a practical suggestion: carbonate bricks are not a good building material, and the transport and construction costs would be additional.

The point of this graphic detail is to make clear the magnitude of the cleanup task and potential costs, if fossil fuel emissions continue unabated. More useful and economic ways of removing CO_2 may be devised with the incentive of a sufficient carbon price. For example, a stream of pure CO_2 becomes available for capture and storage if biomass is used as the fuel for power plants or as feedstock for production of liquid hydrocarbon fuels. Such clean energy schemes and improved agricultural and forestry practices are likely to be more economic than direct air capture of CO_2, but they must be carefully designed to minimize undesirable impacts and the amount of CO_2 that can be extracted on the time scale of decades will be limited, thus emphasizing the need to limit the magnitude of the cleanup task.

Policy Implications

Human-made climate change concerns physical sciences, but leads to implications for policy and politics. Conclusions from the physical sciences, such as the rapidity with which emissions must be reduced to avoid obviously unacceptable consequences and the long lag between emissions and consequences, lead to implications in social sciences, including economics, law and ethics. Intergov-

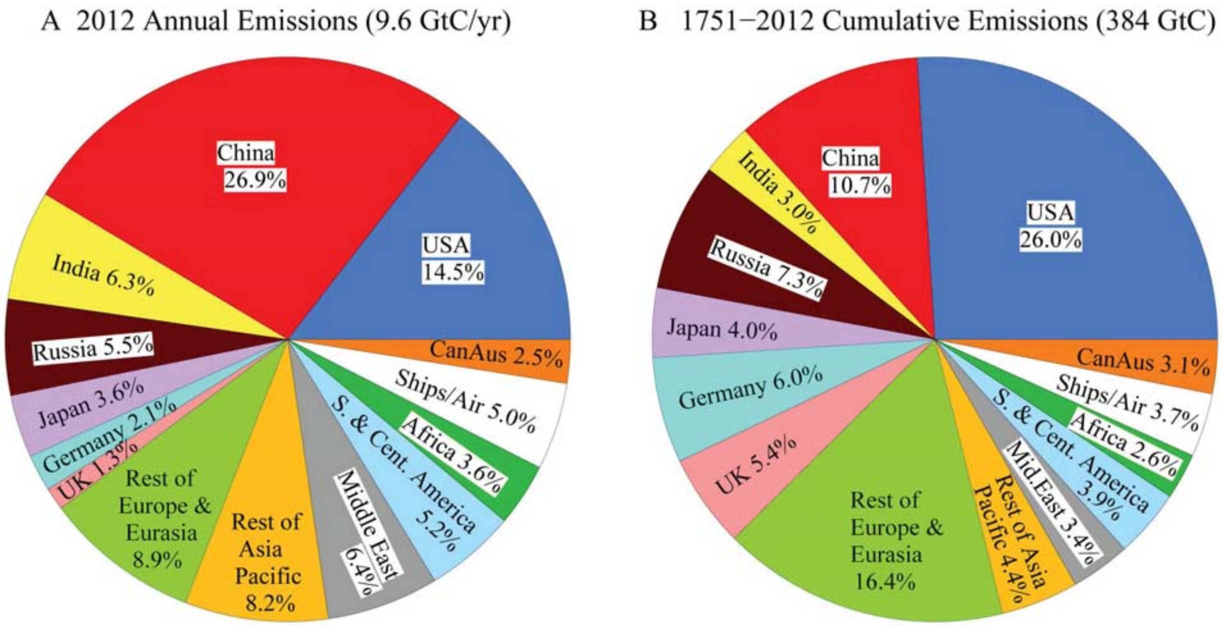

Figure 11. Fossil fuel CO_2 emissions. (A) 2012 emissions by source region, and (B) cumulative 1751–2012 emissions. Results are an update of Fig. 10 of [190] using data from [5].
doi:10.1371/journal.pone.0081648.g011

ernmental climate assessments [1,14] purposely are not policy prescriptive. Yet there is also merit in analysis and discussion of the full topic through the objective lens of science, i.e., "connecting the dots" all the way to policy implications.

Energy and Carbon Pathways: A Fork in the Road

The industrial revolution began with wood being replaced by coal as the primary energy source. Coal provided more concentrated energy, and thus was more mobile and effective. We show data for the United States (Fig. 13) because of the availability of a long data record that includes wood [229]. More limited global records yield a similar picture [Fig. 14], the largest difference being global coal now at ~30% compared with ~20% in the United States. Economic progress and wealth generation were further spurred in the twentieth century by expansion into liquid and gaseous fossil fuels, oil and gas being transported and burned more readily than coal. Only in the latter part of the twentieth century did it become clear that long-lived combustion products from fossil fuels posed a global climate threat, as formally acknowledged in the 1992 Framework Convention on Climate Change [6]. However, efforts to slow emissions of the principal atmospheric gas driving climate change, CO_2, have been ineffectual so far (Fig. 1).

Consequently, at present, as the most easily extracted oil and gas reserves are being depleted, we stand at a fork in the road to our energy and carbon future. Will we now feed our energy needs by pursuing difficult to extract fossil fuels, or will we pursue energy policies that phase out carbon emissions, moving on to the post fossil fuel era as rapidly as practical?

This is not the first fork encountered. Most nations agreed to the Framework Convention on Climate Change in 1992 [6]. Imagine if a bloc of countries favoring action had agreed on a common gradually rising carbon fee collected within each of country at domestic mines and ports of entry. Such nations might place equivalent border duties on products from nations not having a carbon fee and they could rebate fees to their domestic industry for export products to nations without an equivalent carbon fee. The legality of such a border tax adjustment under international trade law is untested, but is considered to be plausibly consistent with trade principles [230]. As the carbon fee gradually rose and as additional nations, for their own benefit, joined this bloc of nations, development of carbon-free energies and energy efficiency would have been spurred. If the carbon fee had begun in 1995, we

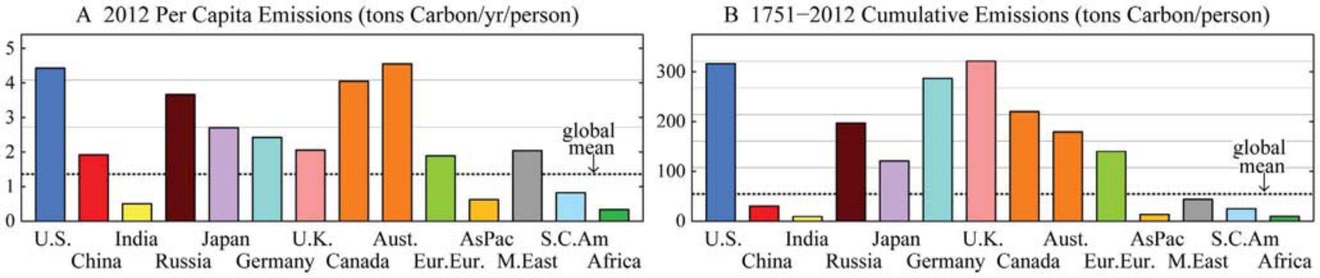

Figure 12. Per capita fossil fuel CO_2 emissions. Countries, regions and data sources are the same as in Fig. 11. Horizontal lines are the global mean and multiples of the global mean.
doi:10.1371/journal.pone.0081648.g012

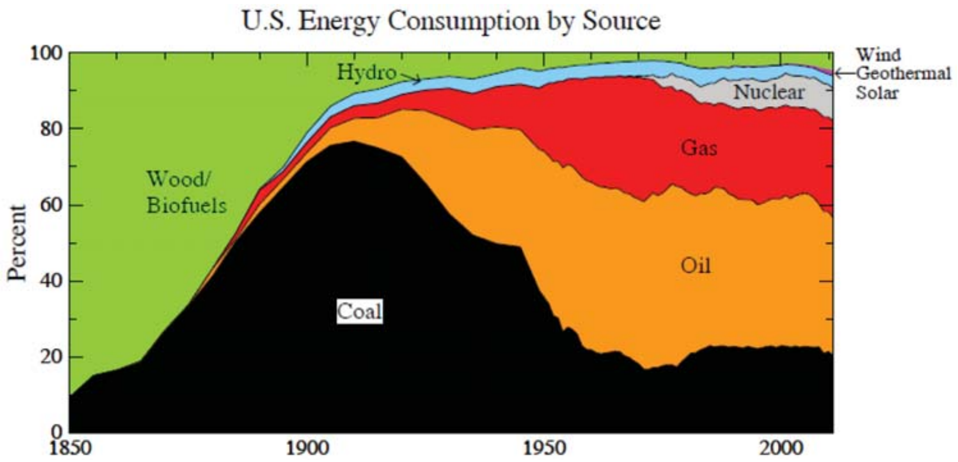

Figure 13. United States energy consumption [229].
doi:10.1371/journal.pone.0081648.g013

calculate that global emissions would have needed to decline 2.1%/year to limit cumulative fossil fuel emissions to 500 GtC. A start date of 2005 would have required a reduction of 3.5%/year for the same result.

The task faced today is more difficult. Emissions reduction of 6%/year and 100 GtC storage in the biosphere and soils are needed to get CO_2 back to 350 ppm, the approximate requirement for restoring the planet's energy balance and stabilizing climate this century. Such a pathway is exceedingly difficult to achieve, given the current widespread absence of policies to drive rapid movement to carbon-free energies and the lifetime of energy infrastructure in place.

Yet we suggest that a pathway is still conceivable that could restore planetary energy balance on the century time scale. That path requires policies that spur technology development and provide economic incentives for consumers and businesses such that social tipping points are reached where consumers move rapidly to energy conservation and low carbon energies. Moderate overshoot of required atmospheric CO_2 levels can possibly be counteracted via incentives for actions that more-or-less naturally sequester carbon. Developed countries, responsible for most of the excess CO_2 in the air, might finance extensive efforts in developing countries to sequester carbon in the soil and in forest regrowth on marginal lands as described above. Burning sustainably designed biofuels in power plants, with the CO_2 captured and sequestered, would also help draw down atmospheric CO_2. This pathway would need to be taken soon, as the magnitude of such carbon extractions is likely limited and thus not a solution to unfettered fossil fuel use.

The alternative pathway, which the world seems to be on now, is continued extraction of all fossil fuels, including development of unconventional fossil fuels such as tar sands, tar shale, hydrofracking to extract oil and gas, and exploitation of methane hydrates. If that path (with 2%/year growth) continues for 20 years and is then followed by 3%/year emission reduction from 2033 to 2150, we find that fossil fuel emissions in 2150 would total 1022 GtC. Extraction of the excess CO_2 from the air in this case would be very expensive and perhaps implausible, and warming of the ocean and resulting climate impacts would be practically irreversible.

Economic Implications: Need for a Carbon Fee

The implication is that the world must move rapidly to carbon-free energies and energy efficiency, leaving most remaining fossil fuels in the ground, if climate is to be kept close to the Holocene range and climate disasters averted. Is rapid change possible?

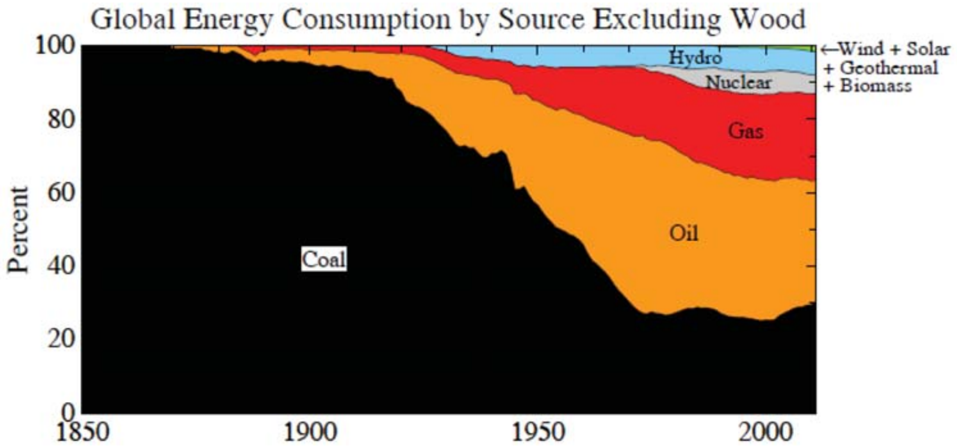

Figure 14. World energy consumption for indicated fuels, which excludes wood [4].
doi:10.1371/journal.pone.0081648.g014

The potential for rapid change can be shown by examples. A basic requirement for phasing down fossil fuel emissions is abundant carbon-free electricity, which is the most rapidly growing form of energy and also has the potential to provide energy for transportation and heating of buildings. In one decade (1977–1987), France increased its nuclear power production 15-fold, with the nuclear portion of its electricity increasing from 8% to 70% [231]. In one decade (2001–2011) Germany increased the non-hydroelectric renewable energy portion of its electricity from 4% to 19%, with fossil fuels decreasing from 63% to 61% (hydroelectric decreased from 4% to 3% and nuclear power decreased from 29% to 18%) [231].

Given the huge task of replacing fossil fuels, contributions are surely required from energy efficiency, renewable energies, and nuclear power, with the mix depending on local preferences. Renewable energy and nuclear power have been limited in part by technical challenges. Nuclear power faces persistent concerns about safety, nuclear waste, and potential weapons proliferation, despite past contributions to mortality prevention and climate change mitigation [232]. Most renewable energies tap diffuse intermittent sources often at a distance from the user population, thus requiring large-scale energy storage and transport. Developing technologies can ameliorate these issues, as discussed below. However, apparent cost is the constraint that prevents nuclear and renewable energies from fully supplanting fossil fuel electricity generation.

Transition to a post-fossil fuel world of clean energies will not occur as long as fossil fuels appear to the investor and consumer to be the cheapest energy. Fossil fuels are cheap only because they do not pay their costs to society and receive large direct and indirect subsidies [233]. Air and water pollution from fossil fuel extraction and use have high costs in human health, food production, and natural ecosystems, killing more than 1,000,000 people per year and affecting the health of billions of people [232,234], with costs borne by the public. Costs of climate change and ocean acidification, already substantial and expected to grow considerably [26,235], also are borne by the public, especially by young people and future generations.

Thus the essential underlying policy, albeit not sufficient, is for emissions of CO_2 to come with a price that allows these costs to be internalized within the economics of energy use. Because so much energy is used through expensive capital stock, the price should rise in a predictable way to enable people and businesses to efficiently adjust lifestyles and investments to minimize costs. Reasons for preference of a carbon fee or tax over cap-and-trade include the former's simplicity and relative ease of becoming global [236]. A near-global carbon tax might be achieved, e.g., via a bi-lateral agreement between China and the United States, the greatest emitters, with a border duty imposed on products from nations without a carbon tax, which would provide a strong incentive for other nations to impose an equivalent carbon tax. The suggestion of a carbon fee collected from fossil fuel companies with all revenues distributed to the public on a per capita basis [237] has received at least limited support [238].

Economic analyses indicate that a carbon price fully incorporating environmental and climate damage would be high [239]. The cost of climate change is uncertain to a factor of 10 or more and could be as high as ~$1000/$tCO_2$ [235,240]. While the imposition of such a high price on carbon emissions is outside the realm of short-term political feasibility, a price of that magnitude is not required to engender a large change in emissions trajectory.

An economic analysis indicates that a tax beginning at $15/$tCO_2$ and rising $10/$tCO_2$ each year would reduce emissions in the U.S. by 30% within 10 years [241]. Such a reduction is more than 10 times as great as the carbon content of tar sands oil carried by the proposed Keystone XL pipeline (830,000 barrels/day) [242]. Reduced oil demand would be nearly six times the pipeline capacity [241], thus the carbon fee is far more effective than the proposed pipeline.

A rising carbon fee is the *sine qua non* for fossil fuel phase out, but not enough by itself. Investment is needed in RD&D (research, development and demonstration) to help renewable energies and nuclear power overcome obstacles limiting their contributions. Intermittency of solar and wind power can be alleviated with advances in energy storage, low-loss smart electric grids, and electrical vehicles interacting with the grid. Most of today's nuclear power plants have half-century-old technology with light-water reactors [243] utilizing less than 1% of the energy in the nuclear fuel and leaving unused fuel as long-lived nuclear "waste" requiring sequestration for millennia. Modern light-water reactors can employ convective cooling to eliminate the need for external cooling in the event of an anomaly such as an earthquake. However, the long-term future of nuclear power will employ "fast" reactors, which utilize ~99% of the nuclear fuel and can "burn" nuclear waste and excess weapons material [243]. It should be possible to reduce the cost of nuclear power via modular standard reactor design, but governments need to provide a regulatory environment that supports timely construction of approved designs. RD&D on carbon capture and storage (CCS) technology is needed, especially given our conclusion that the current atmospheric CO_2 level is already in the dangerous zone, but continuing issues with CCS technology [7,244] make it inappropriate to construct fossil fuel power plants with a promise of future retrofit for carbon capture. Governments should support energy planning for housing and transportation, energy and carbon efficiency requirements for buildings, vehicles and other manufactured products, and climate mitigation and adaptation in undeveloped countries.

Economic efficiency would be improved by a rising carbon fee. Energy efficiency and alternative low-carbon and no-carbon energies should be allowed to compete on an equal footing, without subsidies, and the public and business community should be made aware that the fee will continually rise. The fee for unconventional fossil fuels, such as oil from tar sands and gas from hydrofracking, should include carbon released in mining and refining processes, e.g., methane leakage in hydrofracking [245–249]. If the carbon fee rises continually and predictably, the resulting energy transformations should generate many jobs, a welcome benefit for nations still suffering from long-standing economic recession. Economic modeling shows that about 60% of the public, especially low-income people, would receive more money via a per capita 100% dispersal of the collected fee than they would pay because of increased prices [241].

Fairness: Intergenerational Justice and Human Rights

Relevant fundamentals of climate science are clear. The physical climate system has great inertia, which is due especially to the thermal inertia of the ocean, the time required for ice sheets to respond to global warming, and the longevity of fossil fuel CO_2 in the surface carbon reservoirs (atmosphere, ocean, and biosphere). This inertia implies that there is additional climate change "in the pipeline" even without further change of atmospheric composition. Climate system inertia also means that, if large-scale climate change is allowed to occur, it will be exceedingly long-lived, lasting for many centuries.

One implication is the likelihood of intergenerational effects, with young people and future generations inheriting a situation in which grave consequences are assured, practically out of their control, but not of their doing. The possibility of such intergenerational injustice is not remote – it is at our doorstep now. We have a planetary climate crisis that requires urgent change to our energy and carbon pathway to avoid dangerous consequences for young people and other life on Earth.

Yet governments and industry are rushing into expanded use of fossil fuels, including unconventional fossil fuels such as tar sands, tar shale, shale gas extracted by hydrofracking, and methane hydrates. How can this course be unfolding despite knowledge of climate consequences and evidence that a rising carbon price would be economically efficient and reduce demand for fossil fuels? A case has been made that the absence of effective governmental leadership is related to the effect of special interests on policy, as well as to public relations efforts by organizations that profit from the public's addiction to fossil fuels [237,250].

The judicial branch of governments may be less subject to pressures from special financial interests than the executive and legislative branches, and the courts are expected to protect the rights of all people, including the less powerful. The concept that the atmosphere is a public trust [251], that today's adults must deliver to their children and future generations an atmosphere as beneficial as the one they received, is the basis for a lawsuit [252] in which it is argued that the U.S. government is obligated to protect the atmosphere from harmful greenhouse gases.

Independent of this specific lawsuit, we suggest that intergenerational justice in this matter derives from fundamental rights of equality and justice. The Universal Declaration of Human Rights [253] declares "All are equal before the law and are entitled without any discrimination to equal protection of the law." Further, to consider a specific example, the United States Constitution provides all citizens "equal protection of the laws" and states that no person can be deprived of "life, liberty or property without due process of law". These fundamental rights are a basis for young people to expect fairness and justice in a matter as essential as the condition of the planet they will inhabit. We do not prescribe the legal arguments by which these rights can be achieved, but we maintain that failure of governments to effectively address climate change infringes on fundamental rights of young people.

Ultimately, however, human-made climate change is more a matter of morality than a legal issue. Broad public support is probably needed to achieve the changes needed to phase out fossil fuel emissions. As with the issue of slavery and civil rights, public recognition of the moral dimensions of human-made climate change may be needed to stir the public's conscience to the point of action.

A scenario is conceivable in which growing evidence of climate change and recognition of implications for young people lead to massive public support for action. Influential industry leaders, aware of the moral issue, may join the campaign to phase out emissions, with more business leaders becoming supportive as they recognize the merits of a rising price on carbon. Given the relative ease with which a flat carbon price can be made international [236], a rapid global emissions phasedown is feasible. As fossil fuels are made to pay their costs to society, energy efficiency and clean energies may reach tipping points and begin to be rapidly adopted.

Our analysis shows that a set of actions exists with a good chance of averting "dangerous" climate change, if the actions begin now. However, we also show that time is running out. Unless a human "tipping point" is reached soon, with implementation of effective policy actions, large irreversible climate changes will become unavoidable. Our parent's generation did not know that their energy use would harm future generations and other life on the planet. If we do not change our course, we can only pretend that we did not know.

Discussion

We conclude that an appropriate target is to keep global temperature within or close to the temperature range in the Holocene, the interglacial period in which civilization developed. With warming of 0.8°C in the past century, Earth is just emerging from that range, implying that we need to restore the planet's energy balance and curb further warming. A limit of approximately 500 GtC on cumulative fossil fuel emissions, accompanied by a net storage of 100 GtC in the biosphere and soil, could keep global temperature close to the Holocene range, assuming that the net future forcing change from other factors is small. The longevity of global warming (Fig. 9) and the implausibility of removing the warming if it is once allowed to penetrate the deep ocean emphasize the urgency of slowing emissions so as to stay close to the 500 GtC target.

Fossil fuel emissions of 1000 GtC, sometimes associated with a 2°C global warming target, would be expected to cause large climate change with disastrous consequences. The eventual warming from 1000 GtC fossil fuel emissions likely would reach well over 2°C, for several reasons. With such emissions and temperature tendency, other trace greenhouse gases including methane and nitrous oxide would be expected to increase, adding to the effect of CO_2. The global warming and shifting climate zones would make it less likely that a substantial increase in forest and soil carbon could be achieved. Paleoclimate data indicate that slow feedbacks would substantially amplify the 2°C global warming. It is clear that pushing global climate far outside the Holocene range is inherently dangerous and foolhardy.

The fifth IPCC assessment Summary for Policymakers [14] concludes that to achieve a 50% chance of keeping global warming below 2°C equivalent CO_2 emissions should not exceed 1210 GtC, and after accounting for non-CO_2 climate forcings this limit on CO_2 emissions becomes 840 GtC. The existing drafts of the fifth IPCC assessment are not yet approved for comparison and citation, but the IPCC assessment is consistent with studies of Meinshausen et al. [254] and Allen et al. [13], hereafter M2009 and A2009, with which we can make comparisons. We will also compare our conclusions with those of McKibben [255]. M2009 and A2009 appear together in the same journal with the two lead authors on each paper being co-authors on the other paper. McKibben [255], published in a popular magazine, uses quantitative results of M2009 to conclude that most remaining fossil fuel reserves must be left in the ground, if global warming this century is to be kept below 2°C. McKibben [255] has been very successful in drawing public attention to the urgency of rapidly phasing down fossil fuel emissions.

M2009 use a simplified carbon cycle and climate model to make a large ensemble of simulations in which principal uncertainties in the carbon cycle, radiative forcings, and climate response are allowed to vary, thus yielding a probability distribution for global warming as a function of time throughout the 21st century. M2009 use this distribution to infer a limit on total (fossil fuel+net land use) carbon emissions in the period 2000–2049 if global warming in the 21st century is to be kept below 2°C at some specified probability. For example, they conclude that the limit on total 2000–2049 carbon emissions is 1440 $GtCO_2$ (393 GtC) to achieve a 50% chance that 21st century global warming will not exceed 2°C.

A2009 also use a large ensemble of model runs, varying uncertain parameters, and conclude that total (fossil fuel+net land use) carbon emissions of 1000 GtC would most likely yield a peak

CO_2-induced warming of 2°C, with 90% confidence that the peak warming would be in the range 1.3–3.9°C. They note that their results are consistent with those of M2009, as the A2009 scenarios that yield 2°C warming have 400–500 GtC emissions during 2000–2049; M2009 find 393 GtC emissions for 2°C warming, but M2009 included a net warming effect of non-CO_2 forcings, while A2009 neglected non-CO_2 forcings.

McKibben [255] uses results of M2009 to infer allowable fossil fuel emissions up to 2050 if there is to be an 80% chance that maximum warming in the 21st century will not exceed 2°C above the pre-industrial level. M2009 conclude that staying under this 2°C limit with 80% probability requires that 2000–2049 emissions must be limited to 656 $GtCO_2$ (179 GtC) for 2007–2049. McKibben [255] used this M2009 result to determine a remaining carbon budget (at a time not specified exactly) of 565 $GtCO_2$ (154 GtC) if warming is to stay under 2°C. Let us update this analysis to the present: fossil fuel emissions in 2007–2012 were 51 GtC [5], so, assuming no net emissions from land use in these few years, the M2009 study implies that the remaining budget at the beginning of 2013 was 128 GtC.

Thus, coincidentally, the McKibben [255] approach via M2009 yields almost exactly the same remaining carbon budget (128 GtC) as our analysis (130 GtC). However, our budget is that required to limit warming to about 1°C (there is a temporary maximum during this century at about 1.1–1.2°C, Fig. 9), while McKibben [255] is allowing global warming to reach 2°C, which we have concluded would be a disaster scenario! This apparently vast difference arises from three major factors.

First, we assumed that reforestation and improved agricultural and forestry practices can suck up the net land use carbon of the past. We estimate net land use emissions as 100 GtC, while M2009 have land use emissions almost twice that large (~180 GtC). We argue elsewhere (see section 14 in Supporting Information of [54]) that the commonly employed net land use estimates [256] are about a factor of two larger than the net land use carbon that is most consistent with observed CO_2 history. However, we need not resolve that long-standing controversy here. The point is that, to make the M2009 study equivalent to ours, negative land use emissions must be included in the 21st century equal to earlier positive land use emissions.

Second, we have assumed that future net change of non-CO_2 forcings will be zero, while M2009 have included significant non-CO_2 forcings. In recent years non-CO_2 GHGs have provided about 20% of the increase of total GHG climate forcing.

Third, our calculations are for a single fast-feedback equilibrium climate sensitivity, 3°C for doubled CO_2, which we infer from paleoclimate data. M2009 use a range of climate sensitivities to compute a probability distribution function for expected warming, and then McKibben [255] selects the carbon emission limit that keeps 80% of the probability distribution below 2°C.

The third factor is a matter of methodology, but one to be borne in mind. Regarding the first two factors, it may be argued that our scenario is optimistic. That is true, but both goals, extracting 100 GtC from the atmosphere via improved forestry and agricultural practices (with possibly some assistance from CCS technology) and limiting additional net change of non-CO_2 forcings to zero, are feasible and probably much easier than the principal task of limiting additional fossil fuel emissions to 130 GtC.

We noted above that reforestation and improving agricultural and forestry practices that store more carbon in the soil make sense for other reasons. Also that task is made easier by the excess CO_2 in the air today, which causes vegetation to take up CO_2 more efficiently. Indeed, this may be the reason that net land use emissions seem to be less than is often assumed.

As for the non-CO_2 forcings, it is noteworthy that greenhouse gases controlled by the Montreal Protocol are now decreasing, and recent agreement has been achieved to use the Montreal Protocol to phase out production of some additional greenhouse gases even though those gases do not affect the ozone layer. The most important non-CO_2 forcing is methane, whose increases in turn cause tropospheric ozone and stratospheric water vapor to increase. Fossil fuel use is probably the largest source of methane [1], so if fossil fuel use begins to be phased down, there is good basis to anticipate that all three of these greenhouse gases could decrease, because of the approximate 10-year lifetime of methane.

As for fossil fuel CO_2 emissions, considering the large, long-lived fossil fuel infrastructure in place, the science is telling us that policy should be set to reduce emissions as rapidly as possible. The most fundamental implication is the need for an across-the-board rising fee on fossil fuel emissions in order to allow true free market competition from non-fossil energy sources. We note that biospheric storage should not be allowed to offset further fossil fuel emissions. Most fossil fuel carbon will remain in the climate system more than 100,000 years, so it is essential to limit the emission of fossil fuel carbon. It will be necessary to have incentives to restore biospheric carbon, but these must be accompanied by decreased fossil fuel emissions.

A crucial point to note is that the three tasks [limiting fossil fuel CO_2 emissions, limiting (and reversing) land use emissions, limiting (and reversing) growth of non-CO_2 forcings] are interactive and reinforcing. In mathematical terms, the problem is non-linear. As one of these climate forcings increases, it increases the others. The good news is that, as one of them decreases, it tends to decrease the others. In order to bestow upon future generations a planet like the one we received, we need to win on all three counts, and by far the most important is rapid phasedown of fossil fuel emissions.

It is distressing that, despite the clarity and imminence of the danger of continued high fossil fuel emissions, governments continue to allow and even encourage pursuit of ever more fossil fuels. Recognition of this reality and perceptions of what is "politically feasible" may partially account for acceptance of targets for global warming and carbon emissions that are well into the range of "dangerous human-made interference" with climate. Although there is merit in simply chronicling what is happening, there is still opportunity for humanity to exercise free will. Thus our objective is to define what the science indicates is needed, not to assess political feasibility. Further, it is not obvious to us that there are physical or economic limitations that prohibit fossil fuel emission targets far lower than 1000 GtC, even targets closer to 500 GtC. Indeed, we suggest that rapid transition off fossil fuels would have numerous near-term and long-term social benefits, including improved human health and outstanding potential for job creation.

A world summit on climate change will be held at United Nations Headquarters in September 2014 as a preliminary to negotiation of a new climate treaty in Paris in late 2015. If this treaty is analogous to the 1997 Kyoto Protocol [257], based on national targets for emission reductions and cap-and-trade-with-offsets emissions trading mechanisms, climate deterioration and gross intergenerational injustice will be practically guaranteed. The palpable danger that such an approach is conceivable is suggested by examination of proposed climate policies of even the most forward-looking of nations. Norway, which along with the other Scandinavian countries has been among the most ambitious and successful of all nations in reducing its emissions, nevertheless approves expanded oil drilling in the Arctic and development of tar sands as a majority owner of Statoil [258–259]. Emissions foreseen by the Energy Perspectives of Statoil [259], if they occur, would approach or exceed 1000 GtC and cause dramatic climate change that would run out of control of future generations. If, in contrast, leading nations agree in 2015 to have internal rising fees on carbon with border duties on products from nations without a carbon fee, a foundation would be established for phaseover to carbon free energies and stable climate.

Supporting Information

Table S1
(ODS)

Table S2
(ODS)

Table S3
(ODS)

Text S1
(DOC)

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Author Contributions

Conceived and designed the experiments: JH PK MS. Performed the experiments: MS PK. Wrote the paper: JH. Wrote the first draft: JH. All authors made numerous critiques and suggested specific wording and references: JH PK MS VM-D FA DJB PJH OHG SLH CP JR EJR JS PS KS LVS KvS JCZ. Especially: PK MS VM-D.

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Exhibit C.2

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Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous

James Hansen[1], Makiko Sato[1], Paul Hearty[2], Reto Ruedy[3,4], Maxwell Kelley[3,4], Valerie Masson-Delmotte[5], Gary Russell[4], George Tselioudis[4], Junji Cao[6], Eric Rignot[7,8], Isabella Velicogna[7,8], Blair Tormey[9], Bailey Donovan[10], Evgeniya Kandiano[11], Karina von Schuckmann[12], Pushker Kharecha[1,4], Allegra N. Legrande[4], Michael Bauer[4,13], and Kwok-Wai Lo[3,4]

[1]Climate Science, Awareness and Solutions, Columbia University Earth Institute, New York, NY 10115, USA
[2]Department of Environmental Studies, University of North Carolina at Wilmington, NC 28403, USA
[3]Trinnovium LLC, New York, NY 10025, USA
[4]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA
[5]Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ), Gif-sur-Yvette, France
[6]Key Lab of Aerosol Chemistry & Physics, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China
[7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[8]Department of Earth System Science, University of California, Irvine, CA 92697, USA
[9]Program for the Study of Developed Shorelines, Western Carolina University, Cullowhee, NC 28723, USA
[10]Department of Geological Sciences, East Carolina University, Greenville, NC 27858, USA
[11]GEOMAR, Helmholtz Centre for Ocean Research, Wischhofstrasse 1–3, Kiel 24148, Germany
[12]Mediterranean Institute of Oceanography, University of Toulon, La Garde, France
[13]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA

Correspondence to: James Hansen (jeh1@columbia.edu)

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Abstract. We use numerical climate simulations, paleoclimate data, and modern observations to study the effect of growing ice melt from Antarctica and Greenland. Meltwater tends to stabilize the ocean column, inducing amplifying feedbacks that increase subsurface ocean warming and ice shelf melting. Cold meltwater and induced dynamical effects cause ocean surface cooling in the Southern Ocean and North Atlantic, thus increasing Earth's energy imbalance and heat flux into most of the global ocean's surface. Southern Ocean surface cooling, while lower latitudes are warming, increases precipitation on the Southern Ocean, increasing ocean stratification, slowing deepwater formation, and increasing ice sheet mass loss. These feedbacks make ice sheets in contact with the ocean vulnerable to accelerating disintegration. We hypothesize that ice mass loss from the most vulnerable ice, sufficient to raise sea level several meters, is better approximated as exponential than by a more linear response. Doubling times of 10, 20 or 40 years yield multi-meter sea level rise in about 50, 100 or 200 years. Recent ice melt doubling times are near the lower end of the 10–40-year range, but the record is too short to confirm the nature of the response. The feedbacks, including subsurface ocean warming, help explain paleoclimate data and point to a dominant Southern Ocean role in controlling atmospheric CO_2, which in turn exercised tight control on global temperature and sea level. The millennial (500–2000-year) timescale of deep-ocean ventilation affects the timescale for natural CO_2 change and thus the timescale for paleo-global climate, ice sheet, and sea

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level changes, but this paleo-millennial timescale should not be misinterpreted as the timescale for ice sheet response to a rapid, large, human-made climate forcing. These climate feedbacks aid interpretation of events late in the prior interglacial, when sea level rose to +6–9 m with evidence of extreme storms while Earth was less than 1 °C warmer than today. Ice melt cooling of the North Atlantic and Southern oceans increases atmospheric temperature gradients, eddy kinetic energy and baroclinicity, thus driving more powerful storms. The modeling, paleoclimate evidence, and ongoing observations together imply that 2 °C global warming above the preindustrial level could be dangerous. Continued high fossil fuel emissions this century are predicted to yield (1) cooling of the Southern Ocean, especially in the Western Hemisphere; (2) slowing of the Southern Ocean overturning circulation, warming of the ice shelves, and growing ice sheet mass loss; (3) slowdown and eventual shutdown of the Atlantic overturning circulation with cooling of the North Atlantic region; (4) increasingly powerful storms; and (5) nonlinearly growing sea level rise, reaching several meters over a timescale of 50–150 years. These predictions, especially the cooling in the Southern Ocean and North Atlantic with markedly reduced warming or even cooling in Europe, differ fundamentally from existing climate change assessments. We discuss observations and modeling studies needed to refute or clarify these assertions.

1 Introduction

Humanity is rapidly extracting and burning fossil fuels without full understanding of the consequences. Current assessments place emphasis on practical effects such as increasing extremes of heat waves, droughts, heavy rainfall, floods, and encroaching seas (IPCC, 2014; USNCA, 2014). These assessments and our recent study (Hansen et al., 2013a) conclude that there is an urgency to slow carbon dioxide (CO_2) emissions, because the longevity of the carbon in the climate system (Archer, 2005) and persistence of the induced warming (Solomon et al., 2010) may lock in unavoidable, highly undesirable consequences.

Despite these warnings, fossil fuels remain the world's primary energy source and global CO_2 emissions continue at a high level, perhaps with an expectation that humanity can adapt to climate change and find ways to minimize effects via advanced technologies. We suggest that this viewpoint fails to appreciate the nature of the threat posed by ice sheet instability and sea level rise. If the ocean continues to accumulate heat and increase melting of marine-terminating ice shelves of Antarctica and Greenland, a point will be reached at which it is impossible to avoid large-scale ice sheet disintegration with sea level rise of at least several meters. The economic and social cost of losing functionality of all coastal cities is practically incalculable. We suggest that a strategy relying on adaptation to such consequences will be unacceptable to most of humanity, so it is important to understand this threat as soon as possible.

We investigate the climate threat using a combination of atmosphere–ocean modeling, information from paleoclimate data, and observations of ongoing climate change. Each of these has limitations: modeling is an imperfect representation of the climate system, paleo-data consist mainly of proxy climate information usually with substantial ambiguities, and modern observations are limited in scope and accuracy. However, with the help of a large body of research by the scientific community, it is possible to draw meaningful conclusions.

2 Background information and organization of the paper

Our study germinated a decade ago. Hansen (2005, 2007) argued that the modest 21st century sea level rise projected by IPCC (2001), less than a meter, was inconsistent with presumed climate forcings, which were larger than paleoclimate forcings associated with sea level rise of many meters. His argument about the potential rate of sea level rise was necessarily heuristic, because ice sheet models are at an early stage of development, depending sensitively on many processes that are poorly understood. This uncertainty is illustrated by Pollard et al. (2015), who found that addition of hydro-fracturing and cliff failure into their ice sheet model increased simulated sea level rise from 2 to 17 m, in response to only 2 °C ocean warming and accelerated the time for substantial change from several centuries to several decades.

The focus for our paper developed in 2007, when the first author (JH) read several papers by co-author P. Hearty. Hearty used geologic field data to make a persuasive case for rapid sea level rise late in the prior interglacial period to a height +6–9 m relative to today, and he presented evidence of strong storms in the Bahamas and Bermuda at that time. Hearty's data suggested violent climate behavior on a planet only slightly warmer than today.

Our study was designed to shed light on, or at least raise questions about, physical processes that could help account for the paleoclimate data and have relevance to ongoing and future climate change. Our assumption was that extraction of significant information on these processes would require use of and analysis of (1) climate modeling, (2) paleoclimate data, and (3) modern observations. It is the combination of all of these that helps us interpret the intricate paleoclimate data and extract implications about future sea level and storms.

Our approach is to postulate existence of feedbacks that can rapidly accelerate ice melt, impose such rapidly growing freshwater injection on a climate model, and look for a climate response that supports such acceleration. Our imposed ice melt grows nonlinearly in time, specifically exponentially, so the rate is characterized by a doubling time. Total amounts of freshwater injection are chosen in the range

1–5 m of sea level, amounts that can be provided by vulnerable ice masses in contact with the ocean. We find significant impact of meltwater on global climate and feedbacks that support ice melt acceleration. We obtain this information without use of ice sheet models, which are still at an early stage of development, in contrast to global general circulation models that were developed over more than half a century and do a capable job of simulating atmosphere and ocean circulation.

Our principal finding concerns the effect of meltwater on stratification of the high-latitude ocean and resulting ocean heat sequestration that leads to melting of ice shelves and catastrophic ice sheet collapse. Stratification contrasts with homogenization. Winter conditions on parts of the North Atlantic Ocean and around the edges of Antarctica normally produce cold, salty water that is dense enough to sink to the deep ocean, thus stirring and tending to homogenize the water column. Injection of fresh meltwater reduces the density of the upper ocean wind-stirred mixed layer, thus reducing the rate at which cold surface water sinks in winter at high latitudes. Vertical mixing normally brings warmer water to the surface, where heat is released to the atmosphere and space. Thus the increased stratification due to freshwater injection causes heat to be retained at ocean depth, where it is available to melt ice shelves. Despite improvements that we make in our ocean model, which allow Antarctic Bottom Water to be formed at proper locations, we suggest that excessive mixing in many climate models, ours included, limits this stratification effect. Thus, human impact on ice sheets and sea level may be even more imminent than in our model, suggesting a need for confirmatory observations.

Our paper published in *Atmospheric Chemistry and Physics Discussion* was organized in the chronological order of our investigation. Here we reorganize the work to make the science easier to follow. First, we describe our climate simulations with specified growing freshwater sources in the North Atlantic and Southern oceans. Second, we analyze paleoclimate data for evidence of these processes and possible implications for the future. Third, we examine modern data for evidence that the simulated climate changes are already occurring.

We use paleoclimate data to find support for and deeper understanding of these processes, focusing especially on events in the last interglacial period warmer than today, called Marine Isotope Stage (MIS) 5e in studies of ocean sediment cores, Eemian in European climate studies, and sometimes Sangamonian in US literature (see Sect. 4.2 for timescale diagram of marine isotope stages). Accurately known changes of Earth's astronomical configuration altered the seasonal and geographical distribution of incoming radiation during the Eemian. Resulting global warming was due to feedbacks that amplified the orbital forcing. While the Eemian is not an analog of future warming, it is useful for investigating climate feedbacks, including the interplay between ice melt at high latitudes and ocean circulation.

3 Simulations of 1850–2300 climate change

We make simulations for 1850–2300 with radiative forcings that were used in CMIP (Climate Model Intercomparison Project) simulations reported by IPCC (2007, 2013). This allows comparison of our present simulations with prior studies. First, for the sake of later raising and discussing fundamental questions about ocean mixing and climate response time, we define climate forcings and the relation of forcings to Earth's energy imbalance and global temperature.

3.1 Climate forcing, Earth's energy imbalance, and climate response function

A climate forcing is an imposed perturbation of Earth's energy balance, such as change in solar irradiance or a radiatively effective constituent of the atmosphere or surface. Non-radiative climate forcings are possible, e.g., change in Earth's surface roughness or rotation rate, but these are small and radiative feedbacks likely dominate global climate response even in such cases. The net forcing driving climate change in our simulations (Fig. S16 in the Supplement) is almost $2\,\mathrm{W\,m^{-2}}$ at present and increases to $5\text{–}6\,\mathrm{W\,m^{-2}}$ at the end of this century, depending on how much the (negative) aerosol forcing is assumed to reduce the greenhouse gas (GHG) forcing. The GHG forcing is based on IPCC scenario A1B. "Orbital" forcings, i.e., changes in the seasonal and geographical distribution of insolation on millennial timescales caused by changes of Earth's orbit and spin axis tilt, are near zero on global average, but they spur "slow feedbacks" of several $\mathrm{W\,m^{-2}}$, mainly change in surface reflectivity and GHGs.

When a climate forcing changes, say solar irradiance increases or atmospheric $\mathrm{CO_2}$ increases, Earth is temporarily out of energy balance, that is, more energy coming in than going out in these cases, so Earth's temperature will increase until energy balance is restored. Earth's energy imbalance is a result of the climate system's inertia, i.e., the slowness of the surface temperature to respond to changing global climate forcing. Earth's energy imbalance is a function of ocean mixing, as well as climate forcing and climate sensitivity, the latter being the equilibrium global temperature response to a specified climate forcing. Earth's present energy imbalance, $+0.5\text{–}1\,\mathrm{W\,m^{-2}}$ (von Schuckmann et al., 2016), provides an indication of how much additional global warming is still "in the pipeline" if climate forcings remain unchanged. However, climate change generated by today's energy imbalance, especially the rate at which it occurs, is quite different than climate change in response to a new forcing of equal magnitude. Understanding this difference is relevant to issues raised in this paper.

The different effect of old and new climate forcings is implicit in the shape of the climate response function, $R(t)$, where R is the fraction of the equilibrium global temperature change achieved as a function of time following imposition of a forcing. Global climate models find that a large fraction of the equilibrium response is obtained quickly, about half of the response occurring within several years, but the remainder is "recalcitrant" (Held et al., 2010), requiring many decades or even centuries for nearly complete response. Hansen (2008) showed that once a climate model's response function R is known, based on simulations for an instant forcing, global temperature change, $T(t)$, in response to any climate forcing history, $F(t)$, can be accurately obtained from a simple (Green's function) integration of R over time:

$$T(t) = \int R(t)[\mathrm{d}F/\mathrm{d}t]\mathrm{d}t. \tag{1}$$

$\mathrm{d}F/\mathrm{d}t$ is the annual increment of the net forcing and the integration begins before human-made climate forcing became substantial.

We use these concepts in discussing evidence that most ocean models, ours included, are too diffusive. Such excessive mixing causes the Southern and North Atlantic oceans in the models to have an unrealistically slow response to surface meltwater injection. Implications include a more imminent threat of slowdowns of Antarctic Bottom Water and North Atlantic Deep Water formation than present models suggest, with regional and global climate impacts.

3.2 Climate model

Simulations are made with an improved version of a coarse-resolution model that allows long runs at low cost: GISS (Goddard Institute for Space Studies) modelE-R. The atmosphere model is the documented modelE (Schmidt et al., 2006). The ocean is based on the Russell et al. (1995) model that conserves water and salt mass; has a free surface with divergent flow; uses a linear upstream scheme for advection; allows flow through 12 sub-resolution straits; and has background diffusivity of $0.3\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, resolution of 4° × 5° and 13 layers that increase in thickness with depth.

However, the ocean model includes simple but significant changes, compared with the version documented in simulations by Miller et al. (2014). First, an error in the calculation of neutral surfaces in the Gent–McWilliams (GM; Gent and McWilliams, 1990) mesoscale eddy parameterization was corrected; the resulting increased slope of neutral surfaces provides proper leverage to the restratification process and correctly orients eddy stirring along those surfaces.

Second, the calculation of eddy diffusivity K_{meso} for GM following Visbeck et al. (1997) was simplified to use a length scale independent of the density structure (J. Marshall, personal communication, 2012):

$$K_{\mathrm{meso}} = C/[T_{\mathrm{Eady}} \times f(\text{latitude})], \tag{2}$$

where $C = (27.9\,\mathrm{km})^2$, Eady growth rate $1/T_{\mathrm{Eady}} = \{|S \times N|\}$, S is the neutral surface slope, N the Brunt–Väisälä frequency, $\{\,\}$ signifies averaging over the upper D meters of ocean depth, $D = \min(\max(\text{depth}, 400\,\mathrm{m}), 1000\,\mathrm{m})$, and $f(\text{latitude}) = \max(0.1, \sin(|\text{latitude}|))$[1] to qualitatively mimic the larger values of the Rossby radius of deformation at low latitudes. These choices for K_{meso}, whose simplicity is congruent with the use of a depth-independent eddy diffusivity and the use of $1/T_{\mathrm{eady}}$ as a metric of eddy energy, result in the zonal average diffusivity shown in Fig. 1. Third, the so-called nonlocal terms in the KPP mixing parameterization (Large et al., 1994) were activated. All of these modifications tend to increase the ocean stratification, and in particular the Southern Ocean state is fundamentally improved. For example, we show in Sect. 3.8.5 that our current model produces Antarctic Bottom Water on the Antarctic coastline, as observed, rather than in the middle of the Southern Ocean as occurs in many models, including the GISS-ER model documented in CMIP5. However, although overall realism of the ocean circulation is much improved, significant model deficiencies remain, as we will describe.

The simulated Atlantic meridional overturning circulation (AMOC) has maximum flux that varies within the range ∼ 14–18 Sv in the model control run (Figs. 2 and 3). AMOC strength in recent observations is 17.5 ± 1.6 Sv (Baringer et al., 2013; Srokosz et al., 2012), based on 8 years (2004–2011) of data for an in situ mooring array (Rayner et al., 2011; Johns et al., 2011).

Ocean model control run initial conditions are climatology for temperature and salinity (Levitus and Boyer, 1994; Levitus et al., 1994); atmospheric composition is that of 1880 (Hansen et al., 2011). Overall model drift from control run initial conditions is moderate (see Fig. S1 for planetary energy imbalance and global temperature), but there is drift in the North Atlantic circulation. The AMOC circulation cell initially is confined to the upper 3 km at all latitudes (1st century in Figs. 2 and 3), but by the 5th century the cell reaches deeper at high latitudes.

Atmospheric and surface climate in the present model is similar to the documented modelE-R, but because of changes to the ocean model we provide several diagnostics in the Supplement. A notable flaw in the simulated surface climate is the unrealistic double precipitation maximum in the tropical Pacific (Fig. S2). This double Intertropical Convergence Zone (ITCZ) occurs in many models and may be related to cloud and radiation biases over the Southern Ocean (Hwang and Frierson, 2013) or deficient low level clouds in the tropical Pacific (de Szoeke and Xie, 2008). Another flaw is unrealistic hemispheric sea ice, with too much sea ice in the

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[1] Where ocean depth exceeds 1000 m, these conditions yield $D = 1000$ m, thus excluding any first-order abyssal bathymetric imprint on upper ocean eddy energy, consistent with theory and observations. The other objective of the stated condition is to limit release of potential energy in the few ocean gridboxes with ocean depth less than 400 m, because shallow depths limit the ability of baroclinic eddies to release potential energy via vertical motion.

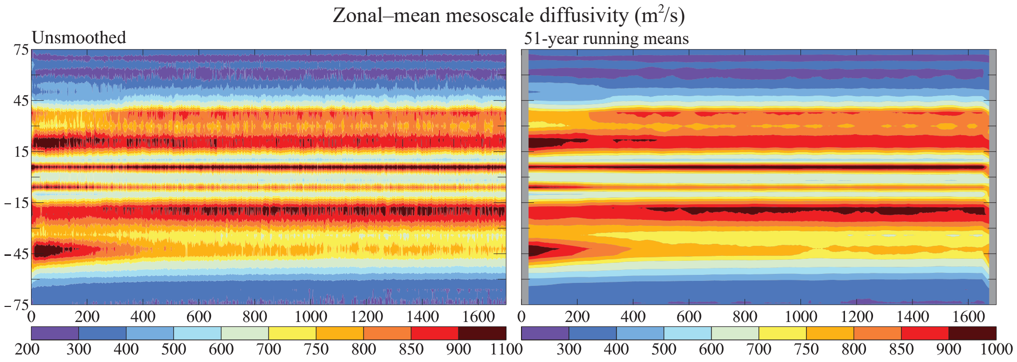


Figure 1. Zonal-mean mesoscale diffusivity ($m^2\,s^{-1}$) versus time in control run.

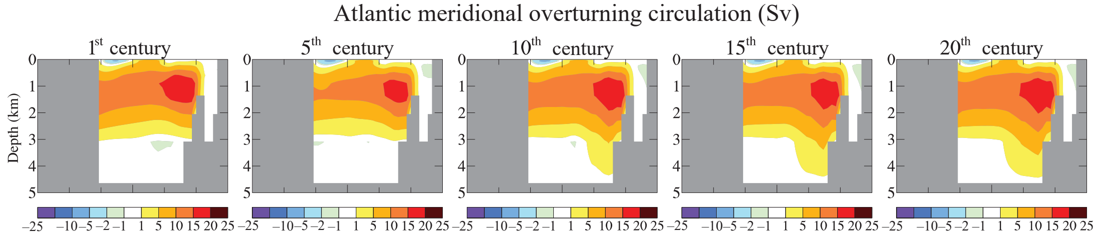


Figure 2. AMOC (Sv) in the 1st, 5th, 10th, 15th and 20th centuries of the control run.

Northern Hemisphere and too little in the Southern Hemisphere (Figs. S3 and S4). Excessive Northern Hemisphere sea ice might be caused by deficient poleward heat transport in the Atlantic Ocean (Fig. S5). However, the AMOC has realistic strength and Atlantic meridional heat transport is only slightly below observations at high latitudes (Fig. S5). Thus we suspect that the problem may lie in sea ice parameterizations or deficient dynamical transport of ice out of the Arctic. The deficient Southern Hemisphere sea ice, at least in part, is likely related to excessive poleward (southward) transport of heat by the simulated global ocean (Fig. S5), which is related to deficient northward transport of heat in the modeled Atlantic Ocean (Fig. S5).

A key characteristic of the model and the real world is the response time: how fast does the surface temperature adjust to a climate forcing? ModelE-R response is about 40 % in 5 years (Fig. 4) and 60 % in 100 years, with the remainder requiring many centuries. Hansen et al. (2011) concluded that most ocean models, including modelE-R, mix a surface temperature perturbation downward too efficiently and thus have a slower surface response than the real world. The basis for this conclusion was empirical analysis using climate response functions, with 50, 75 and 90 % response at year 100 for climate simulations (Hansen et al., 2011). Earth's measured energy imbalance in recent years and global temperature change in the past century revealed that the response function with 75 % response in 100 years provided a much better fit with observations than the other choices. Durack et al. (2012) compared observations of how rapidly surface salinity changes are mixed into the deeper ocean with the large number of global models in CMIP3, reaching a similar conclusion, that the models mix too rapidly.

Our present ocean model has a faster response on 10–75-year timescales than the old model (Fig. 4), but the change is small. Although the response time in our model is similar to that in many other ocean models (Hansen et al., 2011), we believe that it is likely slower than the real-world response on timescales of a few decades and longer. A too slow surface response could result from excessive small-scale mixing. We will argue, after the studies below, that excessive mixing likely has other consequences, e.g., causing the effect of freshwater stratification on slowing Antarctic Bottom Water (AABW) formation and growth of Antarctic sea ice cover to occur 1–2 decades later than in the real world. Similarly, excessive mixing probably makes the AMOC in the model less sensitive to freshwater forcing than the real-world AMOC.

3.3 Experiment definition: exponentially increasing freshwater

Freshwater injection is 360 Gt year^{-1} (1 mm sea level) in 2003–2015, then grows with 5-, 10- or 20-year doubling time (Fig. 5) and terminates when global sea level reaches 1 or 5 m. Doubling times of 10, 20 and 40 years, reaching meter-scale sea level rise in 50, 100, and 200 years may be a more realistic range of timescales, but 40 years yields little effect this century, the time of most interest, so we learn more with

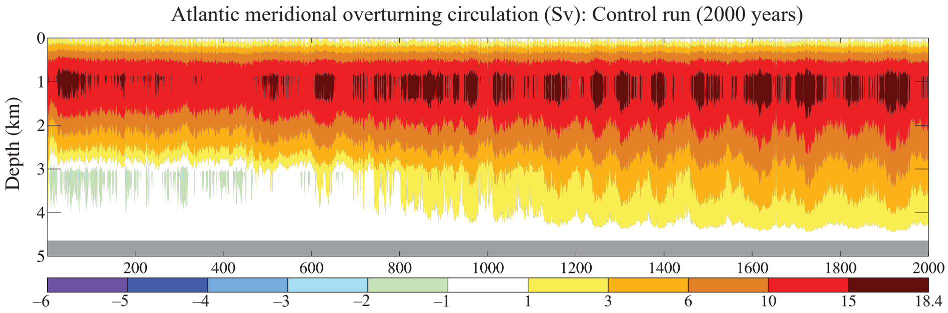


Figure 3. Annual mean AMOC (Sv) at 28° N in the model control run.

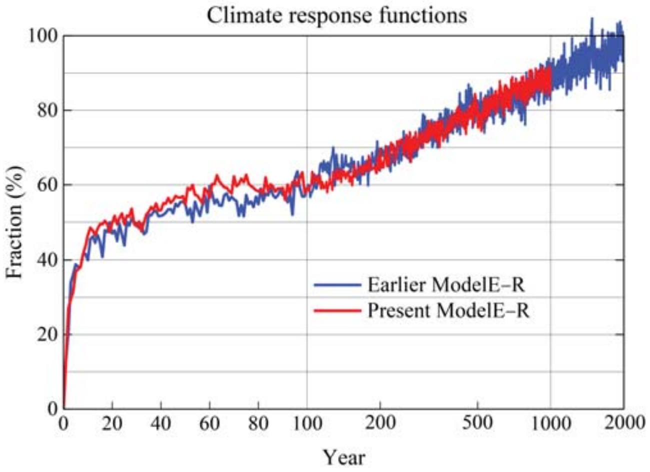


Figure 4. Climate response function, $R(t)$, i.e., the fraction (%) of equilibrium surface temperature response for GISS modelE-R based on a 2000-year control run (Hansen et al., 2007a). Forcing was instant CO_2 doubling with fixed ice sheets, vegetation distribution, and other long-lived GHGs.

less computing time using the 5-, 10- and 20-year doubling times. Observed ice sheet mass loss doubling rates, although records are short, are ∼ 10 years (Sect. 5.1). Our sharp cutoff of melt aids separation of immediate forcing effects and feedbacks.

We argue that such a rapid increase in meltwater is plausible if GHGs keep growing rapidly. Greenland and Antarctica have outlet glaciers in canyons with bedrock below sea level well back into the ice sheet (Fretwell et al., 2013; Morlighem et al., 2014; Pollard et al., 2015). Feedbacks, including ice sheet darkening due to surface melt (Hansen et al., 2007b; Robinson et al., 2012; Tedesco et al., 2013; Box et al., 2012) and lowering and thus warming of the near-coastal ice sheet surface, make increasing ice melt likely. Paleoclimate data reveal sea level rise of several meters in a century (Fairbanks, 1989; Deschamps et al., 2012). Those cases involved ice sheets at lower latitudes, but 21st century climate forcing is larger and increasing much more rapidly.

Radiative forcings (Fig. S16a, b) are from Hansen et al. (2007c) through 2003 and IPCC scenario A1B for later GHGs. A1B is an intermediate IPCC scenario over the century, but on the high side early this century (Fig. 2 of Hansen et al., 2007c). We add freshwater to the North Atlantic (ocean area within 52–72° N and 15° E–65° N) or Southern Ocean (ocean south of 60° S), or equally divided between the two oceans. Ice sheet discharge (icebergs plus meltwater) is mixed as freshwater with mean temperature −15 °C into the top three ocean layers (Fig. S6).

3.4 Simulated surface temperature and energy balance

We present surface temperature and planetary energy balance first, thus providing a global overview. Then we examine changes in ocean circulation and compare results with prior studies.

Temperature change in 2065, 2080 and 2096 for 10-year doubling time (Fig. 6) should be thought of as results when sea level rise reaches 0.6, 1.7 and 5 m, because the dates depend on initial freshwater flux. Actual current freshwater flux may be about a factor of 4 higher than assumed in these initial runs, as we will discuss, and thus effects may occur ∼ 20 years earlier. A sea level rise of 5 m in a century is about the most extreme in the paleo-record (Fairbanks, 1989; Deschamps et al., 2012), but the assumed 21st century climate forcing is also more rapidly growing than any known natural forcing.

Meltwater injected into the North Atlantic has larger initial impact, but Southern Hemisphere ice melt has a greater global effect for larger melt as the effectiveness of more meltwater in the North Atlantic begins to decline. The global effect is large long before sea level rise of 5 m is reached. Meltwater reduces global warming about half by the time sea level rise reaches 1.7 m. Cooling due to ice melt more than eliminates A1B warming in large areas of the globe.

The large cooling effect of ice melt does not decrease much as the ice melting rate varies between doubling times of 5, 10 or 20 years (Fig. 7a). In other words, the cumulative ice sheet melt, rather than the rate of ice melt, largely determines the climate impact for the range of melt rates covered by 5-, 10- and 20-year doubling times. Thus if ice sheet loss

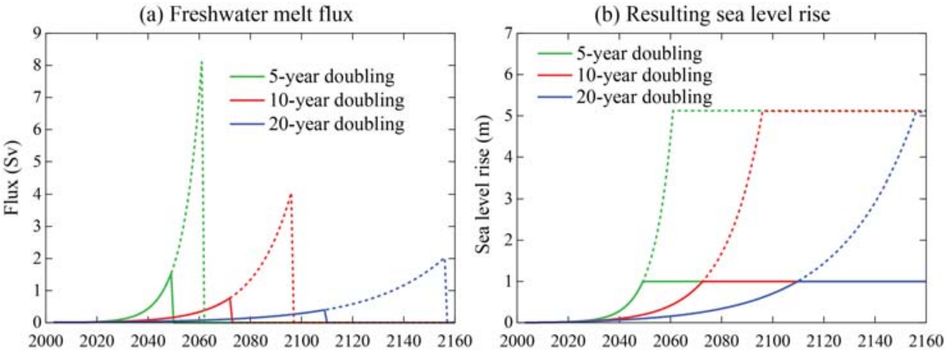


Figure 5. (a) Total freshwater flux added in the North Atlantic and Southern oceans and **(b)** resulting sea level rise. Solid lines for 1 m sea level rise, dotted for 5 m. One sverdrup (Sv) is 10^6 m^3 s^{-1}, which is $\sim 3\times 10^4$ Gt year^{-1}.

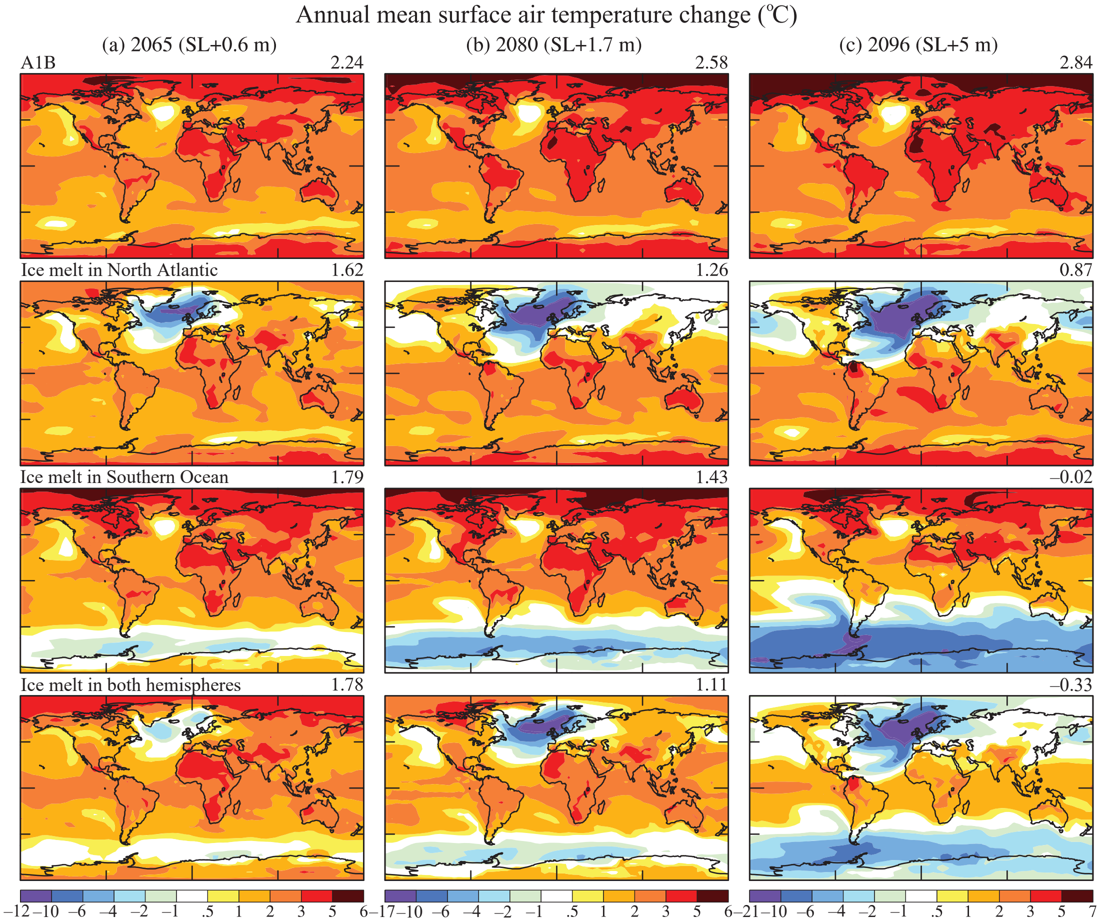


Figure 6. Surface air temperature (°C) relative to 1880–1920 in **(a)** 2065, **(b)** 2080, and **(c)** 2096. Top row is IPCC scenario A1B. Ice melt with 10-year doubling is added in other scenarios.

occurs even to an extent of 1.7 m sea level rise (Fig. 7b), a large impact on climate and climate change is predicted.

Greater global cooling occurs for freshwater injected into the Southern Ocean, but the cooling lasts much longer for North Atlantic injection (Fig. 7a). That persistent cooling, mainly at Northern Hemisphere middle and high latitudes (Fig. S7), is a consequence of the sensitivity, hysteresis effects, and long recovery time of the AMOC (Stocker and Wright, 1991; Rahmstorf, 1995, and earlier studies referenced therein). AMOC changes are described below.

When freshwater injection in the Southern Ocean is halted, global temperature jumps back within two decades to the

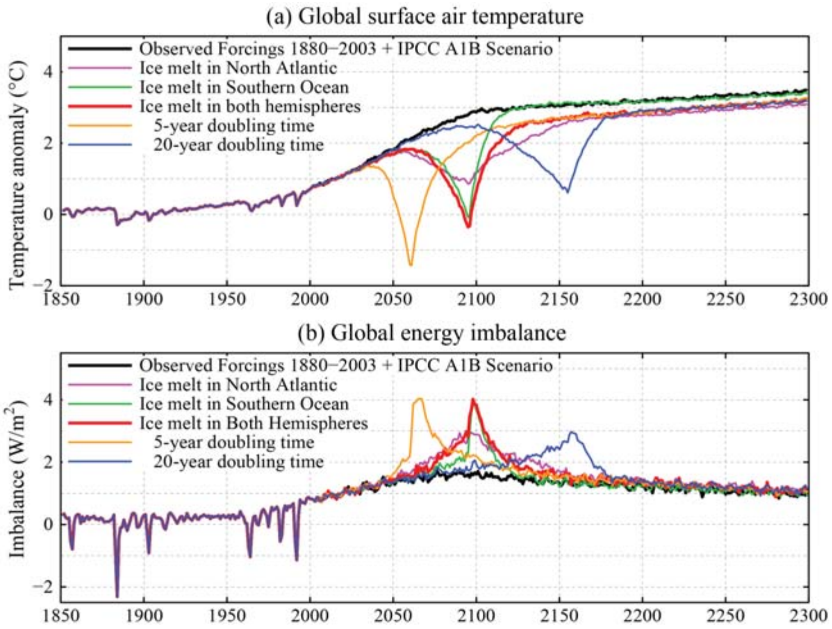


Figure 7. (a) Surface air temperature (°C) relative to 1880–1920 for several scenarios. **(b)** Global energy imbalance (W m^{-2}) for the same scenarios.

value it would have had without any freshwater addition (Fig. 7a). Quick recovery is consistent with the Southern Ocean-centric picture of the global overturning circulation (Fig. 4; Talley, 2013), as the Southern Ocean meridional overturning circulation (SMOC), driven by AABW formation, responds to change in the vertical stability of the ocean column near Antarctica (Sect. 3.7) and the ocean mixed layer and sea ice have limited thermal inertia.

Cooling from ice melt is largely regional, temporary, and does not alleviate concerns about global warming. Southern Hemisphere cooling is mainly in uninhabited regions. Northern Hemisphere cooling increases temperature gradients that will drive stronger storms (Sect. 3.9).

Global cooling due to ice melt causes a large increase in Earth's energy imbalance (Fig. 7b), adding about +2 W m^{-2}, which is larger than the imbalance caused by increasing GHGs. Thus, although the cold freshwater from ice sheet disintegration provides a negative feedback on regional and global surface temperature, it increases the planet's energy imbalance, thus providing more energy for ice melt (Hansen, 2005). This added energy is pumped into the ocean.

Increased downward energy flux at the top of the atmosphere is not located in the regions cooled by ice melt. However, those regions suffer a large reduction of net incoming energy (Fig. 8a). The regional energy reduction is a consequence of increased cloud cover (Fig. 8b) in response to the colder ocean surface. However, the colder ocean surface reduces upward radiative, sensible and latent heat fluxes, thus causing a large (~ 50 W m^{-2}) increase in energy into the North Atlantic and a substantial but smaller flux into the Southern Ocean (Fig. 8c).

Below we conclude that the principal mechanism by which this ocean heat increases ice melt is via its effect on ice shelves. Discussion requires examination of how the freshwater injections alter the ocean circulation and internal ocean temperature.

3.5 Simulated Atlantic meridional overturning circulation (AMOC)

Broecker's articulation of likely effects of freshwater outbursts in the North Atlantic on ocean circulation and global climate (Broecker, 1990; Broecker et al., 1990) spurred quantitative studies with idealized ocean models (Stocker and Wright, 1991) and global atmosphere–ocean models (Manabe and Stouffer, 1995; Rahmstorf 1995, 1996). Scores of modeling studies have since been carried out, many reviewed by Barreiro et al. (2008), and observing systems are being developed to monitor modern changes in the AMOC (Carton and Hakkinen, 2011).

Our climate simulations in this section are five-member ensembles of runs initiated at 25-year intervals at years 901–1001 of the control run. We chose this part of the control run because the planet is then in energy balance (Fig. S1), although by that time model drift had altered the slow deep-ocean circulation. Some model drift away from initial climatological conditions is inevitable, as all models are imperfect, and we carry out the experiments with cognizance of model limitations. However, there is strong incentive to seek basic

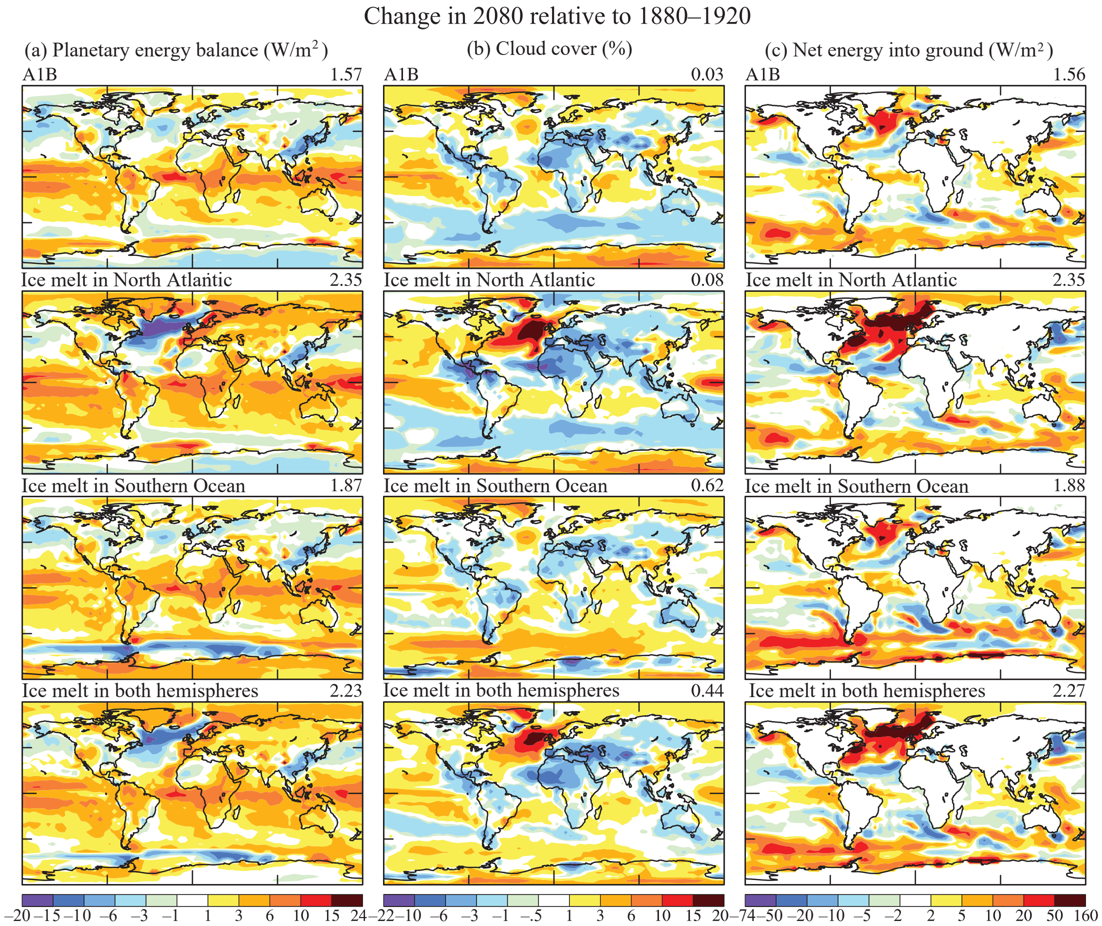


Figure 8. Change in 2080 (mean of 2078–2082), relative to 1880–1920, of annual mean **(a)** planetary energy balance ($\mathrm{W\,m^{-2}}$), **(b)** cloud cover (%), and **(c)** net energy into ground ($\mathrm{W\,m^{-2}}$) for the same scenarios as Fig. 6.

improvements in representation of physical processes to reduce drift in future versions of the model.

GHGs alone (scenario A1B) slow AMOC by the early 21st century (Fig. 9), but variability among individual runs (Fig. S8) would make definitive detection difficult at present. Freshwater injected into the North Atlantic or in both hemispheres shuts down the AMOC (Fig. 9, right side). GHG amounts are fixed after 2100 and ice melt is zero, but after two centuries of stable climate forcing the AMOC has not recovered to its earlier state. This slow recovery was found in the earliest simulations by Manabe and Stouffer (1994) and Rahmstorf (1995, 1996).

Freshwater injection already has a large impact when ice melt is a fraction of 1 m of sea level. By the time sea level rise reaches 59 cm (2065 in the present scenarios), when freshwater flux is 0.48 Sv, the impact on AMOC is already large, consistent with the substantial surface cooling in the North Atlantic (Fig. 6).

3.6 Comparison with prior simulations

AMOC sensitivity to GHG forcing has been examined extensively based on CMIP studies. Schmittner et al. (2005) found that AMOC weakened 25 ± 25 % by the end of the 21st century in 28 simulations of 9 different models forced by the A1B emission scenario. Gregory et al. (2005) found 10–50 % AMOC weakening in 11 models for CO_2 quadrupling (1 % $\mathrm{year^{-1}}$ increase for 140 years), with largest decreases in models with strong AMOCs. Weaver et al. (2007) found a 15–31 % AMOC weakening for CO_2 quadrupling in a single model for 17 climate states differing in initial GHG amount. AMOC in our model weakens 30 % in the century between 1990–2000 and 2090–2100, the period used by Schmittner et al. (2005), for A1B forcing (Fig. S8). Thus our model is more sensitive than the average but within the range of other models, a conclusion that continues to be valid in comparison with 10 CMIP5 models (Cheng et al., 2013).

AMOC sensitivity to freshwater forcing has not been compared as systematically among models. Several studies find little impact of Greenland melt on AMOC (Huybrechts et

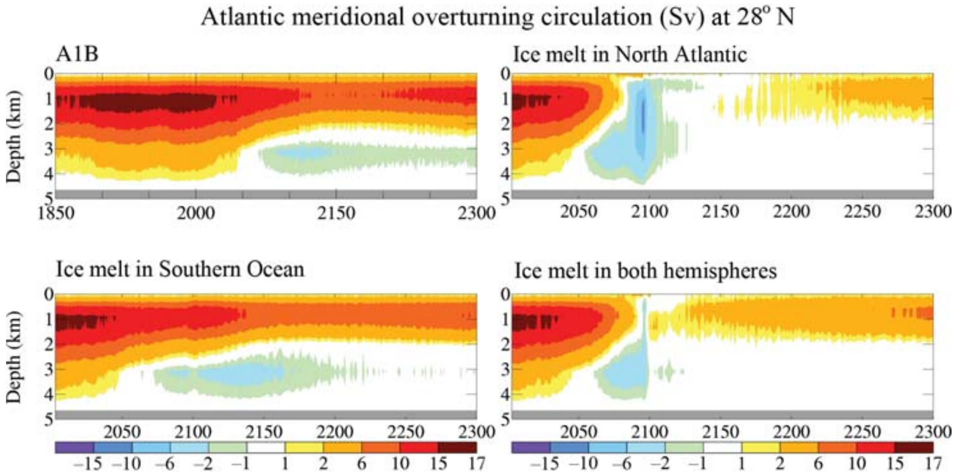


Figure 9. Ensemble-mean AMOC (Sv) at 28° N versus time for the same four scenarios as in Fig. 6, with ice melt reaching 5 m at the end of the 21st century in the three experiments with ice melt.

al., 2002; Jungclaus et al., 2006; Vizcaino et al., 2008) while others find substantial North Atlantic cooling (Fichefet et al., 2003; Swingedouw et al., 2007; Hu et al., 2009, 2011). Studies with little impact calculated or assumed small ice sheet melt rates, e.g., Greenland contributed only 4 cm of sea level rise in the 21st century in the ice sheet model of Huybrechts et al. (2002). Fichefet et al. (2003), using nearly the same atmosphere–ocean model as Huybrechts et al. (2002) but a more responsive ice sheet model, found AMOC weakening from 20 to 13 Sv late in the 21st century, but separate contributions of ice melt and GHGs to AMOC slowdown were not defined.

Hu et al. (2009, 2011) use the A1B scenario and freshwater from Greenland starting at 1 mm sea level per year increasing 7 % year^{-1}, similar to our 10-year doubling case. Hu et al. keep the melt rate constant after it reaches 0.3 Sv (in 2050), yielding 1.65 m sea level rise in 2100 and 4.2 m in 2200. Global warming found by Hu et al. for scenario A1B resembles our result but is 20–30 % smaller (compare Fig. 2b of Hu et al., 2009 to our Fig. 6), and cooling they obtain from the freshwater flux is moderately less than that in our model. AMOC is slowed about one-third by the latter 21st century in the Hu et al. (2011) 7 % year^{-1} experiment, comparable to our result.

General consistency holds for other quantities, such as changes of precipitation. Our model yields southward shifting of the Intertropical Convergence Zone (ITCZ) and intensification of the subtropical dry region with increasing GHGs (Fig. S9), as has been reported in modeling studies of Swingedouw et al. (2007, 2009). These effects are intensified by ice melt and cooling in the North Atlantic region (Fig. S9).

A recent five-model study (Swingedouw et al., 2014) finds a small effect on AMOC for 0.1 Sv Greenland freshwater flux added in 2050 to simulations with a strong GHG forcing. Our larger response is likely due, at least in part, to our freshwater flux reaching several tenths of a sverdrup.

3.7 Pure freshwater experiments

We assumed, in discussing the relevance of these experiments to Eemian climate, that effects of freshwater injection dominate over changing GHG amount, as seems likely because of the large freshwater effect on sea surface temperatures (SSTs) and sea level pressure. However, Eemian CO_2 was actually almost constant at ∼ 275 ppm (Luthi et al., 2008). Thus, to isolate effects better, we now carry out simulations with fixed GHG amount, which helps clarify important feedback processes.

Our pure freshwater experiments are five-member ensembles starting at years 1001, 1101, 1201, 1301, and 1401 of the control run. Each experiment ran 300 years. Freshwater flux in the initial decade averaged 180 km^3 year^{-1} (0.5 mm sea level) in the hemisphere with ice melt and increased with a 10-year doubling time. Freshwater input is terminated when it reaches 0.5 m sea level rise per hemisphere for three five-member ensembles: two ensembles with injection in the individual hemispheres and one ensemble with input in both hemispheres (1 m total sea level rise). Three additional ensembles were obtained by continuing freshwater injection until hemispheric sea level contributions reached 2.5 m. Here we provide a few model diagnostics central to discussions that follow. Additional results are provided in Figs. S10–S12.

The AMOC shuts down for Northern Hemisphere freshwater input yielding 2.5 m sea level rise (Fig. 10). By year 300, more than 200 years after cessation of all freshwater input, AMOC is still far from full recovery for this large freshwater input. On the other hand, freshwater input of 0.5 m does not cause full shutdown, and AMOC recovery occurs in less than a century.

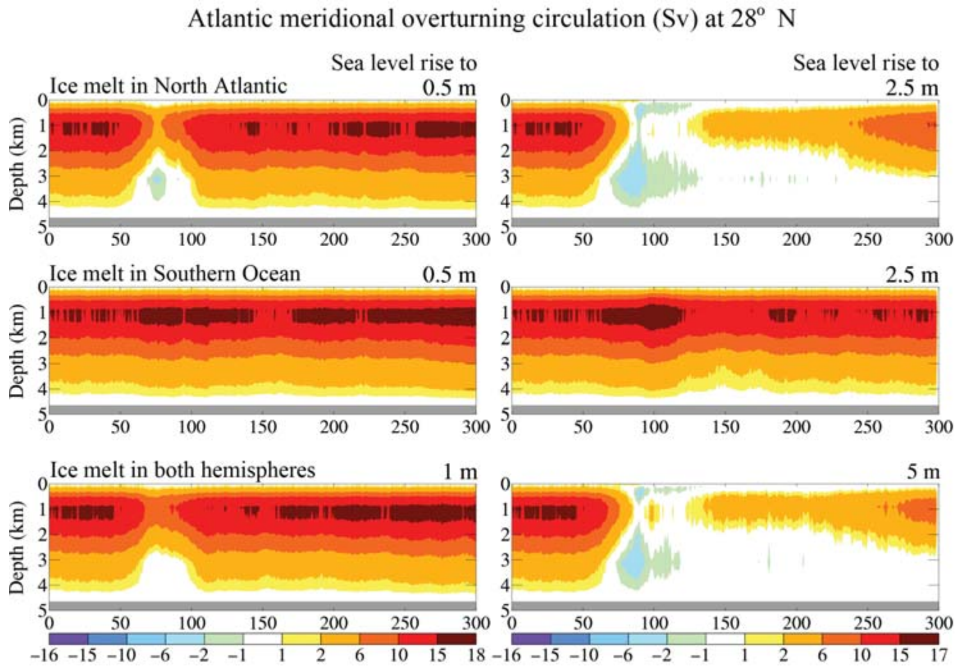


Figure 10. Ensemble-mean AMOC (Sv) at 28° N versus time for six pure freshwater forcing experiments.

Global temperature change (Fig. 11) reflects the fundamentally different impact of freshwater forcings of 0.5 and 2.5 m. The response also differs greatly depending on the hemisphere of the freshwater input. The case with freshwater forcing in both hemispheres is shown only in the Supplement because, to a good approximation, the response is simply the sum of the responses to the individual hemispheric forcings (see Figs. S10–S12). The sum of responses to hemispheric forcings moderately exceeds the response to global forcing.

Global cooling continues for centuries for the case with freshwater forcing sufficient to shut down the AMOC (Fig. 11). If the forcing is only 0.5 m of sea level, the temperature recovers in a few decades. However, the freshwater forcing required to reach the tipping point of AMOC shutdown may be less in the real world than in our model, as discussed below. Global cooling due to freshwater input on the Southern Ocean disappears in a few years after freshwater input ceases (Fig. 11), for both the smaller (0.5 m of sea level) and larger (2.5 m) freshwater forcings.

Injection of a large amount of surface freshwater in either hemisphere has a notable impact on heat uptake by the ocean and the internal ocean heat distribution (Fig. 12). Despite continuous injection of a large amount of very cold (−15 °C) water in these pure freshwater experiments, substantial portions of the ocean interior become warmer. Tropical and Southern Hemisphere warming is the well-known effect of reduced heat transport to northern latitudes in response to the AMOC shutdown (Rahmstorf, 1996; Barreiro et al., 2008).

However, deep warming in the Southern Ocean may have greater consequences. Warming is maximum at grounding line depths (∼ 1–2 km) of Antarctic ice shelves (Rignot and Jacobs, 2002). Ice shelves near their grounding lines (Fig. 13 of Jenkins and Doake, 1991) are sensitive to temperature of the proximate ocean, with ice shelf melting increasing 1 m per year for each 0.1 °C temperature increase (Rignot and Jacobs, 2002). The foot of an ice shelf provides most of the restraining force that ice shelves exert on landward ice (Fig. 14 of Jenkins and Doake, 1991), making ice near the grounding line the buttress of the buttress. Pritchard et al. (2012) deduce from satellite altimetry that ice shelf melt has primary control of Antarctic ice sheet mass loss.

Thus we examine our simulations in more detail (Fig. 13). The pure freshwater experiments add 5 mm sea level in the first decade (requiring an initial 0.346 mm year^{-1} for 10-year doubling), 10 mm in the second decade, and so on (Fig. 13a). Cumulative freshwater injection reaches 0.5 m in year 68 and 2.5 m in year 90.

Antarctic Bottom Water (AABW) formation is reduced ∼ 20 % by year 68 and ∼ 50 % by year 90 (Fig. 13b). When freshwater injection ceases, AABW formation rapidly regains full strength, in contrast to the long delay in reestablishing North Atlantic Deep Water (NADW) formation after AMOC shutdown. The Southern Ocean mixed-layer response time dictates the recovery time for AABW formation. Thus rapid recovery also applies to ocean temperature at depths of ice shelf grounding lines (Fig. 13c). The rapid response of the Southern Ocean meridional overturning cir-

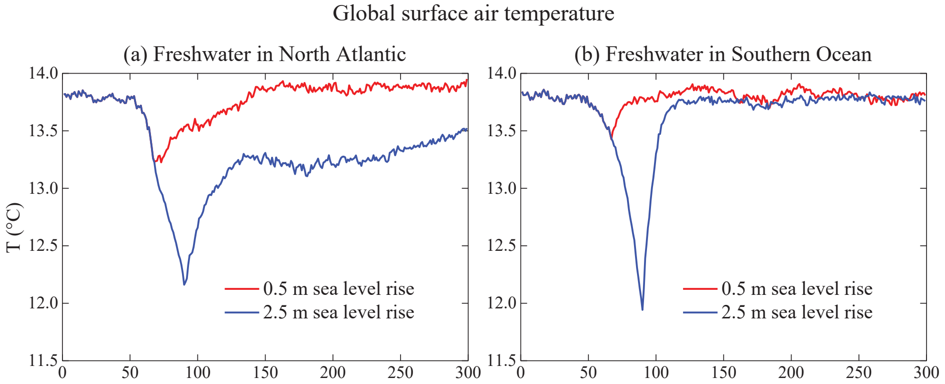


Figure 11. Ensemble-mean global surface air temperature (°C) for experiments (years on x axis) with freshwater forcing in either the North Atlantic Ocean (left) or the Southern Ocean (right).

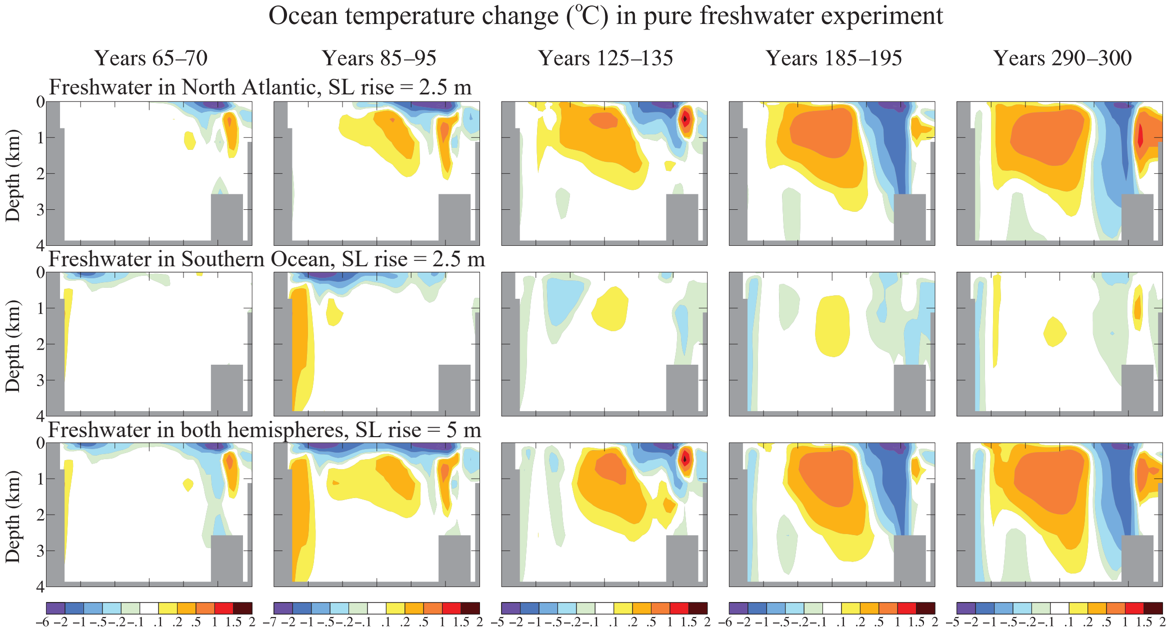


Figure 12. Change of ocean temperature (°C) relative to control run due to freshwater input that reaches 2.5 m of global sea level in a hemisphere (thus 5 m sea level rise in the bottom row).

culation (SMOC) implies that the rate of freshwater addition to the mixed layer is the driving factor.

Freshwater flux has little effect on simulated Northern Hemisphere sea ice until the 7th decade of freshwater growth (Fig. 13d), but Southern Hemisphere sea ice is more sensitive, with substantial response in the 5th decade and large response in the 6th decade. Below we show that "5th decade" freshwater flux (2880 Gt year^{-1}) is already relevant to the Southern Ocean today.

3.8 Simulations to 2100 with modified (more realistic) forcings

Recent data show that current ice melt is larger than assumed in our 1850–2300 simulations. Thus we make one more simulation and include minor improvements in the radiative forcing.

3.8.1 Advanced (earlier) freshwater injection

Atmosphere–ocean climate models, including ours, commonly include a fixed freshwater flux from the Greenland and Antarctic ice sheets to the ocean. This flux is chosen to balance snow accumulation in the model's control run, with

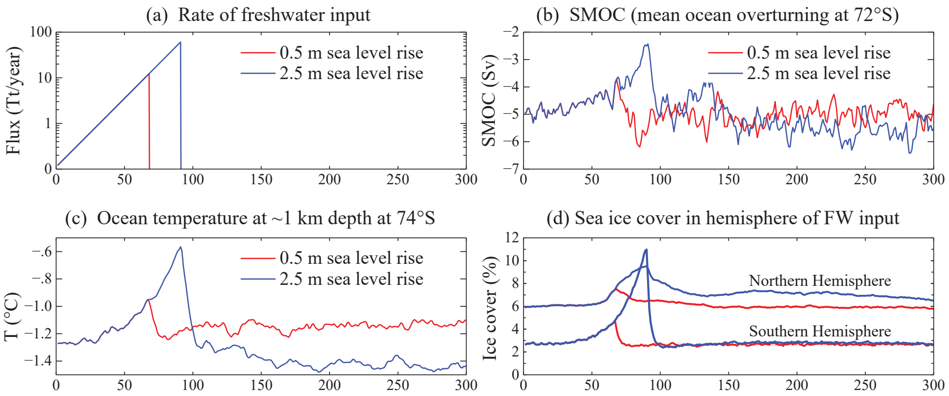


Figure 13. (a) Freshwater input (Tt year^{-1}) to Southern Ocean (1 Tt = 1000 km^3). **(b, c, d)** Simulated overturning strength (Sv) of AABW cell at 72° S, temperature (°C) at depth 1.13 km at 74° S, and sea ice cover (%).

the rationale that approximate balance is expected between net accumulation and mass loss including icebergs and ice shelf melting. Global warming creates a mass imbalance that we want to investigate. Ice sheet models can calculate the imbalance, but it is unclear how reliably ice sheet models simulate ice sheet disintegration. We forgo ice sheet modeling, instead adding a growing freshwater amount to polar oceans with alternative growth rates and initial freshwater amount estimated from available data.

Change of freshwater flux into the ocean in a warming world with shrinking ice sheets consists of two terms: term 1 being net ice melt and term 2 being change in $P - E$ (precipitation minus evaporation) over the relevant ocean. Term 1 includes land based ice mass loss, which can be detected by satellite gravity measurements, loss of ice shelves, and net sea ice mass change. Term 2 is calculated in a climate model forced by changing atmospheric composition, but it is not included in our pure freshwater experiments that have no global warming.

IPCC (Vaughan et al., 2013) estimated land ice loss in Antarctica that increased from 30 Gt year^{-1} in 1992–2001 to 147 Gt year^{-1} in 2002–2011 and in Greenland from 34 to 215 Gt year^{-1}, with uncertainties discussed by Vaughan et al. (2013). Gravity satellite data suggest Greenland ice sheet mass loss ∼ 300–400 Gt year^{-1} in the past few years (Barletta et al., 2013). A newer analysis of gravity data for 2003–2013 (Velicogna et al., 2014), discussed in more detail in Sect. 5.1, finds a Greenland mass loss 280 ± 58 Gt year^{-1} and Antarctic mass loss 67 ± 44 Gt year^{-1}.

One estimate of net ice loss from Antarctica, including ice shelves, is obtained by surveying and adding the mass flux from all ice shelves and comparing this freshwater mass loss with the freshwater mass gain from the continental surface mass budget. Rignot et al. (2013) and Depoorter et al. (2013) independently assessed the freshwater mass fluxes from Antarctic ice shelves. Their respective estimates for the basal melt are 1500 ± 237 and 1454 ± 174 Gt year^{-1}. Their respective estimates for calving are 1265 ± 139 and 1321 ± 144 Gt year^{-1}.

This estimated freshwater loss via the ice shelves (∼ 2800 Gt year^{-1}) is larger than freshwater gain by Antarctica. Vaughan et al. (1999) estimated net surface mass balance of the continent as +1811 and +2288 Gt year^{-1} including precipitation on ice shelves. Vaughan et al. (2013) estimates the net Antarctic surface mass balance as +1983 ± 122 Gt year^{-1} excluding ice shelves. Thus comparison of continental freshwater input with ice shelf output suggests a net export of freshwater to the Southern Ocean of several hundred Gt year^{-1} in recent years. However, substantial uncertainty exists in the difference between these two large numbers.

An independent evaluation has recently been achieved by Rye et al. (2014) using satellite measured changes of sea level around Antarctica in the period 1992–2011. Sea level along the Antarctic coast rose 2 mm year^{-1} faster than the regional mean sea level rise in the Southern Ocean south of 50° S, an effect that they conclude is almost entirely a steric adjustment caused by accelerating freshwater discharge from Antarctica. They conclude that an excess freshwater input of 430 ± 230 Gt year^{-1}, above the rate needed to maintain a steady ocean salinity, is required. Rye et al. (2014) note that these values constitute a lower bound for the actual excess discharge above a "steady salinity" rate, because numerous in situ data, discussed below, indicate that freshening began earlier than 1992.

Term 2, change in $P - E$ over the Southern Ocean relative to its preindustrial amount, is large in our climate simulations. In our ensemble of runs (using observed GHGs for 1850–2003 and scenario A1B thereafter) the increase in $P - E$ in the decade 2011–2020, relative to the control run, was in the range 3500 to 4000 Gt year^{-1}, as mean precipitation over the Southern Ocean increased ∼ 35 mm year^{-1} and evaporation decreased ∼ 3 mm year^{-1}.

Increasing ice melt and increasing $P - E$ are climate feedbacks, their growth in recent decades driven by global warming. Our pure freshwater simulations indicate that their sum, at least 4000 Gt year^{-1}, is sufficient to affect ocean circulation, sea ice cover, and surface temperature, which can spur other climate feedbacks. We investigate these feedbacks via climate simulations using improved estimates of freshwater flux from ice melt. $P-E$ is computed by the model.

We take freshwater injection to be 720 Gt year^{-1} from Antarctica and 360 Gt year^{-1} in the North Atlantic in 2011, with injection rates at earlier and later times defined by assumption of a 10-year doubling time. Resulting mean freshwater injection around Antarctica in 1992–2011 is ∼ 400 Gt year^{-1}, similar to the estimate of Rye et al. (2014). A recent estimate of 310 ± 74 km^3 volume loss of floating Antarctic ice shelves in 2003–2012 (Paolo et al., 2015) is not inconsistent, as the radar altimeter data employed for ice shelves do not include contributions from the ice sheet or fast ice tongues at the ice shelf grounding line. Greenland ice sheet mass loss provides most of the assumed 360 Gt year^{-1} freshwater, and this would be supplemented by shrinking ice shelves (Rignot and Steffen, 2008) and small ice caps in the North Atlantic and west of Greenland (Ohmura, 2009) that are losing mass (Abdalati et al., 2004; Bahr et al., 2009).

We add freshwater around Antarctica at coastal grid boxes (Fig. S13) guided by the data of Rignot et al. (2013) and Depoorter et al. (2013). Injection in the Western Hemisphere, especially from the Weddell Sea to the Ross Sea, is more than twice that in the other hemisphere (Fig. 14). Specified freshwater flux around Greenland is similar on the east and west coasts, and small along the north coast (Fig. S13).

3.8.2 Modified radiative forcings

Actual GHG forcing is less than scenario A1B, because CH_4 and minor gas growth declined after IPCC scenarios were defined (Fig. 5; Hansen et al., 2013c, update at http://www.columbia.edu/~mhs119/GHGs/). As a simple improvement we decreased the A1B CH_4 scenario during 2003–2013 so that subsequent CH_4 is reduced 100 ppb, decreasing radiative forcing ∼ 0.05 W m^{-2}.

Stratospheric aerosol forcing to 2014 uses the data set of Sato et al. (1993) as updated at http://www.columbia.edu/~mhs119/StratAer/. Future years have constant aerosol optical depth 0.0052 yielding effective forcing $-0.12\ \text{W m}^{-2}$, implemented by using fixed 1997 aerosol data. Tropospheric aerosol growth is assumed to slow smoothly, leveling out at $-2\ \text{W m}^{-2}$ in 2100. Future solar forcing is assumed to have an 11-year cycle with amplitude 0.25 W m^{-2}. Net forcing exceeds 5 W m^{-2} by the end of the 21st century, about 3 times the current forcing (Fig. S16).

3.8.3 Climate simulations with modified forcings

Global temperature has a maximum at +1.2 °C in the 2040s for the modified forcings (Fig. 15). Ice melt cooling is advanced as global ice melt reaches 1 m of sea level in 2060, 1/3 from Greenland and 2/3 from Antarctica. Global temperature rise resumes in the 2060s after cessation of freshwater injection.

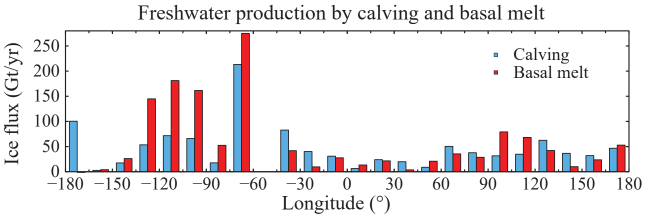


Figure 14. Freshwater flux (Gt year^{-1}) from Antarctic ice shelves based on data of Rignot et al. (2013), integrated here into intervals of 15° of longitude. Depoorter et al. (2013) data yield a similar distribution.

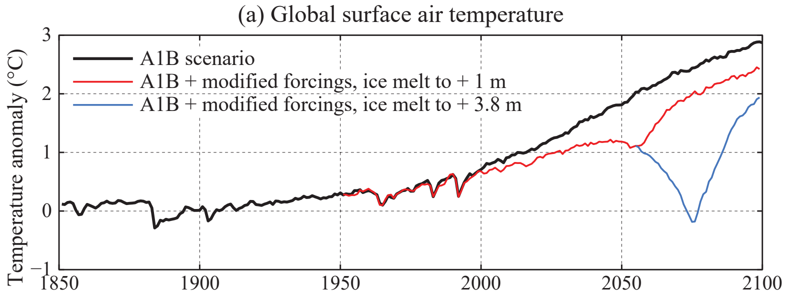
Global temperature becomes an unreliable diagnostic of planetary condition as the ice melt rate increases. Global energy imbalance (Fig. 15b) is a more meaningful measure of planetary status as well as an estimate of the climate forcing change required to stabilize climate. Our calculated present energy imbalance of ∼ 0.8 W m^{-2} (Fig. 15b) is larger than the observed 0.58 ± 0.15 W m^{-2} during 2005–2010 (Hansen et al., 2011). The discrepancy is likely accounted for by excessive ocean heat uptake at low latitudes in our model, a problem related to the model's slow surface response time (Fig. 4) that may be caused by excessive small-scale ocean mixing.

Large scale regional cooling occurs in the North Atlantic and Southern oceans by mid-century (Fig. 16) for 10-year doubling of freshwater injection. A 20-year doubling places similar cooling near the end of this century, 40 years earlier than in our prior simulations (Fig. 7), as the factor of 4 increase in current freshwater from Antarctica is a 40-year advance.

Cumulative North Atlantic freshwater forcing in sverdrup years (Sv years) is 0.2 Sv years in 2014, 2.4 Sv years in 2050, and 3.4 Sv years (its maximum) prior to 2060 (Fig. S14). The critical issue is whether human-spurred ice sheet mass loss can be approximated as an exponential process during the next few decades. Such nonlinear behavior depends upon amplifying feedbacks, which, indeed, our climate simulations reveal in the Southern Ocean.

3.8.4 Southern Ocean feedbacks

Amplifying feedbacks in the Southern Ocean and atmosphere contribute to dramatic climate change in our simulations (Fig. 16). We first summarize the feedbacks to identify processes that must be simulated well to draw valid conclusions. While recognizing the complexity of the global ocean circulation (Lozier, 2012; Lumpkin and Speer, 2007; Marshall and Speer, 2012; Munk and Wunsch, 1998; Orsi et al., 1999; Sheen et al., 2014; Talley, 2013; Wunsch and Ferrari,


(a) Global surface air temperature

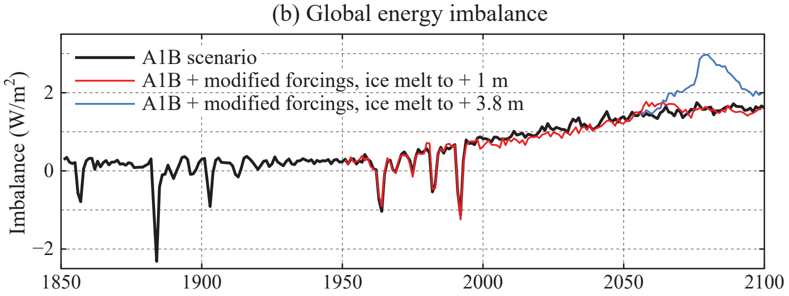
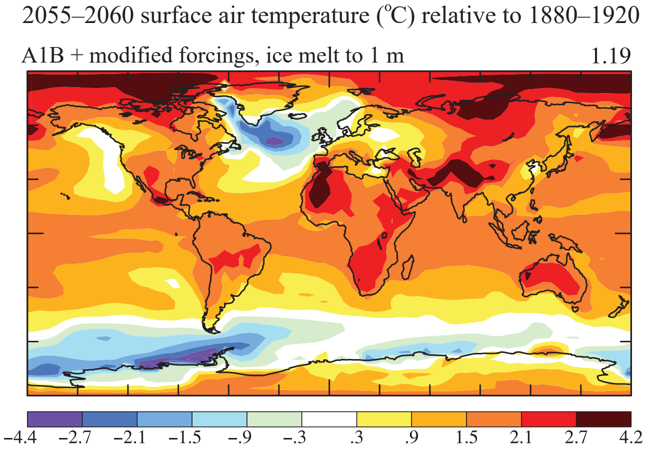

(b) Global energy imbalance

Figure 15. (a) Surface air temperature (°C) change relative to 1880–1920 and **(b)** global energy imbalance (W m^{-2}) for the modified forcing scenario including cases with global ice melt reaching 1 and 3.8 m.


2055–2060 surface air temperature (ºC) relative to 1880–1920

A1B + modified forcings, ice melt to 1 m 1.19

Figure 16. Surface air temperature (°C) change relative to 1880–1920 in 2055–2060 for modified forcings.

2004), we use a simple two-dimensional representation to discuss the feedbacks.

Climate change includes slowdown of AABW formation, indeed shutdown by mid-century if freshwater injection increases with a doubling time as short as 10 years (Fig. 17). Implications of AABW shutdown are so great that we must ask whether the mechanisms are simulated with sufficient realism in our climate model, which has coarse resolution and relevant deficiencies that we have noted. After discussing the feedbacks here, we examine how well the processes are included in our model (Sect. 3.8.5). Paleoclimate data (Sect. 4) provide much insight about these processes, and modern observations (Sect. 5) suggest that these feedbacks are already underway.

Large-scale climate processes affecting ice sheets are sketched in Fig. 18. The role of the ocean circulation in the global energy and carbon cycles is captured to a useful extent by the two-dimensional (zonal-mean) overturning circulation featuring deep water (NADW) and bottom water (AABW) formation in the polar regions. Marshall and Speer (2012) discuss the circulation based in part on tracer data and analyses by Lumpkin and Speer (2007). Talley (2013) extends the discussion with diagrams clarifying the role of the Pacific and Indian oceans.

Wunsch (2002) emphasizes that the ocean circulation is driven primarily by atmospheric winds and secondarily by tidal stirring. Strong circumpolar westerly winds provide energy drawing deep water toward the surface in the Southern Ocean. Ocean circulation also depends on processes maintaining the ocean's vertical density stratification. Winter cooling of the North Atlantic surface produces water dense enough to sink (Fig. 18), forming North Atlantic Deep Water (NADW). However, because North Atlantic water is relatively fresh, compared to the average ocean, NADW does not sink all the way to the global ocean bottom. Bottom water is formed instead in the winter around the Antarctic coast, where very salty cold water (AABW) can sink to the ocean floor. This ocean circulation (Fig. 18) is altered by natural and human-made forcings, including freshwater from ice sheets, engendering powerful feedback processes.

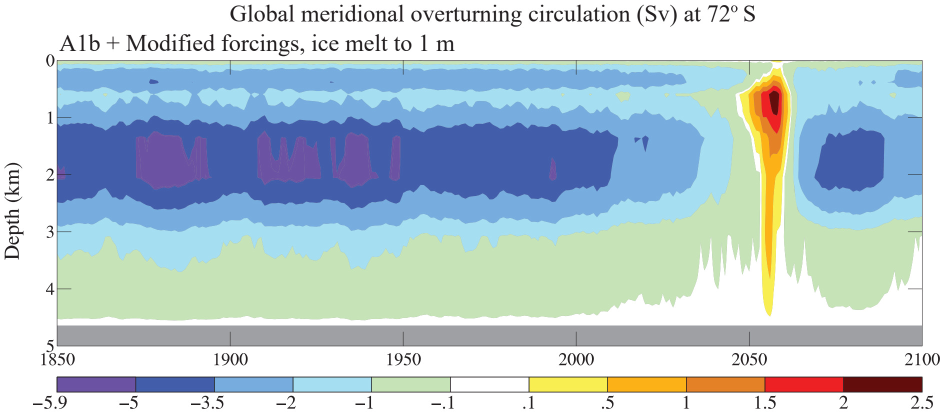


Figure 17. SMOC, ocean overturning strength (Sv) at 72° S, including only the mean (Eulerian) transport. This is the average of a five-member model ensemble for the modified forcing including advanced ice melt (720 Gt year^{-1} from Antarctica in 2011) and 10-year doubling.

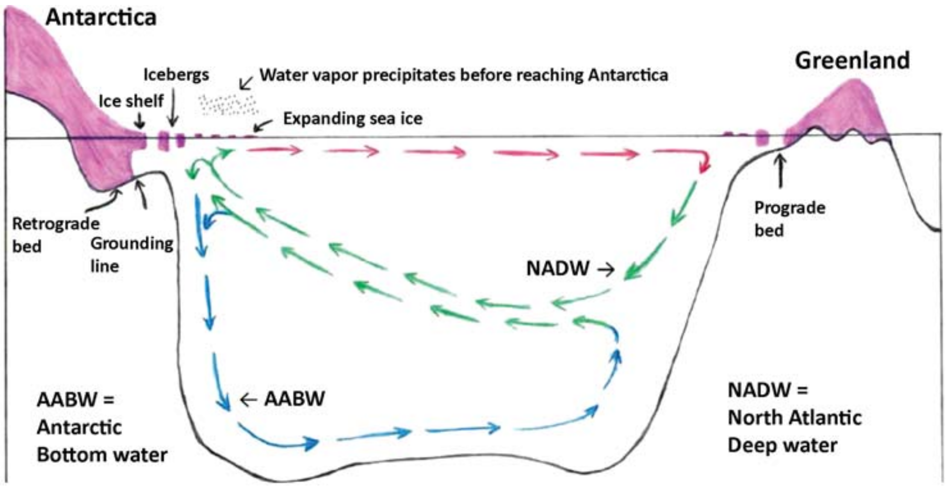


Figure 18. Schematic of stratification and precipitation amplifying feedbacks. Stratification: increased freshwater flux reduces surface water density, thus reducing AABW formation, trapping NADW heat, and increasing ice shelf melt. Precipitation: increased freshwater flux cools ocean mixed layer, increases sea ice area, causing precipitation to fall before it reaches Antarctica, reducing ice sheet growth and increasing ocean surface freshening. Ice in West Antarctica and the Wilkes Basin, East Antarctica, is most vulnerable because of the instability of retrograde beds.

A key Southern Ocean feedback is meltwater stratification effect, which reduces ventilation of ocean heat to the atmosphere and space. Our "pure freshwater" experiments show that the low-density lid causes deep-ocean warming, especially at depths of ice shelf grounding lines that provide most of the restraining force limiting ice sheet discharge (Fig. 14 of Jenkins and Doake, 1991). West Antarctica and Wilkes Basin in East Antarctica have potential to cause rapid sea level rise, because much of their ice sits on retrograde beds (beds sloping inland), a situation that can lead to unstable grounding line retreat and ice sheet disintegration (Mercer, 1978).

Another feedback occurs via the effect of surface and atmospheric cooling on precipitation and evaporation over the Southern Ocean. CMIP5 climate simulations, which do not include increasing freshwater injection in the Southern Ocean, find snowfall increases on Antarctica in the 21st century, thus providing a negative term to sea level change. Frieler et al. (2015) note that 35 climate models are consistent in showing that warming climate yields increasing snow accumulation in accord with paleo-data for warmer climates, but the paleo-data refer to slowly changing climate in quasi-equilibrium with ocean boundary conditions. In our experiments with growing freshwater injection, the increasing sea ice cover and cooling of the Southern Ocean surface and atmosphere cause the increased precipitation to occur over the Southern Ocean, rather than over Antarctica. This feedback not only reduces any increase in snowfall over Antarctica but also provides a large freshening term to the surface of the

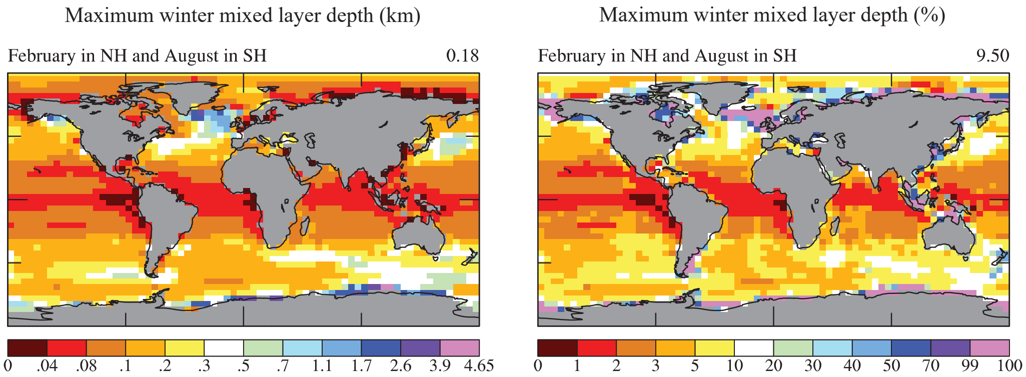


Figure 19. Maximum mixed-layer depth (in km, left, and % of ocean depth, right) in February (Northern Hemisphere) and August (Southern Hemisphere) using the mixed-layer definition of Heuze et al. (2013).

Southern Ocean, thus magnifying the direct freshening effect from increasing ice sheet melt.

North Atlantic meltwater stratification effects are also important, but different. Meltwater from Greenland can slow or shutdown NADW formation, cooling the North Atlantic, with global impacts even in the Southern Ocean, as we will discuss later. One important difference is that the North Atlantic can take centuries to recover from NADW shutdown, while the Southern Ocean recovers within 1–2 decades after freshwater injection stops (Sect. 3.7).

3.8.5 Model's ability to simulate these feedbacks

Realistic representation of these feedbacks places requirements on both the atmosphere and ocean components of our climate model. We discuss first the atmosphere, then the ocean.

There are two main requirements on the atmospheric model. First, it must simulate $P-E$ well, because of its importance for ocean circulation and the amplifying feedback in the Southern Ocean. Second, it must simulate winds well, because these drive the ocean.

Simulated $P-E$ (Fig. S15b) agrees well with meteorological reanalysis (Fig. 3.4b of Rhein et al., 2013). Resulting sea surface salinity (SSS) patterns in the model (Fig. S15a) agree well with global ocean surface salinity patterns (Antonov et al., 2010, and Fig. 3.4a of Rhein et al., 2013). SSS trends in our simulation (Fig. S15c), with the Pacific on average becoming fresher while most of the Atlantic and the subtropics in the Southern Hemisphere become saltier, are consistent with observed salinity trends (Durack and Wijffels, 2010). Recent freshening of the Southern Ocean in our simulation is somewhat less than in observed data (Fig. 3.4c, d of Rhein et al., 2013), implying that the amplifying feedback may be *under*estimated in our simulation. A likely reason for that is discussed below in conjunction with observed sea ice change.

Obtaining accurate winds requires the model to simulate well atmospheric pressure patterns and their change in response to climate forcings. A test is provided by observed changes of the Southern Annular Mode (SAM), with a decrease in surface pressure near Antarctica and a small increase at midlatitudes (Marshall, 2003) that Thompson et al. (2011) relate to stratospheric ozone loss and increasing GHGs. Our climate forcing (Fig. S16) includes ozone change (Fig. 2 of Hansen et al., 2007a) with stratospheric ozone depletion in 1979–1997 and constant ozone thereafter. Our model produces a trend toward the high index polarity of SAM (Fig. S17) similar to observations, although perhaps a slightly smaller change than observed (compare Fig. S17 with Fig. 3 of Marshall, 2003). SAM continues to increase in our model after ozone stabilizes (Fig. S17), suggesting that GHGs may provide a larger portion of the SAM response in our model than in the model study of Thompson et al. (2011). It would not be surprising if the stratospheric dynamical response to ozone change were weak in our model, given the coarse resolution and simplified representation of atmospheric drag and dynamical effects in the stratosphere (Hansen et al., 2007a), but that is not a major concern for our present purposes.

The ocean model must be able to simulate realistically the ocean's overturning circulation and its response to forcings including freshwater additions. Heuze et al. (2013, 2015) point out that simulated deep convection in the Southern Ocean is unrealistic in most models, with AABW formation occurring in the open ocean where it rarely occurs in nature. Our present ocean model contains significant improvements (see Sect. 3.2) compared to the GISS E2-R model that Heuze et al. include in their comparisons. Thus we show (Fig. 19) the maximum mixed-layer depth in winter (February in the Northern Hemisphere and August in the Southern Hemisphere) using the same criterion as Heuze et al. to define the mixed-layer depth, i.e., the layers with a density difference from the ocean surface layer less than $0.03\,\mathrm{kg\,m^{-3}}$.

Southern Ocean mixing in the model reaches a depth of ~ 500 m in a wide belt near 60° S stretching west from the southern tip of South America, with similar depths south of Australia. These open-ocean mixed-layer depths compare favorably with observations shown in Fig. 2a of Heuze et al. (2015), based on data of de Boyer Montegut et al. (2004). There is no open-ocean deep convection in our model.

Deep convection occurs only along the coast of Antarctica (Fig. 19). Coastal grid boxes on the continental shelf are a realistic location for AABW formation. Orsi et al. (1999) suggest that most AABW is formed on shelves around the Weddell–Enderby Basin (60 %) and shelves of the Adélie–Wilkes Coast and Ross Sea (40 %). Our model produces mixing down to the shelf in those locations (Fig. 19b), and also on the Amery Ice Shelf near the location where Ohshima et al. (2013) identified AABW production, which they term Cape Darnley Bottom Water.

With our coarse 4° stair step to the ocean bottom, AABW cannot readily slide down the slope to the ocean floor. Thus dense shelf water mixes into the open-ocean grid boxes, making our modeled Southern Ocean less stratified than the real world (cf. temporal drift of Southern Ocean salinity in Fig. S18), because the denser water must move several degrees of latitude horizontally before it can move deeper. Nevertheless, our Southern Ocean is sufficiently stratified to avoid the unrealistic open-ocean convection that infects many models (Heuze et al., 2013, 2015).

Orsi et al. (1999) estimate the AABW formation rate in several ways, obtaining values in the range 8–12 Sv, larger than our modeled 5–6 Sv (Fig. 17). However, as in most models (Heuze et al., 2015), our SMOC diagnostic (Fig. 17) is the mean (Eulerian) circulation, i.e., excluding eddy-induced transport. Rerun of a 20-year segment of our control run to save eddy-induced changes reveals an increase in SMOC at 72° S by 1–2 Sv, with negligible change at middle and low latitudes, making our simulated transport close to the range estimated by Orsi et al. (1999).

We conclude that the model may simulate Southern Ocean feedbacks that magnify the effect of freshwater injected into the Southern Ocean: the $P-E$ feedback that wrings global-warming-enhanced water vapor from the air before it reaches Antarctica and the AABW slowdown that traps deep-ocean heat, leaving that heat at levels where it accelerates ice shelf melting. Indeed, we will argue that both of these feedbacks are probably underestimated in our current model.

The model seems less capable in Northern Hemisphere polar regions. Deep convection today is believed to occur mainly in the Greenland–Iceland–Norwegian (GIN) seas and at the southern end of Baffin Bay (Fig. 2b of Heuze et al., 2015). In our model, perhaps because of excessive sea ice in those regions, open-ocean deep convection occurs to the southeast of the southern tip of Greenland and at less deep grid boxes between that location and the United Kingdom (Fig. 19). Mixing reaching the ocean floor on the Siberian coast in our model (Fig. 19) may be realistic, as coastal polynya are observed on the Siberian continental shelf (D. Bauch et al., 2012). However, the winter mixed layer on the Alaska south coast is unrealistically deep (Fig. 19). These model limitations must be kept in mind in interpreting simulated Northern Hemisphere climate change.

3.9 Impact of ice melt on storms

Our inferences about potential storm changes from continued high growth of atmospheric GHGs are fundamentally different than modeling results described in IPCC (2013, 2014), where the latter are based on CMIP5 climate model results without substantial ice sheet melt. Lehmann et al. (2014) note ambiguous results for storm changes from prior model studies and describe implications of the CMIP5 ensemble of coupled climate models. Storm changes are moderate in nature, with even a weakening of storms in some locations and seasons. This is not surprising, because warming is greater at high latitudes, reducing meridional temperature gradients.

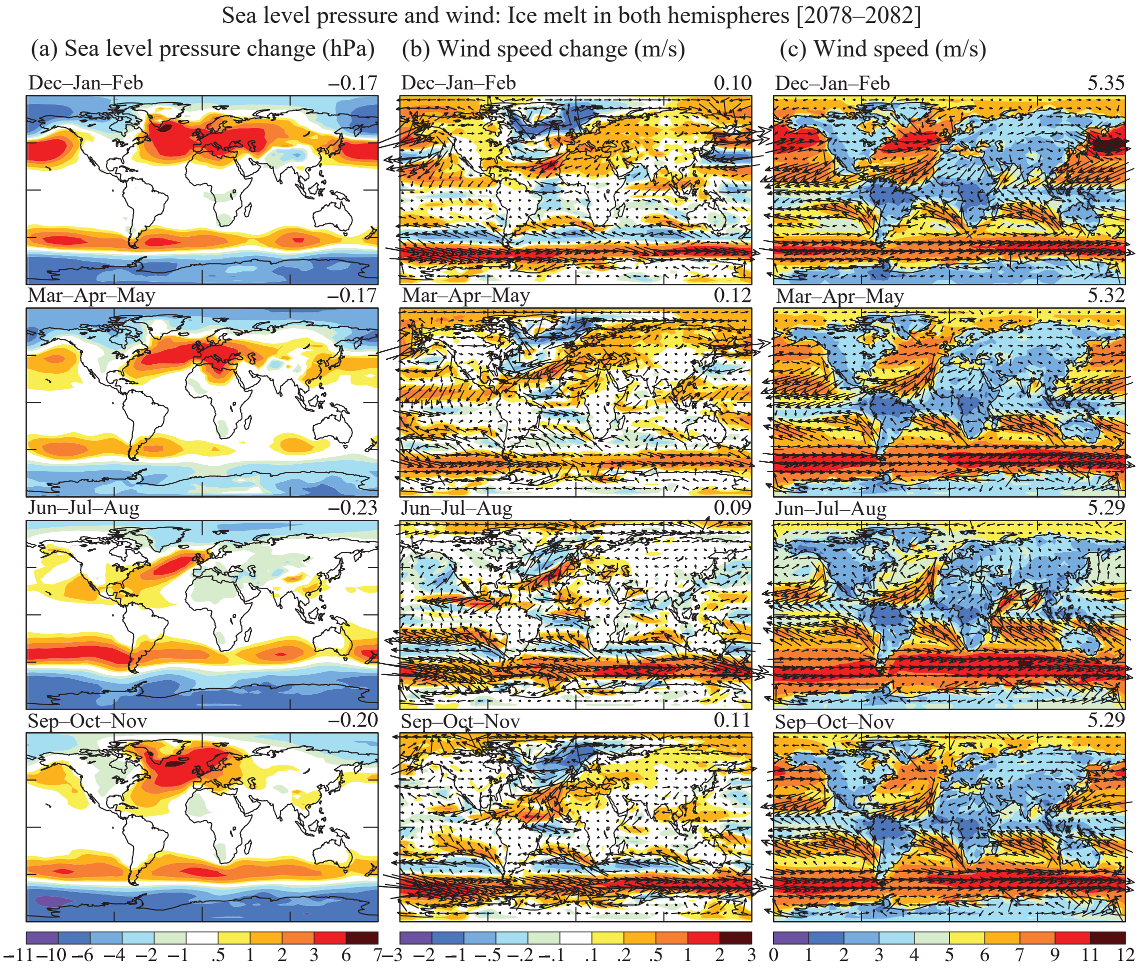
Before describing our model results, we note the model limitations for study of storms, including its coarse resolution (4° × 5°), which may contribute to slight misplacement of the Bermuda high-pressure system for today's climate (Fig. S2). Excessive Northern Hemisphere sea ice may cause a bias in location of deepwater formation toward lower latitudes. Simulated effects also depend on the location chosen for freshwater injection; in model results shown here (Fig. 20), freshwater was spread uniformly over all longitudes in the North Atlantic between 65° W and 15° E. It would be useful to carry out similar studies with higher-resolution models including the most realistic possible distribution of meltwater.

Despite these caveats, we have shown that the model realistically simulates meridional changes of sea level pressure in response to climate forcings (Sect. 3.8.5). Specifically, the model yields a realistic trend to the positive phase of the Southern Annular Mode (SAM) in response to a decrease in stratospheric ozone and increase in other GHGs (Fig. S17). We also note that the modeled response of atmospheric pressure to the cooling effect of ice melt is large scale, tending to be of a meridional nature that should be handled by our model resolution.

Today's climate, not Eemian climate, is the base climate state upon which we inject polar freshwater. However, the simulated climate effects of the freshwater are so large that they should also be relevant to freshwater injection in the Eemian period.

3.9.1 Modeling insights into Eemian storms

Ice melt in the North Atlantic increases simulated sea level pressure in that region in all seasons (Fig. 20). In summer the Bermuda high-pressure system (Fig. S2) increases in strength and moves northward. Circulation around the high pressure creates stronger prevailing northeasterly winds at latitudes of Bermuda and the Bahamas. A1B climate forcing alone (Fig. S21, top row) has only a small impact on


Sea level pressure and wind: Ice melt in both hemispheres [2078–2082]

(a) Sea level pressure change (hPa) (b) Wind speed change (m/s) (c) Wind speed (m/s)

Figure 20. Change of seasonal-mean **(a)** sea level pressure (hPa), **(b)** wind speed ($\mathrm{m\,s^{-1}}$) in 2078–2082 relative to 1880–1920, and **(c)** the wind speed ($\mathrm{m\,s^{-1}}$) itself, all for the scenario with ice melt in both hemispheres.

the winds, but cold meltwater in the North Atlantic causes a strengthening and poleward shift of the high pressure.

The high pressure in the model is located further east than needed to produce the fastest possible winds at the Bahamas. Our coarse-resolution (4° × 5°) model may be partly responsible for the displacement. However, the location of high pressure also depends on meltwater placement, which we spread uniformly over all longitudes in the North Atlantic between 65° W and 15° E, and on the specific location of ocean currents and surface temperature during the Eemian.

North Atlantic cooling from AMOC shutdown creates faster winds in our simulations, with a seasonal-mean increment as much as 10–20 %. Such a percentage translates into an increase in storm power dissipation by a factor ∼ 1.4–2, because dissipation is proportional to the cube of wind speed (Emanuel, 1987, 2005). Our simulated changes refer to mean winds over large grid boxes, not individual storms, for which the change in the most extreme cases might be larger.

Increased North Atlantic high pressure strengthens prevailing northeasterly winds blowing onto the Bahamas in the direction of Eemian wave-formed deposits (Sect. 4.1.2). Consistent increase in these winds would contribute to creation of long-wavelength, deep-ocean waves that scour the ocean floor as they reach the shallow near-shore region. However, extreme events may require the combined effect of increased prevailing winds and tropical storms guided by the strengthened blocking high pressure and nurtured by the unusually warm late-Eemian tropical sea surface temperatures (Cortijo et al., 1999), which would favor more powerful tropical storms (Emanuel, 1987). This enhanced meridional temperature gradient – warmer tropics and cooler high latitudes – was enhanced by low obliquity of Earth's spin axis in the late Eemian.

3.9.2 21st century storms

If GHGs continue to increase rapidly and ice melt grows, our simulations yield shutdown or major slowdown of the AMOC in the 21st century, implying an increase in severe weather. This is shown by zonal-mean temperature and eddy kinetic energy changes in simulations of Sects. 3.3–3.6 with and without ice melt (Fig. 21). Without ice melt, surface warming is largest in the Arctic (Fig. 21, left), resulting in a decrease in lower tropospheric eddy energy. However, the surface cooling from ice melt increases surface and lower tropospheric temperature gradients, and in stark contrast to the case without ice melt, there is a large increase in midlatitude eddy energy throughout the midlatitude troposphere. The increase in zonal-mean midlatitude baroclinicity (Fig. 21) is in agreement with the localized, North Atlantic-centered increases in baroclinicity found in the higher-resolution simulations of Jackson et al. (2015) and Brayshaw et al. (2009).

Increased baroclinicity produced by a stronger temperature gradient provides energy for more severe weather events. Many of the most significant and devastating storms in eastern North America and western Europe, popularly known as superstorms, have been winter cyclonic storms, though sometimes occurring in late fall or early spring, that generate near-hurricane-force winds and often large amounts of snowfall (Chapter 11, Hansen, 2009). Continued warming of low-latitude oceans in coming decades will provide a larger water vapor repository that can strengthen such storms. If this tropical warming is combined with a cooler North Atlantic Ocean from AMOC slowdown and an increase in midlatitude eddy energy (Fig. 21), we can anticipate more severe baroclinic storms. Increased high pressure due to cooler high-latitude ocean (Fig. 20) can make blocking situations more extreme, with a steeper pressure gradient between the storm's low-pressure center and the blocking high, thus driving stronger North Atlantic storms.

Freshwater injection into the North Atlantic and Southern oceans increases sea level pressure at middle latitudes and decreases it at polar latitudes (Figs. 20, S22), but the impact is different in the North Atlantic than in the Southern Ocean. In the Southern Ocean the increased meridional temperature gradient increases the strength of westerlies in all seasons at all longitudes. In the North Atlantic Ocean the increase in sea level pressure in winter slows the westerlies (Fig. 20). Thus instead of a strong zonal wind that keeps cold polar air locked in the Arctic, there is a tendency for a less zonal flow and thus more cold air outbreaks to middle latitudes.

4 Earth's climate history

Earth's climate history is our richest source of information about climate processes. We first examine the Eemian or MIS 5e period, the last time Earth was as warm as today, because it is especially relevant to the issue of rapid sea level rise and storms when ice sheets existed only on Greenland and Antarctica. A fuller interpretation of late-Eemian climate events, as well as projection of climate change in the Anthropocene, requires understanding mechanisms involved in Earth's millennial climate oscillations, which we discuss in the following subsection.

4.1 Eemian interglacial period (marine isotope substage MIS 5e)

We first discuss Eemian sea level (Sect. 4.1.1), especially evidence for rapid sea level rise late in the Eemian to +6–9 m relative to today's sea level, and then evidence for strong late-Eemian storms (Sect. 4.1.2). We provide in the Supplement more detailed geologic analysis of data on Eemian sea level, because the rapid late-Eemian sea level rise relates to our expectation of likely near-future events if rapid global warming continues. In Sect. 4.1.3 we present evidence from ocean sediment cores for strong late-Eemian cooling in the North Atlantic associated with shutdown of the Atlantic meridional overturning circulation (AMOC), and in Sect. 4.1.4 we show that Earth orbital parameters in the late Eemian were consistent with cooling in the North Atlantic and global sea level rise from Antarctic ice sheet collapse.

4.1.1 Eemian sea level

Eemian sea level is of special interest because Eemian climate was little warmer than today. Masson-Delmotte et al. (2013) conclude, based on multiple data and model sources, that peak Eemian temperature probably was only a few tenths of a degree warmer than today. Yet Eemian sea level reached heights several meters above today's level (Land et al., 1967; Chen et al., 1991; Neumann and Hearty, 1996; Hearty et al., 2007; Kopp et al., 2009; Dutton and Lambeck, 2012; O'Leary et al., 2013; Dutton et al., 2015).

Change of sea level within the Eemian period is particularly relevant to concerns about ice sheet stability and the potential for rapid sea level rise. Hearty et al. (2007) used data from 15 sites around the world to construct an Eemian sea level curve that had sea level rising in the early Eemian to +2–3 m ("+" indicates above today's sea level), possibly falling in the mid-Eemian to near today's sea level, rapidly rising in the late Eemian to +6–9 m, and then plummeting as Earth moved from the Eemian into the 100 000-year glacial period preceding the Holocene. Evidence from a variety of sources supports this interpretation, as discussed in the Supplement.

The most comprehensive analyses of sea level and paleoclimate storms are obtained by combining information from different geologic sources, each with strengths and weaknesses. Coral reefs, for example, allow absolute U/Th dating with age uncertainty as small as 1–2 ky, but inferred sea levels are highly uncertain because coral grows below sea level at variable depths as great as several meters. Carbonate platforms such as Bermuda and the Bahamas, in contrast, have few coral reefs for absolute dating, but the ability of carbonate sediments to cement rapidly preserves rock evidence of short-lived events such as rapid sea level rise and storms.

The important conclusion, that sea level rose rapidly in the late Eemian by several meters, to +6–9 m, is supported by records preserved in both the limestone platforms and coral

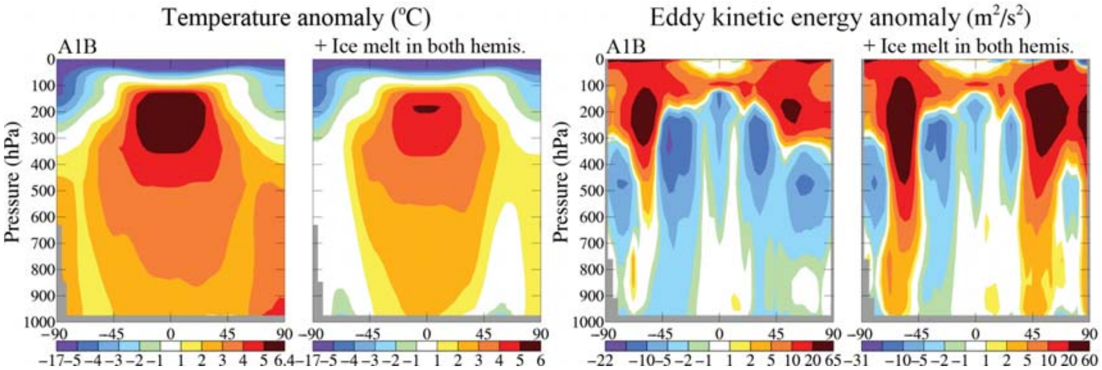


Figure 21. Simulated zonal-mean atmospheric temperature (°C) and eddy kinetic energy ($m^2\,s^{-2}$) in 2078–2082 relative to 1880–1920 for A1B scenario and A1B plus 2.5 m ice melt in each hemisphere.

reefs. Figure 6 of Hearty and Kindler (1995), for example, based on Bermuda and Bahamas geological data from marine and eolian limestone, reveals the rapid late-Eemian sea level rise and fall. Based on the limited size of the notches cut in Bahamian shore during the rapid late-Eemian level rise and crest, Neumann and Hearty (1996) inferred that this period was at most a few hundred years. Independently, Blanchon et al. (2009) used coral reef "back-stepping" on the Yucatán Peninsula, i.e., movement of coral reef building shoreward as sea level rises, to conclude that sea level in the late Eemian jumped 2–3 m within an "ecological" period, i.e., within several decades.

Despite general consistency among these studies, considerable uncertainty remains about absolute Eemian sea level elevation and exact timing of end-Eemian events. Uncertainties include effects of local tectonics and glacio-isostatic adjustment (GIA) of Earth's crust. Models of GIA of Earth's crust to ice sheet loading and unloading are increasingly used to improve assessments. O'Leary et al. (2013) use over 100 corals from reefs at 28 sites along the 1400 km west coast of Australia, incorporating minor GIA corrections, to conclude that sea level in most of the Eemian was relatively stable at +3–4 m, followed by a rapid late-Eemian sea level rise to about +9 m. U-series dating of the corals has peak sea level at 118.1 ± 1.4 ky b2k.

A more complete discussion of data on Eemian sea level is provided in the Supplement.

Late-Eemian sea level rise may seem a paradox, because orbital forcing then favored growth of Northern Hemisphere ice sheets. We will find evidence, however, that the sea level rise and increased storminess are consistent, and likely related to events in the Southern Ocean.

4.1.2 Evidence of end-Eemian storms in Bahamas and Bermuda

Geologic data indicate that the rapid end-Eemian sea level oscillation was accompanied by increased temperature gradients and storminess in the North Atlantic region. We summarize several interconnected lines of evidence for end-Eemian storminess, based on geological studies in Bermuda and the Bahamas referenced below. It is important to consider *all* the physical evidence of storminess rather than exclusively the transport mechanism of the boulders; indeed, it is essential to integrate data from obviously wave-produced runup and chevron deposits that exist within a few kilometers on North Eleuthera, Bahamas, as well as across the Bahamas Platform.

The Bahama Banks are flat, low-lying carbonate platforms that are exposed as massive islands during glacials and largely inundated during interglacial high stands. From a tectonic perspective, the platforms are relatively stable, as indicated by near-horizontal +2–3 m elevation of Eemian reef crests across the archipelago (Hearty and Neumann, 2001). During MIS 5e sea level high stands, an enormous volume of aragonitic oolitic grains blanketed the shallow, high-energy banks. Sea level shifts and storms formed shoals, ridges, and dunes. Oolitic sediments indurated rapidly ($\sim 10^1$ to $\sim 10^2$ years) once stabilized, preserving detailed and delicate lithic evidence of these brief, high-energy events. This shifting sedimentary substrate across the banks was inimical to coral growth, which partially explains the rarity of reefs during late MIS 5e.

The preserved regional stratigraphic, sedimentary and geomorphic features attest to a turbulent end-Eemian transition in the North Atlantic. As outlined below, a coastal gradient of sedimentological features corresponds with coastal morphology, distance from the coast, and increasing elevation, reflecting the attenuating force and inland "reach" of large waves, riding on high late-Eemian sea levels. On rocky, steep coasts, giant limestone boulders were detached and catapulted onto and over the coastal ridge by ocean waves. On higher, Atlantic-facing built-up dune ridges, waves ran up to over 40 m elevation, leaving meter-thick sequences of fenestral beds, pebble lenses, and scour structures. Across kilometers of low-lying tidal inlets and flats, "nested" chevron clusters were formed as stacked, multi-meter thick, tabular fenestral beds.

Figure 22. Megaboulders #1 (left) and #2 resting on MIS 5e eolianite at the crest of a 20 m high ridge with person (1.7 m) showing scale and orientation of bedding planes in the middle Pleistocene limestone. The greater age compared to underlying strata and disorientation of the primary bedding beyond natural in situ angles indicates that the boulders were wave-transported.

The complexity of geomorphology and stratigraphy of these features are temporal measures of sustained sea level and storm events, encompassing perhaps hundreds of years. These features exclude a single wave cluster from a local point-source tsunami. Here we present data showing the connections among the megaboulders, runup deposits, and chevron ridges.

Megaboulders

In North Eleuthera enormous boulders were plucked from seaward middle Pleistocene outcrops and washed onto a younger Pleistocene landscape (Hearty and Neumann, 2001). The average 1000 t megaclasts provide a metric of powerful waves at the end of MIS 5e. Evidence of transport by waves includes that (1) they are composed of recrystallized oolitic–peloidal limestone of MIS 9 or 11 age (300–400 ky; Kindler and Hearty, 1996) and hammer-ringing hardness; (2) they rest on oolitic sediments typical of early to mid-MIS 5e that are soft and punky under hammer blows; (3) *Cerion* land snail fossils beneath boulder #4 (Hearty, 1997) correlate with the last interglacial period (Garrett and Gould, 1984; Hearty and Kaufman, 2009); (4) calibrated amino acid racemization (AAR) ratios (Hearty, 1997; Hearty et al., 1998; Hearty and Kaufman, 2000, 2009) confirm the last interglacial age of the deposits as well as the stratigraphic reversal; (5) dips of bedding planes in boulders between 50 and 75° (Fig. 22) far exceed natural angles; and (6) some of the largest boulders are located on MIS 5e deposits at the crest of the island's ridge, proving that they are not karstic relicts of an ancient landscape (Mylroie, 2008).

The ability of storm waves to transport large boulders is demonstrated. Storms in the North Atlantic tossed boulders as large as 80 t to a height +11 m on the shore on Ireland's Aran Islands (Cox et al., 2012), this specific storm on 5 January 1991 being driven by a low-pressure system that recorded a minimum 946 mb, producing wind gusts to 80 kn and sustained winds of 40 kn for 5 h (Cox et al., 2012). Typhoon Haiyan (8 November 2013) in the Philippines produced longshore transport of a 180 t block and lifted boulders of up to ∼ 24 t to elevations as high as 10 m (May et al., 2015). May et al. (2015) conclude that these observed facts "demand a careful re-evaluation of storm-related transport where it, based on the boulder's sheer size, has previously been ascribed to tsunamis".

The situation of the North Eleuthera megaboulders is special in two ways. First, all the large boulders are located at the apex of a horseshoe-shaped bay that would funnel energy of storm waves coming from the northeast, the direction of prevailing winds. Second, the boulders are above a vertical cliff at right angles to the incoming waves, a situation that allows constructive interference of reflected and incoming waves (Cox et al., 2012). The ability of waves hitting that cliff to produce large near-vertical splash is shown by a photograph in the Supplement taken on 31 October 1991, when a storm in the North Atlantic produced large waves impacting Eleuthera.

It is generally accepted that the boulders were wave-transported in the late Eemian. The boulders were deposited near complex chevron ridges and widespread runup deposits, which must be considered in analyzing wave-generating mechanisms. Lower elevation areas such as tidal inlets would have been flooded and scoured by the same waves, forming chevron ridges, and such large waves would also wash up onto higher, older ridges.

Runup deposits

Across several hundred kilometers of the Bahama Islands, older built-up dune ridges are mantled with wave runup deposits that reach heights over +40 m (Fig. 23). They are generally 1–5 m thick, fenestrae-filled, and seaward-sloping tabular beds (Wanless and Dravis, 1989; Chen et al., 1991; Neumann and Hearty, 1996; Tormey and Donovan, 2015). These stratigraphically youngest Eemian deposits mantle older MIS 5e dune deposits on the shore-parallel ridges, and are the upland correlative to wave-generated boulders and chevron formations.

If these are deposits of powerful storms driven by an unusually warm tropical ocean and strong temperature gradients in the North Atlantic, as opposed to a tsunami, should there not be evidence of comparable end-Eemian storms in Bermuda? Indeed, along several kilometers of the north coast of Bermuda (Land et al., 1967; Vacher and Rowe, 1997; Hearty et al., 1998) there are seaward sloping planar beds rising to about +20 m. Although interpretations of these beds vary, they are filled with beach fenestrae and stratigraphically of latest MIS 5e carbonate sediments equivalent to runup in the Bahamas. These planar beds contrast with older MIS 5e sedimentary (dune) structures that underlie them (Hearty et al., 1998). Massive subtidal cross beds comprise the seaward facies of the elevated beach beds, pointing to an exceptional energy anomaly on the normally tranquil, shallow, broad and protected north shore platform of Bermuda.

Chevrons

In the Bahama Islands, extensive oolitic sand ridges with a distinctive landward-pointing V shape are common, standing $\sim$ 5–15 m high across several kilometers on broad, low-lying platforms or ramps throughout the Atlantic-facing, deep-water margins of the Bahamas (Hearty et al., 1998). Hearty et al. (1998) examined 35 areas with chevron ridges across the Bahamas, which all point generally in a southwest direction (S65° W) with no apparent relation to the variable aspect of the coastline, nor to a point source event as would be expected for a tsunami generated by flank margin collapse.

These chevron formations are the lowland correlative to the wave-generated rocky coast boulder deposits. The chevron ridges often occur in nested groups of several ridges (e.g., North Eleuthera and Great Exuma; Hearty et al., 1998) and show multiple complex sets and subsets of fenestrae-filled beds, indicating the passage of a sustained interval of time late in the interglacial. Their definitive and complex characteristics preclude formation during a single tsunami event.

The character of fenestral beds in both the Eemian chevron ridges and runup deposits change with increasing elevation and distance from shore, as do the abundance and geometry of fenestral pores (Tormey and Donovan, 2015): (1) at low elevations and in proximal locations, the chevron ridges are dominated by multiple truncated, thick, tabular, fenestrae-rich beds (Fig. 24a, b); (2) at moderate elevations and further inland, fenestrae are concentrated in discrete packages within eolianites, often associated with scour (Fig. 23) and rip-up clasts; and (3) in the highest and most distal eolian ridges, only rare, thin, discontinuous fenestrae beds can be found (Fig. 24c of Tormey and Donovan, 2015). This spatial transition is improbable if torrential rain was falling across the area during a storm as asserted by Bain and Kindler (1994); rather this is exactly the pattern expected as waves attenuate with greater distance and elevation inland.

Presence of a few eolian structures (Engel et al., 2015) does not imply that the chevron ridges are parabolic dunes; it suggests the deposits were sub-aerially exposed and wind blew during periods of relative quiescence (as commonly observed on today's beaches after a storm). Unlike parabolic dunes, the chevron ridges are dominated by thick, low-angle ($< 10°$) seaward-dipping, aggradational oolitic bedding (Hearty et al., 1998; Tormey, 1999; Fig. 24a–c). Foreset beds, diagnostic of migrating parabolic dunes, are rare or absent from many chevron ridges, supporting formation primarily by waves (Hearty et al., 2002). Furthering the distinction, fenestral porosity in low-angle bedding is prevalent throughout chevron ridges, occurring in repeated cycles of centimeter-thick beds that onlap the underlying strata, and often comprise meter-thick fenestrae-rich packages that can be followed in outcrop for tens of meters (Fig. 24a, b).

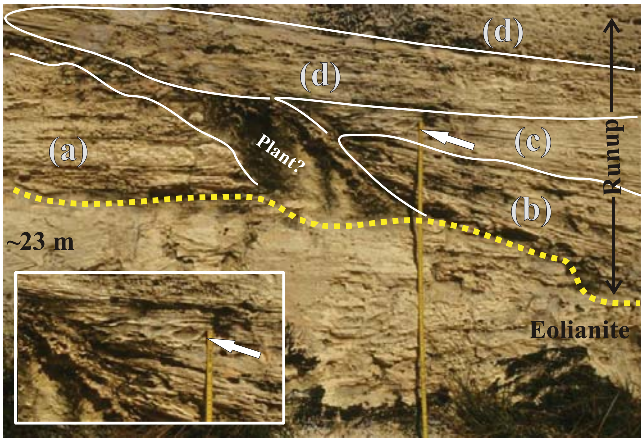


Figure 23. Photograph of runup deposits in a road cutting above +23 m (1 m scale in photo) on Old Land Road, Great Exuma Island, situated deep in Exuma Sound $\sim$ 200 km south of North Eleuthera. The older built-up eolianite forms the lower half of the image; the upper half has multiple "packages" of planar, fenestrae-filled beach sets. The upper progression of sedimentary packages (labeled **a**–**e**) clearly shows an onlapping, rising sequence of beds, indicating increasing wave energy and degree of runup. Further, the individual laminae of scour structures (arrows and inset image) display the same onlapping, upward-climbing succession. It would be impossible to achieve such bedding if rain-saturated sediments were sloughing downhill on low-angle slopes under the influence of gravity, especially near the crest of a ridge.

Summary of evidence

Alternative interpretations of the geologic data have been made (Bain and Kindler, 1994; Kindler and Strasser, 2000, 2002; Engel et al., 2015); specifically, (1) the boulders were thrown by a tsunami caused by flank margin collapse in North Eleuthera, (2) beach fenestrae in runup and chevron beds were caused by heavy rainfall, and (3) the chevron beach ridges are parabolic dunes. These views are challenged by Hearty et al. (2002) and again here for the following reasons. (1) extensive research in the Bahamas has revealed no geologic evidence of a point-source tsunami radiating from North Eleuthera. A slow speed margin failure is possible, without a tsunami, and indeed such a flank margin collapse could have been initiated by massive storm waves impacting an over-steepened margin. (2) If heavy rainfall was a significant process in the formation of fenestrae in dunes, they should commonly occur in all dunes of all ages, which is not

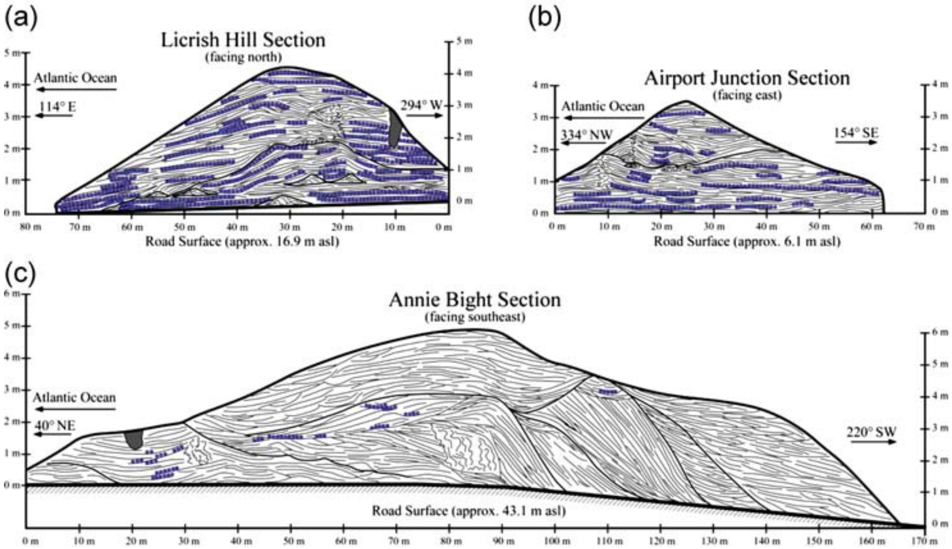


Figure 24. Cross-section diagrams (Tormey, 1999) of Eemian chevron and dune deposits in North Eleuthera (**a, b** ∼ 10 km west of megaboulders) showing geometry of bedding, fenestral porosity (lines of blue dots), and fossil roots (vertical wavy lines). **(a)** Chevron ridge exposure at Licrish Hill characterized by rising sequences of thick, tabular fenestral beds. **(b)** Chevron ridge exposure at Airport Junction characterized by rising sequences of thick, tabular fenestral beds. **(c)** Eolian ridge exposure at a higher elevation road cutting at Annie Bight (6 km south of megaboulders) characterized by dominantly backset and topset bedding with scattered, thin, wispy fenestrae beds.

the case. (3) Carbonate dunes, particularly oolitic ones, generally do not migrate unless exposed to extremely arid climates, which contradicts point 2, and chevrons lack the most diagnostic feature of migration – foreset bedding.

It is too random and chronologically coincidental to argue that the trilogy of evidence – boulders, runup deposits, and chevron ridges – was caused by unconnected processes. If large, long-period waves lifted 1000 t boulders onto and over the coastal ridge, as is generally agreed, the same waves must have also impacted large areas of the eastern Bahamas, for which there is abundant documentation. A radiating pattern of landforms outward from a North Eleuthera point source, as from a tsunami generated from a local bank margin collapse, is not observed in the area or broader region. Absence of evidence for tsunamis on the United States East Coast refutes the possibility of a large remote tsunami source.

Our interpretation of these features is the most parsimonious, and we have argued that it is most consistent with the data. A common, synchronous, and non-random set of super-storm-related processes best explains boulder transport by waves, emplacement of runup deposits on older built-up ridges, and the formation of complex chevron deposits over time across lower areas of the Bahamas. Indeed, given the geologic evidence of high seas and storminess from Bermuda and the Bahamas, Hearty and Neumann (2001) suggested "steeper pressure, temperature, and moisture gradients adjacent to warm tropical waters could presumably spawn larger and more frequent cyclonic storms in the North Atlantic than those seen today".

We now seek evidence about end-Eemian climate change to help clarify how North Atlantic storms could have dispersed such strong long-period, well-organized waves to the southwest.

4.1.3 End-Eemian cold event: evidence from North Atlantic sediment cores

We present here evidence for rapid end-Eemian cooling in the North Atlantic at a time with the tropics warmer than today. The cooling marked initial descent from interglacial conditions toward global ice age conditions, occurring at ∼ 118 ky b2k in ocean cores with uncertainty ∼ 2 ky. It is identified by Chapman and Shackleton (1999) as cold event C26 in Greenland ice cores.

This section discusses ocean core data, but we first note the relation with ice core data and dating uncertainties. Ice cores have become of great value for climate studies, partly because the relative timing of events in ice cores at different locations can be determined very accurately via marker events such as volcanic eruptions and CH_4 fluctuations, even though the absolute dating error in ice cores is comparable to the dating uncertainty in ocean cores.

C26 is the cold phase of Dansgaard–Oeschger (D-O) climate oscillation D-O 26 in the NGRIP (North Greenland Ice Core Project) ice core (NGRIP, 2004). C26 begins with a sharp cooling at 119.14 ky b2k on the GICC05modelext timescale (Rasmussen et al., 2014). The GICC05 timescale is based on annual layer counting in Greenland ice cores for the last 60 ky and an ice-flow-model extension for ear-

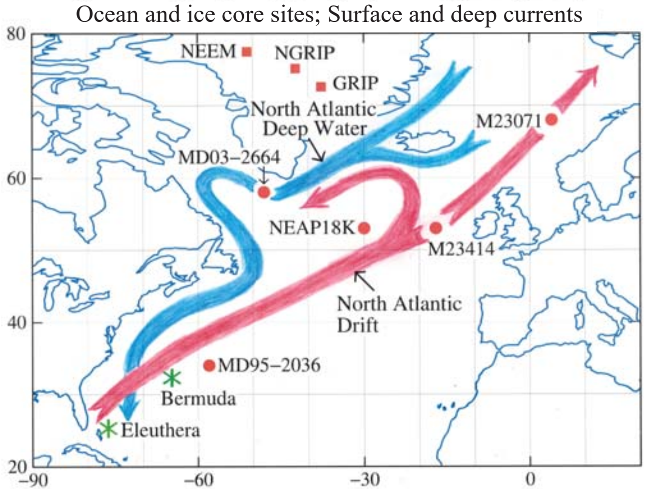


Figure 25. Ocean and ice core sites and simplified sketch of upper ocean North Atlantic Current and North Atlantic Deep Water return flow. In interglacial periods the North Atlantic Current extends further north, allowing the Greenland-Iceland-Norwegian Sea to become an important source of deepwater formation.

lier times. An alternative timescale is provided by Antarctic ice core chronology AICC2012 (Bazin et al., 2013; Veres et al., 2013), on which Greenland ice core records are synchronized via global markers, mainly oscillations of atmospheric CH_4 amount, which is globally well mixed. C26 on Greenland is at 116.72 ky b2k on the AICC2012 timescale. Figure S19 shows the difference between GICC05 and AICC2012 timescales versus time.

This age uncertainty for C26 is consistent with the ice core 2σ error estimate of 3.2 ky at Eemian time (Bazin et al., 2013). Despite this absolute age uncertainty, we can use Greenland data synchronized to the AICC2012 timescale to determine the relative timing of Greenland and Antarctic climate changes (Sect. 4.2.1) to an accuracy of a few decades (Bazin et al., 2013).

Sediment cores from multiple locations provide information not only on ocean temperature and circulation (Fig. 25) but also on ice sheet via information inferred from ice-rafted debris. Comparison of data from different sites is affected by inaccuracy in absolute dating and use of different age models. Dating of sediments is usually based on tuning to the timescale of Earth orbital variations (Martinson et al., 1987) or "wiggle matching" to another record (Sirocko et al., 2005), which limits accuracy to several thousand years. Temporal resolution is limited by bioturbation of sediments; thus resolution varies with core location and climate (Keigwin and Jones, 1994). For example, high deposition rates during ice ages at the Bermuda Rise yield a resolution of a few decades, but low sedimentation rates during the Eemian yield a resolution of a few centuries (Lehman et al., 2002). Lateral transport of sedimentary material prior to deposition complicates data interpretation and can introduce uncertainty, as argued specifically regarding data from the Bermuda Rise (Ohkouchi et al., 2002; Engelbrecht and Sachs, 2005).

Adkins et al. (1997) analyzed a sediment core (MD95-2036; 34° N, 58° W) from the Bermuda Rise using an age model based on Martinson et al. (1987) orbital tuning with the MIS stage 5–6 transition set at 131 ky b2k and the stage 5d–5e transition at 114 ky b2k. They found that oxygen isotope δ^{18}O of planktonic (near-surface dwelling) foraminifera and benthic (deep-ocean) foraminifera both attain full interglacial values at ∼ 128 ky b2k and remain nearly constant for ∼ 10 ky (their Fig. 2). Adkins et al. (1997) infer that "late within isotope stage 5e (∼ 118 ky b2k), there is a rapid shift in oceanic conditions in the western North Atlantic. . . ". They find in the sediments at that point an abrupt increase in clays indicative of enhanced land-based glacier melt and an increase in high nutrient "southern source waters". The latter change implies a shutdown or diminution of NADW formation that allows Antarctic Bottom Water (AABW) to push into the deep North Atlantic Ocean (Duplessy et al., 1988; Govin et al., 2009). Adkins et al. (1997) continue: "The rapid deep and surface hydrographic changes found in this core mark the end of the peak interglacial and the beginning of climate deterioration towards the semi-glacial stage 5d. Before and immediately after this event, signaling the impeding end of stage 5e, deep-water chemistry is similar to modern NADW." This last sentence refers to a temporary rebound to near-interglacial conditions. In Sect. 4.2.4 we use accurately synchronized Greenland and Antarctic ice cores, which also reveal this temporary end-Eemian climate rebound, to interpret the glacial inception and its relation to ice melt and late-Eemian sea level rise.

Ice-rafted debris (IRD) found in ocean cores provides a useful climate diagnostic tool (Heinrich, 1988; Hemming, 2004). Massive ice rafting ("Heinrich") events are often associated with decreased NADW production and shutdown or slowdown of the Atlantic meridional overturning circulation (AMOC) (Broecker, 2002; Barreiro et al., 2008; Srokosz et al., 2012). However, ice rafting occurs on a continuum of scales, and significant IRD is found in the cold phase of all the 24 D-O climate oscillations first identified in Greenland ice cores (Dansgaard et al., 1993). D-O events exhibit rapid warming on Greenland of at least several degrees within a few decades or less, followed by cooling over a longer period. Chapman and Shackleton (1999) found IRD events in the NEAP18K core for all D-O events (C19–C24) within the core interval that they studied, and they also labeled two additional events (C25 and C26). C26 did not produce identifiable IRD at the NEAP18K site, but it was added to the series because of its strong surface cooling.

Lehman et al. (2002) quantify the C26 cooling event using the same Bermuda Rise core (MD95-2036) and age model as Adkins et al. (1997). Based on the alkenone paleotemperature technique (Sachs and Lehman, 1999), Lehman et al. (2002) find a sharp SST decrease of ∼ 3 °C (their Fig. 1) at ∼ 118 ky BP, coinciding with the end-Eemian shoulder of the benthic δ^{18}O plateau that defines stage 5e in the deep ocean. The SST partially recovered after several centuries, but C26 marked the start of a long slide into the depths of stage 5d cold, as ice sheets grew and sea level fell ∼ 50 m in 10 ky (Lambeck and Chappell, 2001; Rohling et al., 2009). Lehman et al. (2002) wiggle-match the MD95-2036 and NEAP18K cores, finding a simple adjustment to the age model of Chapman and Shackleton (1999) that maximizes correlation of the benthic δ^{18}O records with the Adkins et al. (1997) δ^{18}O record. Specifically, they adjust the NEAP timescale by +4 ky before the MIS 5b δ^{18}O minimum and by +2 ky after it, which places C26 cooling at 118 ky b2k in both records. They give preference to the Adkins et al. (1997) age scale because it employs a ^{230}Th-based timescale between 100 and 130 ky b2k.

We do not assert that the end-Eemian C-26 cooling was necessarily at 118 ky b2k, but we suggest that the strong rapid cooling observed in several sediment cores in this region of the subtropical and midlatitude North Atlantic Drift at about this time were all probably the same event. Such a large cooling lasting for centuries would not likely be confined to a small region. The dating models in several other studies place the date of the end-Eemian shoulder of the deep-ocean δ^{18}O and an accompanying surface cooling event in the range 116–118 ky b2k.

Kandiano et al. (2004) and Bauch and Kandiano (2007) analyze core M23414 (53° N, 17° W), west of Ireland, finding a major SST end-Eemian cooling that they identify as C26 and place at 117 ky b2k. The 1 ky change in the timing of this event compared with Lehman et al. (2002) is due to a minor change in the age model; specifically, Bauch and Kandiano say that "the original age model of MD95-2036 (Lehman et al., 2002) has been adjusted to our core M23414 by alignment of the 4 per mil level in the benthic δ^{18}O records (at 130 ka in M23414) and the prominent C24 event in both cores". Bauch and Erlenkeuser (2008) and H. Bauch et al. (2012) examine ocean cores along the North Atlantic Current including its continuation into the Nordic Seas. They find that, in the Greenland–Iceland–Norwegian (GIN) seas, unlike middle latitudes, the Eemian was warmest near the end of the interglacial period. The age model employed by Bauch and Erlenkeuser (2008) has the Eemian about 2 ky younger than the Adkins et al. (1997) age model, Bauch and Erlenkeuser (2008) having the benthic δ^{18}O plateau at ∼ 116–124 ky BP (their Fig. 6). Rapid cooling they illustrate there at ∼ 116.6 ky BP for core M23071 on the Vøring Plateau (67° N, 3° E) likely corresponds to the C26 end-Eemian cooling event.

Identification of end-Eemian cooling in ocean cores is hampered by the fact that Eemian North Atlantic climate was more variable than in the Holocene (Fronval and Jansen, 1996). There were at least three cooling events within the Eemian, each with minor increases in IRD, which are labeled C27, C27a and C27b by Oppo et al. (2006); see their Fig. 2 for core site ODP-980 in the eastern North Atlantic (55° N, 15° W) near Ireland. High- (sub-centennial) resolution cores in the Eirik drift region (MD03-2664, 57° N, 49° W) near the southern tip of Greenland reveal an event with rapid cooling accompanied by reduction in NADW production (Irvali et al., 2012; Galaasen et al., 2014), which they place at ∼ 117 ky b2k. However, their age scale has the benthic δ^{18}O shoulder at ∼ 115 ky b2k (Fig. S1 of Galaasen et al., 2014), so that event may have been C27b, with C26 being stronger cooling that occurred thereafter.

4.1.4 Eemian timing consistency with insolation anomalies

Glacial–interglacial climate cycles are related to insolation change, as shown persuasively by Hays et al. (1976). Each "termination" (Broecker, 1984) of glacial conditions in the past several hundred thousand years coincided with a large positive warm-season insolation anomaly at the latitude of North American and Eurasian ice sheets (Raymo, 1997; Paillard, 2001). The explanation is that positive summer insolation anomalies (negative in winter) favor increased summer melting and reduced winter snowfall, thus shrinking ice sheets.

Termination timing is predicted better by high Northern Hemisphere late spring (April–May–June) insolation than by summer anomalies. For example, Raymo (1997) places midpoints of Termination I and II (preceding the Holocene and Eemian) at 13.5 and 128–131 ky b2k. Late spring insolation maxima are at 13.2 and 129.5 ky b2k (Fig. 26a). The AICC2012 ice core chronology (Bazin et al., 2013) places Termination II at 128.5 ky b2k, with 2σ uncertainty of 3.2 ky. Late spring irradiance maximizes warm-season ice melt by producing the earliest feasible warm-season ice sheet darkening via snow melt and snow recrystallization (Hansen et al., 2007b).

Summer insolation anomalies are also shown in Fig. 26, because interglacial periods can be expected to continue as long as summer insolation is large enough to prevent ice sheet genesis. Summer insolation anomalies at 60° N became negative at ∼ 118 ky b2k (Fig. 26a). Dating of insolation anomalies has high absolute accuracy, unlike ocean and ice core dating, as orbital anomalies are based on well-known planetary orbital mechanics (Berger, 1978).

Late Eemian sea level rise might appear to be a paradox, because glacial–interglacial sea level change is mainly a result of the growth and decay of Northern Hemisphere ice sheets. Northern warm-season insolation anomalies were declining rapidly in the latter part of the Eemian (Fig. 26a), so Northern Hemisphere ice should have been just beginning to grow. We suggest that the explanation for a late-Eemian sea level maximum is a late-Eemian collapse of Antarctic ice facilitated by the positive warm-season insolation anomaly on Antarctica and the Southern Ocean during the late Eemian (Fig. 26b) and possibly aided by an AMOC shutdown, which would increase warming of the Southern Ocean.

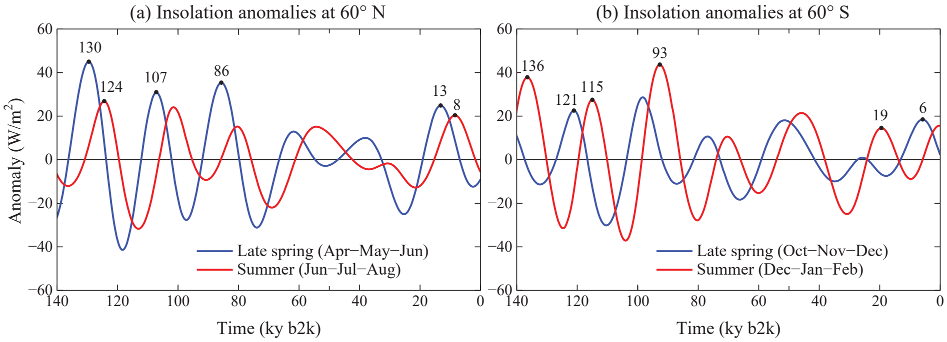


Figure 26. Summer (June–July–August) and late spring (April–May–June) insolation anomalies (W m^{-2}) at 60° N and summer (December–January–February) and late spring (October–November–December) anomalies at 60° S.

Persuasive evidence for this interpretation is provided by detailed paleoclimate data discussed in the next section, and is supported by modeling of relevant climate mechanisms. We will show that these mechanisms in turn help to explain ongoing climate change today, with implications for continuing climate change this century.

4.2 Millennial climate oscillations

Paleoclimate data are essential for understanding the major climate feedbacks. Processes of special importance are (1) the role of the Southern Ocean in ventilating the deep ocean, affecting CO_2 control of global temperature, and (2) the role of subsurface ocean warming in ice shelf melt, affecting ice sheet disintegration and sea level rise. An understanding of timescales imparted by the ocean and the carbon cycle onto climate change is important, so that slow paleo-ice-sheet changes are not ascribed to ice physics, when the timescale is actually set elsewhere.

Major glacial–interglacial climate oscillations are spurred by periodic variation of seasonal and geographical insolation (Hays et al., 1976). Insolation anomalies are due to slow changes of the eccentricity of Earth's orbit, the tilt of Earth's spin axis, and the precession of the equinoxes, and thus the day of year at which Earth is closest to the Sun, with dominant periodicities near 100 000, 40 000 and 20 000 years (Berger, 1978). These periods emerge in long climate records, yet a large fraction of climate variability at any site is stochastic (Wunsch, 2004; Lisiecki and Raymo, 2005). Such behavior is expected for a weakly-forced system characterized by amplifying feedbacks, complex dynamics, and multiple sources of inertia with a range of timescales.

Large glacial–interglacial climate change and stochastic variability are a result of two strong amplifying feedbacks, surface albedo and atmospheric CO_2. Orbit-induced insolation anomalies, per se, cause a direct climate forcing, i.e., an imposed Earth energy imbalance, only of the order of 0.1 W m^{-2}, but the persistent regional insolation anomalies spur changes of ice sheet size and GHGs. The albedo and GHG changes arise as slow climate feedbacks, but they are the forcings that maintain a quasi-equilibrium climate state nearly in global radiative balance.

Glacial–interglacial albedo and greenhouse forcings are each ∼ 3 W m^{-2} (Fig. 27e, f)[2]. These forcings fully account for glacial–interglacial global temperature change with a climate sensitivity of 0.5–1 °C per W m^{-2} (Hansen et al., 2008; Masson-Delmotte et al., 2010; Palaeosens, 2012).

The insolation anomaly peaking at 129.5 ky b2k (Fig. 27a) succeeded in removing ice sheets from North America and Eurasia and in driving atmospheric CO_2 up to ∼ 285 ppm, as discussed below. However, smaller climate oscillations within the last glacial cycle are also instructive about ice feedbacks. Some of these oscillations are related to weak insolation anomalies, and all are affected by predominately amplifying climate feedbacks.

Insolation anomalies peaking at 107 and 86 ky b2k (Fig. 27a) led to ∼ 40 m sea level rises at rates exceeding 1 m century^{-1} (Stirling et al., 1998; Cutler et al., 2003) in early MIS 5c and 5a (Fig. 27f), but CO_2 did not rise above 250 ppm and interglacial status (with large ice sheets only on Greenland and Antarctica) was not achieved. CO_2 then continued on a 100 ky decline until ∼ 18 ky b2k. Sea level continued its long decline, in concert with CO_2, reaching a minimum at least 120 m below today's sea level (Peltier and Fairbanks, 2006; Lambeck et al., 2014).

Progress achieved by the paleoclimate and oceanographic research communities allows interpretation of the role of the Southern Ocean in the tight relationship between CO_2 and

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[2] Other parts of Fig. 27 are discussed later, but they are most informative if aligned together. In interpreting Fig. 27, note that long-lived greenhouse gas amounts in ice cores have global relevance, but ice core temperatures are local to Greenland and Antarctica. Also, because our analysis does not depend on absolute temperature, we do not need to convert the temperature proxy, $\delta^{18}O$, into an estimated absolute temperature. We include CH_4 and N_2O in the total GHG climate forcing, but we do not discuss the reasons for CH_4 and N_2O variability (see Schilt et al., 2010), because CO_2 provides ∼ 80 % of the GHG forcing.

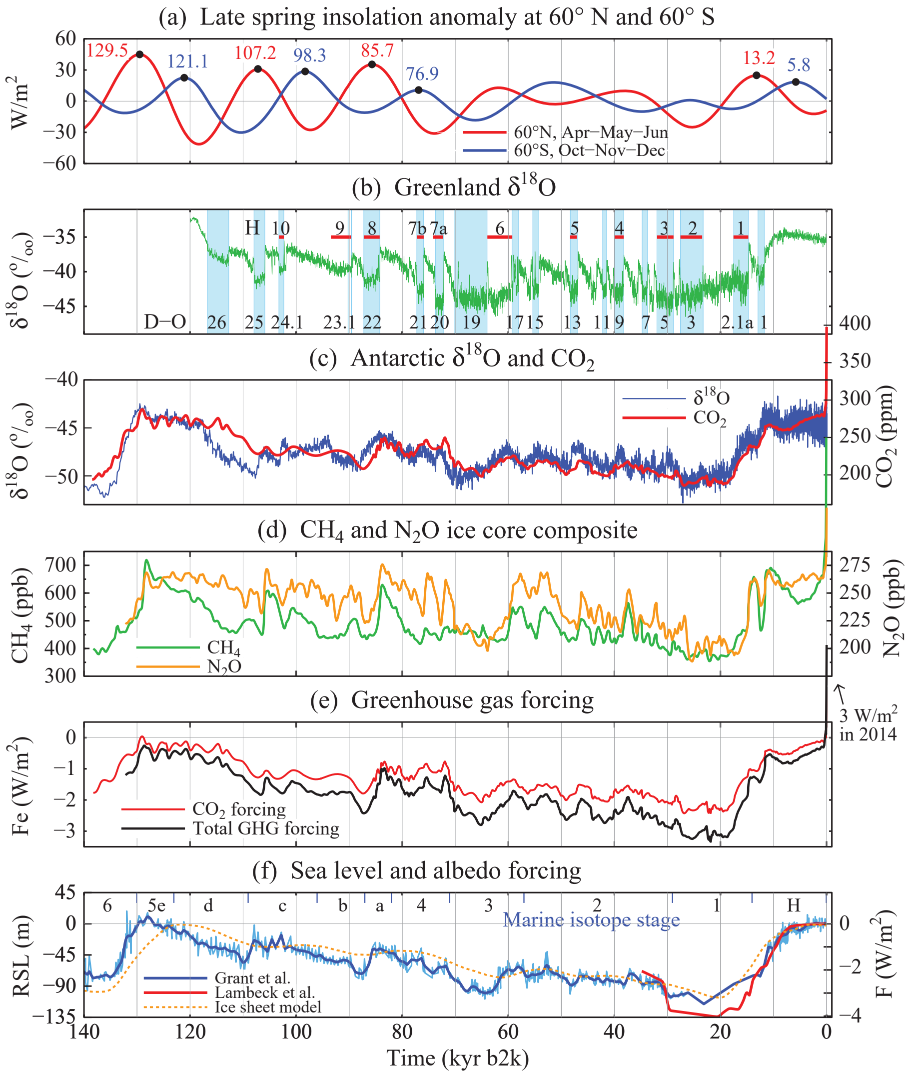

Figure 27. (a) Late spring insolation anomalies relative to the mean for the past million years. **(b)** $\delta^{18}O_{ice}$ of composite Greenland ice cores (Rasmussen et al., 2014) with Heinrich events of Guillevic et al. (2014). **(c, d)** $\delta^{18}O_{ice}$ of EDML Antarctic ice core (Ruth et al., 2007), multi-ice-core CO_2, CH_4, and N_2O based on a spline fit with a 1000-year cut-off (Schilt et al., 2010); scales are such that CO_2 and $\delta^{18}O$ means coincide and standard deviations have the same magnitude. **(e)** GHG forcings from equations in Table 1 of Hansen et al. (2000), but with the CO_2, CH_4, and N_2O forcings multiplied by factors 1.024, 1.60, and 1.074, respectively, to account for each forcing's "efficacy" (Hansen et al., 2005a), with CH_4 including a factor of 1.4 to account for indirect effect on ozone and stratospheric water vapor. **(f)** Sea level data from Grant et al. (2012) and Lambeck et al. (2014) and ice sheet model results from de Boer et al. (2010). Marine isotope stage boundaries from Lisiecki and Raymo (2005). Panels **(b–e)** are on AICC2012 timescale (Bazin et al., 2013),

temperature, as well as discussion of the role of subsurface ocean warming in sea level rise. Both topics are needed to interpret end-Eemian climate change and ongoing climate change.

4.2.1 Southern Ocean and atmospheric CO_2

There is ample evidence that reduced atmospheric CO_2 in glacial times, at least in substantial part, results from increased stratification of the Southern Ocean that reduces ventilation of the deep ocean (Toggweiler, 1999; Anderson et al., 2009; Skinner et al., 2010; Tschumi et al., 2011; Burke and Robinson, 2012; Schmitt et al., 2012; Marcott et al., 2014). Today the average "age" of deep water, i.e., the time since it left the ocean surface, is ∼ 1000 years (DeVries and Primeau, 2011), but it was more than twice that old during the Last Glacial Maximum (Skinner et al., 2010). The Southern Ocean dominates exchange between the deep ocean and atmosphere because ∼ 80 % of deep water resurfaces in the Southern Ocean (Lumpkin and Speer, 2007), as westerly circumpolar winds and surface flow draw up deep water (Talley, 2013).

Mechanisms causing more rapid deep-ocean ventilation during interglacials include warmer Antarctic climate that increases heat flux into the ocean and buoyancy mixing that supports upwelling (Watson and Garabato, 2006), poleward shift of the westerlies (Toggweiler et al., 2006), and reduced sea ice (Keeling and Stephens, 2001). Fischer et al. (2010) question whether the latitudinal shift of westerlies is an important contributor; however, the basic point is the empirical fact that a warmer interglacial Southern Ocean produces faster ventilation of the deep ocean via a combination of mechanisms.

Although a complete quantitative understanding is lacking for mechanisms to produce the large glacial–interglacial swings of atmospheric CO_2, we can safely assume that deep-ocean ventilation acts to oppose the sequestration of carbon in the ocean by the "pumps" that move carbon from the surface to ocean depths, and changes in the ventilation rate have a significant effect on atmospheric CO_2. Ridgwell and Arndt (2015) describe several conceptual pumps: (1) the organic carbon pump, in which the sinking material also controls nutrient cycling by the ocean; (2) the carbonate pump, with biological precipitation of mainly calcium carbonate, a fraction of which escapes dissolution to form a new geological carbon reservoir; (3) the simple solubility pump, as CO_2 is more soluble in the cold polar waters where deep water forms; and (4) a microbial carbon pump that seems capable of altering deep-ocean dissolved organic carbon.

No doubt the terrestrial biosphere also contributes to glacial–interglacial atmospheric CO_2 change (Archer et al., 2000; Sigman and Boyle, 2000; Kohler et al., 2005; Menviel et al., 2012; Fischer et al., 2015). Also, the efficacy of the ocean pumps depends on terrestrial conditions, e.g., dust-borne iron fertilization of the biological pump (Martin and Fitzwater, 1988) contributes to millennial and full glacial CO_2 drawdown (Martinez-Garcia et al., 2014). Moreover, the Southern Ocean is not the only conduit to the deep ocean; for example, AMOC changes are associated with at least two rapid CO_2 increases of about 10 ppm, as revealed by a high-resolution West Antarctic ice core (Marcott et al., 2014). Nevertheless, it is reasonable to hypothesize that sequestration of CO_2 in the glacial ocean is the largest cause of glacial–interglacial CO_2 change, and it is known that ocean ventilation occurs mainly via the Southern Ocean.

Southern Ocean ventilation, as the dominant cause of atmospheric CO_2 change, helps explain temperature-CO_2 leads and lags. Temperature and CO_2 rises are almost congruent at ice age terminations (Masson-Delmotte et al., 2010; Pedro et al., 2012; Parrenin et al., 2013). Southern Ocean temperature is expected to lead, spurring deep-ocean ventilation and atmospheric CO_2 increase, with global temperature following. Termination I is dated best and Shakun et al. (2012) have reconstructed global temperature for that period, finding evidence for this expected order of events.

Correlation of $\delta^{18}O$ and CO_2 over the past 140 ky (Fig. 27c) is 84.4 %, with CO_2 lagging by 760 years. For the period 100–20 ky b2k, which excludes the two terminations, the correlation is 77.5 %, with CO_2 lagging by 1040 years. Briefer lag for the longer period and longer lag during glacial inception are consistent with the rapid deep-ocean ventilation that occurs at terminations.

4.2.2 CO_2 as a climate control knob

CO_2 is the principal determinant of Earth's climate state, the radiative "control knob" that sets global mean temperature (Lacis et al., 2010, 2013). Degree of control is shown by comparison of CO_2 amount with Antarctic temperature for the past 800 000 years (Fig. 28a). Control should be even tighter for global temperature than for Antarctic temperature, because of regional anomalies such as Antarctic temperature overshoot at terminations (Masson-Delmotte et al., 2006, 2010), but global data are not available.[3]

The CO_2 dial must be turned to ~ 260 ppm to achieve a Holocene-level interglacial. CO_2 ~ 250 ppm was sufficient for quasi-interglacials in the period 800–450 ky b2k, with sea level 10–25 m lower than in the Holocene (Fig. S18 of Hansen et al., 2008). Interglacials with $CO_2 \sim 280$ ppm, i.e., the Eemian and Holsteinian ($\sim$400 ky b2k), were warmer than the Holocene and had sea level at least several meters higher than today.

CO_2 and albedo change are closely congruent over the last 800 000 years (Fig. S18 of Hansen et al., 2008). GHG and albedo forcings, which are both amplifying feedbacks that boost each other, are each of amplitude $\sim 3\,\mathrm{W\,m^{-2}}$. So why do we say that CO_2 is the control knob?

First, CO_2, in addition to being a slow climate feedback, changes independently of climate. Natural CO_2 change includes an increase to $\sim$ 1000 ppm about 50 million years ago (Zachos et al., 2001) as a result of plate tectonics, specifically volcanic emissions associated with movement of the Indian plate across the Tethys Ocean and collision with Asia (Kent and Muttoni, 2008). Humankind, mainly by burning fossil fuels, also moves the CO_2 control knob.

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[3] The tight fit of CO_2 and Antarctic temperature (Fig. 28a) implies an equilibrium Antarctic sensitivity of 20 °C for $2 \times CO_2$ ($4\,\mathrm{W\,m^{-2}}$) forcing ($200 \rightarrow 300$ ppm forcing is $\sim 2.3\,\mathrm{W\,m^{-2}}$; Table 1 of Hansen et al., 2000) and thus 10 °C global climate sensitivity (Antarctic temperature change is around twice that of global change) with CO_2 taken as the ultimate control knob, i.e., if snow/ice area and other GHGs are taken to be slaves to CO_2-driven climate change. This implies a conventional climate sensitivity of 4 °C for $2 \times CO_2$, as GHG and albedo forcings are similar for glacial-to-interglacial climate change and non-CO_2 GHGs account for $\sim$ 20 % of the GHG forcing. The inferred sensitivity is reduced to 2.5–3 °C for $2 \times CO_2$ if, as some studies suggest, global mean glacial–interglacial temperature change is only about one-third of the Antarctic temperature change (Palaeosens, 2012; Hansen et al., 2013b).

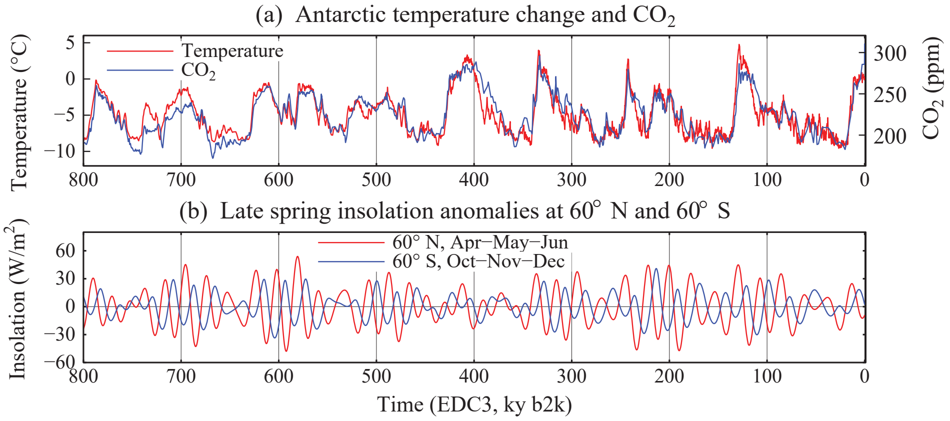

Figure 28. (a) Antarctic (Dome C) temperature relative to last 10 ky (Jouzel et al., 2007) on AICC2012 timescale and CO_2 amount (Luthi et al., 2008). Temperature scale is such that standard deviation of T and CO_2 are equal, yielding ΔT (°C) $= 0.114\ \Delta CO_2$ (ppm). **(b)** Late spring insolation anomalies at 60° N and 60° S.

Second, CO_2 is more recalcitrant than snow and ice, i.e., its response time is longer. CO_2 inserted into the climate system, by humans or plate tectonics, remains in the climate system of the order of 100 000 years before full removal by weathering (Archer, 2005). Even CO_2 exchange between the atmosphere (where it affects climate) and ocean has a lag of the order of a millennium (Fig. 27). In contrast, correlations of paleo-temperatures and sea level show that lag of sea level change behind temperature is of the order of a century, not a millennium (Grant et al., 2012).

We suggest that limitations on the speed of ice volume (and thus sea level) changes in the paleo-record are more a consequence of the pace of orbital changes and CO_2 changes, as opposed to being a result of lethargic ice physics. "Fast" changes of CO_2 have been identified, e.g., an increase of ∼10 ppm in about a century at ∼39.6 ky b2k (Ahn et al., 2012) and three increases of 10–15 ppm each within 1–2 centuries during the deglaciation following the last ice age (Marcott et al., 2014), but the magnitude of these CO_2 increases is not sufficient to provide a good empirical test of ice sheet sensitivity to the CO_2 forcing.

Dominance of SMOC, the Southern Ocean meridional overturning circulation, in affecting the CO_2 control knob and thus glacial–interglacial change is contrary to the idea that the AMOC is a prime driver that flips global climate between quasi-stable glacial and interglacial states, yet AMOC retains a significant role. AMOC can affect CO_2 via the volume and residence time of NADW, but its largest effect is probably via its impact on the Southern Ocean. When AMOC is not shut down it cools the Southern Hemisphere, transferring heat from the Southern to the Northern Hemisphere at a rate of ∼1 PW, which is $\sim 4\,\mathrm{W\,m^{-2}}$ averaged over a hemisphere (Crowley, 1992). However, the Southern Ocean slowly warms when AMOC shuts (or slows) down; the response time is of the order of 1000 years because of the Southern Ocean's large thermal inertia (Stocker and Johnson, 2003). These mechanisms largely account for the nature of the "bipolar seesaw" (Broecker, 1998; Stocker, 1998; Stenni et al., 2011; Landais et al., 2015), including the lag between AMOC slowdown and Antarctic warming.

4.2.3 Dansgaard–Oeschger (D-O) events and subsurface ocean warming

The magnitude and rapidity of Greenland climate change during D-O events would deter prediction of human-made climate effects if D-O events remained a mystery. Instead, however, enough is now understood about D-O events that they provide insight related to the vulnerability of ice shelves and ice sheets, including the role of subsurface ocean warming.

Broecker (2000) inferred from the rapidity of D-O warmings that a reduction of sea ice cover was probably involved. Li et al. (2005, 2010) modeling showed that removal of Nordic Seas ice cover is needed to yield the magnitude of observed Greenland warming. The spatial gradient of D-O warming, with smaller warming in northwest Greenland, agrees with that picture (Guillevic et al., 2013; Buizert et al., 2014). Such sea ice change is consistent with changes in deuterium excess in Greenland ice cores at D-O transitions, which indicate shifts of Greenland moisture source regions (Masson-Delmotte et al., 2005; Jouzel et al., 2007).

Fluckiger et al. (2006), Álvarez-Solas et al. (2010, 2011, 2013) and Marcott et al. (2011) noted modern and paleo-data that point to ocean–ice shelf interaction as key to the ice discharge of accompanying Heinrich events, and they used a range of models to support this interpretation and overturn earlier suggestions of a central role for ice sheets via binge–purge oscillations (MacAyeal, 1993) or outburst flooding from subglacial reservoirs (Alley et al., 2006). Shaffer et al. (2004) and Petersen et al. (2013) conclude that subsurface ocean warming in the North Atlantic takes place during the stadial (cold) phase of all D-O events, and eventually this subsurface warming leads to ice shelf collapse or retreat, ice rafting, sea level rise, and sea ice changes. Rasmussen et al. (2003) examined ocean cores from the southeast Labrador Sea and found that for all 11 Heinrich events "the icy surface water was overlying a relatively warm, poorly ventilated and nutrient rich intermediate water mass to a water depth of at least 1251 m". Collapse of a Greenland ice shelf fronting the Jakoshavn ice stream during the Younger Dryas cold event has been documented (Rinterknecht et al., 2014), apparently due to subsurface warming beneath the ice shelf leading to rapid discharge of icebergs.

Some D-O details are uncertain, e.g., the relation between changing sea ice cover and changing location of deep water formation (Rahmstorf, 1994) and whether an ice shelf between Greenland and Iceland contributed to the sea ice variability (Petersen et al., 2013). However, ocean–ice interactions emerge as key mechanisms, spurred by subsurface ocean warming, as ocean stratification slows but does not stop northward heat transport by AMOC.

We consider a specific D-O event for the sake of discussing mechanisms. D-O 22 cold phase, labeled C22 in ocean cores and coinciding with Heinrich H8 (Fig. 27), occurred as Northern Hemisphere insolation was rising (Fig. 27a). The North Atlantic surface was cooled by rapid ice discharge; sea level rose more than 40 m, a rate exceeding 1.6 m per century (Cutler et al., 2003). Ice discharge kept the North Atlantic highly stratified, slowing AMOC. Antarctic warming from a slowed AMOC increases almost linearly with the length of the D-O cold phase (Fig. 3 of EPICA Community Members, 2006; Fig. 6 of Capron et al., 2010) because of the Southern Ocean's large heat capacity (Stocker and Johnson, 2003). Antarctic warming, aided by the 2500-year D-O 22 event, spurred SMOC enough to raise atmospheric CO_2 40 ppm (Fig. 27c).

As the Antarctic warmed, ocean heat transport to the North Atlantic would have increased, with most heat carried at depths below the surface layer. When the North Atlantic became warm enough at depth, stratification of cold fresh surface water eventually could not be maintained. The warming breakthrough may have included change in NADW formation location (Rahmstorf, 1994) or just large movement of the polar front. Surface warming east of Greenland removed most sea ice and Greenland warmed $\sim$ 10 °C (Capron et al., 2010). As the warm phase of D-O 21 began, AMOC was pumping heat from the Antarctic into the Nordic Seas and Earth must have been slightly out of energy balance, cooling to space, so both Antarctica and Greenland slowly cooled. Once the North Atlantic had cooled enough, sea ice formed east of Greenland again, ice sheets and ice shelves grew, sea level fell, and the polar front moved southward.

Sea level rise associated with D-O events covers a wide range. Sea level increases as large as $\sim$ 40 m were associated with large insolation forcings at 107 and 86 ky b2k (Fig. 27). However, rapid sea level change occurred even when forcing was weak. Roche et al. (2004) conclude from analyses of $\delta^{18}O$ that H4, at a time of little insolation forcing ($\sim$ 40 ky b2k, Fig. 27), produced 1.9 ± 1.1 m sea level rise over 250 $\pm$ 150 years. Sea level rise as great as 10–15 m occurred in conjunction with some other D-O events during 65–30 ky b2k (Lambeck and Chappell, 2001; Yokoyama et al., 2001; Chappell, 2002).

Questions about possible D-O periodicity and external forcing were raised by a seeming 1470-year periodicity (Schulz, 2002). However, improved dating indicates that such periodicity is an artifact of ice core chronologies and not statistically significant (Ditlevsen et al., 2007), and inspection of Fig. 27b reveals a broad range of timescales. Instead, the data imply a climate system that responds sensitively to even weak forcings and stochastic variability, both of which can spur amplifying feedbacks with a range of characteristic response times.

Two conclusions are especially germane. First, subsurface ocean warming is an effective mechanism for destabilizing ice shelves and thus the ice sheets buttressed by the ice shelves. Second, large rapid sea level rise can occur as a result of melting ice shelves.

However, ice shelves probably were more extensive during glacial times. So are today's ice sheets much more stable? The need to understand ice sheet vulnerability focuses attention on end-Eemian events, when ice sheets were comparable in size to today's ice sheets.

4.2.4 End-Eemian climate and sea level change

Termination II, ushering in the Eemian, was spurred by a late spring 60° N insolation anomaly peaking at $+45\,\mathrm{W\,m^{-2}}$ at 129.5 ky b2k (Fig. 27a), the largest anomaly in at least the past 425 ky (Fig. 3 of Hansen et al., 2007b). CO_2 and albedo forcings were mutually reinforcing. CO_2 began to rise before Antarctic $\delta^{18}O$, as deglaciation and warming began in the Northern Hemisphere. Most of the total CO_2 rise was presumably from deep-ocean ventilation in the Southern Ocean, aided by meltwater that slowed the AMOC and thus helped to warm the Southern Ocean.

The northern late spring insolation anomaly fell rapidly, becoming negative at 123.8 ky b2k (Fig. 27a), by which time summer insolation also began to fall (Fig. 26). Northern Hemisphere ice sheets must have increased intermittently while Southern Hemisphere ice was still declining, consistent with minor, growing ice rafting events C27, C27a, C27b and C26 and a sea level minimum during 125–121 ky b2k (Sect. 4.1.1). High Eemian climate variability in the Antarctic (Pol et al., 2014) was likely a result of the see-saw relation with North Atlantic events.

CO_2 (Fig. 27c) remained at ∼ 270 ppm for almost 15 ky as the positive insolation anomaly on the Southern Ocean (Fig. 27a) kept the deep ocean ventilated. Sea level in the Red Sea analysis (Grant et al., 2012) shown in Fig. 27f seems to be in decline through the Eemian, but that must be a combination of dating and sea level error, as numerous sea level analyses cited in Sect. 4.1.1, our Supplement, and others (e.g., Chen et al., 1991; Stirling et al., 1998; Cutler et al., 2003) indicate high sea level throughout the Eemian and allow a possible late-Eemian maximum. Chen et al. (1991), using a U-series dating with 2σ uncertainty ±1.5 ky, found that the Eemian sea level high stand began between 132 and 129 ky b2k, lasted for 12 ky, and was followed by rapid sea level fall.

We assume that C26, the sharp cooling at 116.72 ky b2k in the NGRIP ice on the AICC2012 timescale, marks the end of fully interglacial Eemian conditions, described as 5e sensu stricto by Bauch and Erlenkeuser (2008). $\delta^{18}O$ in Antarctica was approaching a relative minimum (−46.7 ‰ at EDML; see Fig. S20 for details) and CO_2 was slowly declining at 263 ppm. In the next 300 years $\delta^{18}O$ increased to −45.2 and CO_2 increased by 13 ppm with lag ∼ 1500 years, which we interpret as see-saw warming of the Southern Ocean in response to the C26-induced AMOC slowdown and resulting increased SMOC ventilation of CO_2.

Freshwater causing the C26 AMOC shutdown could not have been Greenland surface melt. Greenland was already 2000 years into a long cooling trend and the northern warm-season insolation anomaly was in the deepest minimum of the last 150 ky (Fig. 26a). Instead, C26 was one event in a series, preceded by C27b and followed by C25, each a result of subsurface North Atlantic warming that melted ice shelves, causing ice sheets to discharge ice. Chapman and Shackleton (1999) did not find IRD from C26 in the mid-Atlantic, but Carlson et al. (2008) found a sharp increase in sediments near the southern tip of Greenland that they identified with C26.

We suggest that the Southern Hemisphere was the source for brief late-Eemian sea level rise. The positive warm-season insolation anomaly on the Southern Ocean and AMOC slowdown due to C26 added to Southern Ocean heat, causing ice shelf melt, ice sheet discharge, and sea level rise. Rapid Antarctica ice loss would cool the Southern Ocean and increase sea ice cover, which may have left telltale evidence in ice cores. Indeed, Masson-Delmotte et al. (2011) suggest that abrupt changes of $\delta^{18}O$ in the EDML and TALDICE ice cores (those most proximal to the coast) indicate a change in moisture origin, likely due to increased sea ice. Further analysis of Antarctic data for the late Eemian might help pinpoint the melting and help assess vulnerability of Antarctic ice sheets to ocean warming, but this likely will require higher-resolution models with more realistic sea ice distribution and seasonal change than our present model produces.

Terrestrial records in Northern Europe reveal rapid end-Eemian cooling. Sirocko et al. (2005) find cooling of 3 °C in summer and 5–10 °C in winter in southern Germany, with annual layering in a dry Eifel maar lake revealing a 468-year period of aridity, dust storms, bushfires, and a decline of thermophilous trees. Similar cooling is found at other German sites and La Grande Pile in France (Kuhl and Litt, 2003). Authors in both cases interpret the changes as due to a southward shift of the polar front in the North Atlantic corresponding to C26. Cooling of this magnitude in northern Europe and increased aridity are found by Brayshaw et al. (2009) and Jackson et al. (2015) in simulations with high-resolution climate models forced by AMOC shutdown.

While reiterating dating uncertainties, we note that the cool period with reduced NADW formation identified in recent high-resolution ocean core studies for Eirik Drift site MD03-2664 (Fig. 25) near Greenland (Irvali et al., 2012; Galaasen et al., 2014) at ∼ 117 ky b2k has length similar to the 468-year cold stormy period found in a German lake core (Sirocko et al., 2005).

The Eirik core data show a brief return to near-Eemian conditions and then a slow decline, similar to the oscillation in the NGRIP ice core at 116.72 ky b2k on the AICC2012 timescale.

The principal site of NADW formation may have moved from the GIN seas to just south of Greenland at end of the Eemian. Southward shift of NADW formation and the polar front is consistent with the sudden, large end-Eemian cooling in the North Atlantic and northern Europe, while cooling in southern European was delayed by a few millennia (Brauer et al., 2007). Thus end-Eemian midlatitude climate was characterized by an increased meridional temperature gradient, an important ingredient for strengthening storms.

5 Modern data

Observations help check our underlying assumption of nonlinear meltwater growth and basic simulated climate effects. As these data are updated, and as more extensive observations of the ocean and ice processes are obtained, a clearer picture should emerge over the next several years.

5.1 Ice sheet mass loss and sea level rise

The fundamental question we raise is whether ice sheet melt in response to rapid global warming will be nonlinear and better characterized by a doubling time for its rate of change or whether more linear processes dominate. Hansen (2005, 2007) argued on heuristic grounds that ice sheet disintegration is likely to be nonlinear if climate forcings continue to grow, and that sea level rise of several meters is possible on a timescale of the order of a century. Given current ice sheet melt rates, a 20-year doubling rate produces multi-meter sea level rise in a century, while 10- and 40-year doubling times require about 50 and 200 years, respectively.

Church et al. (2013) increased estimates of sea level rise compared to prior IPCC reports, but scenarios they discuss are close to linear responses to the assumed rising climate forcing. The most extreme climate forcing (RCP8.5, 936 ppm CO_2 in 2100 and GHG forcing 8.5 W m^{-2}) is estimated to produce 0.74 m sea level rise in 2100 relative to the 1986–2005 mean sea level, with the "likely" range of uncertainty at 0.52–0.98 m. Church et al. (2013) also discuss semi-empirical estimates of sea level rise, which yield ∼ 0.7–1.5 m for the RCP8.5 scenario, but express low confidence in the latter, thus giving preference to the model-based estimate of 0.52–0.98 m. We note that Sect. 4.4.4.2 on ice sheet processes in the IPCC chapter on cryosphere observations (Vaughan et al., 2013) contains valuable discussion of nonlinear ice sheet processes that could accelerate ice sheet mass loss but which are not fully included in current ice sheet models.

Empirical analyses are needed if we doubt the realism of ice sheet models, but semi-empirical analyses lumping multiple processes together may yield a result that is too linear. Sea level rises as a warming ocean expands, as water storage on continents changes (e.g., in aquifers and behind dams), and as glaciers, small ice caps, and the Greenland and Antarctic ice sheets melt. We must isolate the ice sheet contribution, because only the ice sheets threaten multi-meter sea level rise.

Hay et al. (2015) reanalyzed tide-gauge data for 1901–1990 including isostatic adjustment at each station, finding global sea level rise to be 1.2 ± 0.2 mm year^{-1}. Prior tide-gauge analyses of 1.6–1.9 mm year^{-1} were inconsistent with estimates for each process, which did not add up to such a large value (Church et al., 2013). This estimate of 1.2 ± 0.2 mm year^{-1} for 1900–1990 compares with estimated sea level rise of ∼ 0.2 m in the prior two millennia or ∼ 0.1 mm year^{-1} (Kemp et al., 2011) and several estimates of ∼ 3 mm year^{-1} for the satellite era (1993–present). Nerem et al. (2010) find sea level increase of 3.3 mm year^{-1} in the satellite era, while Watson et al. (2015), based in part on calibration to tide-gauge data, suggest alternative rates of 2.9 or 2.6 mm year^{-1}.

Accepting the analyses of Hay et al. (2015) for 1901–1990 and estimates of 2.5–3.5 mm year^{-1} for the satellite era leads to a picture of a rising sea level rate (Fig. 29) that differs from the perception of near-linear sea level rise created by Fig. 13.3 in the IPCC report (Church et al., 2013). We do not argue for the details in Fig. 29 or suggest any change points for the rate of sea level rise, but the data do reveal a substantial increase in the rate of sea level rise.

The majority of sea level rise in the 20th century was from the several processes other than Greenland and Antarctica mass loss (Church et al., 2013), so the timescale for ice sheet mass loss may differ from the timescale for past sea level change. A direct measure of ice sheet mass loss is obtained from satellite gravity measurements by Velicogna et al. (2014), who find Greenland's mass loss in 2003–2013 of 280 ± 58 Gt year^{-1} [4] accelerating by 25.4 ± 1.2 Gt year^{-2}, and Antarctic mass loss of 67 ± 44 Gt year^{-1} accelerating by 11 ± 4 Gt year^{-2}. The Velicogna et al. (2014) data are updated in Fig. 30. The reduced mass loss rate of Greenland in 2013–2014 makes it difficult to infer an empirical growth rate for mass loss, as discussed below.

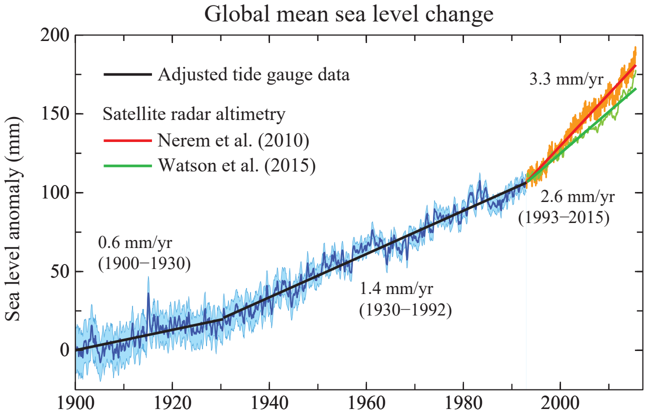

Figure 29. Estimated sea level change (mm) since 1900. Data through 1992 are the tide-gauge record of Church and White (2011) with the change rate multiplied by 0.78, so as to yield a mean 1901–1990 change rate of 1.2 mm year^{-1} (Hay et al., 2015). The two estimates for the satellite era (1993–2015) are from Nerem et al. (2010, updated at http://sealevel.colorado.edu) and Watson et al. (2015).

Reliability of mass loss inferred from gravity data is supported by comparison to surface mass balance studies (Fig. 30). Mass loss accelerations over 1992–2011 obtained via the mass budget method (Rignot et al., 2011) for Greenland (21.9 ± 1 Gt year^{-2}) and Antarctica (14.5 ± 2 Gt year^{-2}) are similar to or larger than results from gravity analysis. A third approach, based on satellite radar altimetry, is consistent with the other two for mass loss from Greenland and West Antarctica (Shepherd et al., 2012), including the Amundsen Sea sector, which is the dominant contributor to Antarctic ice mass loss (Sutterley et al., 2014). Differences among techniques exist in East Antarctica, but mass changes there are small (Shepherd et al., 2012).

Best-fit exponential doubling times for Greenland are 4.8 years (MBM 1992–2010 data), 18.9 years (GRACE 2003–2015 data) and 8.8 years (MBM + GRACE 1992–2015 data); in the latter case only GRACE data are used after 2002. The best fit to MBM + GRACE is shown in Fig. 30. The equivalent results for Antarctica are 5.3, 3.2 and

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[4] For comparison, our assumed freshwater injection of 360 Gt year^{-1} in 2011 with 10-year doubling yields an average mass loss of 292 Gt year^{-1} for 2003–2013. Further, Velicogna et al. (2014) find an ice mass loss of 74 ± 7 Gt year^{-1} from nearby Canadian glaciers and ice caps with acceleration of 10 ± 2 Gt year^{-2}, and there is an unknown freshwater input from melting ice shelves. Thus our assumed Northern Hemisphere meltwater was conservative.

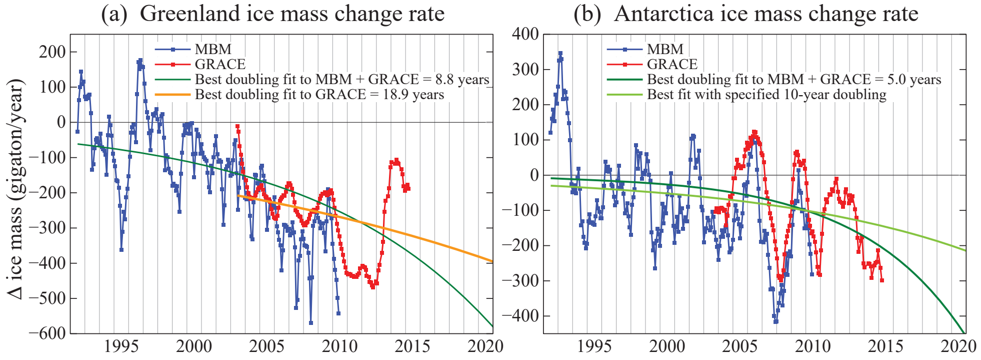

Figure 30. Greenland and Antarctic ice mass change. GRACE data are extension of Velicogna et al. (2014) gravity data. MBM (mass budget method) data are from Rignot et al. (2011). Red curves are gravity data for Greenland and Antarctica only; small Arctic ice caps and ice shelf melt add to freshwater input.

5.0 years. Clearly the data records are too short to infer a doubling rate, let alone confirm that mass loss is exponential. Thus we also show a 10-year doubling growth curve for Antarctic ice mass loss (Fig. 30b). The recent reduction of mass loss from Greenland illustrates how sensitive the empirical result is to record brevity, but the curves should become more informative over the next several years.

Additional insight is provided by the regional breakdown of the mass change data as achieved in the Velicogna et al. (2014) analysis. The regional data suggest that the Antarctic situation may be more threatening than indicated by the continental mass loss rate. This net mass loss combines mass loss via ice streams with regions of net snow accumulation. Queen Maud Land, for example, is gaining $63 \pm 6\,\mathrm{Gt\,year^{-1}}$, accelerating by $15 \pm 1\,\mathrm{Gt\,year^{-2}}$, but this mass gain may be temporary. Our simulations with increasing freshwater input indicate that circum-Antarctic cooling and sea ice increase eventually may limit precipitation reaching the continent, and recent SST and sea ice data have a tendency consistent with that expectation (Sect. 5.2).

Amundsen Sea glaciers are a gateway to West Antarctic ice, which has potential for several meters of sea level. Mass loss of the Amundsen Sea sector was $116 \pm 6\,\mathrm{Gt\,year^{-1}}$ in 2003–2013, growing $13 \pm 2\,\mathrm{Gt\,year^{-2}}$ (Velicogna et al., 2014; Rignot et al., 2014; Sutterley et al., 2014).

Totten Glacier in East Antarctica fronts the Aurora Subglacial Basin, which has the potential for ~ 6.7 m of sea level rise (Greenbaum et al., 2015). Williams et al. (2011) find that warm modified Circumpolar Deep Water is penetrating the continental shelf near Totten beneath colder surface layers. Details of how warmer water reaches the ice shelf are uncertain (Khazendar et al., 2013), but, as in West Antarctica, the inland-sloping trough connecting the ocean with the main ice shelf cavity (Greenbaum et al., 2015) makes Totten Glacier susceptible to unstable retreat (Goldberg et al., 2009). Cook Glacier, further east in East Antarctica, also rests on a submarine inland-sloping bed and fronts ice equivalent to 3–4 m of sea level. The Velicogna et al. (2014) analysis of gravity data for 2003–2013 finds the Totten sector of East Antarctica losing $17 \pm 4\,\mathrm{Gt\,year^{-1}}$, with the loss accelerating by $4 \pm 1\,\mathrm{Gt\,year^{-2}}$, and the Victoria/Wilkes sector including Cook Glacier losing $16 \pm 5\,\mathrm{Gt\,year^{-1}}$, with a small deceleration ($2 \pm 1\,\mathrm{Gt\,year^{-2}}$).

Greenland ice melt is subject to multiple feedbacks, some of which are largely absent on Antarctica, so it is not certain whether Greenland ice is less or more vulnerable than Antarctic ice. On the one hand, some differences make the Greenland ice sheet seem less vulnerable. Greenland does not have as much unstable ice volume sitting behind retrograde beds. Also, although surface cooling due to freshwater injection leads to subsurface ocean warming (Fig. 12), freshwater injection may also reduce poleward transport of heat by the Atlantic Ocean if the AMOC slows down, and North Atlantic cooling may affect summer surface melt on Greenland.

On the other hand, the Greenland ice sheet is subject to forcings and feedbacks that are less important on Antarctica. Greenland experiences extensive summer surface melt (Tedesco et al., 2011; Box et al., 2012), which makes surface albedo changes more important on Greenland. Greenland mass loss is thus more affected by snow darkening via dust, black carbon and biological substances including algae (Benning et al., 2014; Yasunari et al., 2015), which are in part an imposed climate forcing but in some cases also a substantial amplifying feedback. Soot from forest fires occurs naturally, but the magnitude of fire events is increasing (Flannigan et al., 2013; Jolly et al., 2015) and may have contributed to widespread Greenland melt events in recent years (Keegan et al., 2014). Pigmented algae can substantially reduce spring and summer ice albedo and may be an important feedback in a warming world (Benning et al., 2014). Other amplifying feedbacks for Greenland include the ice surface elevation feedback, cryo-hydrologic warming in which percolating water alters thermal regime and weakens the ice sheet on decadal timescales (Colgan et al., 2015) and ocean-mediated melting of ice shelves and glacier fronts (Rignot et al., 2010). Increasing ice sheet surface melt and increasing ice stream mass discharge are both contributing to the observed growing mass loss rate of the Greenland ice sheet, as discussed in our response AC7962 on the ACPD website. Such mutually reinforcing processes provide an expectation of nonlinear mass loss increase if the climate forcing continues to increase.

Interpretation of Greenland mass loss is made difficult by its high variability. Large 2010–2012 mass loss was related to unusual summer high pressure over Greenland (Fettweis et al., 2013; Bellflamme et al., 2015), which produced a persistent "atmospheric river" of warm air of continental origin (Neff et al., 2014). However, weather patterns were much less favorable for surface melt in 2013 and 2014, and Greenland mass loss was much reduced (Fig. 30a).

We conclude that empirical data are too brief to imply a characteristic time for ice sheet mass loss or to confirm our hypothesis that continued high fossil fuel emissions leading to $CO_2 \sim 600$–900 ppm will cause exponential ice mass loss up to several meters of sea level. The empirical data are consistent with a doubling time of the order of a decade, but they cannot exclude slower responses. Our expectation of nonlinear behavior is based in part on recognition of how multiple amplifying feedbacks feed upon each other (Hansen et al., 1984; Pollard et al., 2015) and thus can result in large rapid change.

5.2 Sea surface temperature and sea ice

The fundamental difference between climate forecasts of our model and CMIP simulations employed in IPCC assessments should appear in sea surface temperature (SST), which is well monitored. The Southern Ocean warms steadily in CMIP5 models (Fig. 12.11 of Collins et al., 2013) that have little or no freshwater injection. In contrast, ice melt causes Southern Ocean cooling in our model, especially in the Western Hemisphere (Fig. 16). The model's cooling is largest in the Western Hemisphere because the specified freshwater injection (Fig. 14), based on data of Rignot et al. (2013) and Depoorter et al. (2013), is largest there. The cooling pattern is very strong by 2055–2060 (Fig. 16), when freshwater injection reaches 3.8 Sv years on the North Atlantic and 7.6 Sv years on the Southern Ocean, amounts that yield 1 m global sea level rise with one-third from Northern Hemisphere ice. SST observations already show a cooling trend in the Southern Ocean off West Antarctica (Fig. 31) and are suggestive that the real world may be more sensitive than the model, but additional years of data are needed to confirm that.

Our model also differs from models in the predicted sense of Southern Hemisphere sea ice change. Freshwater effects dominate over direct effects of GHGs in our model, and thus sea ice cover grows. Thompson et al. (2011) suggest that O_3 depletion may account for observed Antarctic sea ice growth, but Sigmond and Fyfe (2014) found that all CMIP5 models yield decreasing sea ice in response to observed changes of O_3 and other GHGs. Ferreira et al. (2015) show that O_3 depletion yields a short timescale sea ice increase that is soon overtaken by warming and sea ice decrease with realistic GHG forcing. We suggest that these models are missing the dominant driver of change on the Southern Ocean: freshwater input.

Our modeled SMOC has begun to slow already (Fig. 32a), consistent with tracer observations in the Weddell Sea by Huhn et al. (2013), which reveal a 15–21 % reduction in the ventilation of Weddell Sea Bottom Water and Weddell Sea Deep Water in 1984–2008. Delayed growth of sea ice in the model (Fig. 32b) may be in part related to the model's muted vertical stratification, as we will discuss, and the model's general difficulty in producing Southern Hemisphere sea ice.

We infer that observed cooling in the western part of the Southern Ocean, growing Southern Ocean sea ice, and slowdown of at least the Weddell Sea component of SMOC are early responses to increasing freshwater injection. Although observed sea ice increase is smaller in 2015 than in the previous few years (data are updated daily at http://nsidc.org/data/seaice_index), but Hansen and Sato (2016) note a negative correlation between sea ice area and El Niños, so we expect that sea ice growth may resume after the present strong El Niño fades.

Let us compare North Atlantic and Southern Ocean responses to freshwater forcing. The modeled AMOC response does not become significant until ∼ 2040 (Fig. 33). Even discounting the decade lead in Southern Hemisphere forcing (720 Gt year^{-1} in 2011, double that in the North Atlantic), SMOC still responds quicker, albeit gradually, to freshwater forcing (Fig. 32).

Observations suggest that the real world may be responding more quickly than the model to freshwater forcing in the North Atlantic. Rahmstorf et al. (2015) develop an AMOC index based on SST in the "global warming hole" southeast of Greenland (Drijfhout et al., 2012), and they use the AMOC index to conclude that an AMOC slowdown unprecedented in the prior 1000 years occurred in the late 20th century. That slowdown seems to have been a response to the "Great Salinity Anomaly", which is thought to have resulted from an estimated ∼ 2000 km^3 anomalous sea ice export from the Arctic (Dickson et al., 1988). Although the AMOC partially recovered in the early 21st century, further slowdown has returned in the past several years, judging from a measurement array (Robson et al., 2014) as well as from the AMOC index (Rahmstorf et al., 2015). The recent AMOC slowdown could be related to ice melt, as Greenland (Fig. 30) and neighboring ice caps contributed more than 1000 km^3 meltwater in 2011–2012. The model (Fig. 33), in contrast, does not reach substantial AMOC reduction until ∼ 2040, when the annual freshwater injection into the North Atlantic is ∼ 7500 $\text{km}^3\ \text{year}^{-1}$ and the cumulative injection is ∼ 1.2 Sv years.

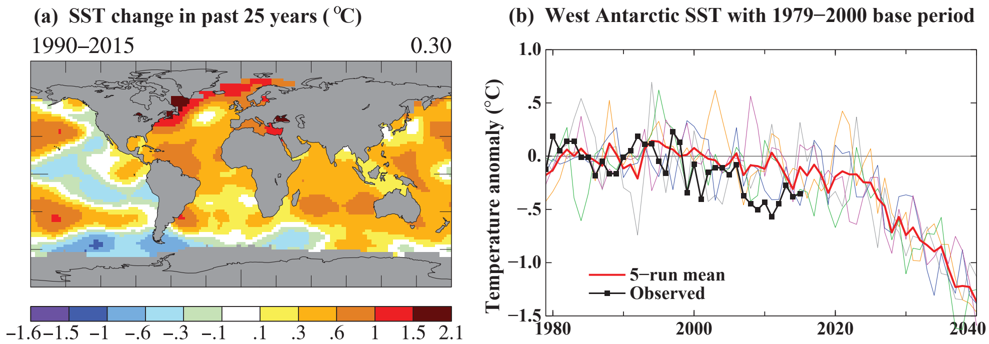

Figure 31. (a) Observed 1990–2015 SST change based on local linear trends and **(b)** SST anomaly relative to 1979–2000 for area south of 56° S between the dateline and 50° W. Base period excludes data prior to 1979 to avoid use of Southern Ocean climatology that artificially reduces variability (Huang et al., 2015).

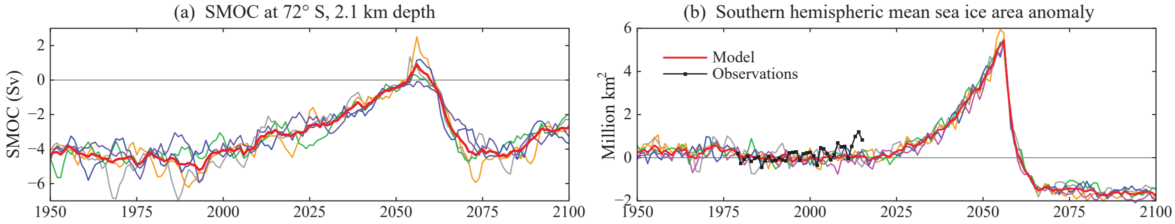

Figure 32. (a) Global meridional overturning circulation (Sv) at 72° S. Freshwater injection near Antarctica is 720 Gt year^{-1} in 2011, increasing with 10-year doubling time, and half as much around Greenland. SMOC diagnostic includes only the mean (Eulerian) term. **(b)** Annual-mean Southern Hemisphere sea ice area anomaly (10^6 km^2) in five runs (relative to 1979–2000). Observations include 2015.

A useful calibration of AMOC sensitivity to freshwater forcing is provided by the 8.2 ky b2k glacial Lake Agassiz freshwater outburst (Kleiven et al., 2008) that occurred with the demise of the Hudson Bay ice dome. Freshwater injected into the North Atlantic was ∼ 2.5–5 Sv years (Clarke et al., 2004). Proxy temperature records (see LeGrande et al., 2006) suggest that real-world cooling reached about 6 °C on Greenland, 3–4 °C in the east Norwegian Sea and 1.7 °C in Germany. The duration of the 8.2 ky b2k event was 160 years (Rasmussen et al., 2014). The LeGrande et al. (2006) model, which has the same atmospheric model as our present model but does not include the basic improvements in the ocean described in Sect. 3.2, produced results not inconsistent with real-world changes, but the modeled temperature response seemed to be on the low side (Fig. 1 of LeGrande et al., 2006). The mean decrease in the modeled AMOC was 40 %, with AMOC recovering within 20–30 years but secondary and tertiary slowdowns in some of the model runs extending as long as in the observed 8.2 ky b2k event (160 years). Although this model response is within the range suggested by paleo-data, it is on the weak side.

This model check based on the 8.2 ky b2k event does not prove that the model has correct sensitivity for today's weaker forcing. We suspect that the model is less sensitive than the real world because the model has difficulty maintaining vertical stratification, which could result from coarse vertical resolution, excess parameterized small-scale mixing, or numerical noise. Excessive mixing could also explain a too-long climate response time, as discussed in connection with Fig. 4. Hansen et al. (2011) showed that surface temperature is probably too sluggish in response to a climate forcing, not only in the GISS model but also in several other models. Hofmann and Rahmstorf (2009) suggest another reason for models being too insensitive to freshwater forcing: a bias in ocean model development spurred by desire for a stable AMOC. Below we suggest studies that are needed to investigate the model sensitivity issue.

5.3 Southern Ocean internal processes

Although the ocean surface is observed in detail on a daily basis, our main interest is in implications for long-term processes in the ocean below. Paleoclimate data discussed in Sect. 4 reveal that the Southern Ocean, as a gateway to the global deep ocean, exerts a powerful control over glacial/interglacial climate.

The Southern Ocean has significant control on release of ocean heat to space. In an extreme case, polynyas form in the dead of Antarctic winter, as upwelling warm water melts the sea ice and raises the air temperature by tens of degrees, increasing thermal radiation to space, thus serving as a valve that releases ocean heat. Today, as surface meltwater stabi-

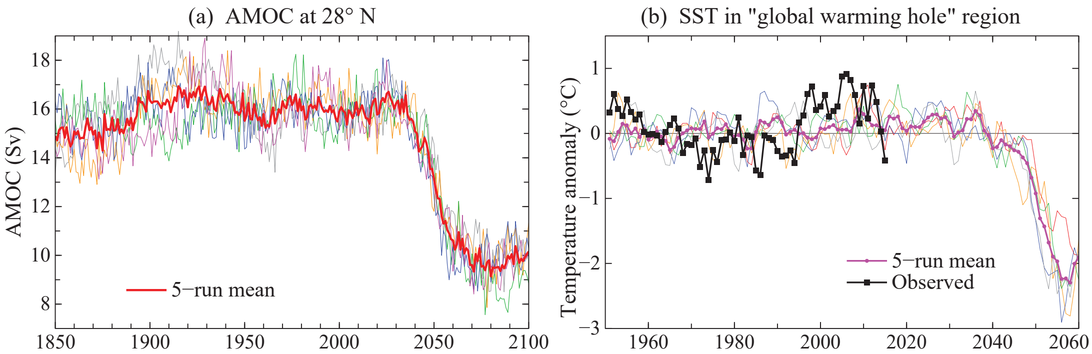

Figure 33. (a) AMOC (Sv) at 28° N in simulations with the forcings of Sect. 4.2 (i.e., including freshwater injection of 720 Gt year^{-1} in 2011 around Antarctica, increasing with a 10-year doubling time, and half that amount around Greenland). **(b)** SST (°C) in the North Atlantic region (44–60° N, 10–50° W).

lizes the vertical water column, that valve is being partially closed. De Lavergne et al. (2014) relate the absence of large open-ocean polynyas in recent decades to surface freshening. Release of heat to the atmosphere and space, which occurs without the need for large open-ocean polynyas, is slowed by increasing sea ice cover in response to increasing ice shelf melt (Bintanja et al., 2013).

Internal Southern Ocean effects of ocean surface freshening and cooling seem to be well underway. Schmidtko et al. (2014) and Roemmich et al. (2015) document changes in the Southern Ocean in recent decades, especially warming of Circumpolar Deep Water (CDW), which they and others (Jacobs et al., 2011; Rignot et al., 2013) note is the likely cause of increased ice shelf melt. Observations of ocean surface freshening and freshening of the water column (Rintoul, 2007; Jacobs and Giulivi, 2010) and deep-ocean warming (Johnson et al., 2007; Purkey and Johnson, 2013) leave little doubt that these processes are occurring.

6 Summary and implications

Via a combination of climate modeling, paleoclimate analyses, and modern observations we have identified climate feedback processes that help explain paleoclimate change and may be of critical importance in projections of human-made climate change. Here we summarize our interpretation of these processes, their effect on past climate change, and their impact on climate projections. We then discuss key observations and modeling studies needed to assess the validity of these interpretations. We argue that these feedback processes may be understated in our model, and perhaps other models, because of an excessively diffusive ocean model. Thus, there is urgency to obtain a better understanding of these processes and models.

6.1 Ocean stratification and ocean warming

Global ocean circulation (Fig. 16) is altered by the effect of low-density freshwater from melting of Greenland or Antarctic ice sheets. While the effects of shutdown of NADW have been the subject of intensive research for a quarter of a century, we present evidence that models have understated the threat and imminence of slowdown and shutdown AMOC and SMOC. Below we suggest modeling and observations that would help verify the reality of stratification effects on polar oceans and improve assessment of likely near-term and far-term impacts.

Almost counter-intuitively, regional cooling from ice melt produces an amplifying feedback that accelerates ice melt by placing a lid on the polar ocean that limits heat loss to the atmosphere and space, warming the ocean at the depth of ice shelves. The regional surface cooling increases Earth's energy imbalance, thus pumping into the ocean energy required for ice melt.[5]

6.2 Southern Ocean, CO_2 control knob, and ice sheet timescale

Our climate simulations and analysis of paleoclimate oscillations indicate that the Southern Ocean has the leading role in global climate change, with the North Atlantic a supporting actor. The Southern Ocean dominates by controlling ventilation of the deep-ocean CO_2 reservoir.

CO_2 is the control knob that regulates global temperature. On short timescales, i.e., fixed surface climate, CO_2 sets atmospheric temperature because CO_2 is stable; thus, the ephemeral radiative constituents, H_2O and clouds, adjust to CO_2 amount (Lacis et al., 2010, 2013).

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[5] Planetary energy imbalance induced by meltwater cooling helps provide the energy required by ice heat of fusion. Ice melt to raise sea level 1 m requires a 10-year Earth energy imbalance 0.9 W m^{-2} (Table S1; Hansen et al., 2005b).

On millennial timescales both CO_2 and surface albedo (determined by ice and snow cover) are variable and contribute about equally to global temperature change (Hansen et al., 2008). However, here too CO_2 is the more stable constituent with timescale for change $\sim 10^3$ years, while surface albedo is more ephemeral judging from the difficulty of finding any lag of more than the order of 10^2 years between sea level and polar temperature (Grant et al., 2012).

Here we must clarify that ice and snow cover are both a consequence of global temperature change, generally responding to the CO_2 control knob, but also a mechanism for global climate change. Specifically, regional or hemispheric snow and ice respond to seasonal insolation anomalies (as well as to CO_2 amount), thus affecting hemispheric and global climate, but to achieve large global change the albedo-driven climate change needs to affect the CO_2 amount.

We also note that Southern Ocean ventilation is not the only mechanism affecting airborne CO_2 amount. Terrestrial sources, dust fertilization of the ocean, and other factors play roles, but deep-ocean ventilation seems to be the dominant mechanism on glacial–interglacial timescales.

The most important practical implication of this "control knob" analysis is realization that the timescale for ice sheet change in Earth's natural history has been set by CO_2, not by ice physics. With the rapid large increase in CO_2 expected this century, we have no assurance that large ice sheet response will not occur on the century timescale or even faster.

6.3 Heinrich and Dansgaard–Oeschger events

Heinrich and Dansgaard-Oeschger events demonstrate the key role of subsurface ocean warming in melting ice shelves and destabilizing ice sheets, and they show that melting ice shelves can result in large rapid sea level rise. A cold lens of fresh meltwater on the ocean surface may make surface climate uncomfortable for humans, but it abets the provision of warmth at depths needed to accelerate ice melt.

6.4 End-Eemian climate events

We presented evidence for a rapid sea level rise of several meters late in the Eemian, as well as evidence of extreme storms in the Bahamas and Bermuda that must have occurred when sea level was near its maximum. This evidence is consistent with the fact that the North Atlantic was cooling in the late Eemian, while the tropics were unusually warm, the latter being consistent with the small obliquity of Earth's spin axis at that time.

Giant boulders of mid-Pleistocene limestone placed atop an Eemian substrate in North Eleuthera, which must have been deposited by waves, are emblematic of stormy end-Eemian conditions. Although others have suggested the boulders may have been emplaced by a tsunami, we argue that the most straightforward interpretation of all evidence favors storm emplacement. In any case, there is abundant evidence for strong late-Eemian storminess and high sea level.

A late-Eemian shutdown of the AMOC would have caused the most extreme North Atlantic temperature gradients. AMOC shutdown in turn would have added to Southern Ocean warmth, which may have been a major factor in the Antarctic ice sheet collapse that is required to account for the several meters of rapid late-Eemian sea level rise.

Confirmation of the exact sequence of late-Eemian events does not require absolute dating, but it probably requires finding markers that allow accurate correlation of high-resolution ocean cores with ice cores, as has proved possible for correlating Antarctic and Greenland ice cores. Such accurate relative dating would make it easier to interpret the significance of abrupt changes in two Antarctic ice cores at about end-Eemian time (Masson-Delmotte et al., 2011), which may indicate rapid large change in Antarctic sea ice cover.

Understanding end-Eemian storminess is important in part because the combination of strong storms with sea level rise poses a special threat. However, sea level rise itself is the single greatest global concern, and it is now broadly accepted that late-Eemian sea level reached +6–9 m, implicating a substantial contribution from Antarctica, at a time when Earth was little warmer than today (Dutton et al., 2015; Supplement to our present paper).

6.5 The Anthropocene

The Anthropocene (Crutzen and Stoermer, 2000), the era in which humans have contributed to global climate change, is usually assumed to have begun in the past few centuries. Ruddiman (2003) suggests that it began earlier, as deforestation began to affect CO_2 about 8000 years ago. Southern Ocean feedbacks considered in our present paper are relevant to that discussion.

Ruddiman (2003) assumed that 40 ppm of human-made CO_2 was needed to explain a 20 ppm CO_2 increase in the Holocene (Fig. 27c), because CO_2 decreased by ~ 20 ppm, on average, during several prior interglacials. Such a large human source should have left an imprint on $\delta^{13}CO_2$ that is not observed in ice core CO_2 (Elsig et al., 2009). Ruddiman (2013) suggests that ^{13}C was taken up in peat formation, but the required peat formation would be large and no persuasive evidence has been presented to support such a dominant role for peat in the glacial carbon cycle.

We suggest that Ruddiman's hypothesis may be right, but the required human-made carbon source is much smaller than he assumed. Decline of CO_2 in interglacial periods is a climate feedback, a result of declining Southern Ocean temperature, which slows the ventilation of the deep ocean and exhalation of deep-ocean CO_2. Human-made CO_2 forcing needed to avoid Antarctic cooling and atmospheric CO_2 decline is only the amount needed to counteract the weak natural forcing trend, not the larger feedback-driven CO_2 declines in prior interglacials, because the feedback does not occur if the natural forcings are counteracted.

The warm-season insolation anomaly on the Southern Ocean was positive and growing 8 ky ago (Fig. 27a). Thus the human-made CO_2 contribution required to make the Southern Ocean a CO_2 source sufficient to yield the observed CO_2 growth (Fig. 27c) is unlikely to have been larger than ~ 10 ppm, but quantification requires carbon cycle modeling beyond present capabilities.

However, the modest requirement on the human CO_2 source and the low $\delta^{13}C$ content of deep-ocean CO_2 make the Ruddiman hypothesis more plausible and likely.

6.6 The "Hyper-Anthropocene"

A fundamentally different climate phase, a "Hyper-Anthropocene", began in the latter half of the 18th century as improvements of the steam engine ushered in the industrial revolution (Hills, 1993) and exponential growth of fossil fuel use. Human-made climate forcings now overwhelm natural forcings. CO_2, at 400 ppm in 2015, is off the scale in Fig. 27c. CO_2 climate forcing is a reasonable approximation of the net human forcing, because forcing by other GHGs tends to offset negative human forcings, mainly aerosols (Myhre et al., 2013). Most of the CO_2 growth occurred in the past several decades, and three-quarters of the ~ 1 °C global warming since 1850 (update of Hansen et al., 2010, available at http://www.columbia.edu/~mhs119/Temperature/) has occurred since 1975. Climate response to this CO_2 level, so far, is only partial.

Our analysis paints a very different picture than IPCC (2013) for continuation of this Hyper-Anthropocene phase, if GHG emissions continue to grow. In that case, we conclude that multi-meter sea level rise would become practically unavoidable, probably within 50–150 years. Full shutdown of the North Atlantic Overturning Circulation would be likely within the next several decades in such a climate forcing scenario. Social disruption and economic consequences of such large sea level rise, and the attendant increases in storms and climate extremes, could be devastating. It is not difficult to imagine that conflicts arising from forced migrations and economic collapse might make the planet ungovernable, threatening the fabric of civilization.

Our study, albeit with a coarse-resolution model and simplifying assumptions, raises fundamental questions that point toward specific modeling and measurement needs.

6.7 Modeling priorities

Predictions from our modeling are shown vividly in Fig. 16, which shows simulated climate four decades in the future. However, we concluded that the basic features there are already beginning to evolve in the real world, that our model underestimates sensitivity to freshwater forcing and the stratification feedback, and that the surface climate effects are likely to emerge sooner than models suggest, if GHG climate forcing continues to grow.

This interpretation arises from evidence of excessive small-scale mixing in our ocean model and some other models, which reduces the stratification feedback effect of freshwater injection. Our climate model, with ~ 3 °C equilibrium sensitivity for 2 × CO_2, achieves only ~ 60 % of its equilibrium response in 100 years (Fig. 4). Hansen et al. (2011) conclude that such a slow response is inconsistent with Earth's measured energy imbalance; if the ocean were that diffusive it would be soaking up heat faster than the measured planetary energy imbalance ~ $0.6\,\mathrm{W\,m^{-2}}$ (Hansen et al., 2011; von Schuckmann et al., 2016). Hansen (2008) found the response time of climate models of three other modeling centers to be as slow as or slower than the GISS model, implying that the oceans in those models were also too diffusive and thus their climate response times too long. The climate response time is fundamental to interpretation of climate change and the impact of excessive small-scale mixing, if such exists, is so important that we suggest that all modeling groups participating in future CMIP studies should be asked to calculate and report their climate response function, R (Fig. 4). An added merit of that information is the fact that R permits easy calculation of the global temperature response for any climate forcing (Eq. 1).

It may be possible to quickly resolve or at least clarify this modeling issue. A fundamental difficulty with ocean modeling is that the scale of eddies and jet-like flows is much smaller than comparable features in the atmosphere, which is the reason for the Gent and McWilliams (1990) parameterization of eddy mixing in coarse-resolution models. However, computers at large modeling centers today allow simulations with ocean resolution as fine as ~ 0.1°, which can resolve eddies and minimize need for parameterizations. Winton et al. (2014) used a GFDL model (one of the models Hansen, 2008, found to have R similar to that of our model) with 0.1° ocean resolution for a 1 % $\mathrm{year^{-1}}$ increasing CO_2 experiment, finding an ~ 25 % increase in transient global warming, which is about the increment needed to increase R (100 years) to ~ 0.75, consistent with Earth's measured energy imbalance (Hansen et al., 2011). The increased surface response implies that small-scale mixing that limits stratification is reduced. Saba et al. (2016) show that this model with 0.1° ocean resolution yields 3–4 °C warming along the United States East Coast at doubled CO_2 and cooling (~ −1 °C) southeast of Greenland, both temperature changes a result of AMOC slowdown that reduces poleward transport of heat.

The model results are striking because similar temperature patterns seem to be emerging in observations (Figs. 31, S24). Annual and decadal variability limit interpretation, but given the AMOC sensitivity revealed in paleoclimate data, we infer that stratification effects are beginning to appear in the North Atlantic due to the combination of ice melt and GHG forcing. Eddy-resolving ocean models are just beginning to be employed and analyzed (Bryan et al., 2014), but there needs to be an added focus in CMIP runs to include freshwater from ice melt. CMIP5 simulations led to IPCC estimates of AMOC weakening in 2100 (Collins et al., 2013) of only 11 % for the weakest forcing scenario and 34 % for the strongest forcing ($CO_2 = 936$ ppm), but the CMIP5 runs do not include ice melt. This moderate change on a century timescale may be a figment of (1) excluding ice melt and (2) understated stratification, as can be checked with improved high-resolution models that include realistic meltwater injection. Reliable projections of AMOC and North Atlantic climate will not flow simply from new high-resolution model runs, as Winton et al. (2014) note that ocean models have other tuning parameters that can sensitively affect AMOC stability (Hofmann and Rahmstorf, 2009), which is reason for a broad comparative study with the full set of CMIP models.

High resolution ocean models are also needed to realistically portray deepwater formation around Antarctica, penetration of warm waters into ice shelf environments, and, eventually, ocean–ice sheet feedbacks. More detailed models should also include the cooling effect of ice phase change (heat of fusion) more precisely, perhaps including iceberg tracks. However, there is merit in also having a coarser-resolution version of major models with basically the same model physics. Coarser resolution allows long simulations, facilitating analysis of the equilibrium response, paleoclimate studies, and extensive testing of physical processes.

6.8 Measurement priorities

A principal issue is whether ice melt will increase exponentially, as we hypothesize if GHGs continue to grow rapidly. Continuous gravity measurements, coupled with surface mass balance and physical process studies on the ice sheets, are needed to obtain and understand regional ice mass loss on both Greenland and Antarctica. Ocean–ice shelf interactions need to be monitored, especially in Antarctica, but some Greenland ice is also vulnerable to thermal forcing by a warming ocean via submarine glacial valleys (Morlighem et al., 2014; Khan et al., 2014).

Summer weather variability makes mass loss in the Greenland melt season highly variable, but continued warming of North American continental air masses likely will spur multiple amplifying feedbacks. These feedbacks need to be monitored and quantified because their combination can lead to rapid meltwater increase. In addition to feedbacks discussed in Sect. 5.1, Machguth et al. (2016) note that meltwater injection to the ocean will increase as surface melt and refreeze limits the ability of firn to store meltwater. Meltwater in the past several years is already of the magnitude of the "Great Salinity Anomaly" (Dickson et al., 1988) that Rahmstorf et al. (2015) conclude produced significant AMOC slowdown in the late 20th century.

Continued global measurements of SST from satellites, calibrated with buoy and ship data (Huang et al., 2015) will reveal whether coolings in the Southern Ocean and southeast of Greenland are growing. Internal ocean temperature, salinity and current measurements by the ARGO float program (von Schuckmann et al., 2016), including planned extensions into the deep ocean and under sea ice, are crucial for several reasons. ARGO provides global measurements of ocean quantities that are needed to understand observed surface changes. If climate models are less sensitive to surface forcings than the real world, as we have concluded, the ARGO data will help analyze the reasons for model shortcomings. In addition, ARGO measurements of the rate of ocean heat content change are the essential data for accurate determination of Earth's energy imbalance, which determines the amount of global warming that is still "in the pipeline" and the changes of atmospheric composition that would be needed to restore energy balance, the fundamental requirement for approximately stabilizing climate.

6.9 Practical implications

The United Nations Framework Convention on Climate Change (UNFCCC, 1992) states the following:

> The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

"Dangerous" is not further defined by the UNFCCC. Our present paper has several implications with regard to the concerns that the UNFCCC is meant to address.

First, our conclusions suggest that a target of limiting global warming to 2 °C, which has sometimes been discussed, does not provide safety. We cannot be certain that multi-meter sea level rise will occur if we allow global warming of 2 °C. However, we know the warming would remain present for many centuries, if we allow it to occur (Solomon et al., 2010), a period exceeding the ice sheet response time implied by paleoclimate data. Sea level reached +6–9 m in the Eemian, a time that we have concluded was probably no more than a few tenths of a degree warmer than today. We observe accelerating mass losses from the Greenland and Antarctic ice sheets, and we have identified amplifying feedbacks that will increase the rates of change. We also observe changes occurring in the North Atlantic and Southern oceans, changes that we can attribute to ongoing warming and ice melt, which imply that this human-driven climate change seems poised to affect these most powerful overturning ocean circulation systems, systems that we know have had huge effects on the planetary environment in the past. We conclude that, in the common meaning of the word danger, 2 °C global warming is dangerous.

Second, our study suggests that global surface air temperature, although an important diagnostic, is a flawed metric of planetary "health", because faster ice melt has a cooling effect for a substantial period. Earth's energy imbalance is in some sense a more fundamental climate diagnostic. Stabilizing climate, to first order, requires restoring planetary energy balance. The UNFCCC never mentions temperature – instead it mentions stabilization of greenhouse gas concentrations at a level to avoid danger. It has been shown that the dominant climate forcing, CO_2, must be reduced to no more than 350 ppm to restore planetary energy balance (Hansen et al., 2008) and keep climate near the Holocene level, if other forcings remain unchanged. Rapid phasedown of fossil fuel emissions is the crucial need, because of the millennial timescale of this carbon in the climate system. Improved understanding of the carbon cycle is needed to determine the most effective complementary actions. It may be feasible to restore planetary energy balance via improved agricultural and forestry practices and other actions to draw down atmospheric CO_2 amount, if fossil fuel emissions are rapidly phased out.

Third, not only do we see evidence of changes beginning to happen in the climate system, as discussed above, but we have also associated these changes with amplifying feedback processes. We understand that in a system that is out of equilibrium, a system in which the equilibrium is difficult to restore rapidly, a system in which major components such as the ocean and ice sheets have great inertia but are beginning to change, the existence of such amplifying feedbacks presents a situation of great concern. There is a possibility, a real danger, that we will hand young people and future generations a climate system that is practically out of their control.

We conclude that the message our climate science delivers to society, policymakers, and the public alike is this: we have a global emergency. Fossil fuel CO_2 emissions should be reduced as rapidly as practical.

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Exhibit C.3

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Young people's burden: requirement of negative CO_2 emissions

James Hansen[1], **Makiko Sato**[1], **Pushker Kharecha**[1], **Karina von Schuckmann**[2], **David J. Beerling**[3], **Junji Cao**[4], **Shaun Marcott**[5], **Valerie Masson-Delmotte**[6], **Michael J. Prather**[7], **Eelco J. Rohling**[8,9], **Jeremy Shakun**[10], **Pete Smith**[11], **Andrew Lacis**[12], **Gary Russell**[12], **and Reto Ruedy**[12,13]

[1]Climate Science, Awareness and Solutions, Columbia University Earth Institute, New York, NY 10115, USA
[2]Mercator Ocean, 10 Rue Hermes, 31520 Ramonville St Agne, France
[3]Leverhulme Centre for Climate Change Mitigation, University of Sheffield, Sheffield, S10 2TN, UK
[4]Key Lab of Aerosol Chemistry and Physics, SKLLQG, Institute of Earth Environment, Xi'an, 710061, China
[5]Department of Geoscience, 1215 W. Dayton St., Weeks Hall, University of Wisconsin-Madison, Madison, WI 53706, USA
[6]Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ) Université Paris Saclay, Gif-sur-Yvette, France
[7]Earth System Science Department, University of California at Irvine, CA, USA
[8]Research School of Earth Sciences, The Australian National University, Canberra, 2601, Australia
[9]Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton, SO14 3ZH, UK
[10]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA 02467, USA
[11]Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK
[12]NASA Goddard Institute for Space Studies, New York, NY 10025, USA
[13]SciSpace LLC, 2880 Broadway, New York, NY 10025, USA

Correspondence to: James Hansen (jeh1@columbia.edu)

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Abstract. Global temperature is a fundamental climate metric highly correlated with sea level, which implies that keeping shorelines near their present location requires keeping global temperature within or close to its preindustrial Holocene range. However, global temperature excluding short-term variability now exceeds +1 °C relative to the 1880–1920 mean and annual 2016 global temperature was almost +1.3 °C. We show that global temperature has risen well out of the Holocene range and Earth is now as warm as it was during the prior (Eemian) interglacial period, when sea level reached 6–9 m higher than today. Further, Earth is out of energy balance with present atmospheric composition, implying that more warming is in the pipeline, and we show that the growth rate of greenhouse gas climate forcing has accelerated markedly in the past decade. The rapidity of ice sheet and sea level response to global temperature is difficult to predict, but is dependent on the magnitude of warming. Targets for limiting global warming thus, at minimum, should aim to avoid leaving global temperature at Eemian or higher levels for centuries. Such targets now require "negative emissions", i.e., extraction of CO_2 from the air. If phasedown of fossil fuel emissions begins soon, improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content, may provide much of the necessary CO_2 extraction. In that case, the magnitude and duration of global temperature excursion above the natural range of the current interglacial (Holocene) could be limited and irreversible climate impacts could be minimized. In contrast, continued high fossil fuel emissions today place a burden on young people to undertake massive technological CO_2 extraction if they are to limit climate change and its consequences. Proposed methods of extraction such as bioenergy with carbon capture and storage (BECCS) or air capture of CO_2 have minimal estimated costs of USD 89–535 trillion this century and also have large risks and uncertain feasibility. Continued high fossil fuel emissions unarguably sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both.

1 Introduction

The United Nations 1992 Framework Convention on Climate Change (United Nations, 1992) stated its objective as "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The 15th Conference of the Parties (Copenhagen Accord, 2009) concluded that this objective required a goal to "reduce global emissions so as to hold the increase of global temperature below 2 °C". The 21st Conference of the Parties (Paris Agreement, 2015), currently ratified by 148 nations, aims to strengthen the global response to the climate change threat by "[h]olding the increase in the global average temperature to well below 2 °C above the pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above the pre-industrial levels".

Global surface temperature has many merits as the principal metric for climate change, but additional metrics, such as atmospheric CO_2 amount and Earth's energy imbalance, help refine targets for avoiding dangerous human-made climate change. Paleoclimate data and observations of Earth's present energy imbalance led Hansen et al. (2008, 2013a, 2016) to recommend reducing CO_2 to less than 350 ppm, with the understanding that this target must be adjusted as CO_2 declines and empirical data accumulate. The 350 ppm CO_2 target is moderately stricter than the 1.5 °C warming target. The near-planetary energy balance anticipated at 350 ppm CO_2 implies a global temperature close to recent values, i.e., about $+1$ °C relative to preindustrial.

We advocate pursuit of this goal within a century to limit the period with global temperature above that of the current interglacial period, the Holocene.[1] Limiting the period and magnitude of temperature excursion above the Holocene range is crucial to avoid strong stimulation of slow feedbacks. Slow feedbacks include ice sheet disintegration and thus sea level rise, which is probably the most threatening climate impact, and release of greenhouse gases (GHGs) via such mechanisms as thawing tundra and loss of soil carbon. Holocene climate stability allowed sea level to be stable for the past several millennia (Kopp et al., 2016) as civilizations developed. But there is now a danger that temperature rises so far above the Holocene range that slow feedbacks are activated to a degree that continuing climate change will be out of humanity's control. Both the 1.5 °C and 350 ppm targets require rapid phasedown of fossil fuel emissions.

Today, global fossil fuel emissions continue at rates that make these targets increasingly improbable (Fig. 1 and Appendix A1). On a per capita historical basis the US is 10 times more accountable than China and 25 times more accountable than India for the increase in atmospheric CO_2 above its preindustrial level (Hansen and Sato, 2016). In response, a lawsuit (Juliana et al. vs. United States, 2016, hereafter J. et al. vs. US, 2016) was filed against the United States asking the US District Court, District of Oregon, to require the US government to produce a plan to rapidly reduce emissions. The suit requests that the plan reduce emissions at the 6 % yr^{-1} rate that Hansen et al. (2013a) estimated as the requirement for lowering atmospheric CO_2 to a level of 350 ppm. At a hearing in Eugene Oregon on 9 March 2016 the United States and three interveners (American Petroleum Institute, National Association of Manufacturers, and the American Fuels and Petrochemical Association) asked the court to dismiss the case, in part based on the argument that the requested rate of fossil fuel emissions reduction was beyond the court's authority. Magistrate Judge Coffin stated that he found "the remedies aspect of the plaintiff's complaint [to be] *troublesome*", in part because it involves "a separation of powers issue". But he also noted that some of the alleged climate change consequences, if accurate, could be considered "beyond the pale", and he rejected the motion to dismiss the case. Judge Coffin's ruling was certified, as required, by a second judge (Aiken, 2016) on 9 September 2016, and, barring a settlement that would be overseen by the court, the case is expected to proceed to trial in late 2017. It can be anticipated that the plausibility of achieving the emission reductions needed to stabilize climate will be a central issue at the remedy stage of the trial.

Urgency of initiating emissions reductions is well recognized (IPCC, 2013, 2014; Huntingford et al., 2012; Friedlingstein et al., 2014; Rogelj et al., 2016a) and was stressed in the paper (Hansen et al., 2013a) used in support of the lawsuit J. et al. vs. US (2016). It is also recognized that the goal to keep global warming less than 1.5 °C likely requires negative net CO_2 emissions later this century if high global emissions continue in the near term (Fuss et al., 2014; Anderson, 2015; Rogelj et al., 2015; Sanderson et al., 2016). The Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2013, 2014) do not address environmental and ecological feasibility and impacts of large-scale CO_2 removal, but recent studies (Smith et al., 2016; Williamson,

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[1] By Holocene we refer to the preindustrial portion of the present interglacial period. As we will show, the rapid warming of the past century has brought temperature above the range in the prior 11 700 years of the Holocene.

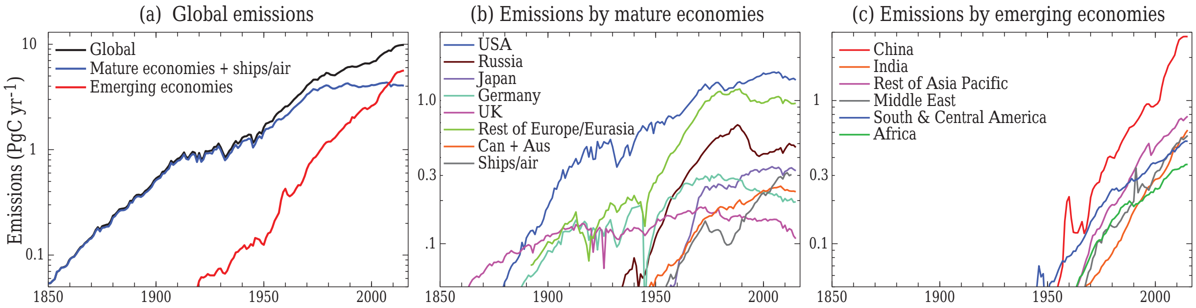

Figure 1. Fossil fuel (and cement manufacture) CO_2 emissions (note log scale) based on Boden et al. (2016) with BP data used to infer 2014–2015 estimates. Europe/Eurasia is Turkey plus the Boden et al. categories Western Europe and Centrally Planned Europe. Asia Pacific is sum of Centrally Planned Asia, Far East and Oceania. Middle East is Boden et al. (2016) Middle East less Turkey. Russia is Russian Federation since 1992 and 60 % of USSR in 1850–1991. Ships/air is sum of bunker fuels of all nations. Can + Aus is the sum of emissions from Canada and Australia.

2016) are taking up this crucial issue and raising the question of whether large-scale negative emissions are even feasible.

Our aim is to contribute to understanding of the required rate of CO_2 emissions reduction via an approach that is transparent to non-scientists. We consider potential drawdown of atmospheric CO_2 by reforestation and afforestation, the potential for improved agricultural practices to store more soil carbon, and potential reductions of non-CO_2 GHGs that could reduce human-made climate forcing.[2] Quantitative examination reveals the merits of these actions to partly offset demands on fossil fuel CO_2 emission phasedown, but also their limitations, thus clarifying the urgency of government actions to rapidly advance the transition to carbon-free energies to meet the climate stabilization targets they have set.

We first describe the status of global temperature change and then summarize the principal climate forcings that drive long-term climate change. We show that observed global warming is consistent with knowledge of changing climate forcings, Earth's measured energy imbalance, and the canonical estimate of climate sensitivity,[3] i.e., about 3 °C global warming[4] for doubled atmospheric CO_2. For clarity we make global temperature calculations with our simple climate model, which we show (Appendix A2) has a transient climate sensitivity near the midpoint of the sensitivity of models illustrated in Fig. 10.20a of IPCC (2013). The standard climate sensitivity and climate model do not include effects of "slow" climate feedbacks such as change in ice sheet size. There is increasing evidence that some slow feedbacks can be triggered within decades, so they must be given major consideration in establishing the dangerous level of human-made climate interference. We thus incorporate consideration of slow feedbacks in our analysis and discussion, even though precise specification of their magnitude and timescales is not possible. We present updates of GHG observations and find a notable acceleration during the past decade of the growth rate of GHG climate forcing. For future fossil fuel emissions we consider both the representative concentration pathway (RCP) scenarios used in Climate Model Intercomparison Project 5 (CMIP5) IPCC studies, and simple emission growth rate changes that help evaluate the plausibility of needed emission changes. We use a Green's function calculation of global temperature with canonical climate sensitivity for each emissions scenario, which yields the amount of CO_2 that must be extracted from the air – effectively the climate debt – to return atmospheric CO_2 to less than 350 ppm or limit global warming to less than 1.5 °C above preindustrial levels. We discuss alternative extraction technologies and their estimated costs, and finally we consider the potential alleviation of CO_2 extraction requirements that might be obtained via special efforts to reduce non-CO_2 GHGs.

2 Global temperature change

The framing of human-caused climate change by the Paris Agreement uses global mean surface temperature as the metric for assessing dangerous climate change. We have previously argued the merits of additional metrics, especially Earth's energy imbalance (Hansen et al., 2005; von Schuckmann et al., 2016) and atmospheric CO_2 amount (Hansen et al., 2008). Earth's energy imbalance integrates over all climate forcings, known and unknown, and informs us where climate is heading, because it is this imbalance that drives

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[2] A climate forcing is an imposed change in Earth's energy balance, measured in $W\,m^{-2}$. For example, Earth absorbs about 240 $W\,m^{-2}$ of solar energy, so if the Sun's brightness increases 1 % it is a forcing of +2.4 $W\,m^{-2}$.

[3] Climate sensitivity is the response of global average surface temperature to a standard forcing, with the standard forcing commonly taken to be doubled atmospheric CO_2, which is a forcing of about 4 $W\,m^{-2}$ (Hansen et al., 2005).

[4] IPCC (2013) finds that $2 \times CO_2$ equilibrium sensitivity is likely in the range 3 ± 1.5 °C, as was estimated by Charney et al. (1979). Median sensitivity in recent model inter-comparisons is 3.2 °C (Andrews et al., 2012; Vial et al., 2013).

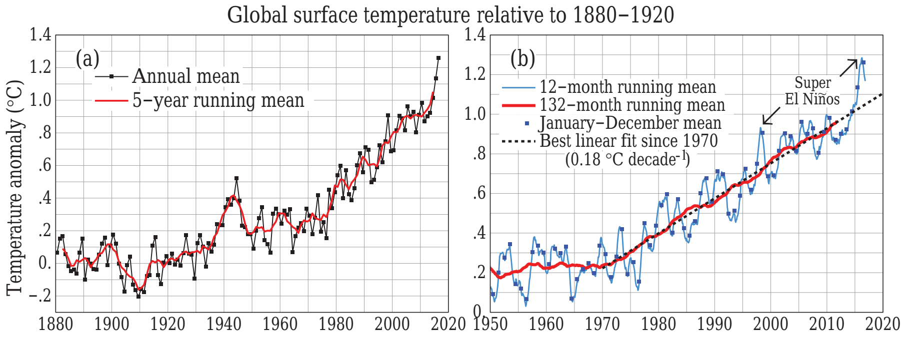

Figure 2. Global surface temperature relative to 1880–1920 based on GISTEMP data (Appendix A3). **(a)** Annual and 5-year means since 1880, **(b)** 12- and 132-month running means since 1970. Blue squares in **(b)** are calendar year (January–December) means used to construct **(a)**. Panel **(b)** uses data through April 2017.

continued warming. The CO_2 metric has merit because CO_2 is the dominant control knob on global temperature (Lacis et al., 2010, 2013), including paleo-temperature change (cf. Fig. 28 of Hansen et al., 2016). Our present paper uses these alternative metrics to help sharpen determination of the dangerous level of global warming, and to quantify actions that are needed to stabilize climate. We here use global temperature as the principal metric because several reasons of concern are scaled to global warming (O'Neill et al., 2017), including specifically the potential for slow feedbacks such as ice sheet melt and permafrost thaw. The slow feedbacks, whose timescales depend on how strongly the climate system is being forced, will substantially determine the magnitude of climate impacts and affect how difficult the task of stabilizing climate will be.

Quantitative assessment of both ongoing and paleo-temperature change is needed to define acceptable limits on human-made interference with climate, with paleoclimate especially helpful for characterizing long-term ice sheet and sea level response to temperature change. Thus, we examine the modern period with near-global instrumental temperature data in the context of the current and prior (Holocene and Eemian) interglacial periods, for which less precise proxy-based temperatures have recently emerged. The Holocene, over 11 700 years in duration, had relatively stable climate, prior to the remarkable warming in the past half century. The Eemian, which lasted from about 130 000 to 115 000 years ago, was moderately warmer than the Holocene and experienced sea level rise to heights 6–9 m (20–30 ft) greater than today.

2.1 Modern temperature

The several analyses of temperature change since 1880 are in close agreement (Hartmann et al., 2013). Thus, we can use the current GISTEMP analysis (see Supplement), which is updated monthly and available (http://www.columbia.edu/~mhs119/Temperature/).

The popular measure of global temperature is the annual-mean global mean value (Fig. 2a), which is publicized at the end of each year. However, as discussed by Hansen et al. (2010), the 12-month running mean global temperature is more informative and removes monthly "noise" from the record just as well as the calendar year average. For example, the 12-month running mean for the past 67 years (Fig. 2b) defines clearly the super-El Niños of 1997–1998 and 2015–2016 and the 3-year cooling after the Mount Pinatubo volcanic eruption in the early 1990s.

Global temperature in 2014–2016 reached successive record high levels for the period of instrumental data (Fig. 2). Temperature in the latter 2 years was partially boosted by the 2015–2016 El Niño, but the recent warming is sufficient to remove the illusion of a hiatus of global surface warming after the 1997–1998 El Niño (Appendix A4).

The present global warming rate, based on a linear fit for 1970–present (dashed line in Fig. 2b) is +0.18 °C per decade.[5] The period since 1970 is the time with high growth rate of GHG climate forcing, which has been maintained at approximately $+0.4\,\mathrm{W\,m^{-2}\,decade^{-1}}$ (see Sect. 6 below)[6] causing Earth to be substantially out of energy balance (Cheng et al., 2017). The energy imbalance drives global warming, so unless and until there is substantial change in the rate of added climate forcing we expect the underlying warming to continue at a comparable rate.

Global temperature defined by the linear fit to temperature since 1970 now exceeds 1 °C[7] relative to the 1880–1920 mean (Fig. 2b), where the 1880–1920 mean provides our best estimate of "preindustrial" temperature (Ap-

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[5] Extreme end points affect linear trends, but if the 2016 temperature is excluded the calculated trend ($0.176\,°\mathrm{C\,decade^{-1}}$) still rounds to $0.18\,°\mathrm{C\,decade^{-1}}$.

[6] As forcing additions from chlorofluorocarbons (CFCs) and CH_4 declined, CO_2 growth increased (Sect. 6).

[7] It is 1.05 °C for linear fit to 132-month running mean, but can vary by a few hundredths of a degree depending on the method chosen to remove short-term variability.

pendix A5). At the rate of 0.18 °C decade^{-1} the linear trend line of global temperature will reach +1.5 °C in about 2040 and +2 °C in the late 2060s. However, the warming rate can accelerate or decelerate, depending on policies that affect GHG emissions, developing climate feedbacks, and other factors discussed below.

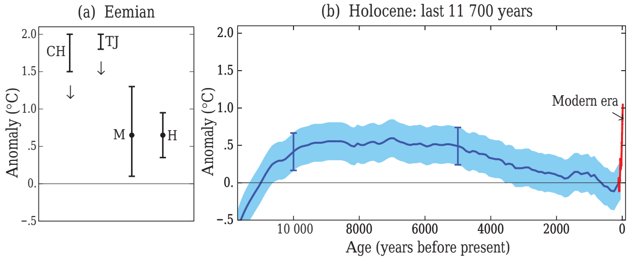

Figure 3. Estimated average global temperature for **(a)** last interglacial (Eemian) period (Clark and Huybers, 2009; Turney and Jones, 2010; McKay et al., 2011; Hoffman et al., 2017) and **(b)** centennially smoothed Holocene (Marcott et al., 2013) temperature and the 11-year mean of modern data (Fig. 2), as anomalies relative to 1880–1920. Vertical downward arrows indicate likely overestimates (see text).

2.2 Temperature during current and prior interglacial periods

Holocene temperature has been reconstructed at centennial-scale resolution from 73 globally distributed proxy temperature records by Marcott et al. (2013). This record shows a decline of 0.6 °C from early Holocene maximum temperature to a "Little Ice Age" minimum in the early 1800s (that minimum being better defined by higher resolution data of Abram et al., 2016). Concatenation of the modern and Holocene temperature records (Fig. 3; Appendix A5) assumes that 1880–1920 mean temperature is 0.1 °C warmer than the Little Ice Age minimum (Abram et al., 2016). The early Holocene maximum in the Marcott et al. (2013) data thus reaches +0.5 °C relative to the 1880–1920 mean of modern data. The formal 95 % confidence bounds to Holocene temperature (Marcott et al., 2013) are ±0.25 °C (blue shading in Fig. 3b), but total uncertainty is larger. Specifically, Liu et al. (2014) points out a bias effect caused by seasonality in the proxy temperature reconstruction. Correction for this bias will tend to push early Holocene temperatures lower, increasing the gap between today's temperature and early Holocene temperature (Marcott and Shakun, 2015).

We emphasize that comparisons of current global temperature with the earlier Holocene must bear in mind the centennial smoothing inherent in the Holocene data (Marcott et al., 2013). Thus, the temperature in an anomalous single year such as 2016 is not an appropriate comparison. However, the temperature in 2016 based on the 1970–present linear trend (at least 1 °C relative to the 1880–1920 mean) does provide a meaningful comparison. The trend line reduces the effect of interannual variability, but the more important point is that Earth's energy imbalance assures that this temperature will continue to rise unless and until the global climate forcing begins to decline. In other words, we know that mean temperature over the next several decades will not be lower than 1 °C.

We conclude that the modern trend line of global temperature crossed the early Holocene (smoothed) temperature maximum (+0.5 °C) in about 1985. This conclusion is supported by the accelerating rate of sea level rise, which approached 3 mm yr^{-1} at about that date (Hansen et al., 2016 show a relevant concatenation of measurements in their Fig. 29). Such a high rate of sea level rise, which is 3 m per millennium, far exceeds the prior rate of sea level rise in the last six millennia of the Holocene (Lambeck et al., 2014). Note that near stability of sea level in the latter half of the Holocene as global temperature fell about 0.5 °C, prior to rapid warming of the modern era (Fig. 3), is not inconsistent with that global cooling. Hemispheric solar insolation anomalies in the latter half of the Holocene favored ice sheet growth in the Northern Hemisphere and ice sheet decay in Antarctica (Fig. 27a, Hansen et al., 2016), but the Northern Hemisphere did not become cool enough to reestablish ice sheets on North America or Eurasia. There was a small increase in Greenland ice sheet mass (Larsen et al., 2015), but this was presumably at least balanced by Antarctic ice sheet mass loss (Lambeck et al., 2014).

The important point is that global temperature has risen above the centennially smoothed Holocene range. Global warming is already having substantial adverse climate impacts (IPCC, 2014), including extreme events (NAS, 2016). There is widespread agreement that 2 °C warming would commit the world to multi-meter sea level rise (Levermann et al., 2013; Dutton et al., 2015; Clark et al., 2016). Sea level reached 6–9 m higher than today during the Eemian (Dutton et al., 2015), so it is particularly relevant to know how global mean Eemian temperature compares to the preindustrial level and thus to today.

McKay et al. (2011) estimated peak Eemian annual global ocean sea surface temperature (SST) as +0.7 ± 0.6 °C relative to late Holocene temperature, while models, as described by Masson-Delmotte et al. (2013), give more confidence to the lower part of that range. Hoffman et al. (2017) report the maximum Eemian annual global SST as +0.5 ± 0.3 °C relative to 1870–1889, which is +0.65 °C relative to 1880–1920. The response of surface air temperature (SAT) over land is twice as large as the SST response to climate forcings in 21st century simulations with models (Collins et al., 2013), in good agreement with observed warming in the industrial era (Appendix A3 this paper, Fig. A3a). The ratio of land SAT change to SST change is reduced only to ∼ 1.8 after 1000 years in climate models (Fig. A6, Appendix A6). This implies that, because land covers ∼ 30 % of the globe, SST warmings should be multiplied by 1.24–

1.3 to estimate global temperature change. Thus, the McKay et al. (2011) and Hoffman et al. (2017) data are equivalent to a global Eemian temperature of just under +1 °C relative to the Holocene. Clark and Huybers (2009) and Turney and Jones (2010) estimated global temperature in the Eemian as 1.5–2 °C warmer than the Holocene (Fig. 3), but Bakker and Renssen (2014) point out two biases that may cause this range to be an overestimate. Bakker and Rennsen (2014) use a suite of models to estimate that the assumption that maximum Eemian temperature was synchronous over the planet overestimates Eemian temperature by 0.4 ± 0.3 °C – a feature supported by a lack of synchroneity of warmest conditions in assessments with improved synchronization of records (Govin et al., 2015) – and that they also suggest that a possible seasonal bias of proxy temperature could make the total overestimate as large as 1.1 ± 0.4 °C. Given uncertainties in the corrections, it becomes a matter of expert judgment. Dutton et al. (2015) conclude that the best estimate for Eemian temperature is +1 °C relative to preindustrial. Consistent with these estimates and the discussion of Masson-Delmotte et al. (2013), we assume that maximum Eemian temperature was +1 °C relative to preindustrial with an uncertainty of at least 0.5 °C..

These considerations raise the question of whether 2 °C, or even 1.5 °C, is an appropriate target to protect the well-being of young people and future generations. Indeed, Hansen et al. (2008) concluded that "if humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, … CO_2 will need to be reduced … to at most 350 ppm, but likely less than that", and further "if the present overshoot of the target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects".

A danger of 1.5 or 2 °C targets is that they are far above the Holocene temperature range. If such temperature levels are allowed to long exist they will spur "slow" amplifying feedbacks (Hansen et al., 2013b; Rohling et al., 2013; Masson-Delmotte et al., 2013), which have potential to run out of humanity's control. The most threatening slow feedback likely is ice sheet melt and consequent significant sea level rise, as occurred in the Eemian, but there are other risks in pushing the climate system far out of its Holocene range. Methane release from thawing permafrost and methane hydrates is another potential feedback, for example, but the magnitude and timescale of this is unclear (O'Connor et al., 2010; Quiquet et al., 2015).

Here we examine the fossil fuel emission reductions required to restore atmospheric CO_2 to 350 ppm or less, so as to keep global temperature close to the Holocene range, in addition to the canonical 1.5 and 2 °C targets. Quantitative investigation requires consideration of Earth's energy imbalance, changing climate forcings, and climate sensitivity.

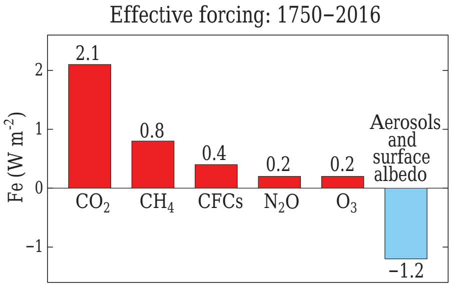

Figure 4. Estimated effective climate forcings (update through 2016 of Fig. 28b of Hansen et al., 2005, which are consistent with estimates of Myhre et al., 2013, in the most recent IPCC report, IPCC, 2013). Forcings are based on observations of each gas, except simulated CH_4-induced changes of O_3 and stratospheric H_2O included in the CH_4 forcing. Aerosols and surface albedo change are estimated from historical scenarios of emissions and land use. Oscillatory and intermittent natural forcings (solar irradiance and volcanoes) are excluded. CFCs include not only chlorofluorocarbons, but all Montreal Protocol trace gases (MPTGs) and other trace gases (OTGs). Uncertainties (for 5–95 % confidence) are 0.6 W m^{-2} for total GHG forcing and 0.9 W m^{-2} for aerosol forcing (Myhre et al., 2013).

3 Global climate forcings and Earth's energy imbalance

The dominant human-caused drivers of climate change are changes of atmospheric GHGs and aerosols (Fig. 4). GHGs absorb Earth's infrared (heat) radiation, thus serving as a "blanket" warms Earth's surface by reducing heat radiation to space. Aerosols, fine particles/droplets in the air that cause visible air pollution, both reflect and absorb solar radiation, but reflection of solar energy to space is their dominant effect, so they cause a cooling that partly offsets GHG warming. Estimated forcings (Fig. 4), an update of Fig. 28b of Hansen et al. (2005), are similar to those of Myhre et al. (2013) in the most recent IPCC report (IPCC, 2013).[8]

Climate forcings in Fig. 4 are the planetary energy imbalance that would be caused by the preindustrial-to-present change in each atmospheric constituent, if the climate were held fixed at its preindustrial state (Hansen et al., 2005). The CH_4 forcing includes its indirect effects, as increasing atmospheric CH_4 causes tropospheric ozone (O_3) and stratospheric water vapor to increase (Myhre et al., 2013). Uncertainties, discussed by Myhre et al. (2013), are typically 10–15 % for GHG forcings. The aerosol forcing uncertainty, described by a probability distribution function (Boucher et al., 2013), is of order 50 %. Our estimate of aerosol plus surface albedo forcing (−1.2 W m^{-2}) differs from the −1.5 W m^{-2}

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[8] Our GHG forcings, calculated with formulae of Hansen et al. (2000), yield a CO_2 forcing 6.7 % larger than the central IPCC estimate (Table 8.2 of Myhre et al., 2013) for the CO_2 change from 1750 to 2011. For all well-mixed (long-lived) GHGs we obtain 3.03 W m^{-2}, which is within the IPCC range 2.83 ± 0.29 W m^{-2}.

of Hansen et al. (2005), as discussed below, but both are within the range of the distribution function of Boucher et al. (2013).

Positive net forcing (Fig. 4) causes Earth to be temporarily out of energy balance, with more energy coming in than going out, which drives slow global warming. Eventually Earth will become hot enough to restore planetary energy balance. However, because of the ocean's great thermal inertia (heat capacity), full atmosphere–ocean response to the forcing requires a long time: atmosphere–ocean models suggest that even after 100 years only 60–75 % of the surface warming for a given forcing has occurred, the remaining 25–40 % still being "in the pipeline" (Hansen et al., 2011; Collins et al., 2013). Moreover, we outline in the next section that global warming can activate "slow" feedbacks, such as changes of ice sheets or melting of methane hydrates, so the time for the system to reach a fully equilibrated state is even longer.

GHGs have been increasing for more than a century and Earth has partially warmed in response. Earth's energy imbalance is the portion of the forcing that has not yet been responded to. This imbalance thus defines additional global warming that will occur without further change in forcings. Earth's energy imbalance can be measured by monitoring ocean subsurface temperatures, because almost all excess energy coming into the planet goes into the ocean (von Schuckmann et al., 2016). Most of the ocean's heat content change occurs in the upper 2000 m (Levitus et al., 2012), which has been well measured since 2005, when the distribution of Argo floats achieved good global coverage (von Schuckmann and Le Traon, 2011). Here we update the von Schuckmann and Le Traon (2011) analysis with data for 2005–2015 (Fig. 5) finding a decade-average 0.7 $W\,m^{-2}$ heat uptake in the upper 2000 m of the ocean. Addition of the smaller terms raises the imbalance to $+0.75 \pm 0.25\,W\,m^{-2}$ averaged over the solar cycle (Appendix A7).

4 Climate sensitivity and feedbacks

Climate sensitivity has been a fundamental issue at least since the 19th century, when Tyndall (1861) and Arrhenius (1896) stimulated interest in the effect of CO_2 change on climate. Evaluation of climate sensitivity involves the full complexity of the climate system, as all components and processes in the system are free to interact on all timescales. Tyndall and Arrhenius recognized some of the most important climate feedbacks on both fast and slow timescales. The amount of water vapor in the air increases with temperature, which is an amplifying feedback because water vapor is a very effective greenhouse gas; this is a "fast" feedback, because water vapor amount in the air adjusts within days to temperature change. The area covered by glaciers and ice sheets is a prime "slow" feedback; it, too, is an amplifying feedback, because the darker surface exposed by melting ice absorbs more sunlight.

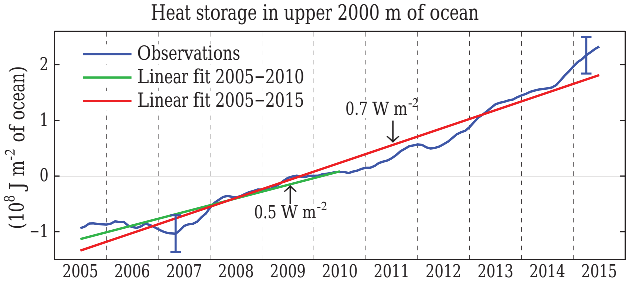

Figure 5. Ocean heat uptake in the upper 2 km of ocean during 11 years from 2005 to 2015 using analysis method of von Schuckmann and Le Traon (2011). Heat uptake in $W\,m^{-2}$ (0.5 and 0.7) refers to global (ocean + land) area – i.e., it is the contribution of the upper ocean to the heat uptake averaged over the entire planet.

Diminishing climate feedbacks also exist. Cloud-cover changes, for example, can either amplify or reduce climate change (Boucher at al., 2013). Thus, it is not inherent that amplifying feedbacks should be dominant, but climate models and empirical data concur that amplifying feedbacks dominate on both short and long timescales, as we will discuss. Amplifying feedbacks lead to large climate change in response to even weak climate forcings such as ice age cycles caused by small perturbations of Earth's orbit, and still larger climate change occurs on even longer timescales in response to gradual changes in the balance between natural sources and sinks of atmospheric CO_2 (Zachos et al., 2001; Royer et al., 2012; Franks et al., 2014).

4.1 Fast-feedback climate sensitivity

Doubled atmospheric CO_2, a forcing of $\sim 4\,W\,m^{-2}$, is a standard forcing in studies of climate sensitivity. Charney et al. (1979) concluded that equilibrium sensitivity, i.e., global warming after a time sufficient for the planet to restore energy balance with space, was $3 \pm 1.5\,°C$ for $2 \times CO_2$ or $0.75\,°C\,(W\,m^{-2})^{-1}$ forcing. The Charney analysis was based on climate models in which ice sheets and all long-lived GHGs (except for the specified CO_2 doubling) were fixed. The climate sensitivity thus inferred is the "fast-feedback" climate sensitivity. The central value found in a wide range of modern climate models (Flato et al., 2013) remains 3 °C for $2 \times CO_2$.

The possibility of unknown unknowns in models would keep the uncertainty in the fast-feedback climate sensitivity high, if it were based on models alone, but as discussed by Rohling et al. (2012a), paleoclimate data allow narrowing of the uncertainty. Ice sheet size and the atmospheric amount of long-lived GHGs (CO_2, CH_4, N_2O) under natural conditions change on multi-millennial timescales. These changes are so slow that the climate is in quasi-equilibrium with the changing surface condition and long-lived GHG amounts. Thus, these changing boundary conditions, along with knowledge of the associated global temperature change, allow empirical assessment of the fast-feedback climate sensitivity. The central result agrees well with the model-based climate sensitivity estimate of 3 °C for 2 × CO_2 (Rohling et al., 2012b), with an uncertainty that is arguably 1 °C or less (Hansen et al., 2013b).

The ocean has great heat capacity (thermal inertia), so it takes decades to centuries for Earth's surface temperature to achieve most of its fast-feedback response to a change in climate forcing (Hansen et al., 1985). Thus, Earth has only partly responded to the human-made increase in GHGs in the air today, the planet must be out of energy balance with the planet gaining energy (via reduced heat radiation to space), and more global warming is "in the pipeline".

A useful check on understanding of ongoing climate change is provided by the consistency of the net climate forcing (Fig. 4), Earth's energy imbalance, observed global warming, and climate sensitivity. Observed warming since 1880–1920 is 1.05 °C[9] based on the linear fit to the 132-month running mean (Fig. 2b), which limits its bias from short-term oscillations. Global warming between 1700 and 1800 as well as 1880 and 1920 was ∼ 0.1 °C (Abram et al., 2016; Hawkins et al., 2017; Marcott et al., 2013), so 1750–2015 warming is ∼ 1.15 °C. Taking climate sensitivity as 0.75 °C $(\mathrm{W\,m^{-2}})^{-1}$ forcing, global warming of 1.15 °C implies that 1.55 $\mathrm{W\,m^{-2}}$ of the total 2.5 $\mathrm{W\,m^{-2}}$ forcing has been "used up" to cause observed warming. Thus, 0.95 $\mathrm{W\,m^{-2}}$ forcing should remain to be responded to – i.e., the expected planetary energy imbalance is 0.95 $\mathrm{W\,m^{-2}}$, which is reasonably consistent with the observed $0.75 \pm 0.25\,\mathrm{W\,m^{-2}}$. If we instead take the aerosol + surface albedo forcing as $-1.5\,\mathrm{W\,m^{-2}}$, as estimated by Hansen et al. (2005), the net climate forcing is 2.2 $\mathrm{W\,m^{-2}}$ and the forcing not responded to is 0.65 $\mathrm{W\,m^{-2}}$, which is also within the observational error of Earth's energy imbalance.

4.2 Slow climate feedbacks

Large glacial-to-interglacial climate oscillations occur on timescales of tens and hundreds of thousands of years, with atmospheric CO_2 amount and the size of ice sheets (and thus sea level) changing almost synchronously on these timescales (Masson-Delmotte et al., 2013). It is readily apparent that these climate cycles are due to small changes in Earth's orbit and the tilt of its spin axis, which alter the geographical and seasonal distribution of sunlight striking Earth. The large climate response is a result of two amplifying feedbacks: (1) atmospheric GHGs (mainly CO_2 but accompanied by CH_4 and N_2O), which increase as Earth warms and decrease as it cools (Ciais et al., 2013), thus amplifying the temperature change, and (2) the size of ice sheets, which shrink as Earth warms and grow as it cools, thus changing the amount of absorbed sunlight in the sense that also amplifies the climate change. For example, 20 000 years ago most of Canada and parts of the US were covered by an ice sheet, and sea level was about 130 m (∼ 400 ft) lower than today. Global warming of ∼ 5 °C between the last glacial maximum and the Holocene (Masson-Delmotte et al., 2013) is accounted for almost entirely by radiative forcing caused by decrease in ice sheet area and increase in GHGs (Lorius et al., 1990; Hansen et al., 2007).

The glacial–interglacial timescale is set by the timescale of the weak orbital forcings. Before addressing the crucial issue of the inherent timescale of slow feedbacks, we need to say more about the two dominant slow feedbacks, described above as ice sheets and GHGs.

The ice sheet feedback works mainly via the albedo (reflectivity) effect. A shrinking ice sheet exposes darker ground and warming darkens the ice surface by increasing the area and period with wet ice, thus increasing the ice grain size and increasing the surface concentration of light-absorbing impurities (Tedesco et al., 2016). The ice albedo effect is supplemented by a change in surface albedo in ice-free regions due to vegetation changes. This vegetation albedo effect provides a significant amplification of warming as Earth's temperature increases from its present climate state, because dark forests tend to replace tundra or sparse low-level vegetation in large areas of Eurasia and North America (Lunt et al., 2010).

The GHG feedback on glacial–interglacial timescales is 75–80 % from CO_2 change; N_2O and CH_4 account for 20–25 % (Lorius et al., 1990; Hansen et al., 2007; Masson-Delmotte et al., 2013). In simple terms, the ocean and land release more of these gases as the planet becomes warmer. Mechanisms that control GHG release as Earth warms, and GHG drawdown as Earth cools, are complex, including many processes that affect the distribution of carbon, among the ocean, atmosphere, and biosphere (Yu et al., 2016; Ciais et al., 2013, and references therein). Release of carbon from methane hydrates and permafrost contributed to climate change in past warm periods (Zachos et al., 2008; DeConto et al., 2012) and potentially could have a significant effect in the future (O'Connor et al., 2010; Schädel et al., 2016).

Paleoclimate data help assess the possible timescale for ice sheet change. Ice sheet size, judged from sea level, varies almost synchronously with temperature for the temporal resolution available in paleoclimate records, but Grant et al. (2012) find that sea level change lags temperature change by 1–4 centuries. Paleoclimate forcing, however, is both weak and very slow, changing on millennial timescales. Hansen (2005, 2007) argues on heuristic grounds that the much faster and stronger human-made climate forcing pro-

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[9] The IPCC (2013; p. 37 of Technical Summary) estimate of warming for 1880–2012 is 0.85 °C (range 0.65 to 1.06 °C). While within that range, our value is higher because (1) use of 4-year longer period, (2) warming in the past few years eliminates the effect on the 1970–present trend from a seeming 1998–2012 warming hiatus, and (3) the GISTEMP analysis has greater coverage of the large Arctic warming than the other analyses (Fig. TS.2, p. 39 of IPCC, 2013).

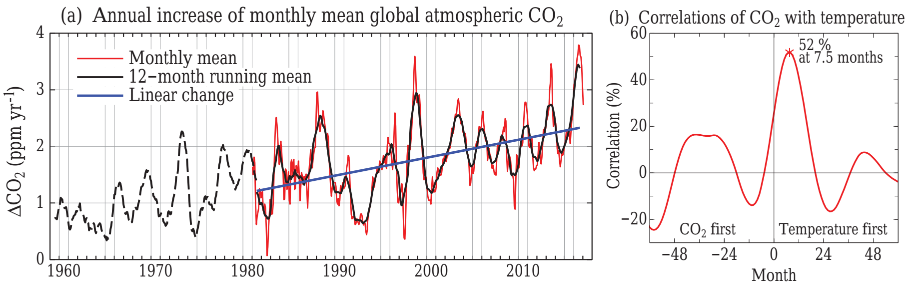

Figure 6. **(a)** Global CO_2 annual growth based on NOAA data (http://www.esrl.noaa.gov/gmd/ccgg/trends/). Dashed curve is for a single station (Mauna Loa). Red curve is monthly global mean relative to the same month of prior year; black curve is 12-month running mean of red curve. **(b)** CO_2 growth rate is highly correlated with global temperature, with the CO_2 change lagging global temperature change by 7–8 months.

jected this century with continued high fossil fuel emissions, equivalent to doubling atmospheric CO_2, would likely lead to substantial ice sheet collapse and multi-meter sea level rise on the timescale of a century. Modeling supports this conclusion, as Pollard et al. (2015) found that addition of hydro-fracturing and cliff failure to their ice sheet model not only increased simulated sea level rise from 2 to 17 m in response to 2 °C ocean warming but also accelerated the time for multi-meter change from several centuries to several decades. Ice sheet modeling of Applegate et al. (2015) explicitly shows that the timescale for large ice sheet melt decreases dramatically as the magnitude of warming increases. Hansen et al. (2016), based on a combination of climate modeling, paleo-data, and modern observations, conclude that continued high GHG emissions would likely cause multi-meter sea level rise within 50–150 years.

The GHG feedback plays a leading role in determining the magnitude of paleoclimate change and there is reason to suspect that it may already be important in modern climate. Rising temperatures increase the rate of CO_2 and CH_4 release from drying soils, thawing permafrost (Schädel et al., 2016; Schuur et al., 2015) and warming continental shelves (Kvenvolden, 1993; Judd et al., 2002), and affect the ocean carbon cycle as noted above. Crowther et al. (2016) synthesize results of 49 field experiments across North America, Europe and Asia, inferring that every 1 °C global mean soil surface warming can cause a 30 PgC soil carbon loss and suggesting that continued high fossil fuel emissions might drive 2 °C soil warming and a 55 PgC soil carbon loss by 2050. Although this analysis admits large uncertainty, such large soil carbon loss could wreak havoc with efforts to achieve the net soil and biospheric carbon storage that is likely necessary for climate stabilization, as we discuss in subsequent sections.

Recent changes of GHGs result mainly from industrial and agricultural emissions, but they also include any existing climate feedback effects. CO_2 and CH_4 are the largest forcings (Fig. 4), so it is especially important to examine their ongoing changes.

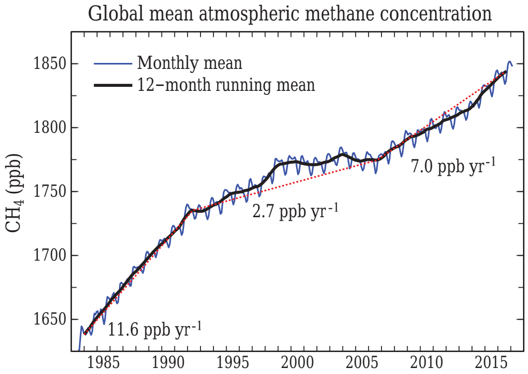

Figure 7. Global CH_4 from Dlugokencky (2016), NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/). End months for three indicated slopes are January 1984, May 1992, August 2006, and February 2017.

5 Observed CO_2 and CH_4 growth rates

Annual increase in atmospheric CO_2, averaged over a few years, grew from less than 1 ppm yr^{-1} 50 years ago to more than 2 ppm yr^{-1} today (Fig. 6), with global mean CO_2 now exceeding 400 ppm (Betts et al., 2016). Growth of atmospheric CO_2 is about half of fossil fuel CO_2 emissions as discussed in Appendix A8 and illustrated in Fig. A8. The large oscillations of annual growth are correlated with global temperature and with the El Niño/La Niña cycle, as discussed in Appendix A8. Recent global temperature anomalies peaked in February 2016, so as expected the CO_2 growth rate has been declining for the past several months (Fig. 6a).

Atmospheric CH_4 stopped growing between 1998 and 2006, indicating that its sources were nearly in balance with the atmospheric oxidation sink, but growth resumed in the past decade (Fig. 7). CH_4 growth averaged 10 ppb yr^{-1} in 2014–2016, almost as fast as in the 1980s. Likely reasons for the recent increased growth of CH_4 are discussed in Appendix A8.

The continued growth of atmospheric CO_2 and reaccelerating growth of CH_4 raise important questions related to prospects for stabilizing climate. How consistent with reality are scenarios for phasing down climate forcing when tested by observational data? What changes to industrial and agricultural emissions are required to stabilize climate? We address these issues below.

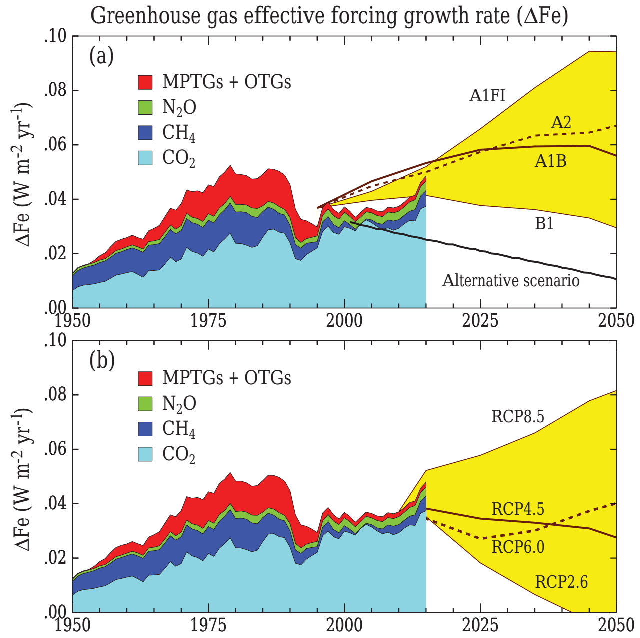

Figure 8. GHG climate forcing annual growth rate (ΔFe) with historical data being 5-year running means, except 2015 is a 3-year mean. Panel **(a)** includes scenarios used in IPCC AR3 and AR4 reports, and panel **(b)** has AR5 scenarios. GHG amounts are from NOAA/ESRL Global Monitoring Division. O_3 changes are not fully included, as they are not well measured, but its tropospheric changes are partially included via the effective CH_4 forcing. Effective climate forcing (Fe), MPTGs and OTGs are defined in the Fig. 4 caption.

6 GHG climate forcing growth rates and emission scenarios

Insight is obtained by comparing the growth rate of GHG climate forcing based on observed GHG amounts with past and present GHG scenarios. We examine forcings of IPCC Special Report on Emissions Scenarios (IPCC SRES, 2000) used in the 2001 AR3 and 2007 AR4 reports (Fig. 8a) and RCP scenarios (Moss et al., 2010; Meinshausen et al., 2011a) used in the 2013 IPCC AR5 report (Fig. 8b). We include the "alternative scenario" of Hansen et al. (2000) in which CO_2 and CH_4 emissions decline such that global temperature stabilizes near the end of the century.[10] We use the same radiation equations for observed GHG amounts and scenarios, so errors in the radiation calculations do not alter the comparison. Equations for GHG forcings are from Table 1 of Hansen et al. (2000) with the CH_4 forcing using an efficacy factor 1.4 to include effects of CH_4 on tropospheric O_3 and stratospheric H_2O (Hansen et al., 2005).

The growth of GHG climate forcing peaked at $\sim 0.05\,\mathrm{W\,m^{-2}\,yr^{-1}}$ ($5\,\mathrm{W\,m^{-2}\,century^{-1}}$) in 1978–1988, then falling to a level 10–25 % below IPCC SRES (2000) scenarios during the first decade of the 21st century (Fig. 8a). The decline was due to (1) decline of the airborne fraction of CO_2 emissions (Fig. A8), (2) slowdown of CH_4 growth (Fig. 7), and (3) the Montreal Protocol, which initiated phase-out of the production of gases that destroy stratospheric ozone, primarily chlorofluorocarbons (CFCs).

The 2013 IPCC RCP scenarios (Fig. 8b) use observed GHG amounts up to 2005 and diverge thereafter, fanning out into an array of potential futures driven by assumptions about energy demand, fossil fuel prices, and climate policy, chosen to be representative of an extensive literature on possible emissions trajectories (Moss et al., 2010; van Vuuren et al., 2011; Meinshausen et al., 2011a, b). Numbers on the RCP scenarios (8.5, 6.0, 4.5 and 2.6) refer to the GHG climate forcing ($\mathrm{W\,m^{-2}}$) in 2100.

Scenario RCP2.6 has the world moving into negative growth (net contraction) of GHG forcing 25 years from now (Fig. 8b), through rapid reduction of GHG emissions, along with CO_2 capture and storage. Already in 2015 there is a huge gap between reality and RCP2.6. Closing the gap ($0.01\,\mathrm{W\,m^{-2}}$) between actual growth of GHG climate forcing in 2015 and RCP2.6 (Fig. 8b), with CO_2 alone, would require extraction from the atmosphere of more than 0.7 ppm of CO_2 or 1.5 PgC due to the emissions gap of a single year (2015). We discuss the plausibility and estimated costs of scenarios with CO_2 extraction in Sect. 9.

As a complement to RCP scenarios, we define scenarios with focus on the dominant climate forcing, CO_2, with its changes defined simply by percent annual emission decrease or increase. Below (Sect. 10.1 and Appendix A13) we conclude that efforts to limit non-CO_2 forcings could keep their growth small or even slightly negative, so a focus on long-lived CO_2 is appropriate. Thus, for the non-CO_2 GHGs we use RCP6.0, a scenario with small changes of these gases. For CO_2 we consider rates -6, $-3\,\%\,\mathrm{yr^{-1}}$, constant emissions, and $+2\,\%\,\mathrm{yr^{-1}}$; emissions stop increasing in the $+2\,\%\,\mathrm{yr^{-1}}$ case when they reach $25\,\mathrm{Gt\,yr^{-1}}$ (Fig. 9a). Scenarios with decreasing emissions are preceded by constant emissions for 2015–2020, in recognition that some time is required to achieve policy change and implementation. Note the similarity of RCP2.6 with $-3\,\%\,\mathrm{yr^{-1}}$, RCP4.5 with constant emissions, and RCP8.5 with $+2\,\%\,\mathrm{yr^{-1}}$ (Fig. 9).

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[10] This scenario is discussed by Hansen and Sato (2004). CH_4 emissions decline moderately, producing a small negative forcing. CO_2 emissions (not captured and sequestered) are assumed to decline until in 2100 fossil fuel emissions just balance uptake of CO_2 by the ocean and biosphere. CO_2 emissions continue to decline after 2100.

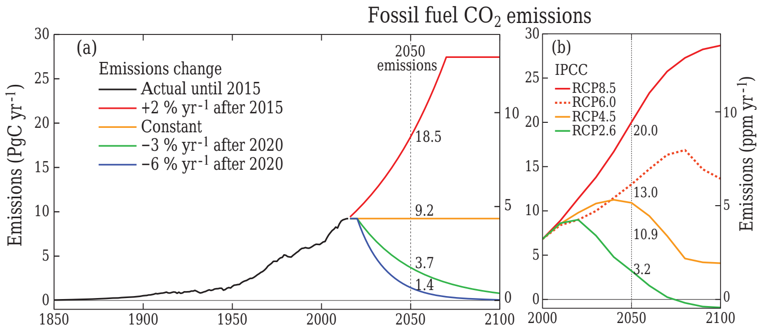

Figure 9. Fossil fuel emission scenarios. **(a)** Scenarios with simple specified rates of emission increase or decrease. **(b)** IPCC (2013) RCP scenarios. Note: 1 ppm atmospheric CO_2 is ~2.12 GtC.

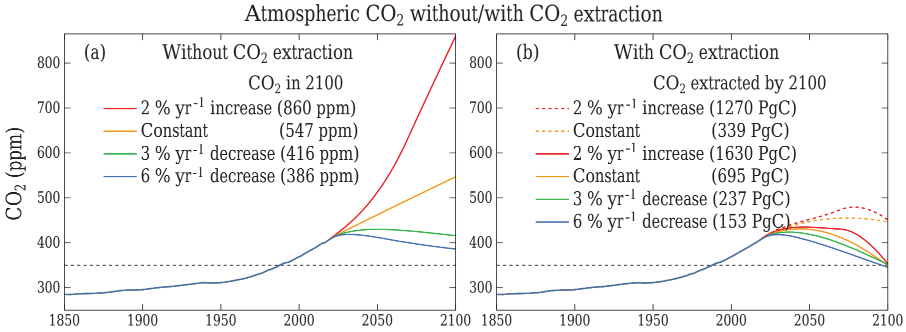

Figure 10. (a) Atmospheric CO_2 for Fig. 9a emission scenarios. **(b)** Atmospheric CO_2 including effect of CO_2 extraction that increases linearly after 2020 (after 2015 in +2 % yr^{-1} case).

7 Future CO_2 for assumed emission scenarios

We must model Earth's carbon cycle, including ocean uptake of carbon, deforestation, forest regrowth and carbon storage in the soil, for the purpose of simulating future atmospheric CO_2 as a function of the fossil fuel emission scenario. Fortunately, the convenient dynamic-sink pulse-response function version of the well-tested Bern carbon cycle model (Joos et al., 1996) does a good job of approximating more detailed models, and it produces a good match to observed industrial-era atmospheric CO_2. Thus, we use this relatively simple model, described elsewhere (Joos et al., 1996; Kharecha and Hansen, 2008, and references therein), to examine the effect of alternative fossil fuel use scenarios on the growth or decline of atmospheric CO_2. Assumptions about emissions in the historical period are given in Appendix A9.

Figure 10a shows the simulated atmospheric CO_2 for the baseline emission cases (Fig. 9a). These cases do not include active CO_2 removal. Five additional cases including CO_2 removal (Fig. 10b) achieve atmospheric CO_2 targets of either 350 or 450 ppm in 2100, with cumulative removal amounts listed in parentheses (Fig. 10b). The rate of CO_2 extraction in all cases increases linearly from zero in 2010 to the value in 2100 that achieves the atmospheric CO_2 target (350 or 450 ppm). The amount of CO_2 that must be extracted from the system exceeds the difference between the atmospheric amount without extraction and the target amount (e.g., constant CO_2 emissions and no extraction yield 547 ppm for atmospheric CO_2 in 2100), but to achieve a target of 350 ppm the required extraction is 328 ppm, not 547–350 = 197 ppm. The well-known reason (Cao and Caldeira, 2010) is that ocean outgassing increases and vegetation productivity and ocean CO_2 uptake decrease with decreasing atmospheric CO_2, as explored in a wide range of Earth system models (Jones et al., 2016).

8 Simulations of global temperature change

Analysis of future climate change, and policy options to alter that change, must address various uncertainties. One useful way to treat uncertainty is to use results of many models and construct probability distributions (Collins et al., 2013). Such distributions have been used to estimate the remaining budget for fossil fuel emissions for a specified likelihood of staying under a given global warming limit and to compare alternative policies for limiting climate forcing and global warming (Rogelj et al., 2016a, b).

Our aim here is a fundamental, transparent calculation that clarifies how future warming depends on the rate of fossil fuel emissions. We use best estimates for basic uncertain quantities such as climate sensitivity. If these estimates are accurate, actual temperature should have about equal chances of falling higher or lower than the calculated value. Important uncertainties in projections of future climate change include climate sensitivity, the effects of ocean mixing and dynamics on the climate response function discussed below, and aerosol climate forcing. We provide all defining data so that others can easily repeat calculations with alternative choices.

One clarification is important for our present paper. The climate calculations in this section include only fast-feedbacks, which is also true for most climate simulations by the scientific community for IPCC (2013). This is not a limitation for the past, i.e., for the period 1850–present, because we employ measured GHG changes, which include any GHG change due to slow feedbacks. Also, we know that ice sheets did not change significantly in size in that period; there may have been some change in Greenland's albedo and expansion of forests in the Northern Hemisphere (Pearson et al., 2013), but those feedbacks so far have only a small global effect. However, this limitation to fast feedbacks may soon become important; it is only in the past few decades that global temperature rose above the prior Holocene range and only in the past 2 years that it shot far above that range. This limitation must be borne in mind when we consider the role of slow feedbacks in establishing the dangerous level of warming.

We calculate global temperature change T at time t in response to any climate forcing scenario using the Green's function (Hansen, 2008)

$$T(t) = \int_{1850}^{t} R(t-t')[\mathrm{d}F(t')/\mathrm{d}t']\mathrm{d}t' + \mathrm{Fv} \times R(t-1850), \qquad (1)$$

where $R(t')$ is the product of equilibrium global climate sensitivity and the dimensionless climate response function (percent of equilibrium response), $\mathrm{d}F(t')/\mathrm{d}t'$ is the annual increment of the net forcing, and Fv is the negative of the average volcanic aerosol forcing during the few centuries preceding 1850. $\mathrm{Fv} \times R(t)$ is a small correction term that prevents average volcanic aerosol activity from causing a long-term cooling – i.e., it accounts for the fact that the ocean in 1850 was slightly cooled by prior volcanoes. We take $\mathrm{Fv} = 0.3\,\mathrm{W\,m^{-2}}$, the average stratospheric aerosol forcing for 1850–2015. The assumed-constant pre-1850 volcanic aerosols caused a constant cooling up to 1850, which gradually decreases to zero after 1850 and is replaced by post-1850 time-dependent volcanic cooling; note that $T(1850) = 0\,^\circ\mathrm{C}$. We use the "intermediate" response function in Fig. 5 of Hansen et al. (2011), which gives good agreement with Earth's measured energy imbalance. The response function is 0.15, 0.55, 0.75 and 1 at years 1, 10, 100 and 2000 with these values connected linearly in log (year). This defined response function allows our results to be exactly reproduced, or altered with alternative choices for climate forcings, climate sensitivity and response function. Forcings that we use are tabulated in Appendix A10.

We use equilibrium fast-feedback climate sensitivity $0.75\,^\circ\mathrm{C}\,(\mathrm{W\,m^{-2}})^{-1}$ ($3\,^\circ\mathrm{C}$ for $2 \times CO_2$). This is consistent with climate models (Collins et al., 2013: Flato et al., 2013) and paleoclimate evidence (Rohling et al., 2012a; Masson-Delmotte et al., 2013; Bindoff and Stott, 2013). We use RCP6.0 for the non-CO_2 GHGs.

We take tropospheric aerosol plus surface albedo forcing as $-1.2\,\mathrm{W\,m^{-2}}$ in 2015, presuming the aerosol and albedo contributions to be -1 and $-0.2\,\mathrm{W\,m^{-2}}$, respectively. We assume a small increase this century as global population rises and increasing aerosol emission controls in emerging economies tend to be offset by increasing development elsewhere, so aerosol + surface forcing is $-1.5\,\mathrm{W\,m^{-2}}$ in 2100. The temporal shape of the historic aerosol forcing curve (Table A10) is from Hansen et al. (2011), which in turn was based on the Novakov et al. (2003) analysis of how aerosol emissions have changed with technology change.

Historic stratospheric aerosol data (Table A10, annual version), an update of Sato et al. (1993), include moderate 21st century aerosol amounts (Bourassa et al., 2012). Future aerosols, for realistic variability, include three volcanic eruptions in the rest of this century with properties of the historic Agung, El Chichón and Pinatubo eruptions, plus a background stratospheric aerosol forcing of $-0.1\,\mathrm{W\,m^{-2}}$. This leads to mean stratospheric aerosol climate forcing of $-0.3\,\mathrm{W\,m^{-2}}$ for remainder of the 21st century, similar to the mean stratospheric aerosol forcing for 1850–2015 (Table A10). Reconstruction of historical solar forcing (Coddington et al., 2016; Kopp et al., 2016), based on data in Fig. A11, is extended with an 11-year cycle.

Individual and net climate forcings for the several fossil fuel emission reduction rates are shown in Fig. 11a and c. Scenarios with linearly growing CO_2 extraction at rates required to yield 350 or 450 ppm airborne CO_2 in 2100 are in Fig. 11b and d. These forcings and the assumed climate response function define expected global temperature for the entire industrial era considered here (Fig. 12). We extended the global temperature calculations from 2100 to 2200 by continuing the $\%\,\mathrm{yr}^{-1}$ change in CO_2 emissions. In the cases with CO_2 extraction we kept the GHG climate forcing fixed in the 22nd century, which meant that large CO_2 extraction continued in cases with continuing high emissions; for example, the case with constant emissions that required extraction of 695 PgC during 2020–2100 required further extraction of ∼ 900 PgC during 2100–2200. Even the cases with annual emission reductions -6 and $-3\,\%\,\mathrm{yr}^{-1}$ required small extractions to compensate for back-flux of CO_2 from the ocean that accumulated there historically.

A stark summary of alternative futures emerges from Fig. 12a. If emissions grow $2\,\%\,\mathrm{yr}^{-1}$, modestly slower than the $2.6\,\%\,\mathrm{yr}^{-1}$ growth of 2000–2015, warming reaches ∼ 4 °C by 2100. Warming is about 2 °C if emissions are constant until 2100. Furthermore, both scenarios launch.

Earth onto a course of more dramatic change well beyond the initial 2–3 °C global warming, because (1) warming con-

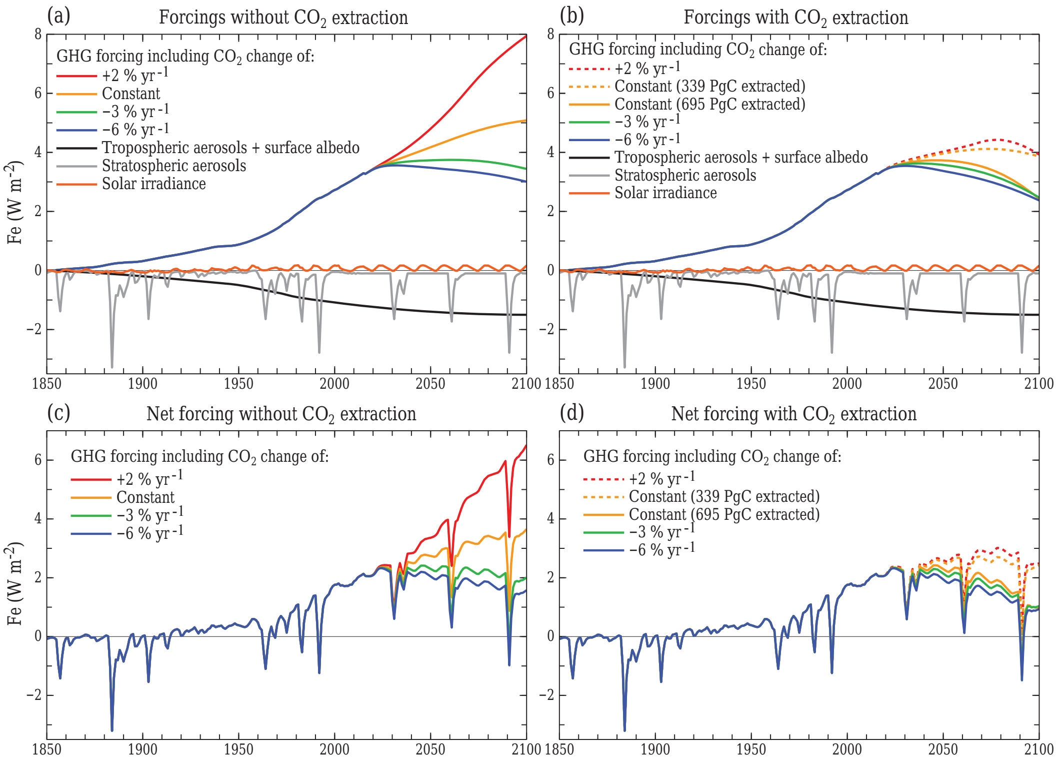

Figure 11. Climate forcings used in our climate simulations; Fe is effective forcing, as discussed in connection with Fig. 4. **(a)** Future GHG forcing uses four alternative fossil fuel emission growth rates. **(b)** GHG forcings are altered based on CO_2 extractions of Fig. 10.

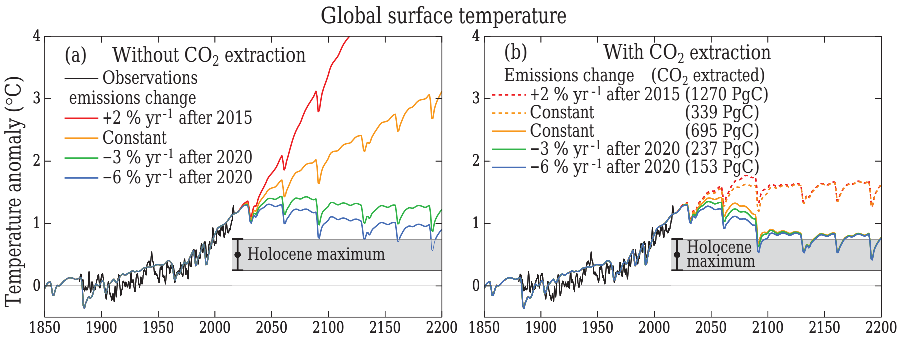

Figure 12. Simulated global temperature for Fig. 11 forcings. Observations as in Fig. 2. Temperature zero-point is the 1880–1920 mean temperature for both observations and model. Gray area is 2σ (95 % confidence) range for centennially smoothed Holocene maximum, but there is further uncertainty about the magnitude of the Holocene maximum, as noted in the text and discussed by Liu et al. (2014).

tinues beyond 2100 as the planet is still far from equilibrium with the climate forcing, and (2) warming of 2–3 °C would unleash strong slow feedbacks, including melting of ice sheets and increases of GHGs.

The most important conclusion from Fig. 12a is the proximity of results for the cases with emission reductions of 6 and 3 % yr^{-1}. Although Hansen et al. (2013a) called for emission reduction of 6 % yr^{-1} to restore CO_2 to 350 ppm by 2100, that rate of reduction may have been regarded as implausibly steep by a federal court in 2012, when it declined to decide whether the US was violating the public trust by causing or contributing to dangerous climate change (Alec L v. Jackson, 2012). Such a concern is less pressing for emission reductions of 3 % yr^{-1}. Note that reducing global emissions at a rate of 3 % yr^{-1} (or more steeply) maintains global warming at less than 1.5 °C above preindustrial temperature.

However, end-of-century temperature still rises 0.5 °C or more above the prior Holocene maximum with consequences for slow feedbacks that are difficult to foresee. Desire to minimize sea level rise spurs the need to get global temperature back into the Holocene range. That goal preferably should be achieved on the timescale of a century or less, because paleoclimate evidence indicates that the response time of sea level to climate change is 1–4 centuries (Grant et al., 2012, 2014) for natural climate change, and if anything the response should be faster to a stronger, more rapid human-made climate forcing. The scenarios that reduce CO_2 to 350 ppm succeed in getting temperature back close to the Holocene maximum by 2100 (Fig. 12b), but they require extractions of atmospheric CO_2 that range from 153 PgC in the scenario with 6 % yr^{-1} emission reductions to 1630 PgC in the scenario with +2 % yr^{-1} emission growth.

Scenarios ranging from constant emissions to +2 % yr^{-1} emissions growth can be made to yield 450 ppm in 2100 via extraction of 339–1270 PgC from the atmosphere (Fig. 10b). However, these scenarios still yield warming more than 1.5 °C above the preindustrial level (more than 1 °C above the early Holocene maximum). Consequences of such warming and the plausibility of extracting such huge amounts of atmospheric CO_2 are considered below.

9 CO_2 extraction: estimated cost and alternatives

Extraction of CO_2 from the air, also called negative emissions or carbon dioxide removal (CDR), is required if large, long-term excursion of global temperature above its Holocene range is to be averted, as shown above. In estimating the cost and plausibility of CO_2 extraction we distinguish between (1) carbon extracted from the air by improved agricultural and forestry practices, and (2) additional "technological extraction" by intensive negative emission technologies.

We assume that improved practices will aim at optimizing agricultural and forest carbon uptake via relatively natural approaches, compatible with the land delivering a range of ecosystem services (Smith, 2016; Smith et al., 2016). In contrast, proposed technological extraction and storage of CO_2 generally does not have co-benefits and remains unproven at relevant scales (NAS, 2015a). Improved practices have local benefits in agricultural yields and forest products and services (Smith et al., 2016), which may help minimize net costs. The intended nationally determined contributions (INDCs) submitted by 189 countries include carbon drawdown through land use plans (United Nations, 2016) with aggregate removal rate of $\sim 2\,PgCO_2\,yr^{-1}$ ($\sim 0.55\,PgC\,yr^{-1}$) after 2020. These targets are not the maximum possible drawdown, as they are only about a third of amounts Smith (2016) estimated as "realistic".

Developed countries recognize a financial obligation to less developed countries that have done little to cause climate change (Paris Agreement 2015).[11] We suggest that at least part of developed country support should be channeled through agricultural and forestry programs, with continual evaluation and adjustment to reward and encourage progress (Bustamante et al., 2014). Efforts to minimize non-CO_2 GHGs can be included in the improved practices program.

Here, we do not estimate the cost of CO_2 extraction obtained via the "improved agricultural and forestry practices",[12] because that would be difficult given the range of activities it is likely to entail, and because it is not necessary for reaching the conclusion that total CO_2 extraction costs will be high due to the remaining requirements for technological extraction. However, we do estimate the potential magnitude of CO_2 extraction that might be achievable via such improved practices, as that is needed to quantify the required amount of "technological extraction" of CO_2. Finally, we compare costs of extraction with estimated costs of mitigation measures that could limit the magnitude of required extraction, while admitting that there is large uncertainty in both extraction and mitigation cost estimates.

9.1 Estimated cost of CO_2 extraction

Hansen et al. (2013a) suggested a goal of 100 PgC extraction in the 21^{st} century, which would be almost as large as estimated net emissions from historic deforestation and land use (Ciais et al., 2013). Hansen et al. (2013a) assumed that 100 PgC was about as much as could be achieved via relatively natural reforestation and afforestation (Canadell and Raupach, 2008) and improved agricultural practices that increase soil carbon (Smith, 2016).

Here we first reexamine whether a concerted global effort on carbon storage in forests and soil might have potential to provide a carbon sink substantially larger than 100 PgC this century. Smith et al. (2016) estimate that reforestation and afforestation together have carbon storage potential of about 1.1 PgC yr^{-1}. However, as forests mature, their uptake of atmospheric carbon decreases (termed "sink saturation"), thereby limiting CO_2 drawdown. Taking 50 years as the average time for tropical, temperate and boreal trees to experience sink saturation yields 55 PgC as the potential storage in forests this century.

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[11] Another conceivable source of financial support for CO_2 drawdown might be legal settlements with fossil fuel companies, analogous to penalties that courts have imposed on tobacco companies, but with the funds directed to the international "improved practices" programs.

[12] A comment is in order about the relation of "improved agricultural and forestry practices" with an increased role of biofuels in climate mitigation. Agriculture, forestry and other land use have potential for important contributions to climate change mitigation (Smith et al., 2014). However, first-generation biofuel production and use (which is usually based on edible portions of feedstocks, such as starch) is not inherently carbon-neutral; indeed, it is likely carbon-positive, as has been illustrated in specific quantitative analyses for corn ethanol in the United States (Searchinger et al., 2008; DeCicco et al., 2016). The need for caution regarding the role of biofuels in climate mitigation is discussed by Smith et al. (2014).

Smith (2016) shows that soil carbon sequestration and soil amendment with biochar compare favorably with other negative emission technologies with less impact on land use, water use, nutrients, surface albedo, and energy requirements, but understanding of and literature on biochar are limited (NAS, 2015a). Smith (2016) estimates that soil carbon sequestration has potential to store 0.7 PgC yr^{-1}. However, as with carbon storage in forest, there is a saturation effect. A commonly used 20-year saturation time (IPCC, 2006) would yield 14 PgC soil carbon storage, while an optimistic 50-year saturation time would yield 35 PgC. Use of biochar to improve soil fertility provides additional carbon storage of up to 0.7–1.8 PgC yr^{-1} (Woolf et al., 2010; Smith, 2016). Larger industrial-scale biochar carbon storage is conceivable, but belongs in the category of intensive negative emission technologies, discussed below, whose environmental impacts and costs require scrutiny. We conclude that 100 PgC is an appropriate ambitious estimate for potential carbon extraction via a concerted global-scale effort to improve agricultural and forestry practices with carbon drawdown as a prime objective.

Intensive negative emission technologies that could yield greater CO_2 extraction include (1) burning of biofuels, most commonly at power plants, with capture and sequestration of resulting CO_2 (Creutzig et al., 2015), and (2) direct air capture of CO_2 and sequestration (Keith, 2009; NAS, 2015a), and (3) grinding and spreading of minerals such as olivine to enhance geological weathering (Taylor et al., 2016). However, energy, land and water requirements of these technologies impose economic and biophysical limits on CO_2 extraction (Smith et al., 2016).

The popular concept of bioenergy with carbon capture and storage (BECCS) requires large areas and high fertilizer and water use, and may compete with other vital land use such as agriculture (Smith, 2016). Costs estimates are ∼ USD 150–350 $(tC)^{-1}$ for crop-based BECCS (Smith et al., 2016).

Direct air capture has more limited area and water needs than BECCS and no fertilizer requirement, but it has high energy use, has not been demonstrated at scale, and cost estimates exceed those of BECCS (Socolow et al., 2011; Smith et al., 2016). Keith et al. (2006) have argued that, with strong research and development support and industrial-scale pilot projects sustained over decades, it may be possible to achieve costs ∼ USD 200 $(tC)^{-1}$, thus comparable to BECCS costs; however, other assessments are higher, reaching USD 1400–3700 $(tC)^{-1}$ (NAS, 2015a).

Enhanced weathering via soil amendment with crushed silicate rock is a candidate negative emission technology that also limits coastal ocean acidification as chemical products liberated by weathering increase land–ocean alkalinity flux (Kohler et al., 2010; Taylor et al., 2016). If two-thirds of global croplands were amended with basalt dust, as much as 1–3 PgC yr^{-1} might be extracted, depending on application rate (Taylor et al., 2016), but energy costs of mining, grinding and spreading likely reduce this by 10–25 % (Moosdorf et al., 2014). Such large-scale enhanced weathering is speculative, but potential co-benefits for temperate and tropical agroecosystems could affect its practicality, and may put some enhanced weathering into the category of improved agricultural and forestry practices. Benefits include crop fertilization that increases yield and reduces use and cost of other fertilizers, increasing crop protection from insect herbivores and pathogens thus decreasing pesticide use and cost, neutralizing soil acidification to improve yield, and suppression of GHG (N_2O and CO_2) emissions from soils (Edwards et al., 2017; Kantola et al., 2017). Against these benefits, we note potential negative impacts of air and water pollution caused by the mining, including downstream environmental consequences if silicates are washed into rivers and the ocean, causing increased turbidity, sedimentation, and pH, with unknown impacts on biodiversity (Edwards et al., 2017). Cost of enhanced weathering might be reduced by deployment with reforestation and afforestation and with crops used for BECCS; this could significantly enhance the combined carbon sequestration potential of these methods.

For cost estimates, we first consider restoration of airborne CO_2 to 350 ppm in 2100 (Fig. 10b), which would keep global warming below 1.5 °C and bring global temperature back close to the Holocene maximum by the end of the century (Fig. 12b). This scenario keeps the temperature excursion above the Holocene level small enough and brief enough that it has the best chance of avoiding ice sheet instabilities and multi-meter sea level rise (Hansen et al., 2016). If fossil fuel emission phasedown of 6 % yr^{-1} had begun in 2013, as proposed by Hansen et al. (2013a), this scenario would have been achieved via the hypothesized 100 PgC carbon extraction from improved agricultural and forestry practices.

We examine here scenarios with 6 and 3 % yr^{-1} emission reduction starting in 2021, as well as scenarios with constant emissions and +2 % yr^{-1} emission growth starting in 2016 (Figs. 10b and 12b). The −6 and −3 % yr^{-1} scenarios leave a requirement to extract 153 and 237 PgC from the air during this century. Constant emission and +2 % yr emission scenarios yield extraction requirements of 695 and 1630 PgC to reach 350 ppm CO_2 in 2100.

Total CO_2 extraction requirements for these scenarios are given in Fig. 10. Cost estimates here for extraction use amounts 100 Pg less than in Fig. 10 under assumption that 100 PgC can be stored via improved agricultural and forestry practices. Shortfall of this 100 PgC goal will increase our estimated costs accordingly, as will the cost of the improved agricultural and forestry program.

Given a CO_2 extraction cost of USD 150–350 $(tC)^{-1}$ for intensive negative emission technologies (Fig. 3f of Smith et al., 2016), the 53 PgC additional extraction required for the scenario with 6 % yr^{-1} emission reduction would cost USD 8–18.5 trillion, thus USD 100–230 billion per year if spread uniformly over 80 years. We cannot rule out possible future reduction in CO_2 extraction costs, but given the energy requirements for removal and the already optimistic lower limit on our estimate, we do not speculate further about potential cost reduction.

In contrast, continued high emissions, between constant emissions and $+2\,\%\,\mathrm{yr}^{-1}$, would require additional extraction of 595–1530 PgC (Fig. 10b) at a cost of USD 89–535 trillion or 1.1–6.7 trillion per year over 80 years.[13] Such extraordinary cost, along with the land area, fertilizer and water requirements (Smith et al., 2016) suggest that, rather than the world being able to buy its way out of climate change, continued high emissions would likely force humanity to live with climate change running out of control with all the consequences that would entail.

9.2 Mitigation alternative

High costs of CO_2 extraction raise the question of how these costs compare to the alternative: taking actions to mitigate climate change by reducing fossil fuel CO_2 emissions. The Stern Review (Stern, 2006; Stern and Taylor, 2007) used expert opinion to produce an estimate for the cost of reducing emissions to limit global warming to about 2 °C. Their central estimate was 1 % of gross domestic product (GDP) per year, thus about USD 800 billion per year. They argued that this cost was much less than likely costs of future climate damage if high emissions continue, unless we apply a high "discount rate" to future damage, which has ethical implications in its treatment of today's young people and future generations. However, their estimated uncertainty of the cost is ±3 %, i.e., the uncertainty is so large as to encompass GDP gain.

Hsu (2011) and Ackerman and Stanton (2012) argue that economies are more efficient if the price of fossil fuels better reflects costs to society, and thus GDP gain is likely with an increasing carbon price. Mankiw (2009) similarly suggests that a revenue-neutral carbon tax is economically beneficial. Hansen (2009, 2014) advocates an approach in which a gradually rising carbon fee is collected from the fossil fuel industry with the funds distributed uniformly to citizens. This approach provides incentives to business and the public that drive the economy toward energy efficiency, conservation, renewable energies and nuclear power. An economic study of this carbon-fee-and-dividend policy in the US (Nystrom and Luckow, 2014) supports the conclusion that GDP increases as the fee rises steadily. These studies refute the common argument that environmental protection is damaging to economic prosperity.

We can also compare CO_2 extraction cost with the cost of carbon-free energy infrastructure. Global energy consumption in 2015 was 12.9 Gtoe[14] with coal providing 30 % of global energy and almost 45 % of global fossil fuel CO_2 emissions (BP, 2016). Most coal use, and its increases, is in Asia, especially China and India. Carbon-free replacement for coal energy is expected to be some combination of renewables (including hydropower) and nuclear power. China is leading the world in installation of wind, solar and nuclear power, with new nuclear power in 2015 approximately matching the sum of new solar and wind power (BP, 2016). For future decarbonization of electricity it is easiest to estimate the cost of the nuclear power component, because nuclear power can replace coal for baseload electricity without the need for energy storage or major change to national electric grids. Recent costs of Chinese and South Korean light water reactors are in the range USD 2000–3000 per kilowatt (Chinese Academy of Engineering, 2015; Lovering et al., 2016). Although in some countries reactor costs stabilized or declined with repeated construction of the same reactor design, in others costs have risen for a variety of reasons (Lovering et al., 2016). Using USD 2500 per kilowatt as reactor cost and assuming 85 % capacity factor (percent uptime for reactors) yields a cost of USD 10 trillion to produce 20 % of present global energy use (12.9 Gtoe). Note that 20 % of current global energy use is a huge amount (Fig. 13), exceeding the sum of present hydropower (6.8 %), nuclear (4.4 %), wind (1.4 %), solar (0.4 %), and other renewable energies (0.9 %).

We do not suggest that new nuclear power plants on this scale will or necessarily should be built. Rather we use this calculation to show that mitigation costs are not large in comparison to costs of extracting CO_2 from the air. Renewable energy costs have fallen rapidly in the past 2–3 decades with the help of government subsidies, especially renewable portfolio standards that require utilities to achieve a specified fraction of their power from renewable sources. Yet fossil fuel use continues to be high, at least in part because fossil fuel prices do not include their full cost to society. Rapid and economic movement to non-fossil energies would be aided by a rising carbon price, with the composition of energy sources determined by competition among all non-fossil energy sources, as well as energy efficiency and conservation. Sweden provides a prime example: it has cut per capita emissions by two-thirds since the 1990s while doubling per capita income in a capitalistic framework that embodies free-market principles (Pierrehumbert, 2016).

Mitigation of climate change deserves urgent priority. We disagree with assessments such as "the world will probably have only two choices if it wants to stay below 1.5 °C of warming. It must either deploy carbon dioxide removal on an enormous scale or use solar geoengineering" (Parker and Geden, 2016). While we reject 1.5 °C as a safe target – it is likely warmer than the Eemian and far above the Holocene range – Fig. 12 shows that fossil fuel emission reduction of $3\,\%\,\mathrm{yr}^{-1}$ beginning in 2021 yields maximum global warming $\sim 1.5\,°\mathrm{C}$ for climate sensitivity 3 °C for $2 \times CO_2$, with neither CO_2 removal nor geoengineering. These calculations

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[13] For reference, the United Nations global peacekeeping budget is about USD 10 billion per year. National military budgets are larger: the 2015 USA military budget was USD 596 billion and the global military budget was USD 1.77 trillion (SIPRI, 2016).

[14] Gtoe is gigatons oil equivalent; 1 Gtoe, is 41.868 EJ (exajoule $= 10^{18}$ J) or 11 630 TWh (terawatt hours).

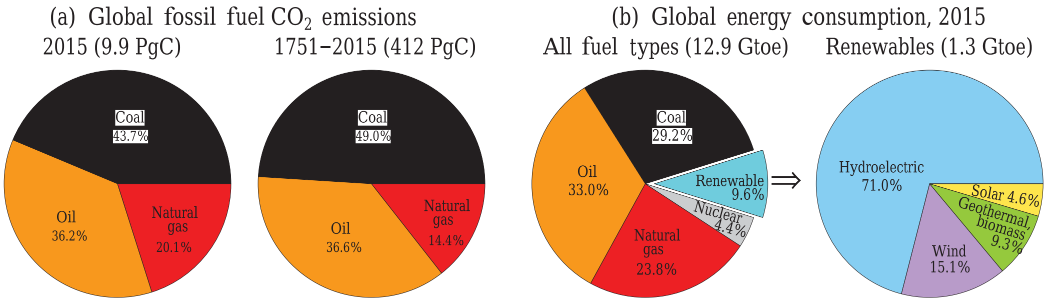

Figure 13. **(a)** Global fossil fuel emissions data from Boden et al. (2017) for 1751–2014 are extended to 2015 using BP (2016) data. **(b)** Global primary energy consumption data from BP (2016); energy accounting method is the substitution method (Macknick, 2011).

show that mitigation – reduction of fossil fuel emissions – is very effective. We know no persuasive scientific reason to a priori reject as implausible a rapid phasedown of fossil fuel emissions.

10 Non-CO_2 GHGs, aerosols and purposeful climate intervention

10.1 Non-CO_2 GHGs

The annual increment in GHG climate forcing is growing, not declining. The increase is more than 20 % in just the past 5 years (Fig. 8). Resurgence of CH_4 growth is partly responsible, but CO_2 is by far the largest contributor to growth of GHG climate forcing (Fig. 8). Nevertheless, given the difficulty and cost of reducing CO_2, we must ask about the potential for reducing non-CO_2 GHGs. Could realistic reductions of these other gases substantially alter the CO_2 abundance required to meet a target climate forcing?

We conclude, as discussed in Appendix A13, that a net decrease in climate forcing by non-CO_2 GHGs of perhaps $-0.25\,\mathrm{W\,m^{-2}}$ relative to today is plausible, but we must note that this is a dramatic change from the growing abundances, indeed accelerating growth, of these gases today. Achievement of this suggested negative forcing requires (i) successful completion of planned phase-out of MPTGs ($-0.23\,\mathrm{W\,m^{-2}}$), (ii) absolute reductions of CH_4 forcing by $0.12\,\mathrm{W\,m^{-2}}$ from its present value, and (iii) N_2O forcing increasing by only $0.1\,\mathrm{W\,m^{-2}}$. Achieving this net negative forcing of $-0.25\,\mathrm{W\,m^{-2}}$ for non-CO_2 gases would allow CO_2 to be 365 ppm, rather than 350 ppm, while yielding the same total GHG forcing. Absolute reduction of non-CO_2 gases is thus helpful but does not alter the requirement for rapid fossil fuel emission reductions. Moreover, this is an optimistic scenario that is unlikely to occur in the absence of a reduction of CO_2, which is needed to limit global warming and thus avoid amplifying GHG feedbacks.

10.2 Aerosols and purposeful climate intervention

Human-made aerosols today are believed to cause a large, albeit poorly measured, negative climate forcing (Fig. 4) of the order of $-1\,\mathrm{W\,m^{-2}}$ with uncertainty of at least $0.5\,\mathrm{W\,m^{-2}}$ (Fig. 7.19, Boucher et al., 2013). Fossil fuel burning is only one of several human-caused aerosol sources (Boucher et al., 2013). Given that human population continues to grow, and that human-caused climate effects such as increased desertification can lead to increased aerosols, we do not anticipate a large reduction in the aerosol cooling effect, even if fossil fuel use declines. Rao et al. (2017) suggest that future aerosol amount will decline due to technological advances and global action to control emissions. We are not confident of such a decline, as past controls have been at least matched by increasing emissions in developing regions, and global population continues to grow. However, to the extent that Rao et al. (2017) projections are borne out, they will only strengthen the conclusions of our present paper about the threat of climate change for young people and the burden of decreasing GHG amounts in the atmosphere.

Recognition that aerosols have a cooling effect, combined with the difficulty of restoring CO_2 to 350 ppm or less, inevitably raises the issue of purposeful climate intervention, also called geoengineering, and specifically solar radiation management (SRM). The cooling mechanism receiving greatest attention is injection of SO_2 into the stratosphere (Budyko, 1974; Crutzen, 2006), thus creating sulfuric acid aerosols that mimic the effect of volcanic aerosol cooling. That idea and others are discussed in a report of the US National Academy of Sciences (NAS, 2015b) and references therein. We limit our discussion to the following summary comments.

Such purposeful intervention in nature, an attempt to mitigate effects of one human-made pollutant with another, raises additional practical and ethical issues. Stratospheric aerosols, for example, could deplete stratospheric ozone and/or modify climate and precipitation patterns in ways that are difficult to predict with confidence, while doing nothing to alleviate ocean acidification caused by rising CO_2; we note that Keith et al. (2016) suggest alternative aerosols that would limit the impact on ozone. However, climate intervention also raises issues of global governance, and introduces the possibility of sudden global consequences if aerosol injection is interrupted (Boucher at al., 2013). Despite these issues, it is apparent that cooling by aerosols, or other methods that alter the amount of sunlight absorbed by Earth, could be effective more quickly than the difficult process of removing CO_2 from the air. Thus, we agree with the NAS (2015b) conclusion that research is warranted to better define the climate, economic, political, ethical, legal and other dimensions of potential climatic interventions.

In summary, although research on climate interventions is warranted, the possibility of geoengineering can hardly be seen as alleviating the overall burden being placed on young people by continued high fossil fuel emissions. We concur with the assessment (NAS, 2015b) that such climate interventions are no substitute for the reduction of carbon dioxide emissions needed to stabilize climate and avoid deleterious consequences of rapid climate change.

11 Discussion

Global temperature is now far above its range during the preindustrial Holocene, attaining at least the warmth of the Eemian period, when sea level reached +6–9 m relative to today. Also, Earth is now out of energy balance, implying that more warming will occur, even if atmospheric GHG amounts are stabilized at today's level. Furthermore, the GHG climate forcing is not only still growing, the growth rate is actually accelerating, as shown in Fig. 14, which is extracted from data in our Fig. 8.

This summary, based on real-world data for temperature, planetary energy balance, and GHG changes, differs from a common optimistic perception of progress toward stabilizing climate. That optimism may be based on the lowered warming target in the Paris Agreement (2015), slowdown in the growth of global fossil fuel emissions in the past few years (Fig. A1), and falling prices of renewable energies, but the hard reality of the climate physics emerges in Figs. 2, 5, 8 and 14. Although the scenarios employed in climate simulations for the most recent IPCC study (AR5) include cases with rapidly declining GHG growth, the scenarios do nothing to alter reality, which reveals that GHG growth rates not only remain high, they are accelerating.

The need for prompt action implied by these realities may not be a surprise to the relevant scientific community, because paleoclimate data revealed high climate sensitivity and the dominance of amplifying feedbacks. However, effective communication with the public of the urgency to stem human-caused climate change is hampered by the inertia of the climate system, especially the ocean and the ice sheets, which respond rather slowly to climate forcings, thus allowing future consequences to build up before broad public concern awakens. Some effects of human-caused global warming are now unavoidable, but is it inevitable that sea level rise of many meters is locked in, and, if so, on what timescale? Precise unequivocal answers to such questions are not possible. However, useful statements can be made.

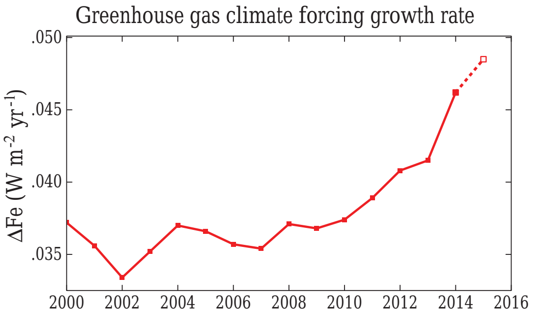

Figure 14. Recent growth rate of total GHG effective climate forcing; points are 5-year running means, except for 2015, which is a 3-year mean. See Fig. 8 for individual gases.

First, the inertia and slow response of the climate system also allow the possibility of actions to limit the climate response by reducing human-caused climate forcing in coming years and decades. Second, the response time itself depends on how strongly the system is being forced; specifically, the response might be much delayed with a weaker forcing.

For example, studies suggesting multi-meter sea level rise in a century assume continued high fossil fuel emissions this century (Hansen et al., 2016) or at least a 2 °C SST increase (DeConto and Pollard, 2016). Ice sheet response time decreases rapidly in models as the forcing increases, because processes such as hydrofracturing and collapse of marine-terminating ice cliffs spur ice sheet disintegration (Pollard et al., 2015). All amplifying feedbacks, including atmospheric water vapor, sea ice cover, soil carbon release and ice sheet melt could be reduced by rapid emissions phasedown. This would reduce the risk of climate change running out of humanity's control and provide time to assess the climate response, develop relevant technologies, and consider further purposeful actions to limit and/or adapt to climate change.

Concern exists that large sea level rise may be inevitable, because of numerous ice streams on Antarctica and Greenland with inward-sloping beds (beds that deepen upstream) subject to runaway marine ice sheet instability (Mercer, 1978; Schoof, 2007, 2010). Some ice stream instabilities may already have been triggered (Rignot et al., 2014), but the number of ice streams affected and the timescale of their response may differ strongly depending on the magnitude of the forcing (DeConto and Pollard, 2016). Sea level rise this century of say half a meter to a meter, which may be inevitable even if emissions decline, would have dire consequences, yet these are dwarfed by the humanitarian and economic disasters that would accompany sea level rise of several meters (McGranahan et al., 2007). Given the increasing proportion of global population living in coastal areas (Hallegatte et al., 2013), there is potential for forced migrations of hundreds of millions of people, dwarfing prior refugee humanitarian crises, challenging global governance (Biermann and Boas, 2010) and security (Gemenne et al., 2014).

Global temperature is a useful metric, because increasing temperature drives amplifying feedbacks. Global ocean temperature is a major factor affecting ice sheet size, as indicated by both model studies (Pollard et al., 2015) and paleoclimate analyses (Overpeck et al., 2006; Hansen et al., 2016). Eemian ocean warmth, probably not more than about +0.7 °C warmer than preindustrial conditions (McKay et al., 2011; Masson-Delmotte et al., 2013; Sect. 2.2 above), corresponding to global warmth about +1 °C relative to preindustrial, led to sea level 6–9 m higher than today. This implies that, in the long run, the El Niño-elevated 2016 temperature of +1.3 °C relative to preindustrial temperature, and even the (+1.05 °C) underlying trend to date without the El Niño boost, is probably too high for maintaining our present coastlines.

We conclude that the world has already overshot appropriate targets for GHG amount and global temperature, and we thus infer an urgent need for (1) rapid phasedown of fossil fuel emissions, (2) actions that draw down atmospheric CO_2, and (3) actions that, at minimum, eliminate net growth of non-CO_2 climate forcings. These tasks are formidable and, with the exception of the Montreal Protocol agreement on hydrofluorocarbons (HFCs) that will halt the growth of their climate forcing (Appendix A13), they are not being pursued globally. Actions at citizen, city, state and national levels to reduce GHG emissions provide valuable experience and spur technical developments, but without effective global policies the impact of these local efforts is reduced by the negative feedback caused by reduced demand for and price of fossil fuels.

Our conclusion that the world has overshot appropriate targets is sufficiently grim to compel us to point out that pathways to rapid emission reductions are feasible. Peters et al. (2013) note that Belgium, France and Sweden achieved emission reductions of 4–5 % yr^{-1} sustained over 10 or more years in response to the oil crisis of 1973. These rates were primarily a result of nuclear power build programs, which historically has been the fastest route to carbon-free energy (Fig. 2 of Cao et al., 2016). These examples are an imperfect analogue, as they were driven by a desire for energy independence from oil, but present incentives are even more comprehensive. Peters et al. (2013) also note that a continuous shift from coal to natural gas led to sustained reductions of 1–2 % yr^{-1} in the UK in the 1970s and in the 2000s, 2 % yr^{-1} in Denmark in 1990–2000s, and 1.4 % yr^{-1} in the USA since 2005. Furthermore, these examples were not aided by the economy-wide effect of a rising carbon fee or tax (Hsu, 2011; Ackerman and Stanton, 2012; Hansen, 2014), which encourages energy efficiency and carbon-free energies.

In addition to CO_2 emission phase-out, large CO_2 extraction from the air is needed and a halt of growth of non-CO_2 climate forcings to achieve the temperature stabilization of our scenarios. Success of both CO_2 extraction and non-CO_2 GHG controls requires a major role for developing countries, given that they have been a large source of recent deforestation (IPCC, 2013) and have a large potential for reduced emissions. Ancillary benefits of the agricultural and forestry practices needed to achieve CO_2 drawdown, such as improved soil fertility, advanced agricultural practices, forest products, and species preservation, are of interest to all nations. Developed nations have a recognized obligation to assist nations that have done little to cause climate change yet suffer some of the largest climate impacts. If economic assistance is made partially dependent on verifiable success in carbon drawdown and non-CO_2 mitigation, this will provide incentives that maximize success in carbon storage. Some activities, such as soil amendments that enhance weathering, might be designed to support both CO_2 and other GHG drawdown.

Considering our conclusion that the world has overshot the appropriate target for global temperature, and the difficulty and perhaps implausibility of negative emissions scenarios, we would be remiss if we did not point out the potential contribution of demand-side mitigation that can be achieved by individual actions as well as by government policies. Numerous studies (e.g. Hedenhus et al., 2014; Popp et al., 2010) have shown that reduced ruminant meat and dairy products is needed to reduce GHG emissions from agriculture, even if technological improvements increase food yields per unit farmland. Such climate-beneficial dietary shifts have also been linked to co-benefits that include improved sustainability and public health (Bajzelj et al., 2014; Tilman and Clark, 2014). Similarly, Working Group 3 of IPCC (2014) finds "robust evidence and high agreement" that demand-side measures in the agriculture and land use sectors, especially dietary shifts, reduced food waste, and changes in wood use have substantial mitigation potential, but they remain under-researched and poorly quantified.

There is no time to delay. CO_2 extraction required to achieve 350 ppm CO_2 in 2100 was ∼ 100 PgC if 6 % yr^{-1} emission reductions began in 2013 (Hansen et al., 2013a). Required extraction is at least ∼ 150 PgC in our updated scenarios, which incorporate growth of emissions in the past 4 years and assume that emissions will continue at approximately current levels until a global program of emission reductions begins in 4 years (in 2021 relative to 2020; see Figs. 9 and 10 for reduction rates). The difficulty of stabilizing climate was thus markedly increased by a delay in emission reductions of 8 years, from 2013 to 2021. Nevertheless, if rapid emission reductions are initiated soon, it is still possible that at least a large fraction of required CO_2 extraction can be achieved via relatively natural agricultural and forestry practices with other benefits. On the other hand, if large fossil fuel emissions are allowed to continue, the scale and cost of industrial CO_2 extraction, occurring in conjunction with a deteriorating climate and costly dislocations, may become unmanageable. Simply put, the burden placed on young people and future generations may become too heavy to bear.

Data availability. Data used to create all the figures are available at https://doi.org/10.5281/zenodo.823301 (Hansen et al., 2017). Our Eq. (1) is used to compute the temperature change in Fig. 12. Continual updates of the data are available at http://www.columbia.edu/~mhs119/Burden_figures/.

Appendix A: Additional figures, tables and explanatory information

A1 Fossil fuel CO_2 emissions

CO_2 emissions from fossil fuels in 2015 were only slightly higher than in 2014 (Fig. A1). Such slowdowns are common, usually reflecting the global economy. Given rising global population and the fact that nations such as India are still at early stages of development, the potential exists for continued emissions growth. Fundamental changes in energy technology are needed for the world to rapidly phase down fossil fuel emissions.

Emissions are growing rapidly in emerging economies; while growth slowed in China in the past 2 years, emissions remain high (Fig. 1). The Kyoto Protocol (1997), a policy instrument of the Framework Convention (United Nations, 1992), spurred emission reductions in some nations, and the collapse of the Soviet Union caused a large decrease in emissions by Russia (Fig. 1b). However, growth of international ship and air emissions (Fig. 1b) largely offset these reductions and the growth rate of global emissions actually accelerated from 1.5 % yr^{-1} in 1973–2000 to ~ 2.5 % yr^{-1} after 2000 (Fig. A1). China is now the largest source of fossil fuel emissions, followed by the US and India, but on a per capita historical basis the US is 10 times more accountable than China and 25 times more accountable than India for the increase in atmospheric CO_2 above its preindustrial level (Hansen and Sato, 2016). Tabular data for Figs. 1 and A1 are available on the web page http://www.columbia.edu/~mhs119/Burden.

A2 Transient climate response to cumulative CO_2 emissions (TCRE)

The transient climate response (TCR), defined as the global warming at year 70 in response to a 1 % yr^{-1} CO_2 increase, for our simple Green's function climate model is 1.89 °C with energy imbalance of 1.52 $W\,m^{-2}$ at that point; this TCR is in the middle of the range reported in the IPCC AR5 report (IPCC, 2013). We calculate the transient climate response to cumulative carbon emissions (TCRE) of our climate plus carbon cycle model as in Sect. 10.8.4 of IPCC (2013), i.e., $\text{TCRE} = \text{TCR} \times \text{CAF}/C_0$, where C_0 = preindustrial atmospheric CO_2 mass = 590 PgC and $\text{CAF} = C_{\text{atm}}/C_{\text{sum}}$, Catm = atmospheric CO_2 mass minus C_0 and C_{sum} = cumulative CO_2 emissions (all evaluated at year 2100).

We find TCRE = 1.54 °C per 1000 PgC at 2100 with constant emissions (which yields cumulative emissions of 1180 PgC at 2100, which is near the midpoint of the range assessed by IPCC, i.e., 0.8 to 2.5 °C per 1000 PgC (IPCC, 2013). Our two cases with rapidly declining emissions never achieve 1000 PgC emissions, but TCRE can still be computed using the IPCC formulae, yielding TCRE = 1.31 and 1.25 °C per 1000 PgC at 2100 for the cases of −3 and −6 % yr^{-1} respective emission reductions. As expected, the rapid emission reductions substantially reduce the temperature rise in 2100.

A3 Observed temperature data and analysis method

We use the current Goddard Institute for Space Studies global temperature analysis (GISTEMP), described by Hansen et al. (2010). The analysis combines data from (1) meteorological station data of the Global Historical Climatology Network (GHCN) described by Peterson and Vose (1997) and Menne et al. (2012), (2) Antarctic research station data reported by the Scientific Committee on Antarctic Research (SCAR), (http://www.antarctica.ac.uk/met/READER), and (3) ocean surface temperature measurements from the NOAA Extended Reconstructed Sea Surface temperature (ERSST) (Smith et al., 2008; Huang et al., 2015).

Surface air temperature change over land is about twice SST change (Fig. A3a), and thus global temperature change is 1.3 times larger than the SST change. Note that the Arctic Ocean and parts of the Southern Ocean are excluded in the calculations because of inadequate data, but these regions are also not sampled in most paleo-analyses and the excluded areas are small. Land area included covers 29 % of the globe and ocean area included covers 65 % of the globe.

The present analysis uses GHCN.v3.3.0 (Menne et al., 2012) for land data and ERSST.v4 for sea surface temperature (Huang et al., 2015). The update from GHCN.v2 used in our 2010 analysis to GHCN.v3 had negligible effect on global temperature change over the past century (see graph at http://www.columbia.edu/~mhs119/Temperature/GHCN_V3vsV2/). However, the adjustments to SST to produce ERSST.v4 have a noticeable effect, especially in the period 1939–1945, as shown by the difference between the two data sets (lower graph in Fig. A3b). This change is of interest mainly because it increases the magnitude of an already unusual global temperature fluctuation in the 1940s, making the 1939–1945 global temperature maximum even more pronounced than it was in ERSST.v3 data. Thompson et al. (2008) show that two natural sources of variability, the El Niño–Southern Oscillation and (possibly related) unusual winter Arctic warmth associated with advection over high Northern Hemisphere latitudes, partly account for global warmth of 1939–1945, and they suggest that the sharp cooling after 1945 is a data flaw, due to a rapid change in the mix of data sources (bucket measurements and engine room intake measurements) and a bias between these that is not fully accounted for.

Huang et al. (2015) justify the changes made to obtain version 4 of ERSST, the changes including more complete input data in ICOADS Release 2.5, buoy SST bias adjustments not present in version 3, updated ship SST bias adjustments using Hadley Nighttime Marine Air Temperature version 2 (HadNMat2), and revised low-frequency data filling in data-sparse regions using nearby observations. ERSST.v4 is surely an improvement in the record during the past half century, when spatial and temporal data coverages are best. On the other hand, the largest changes between v3 and v4 are in 1939–1945, coinciding with World War II and changes in the mix of data sources. Several hot spots appear in the Southern Hemisphere ocean during WWII in the v4 data, and then disappear after the war (Fig. A3c). These hot spots coincide with the locations of large SST changes between v3 and v4 (Fig. A3c), which leads us to suspect that the magnitude of the 1940s global warming maximum (Fig. 2) is exaggerated; i.e., it is partly spurious. We suggest that this warming spike warrants scrutiny in the next version of the SST analysis. However, the important point is that these data adjustments and uncertainties are small in comparison with the long-term warming. Adjustments between ERSST.v3b and ERSST.v4 increase global warming over the period 1950–2015 by about 0.05 °C, which is small compared with the ∼ 1 °C global warming during that period. The effect of the adjustments on total global warming between the beginning of the 20th century and 2015 is even smaller (Fig. A3b).

A4 Recent global warming rate

Recent warming removes the illusion of a hiatus of global warming since the 1997–1998 El Niño (Fig. 2). Several studies, including Trenberth and Fasullo (2013), England et al. (2014), Dai et al. (2015), Rajaratnam et al. (2015) and Medhaug et al. (2017), have showed that temporary plateaus are consistent with expected long-term warming due to increasing atmospheric GHGs. Other analyses of the 1998–2013 plateau illuminate the roles of unforced climate variability and natural and human-caused climate forcings in climate change, with the Interdecadal Pacific Oscillation (a recurring pattern of ocean–atmosphere climate variability) playing a major role in the warming slowdown (Kosaka and Xie, 2013; Huber and Knutti, 2014; Meehl et al., 2014; Fyfe et al., 2016; Medhaug et al., 2017).

A5 Coincidence of 1880–1920 mean and preindustrial global mean temperatures

The Framework Convention (United Nations, 1992) and Paris Agreement (2015) define goals relative to "preindustrial" temperature, but do not define that period. We use 1880–1920, the earliest time with near-global coverage of instrumental data, as the zero-point for temperature anomalies. Although human-caused increases of GHGs would be expected to have caused a small warming by then, that warming was at least partially balanced by cooling from larger than average volcanic activity in 1880–1920. Extreme Little Ice Age conditions may have been ∼ 0.1 °C cooler than the 1880–1920 mean (Abram et al., 2016), but the Little Ice Age is inappropriate to define preindustrial because the deep ocean temperature did not have time to reach equilibrium. Thus, preindustrial global temperature has uncertainty of at least 0.1 °C, and the 1880–1920 period, which has the merit of near-global data, yields our best estimate of preindustrial temperature.

A6 Land vs. ocean warming at equilibrium

Observations (Fig. A3a) show surface air temperature (SAT) over land increasing almost twice as much as sea surface temperature (SST) during the past century. This large difference is likely partly due to the thermal inertia of the ocean, which has not fully responded to the climate forcing due to increasing GHGs. However, land warming is heavily modulated by the ocean temperature, so land temperature too has not achieved its equilibrium response.

We use long climate model simulations to examine how much the ratio of land SAT change over ocean SST change (the observed quantities) is modified as global warming approaches its equilibrium response. This ratio is ∼ 1.8 in years 901–1000 of doubled CO_2 simulations (Fig. A6) for two versions of GISS modelE-R (Schmidt et al., 2014; Hansen et al., 2016).

A7 Earth's energy Imbalance

Hansen et al. (2011) inferred an Earth energy imbalance with the solar cycle effect removed of $+0.75 \pm 0.25\,\mathrm{W\,m^{-2}}$, based on an imbalance of $0.58\,\mathrm{W\,m^{-2}}$ during the 2005–2010 solar minimum, based on the analysis of von Schuckmann and Le Traon (2011) for heat gain in the upper 2 km of the ocean and estimates of small heat gains by the deep ocean, continents, atmosphere, and net melting of sea ice and land ice. The von Schuckmann and Le Traon (2011) analysis for 2005–2015 (Fig. 5) yields a decade-average $0.7\,\mathrm{W\,m^{-2}}$ heat uptake in the upper 2 km of the ocean; addition of the smaller terms raises the imbalance to at least $+0.8\,\mathrm{W\,m^{-2}}$ for 2005–2015, consistent with the recent estimate of $+0.9 \pm 0.1\,\mathrm{W\,m^{-2}}$ by Trenberth et al. (2016) for 2005–2015. Other recent analyses including the most up-to-date corrections for ocean instrumental biases yield $+0.4 \pm 0.1\,\mathrm{W\,m^{-2}}$ by Cheng et al. (2017) for the period 1960–2015 and $+0.7 \pm 0.1\,\mathrm{W\,m^{-2}}$ by Dieng et al. (2017) for the period 2005–2013. We conclude that the estimate of $+0.75 \pm 0.25\,\mathrm{W\,m^{-2}}$ for the current Earth energy imbalance averaged over the solar cycle is still valid.

A8 CO_2 and CH_4 growth rates

Growth of airborne CO_2 is about half of fossil fuel CO_2 emissions (Fig. A8), the remaining portion of emissions being the net uptake by the ocean and biosphere (Ciais et al., 2013). Here we use the Keeling et al. (1973) definition of airborne fraction, which is the ratio of quantities that are known with good accuracy: the annual increase in CO_2 in the atmosphere and the annual amount of CO_2 injected into the atmosphere by fossil fuel burning. The data reveal that, even as fossil fuel emissions have increased by a factor of 4 over the past half century, the ocean and biosphere have continued to take up about half of the emissions (Fig. A8, right-hand scale). This seemingly simple relation between emissions and atmospheric CO_2 growth is not predictive as it depends on the growth rate of emissions being maintained, which is not true in cases with major changes in the emission scenario, so we use a carbon cycle model in Sect. 7 to compute atmospheric CO_2 as a function of emission scenario.

Oscillations of annual CO_2 growth are correlated with global temperature and with the El Niño/La Niña cycle.[15] Correlations (Fig. 6) are calculated for the 12-month running means, which effectively remove the seasonal cycle and monthly noise. Maxima of the CO_2 growth rate lag global temperature maxima by 7–8 months (Fig. 6b) and lag Niño3.4 (latitudes 5° N–5° S, longitudes 120–170° W) temperature by ~ 10 months. These lags imply that the current CO_2 growth spike (Fig. 6 uses data through January 2017), associated with the 2015–2016 El Niño, is well past its maximum, as Niño3.4 peaked in December 2015 and the global temperature anomaly peaked in February 2016.

CH_4 growth rate has varied over the past two decades, probably driven primarily by changes in emissions, as observations of CH_3CCl_3 show very little change in the atmospheric sink for CH_4 (Montzka et al., 2011; Holmes et al., 2013). Recent box-model inversions of the CH_4–CH_3CCl_3 system have argued for large fluctuations in the atmospheric sink over this period but there is no identified cause for such changes (Rigby et al., 2017; Turner et al., 2017; Prather and Holmes, 2017). Future changes in the sink could lead to increased atmospheric CH_4 separate from emission changes, but this effect is difficult to project and not included in the RCP scenarios (Voulgarakis et al., 2013).

Carbon isotopes provide a valuable constraint (Saunois et al., 2016) that aids analysis of which CH_4 sources[16] contribute to the CH_4 growth resurgence in the past decade (Fig. 7). Schaefer et al. (2016) conclude that the growth was primarily biogenic, thus not fossil fuel, and located outside the tropics, most likely ruminants and rice agriculture. Such an increasing biogenic source is consistent with effects of increasing population and dietary changes (Tilman and Clark, 2014). Nisbet et al. (2016) concur with Schaefer et al. (2016) that the CH_4 growth is from biogenic sources, but from the latitudinal distribution of growth they conclude that tropical wetlands[17] have been an important contributor to the CH_4 increase. Their conclusion that increasing tropical precipitation and temperature may be major factors driving CH_4 growth suggests the possibility that the slow climate-methane amplifying feedback might already be significant. There is also concern that global warming will lead to a massive increase in CH_4 emissions from methane hydrates and permafrost (O'Connor et al., 2010), but as yet there is little evidence for a substantial increase in emissions from hydrates or permafrost either now or over the last 1 000 000 years (Berchet et al., 2016; Warwick et al., 2016; Quiquet et al., 2015).

Schwietzke et al. (2016) use isotopic constraints to show that the fossil fuel contribution to atmospheric CH_4 is larger than previously believed, but total fossil fuel CH_4 emissions are not increasing. This conclusion is consistent with the above studies, and it does not contradict evidence of increased fossil fuel CH_4 emissions at specific locations (Turner et al., 2016). A recent inverse model study, however, contradicts the satellite studies and finds no evidence for increased US emissions (Bruhwiler et al., 2017). The recent consortium study of global CH_4 emissions finds with top-down studies that the recent increase is likely due to biogenic (natural and human sources) sources in the tropics, but it is difficult to attribute the magnitude of the rise to tropical wetlands alone (Saunois et al., 2017).

A9 CO_2 emissions in historical period

For land use CO_2 emissions in the historical period, we use the values labeled Houghton/2 by Hansen et al. (2008), which were shown in the latter publication to yield good agreement with observed CO_2. We use fossil fuel CO_2 emissions data for 1850–2013 from Boden et al. (2016). BP (2016) fuel consumption data for 2013–2015 are used for the fractional annual changes of each nation to allow extension of the Boden analysis through 2015. Emissions were almost flat from 2014 to 2015, due to economic slowdown and increased use of low-carbon energies, but, even if a peak in global emissions is near, substantial decline of emissions is dependent on acceleration in the transformation of energy production and use (Jackson et al., 2016).

A10 Tables of effective climate forcings, 1850–2100

CO_2, CH_4 and N_2O forcings are calculated with analytic formulae of Hansen et al. (2000). CH_4 forcing includes the factor 1.4 to convert adjusted forcing to effective forcing, thus incorporating the estimated effect of a CH_4 increase on tropospheric ozone and stratospheric water vapor. Our CH_4 ad-

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[15] One mechanism for greater than normal atmospheric CO_2 growth during El Niños is the impoverishment of nutrients in equatorial Pacific surface water and thus reduced biological productivity that result from reduced upwelling of deep water (Chavez et al., 1999). However, the El Niño/La Niña cycle seems to have an even greater impact on atmospheric CO_2 via the terrestrial carbon cycle through effects on the water cycle, temperature, and fire, as discussed in a large body of literature (referenced, for example, by Schwalm et al., 2011).

[16] Estimated human-caused CH_4 sources (Ciais et al., 2013) are fossil fuels (29 %), biomass/biofuels (11 %), waste and landfill (23 %), ruminants (27 %) and rice (11 %).

[17] Wetlands compose a majority of natural CH_4 emissions and are estimated to be equivalent to about 36 % of the anthropogenic source (Ciais et al., 2013).

justed forcing is significantly (∼ 17 %) higher that the values in IPCC (2013), but (∼ 9 %) smaller than values of Etminan et al. (2017). Our factor of 1.4 to convert direct radiative forcing to effective forcing is in the upper portion of the indirect effects discussed by Myhre et al. (2013), so our net CH_4 forcing agrees with Etminan et al. (2017) within uncertainties.

A11 Solar irradiance

Solar irradiance has been measured from satellites since the late 1970s. Figure A11 is a composite of several satellite-measured time series. Data through 28 February 2003 are an update of Frohlich and Lean (1998) obtained from the Physikalisch Meteorologisches Observatorium Davos, World Radiation Center. Subsequent update is from University of Colorado Solar Radiation & Climate Experiment (SORCE). Historical total solar irradiance reconstruction is available at http://lasp.colorado.edu/home/sorce/data/tsi-data/. Data sets are concatenated by matching the means over the first 12 months of SORCE data. Monthly sunspot numbers support the conclusion that the solar irradiance in the current solar cycle is significantly lower than in the three preceding solar cycles.

The magnitude of the change in solar irradiance from the prior solar cycle to the current solar cycle is of the order of $-0.1\,\mathrm{W\,m^{-2}}$, which is not negligible but small compared with greenhouse gas climate forcing. On the other hand, the variation of solar irradiance from solar minimum to solar maximum is of the order of $0.25\,\mathrm{W\,m^{-2}}$, so the high solar irradiance in 2011–2015 contributes to the increase in Earth's energy imbalance between 2005 and 2010 as well as 2010 and 2015.

A12 Alternative scenario

Simulated global temperature for the climate forcings of the "alternative scenario" discussed in Sect. 6 are shown in Fig. A12. The climate model, with sensitivity 3 °C for doubled CO_2, is the same as used for Fig. 12.

A13 Non-CO_2 GHGs

CO_2 is the dominant forcing in future climate scenarios. Growth of non-CO_2 GHG climate forcing is likely to be even smaller, relative to CO_2 forcing, than in recent decades (Fig. 8) if there is a strong effort to limit climate change. Indeed, recent agreement to use the Montreal Protocol (2016) to phase down production of minor trace gases, the hydrofluorocarbons (HFCs), should cause annually added forcing of Montreal Protocol trace gases (MPTGs) + other trace gases (OTGs) (red region in Fig. 8) to become near zero or slightly negative, thus at least partially off-setting growth of other non-CO_2 GHGs, especially N_2O.

Methane (CH_4) is the largest climate forcing other than CO_2 (Fig. 4). The CH_4 atmospheric lifetime is only about 10 years (Prather et al., 2012), so there is potential to reduce this climate forcing rapidly if CH_4 sources are reduced. Our climate simulations, based on the RCP6.0 non-CO_2 GHG scenarios, follow an optimistic path in which CH_4 increases moderately in the next few decades to 1960 ppb in 2070 and then decreases rapidly to 1650 ppb in 2100, yielding a forcing change of $-0.1\,\mathrm{W\,m^{-2}}$. However, the IPCC (Kirtman et al., 2013) uses a more modern chemical model projection for the RCP anthropogenic emissions and gives a less beneficial view with a decrease to only 1734 ppb and a forcing change of $-0.03\,\mathrm{W\,m^{-2}}$. RCP2.6 makes a more optimistic assumption: that CH_4 will decline monotonically to 1250 ppb in 2100, yielding a forcing of $-0.3\,\mathrm{W\,m^{-2}}$ (relative to today's 1800 ppb CH_4), but the IPCC projections of RCP2.6 reduce this to $-0.2\,\mathrm{W\,m^{-2}}$ (Kirtman et al., 2013).

Observed atmospheric CH_4 amount (Fig. A13a) is diverging on the high side of these optimistic scenarios. The downward offset (∼ 20 ppb) of CH_4 scenarios relative to observations (Fig. A13a) is due to the fact that RCP scenarios did not include a data adjustment that was made in 2005 to match a revised CH_4 standard scale (E. Dlugokencky, personal communication, 2016), but observed CH_4 is also increasing more rapidly than in most scenarios. Reversal of CH_4 growth is made difficult by increasing global population, the diverse and widely distributed nature of agricultural sources, and global warming "in the pipeline", as these trends create an underlying tendency for increasing CH_4. The discrepancy between observed and assumed CH_4 growth could also be due in part to increased natural sources or changes in the global OH sink (Dlugokencky et al., 2011; Turner et al., 2017). Evidence for increased natural sources in a warmer climate is suggested by glacial–interglacial CH_4 increases of the order of 300 ppb, and contributions to observed fluctuations cannot be ruled out on the basis of recent budgets (Ciais et al., 2013).

Methane emissions from rice agriculture and ruminants potentially could be mitigated by changing rice growing methods (Epule et al., 2011) and inoculating ruminants (Eckard et al., 2010; Beil, 2015), but that would require widespread adoption of new technologies at the farmer level. California, in implementing a state law to reduce GHG emissions, hopes to dramatically cut agricultural CH_4 emissions (see http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm), but California has one of the most technological and regulated agricultural sectors in the world. It is not clear that this level of management can occur in the top agricultural CH_4 emitters like China, India and Brazil. Methane leaks from fossil fuel mining, transportation and use can be reduced; indeed, percentage leakage from conventional fossil fuel mining and fuel use has declined substantially in recent decades (Schwietzke et al., 2016), but there is danger of increased leakage with expanded shale gas extraction (Caulton et al., 2014; Petron et al., 2013; Howarth, 2015; Kang et al., 2016).

Observed N_2O growth is exceeding all scenarios (Fig. A13b). Major quantitative gaps remain in our understanding of the nitrogen cycle (Kroeze and Bouwman, 2011), but fertilizers are clearly a principal cause of N_2O growth (Röckmann and Levin, 2005; Park et al., 2012). More efficient use of fertilizers could reduce N_2O emissions (Liu and Zhang, 2011), but considering the scale of global agriculture, and the fact that fixed N is an inherent part of feeding people, there will be pressure for continued emissions at least comparable to present emissions. In contrast, agricultural CH_4 emissions are inadvertent and not core to food production. Given the current imbalance (emissions exceeding atmospheric losses by about 30 %; Prather et al., 2012) and the long N_2O atmospheric lifetime (116 ± 9 years; Prather et al., 2015) it is nearly inevitable that N_2O will continue to increase this century, even if emissions growth is checked. There can be no expectation of an N_2O decline that offsets the need to reduce CO_2.

The Montreal Protocol has stifled and even reversed growth of specific trace gases that destroy stratospheric ozone and cause global warming (Prather et al., 1996; Newman et al., 2009). The anticipated benefit over the 21st century is a drop in climate forcing of $-0.23\,\mathrm{W\,m^{-2}}$ (Prather et al., 2013). Protocol amendments that add other gases such as HFCs are important; forcings of these gases are small today, but without the protocol their potential for growth is possibly as large as $+0.2\,\mathrm{W\,m^{-2}}$ (Prather et al., 2013).

We conclude that a $0.25\,\mathrm{W\,m^{-2}}$ decrease in climate forcing by non-CO_2 GHGs is plausible, but requires a dramatic change from the growing abundances of these gases today. Achievement requires (i) successful phase-out of MPTGs ($-0.23\,\mathrm{W\,m^{-2}}$), (ii) reduction of CH_4 forcing by $0.12\,\mathrm{W\,m^{-2}}$, and (iii) limiting N_2O increase to $0.1\,\mathrm{W\,m^{-2}}$. A net negative forcing of $-0.25\,\mathrm{W\,m^{-2}}$ for non-CO_2 gases would allow CO_2 to be 365 ppm, rather than 350 ppm, while yielding the same total GHG forcing. Thus, potential reduction of non-CO_2 gases is helpful, but it does not alter the need for rapid fossil fuel emission reduction.

Table A1. **(a)** Effective forcings ($W\,m^{-2}$) in 1850–2015 relative to 1850. **(b)** Effective forcing ($W\,m^{-2}$) in 2016–2100 relative to 1850.

Year	CO_2	CH_4^a	CFCs^b	N_2O	O_3^c	TA + SA^d	Volcano^e	Solar	Net
(a)									
1850	0.000	0.000	0.000	0.000	0.000	0.000	−0.083	0.000	−0.083
1860	0.024	0.013	0.000	0.004	0.004	−0.029	−0.106	0.032	−0.058
1870	0.048	0.027	0.000	0.008	0.009	−0.058	−0.014	0.048	0.068
1880	0.109	0.041	0.000	0.011	0.014	−0.097	−0.026	−0.049	0.003
1890	0.179	0.058	0.000	0.014	0.018	−0.146	−0.900	−0.070	−0.847
1900	0.204	0.077	0.001	0.017	0.023	−0.195	−0.040	−0.063	0.024
1910	0.287	0.115	0.002	0.022	0.026	−0.250	−0.072	−0.043	0.087
1920	0.348	0.160	0.003	0.029	0.032	−0.307	−0.215	−0.016	0.034
1930	0.425	0.206	0.004	0.037	0.036	−0.364	−0.143	0.014	0.215
1940	0.494	0.247	0.005	0.043	0.045	−0.424	−0.073	0.037	0.374
1950	0.495	0.291	0.009	0.052	0.056	−0.484	−0.066	0.055	0.408
1960	0.599	0.365	0.027	0.061	0.078	−0.621	−0.106	0.102	0.505
1970	0.748	0.461	0.076	0.075	0.097	−0.742	−0.381	0.093	0.427
1980	0.976	0.568	0.185	0.097	0.115	−0.907	−0.108	0.169	1.095
1990	1.227	0.659	0.303	0.125	0.117	−0.997	−0.141	0.154	1.447
2000	1.464	0.695	0.347	0.150	0.117	−1.084	−0.048	0.173	1.814
2005	1.619	0.651	0.356	0.162	0.123	−1.125	−0.079	0.019	1.770
2010	1.766	0.710	0.364	0.177	0.129	−1.163	−0.082	0.028	1.929
2015	1.927	0.730	0.373	0.195	0.129	−1.199	−0.100	0.137	2.192
(b)									
2016	1.942	0.698	0.367	0.192	0.130	−1.207	−0.100	0.097	2.119
2020	2.074	0.702	0.373	0.201	0.130	−1.234	−0.100	−0.008	2.139
2030	2.347	0.708	0.343	0.226	0.130	−1.296	−1.057	−0.008	1.393
2040	2.580	0.735	0.301	0.254	0.123	−1.350	−0.100	0.027	2.569
2050	2.803	0.766	0.267	0.288	0.117	−1.396	−0.100	0.062	2.807
2060	3.017	0.791	0.243	0.322	0.111	−1.433	−1.208	0.097	1.940
2070	3.222	0.804	0.229	0.358	0.105	−1.462	−0.100	0.132	3.289
2080	3.421	0.792	0.215	0.391	0.098	−1.484	−0.100	0.167	3.500
2090	3.614	0.722	0.199	0.427	0.091	−1.495	−1.240	0.167	2.484
2100	3.801	0.619	0.191	0.456	0.085	−1.500	−0.100	0.167	3.719

[a] CH_4: CH_4-induced changes of tropospheric O_3 and stratospheric H_2O are included. [b] CFCs: this includes all GHGs except CO_2, CH_4, N_2O and O_3. [c] O_3: half of troposphere O_3 forcing + stratosphere O_3 forcing from IPCC (2013). [d] TA + SA: tropospheric aerosols and surface albedo forcings combined. [e] Volcano: volcanic forcing is zero when there are no stratospheric aerosols. Annual data are available at http://www.columbia.edu/~mhs119/Burden/.

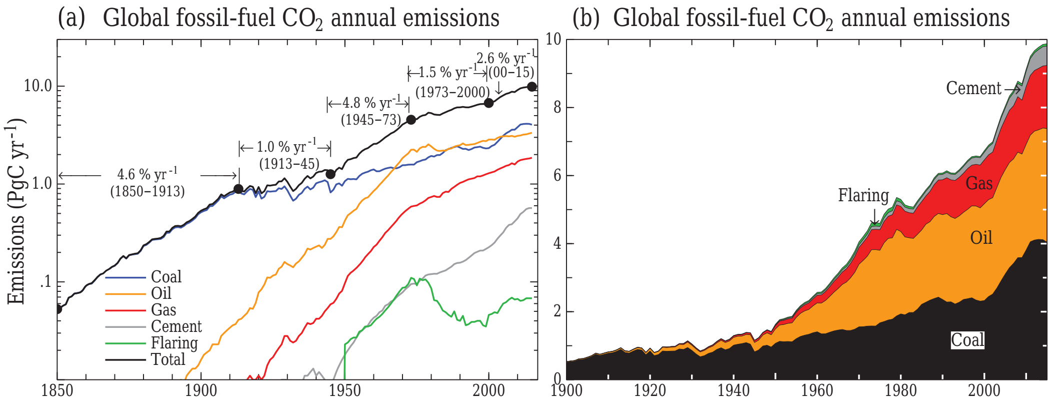

Figure A1. CO_2 emissions from fossil fuels and cement use based on Boden et al. (2017) through 2014, extended using BP (2016) energy consumption data. Panel **(a)** is log scale and **(b)** is linear. Growth rates r in **(a)** for an n-year interval are from $(1+r)^n$ with end values being 3-year means to minimize noise.

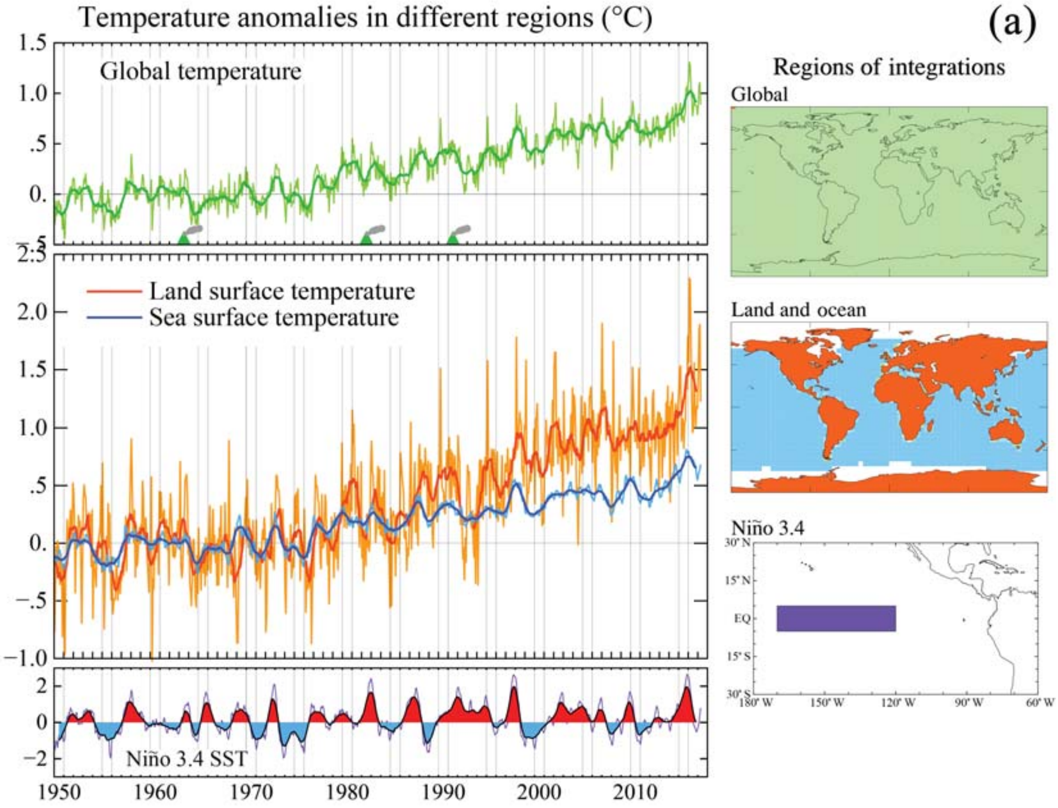

Figure A2.

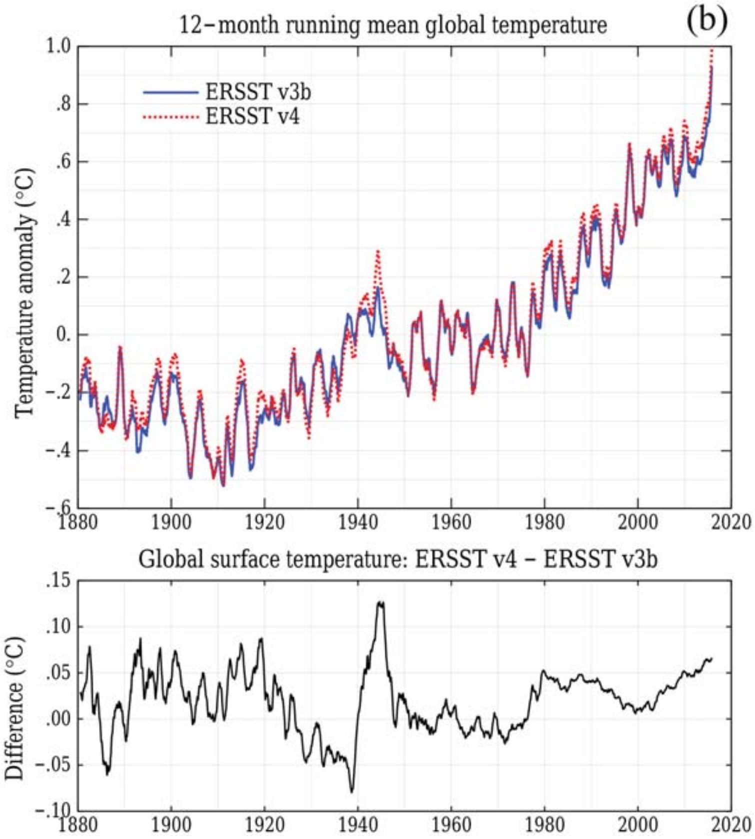
12−month running mean global temperature
(b)
ERSST v3b
ERSST v4
Temperature anomaly (°C)
1.0
.8
.6
.4
.2
0.
-.2
-.4
-.6
1880
1900
1920
1940
1960
1980
2000
2020
Global surface temperature: ERSST v4 − ERSST v3b
Difference (°C)
.15
.10
.05
.00
−.05
−.10

Figure A2.

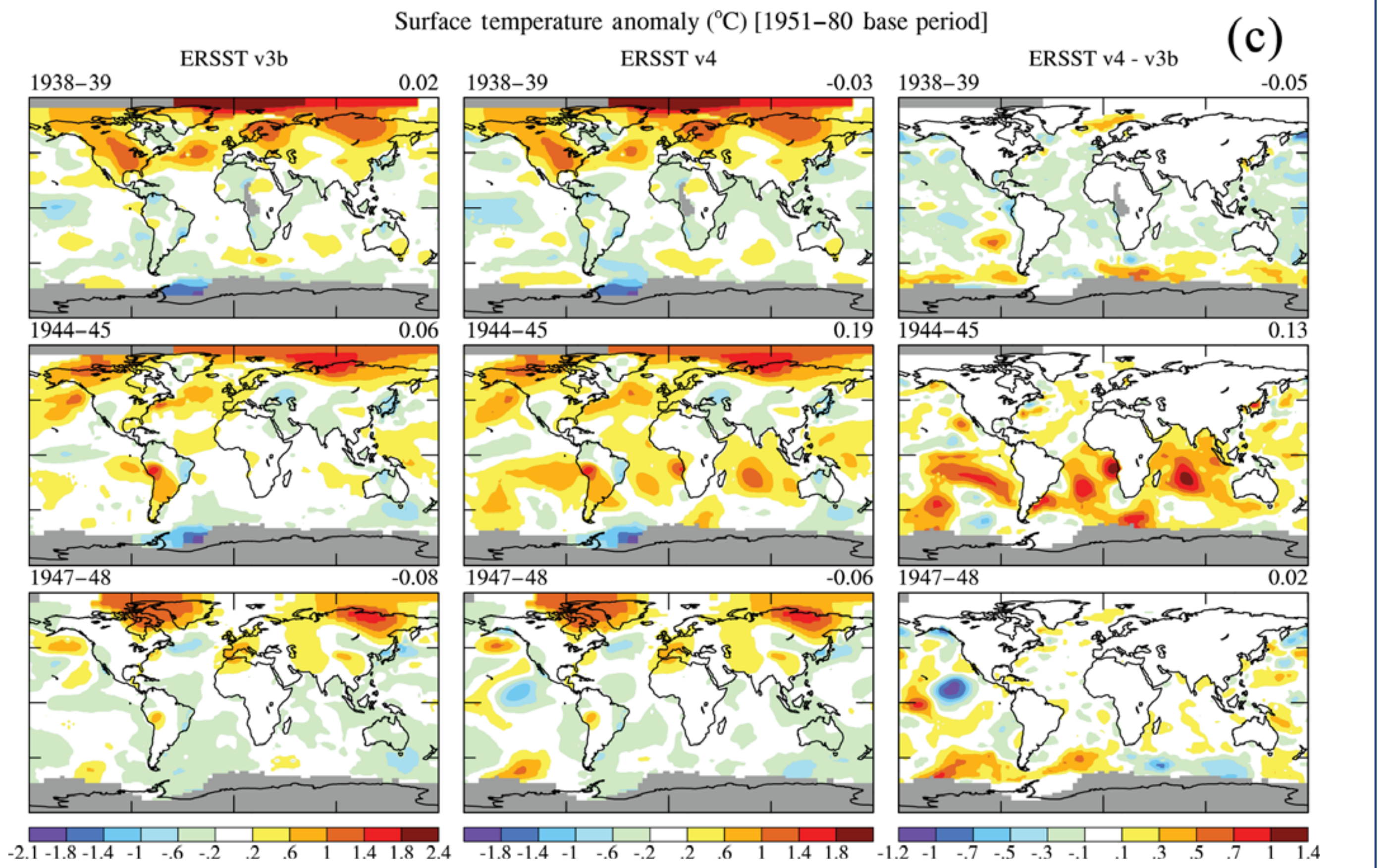

Figure A2. **(a)** Monthly (thin lines) and 12-month running mean (thick lines or filled colors for Niño 3.4) global, global land, sea surface, and Niño 3.4 temperatures. Temperatures are relative to 1951–1980 base period for the current GISTEMP analysis, which uses NOAA ERSST.v4 for sea surface temperature. **(b)** Global surface temperature relative to 1951–1980 in the GISTEMP analysis, comparing the current analysis using NOAA ERSST.v4 for sea surface temperature with results using ERSST.v3b. **(c)** Temperature anomalies in three periods relative to 1951–1980 comparing results obtained using ERSST.v3b (left column panels), ERSST.v4 (center column panels), and their difference (right column panels).

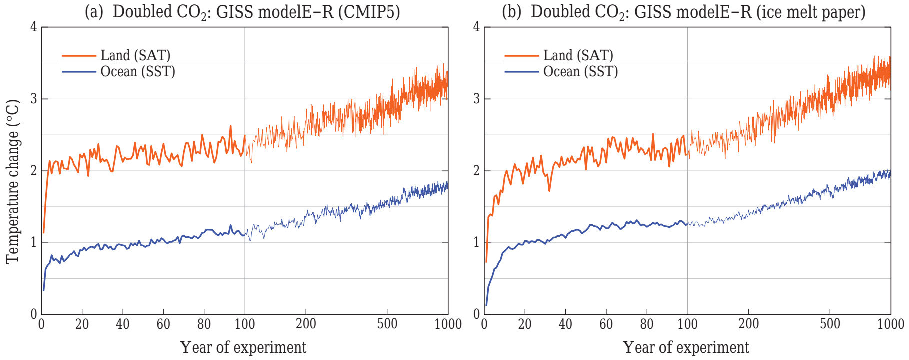

Figure A3. 1000-year temperature response in two versions of GISS modelE-R. **(a)** Version used for CMIP5 simulations (Schmidt et al., 2014), which has higher resolution (40-layer atmosphere at 2° × 2.5°, 32-layer ocean at 1° × 1.25°); **(b)** version used by Hansen et al. (2016), which has coarse resolution (20-layer atmosphere at 4° × 5°, 12-layer ocean at 4° × 5°) and includes two significant improvements to small-scale ocean mixing (see Sect. 3.2 of Hansen et al., 2016).

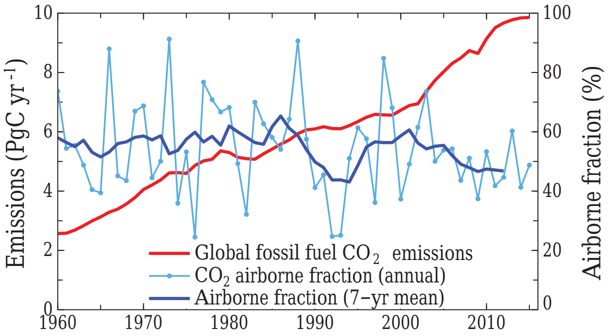

Figure A4. Fossil fuel CO_2 emissions (left scale) and airborne fraction, i.e., the ratio of observed atmospheric CO_2 increase to fossil fuel CO_2 emissions.

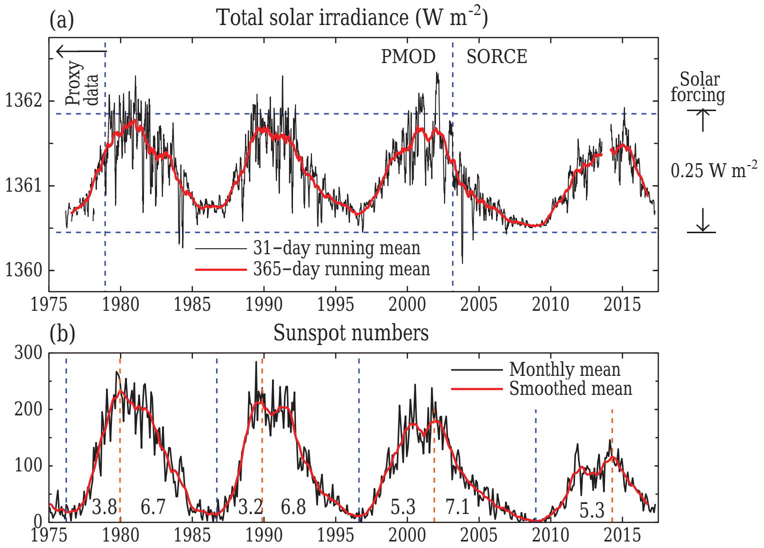

Figure A5. Solar irradiance and sunspot number in the era of satellite data. Left scale is the energy passing through an area perpendicular to Sun–Earth line. Averaged over Earth's surface the absorbed solar energy is ∼ 240 W m^{-2}, so the full amplitude of the measured solar variability is ∼ 0.25 W m^{-2}.

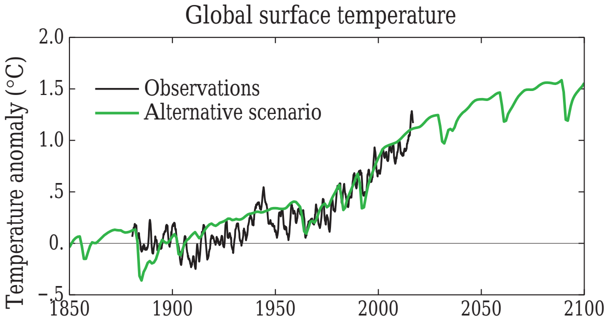

Figure A6. Simulated global temperature with historical climate forcings to 2000 followed by the alternative scenario. Historical climate forcings are discussed in the main text.

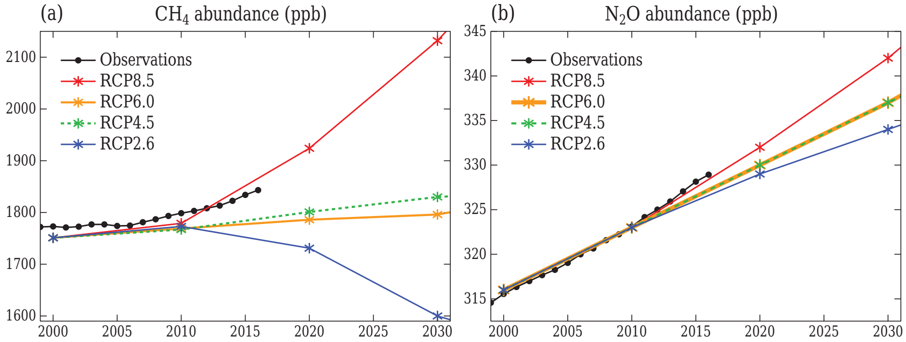

Figure A7. Comparison of observed CH_4 and N_2O amounts with RCP scenarios. RCP6.0 and 4.5 scenarios for N_2O overlap. Observations are from NOAA/ESRL Global Monitoring Division. Natural sources and feedbacks not included in RCP scenarios may contribute to observed growth (see Sect. 11).

Competing interests. The authors declare that they have no conflict of interest.

Disclosure

The first author (James Hansen) notes that he is a plaintiff in the lawsuit Juliana et al. vs. United States.

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