

Link to the final published paper: <http://www.atmos-chem-phys.net/16/3761/2016/>

Link to video discussion: <https://youtu.be/JP-cRqCQRc8>

Link to Hansen's web page, his Communications, etc.: www.columbia.edu/~jeh1

Links to three newspaper articles:

Gillis, New York Times:

<http://www.columbia.edu/~jeh1/mailings/2016/Gillis.NewYorkTimes.22March2016.pdf>

Mooney, Washington Post:

<http://www.columbia.edu/~jeh1/mailings/2016/Mooney.2016.WashingtonPost.22March.pdf>

Urry, grist: <http://www.columbia.edu/~jeh1/mailings/2016/Grist.AmeliaUrry.22March2016.pdf>

Following 19 pages are a short version of the Ice Melt, Sea Level Rise & Superstorms paper, largely extracted from the paper, but with a modicum of additional material.

Ice Melt, Sea Level Rise and Superstorms: Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2°C Global Warming is Dangerous

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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 CO₂, which in turn exercised tight control on global temperature and sea level. The millennial (500-2000 year) time scale of deep ocean ventilation affects the time scale for natural CO₂ change and thus the time scale for paleo global climate, ice sheet, and sea level changes, but this paleo millennial time scale should not be misinterpreted as the time scale 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 meters 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 would 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 time scale 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.

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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 (CO₂) 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 CO₂ 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 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 m 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. Fig. 1 shows two megaboulders, composed of middle Pleistocene (age 300-400 ky) limestone, resting on a surface that is dated to the last interglacial period, the Eemian, about 120 ky ago. The boulders must have been tossed by the sea onto the beach when sea level was near its peak Eemian level.

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.



Fig. 1. Two megaboulders on coastal ridge of North Eleuthera Island, Bahamas. Scale: person = 1.6 m.

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.

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 American literature (see Sec. 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

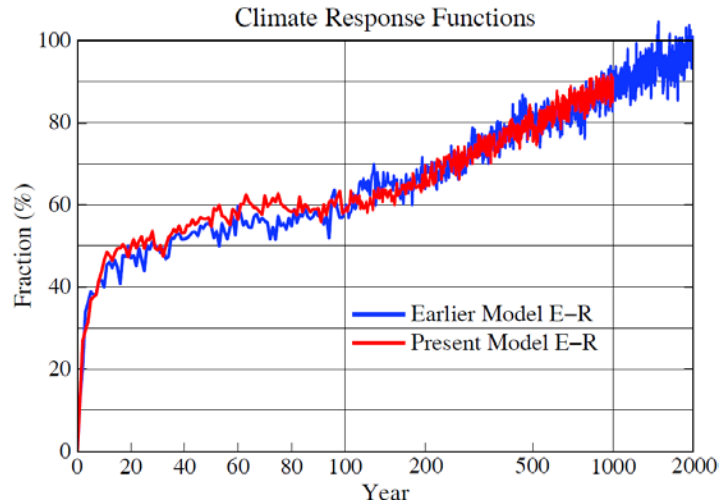


Fig. 2. Climate response function, $R(t)$, i.e., the fraction (%) of equilibrium surface temperature response for GISS model E-R based on a 2000 year control run (Hansen et al., 2007a). Forcing was instant CO_2 doubling with fixed ice sheets, vegetation distribution, and other long-lived GHGs.

reported by IPCC (2007, 2013). This allows comparison of our present simulations with prior studies. Here, 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, e.g., a change of solar irradiance or a radiative constituent of the atmosphere or surface. When a climate forcing changes, say solar irradiance increases or atmospheric CO_2 increases, Earth is temporarily out of energy balance, 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, the slowness of the surface temperature to respond to changing global climate forcing. Earth’s energy imbalance depends on 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, $+0.5\text{-}1 \text{ W/m}^2$ (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 (Fig. 2). 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

$$T(t) = \int R(t) [dF/dt] dt \tag{1}$$

dF/dt is the annual increment of the net forcing and the integration begins before human-made climate forcing became substantial.

These concepts help us reveal that most ocean models are too diffusive. Excessive mixing causes models to have unrealistically slow response to surface meltwater injection. Implications include 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 use an improved version of a coarse-resolution model allowing 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, has background diffusivity $0.3 \text{ cm}^2/\text{s}$, $4^\circ \times 5^\circ$ resolution 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), as described in our full paper.

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 five years (Fig. 2) 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 time scales than the old model (Fig. 2), 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 time scales 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 Climate simulations. We carry out global atmosphere-ocean simulations focused on studying the effect of ice melt from Greenland and Antarctica on 21st century climate. Thus our simulations differ from those of the Intergovernmental Panel on Climate Change (IPCC), which generally do not include a significant accelerating freshwater source from ice sheets. We make simulations for a range of specified nonlinear growth rates for ice melt from Antarctica, Greenland, or both places. This allows us to investigate whether the ice melt might generate amplifying feedback processes that could sustain nonlinear ice sheet disintegration.

Indeed, the modeling reveals powerful amplifying feedbacks that are particularly effective in the Southern Ocean and threaten the stability of a significant fraction of the Antarctic ice sheet.

First, melting Antarctic ice shelves increase the vertical stability of the Southern Ocean, thus reducing Antarctic Bottom Water (AABW) formation (Fig. 3). This "stratification feedback" causes ocean warming at the foot of the ice shelves, which accelerates ice shelf melt. The foot of the ice shelves exerts the strongest restraining force on the ice sheets. Reduction of restraining force is most important in West Antarctica and the Wilkes Basin of East Antarctica, both regions having retrograde beds that could yield rapid loss of ice up to several meters of sea level rise.

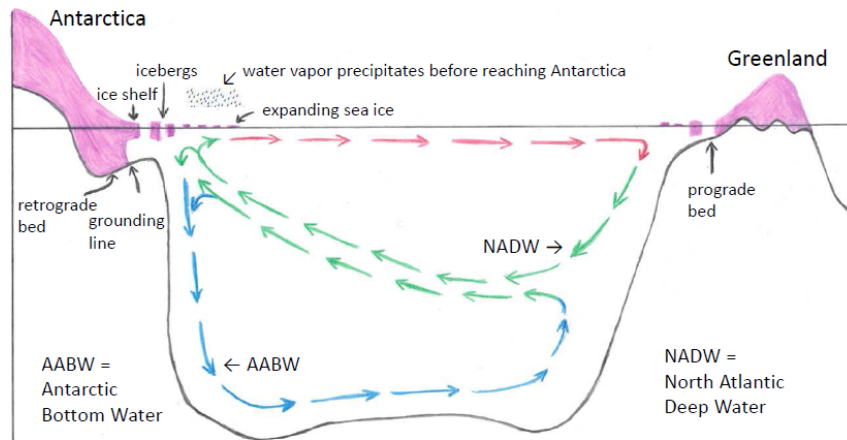


Fig. 3. Schematic of stratification and precipitation amplifying feedbacks. Stratification: increased freshwater/iceberg flux increases ocean vertical stratification, reduces AABW formation, traps NADW heat, thus increasing ice shelf melting. Precipitation: increased freshwater/iceberg flux cools ocean mixed layer, increases sea ice area, causing increase of precipitation that falls before it reaches Antarctica, adding to ocean surface freshening and reducing ice sheet growth. Retrograde beds in West Antarctica and the Wilkes Basin, East Antarctica, make their large ice amounts vulnerable to such melting.

Second, the reduced upwelling of relatively warm North Atlantic Deep Water (NADW) allows sea ice to expand and the surface layer of the Southern Ocean to cool. The expanding cool region on the Southern Ocean causes a “precipitation feedback”, as the cooler atmosphere causes moisture to be wrung from the air before it reaches Antarctica. This feedback amplifies sea level rise by reducing the amount of snowfall that would otherwise fall on Antarctica and by further freshening the surface layer of the Southern Ocean.

Our simulations with freshwater injection based on recent observational data, increasing with a 10-year doubling time, yield large cooling in the Southern Ocean and North Atlantic by mid-century (Fig. 3). Below we discuss reasons why these effects are probably understated in our model and the likelihood that these effects are already beginning to appear in the real world.

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

Climate change includes slowdown of AABW formation, indeed shutdown by midcentury 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 (Sec. 3.7.5). Paleoclimate data (Sec. 4) provides much insight about these processes and modern observations (Sec. 5) suggest that these feedbacks are already underway.

Large-scale climate processes affecting ice sheets are sketched in Fig. 3. 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

2055-2060 Surface Air Temperature (°C) Relative to 1880-1920
 A1B + Modified Forcings, Ice Melt to 1 m 1.19

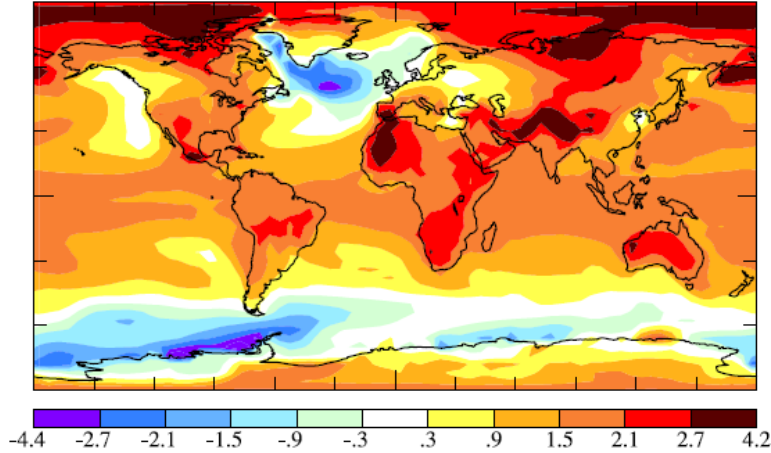


Fig. 4. Surface air temperature change relative to 1880-1920 in 2055-2060 with freshwater injection based on estimates from data (360 Gt/year in the North Atlantic and 720 Gt/year in the Southern Ocean in 2011, increasing with a 10-year doubling time).

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. 3), 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. 3) is altered by natural and human-made forcings, including freshwater from ice sheets, engendering powerful feedback processes.

Our “pure freshwater” experiments allow us to investigate unambiguously the meltwater stratification feedback. The simulations 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).

Our pure freshwater experiments also reveal 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 of snowfall over Antarctica, it also provides a large freshening term to the surface of the 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.

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). In the full paper we discuss evidence for rapid sea level rise late in the Eemian to +6-9 m relative to today's sea level and strong late-Eemian storms. We present evidence from ocean sediment cores for late-Eemian cooling in the North Atlantic associated with shutdown of the Atlantic Meridional Overturning Circulation (AMOC), and 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.

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 late-Eemian by several meters, to +6-9 m, is supported by records preserved in both the limestone platforms and coral 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 Yucatan peninsula, i.e., movement of coral reef building shoreward as sea level rises, to conclude that sea level in 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.

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.

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 a few km distant in North Eleuthera, Bahamas as well as across the Bahama Platform.



Fig. 5. 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 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 $\sim 10^2$ yr) 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.

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.

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-ton megaclasts provide a metric of powerful waves at the end of MIS 5e. Evidence of transport by waves includes: 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 tons 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 knots and sustained winds of 40 knots for 5 hours (Cox et al., 2012). Typhoon Haiyan (8 November 2013) in the Philippines produced longshore transport of a 180 ton block and lifted boulders of up to ~24 tons 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).

Thus the feature about the boulders that may be most puzzling to the lay person, the boulders resting atop a steep cliff, is part of the explanation of how they could get to such height: episodic instances of constructive wave interference can produce powerful “splash.” An example is the splash, exceeding the height of a 10-story building, generated on a fair day on 31 October 1991 (right side of Fig. 5, photo of Tormey, 1999). At that time the northeast side of the island was being hit by waves generated by a strong storm in the distant North Atlantic, the so-called “Perfect Storm” of 1991. The Perfect Storm originated as an extratropical low east of Nova Scotia that tracked first toward the southeast and then west, making landfall on Nova Scotia. While still over the ocean the storm swept up remnants of Hurricane Grace, which deepened the low, leading to sustained winds of 75 mph (120 km/hr). Thus the shoreline cliffs just south of the Glass Window Bridge, facing slightly east of due north (Fig. 3 in Hearty, 1998), were battered by deep long-period waves generated by this North Atlantic storm.

Temporal variability of interference between incident and reflected waves helps explain how an unsuspecting bread truck driver on Eleuthera, seduced by the relative calm and fair weather could be swept off the road by one of the bursts (Fig. 5). The truck was thrown/washed well into the shallow waters on the Caribbean-facing side of the island – the driver escaped in these relatively calm waters to the southwest, but his now rusted-out truck frame remains there today.

It has been suggested that the boulder story is a distraction from the principal conclusions of our paper, specifically that (1) continued high fossil fuel emissions are likely to lock in multi-meter sea level rise that could occur this century, and (2) shutdown of AMOC and SMOC overturning circulations are likely already underway, and numerous implications.

On the contrary, these big conclusions make the storm story all the more relevant. If high fossil fuel emissions continue the tropics will continue to warm and shutdown of AMOC will cause stronger cooling in the North Atlantic, making the situation analogous to the end-Eemian climate state when massive storms battered the Bahamas and Bermuda. We conclude, in appropriate vernacular, that “all Hell will break loose” in the North Atlantic and surrounding land areas if high fossil fuel emissions continue. Modern data (below) provides a small taste: “Sandy” retained hurricane force all the way to New York City because AMOC slowdown has warmed coastal waters; the same warming of the North Atlantic off the East Coast and the resulting increased horizontal temperature gradient contributed to record snowfalls this year.

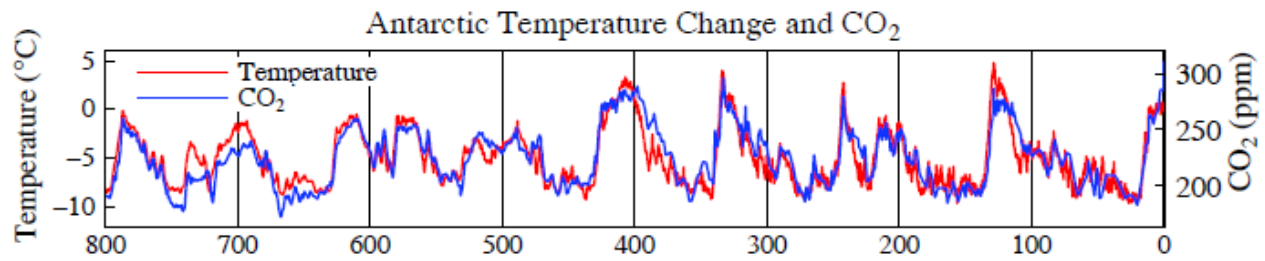


Fig. 6. Antarctic (Dome C) temperature relative to the average for the last 10 ky (Jouzel et al., 2007) and CO₂ amount (Luthi et al., 2008). Temperature scale is chosen such that standard deviations of T and CO₂ are equal, yielding ΔT (°C) = 0.114 ΔCO_2 (ppm).

4.2 Paleoclimate insights: CO₂ and ice sheet time scales, subsurface ocean warming.

Paleoclimate data, revealing how Earth’s climate has changed in the past, provides insight about the mechanisms involved in ice sheet and sea level change and the vulnerability of ice sheets to climate change. The large glacial-interglacial climate oscillations are recorded in detail in ice cores, as shown in Fig. 6 for an ice core drilled in central Antarctica (on Dome C). Temperature on the Antarctic ice sheet varies by about 10°C (18°F) over a glacial-interglacial cycle while CO₂ varies over the range 180-280 ppm (parts per million). Global average temperature changes are about half as large as polar temperature changes.

The glacial-interglacial climate oscillations are initiated by periodic variation of seasonal and geographical insolation, which is caused by slow changes of the eccentricity of Earth’s orbit, tilt of Earth’s spin axis, and precession of the equinoxes, 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. However, the total energy received from the Sun averaged over the year is hardly affected by these oscillations, so the direct climate forcing is small. Instead, the large climate oscillations are a result of two powerful amplifying feedbacks: surface albedo and atmospheric CO₂. The albedo feedback is amplifying because, as Earth becomes warmer, ice and snow melt exposing darker surfaces that absorb more sunlight and make Earth warmer. The CO₂ feedback is amplifying because, as Earth becomes warmer, the ocean and land release CO₂, causing further warming.

We conclude, based mainly on a large number of studies by the research community, that the principal mechanism for the CO₂ feedback is change in the amount of CO₂ sequestered in the ocean, which in turn depends primarily on the rate at which the Southern Ocean “ventilates” the deep global ocean. This is important because the amount of CO₂ in the atmosphere is the “control knob” for global temperature. Just how tightly CO₂ controls temperature is shown in Fig. 6, which compares CO₂ and Antarctic temperature over the past 800,000 years.

The changes of CO₂ and temperature over the 800,000 years were natural, but now CO₂ is being rapidly changed by humanity as we burn fossil fuels, and we need to understand how rapidly temperature and sea level will respond to the human-caused CO₂ increase. [Sea level changes are simply related to the ice/snow amplifying feedback, with the amplitude of glacial-to-interglacial sea level change being about 125 meters (about 400 feet).] The CO₂ control knob should work the same for human-made CO₂ changes as for natural CO₂ changes. However, there are two major complications with the human-made CO₂ change.

First, CO₂ is not the only human-made climate forcing, the main other forcings being (1) other greenhouse gases (GHGs), which add to the CO₂ forcing, and (2) aerosols (fine particles), which cause a negative (cooling) forcing that subtracts from GHG forcing. These two non-CO₂ forcings are substantially off-setting. IPCC (2013) estimates that the non-CO₂ GHG forcing slightly exceeds the absolute value of the aerosol forcing, but the aerosol forcing is too uncertain to confirm that conclusion. However, it is widely agreed, and confirmed by Earth’s measured energy imbalance, that the net forcing is at least similar in magnitude to that for 400 ppm CO₂.

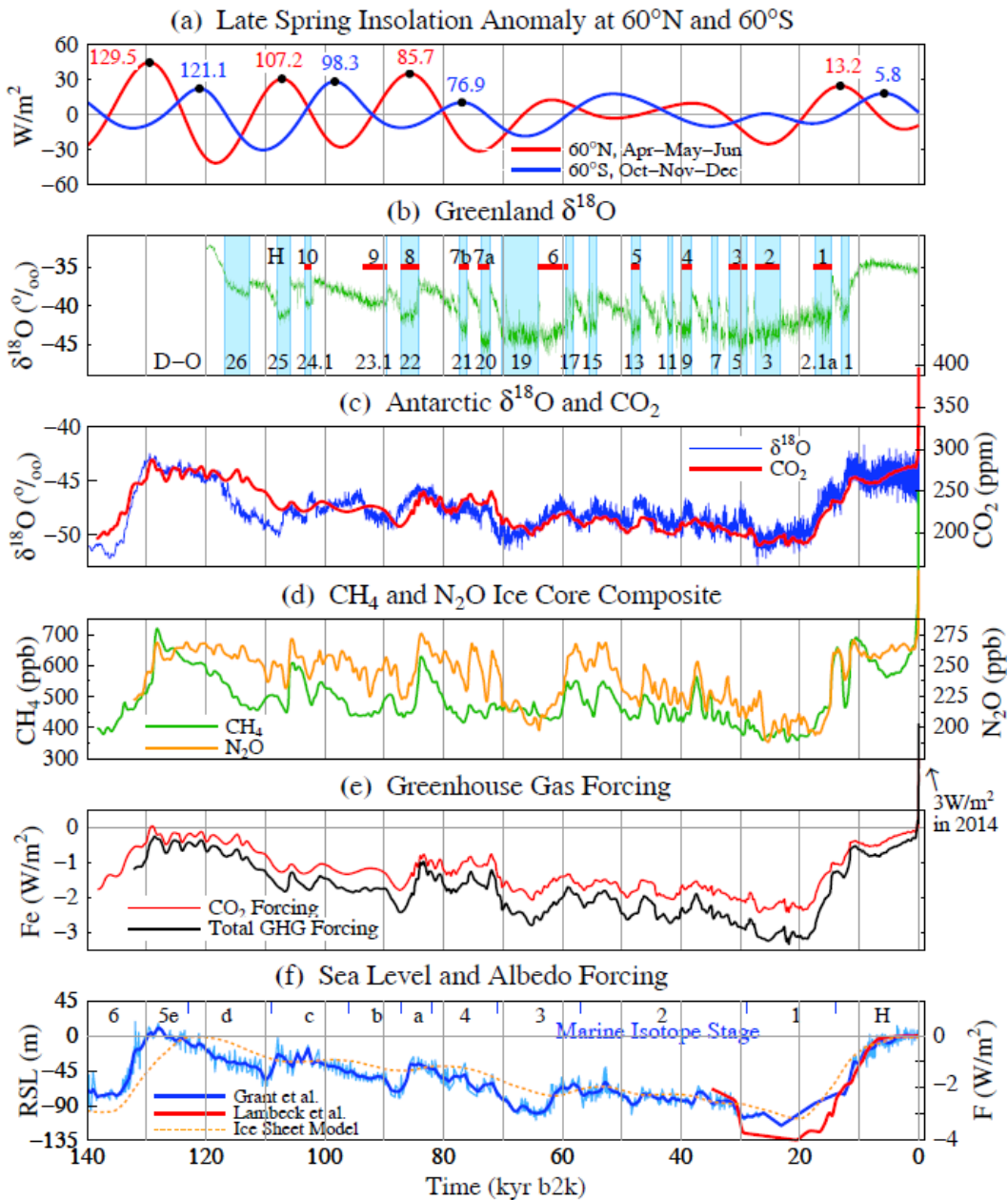


Fig. 7. (a) Late spring insolation anomalies relative to the mean for the past million years, (b) $\delta^{18}O_{ice}$ of composite Greenland ice cores (Rasmussen et al., 2014) with Heinrich events of Guillevic et al. (2014), (c, d) $\delta^{18}O_{ice}$ of EDML Antarctic ice core (Ruth et al., 2007), multi-ice core CO_2 , CH_4 , and N_2O based on 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, respectively, to account for each forcing’s “efficacy” (Hansen et al., 2005), 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).

Second, the human-made CO_2 increase has been so rapid that the climate system has not yet come to equilibrium, i.e., there is still more warming and sea level rise “in the pipeline”. It is often assumed that the time required for sea level to respond to climate change, i.e., the time required for ice sheets to substantially change in size, is millennia. We suggest that this assumption is based on a misattribution of a CO_2 time scale to ice sheets, as we will discuss here.

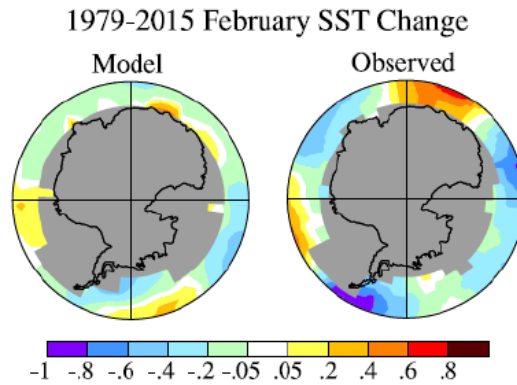


Fig. 8. Observed sea surface temperature change over 1979-2015 in February, which is the time of minimum Southern Hemisphere sea ice. Overall, the sea surface on the Southern Ocean has been cooling, while it is warming at depth. The cooling in the model is a result of increasing freshwater injection.

Graphed for 800,000 years, as in Fig. 6, CO_2 , temperature and sea level all appear to change almost simultaneously. However, closer examination reveals that CO_2 lags Antarctic temperature by of order one millennium (e.g., Fig. 7c, in which $\delta^{18}\text{O}$ is a proxy for Antarctic temperature). This lag is as expected, because the CO_2 change is largely driven by how long it takes for the Southern Ocean to ventilate the deep ocean. In contrast, the lag between temperature change and sea level change is difficult to detect, and probably much smaller. Grant et al. (2012), with perhaps the most precise assessment to date, find a lag of sea level change after temperature change of order a century, not a millennium.

We conclude that limitations on the speed of ice volume (thus sea level) changes in the paleo record are more a consequence of the pace of Earth orbital changes and CO_2 changes, as opposed to being a result of lethargic ice physics. Given that ice sheet models do not reproduce the rapid sea level response that occurred in response to even weak natural forcings, instead of using an ice sheet model, we choose to study the climate response to several alternative rates of freshwater injection onto the ocean and compare results with ongoing observations.

5. Modern data. Observations show that the Southern Ocean surface is cooling and sea ice is expanding, contrary to IPCC (2013) model results, which do not include freshwater injection. Models without increasing ice melt from Antarctica are missing a dominant driver of change. Southern Ocean surface cooling and sea ice expansion in our simulations is delayed relative to observations. Weaker response in our model is probably related to difficulty in maintaining vertical stratification, which may be a result of diffusion from numerical noise in finite differencing, large background diapycnal diffusivity ($0.3 \text{ cm}^2/\text{s}$), and coarse vertical resolution.

Observations and our model concur in showing cooling southeast of Greenland (Fig. 4), with the real world again seemingly more advanced than the model. The cooling in the model is the beginning of AMOC shutdown, which is consistent with increased warming along the East Coast of the U.S. We suspect that ocean models with parameterized subgrid mixing are less sensitive to freshwater forcing than the real world, and thus real-world AMOC shutdown could be imminent, if Greenland melt is allowed to accelerate (see discussion below).

Ice mass losses from Greenland, West Antarctica and Totten/Aurora basin in East Antarctica are growing nonlinearly with doubling times of order 10 years. Continued exponential growth at that rate is doubtful for Greenland; reduced mass loss in the last two years of data (Fig. 9) is consistent with a slower growth of the Greenland mass loss rate. However, Greenland is subject to several amplifying feedbacks and freshwater injection rate may not need to be very high for AMOC shutdown to occur. SMOC shutdown seems to be more gradual than AMOC shutdown, but if GHGs continue to grow, amplifying Southern Ocean feedbacks, including expanded sea ice and SMOC slowdown, are likely to grow and facilitate increasing Antarctic mass loss.

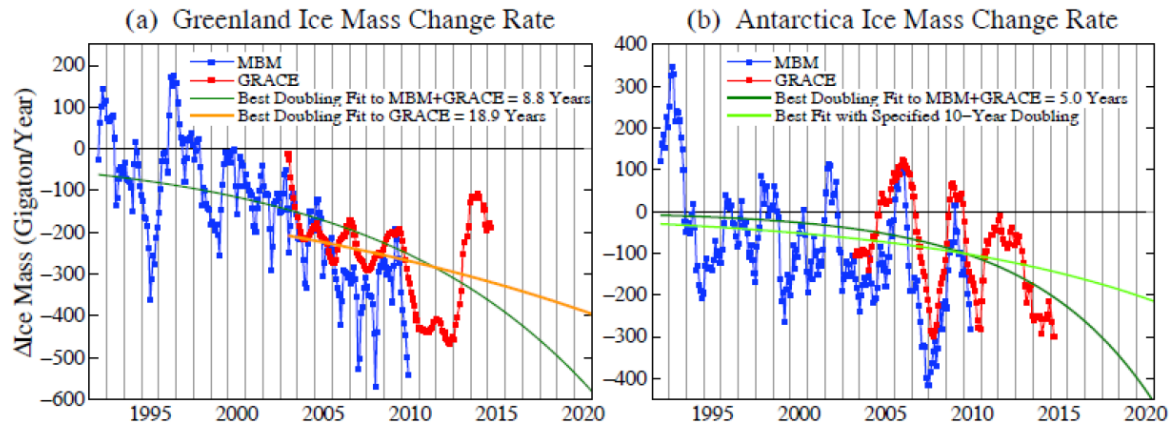


Fig. 9. Greenland and Antarctica ice mass change rates. GRACE data are extension of Velicogna et al. (2014) gravity data. MBM (mass budget method) data from Rignot et al. (2011). Red curves are gravity data for Greenland and Antarctica only: small Arctic ice caps and ice shelf melt add to freshwater input.

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 better understanding of these processes and models.

6.1 Ocean stratification and ocean warming.

Global ocean circulation (Fig. 3) is altered by the effect of low density freshwater from melting of Greenland or Antarctica 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 of 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.¹

6.2 Southern Ocean, CO₂ control knob, and ice sheet time scale.

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 CO₂ reservoir.

CO₂ is the control knob that regulates global temperature. On short time scales, i.e., fixed surface climate, CO₂ sets atmospheric temperature because CO₂ is stable, thus the ephemeral radiative constituents, H₂O and clouds, adjust to CO₂ amount (Lacis et al., 2010, 2013).

¹ 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/m² (Table S1, Hansen et al., 2005b).

On millennial time scales both CO₂ 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 CO₂ is the more stable constituent with time scale for change ~10³ years, while surface albedo is more ephemeral judging from the difficulty of finding any lag of more than order 10² 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 CO₂ 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 CO₂ amount), thus affecting hemispheric and global climate, but to achieve large global change the albedo driven climate change needs to affect the CO₂ amount.

We also note that Southern Ocean ventilation is not the only mechanism affecting airborne CO₂ 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 time scales.

The most important practical implication of this “control knob” analysis is realization that the time scale for ice sheet change in Earth’s natural history has been set by CO₂, not by ice physics. With the rapid large increase of CO₂ expected this century, we have no assurance that large ice sheet response will not occur on the century time scale 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, 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 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 CO₂ 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 CO₂ was needed to explain a 20 ppm CO₂ increase in the Holocene (Fig. 7c), because CO₂ decreased ~20 ppm, on average, during several prior interglacials. Such a large human source should have left an imprint on $\delta^{13}\text{C}$ that is not observed in ice core CO₂ (Elsig, et al., 2009). Ruddiman (2013) suggests that ¹³C 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 CO₂ 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 CO₂. Human-made CO₂ forcing needed to avoid Antarctic cooling and atmospheric CO₂ decline is only the amount needed to counteract the weak natural forcing trend, not the larger feedback-driven CO₂ declines in prior interglacials, because the feedbacks do 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. 7a). Thus the human-made CO₂ contribution required to make the Southern Ocean a CO₂ source sufficient to yield the observed CO₂ growth (Fig. 7c) 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 CO₂ source and the low $\delta^{13}\text{C}$ content of deep-ocean CO₂ 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, 1989) and exponential growth of fossil fuel use. Human-made climate forcings now overwhelm natural forcings. CO₂, at 400 ppm in 2015, is off the scale in Fig. 7c. CO₂ 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 CO₂ 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 CO₂ 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 of 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. 3, 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 $\sim 3^\circ\text{C}$ equilibrium sensitivity for $2\times\text{CO}_2$, achieves only $\sim 60\%$ of its equilibrium response in 100 years (Fig. 2). 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 $\sim 0.6\text{ W/m}^2$ (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 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 models participating in future CMIP studies should be asked to calculate and report their climate response function, R (Fig. 2). 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), although that simple relationship will likely break down if ocean overturning circulations shut down.

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 $\sim 0.1^\circ$, 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 a response function, R , similar to that of our model] with 0.1° ocean resolution for a 1%/year increasing CO_2 experiment, finding $\sim 25\%$ 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. Sabe et al. (2015) show that this model with 0.1° ocean resolution yields $3\text{--}4^\circ\text{C}$ warming along the United States East Coast at doubled CO_2 and cooling ($\sim -1^\circ\text{C}$) 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. 8 here, Fig. S24 in our full paper). 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 ($\text{CO}_2 = 936\text{ ppm}$), but the CMIP5 runs do not include ice melt. This moderate change on century time scale 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 Sec. 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 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 Convention. Our present paper has several implications with regard to the concerns that the Framework Convention 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 multimeter 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 Framework Convention 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, CO₂, 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 time scale 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 CO₂ amount, if fossil fuel emissions are rapidly phased out.

Third, we not only see evidence of changes beginning to happen in the climate system, as discussed above, we have 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 CO₂ emissions should be reduced as rapidly as practical.

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References. References noted above are provided at the end of the full length paper.