Predictions Implicit in "Ice Melt" Paper and Global Implications

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S.L. Marcus suggests that our paper[1] "Ice Melt, Sea Level Rise & Superstorms" would have greater appeal and impact if it featured some notable, verifiable predictions. In related vein, E. Stabenau asks what observations in the next decade or so would verify our assumptions.[2]

Indeed, there are many predictions implicit in our paper, and there is merit in highlighting these. Most revealing, in stark contrast to all IPCC models, is strong cooling of the Southern Ocean surface and in the North Atlantic, as shown in Fig. 1. These coolings are a consequence of fundamental processes induced by injection of meltwater into upper layers of the ocean.

Cooling of the Southern Ocean and North Atlantic results mainly from the stratification effect of freshwater. Lesser density of fresh meltwater, compared to salty ocean water, reduces sinking of surface water to the deep ocean. Reduced Antarctic Bottom Water formation reduces the amount of relatively warm deep water rising to the surface, where it increases heat flux to the atmosphere and space. Instead heat is kept at depth, raising deep water temperature and melting ice shelves (see diagram in Fig. 22 of our paper).

We predict not only that the Southern Ocean surface will cool, rather than warm, but also that the cooling will be largest in the Western Hemisphere. Cooling is larger there because the rate of ice shelf melt is larger there (Fig. 2; note that longitude is shifted 180° in Fig. 2 relative to Fig. 1). Our modeling assumes that warming induced meltwater is three times larger in the Western Hemisphere, stretching from the Ross Sea to the Weddell Sea, than in the other hemisphere.

What we have is a push and shove match between global warming, which warms the global ocean surface with amplification at high latitudes, and the freshwater stratification effect, which causes ocean surface cooling in the North Atlantic and Southern Oceans. IPCC simulations for the 21st century find a warming Southern Ocean with declining sea ice cover, as freshwater

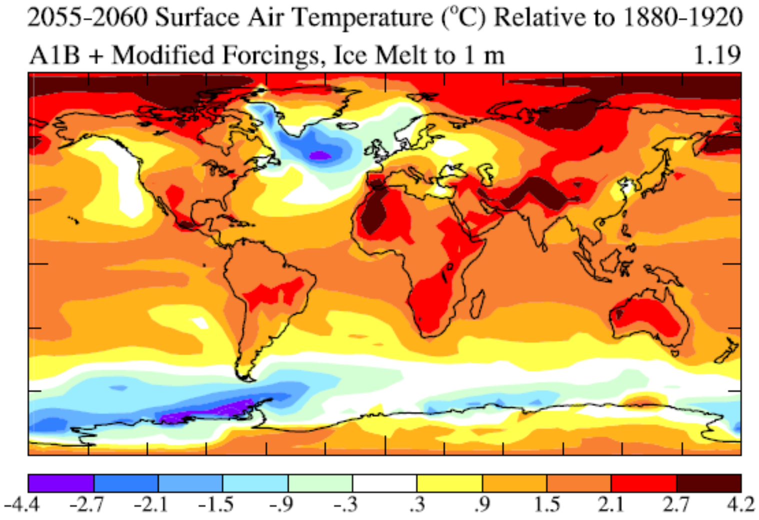

Fig. 1. Modeled temperature change in 2055-2060 with 10-year doubling time for freshwater flux.

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[1] As published in *Atmos. Chem. Phys. Disc.*, the paper is freely available here. An easier-to-read PDF of the paper, with the figures imbedded in the text, is available here.

[2] The Marcus, Stabenau and other Comments are published here.

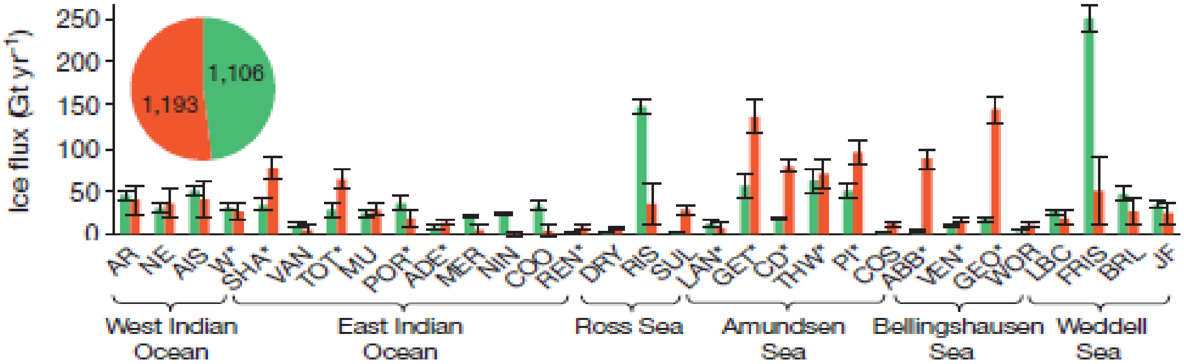

Fig. 2. Freshwater flux from Antarctic ice shelves (from Depoorter et al.[3]), green is calving (icebergs) and brown ice shelf basal melt. Flux includes steady state melt and recent growth (Depoorter et al. Table 1).

injection is either omitted or small. In contrast, with our assumed rates of freshwater injection, estimated from observations today and extrapolated into the future with several alternative doubling rates, the freshwater cooling effect is already comparable to the greenhouse warming effect in the Southern Ocean, and cooling wins out in our model over the next decade or two.

Furthermore, we argue that our model and many ocean models understate the stratification effect because of excessive small scale ocean mixing. At face value our model has meltwater cooling exceeding the global warming effect during the next 1-2 decades, but we suggest that the cooling effect is already beginning to win out. The strong 2015-16 El Nino gives a temporary boost to global warming in this push and shove match, as El Nino tends to warm the Southern Ocean and reduce sea ice. Therefore, our prediction is that, as the El Nino fades, Southern Ocean cooling and ice area will grow, with the signal rising above the noise level during the next several years. The effect of El Nino is considered further below, but first let us comment on North Atlantic cooling and make a “prediction” about ocean mixing.

The exact course of North Atlantic cooling is difficult to predict, because of competition there between amplifying and diminishing feedbacks, as discussed below. Nevertheless, the nature of the prediction is clear: the warming-induced freshwater flux increases ocean stratification, slows North Atlantic Deep Water formation, reduces the strength of Atlantic Meridional Overturning Circulation (AMOC), and cools the North Atlantic Ocean. This is an old concept, studied extensively for many years. However, what we are saying is that the system is more sensitive than has been realized and effects are already beginning to occur.

Prediction about models. Our inference of early arrival of significant freshwater effects in the North Atlantic and Southern Oceans, earlier than generally anticipated, is related to our conclusion that ocean mixing is excessive in many climate models. This matter has important implications about climate sensitivity and the imminence of large human-made climate impacts. We suggest that improved understanding of this issue could be achieved soon via coordination among model studies, without waiting for nature to reveal itself over the next one-two decades.

Our conclusion about ocean mixing in models originated in study of Earth’s energy imbalance: most climate models had a current planetary energy imbalance of at least 1 W/m^2, while

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[3] Depoorter, M.A., J.L. Bamber, J.A. Griggs, J.T.M. Lenaerts, S.R.M. Ligtenberg, M.R. van den Broeke, & G. Moholdt: Calving fluxes and basal melt rates of Antarctic ice shelves, Nature, 502, 89-92, 2013.

observations revealed an imbalance of ~0.6 W/m^2 [see Fig. 15 of Hansen et al.[4] and Trenberth and Fasullo (2010)[5]]. We had presented data earlier[6] and in our 2011 paper[4] that most climate models yield unrealistically large Earth energy imbalance and excessive heat flux into the ocean. A large energy imbalance in models can result from model flaws such as excessive diffusive mixing, too strong polar ocean overturning, or an overly deep tropical thermocline.

Models can be tweaked in various ways to affect the planetary energy imbalance, e.g., change of any climate feedback that reduces the model's equilibrium climate sensitivity will reduce the calculated energy imbalance. It is possible that a desire to obtain the observed magnitude of global warming in the past century and the observed magnitude of Earth's energy imbalance accounts for a tendency of recent climate models to have a lower climate sensitivity than that suggested by paleoclimate data.[7] If so, it is a case of getting the right answer (moderate observed heat flux into the ocean) for the wrong reason, a path that will lead to misinformation.

What we are suggesting is analogous to, and possibly has overlap with, the suggestion of Hofmann and Rahmstorf[8] that there is a bias in ocean model development spurred by a desire for models to have a stable AMOC with overturning strength similar to observations. In both cases, these model development pressures lead to models being less sensitive than the real world to freshwater and other climate forcings.

These important fundamental issues re the sensitivity of the climate system could be investigated via appropriate CMIP (Climate Model Intercomparison Project) studies. All models should be used for a long climate simulation to obtain the model's equilibrium response to instantaneous doubling of atmospheric CO_2 (or alternative forcing such as a 2% increase of solar irradiance). Such a model run establishes the model's equilibrium climate sensitivity and also the model's response function, which is the fraction of the equilibrium response achieved as a function of time. These are fundamental climate model characteristics, which allow interpretation of climate model studies. Note also that the response function is a "Green's function" that can be used to estimate the expected global temperature change as a function of time for any climate forcing[4].

Once these fundamental model characteristics are established, improvements of model physics or numerics become more informative. Also interpretation of differences among various models becomes more conclusive and valuable. Processes that affect model sensitivity to freshwater and other forcings can be analyzed better if these basic model characteristics are defined.

El Nino effect on Southern Ocean. Southern Ocean SST (sea surface temperature) increased during 1950-1980 (Fig. 3) as the Southern Hemisphere warmed. After 1980, even though the world and the Southern Hemisphere continued to warm, Southern Ocean SST was flat for almost

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[4] Hansen, J., M. Sato, P. Kharecha & K. von Schuckmann: Earth's energy imbalance and implications, Atmos. Chem. Phys., 11, 13421-13449, 2011.

[5] Trenberth, K.E. & J.T. Fasullo: Tracking Earth's energy, Science 328, 316-317, 2010.

[6] Hansen, J., R. Bleck, E. Leuliette, K. Lo, R. Ruedy, M. Sato, S. Sun, J. Willis: Earth's energy imbalance and ocean heat storage, Amer. Geophys. Union annual meeting, San Francisco, 14 December 2006.

[7] Hansen, J., M. Sato, G. Russell, and P. Kharecha, 2013: Climate sensitivity, sea level, and atmospheric carbon dioxide. *Phil. Trans. Roy. Soc. A*, **371**, 20120294, doi:10.1098/rsta.2012.0294.

[8] Hofmann, M., & S. Rahmstorf: On the stability of the Atlantic meridional overturning circulation, Proc. Natl. Acad. Sci. USA, 106, 20584-20589, 2009.

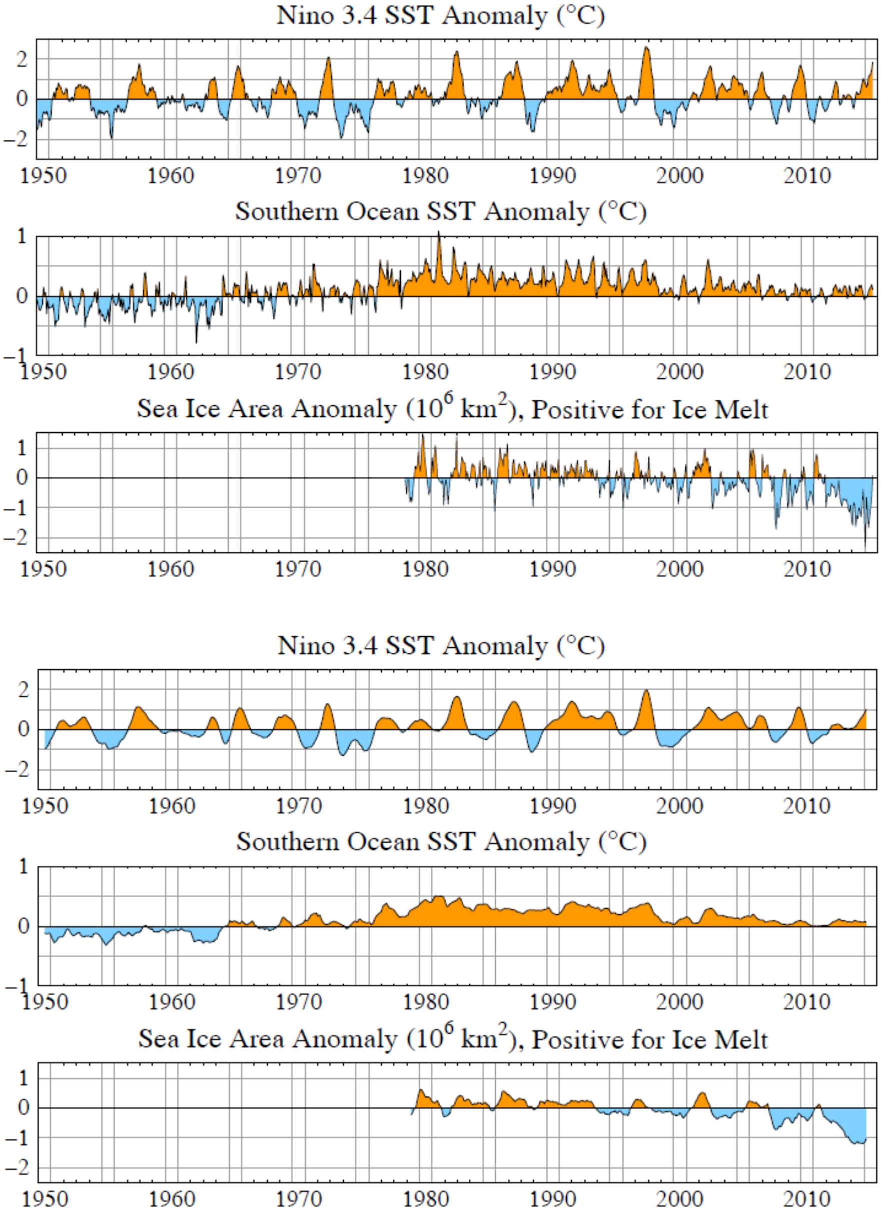

Fig. 3. Monthly (upper chart) and 12-month running mean (lower charts) of Nino 3.4 temperature index, Southern Ocean (south of 60°S) sea surface temperature anomaly, and Southern Ocean sea ice area. Data sources: SST is NOAA ERSST.v4 (http://www.cpc.ncep.noaa.gov/data/indices/), sea ice from National Snow and Ice Data Center (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/). Nino 3.4 area is (5N-5S, 170W-120W). Southern Ocean is defined here as the ocean area south of 60S. Base periods are 1951-1980 for Nino and Southern Ocean SST anomalies and 1981-2010 for sea ice.

two decades and declined over the last two decades. Sea ice area, measured by satellite since 1979, increased in the past two decades, consistent with the cooling Southern Ocean surface.

We interpret the Southern Ocean cooling and sea ice increase of the past two decades as effects of Antarctic ice shelf melt, i.e., increasing freshwater injection. Although some other researchers have suggested that Antarctic ozone loss may have caused sea ice increase, as discussed in our paper[1], ozone loss had already reached its maximum by the late 1990s and thus cannot account for the SST cooling and sea ice increase in the past two decades.

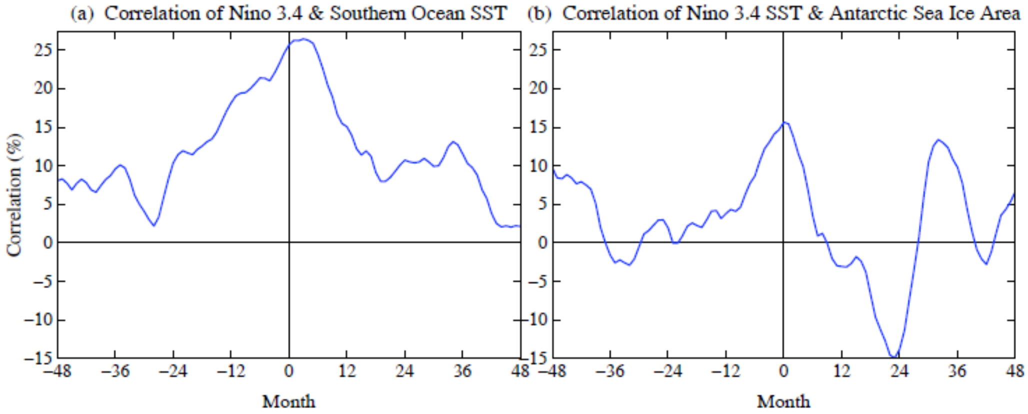

Fig. 4. Correlation between Nino 3.4 SST and (a) Southern Ocean SST or (b) Antarctic sea ice. The sign of correlation in (b) has positive correlation indicating decreasing sea ice area with increasing Nino 3.4 SST.

The sea ice area anomaly decreased sharply in August 2015, back to about the mean value for the base period (1981-2010). We suggest that this sea ice loss is, at least in part, a consequence of the strong 2015-2016 El Nino, which began a few months ago. In other words, in the push and shove match between global warming and freshwater cooling on the Southern Ocean, global warming gets a boost from El Nino, but that boost is temporary. Southern Ocean SST is correlated with El Nino, as shown in Fig. 4a, with Southern Ocean change lagging Nino 3.4 by 3 months. Sea ice area has a weaker correlation (Fig. 4b), less sea ice when Nino 3.4 is warmer.

A fundamental check on the Southern Ocean is provided by a map of global SST change over the past 20 years (Fig. 5). SST is increasing globally, but it is decreasing in the Southern Ocean. This is contrary to IPCC models that exclude increasing freshwater injection. Note that the observed cooling is in the Western Hemisphere, as expected from freshwater injection (Fig. 1).

Caution is dictated by the limited period and wider cooling then (Fig. 5), although the apparent tropical cooling simply reflects a strong El Nino early in the 20-year period. The next few years will provide a good test. Our prediction is that, after the current strong El Nino fades, Southern Ocean cooling will resume with maximum cooling in the Western Hemisphere (see Fig. 1).

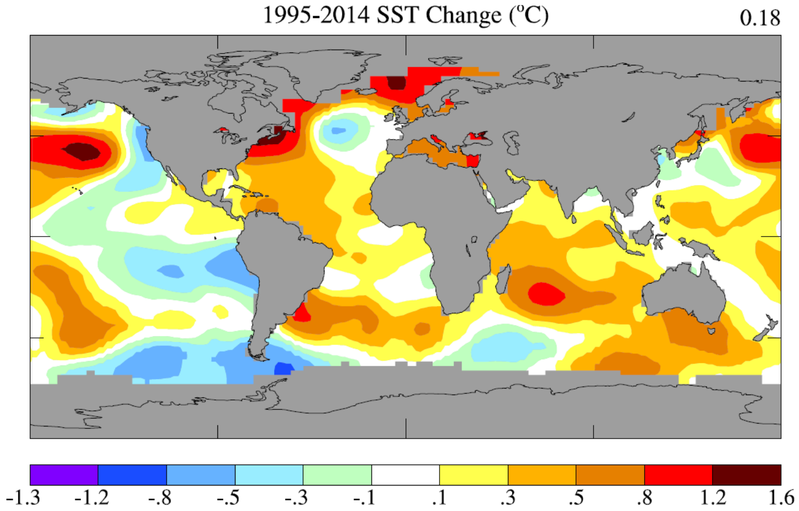

Fig. 5. Sea surface temperature change in past two decades. Tropical Pacific cooling is due to a strong El Nino at the outset of the 2-decade period. In contrast, the Western Hemisphere Southern Ocean cooling is more continuous and apparent in temperature change maps for the past 1-, 2- and 3-decade periods.

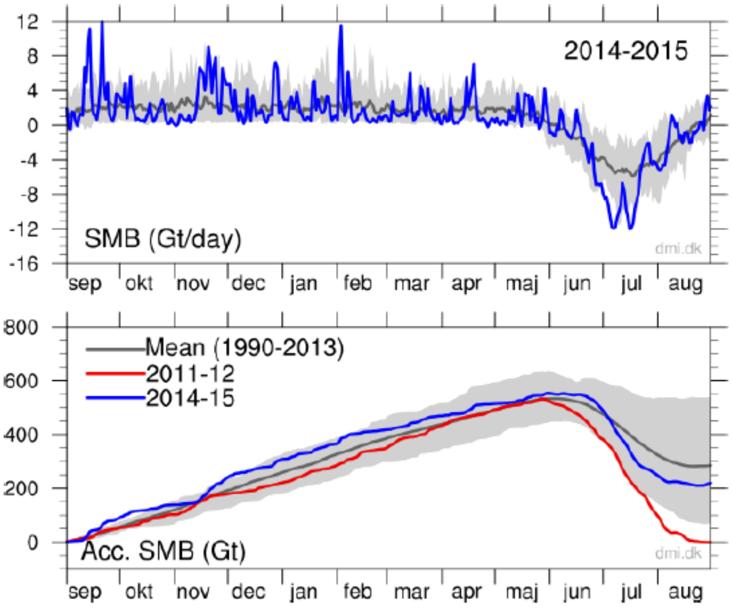

Fig. 6. Top: daily contribution to surface mass balance of Greenland ice sheet from September 2014 through August 2015. Bottom: cumulative mass balance, with comparison to the year with record ice melt (2011-12). Grey regions show the range of values in the past 24 years, excluding the highest and lowest values during that period. Based on daily weather data and model of Danish Meteorological Institute (http://www.dmi.dk/en/groenland/maalinger/greenland-ice-sheet-surface-mass-budget/).

<u>Ice sheet mass balance</u>. Perhaps our most important assumption and prediction concerns the time scale for large scale mass loss from the Antarctic and Greenland ice sheets. We expect different time scales for the two ice sheets, principally for two reasons.

First, the Antarctic ice sheet has large ice volumes in West Antarctica and two East Antarctic basins that are fronted by ice resting on retrograde beds below sea level (beds sloping inland), a configuration with potential for unstable grounding line retreat and ice sheet disintegration (see references in association with Fig. 22 in our paper[1]). Multiple submarine valleys in Greenland make parts of the ice sheet vulnerable to thermal forcing by a warming ocean, but most of these valleys are prograde and thus less subject to rapid retreat.

Second, Antarctic freshwater-induced regional surface cooling yields amplifying feedbacks that melt ice shelves, which is the principal route to increased Antarctic ice sheet mass loss. In contrast, Greenland mass loss is more dependent on surface melt, thus on weather. Moreover, North Atlantic cooling induced by meltwater may have an impact on Greenland surface melt.

For example, the Greenland surface mass balance over the past year is shown as blue curves in Fig. 6, calculated from weather data. In the accumulating seasons (most of the year) there were several unusually large snowfall events, so Greenland ice sheet mass accumulation exceeded the climatological mean (1990-2013 average, the black curve). However, a weather change in late June, lasting only a few weeks, caused a brief period of strong melting. The net surface mass balance for the year was about +200 Gt, almost 100 Gt less than the climatologic +300 Gt. [1 Gt = 1 Gigaton = 1 billion tons = the mass of 1 cubic kilometer of water.]

When the ice sheet was in mass balance, the average year had a surface mass gain of about +300 Gt, which was balanced by a mass loss −300 Gt of iceberg discharge by ice streams.

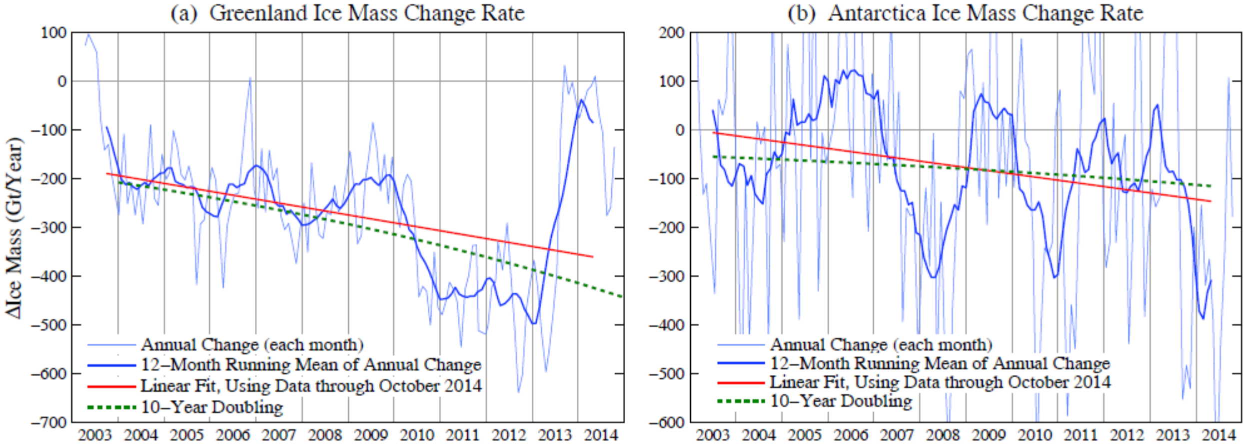

Fig. 7. Greenland and Antarctic ice mass change based on Velicogna et al. (2014)[9] gravity data. Green (dashed) curve for Greenland is freshwater discharge used in our climate model. Blue curves are gravity data for Greenland (and Antarctica) only; small Arctic ice caps and ice shelf melt are additional. Monthly data points are the difference between the ice sheet mass at the point plotted and the mass in the same month one year earlier. The 12-month running mean is plotted at the mid-point of the year.

In 2012, the year with most extreme summer melt (red curve in Fig. 6), the surface melt alone was sufficient to balance the mass gain from precipitation. If ice stream discharge equaled its climatologic value (−300 Gt), the Greenland ice sheet would have lost 300 Gt that year. The gravity satellite data (Fig. 7a) suggests that the net mass change was actually about −450 Gt in 2012, if we accept all these measurements as accurate.

This implies that ice mass discharge in 2012 (~450 Gt) was ~50% larger than its climatologic value (~300 Gt), so speedup of iceberg discharge as well as surface melt contributed to ice sheet mass loss. In 2013 Greenland weather differed drastically from 2012, with large snowfall and little surface melt, causing a dramatic decrease in the net ice sheet mass loss inferred from gravity satellite data (Fig. 7a). The rate of mass loss increased over the 12-year data period, but the large variability makes it impossible to a mass loss doubling time from such a short period.

The rapid acceleration of mass loss from Greenland occurred because of both increased mass loss via changes in the ice sheet's surface mass balance and increased ice stream discharge. For simplicity, let's call these two terms "surface melt" and "iceberg discharge".

Increasingly accurate estimates of the "surface melt" and "iceberg discharge" terms for the total ice sheet, and even their regional distribution, are obtained from improving analyses of gravity data and surface mass balance (see, e.g., Figs. 2 and 3 of Velicogna et al.[9]). Despite interannual variability of the net mass change, the total Greenland "iceberg discharge" now seems to be consistently 100-150 Gt larger than the climatologic 300 Gt. Thus, although gravity data for the 2014-15 net Greenland mass change are not yet available, it is likely to be a mass loss of at least 200-250 Gt, so larger than 2013 and more consistent with the long-term trend in Fig. 7 (a).

Greenland's future, however, will be affected by what happens in the North Atlantic Ocean.

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[9] Velicogna, I., T.C. Sutterley, M.R. van den Broeke: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, Geophys.Res.Lett. 41, 8130-8137, doi10.1002/2014GL061052, 2014

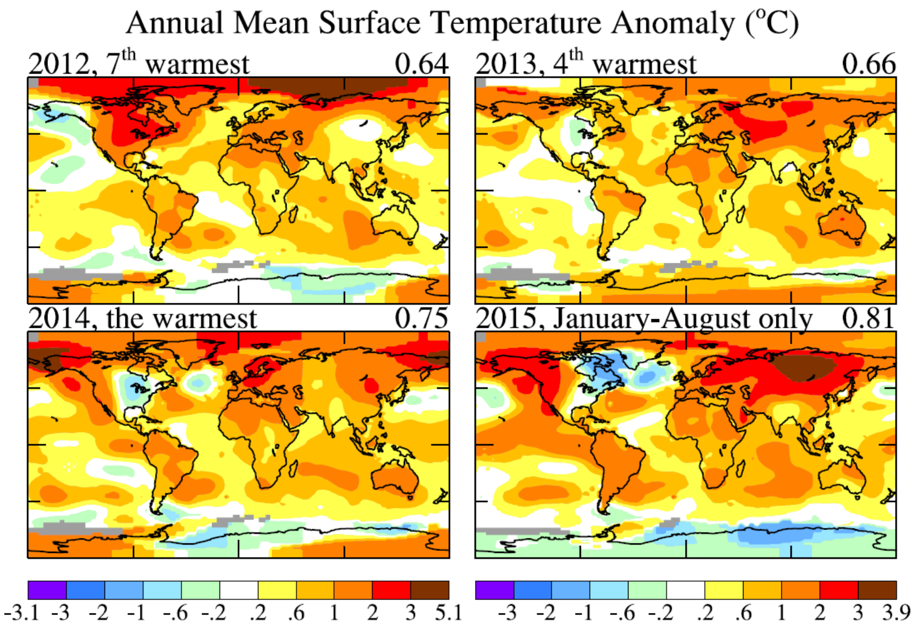

Fig. 8. Surface temperature anomalies (base period 1951-1980) during the current and past three years.

North Atlantic Ocean. Greenland and surroundings were unusually warm in 2012, when record Greenland surface melt and ice sheet mass loss occurred. Since then the North Atlantic southeast of Greenland has progressively cooled (Fig. 8). Meteorologists have noted that extreme warmth in the North Pacific near the west coast of North America could set up a long-wave atmospheric pattern leading to cool season Arctic air outbreaks in eastern North America, as has occurred the past two winters, and that such a long-wave pattern may have led to North Atlantic cooling.

On the other hand, the northeast Pacific warmth and North Atlantic cold developed together, so there is no empirical evidence that one was more the cause of the pattern than the other. Note also that the North Atlantic temperature pattern is similar to that simulated as the response to freshwater injection on the North Atlantic (Fig. 1), and to the paleoclimate North Atlantic temperature pattern found when the AMOC circulation shuts down or slows down.

Ice-melt-induced North Atlantic cooling likely occurs sooner in the real world than in our model (or most models), as models tend to underestimate stratification effects. We thus suggest that the observed North Atlantic cooling is at least in part an effect of increased freshwater discharge, and that AMOC slowdown and North Atlantic cooling will become clearer in coming decades.

AMOC slowdown that causes cooling ~1°C and perhaps affects weather patterns is very different from an AMOC shutdown that cools the North Atlantic several degrees Celsius; the latter would have dramatic effects on storms and be irreversible on the century time scale.

Despite poor understanding of the climate forcing required to transition from moderate AMOC slowdown to AMOC shutdown, the most important conclusion is clear. Business-as-usual fossil fuel use, yielding 600 ppm CO_2 or higher within a century, will almost surely shut down AMOC and spur practically irreversible consequences. In contrast, rapid emissions phase down, as required to restore planetary energy imbalance by finding a path to a safe level of atmospheric CO_2 less than 350 ppm, would yield additional warming of only a few tenths of a degree Celsius, which would not likely shut down AMOC. In at least a broad sense, the need to avoid large sea level rise and the need to avoid AMOC shutdown place comparable limits on emissions.

<u>Predictions of ice sheet mass loss and sea level rise</u>. In our paper[1] we discuss potential ice melt doubling times of 10, 20 and 40 years, which respectively would lead to multi-meter sea level rise in about 50, 100, and 200 years. For the sake of analyzing the effect of freshwater on ocean circulation and planetary energy balance, we made climate simulations for doubling times of 5, 10 and 20 years, omitting 40-year doubling because of its larger computing requirement. These cases were sufficient for conclusions about the effect of freshwater on the planetary energy balance and shutdown of overturning ocean circulations (AMOC and SMOC).

Here we give our opinion about the likely speed at which ice sheets will respond to the climate forcing for "business-as-usual" growth of fossil fuel emissions. The resulting rate of increasing climate forcing is far outside the rate Earth has ever experienced. We suspect that glaciologists anticipating very slow response of ice sheets base their opinion in part on the rates of ice sheet change that occurred in response to natural climate forcings, which changed much more slowly than the human-made forcing. The rate of change of greenhouse gases determines Earth's energy imbalance, and the energy imbalance is the "drive" or "forcing" of ice sheet change.

Antarctica. West Antarctica, with enough ice to raise sea level 3-4 m, is especially vulnerable. If the West Antarctic ice sheet is forced by a large planetary energy imbalance, as it would be with powerful business-as-usual climate forcing, it is inevitable that the West Antarctic ice sheet would become unstable – it is only a question of how rapidly the ice sheet would disintegrate. A sea level rise of at least 3-4 m (or larger, including the other contributions to sea level rise) would occur before a major slowdown in the rate of sea level rise sets in.

Prediction of sea level rise must be based on physical reasoning incorporating the full range of available information: paleo sea level change in response to paleo forcings, empirical evidence of ice sheet response to modern forcings, knowledge about the status of current energy imbalance, and insights from climate modeling. Paleo evidence indicates that multi-meter sea level rise is possible in a century. Modern observations reveal that parts of the Antarctic ice sheet are ripe for rapid ocean-ice interactions that can destabilize enough ice to raise sea level several meters. Ocean data reveal a substantial planetary energy imbalance, which implies that the subsurface temperature near Antarctic ice shelves will continue to increase. Our climate modeling reveals amplifying feedbacks in the Southern Ocean that spur ice shelf melt and iceberg discharge.

Given all the evidence, a claim that a scenario with 600-900 ppm CO_2 forcing within a century would <u>no</u>t yield multi-meter sea level rise this century is an extraordinary claim that would require extraordinary proof. Today's ice sheet models are not capable of providing that proof.

We have shown that amplifying feedbacks are dominant in the Antarctica-Southern Ocean response to a large global climate forcing. In such a case, ice discharge will grow nonlinearly until the West Antarctic source begins to be exhausted. During the growth phase of ice discharge a characteristic time for doubling of the discharge rate is likely a better approximation than linear increase with temperature. Paleo data indicate that the growth rate of ice discharge, even with weak forcing, can be fast enough to yield multi-meter sea level rise in a century.

Gravity satellite data for Antarctic ice sheet mass suggest a doubling time for mass loss of no more than a decade for the Antarctic ice sheet as a whole (Fig. 7b), but the record is only 12 years long and has large variability. More important, the Amundsen Sea sector of Antarctica, which is the window to the West Antarctic ice sheet, is losing more mass (−116 ± 6 Gt/year)[9] than Antarctica as a whole, its mass loss rate is much less noisy (Fig. 3c of Velicogna et al.[9]), and its acceleration (−12.7 ± 1.6 Gt/year^2)[9] indicates a doubling time of no more than a decade.

If CO_2 emissions follow IPCC business-as-usual emissions growth (which yield end-of-century CO_2 in the range ~600-900 ppm), we predict several meters of sea level rise within a century.

A more useful prediction is one for the near term, when policies can still affect the longer-term outcome. In the near-term, over the next several years, we expect the rate of mass loss from West Antarctica to continue to grow with doubling times of the order of 10 years. If such growth continues, it will provide powerful support for strong action to phase down fossil fuel emissions.

Greenland. Greenland ice sheet mass loss rate doubled in the first decade of gravity data, but more than half of the mass loss was from increased surface melt[9], spurred by unusual weather. Iceberg discharge, estimated as the difference between net mass loss (gravity data) and the surface mass balance, is exceeding the rate for ice sheet mass balance. Surface melt and iceberg discharge both should increase as the atmosphere and ocean continue to warm. Other amplifying feedbacks, including decreasing surface albedo and lowering of ice surface altitude, in time will lead to a large reduction in the size of the Greenland ice sheet for large CO_2 climate forcing.

Future rate of growth of Greenland mass loss is difficult to predict, in part because feedbacks induced by freshwater release are more complex than in the Antarctic. Regional cooling caused by meltwater may alter weather patterns, thus affecting both surface melt and snowfall rates. Slowdown of the AMOC and poleward heat transport may limit melting of glacier fronts.

Nevertheless, business-as-usual emissions leading to 600-900 ppm CO_2 is such a huge climate forcing that it will lead to a smaller Greenland ice sheet, eventually contributing sea level rise of as much as a few meters. Greenland ice accessible via below sea level canyons is at least ~2 meters of sea level. Despite ambiguities concerning several feedbacks, noted above, the slow amplifying feedbacks (surface albedo, surface altitude) assure continued increase of the mass loss rate. Given (1) the huge magnitude of the climate forcing for business-as-usual CO_2 growth, and (2) the mutual enhancement of several amplifying feedbacks, we expect the doubling time for increasing mass loss by the Greenland ice sheet to be not greater than ~20 years.

Our prediction for Greenland is thus that ice sheet mass loss, despite substantial variability, will continue to increase exponentially with a doubling time of not more than 20 years. Such a rate yields meter scale contribution to global sea level at latest by the middle of next century. The freshwater injection associated with such sea level rise also implies shutdown of AMOC – not the slowdown found in some IPCC models with North Atlantic cooling ~1°C, but shutdown with cooling of several degrees with great impact on North Atlantic climate including stronger storms, changes that would not be reversible on the time scale of a century.

These predictions refer to business-as-usual fossil fuel emissions. Even though policy actions have little effect on near-term change, our predictions for later this century and beyond become very different if effective policy actions are initiated soon, as described next.

Policy relevance. Climate science has strong policy implications. However, we scientists have not done an adequate job of informing policymakers, as epitomized a few days ago when one of us (JEH) was contacted by a filmmaker requesting participation in a new documentary that would conclude it is already too late to save coastal cities such as Miami.

If the filmmaker's hypothesis were correct, it would be damning – failure of science to clearly define the policy implications until it was too late. However, even though a certain "scientific reticence"[10,11] seems to infect the sea level rise issue, we do not agree that it is already too late to avert climate disasters including: (1) sea level rise inundating coastal cities, (2) shutdown of the Atlantic Meridional Overturning Circulation. Moreover, we will conclude that the actions required to avoid sea level disaster should be sufficient to also avert shutdown of the AMOC and begin to reverse other climate impacts that are beginning to appear and would otherwise be expected to grow under business-as-usual fossil fuel emissions.

Let's discuss actions required to avert climate disasters in the context of responding to a request that we specify needed observations. Critical climate metrics include:

(1) Global surface temperature. Our paper makes clear that the United Nations choice of 2°C as a "guardrail" is not justified by the science, indeed global mean temperature is a flawed metric for that purpose. However, surface temperature is a good diagnostic of the climate system, and, as discussed above, Southern Ocean and North Atlantic temperature patterns will provide an indication of the effect of ice melt on the Southern Ocean and North Atlantic overturning.

(2) Earth's energy imbalance. The planet's energy imbalance provides a simple measure of where climate is headed. We must eliminate this imbalance to stabilize climate, and perhaps we will need to achieve a slightly negative imbalance for the purpose of cooling the ocean and avoiding demise of ice shelves and the ice sheets. Affecting the climate outcome will be a complex problem, because of ocean dynamics, however, a principal diagnostic needed both to measure the changing energy imbalance and analyze the dynamics is accurate monitoring of the internal ocean temperature distribution. The Argo float program needs to be maintained and expanded to the full ocean depth and polar seas, including salinity and other data.

(3) Atmospheric CO_2. Atmospheric CO_2 amount is a critical measure of the state of the planet, which governments apparently prefer to ignore, perhaps because they do not like its implications. The Framework Convention on Climate Change, agreed upon at Rio in 1992, defines GHG amount as the critical metric, saying that GHGs must be stabilized at a level that avoids "dangerous anthropogenic interference" with climate. The need to restore Earth's energy balance informs us about the required limit on greenhouse gases (GHGs), specifically that the CO_2 stabilization level cannot be as high as 450 ppm or even 400 ppm, the present amount. Instead it is no more than 350 ppm and possibly lower[12], which has immediate implications for policy.

(4) Sea level → ice sheet mass change. Most large cities are located on coast lines. Multi-meter sea level rise has the potential to wreak global economic havoc, create hundreds of millions of

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[10] Hansen, J.E., 2007: Scientific reticence and sea level rise. *Environ. Res. Lett.*, **2**, 024002.

[11] Hansen, J., 27 July 2015: Darn!! Sea Level Disaster Ahead! In 200-900 Years. When??

[12] Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231.

refugees, and thus perhaps make the world practically ungovernable. Measurements of sea level from satellites can now be made so precisely that it has become an invaluable metric that should be continuously monitored. However, large ice sheets are the source of potentially disastrous sea level rise and it is important to measure their rates of change accurately on a regional basis. Thus a critical measurement is continuation of precise gravity measurements from satellites.

(5) Aerosols. Measurements of the largest climate forcings affecting Earth's energy imbalance are needed for policy prescription. Greenhouse gases are monitored, but the other large human-made forcing, aerosols, including effects on clouds, are not monitored. Required measurements, including 10-parameter characterization of aerosol and cloud particle microphysical properties, can be made with a relatively inexpensive photopolarimeter making high precision passive measurements of reflected sunlight across the ultraviolet to near-infrared spectral region.[13] Analogous to gravity measurements, precise aerosol measurements would be done best from a small satellite, thus making continuous or near-continuous monitoring feasible.

Now let us return to the question: is it already too late? The conclusion that dangerous climate change is reached at global warming less than 2°C, and that it will be necessary to reduce CO_2 back below 350 ppm, makes clear how difficult the task will be.

The bright side is the fact that the climate forcing limitation required to avoid sea level disaster is so stiff that it should also avert other climate impacts such as AMOC shutdown. Furthermore, we would roll back undesirable climate impacts that are already beginning to appear.

There is a misconception that slow feedbacks associated with climate forcings already in place will have unavoidable consequences. Most slow feedbacks will never occur, if we succeed in restoring Earth's energy balance. Restoration can be aided by reducing non-CO_2 forcings. However, the dominance of CO_2 in present climate forcing growth, and the long life of fossil fuel carbon in the climate system, demand first attention on phase-out of fossil fuel emissions.

Political situation. Climate stabilization at a level avoiding the most disastrous consequences such as loss of coastal cities is physically possible and, we will argue, economically beneficial. The problem seems to be in politics, not in the sciences. We believe that scientific objectivity has a crucial role to play in the urgent task of finding a successful path before it is too late. However, it is appropriate for the political discussion to be pursued elsewhere.[14]

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[13] Mishchenko, M.I., B. Cairns, G. Kopp, C.F. Schueler, B.A. Fafaul, J.E. Hansen, R.J. Hooker, T. Itchkawich, H.B. Maring, and L.D. Travis, 2007: Accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission. *Bull. Amer. Meteorol. Soc.*, **88**, 677-691.

[14] Hansen, J., 2015: "Isolation of 1600 Pennsylvania Avenue", to be provided on web page soon.