Update of Greenland Ice Sheet Mass Loss: Exponential?

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Shepherd et al. (2012) provide an update of the mass loss by the Greenland ice sheet (and the Antarctic ice sheet). They compare several analysis methods, achieving a reasonably well-defined consensus. The data is 2-3 years more current than data we employed recently (Hansen and Sato, 2012), so a new look at the data seems warranted.

A crucial question is how rapidly the Greenland (or Antarctic) ice sheet can disintegrate in response to global warming. Earth's history makes it clear that burning all fossil fuels would cause eventual sea level rise of tens of meters, thus practically wiping out thousands of cities located on global coast lines. However, there seems to be little political or public interest in what happens next century and beyond, so reports of the IPCC (Intergovernmental Panel on Climate Change) focus on sea level change by 2100, i.e., during the next 87 years.

IPCC (2007) suggested a most likely sea level rise of a few tens of centimeters by 2100. Several subsequent papers suggest that sea level rise of ~1 meter is likely by 2100. However, those studies, one way or another, include linearity assumptions, so 1 meter can certainly not be taken as an upper limit on sea level rise (see discussion and references in the appendix below, excerpted from our recent paper). Sea level rise in the past century was nearly linear with global temperature, but that is expected behavior because the main contributions to sea level rise last century were thermal expansion of ocean water and melting mountain glaciers.

In contrast, the future sea level rise of greatest concern is that from the Greenland and Antarctic ice sheets, which has the potential to reach many meters. Hansen (2005) argues that, if business-as-usual increase of greenhouse gases continue throughout this century, the climate forcing will be so large that non-linear ice sheet disintegration should be expected and multi-meter sea level rise not only possible but likely. Hansen (2007) suggests that the position reflected in IPCC documents may be influenced by a "scientific reticence". In such case the consensus movement of sea level rise estimates from a few tens of centimeters to ~1 meter conceivably is analogous to the reticence that the physics community demonstrated in its tentative steps to improve upon estimates of the electron charge made by the famous Millikan.[1]

Perceived authority[2] in the case of ice sheets stems from ice sheet models used to simulate paleoclimate sea level change. However, paleoclimate ice sheet changes were initiated by weak climate forcings changing slowly over thousands of years, not by a forcing as large or rapid as human-made forcing this century. Moreover, in a paper submitted for publication (Hansen et al., 2013) we present evidence that even paleoclimate data do not support the degree of lethargy and hysteresis that exists in such ice sheet models.

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[1] "Millikan measured the charge on an electron by an experiment with falling oil drops, and got an answer which we now know not to be quite right. It's a little bit off because he had the incorrect value for the viscosity of air. It's interesting to look at the history of measurements of the charge of an electron, after Millikan. If you plot them as a function of time, you find that one is a little bit bigger than Millikan's, and the next one's a little bit bigger than that, and the next one's a little bit bigger than that, until finally they settle down to a number which is higher. Why didn't they discover the new number was higher right away? It's a thing that scientists are ashamed of - this history - because it's apparent that people did things like this: When they got a number that was too high above Millikan's, they thought something must be wrong - and they would look for and find a reason why something might be wrong. When they got a number close to Millikan's value they didn't look so hard." (Feynman, 1997).

[2] No real person is blamed for this, but Iceblock Geezer plays a sordid role in the Trial of the Century.

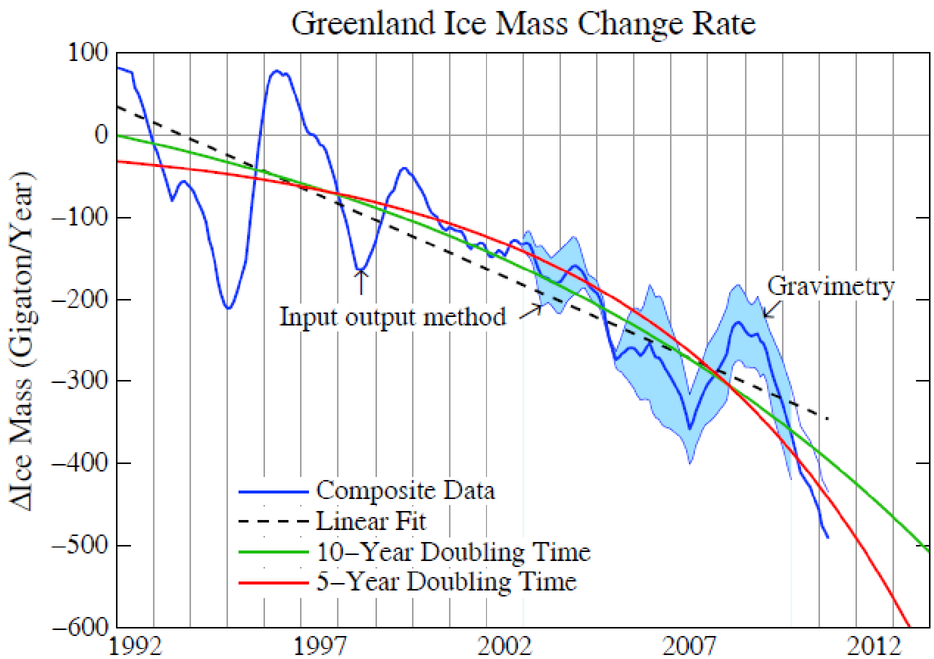

Fig. 1. Annual mass change of Greenland ice sheet based on the input-output method, an analysis of gravity measurements, and a best-estimate composite (Shepherd et al., 2012).

Fig. 1 shows the Greenland ice sheet mass change estimated by Shepherd et al. (2012). The input-output method calculates the difference between mass gained through snowfall and mass lost by sublimation, meltwater runoff, and discharge of ice into the ocean. This record and the analysis of satellite gravity measurements agree within their margins of error (see Shepherd et al., 2012). There are no satellite gravity data to confirm or refute the large amplitude of fluctuations prior to 2000 in Fig. 1, which are based on input-output calculations.

Fig. 1 shows that Greenland has been losing mass at a faster and faster rate over the past decade, with the recent rate corresponding to ~1 mm sea level per year (1 mm sea level = 360 Gt ice). The linear fit to the Shepherd et al. data in Fig. 1 yields a Greenland contribution to global sea level of about 30 cm by 2100.

The increasing Greenland mass loss in Fig. 1 can be fit just as well by exponentially increasing annual mass loss, a behavior that Hansen (2005, 2007) argues could occur because of multiple amplifying feedbacks as an ice sheet begins to disintegrate. A 10-year doubling time would lead to 1 meter sea level rise by 2067 and 5 meters by 2090. The dates are 2045 and 2057 for 5-year doubling time and 2055 and 2071 for a 7-year doubling time.

However, exponential ice loss, if it occurs, would encounter negative (diminishing) feedbacks. Our simulations (Hansen and Sato, 2012) suggest that a strong negative feedback kicks in when sea level rise reaches meter-scale, as the ice-melt has a large cooling and freshening effect on the regional ocean. Such a slowdown in the rate of sea level rise would be little consolation to humanity, however, as the high latitude cooling would increase latitudinal temperature gradients, thus driving powerful cyclonic storms (Hansen, 2009), and coastlines would be continually moving landward for centuries.

West Antarctic ice is probably more vulnerable to rapid disintegration than Greenland ice, because the West Antarctic ice sheet rests mainly on bedrock below sea level (Hughes, 1972). The principal mechanism for mass loss from West Antarctica is warming of the ocean, melting of West Antarctic ice shelves, and thus increased flux from the ice sheet to the ocean.

The several analysis methods compared by Shepherd et al. (2012) concur that the West Antarctic ice sheet mass imbalance has grown since 2005 from an annual mass loss of 0-100 Gt ice to a recent annual mass loss of 100-200 Gt ice (Fig. 4 of Shepherd et al.).

So, what are the shapes of the ice sheet mass loss curves for Greenland and West Antarctica? Is there evidence that they may be exponential? It's too early to tell, as shown by Fig. 1 above. The picture may begin to be clearer within the next several years. The problem is, by the time the data record is long enough to be convincing, it may be exceedingly difficult or impossible to prevent sea level rise of many meters.

Obviously we need to continue to monitor the ice sheets as well as practical, especially with the gravity and input-output methods, which appear to be the most promising. Also, given the fact that we could reduce the dangers of climate change greatly by putting an honest[3] gradually rising price on carbon emissions, and there would be many other merits of doing that (http://www.columbia.edu/~jeh1/mailings/2012/20121213_StormsOfOpa.pdf), it would make good sense to slow down the climate change experiment by placing such a fee on carbon.

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[3] That is, a fee that makes the price of fossil fuels pay their cost to society. The funds collected from a carbon fee should be distributed directly to the public; otherwise the public will not allow the fee to rise to a level that results in clean energies supplanting fossil fuels.

Appendix: Excerpt from Hansen and Sato (2012):

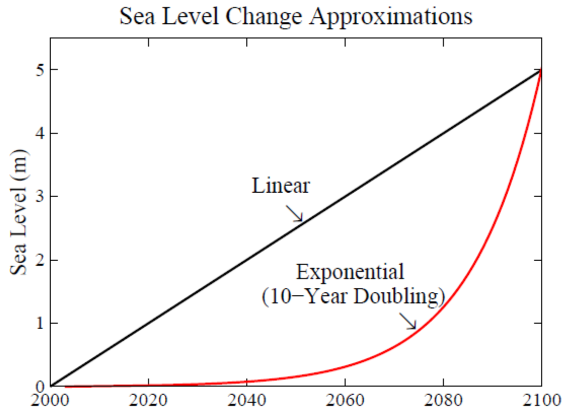

Fig. 7. Five-meter sea level change in 21st century under assumption of linear change and exponential change (Hansen, 2007), the latter with a 10-year doubling time.

Sea level change estimates for 21st century. IPCC (2007) projected sea level rise by the end of this century of about 29 cm (midrange 20-43 cm, full range 18-59 cm). These projections did not include contributions from ice sheet dynamics, on the grounds that ice sheet physics is not understood well enough.

Rahmstorf (2007) made an important contribution to the sea level discussion by pointing out that even a linear relation between global temperature and the rate of sea level rise, calibrated with 20th century data, implies a 21st sea level rise of about a meter, given expected global warming for BAU greenhouse gas emissions. Vermeer and Rahmstorf (2009) extended Rahmstorf's semi-empirical approach by adding a rapid response term, projecting sea level rise by 2100 of 0.75-1.9 m for the full range of IPCC climate scenarios. Grinsted et al. (2010) fit a 4- parameter linear response equation to temperature and sea level data for the past 2000 years, projecting a sea level rise of 0.9-1.3 m by 2100 for a middle IPCC scenario (A1B). These projections are typically a factor of 3-4 larger than the IPCC (2007) estimates, and thus they altered perceptions about the potential magnitude of human-caused sea level change.

Alley (2010) reviewed projections of sea level rise by 2100, showing several clustered around 1 m and one outlier at 5 m, all of these approximated as linear in his graph. The 5 m estimate is what Hansen (2007) suggested was possible under IPCC's BAU climate forcing. Such a graph (Fig. 7) is comforting – not only does the 5-meter sea level rise disagree with all other projections, but its half-meter sea level rise this decade is clearly preposterous.

However, the fundamental issue is linearity versus non-linearity. Hansen (2005, 2007) argues that amplifying feedbacks make ice sheet disintegration necessarily highly non-linear, and that IPCC's BAU forcing is so huge that it is difficult to see how ice shelves would survive. As warming increases, the number of ice streams contributing to mass loss will increase, contributing to a nonlinear response that should be approximated better by an exponential than by a linear fit. Hansen (2007) suggested that a 10-year doubling time was plausible, and pointed out that such a doubling time, from a 1 mm per year ice sheet contribution to sea level in the decade 2005-2015, would lead to a cumulative 5 m sea level rise by 2095.

Nonlinear ice sheet disintegration can be slowed by negative feedbacks. Pfeffer et al. (2008) argue that kinematic constraints make sea level rise of more than 2 m this century physically untenable, and they contend that such a magnitude could occur only if all variables quickly accelerate to extremely high limits. They conclude that more plausible but still accelerated conditions could lead to sea level rise of 80 cm by 2100.

The kinematic constraint may have relevance to the Greenland ice sheet, although the assumptions of Pfeffer at al. (2008) are questionable even for Greenland. They assume that ice streams this century will disgorge ice no faster than the fastest rate observed in recent decades. That assumption is dubious, given the huge climate change that will occur under BAU scenarios, which have a positive (warming) climate forcing that is increasing at a rate dwarfing any known natural forcing. BAU scenarios lead to CO_2 levels higher than any since 32 My ago, when Antarctica glaciated. By mid-century most of Greenland would be experiencing summer melting in a longer melt season. Also some Greenland ice stream outlets are in valleys with bedrock below sea level. As the terminus of an ice stream retreats inland, glacier sidewalls can collapse, creating a wider pathway for disgorging ice.

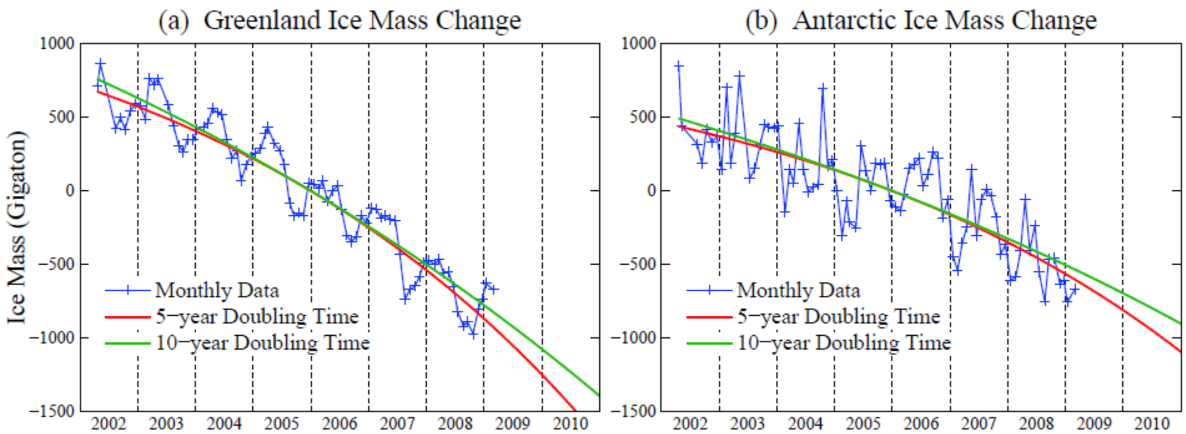

Fig. 8. Greenland (a) and Antarctic (b) mass change deduced from gravitational field measurements by Velicogna (2009) and best-fits with 5-year and 10-year mass loss doubling times.

The main flaw with the kinematic constraint concept is the geology of Antarctica, where large portions of the ice sheet are buttressed by ice shelves that are unlikely to survive BAU climate scenarios. West Antarctica's Pine Island Glacier (PIG) illustrates nonlinear processes already coming into play. The floating ice shelf at PIG's terminus has been thinning in the past two decades as the ocean around Antarctica warms (Shepherd et al., 2004; Jenkins et al., 2010). Thus the grounding line of the glacier has moved inland by 30 km into deeper water, allowing potentially unstable ice sheet retreat. PIG's rate of mass loss has accelerated almost continuously for the past decade (Wingham et al., 2009) and may account for about half of the mass loss of the West Antarctic ice sheet, which is of the order of 100 km^3 per year (Sasgen et al., 2010).

PIG and neighboring glaciers in the Amundsen Sea sector of West Antarctica, which are also accelerating, contain enough ice to contribute 1-2 m to sea level. Most of the West Antarctic ice sheet, with at least 5 m of sea level, and about a third of the East Antarctic ice sheet, with another 15-20 m of sea level, are grounded below sea level. This more vulnerable ice may have been the source of the 25 ± 10 m sea level rise of the Pliocene (Dowsett et al., 1990, 1994). If human-made global warming reaches Pliocene levels this century, as expected under BAU scenarios, these greater volumes of ice will surely begin to contribute to sea level change. Indeed, satellite gravity and radar interferometry data reveal that the Totten Glacier of East Antarctica, which fronts a large ice mass grounded below sea level, is already beginning to lose mass (Rignot et al., 2008).

The eventual sea level rise due to expected global warming under BAU GHG scenarios is several tens of meters, as discussed at the beginning of this section. From the present discussion it seems that there is sufficient readily available ice to cause multi-meter sea level rise this century, if dynamic discharge of ice increases exponentially. Thus current observations of ice sheet mass loss are of special interest.

Ice sheet mass loss. The best indication and quantification of possible non-linear behavior will be precise measurements of ice sheet mass change. Mass loss by the Greenland and Antarctic ice sheets can be deduced from satellite measurements of Earth's gravity field. Fig. 8 shows the changing mass of both ice sheets as reported by Velicogna (2009).

These data records suggest that the rate of mass loss is increasing, indeed nearly doubling over the period of record, but the record is too short to provide a meaningful evaluation of a doubling time. Also there is substantial variation among alternative analyses of the gravity field data (Sorensen and Forsberg, 2010), although all analyses have the rate of mass loss increasing over the period of record.

We conclude that available data for the ice sheet mass change are consistent with our expectation of a non-linear response, but the data record is too short and uncertain to allow quantitative assessment. A 10-year doubling time, or even shorter, is consistent with the gravity field data, but because of the brevity of the record even a linear mass loss cannot be ruled out. Assessments will rapidly become more meaningful in the future, if high-precision gravity measurements are continued.

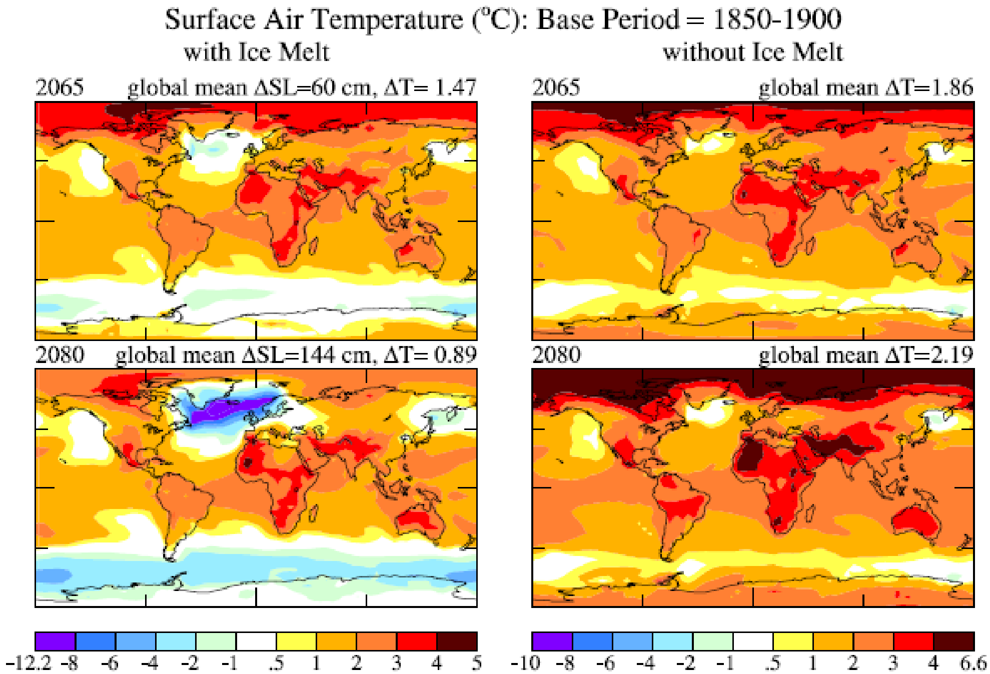

Fig. 9. Surface air temperature change in 2065 (above) and 2080 (below) relative to 18501900 in simulations with GISS climate model using IPCC A1B scenario. Maps on left include ice melt, which is put half into the North Atlantic and half into the Southern Ocean, with ice melt doubling every ten years.

Iceberg cooling effect. Exponential change cannot continue indefinitely. The negative feedback terminating exponential growth of ice loss is probably regional cooling due to the thermal and fresh-water effects of melting icebergs. Temporary cooling occurs as icebergs and cold fresh glacial melt-water are added to the Southern Ocean and the North Atlantic Ocean.

As a concrete example, Fig. 9 shows the global temperature change in simulations with GISS modelE (Schmidt et al., 2006; Hansen et al., 2007c) with and without the melting iceberg effect. GHGs follow the A1B scenario, an intermediate business-as-usual scenario (IPCC, 2001, 2007; see also Figs. 2 and 3 of Hansen et al., 2007b). Ice melt rate is such that it contributes 1mm/year to sea level in 2010, increasing with a 10-year doubling time; this melt rate constitutes 0.034 Sv (1 Sverdrup = 1 million m^3 per second) in 2065 and 0.1 Sv in 2080. Half of this melt-water is added in the North Atlantic and half in the Southern Ocean.

By 2065, when the sea level rise (from ice melt) is 60 cm relative to 2010, the cold fresh-water reduces global mean warming (relative to 1880) from 1.86°C to 1.47°C. By 2080, when sea level rise is 1.4 m, global warming is reduced from 2.19°C to 0.89°C. These experiments are described in a paper in preparation (Hansen, Ruedy and Sato, 2011), which includes other GHG scenarios, cases with ice melt in one hemisphere but not the other, and investigation of the individual effects of freshening and cooling by icebergs (the freshening is more responsible for the reduction of global warming). Note that the magnitude of the regional cooling is comparable to that in 'Heinrich' events in the paleoclimate record (Bond et al., 1992), these events involving massive iceberg discharge at a rate comparable to that in our simulations. Given that the possibility of sea level rise of the order of a meter is now widely accepted, it is important that simulations of climate for the 21^{st} century and beyond include the iceberg cooling effect.

Detailed consideration of the climate effects of freshwater from ice sheet disintegration, which has a rich history (Broecker et al., 1990; Rahmstorf, 1996; Manabe and Stouffer, 1997), is beyond the scope of our present paper. However, we note that the temporary reduction of global warming provided by icebergs is not likely to be a blessing. Stronger storms driven by increased latitudinal temperature gradients, combined with sea level rise, likely will produce global havoc. It was the prospect of increased ferocity of continental-scale frontal storms, with hurricane-strength winds powered by the contrast between air masses cooled by ice melt and tropical air that is warmer and moister than today, which gave rise to the book title "Storms of My Grandchildren" (Hansen, 2009).

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