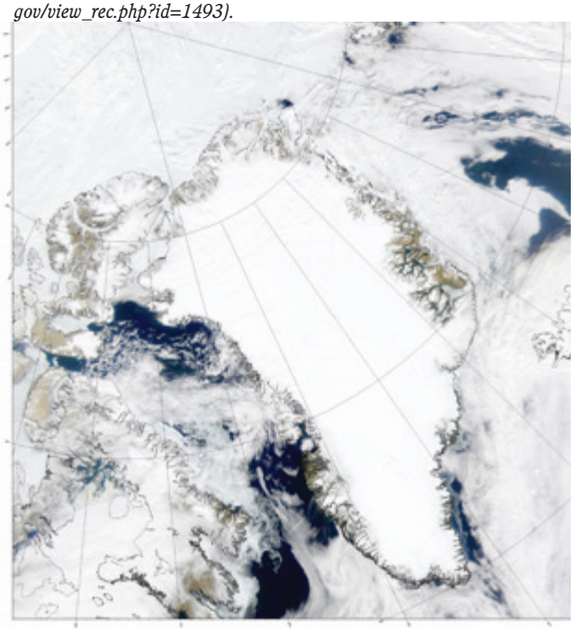
When Can We Expect Irreversible Processes for the Greenland Ice Sheet?

Sebastian H. Mernild, CCS-2

Once an ice sheet starts to have continuously negative surface mass balance, the ice surface gradually decreases in altitude and becomes warmer, leading to further melting in a positive feedback loop. The IPCC A1B climate scenario applied to SnowModel, a surface snow, ice, runoff, and energy-balance model, predicts that the Greenland Ice Sheet will have a negative surface mass balance in the early 2040s following warming of approximately 1.2°C compared to present-day temperatures. Since the Arctic, including Greenland, has been warming at twice the global average global rate, the global temperature increase required for irreversible melting of the Greenland Ice Sheet could be as low as 0.6°C.

The Earth's climate is warming. Observations show that the largest temperature increases are occurring at high northern latitudes, where the loss of snow and sea ice creates positive feedbacks due to the reduced reflection of sunlight. Arctic temperatures have increased at almost twice the global average rate in the past 100 years [1]. Since 1957, air temperatures in the Arctic, including Greenland, have increased more than 2°C [2]. The warming has been accompanied by an increase in precipitation of ~1% per decade [3].

Fig. 1. GrIS seen from above, recorded 2000-11-15 by SeaWiFS. The photo is provided by the SeaWiFS Project, NSAS/Goddard Space Flight Center and ORBIMAGE (http://visibleearth.nasa.gov/view_rec.php?id=1493).



The Greenland ice sheet (GrIS, shown in Fig. 1) is an indicator of ongoing climate changes. Impacts already observed for the GrIS include retreating outlet glaciers, decreasing permanent snow cover, and increasing surface melt extent (Fig. 2) and freshwater runoff to the ocean [4-7]. These changes suggest that the ice sheet responds more quickly to climate perturbations than previously thought. In particular, the rate of GrIS mass loss from surface meltwater runoff and iceberg calving has increased as temperatures have risen. The mass budget for the ice sheet was close to equilibrium during the relatively cold 1970s and 1980s, but the GrIS lost mass rapidly as the climate warmed in the 1990s and 2000s, with no indication of deceleration [8].

There are significant uncertainties in modeling Greenland ice sheet dynamics [9], partly related to insufficient knowledge of conditions at the ice bed and ice-ocean interface. In contrast, Greenland's surface mass balance (SMB, the difference between annual accumulation and ablation) and runoff are better understood and documented from numerical model simulations [6,10-11], even though few high-resolution freshwater runoff observations at the GrIS periphery are available for model verification [7].

The GrIS is the largest mass of land-based ice in the northern hemisphere, containing about 7 m global sea-level equivalent. The net mass balance of the GrIS has an important influence on global sea level [1,12] and on ocean density and circulation [13]. The GrIS plays an essential role in the Arctic hydrological cycle, not only because of its extent, elevation, and reflectivity, but also because of the reservoir of fresh water stored as ice. Recent studies have shown that the present annual GrIS mass loss is around 300 km^3 per year [14], where nearly half of the net loss originates from surface melting and subsequent freshwater runoff, and the other half from iceberg calving [15]. This mass loss is equivalent to a mean global sea-level rise of approximately 0.7–0.8 mm per year [6], or around 25% of the global sea-level rise of 3.1 mm per year.

A highly sophisticated surface snow, ice, runoff, and energy-balance model (SnowModel) [16] was used to simulate the GrIS SMB and surface runoff to the ocean from 1950 through 2080. The simulations were based on input data from the Intergovernmental Panel on Climate Change (IPCC) scenario A1B applied to a high-resolution regional climate model, HIRHAM4 [17-18]. Greenland's average surface air temperature was projected to rise during this period by 4.8°C, with mean annual precipitation on the ice sheet increasing by 80 mm (Fig. 3) [19]. These projected changes will lead to greatly enhanced mass loss and

For more information contact Sebastian Mernild at mernild@lanl.gov.

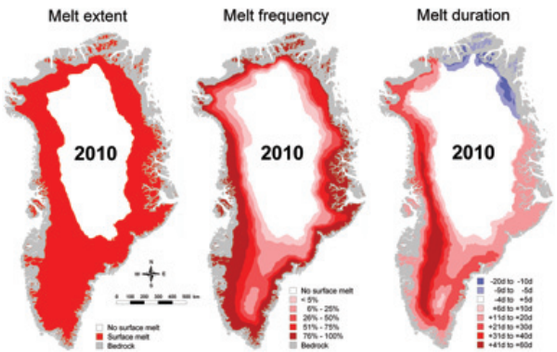


Fig. 2. An example of the maximum simulated GrIS surface melt extent for 2010 (which also turns out to be a record since 1960); 2010 melt frequency in percentage of total melt days, indicating that margin regions had surface melt 76–100% of the time during the summer season (May through September), most pronounced in SW Greenland; and the difference between 2010 melt duration and the 1960–2010 mean.

runoff in the years approaching 2080. The model predicts that the annual SMB will change from positive to negative values soon after 2040 (Fig. 4) [19]. Meanwhile, the ice sheet will continue to lose mass through iceberg calving and subglacial melting. As long as the SMB remains negative, the ice will have no way to recover its volume. The surface will gradually decrease in altitude and warm up, leading to further melting in a positive feedback loop. If this process is maintained for several centuries or longer, the GrIS will lose mass year after year, resulting in its eventual removal [20].

The IPCC climate scenario applied in SnowModel results in a negative surface mass balance following Greenland warming of 1.2°C above present temperatures. If temperatures in the Arctic, including Greenland, continue to increase at twice the global average rate, the threshold for inexorable melting would be reached at a global average temperature increase of approximately 0.6°C. This is a low value compared to temperature predictions based on simple degree-day methods [20], which predict irreversible GrIS retreat for a sustained global temperature increase of around 3°C. Since the HIRHAM4-SnowModel system is more physically realistic and sophisticated than the degree-day approach, there is reason to believe that the threshold for irreversible GrIS melting is closer to 0.6°C than to 3°C [20] and could be reached within the next three to four decades.

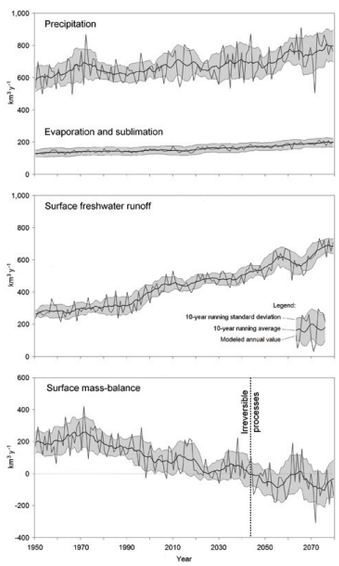


Fig. 4. Time series for the HIRHAM4-SnowModel simulated GrIS precipitation, evaporation and sublimation, surface runoff, and surface mass-balance for the period 1950–2080.

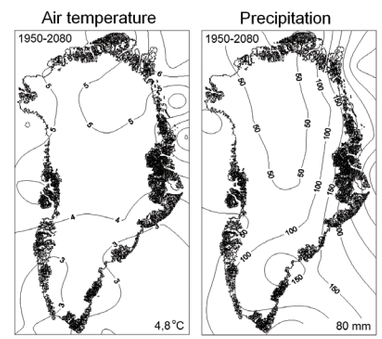


Fig. 3. Greenland HIRHAM4 RCM simulated average annual difference from 1950 through 2080 for the parameters of air temperature and precipitation.

[1] *IPCC*, Cambridge University Press, Cambridge, 996 (2007).
[2] http://giss.nasa.gov/
[3] *ACIA*, Cambridge University Press, Cambridge, 1042 (2005).
[4] Steffen, K., et al., *US Geological Survey,* Reston, VA, 60 (2008).
[5] Ettema, J., et al., *Geophys Res Lett* **36,** L12501, doi:10.1029/2009GL038110 (2009).
[6] Mernild, S.H., et al., *Hydrolog Process,* DOI: 10.1002/hyp.7354 (2009).
[7] Mernild, S.H. and B. Hasholt, *J Glaciol* **55,** 855 (2009).
[8] Rignot, E., et al., *Geophys Res Lett* **35,** L20502, doi:10.1029/2008GL035417 (2008).
[9] Nick, F.M, et al., *Nat Geosci* **2,** 110 (2009).
[10] Box, J.E., et al., *J Clim* **19,** 2783 (2006).
[11] Fettweis, X., *Cryosphere* **1,** 21 (2007).
[12] Box, J.E., et al., *J Clim* **22,** 4029 (2009).
[13] Rahmstorf, S., et al., *Geophys Res Lett* **32,** L23605; doi:10.1029/2005GL023655 (2005).
[14] Allison, I., et al., *The University of New South Wales Climate Change Research Centre (CCRC),* Sydney, Australia (2009).
[15] Rignot E. and P. Kanagaratnam, *Science* **315,** 1559 (2006).
[16] Liston G.E. and K. Elder, *J Hydrometeorol* **7,** 1259 (2006).
[17] Christensen, J.H., et al., DMI Scientific Report, 96-4 (1996).
[18] Stendel, M., et al., *Adv Ecol Res* **40,** 13; DOI: 10.1016/S0065-2504(07)00002-5 (2008).
[19] Mernild, S.H., et al., *J Hydrometeorol* **11,** 3 (2010).
[20] Bamber, J., et al., *IOP Conf Ser: Earth Environ Sci* **6,** 062007, 1; DOI: 10.1088/1755-1307/6/6/062007 (2009).

Funding Acknowledgments
LANL Director's Postdoctoral Fellowship; LANL Institute for Geophysics and Planetary Physics fellowship