Greenland Ice on the Scales

How can the geologic record inform us about the present and future response of the Greenland Ice Sheet to global warming?

by Anders E. Carlson

The most recent Intergovernmental Panel on Climate Change (IPCC) reported in 2007 that the greatest uncertainty in estimating future sea-level rise stems from the poor understanding of ice-sheet sensitivity and response to a warming climate. Of the two remaining ice masses, the Greenland Ice Sheet holds the potential to raise sea level ~7 m if it entirely melted. Recently, glaciologists have observed a speed-up of Greenland outlet glaciers as well as an ever more negative mass balance for this ice sheet. Whether these are short-term fluctuations or the beginning of a longer-term trend remains to be seen as the observational record only spans several decades at most. Thus, I have focused a large portion of my research effort towards elucidating the sensitivity of this ice sheet to past climates warmer than present, where we have geologic archives of Greenland ice behavior.

In particular, periods of peak summer insolation (incoming energy from the sun) during interglacials of the Milankovitch cycle provide time intervals where summer temperatures and radiation were higher than pre-industrial levels, and thus natural paleo-analogues to our future. The two most recent intervals of peak interglacial climate conditions occurred ~10,000 to 6,000 years ago, during the early Holocene, and ~128,000 to 124,000 years ago, during the last interglacial. During both of these intervals, scientists have now established that the Greenland Ice Sheet was smaller than its present extent. While the earth did not experience a sea-level high stand ~6,000 years ago, sea level was 4-6 m higher than present by ~124,000 years ago, indicating a significantly reduced Greenland and/or Antarctic Ice Sheet.

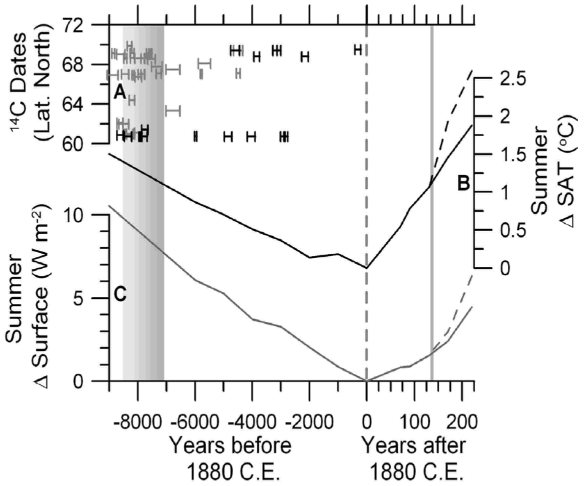

Figure 1: Constraints on southwest Greenland ice extent during the Holocene. (A) Radiocarbon dates on lake sediment, wood and shells. Gray symbols constrain ice behind a given location at that date. Black symbols are reworked dates in historical moraines placing ice smaller than present at that time. Climate model simulated surface air temperature (SAT) (B) and surface radiative forcing (C) for the Holocene and the coming century. Dashed lines are the IPCC A2 scenario, solid lines are A1B scenario after 1880 C.E. Note the y-axis changes scale at year 0 (1880 C.E.) (dashed gray line). Solid gray line denotes the present. Shaded gray bar indicates the range in time when the southwest Greenland Ice Sheet retreated to a smaller than present extent.

Because the Greenland Ice Sheet's maximum extent during the late Holocene occurred during the Little Ice Age (~1600 to 1880 C.E.) and is reflected in historical moraines (see cover figure), the ice-free landscape of Greenland contains an excellent record of when the ice sheet reached its present extent before retreating further inland. Much of this deglacial sequence is constrained by radiocarbon dates on lake sediment and marine shells. However, of more importance and first noticed in the 1970's is the occurrence of reworked marine shells and wood in the historical moraines, which provide a constraint on when the Greenland Ice Sheet was smaller than its present extent during the Holocene. These data indicate that the west Greenland Ice Sheet (the region with most complete record) reached its present extent between 8,500 and 7,000 years ago and that the ice remained smaller than its present extent until the Little Ice Age (Figure 1A).

To place this interval of smaller than present Greenland ice in context of our present and future climate state, I turned to my colleague at the NASA Goddard Institute for Space Studies, Allegra LeGrande. Allegra and I compared changes in summer temperature and surface radiation in her climate model simulations for the Holocene with simulations from the pre-industrial up to 2100 C.E. What we found was both exciting and scary. By the present day, human greenhouse gas emissions have warmed the summer climate of west Greenland by ~1 °C, equivalent to the temperature ~7,000 years ago that drove the ice sheet to a smaller than present extent (Figure 1B). Surface radiation has risen to the level of ~2,000 years ago, a period when the ice sheet was still smaller than present (Figure 1C). Thus, our energy consumption and its by products, greenhouse gases, have already changed Greenland climate to levels where the ice sheet is unstable and will retreat, indicating that the current melting and speed-up of the ice sheet is likely the beginning of a long-term trend.

The predictions for the future are even more grim. Summer temperatures will pass early Holocene levels by mid century and radiation will reach mid Holocene levels by the end of this century (Figure 1). I would note that the early Holocene warm climate was caused by natural changes in the Earth's orbit where the Northern Hemisphere was closer to the sun in the summer. Since 1880 C.E., the dominant forcing is from human produced greenhouse gases. If these are excluded from the model simulations, the model fails to simulate climate correctly over the interval where we have actual direct measurements (i.e., the last 100 yrs). My graduate student, Kelsey Winsor, and I are currently working on pinning down the precise timing of when Greenland ice reached its present extent with funding from the National Geographic Society.

Having established that we have already passed the threshold for a stable Greenland Ice Sheet, the last interglacial (~128,000 to 124,000 years ago) provides a constraint on how much sea-level rise we can expect from melting of the Greenland Ice Sheet in the future. Climate model simulations run by Bette Otto-Bliesner (UW-Madison alumnus, B.S., M.S. and Ph.D. in Meteorology) at the National Center for Atmospheric Research

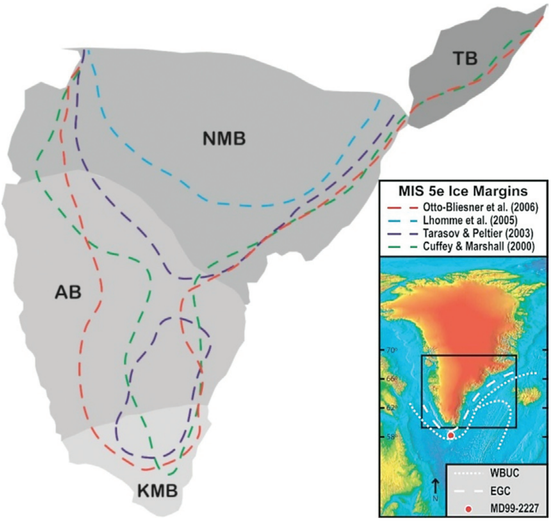

Figure 2: Southern Greenland terrane map. Last interglacial (called Marine Isotope Stage (MIS) 5e). Geologic terranes are indicated in grayscale (AB = Archean Block; KMB = Ketilidian Mobile Belt; NMB = Nagssugtoqidian Mobile Belt; TB = Tertiary Basalts). MIS 5e ice-sheet model margins are delimited (dashed lines). Note that the Lhomme et al. (2005) margin in the NMB does not match our data. Inset shows location of the map (box), ocean currents (white dashed lines; WBUC = Western Boundary Under Current; ECG = East Greenland Current), and Eirik Drift core site (circle).

(NCAR) indicate that Northern Hemisphere summer temperatures for the last interglacial are equivalent to predicted temperatures for the end of this century. As previously noted, sea level was 4-6 m higher than present during this warmer than present period. However, terrestrial records for this interval do not exist on Greenland because the expansion of ice during the subsequent glacial period erased the landscape.

Given this conundrum, graduate student Elizabeth (Lisa) Colville, Brian Beard and I along with colleague Joseph Stoner at Oregon State University devised new means of determining the extent (or volume) of the southern Greenland Ice Sheet during the last interglacial with funding from the National Science Foundation. In our early work, Joe and I showed that the ocean sediment drift (Eirik Drift) off the southern tip of Greenland (Figure 2) records runoff from the ice sheet and that the Greenland Ice Sheet melted for a significantly longer period during the last interglacial relative to the Holocene. This indicates a significantly smaller ice sheet. Lisa further confirmed our results by determining the weight percent silt of Eirik Drift sediments (Figure 3D), where the percent silt reflects the amount of ice-derived glacial flour discharged to the ocean. What we didn't know from these records was exactly how far the ice sheet retreated. Thus we turned to determining the sources of Greenland runoff sediment, using radiogenic isotopic tracers.

Southern Greenland is composed of three main geologic terranes of different ages. In the south, the Ketilidian Mobile Belt is of Proterozoic age, while the Archean Block to the north contains some of the oldest rocks on Earth (Figure 2). Further north, the Nagssugtoqidian Mobile Belt is of late Archean age, but was reworked in the Proterozoic. Each of these terranes has a unique radiogenic isotopic signature, reflected in the sediment derived from that terrane. Our hypothesis is that if ice on a given terrane is melting back, then this sediment will be discharged to the ocean and we will detect this in the Sr, Nd and Pb isotope ratios of the Eirik Drift sediment. If ice retreats off a given terrane, then we will lose that isotopic component in the ocean sediment.

We first measured these isotopes for Eirik Drift sediment spanning the last deglaciation and the Holocene to determine if the proxy truly would work. Indeed, we detected ice melting on all of the southern Greenland terranes through the deglacial period, with no single terrane deglaciating, in agreement with the terrestrial record. Our record for the previous deglaciation showed a similar pattern as the last deglaciation, until the peak of the last interglacial. Throughout the last interglacial, we still detected runoff components from all three terranes, indicating that ice remained on all three terranes despite the greater period of melting (Figure 3C). However, during the interval of highest silt discharge (grey band, Figure 3D), when planktonic foraminifera $\delta^{18}O$ indicate the warmest and freshest conditions (lower $\delta^{18}O$) (Figure 3B) and pollen and spore records from Eirik Drift indicate the greatest expansion of vegetation (Figure 3A), our isotopic data suggest the lowest input of Archean sourced material (higher εNd and lower $^{207}Pb/^{206}Pb$) (Figure 3C). This suggests that the Archean block had significantly smaller ice cover than during the Holocene.

When we compared our results with ice-sheet model simulations of Greenland ice extent during the last interglacial, we found that ice-sheet models that still have ice on all three Greenland terranes (Figure 2), consistent with our data, indicate <2.5 m of sea-level rise from this ice sheet. This new constraint on the Greenland Ice Sheet volume allows us to determine the necessary reduction in Antarctic Ice Sheet volume to account for the 4-6 m sea-level high stand. With these constraints, Antarctic ice supplied >1.5 m of equivalent sea-level rise. Thus this ice sheet also appears to be highly unstable under a climate warmer than present and will likely also contribute to sea-level rise in the coming century in addition. In conclusion, the geologic record indicates that we have already committed ourselves with the current greenhouse gas levels to a significant retreat of the Greenland Ice Sheet in the coming decades. How we choose our energy sources over that same period will determine the magnitude of ice retreat and the amount of sea-level rise we are recording at the end of this century. ●

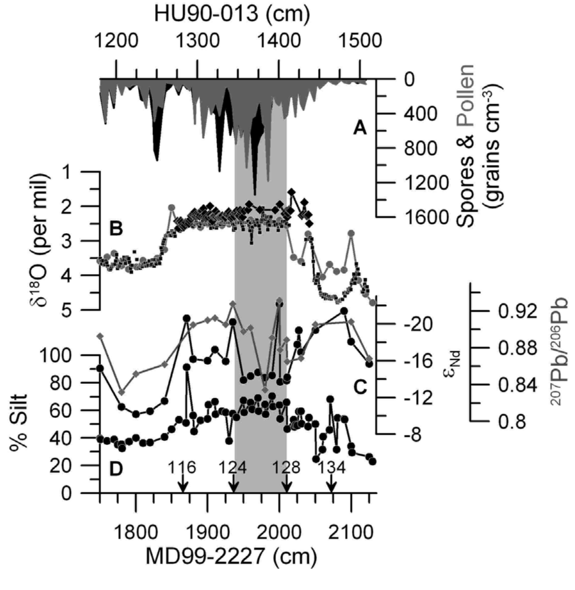

Figure 3: Eirik Drift records for the last interglacial. (A) Abundance of pollen grains (gray) and spores (black). (B) *Neogloboquadrina pachyderma* (s) $\delta^{18}O$ from Eirik Drift cores MD99-2227 (gray circles) and HU90-013 (black squares); black diamonds *Globigerina bulloides* $\delta^{18}O$. (C) Black circles ε_{Nd} values; gray triangles $^{207}Pb/^{206}Pb$. (D) Black circles % silt. Light grey bar denotes peak silt during the last interglacial, the period of greatest ice retreat. Arrows with numbers denote the chronology for the core in thousands of years.