ATMOSPHERIC SCIENCE

Sprucing Up Greenland

Pollen data suggest that the Greenland ice sheet was much smaller during previous warm periods.

Eric J. Steig[1] and Alexander P. Wolfe[2]

How much did the Greenland ice sheet shrink during previous warm episodes of the Pleistocene (from ~1.8 million to ~11,000 years ago)? This question is central to understanding fluctuations in sea level and the future stability of the ice sheet. On page 1622 of this issue, de Vernal and Hillaire-Marcel (*1*) report a record of pollen preserved in marine sediments deposited beyond the ice sheet's margin that sheds considerable new light on the problem.

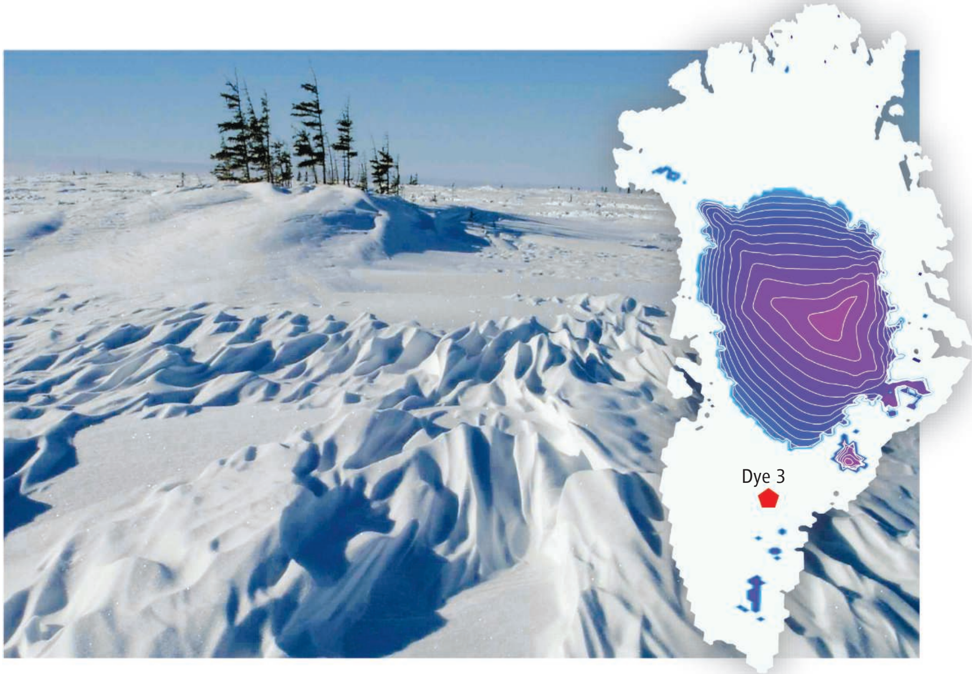
The Pleistocene was characterized by long periods of extensive Northern Hemisphere glaciation, interrupted by relatively brief interglacials during which continental ice retreated to a few strongholds in the Canadian Arctic and Greenland. During the last interglacial—referred to as marine isotope stage (MIS) 5e—global mean sea level was 4 to 6 m higher than during the current Holocene period (*2*). A substantial fraction of this sea-level rise can be attributed to a smaller Greenland ice sheet (*3*).

The last interglacial is an interesting analog for the future, because the Arctic was several degrees Celsius warmer than during the 20th century (*4*), within the scope of projections for the coming decades. However, the analogy only goes so far, because melting of the Greenland ice sheet during MIS 5e was driven mainly by greater summer insolation, not by increased levels of greenhouse gases. During MIS 11 (three interglacials before MIS 5e), summer insolation was not very different from that during the Holocene (*5*). MIS 11, however, lasted from 425,000 to 375,000 years ago, twice the duration of MIS 5e. This interglacial thus provides a different analog for the future, allowing us to examine what happens to the ice sheet and surrounding land mass when subjected to protracted warmth. MIS 11 cannot easily be studied by looking at ice cores: Any ice this old has long since melted away or has been subject to irreparable thinning and distortion at the base of the ice sheet (*6*). On the other hand, a continuous record exists offshore.

de Vernal and Hillaire-Marcel analyzed a marine sediment core from the Ocean Drilling Program (ODP) site 646, raised from a depth of 3460 m. At this site, sediment has been deposited continuously since at least MIS 17 (*7*). The core contains a rich terrestrial pollen record, because the core is located on the south Greenland continental rise, which captures runoff from the adjacent land mass. Taxa currently extant in southern Greenland are well represented, including spores from mosses and club mosses and pollen from shrub birch and alder. During interglacials, the record is punctuated by marked increases in total pollen concentrations and additional contributions from boreal coniferous trees, namely spruce and pine, neither of which survives in Greenland today. The pollen assemblages differ tremendously between interglacials, with direct implications for the past development of ecosystems in south Greenland. For example, spruce pollen concentrations were three times as high during MIS 13 and 5e, and more than 20 times as high during MIS 11, as during the Holocene. On the other hand, MIS 9 and 7, have unspectacular conifer pollen signatures similar to those in the Holocene.

How can we be sure that spruce grew in southern Greenland during MIS 13, 11, and 5e, and thus that the ice sheet was sufficiently reduced to allow for regional development of boreal forests? The spruce pollen in these interglacial sediments cannot be attributed to enhanced long-distance transport from North America or Europe. Because spruce pollen is far less easily dispersed than pine pollen, long-distance transport would lead to reduced spruce/pine ratios. Instead, increased spruce/ pine ratios are found in each warm episode recorded in the core. The exquisite preservation of the spruce grains, and their morphological affinities to Norway spruce, lend further credence to local sources.

There is independent evidence that spruce lived in Greenland in the mid-Pleistocene, in a region now covered by more than 2 km of ice. In 2007, Willerslev *et al.* (*8*) amplified DNA from sediment-rich ice at the base of the Dye 3 ice core, showing not only the presence of spruce but also of pine and yew, consistent with an ancient boreal forest. They could not assign an unambiguous date to the sediments entombing these genetic fossils, but their estimate of between 450,000 and 800,000 years is close enough to MIS 11 to be more than coincidental. Indeed, given current esti-



A modern analog. Spruce copses at Churchill, Manitoba, Canada (59°N, 94°W), are an apt modern analog for southern Greenland during interglacial periods MIS 13, 11, and 5e. The inset shows a plausible ice sheet geometry for MIS 11, based on the ice sheet model used in (*3*); contour intervals of ice elevation (blue and purple) are 200 m.

[1]Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA. E-mail: steig@ess.washington.edu [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada. E-mail: awolfe@ualberta.ca

CREDIT: (PHOTO) G. P. KERSHAW/UNIVERSITY OF ALBERTA; (MAP) S. J. MARSHALL/UNIVERSITY OF CALGARY

Published by AAAS

mates of DNA degradation kinetics (*9*), the results reported by de Vernal and Hillaire-Marcel point to MIS 11 as the most parsimonious age for the Dye 3 sediments.

Evidently, the Greenland ice sheet was smaller during MIS 5e and 13 than it is today, but ice probably still covered the location of the Dye 3 ice core. During MIS 11, deglaciation must have been much more extensive. The sixfold increase in spruce pollen abundance during MIS 11 relative to MIS 5e and 13 is unlikely to reflect minor differences in ice sheet size. Spruce is absent in Greenland today not because of the high latitude but because there is no land sufficiently removed from the hostile microclimate at the ice sheet margin. Thus, the Dye 3 area must have been completely deglaciated during MIS 11. For that to occur, most of southern Greenland must have been ice free (see the figure).

It seems to have taken some time for the extensive spruce populations of MIS 11 to develop. Global temperatures had risen to Holocene levels by ~425,000 years ago, but spruce abundance increased most dramatically 10,000 to 20,000 years later (*1*). This lag is probably not associated with slow rates of forest propagation; spruce can expand northward at rates of more than 100 km per century as climate warms (*10*). Instead, the data suggest that the ice sheet retreated slowly. This would not be surprising: Once the ice retreats beyond the heads of fjords, removing the possibility of glacier calving, the rate of volume loss is likely to decrease.

It was not exceptional warmth, but time, that diminished the size of the Greenland ice sheet during MIS 11, leaving vast tracts of land available for plant colonization. In the future, the Arctic will likely become warmer than it was during MIS 5e and will stay warmer for thousands of years if greenhouse gas concentrations continue to rise over the next century. The Greenland ice sheet will then have to contend with both time and warmth.

References

1. A. de Vernal, C. Hillaire-Marcel, *Science* **320**, 1622 (2008).
2. C. H. Stirling *et al.*, *Earth Planet. Sci. Lett*. **160**, 745 (1998).
3. B. L. Otto-Bliesner *et al.*, *Science* **311**, 1751 (2006).
4. CAPE Last Interglacial Project members, *Quat. Sci. Rev.* **25**, 1383 (2006).
5. D. Raynaud *et al.*, *Nature* **436**, 39-40 (2005).
6. North Greenland Ice Core Project members, *Nature* **141**, 1447 (2004).
7. C. Hillaire-Marcel, A. de Vernal, G. Bilodeau, A. J. Weaver, *Nature* **410,** 1073 (2001).
8. E. Willerslev *et al.*, *Science* **317**, 111 (2007).
9. E. Willerslev, A. Cooper, *Proc. R. Soc. London B* **272,** 3 (2005).
10. G. M. MacDonald *et al., Nature* **361**, 243 (1993).

10.1126/science.1160004

CLIMATE CHANGE

A Matter of Firn

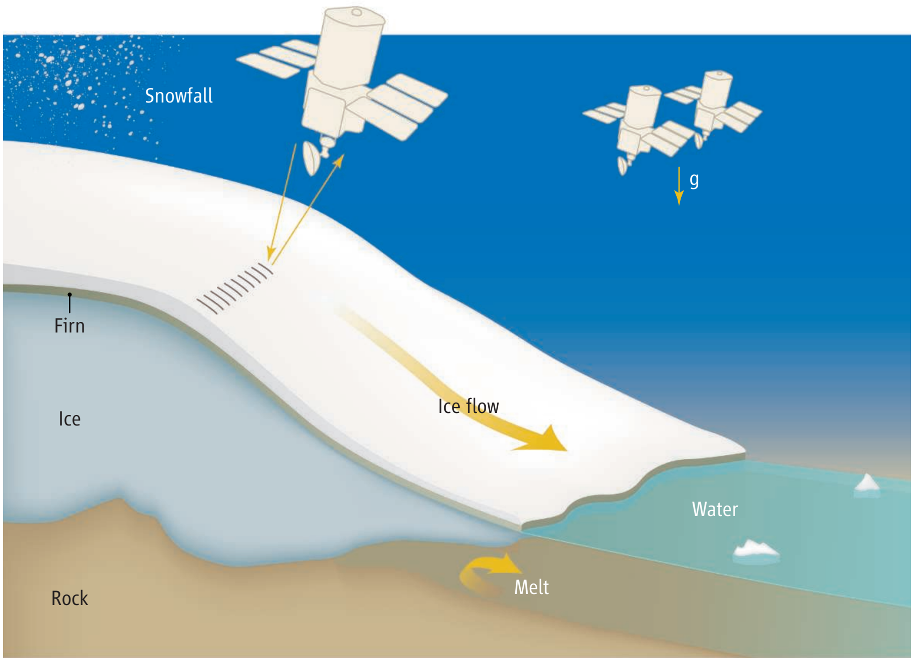
Estimating ice sheet mass changes from elevation surveys requires adjustments for snow density variations at the ice sheet surface.

Kurt M. Cuffey

The Antarctic Ice Sheet is vast, about 3000 km wide and up to 4.5 km thick. If it melted completely, sea level would rise by 70 m worldwide. Such a large change is not plausible, except on geologic time scales, but a loss of even 5% of the total mass would radically transform Earth's coastal regions. How has the ice sheet changed in recent years? Measuring the mass change of such a large feature is difficult, but there are methods available for the task (see the figure) (*1*–*3*). On page 1626 of this issue, Helsen *et al*. (*4*) provide key information that will substantially improve some of these important analyses.

Consider one method that is simple in concept. Map the surface elevations everywhere on the ice sheet, then repeat the process some time later. Determine the difference between the two maps, correct for changes in the elevation of the underlying lithosphere, and integrate over the area; the result is the volume change. Multiply this by the density of ice to find the mass change, and celebrate.

Alas, your celebration is premature; the density of the ice sheet is not a constant. The density varies by a factor of 3 from new snow to solid ice, and most of the ice sheet is mantled with a layer of old snow, called firn, that is tens of meters thick (*5*). This layer densifies over time, at a rate that depends on the temperature and the weight of new snow added to its surface. As Helsen *et al.* report, variations of the firn layer's thickness, over years and decades, complicate assessments of Antarctic mass changes based on maps of elevation. When snowfall increases or temperature decreases, the firn layer thickens. The authors show that, in East Antarctica, such effects con-



How to track mass changes. Changes in the mass of the Antarctic ice sheets can be measured by subtracting the melt and ice flow from the total snowfall; by sensing changes in the strength of gravity using pairs of satellites; or by repeat mapping of surface elevations from satellites. Helsen *et al.* show that, in the repeated-mapping method, a correction must be made for changes in the density of the firn layer on the ice sheet surface.

CREDIT: ADAPTED BY P. HUEY/*SCIENCE*

Department of Geography, University of California, Berkeley, CA 94720, USA. E-mail: kcuffey@berkeley.edu