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Published in:
Science

DOI:
10.1126/science.aad9997

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
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Radar data reveal how sensitive the Greenland Ice Sheet is to long-term climatic changes

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Earth’s large ice sheets in Greenland and Antarctica are major contributors to sea level change. At present, the Greenland Ice Sheet (see the photo) is losing mass in response to climate warming in Greenland (1), but the present changes also include a long-term response to past climate transitions. On page 590 of this issue, MacGregor et al. (2) estimate the mean rates of snow accumulation and ice flow of the Greenland Ice Sheet over the past 9000 years based on an ice sheet–wide dated radar stratigraphy (3). They show that the present changes of the Greenland Ice Sheet are partly an ongoing response to the last deglaciation. The results help to clarify how sensitive the ice sheet is to climate changes.

One of the great challenges in estimating the future evolution and mass loss of the Greenland Ice Sheet is to determine the present flow properties of the ice sheet. The ice sheet is monitored by numerous instruments to provide knowledge of ice thickness, surface velocity, and current mass balance changes. However, key properties such as ice viscosity remain poorly constrained, as do sliding and melting rates at the base of the ice sheet. These properties change over time because warmer surface temperatures are slowly heating up the deeper layers of the ice sheet and because ice from the current interglacial period (the Holocene, which began 11,700 years ago) gradually replaces older and softer ice from the last glacial period.

Direct observations of ice temperature and anisotropic flow properties (4, 5) are available at only a few deep ice core sites on the Greenland Ice Sheet. However, additional information is contained in the internal structure of the ice sheet, which can be detected with radar stratigraphy. The radar layers are isochrones: past surfaces buried by subsequent layers of snow and deformed as ice flows from the interior toward the margins (see the figure). The radar layer depths record the combined effects of external and internal forcings, providing valuable constraints on ice flow history and past accumulation rates.

In their study, MacGregor et al. use a comprehensive dated radar stratigraphy that they have recently constructed from radio echo-sounding data from the Greenland Ice Sheet collected between 1993 and 2013 (3). They dated the stratigraphy by matching radar layers with ice core records at intersections with ice core sites (4), thereby determining the depth-age structure of the ice sheet. In the current study, the authors focused on the
Depth-age distribution of layers younger than 9000 years. Using a one-dimensional ice flow model, they determined the mean thinning rate and accumulation rate for the past 9000 years that provide the best fit between modeled and observed depth-age scales. This approach is similar to that used to determine accumulation rates from ice core records. The resulting mean accumulation rates during the past 9000 years are generally higher in most of Greenland than the modern model-based accumulation rates.

A previous reconstruction of Greenland accumulation rates over the past 400 years based on ice cores and climate models showed the accumulation rate to be sensitive to past temperature (6). Deep ice cores confirm this finding further back in time into the last glacial (7). Warm climate approximately 9000 to 5000 years ago (4) may have been accompanied by higher accumulation rates; this might explain why the mean accumulation rates for the past 9000 years are higher than present-day modeled accumulation rates. The reconstructed mean Holocene accumulation rate reported by MacGregor et al. extends existing observation-based maps of past accumulation rates further back in time and covers a large fraction of the Greenland Ice Sheet. The results are highly relevant for constraining models of past ice sheet evolution.

MacGregor et al. also derived a map of mean Holocene surface velocity. They first calculated the balance velocity field corresponding to the mean Holocene accumulation rate—that is, the depth-averaged horizontal ice velocities needed to balance the accumulation rates. They then used a simplified model of internal deformation to convert balance velocities to surface velocities. Comparison of the reconstructed mean surface velocities with modern surface velocities observed from space revealed an apparent modern deceleration of the Greenland Ice Sheet. This is an interesting and surprising finding.

The authors argue that the higher mean Holocene accumulation rates relative to modern climate model results can only partly explain the deceleration. They propose that changes in ice dynamics have also contributed to the deceleration, mainly because of a general hardening of the ice sheet as glacial ice is being replaced by Holocene ice. Glacial ice contains more impurities than interglacial ice and is softer than ice deposited during the Holocene. The dynamic response to this gradual hardening may be effective for tens of thousands of years after the climate transition at the end of the last glacial period (8), and it affects estimates of future mass loss from the Greenland Ice Sheet.

However, the one-dimensional ice flow model used to derive the 9000-year mean accumulation rate is simplified and does not correct for variations of accumulation rate along the flow direction. MacGregor et al. argue that the local model is suitable because it contains many relatively young layers that reflect local conditions. Nonetheless, future work should account for upstream corrections to ensure that low accumulation rates in the ice sheet’s interior do not propagate with the flow and affect the resulting accumulation rates at lower elevations (9). Thinning of the Greenland Ice Sheet during the Holocene (10) would have affected the ice flow and thinning of layers, but the effect was probably minor over the past 9000 years (7). Future work may benefit from more sophisticated methods to account for vertical thinning and nonsteady conditions.

The termination of the last ice age 11,700 years ago was a large and abrupt climate transition that still continues to affect the Greenland Ice Sheet. Future research should explore in more detail the possible effects of ice rheology changes on local and regional ice dynamics. A general hardening of the Greenland Ice Sheet could increase the long-term resilience of the ice sheet if global warming proceeds. The Greenland Ice Sheet reacts to climate changes on short and long time scales. Better constraining the long-term response is crucial for improved future projections of its contribution to sea level change.

REFERENCES

How an ice sheet flows. The radar data in this figure are from a flight made by Operation IceBridge across the Greenland Ice Sheet on 2 May 2011. The thicknesses and shapes of the layers provide insight into how past climatic changes have affected—and continue to affect—the ice sheet’s flow. On the basis of such radar stratigraphy data, MacGregor et al. show that over the past 9000 years, ice sheet flow has been faster than it is today.

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