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.

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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-

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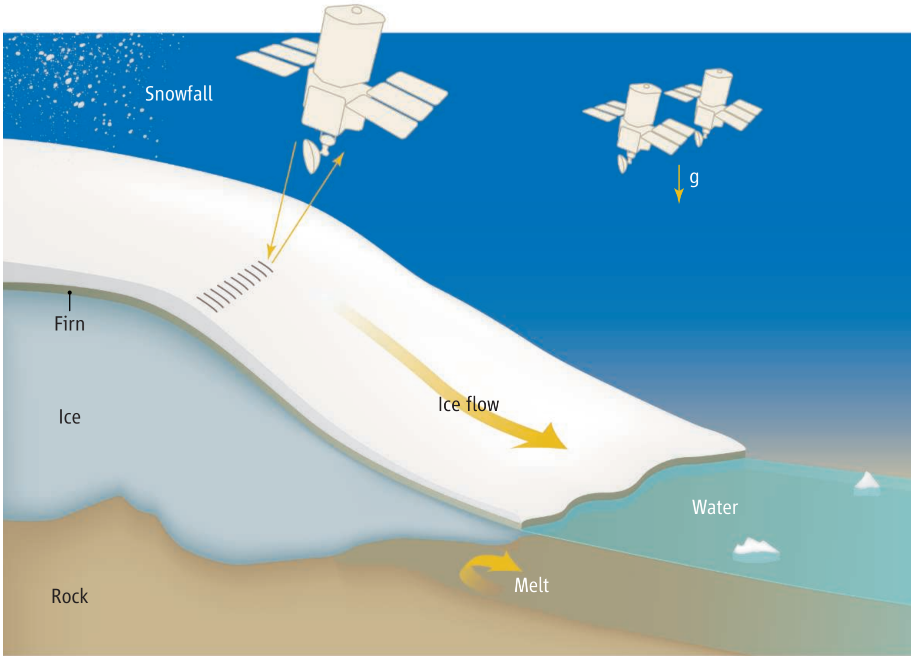

How to track mass changes. Changes in the mass of the Antarctic ice sheets can be measured by subtracting the melt and ice flow from the total snowfall; by sensing changes in the strength of gravity using pairs of satellites; or by repeat mapping of surface elevations from satellites. Helsen *et al.* 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.

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tribute as much to recent measured elevation changes as do the mass changes of interest.

Measurements of contemporary changes are essential for understanding what will happen to the Antarctic Ice Sheet as the planet warms. On one hand, warming will increase the water content of the polar atmosphere, and so increase snowfall on the ice sheet's vast interior. On the other hand, warmer ocean waters and increased summer air temperatures will erode the floating ice shelves fringing the continent, and so increase the discharge of ice to the coast, where it is lost as icebergs. This chain of processes now operates on the Antarctic Peninsula (*6*), the one part of Antarctica that has strongly warmed over the last several decades. And warming ocean waters are likely responsible for similar events in West Antarctica, where the giant ice streams flowing into the Amundsen Sea are accelerating, causing the ice sheet to thin (*7*). The region of thinning extends hundreds of kilometers inland.

In the Amundsen Sea region, the ice sheet rests in a basin that is more than 1 km below sea level. The boundary between grounded and floating ice is retreating into the basin, and the water depth at this boundary is thus increasing. Studies of the tidewater glaciers of southern Alaska have shown that a strong positive feedback operates in such a situation (*8*); thinning of the ice brings more of the glacier close to flotation, which increases the flow, thinning, and rate of retreat. This process caused the ice in Glacier Bay, Alaska, to retreat more than 80 km in the last century. A similar fate may await large regions of Antarctica (*9*).

Will increased snowfall come to the rescue? Climate models suggest that snowfall on Antarctica will increase by about 5% for every degree centrigrade of warming (*10*). Most likely, the ice sheet interior will thicken through increased snowfall even while the coastal regions are diminishing. But these processes operate at different time scales, and one cannot assume that their effects on sea level will cancel one another.

These processes cannot yet be predicted with confidence, and observations are essential. The combined effects of snowfall and ice flow on the ice sheet's mass can be determined by using satellite-based sensors for repeated mappings of surface elevations—as long as changes of firn density are taken into account. Helsen *et al*. reinterpret satellite data from the period 1995 to 2003 (*2*) by applying a model of the firn densification process, forced by climate data. Using meteorological models to derive snowfall and temperature patterns, the authors estimate density changes everywhere on the ice sheet. They show convincingly that such changes are a large part of the elevation signal.

Their analysis demonstrates that the declining elevations observed in the Amundsen Sea region do indeed reflect a significant loss of mass from the West Antarctic Ice Sheet. A second result is that the interior of East Antarctica is gaining mass. By how much is not clear, however, and this uncertainty strikes me as a particularly important result of the analysis. The correction for firn thickness changes is substantial. Unfortunately, calculating the correction accurately requires a long history of climate variations. In their analysis of the entire ice sheet, Helsen *et al*. use a 25-year record from meteorological analyses. For a few locations, they can also use longer histories from ice-core data. Results from the longer and shorter histories are different in Wilkes Land, a region of East Antarctica where the ice sheet is growing. The longer history provides the better estimate of firn thickness changes and implies a much smaller rate of ice sheet growth than does the shorter history.

Thus, even with explicit accounting for firn density variations, the elevation data cannot yet tell us by how much the mass of the East Antarctic ice sheet is changing. To do so appears to require a blending of the elevation data and firn models with longer-term climate histories from ice cores. This is an important task ahead. There are other ways to estimate Antarctica's changing mass: by calculating the difference between the total fluxes into and out of the ice sheet (*1*), and by monitoring the regional gravity field (*3*). These methods face difficulties of their own, however, and elevation measurements are essential for providing a complementary perspective on Antarctica's evolution in the coming decades.

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NEUROSCIENCE

Imaging Astrocyte Activity

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Astrocytes, like neurons, respond to visual stimuli, affecting vascular dynamics in the brain that provide the basis for imaging techniques.

Astrocytes are the most abundant type of glial cell in the mammalian central nervous system. They are not only metabolically coupled to neighboring neurons but also communicate with them through signals (neurotransmitters) that were once considered a language exclusive to neurons. The generation of neurons from embryonic glia has also garnered recent attention. Yet, without in vivo experiments, the role of astrocytes in brain function has not been clear. On page 1638 in this issue, Schummers *et al*. (*1*) show that astrocyte activity is functionally coupled to neuronal activity with unanticipated spatial specificity. This suggests that the quality and spatial resolution of noninvasive-imaging techniques that assess brain activity, including functional magnetic resonance imaging, reflect the responses of both cell populations in the brain.

Neurons in the mammalian visual cortex are organized into orientation columns, which consist of neurons that extend vertically through the cortex and respond to visual stimuli of the same orientation (*2*). Columns encoding the complete set of all stimulus orientations are organized around so-called pinwheel centers like the spokes of a wheel (*3*). Remote from these centers, neighboring neurons are activated by stimuli of the same orientation. However, in pinwheel centers, neighboring neurons are selective for very dissimilar orientations, but still form a highly ordered orientation map of neurons.

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