CLIMATE CHANGE

Understanding Glacier Flow in Changing Times

Subannual lurches of the Greenland and Antarctic ice sheets may reduce uncertainties about climate change effects on sea-level rise.

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Unexpected accelerations in outlet glaciers of the Greenland and Antarctic ice sheets in the last decade, in response to processes not fully understood, prompted the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment to conclude that poorly characterized uncertainties prevented a best estimate or upper bound on sea-level rise. These changes in ice sheet outlet glaciers come at a time when smaller glaciers and ice caps are wasting quickly as well. The focus of present glacier research must be the rapid reduction of the uncertainty identified by the IPCC. Rapid progress will require identification of the most relevant of the recent changes, effective moves toward understanding the controlling physics, and careful consideration of the differing time scales involved. We briefly review recent changes with a view toward an effective path forward.

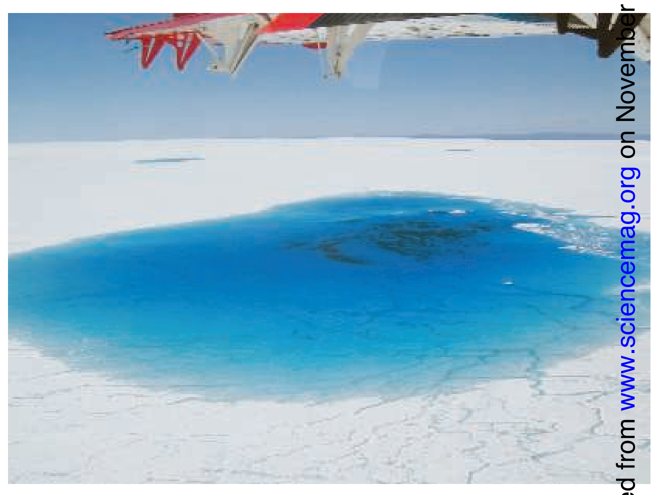
About 6 years ago, Zwally *et al.* discovered that lubricating surface meltwater can reach the base of the Greenland Ice Sheet, thereby speeding up summer ice flow (*1*). Subsequent work confirms the broad picture of seasonal lubrication (*2*) but shows that annual motion is enhanced only by 10 to 20% (*3*). More important, the fast outlet glaciers responsible for most of the ice discharge to the ocean are relatively insensitive to summer melt, making it unlikely that enhanced seasonal lubrication will destabilize the ice sheet (*2*).

Meltwater drainage to the bed can play a second and possibly more important role, however, speeding ice flow by delivering heat rapidly to the bed. The water in surface lakes (see the figure) can wedge open crevasses, fracturing through to the bed catastrophically (*4*). Were this phenomenon to spread inland in a warming world, it would deliver sufficient heat to thaw areas where the bed is currently frozen (*5*). In this event, twofold accelerations would not be surprising, with the slight chance of an order-of-magnitude or more locally if extensive regions with soft sediments were to thaw (*6*). Some issues remain: Reliable mapping of the basal characteristics of regions now frozen but that might thaw is unavailable, and our present understanding is not sufficient to tell us whether inland migration of melting will be accompanied by the changes in ice flow required to open cracks beneath any new lakes.

Lakes exist not only on top of but also beneath the ice. Increasingly seen to be widespread and dynamic, these subglacial lakes occur at and may be linked to the upglacier limit of rapid ice flow (*7*). However, release of stored lake water in outburst floods (*8*) does not seem to have major ice-flow effects. It is even possible that an ice sheet with more subglacial lakes will be less variable, because the lakes focus water drainage in space and time and thus reduce lubrication overall.

Far more ominous for future sea levels are the changes that originate where ice meets ocean. Ice shelves, the floating-but-still-attached parts of the ice sheets extending over the ocean, restrain the nonfloating ice through friction with local bedrock highs or with fjord walls. Because ice shelves are near sea level and in contact with the ocean, they are the elements of the coupled sheet-shelf system that are most susceptible to warming. Extensive surface melting can fill surface crevasses and destroy an ice shelf through the same fracture process that allows surface lakes to drain to the bed (*9*). Furthermore, even small changes in water temperature below the ice shelf can speed basal melting by roughly 10 meters per year for each 1°C warming (*10*).

Such wasting of shelves has no direct effect on sea level, but the loss of restraint and associated acceleration of inland flow to the ocean has triggered doublings of flow speed, with one change reaching eightfold (*11*). Large diurnal changes in flow speed of Antarctic ice streams feeding ice shelves occur in response to the small changes in loading at the ends caused by the tides (*12*), showing that these ice streams will respond rapidly if the buttressing from their ice shelves is reduced. Ice shelves are far less prevalent in Greenland than in Antarctica, but loss of floating and grounded ice at marine-terminating outlet glaciers has had similarly large effects (*13*). Present seasonal acceleration in the flow speed of Jakobshavn Glacier in Greenland begins in response to loss of sea ice damming the fjord. This commences well before the springtime onset of surface melt (*14*).



Lakes on the western flank of the Greenland Ice Sheet. The nearest lake is roughly 1500 m across and 10 m deep. Meltwater from these lakes can drain catastrophically into the ice sheet, causing brief but strong local disturbance of the ice flow. More important, these drainage events establish a meltwater pathway from surface to bed. Inland migration of this phenomenon might thaw now-frozen regions of the ice-sheet bed and speed up flow. The wing of a De Havilland Twin Otter occupies the top of the frame.

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In the absence of validated models incorporating these processes, scientists have turned to a range of ice-flow scaling exercises and back-of-the-envelope estimates to constrain estimates of future ice-sheet contributions to sea-level change (see supporting online material). Although these estimates are instructive and useful, there is a lack of strong convergence among them, and a wide range of possible answers remains.

Progress toward more rigorously quantitative estimates will not be easy. When each major new project turns up something unexpected, we can be confident that the field is undersampled. For decades, the major atmo-

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Published by AAAS

sphere-ocean general-circulation modeling groups have assumed that ice sheets are static, white mountain ranges; reversing this approach by having such groups develop sophisticated treatments of ice sheets would unleash great talent on this crucial problem. Such a modeling effort, however, must be coordinated tightly with remote-sensing, field- and laboratory-based efforts to understand the processes that control ice flow.

Perhaps the key uncertainty remains the interaction between the ice and its underlying bed, which controls how basal velocity will change as ice-sheet stresses evolve. Geophysical exploration is essential but, realistically, cannot sample everything. Inversions from remotely sensed data provide modern snapshots (*15*) but do not elucidate the dependence of basal velocity on changing stress. If we wait for the ice sheets to evolve through a wide enough range of stresses, then we or some future generation of glaciologists will retrodict changes rather than predict them usefully.

Fortunately, the lake drainages, calving events, tidal responses, and other recently observed phenomena discussed above are exciting the ice sheet, providing short-period samples of a wide range of stress and lubrication states and the associated velocity response necessary to characterize the system. Such short-period changes, however, are so fast that they have been difficult to observe fully and may involve elastic responses that are not captured by comprehensive ice-flow models. A more holistic approach that uses appropriately designed experiments that assimilate ground-based and remotely sensed data into improved models may provide the improved understanding needed to constrain future sea-level changes.

Although crucial, such experiments are increasingly difficult, as field efforts are eliminated or delayed in the face of rising fuel costs (*16*). The U.S. National Aeronautics and Space Administration's Decadal Survey missions addressing ice [the Ice, Cloud, and land Elevation Satellite II (ICESAT-II) and the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission] are a number of years from providing data to replace those endangered by failing satellites and access limitations. In the interim, this gap could be partly closed through closer coordination and improved data distribution among the various space agencies that operate the international constellation of remote-sensing spacecraft.

For a student of ice flow, these are exciting times, with the pace of discovery seemingly accelerating. For a student of policy, the possibility looms of a fifth IPCC assessment lacking projections of sea-level rise sufficiently constrained for effective policy design. Wise choices may yet beat this unpleasant outcome. A coupled observation and modeling approach that lets the ice sheets tell us the answer may be the quickest path.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/322/5904/1061/DC1
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10.1126/science.1166366

MICROBIOLOGY

A Protein Pupylation Paradigm

Tagging proteins with ubiquitin molecules so that they will be degraded in the proteasome is not a mechanism unique to eukaryotes.

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Tuberculosis, a devastating infectious disease caused by *Mycobacterium tuberculosis* (*Mtb*), is a global health threat that presently afflicts one-third of the world's population. The culprit bacterium is an obligate and persistent pathogen that maintains viability, in a latent state, within phagocytes—cells that ingest foreign materials and microorganisms—that reside in the lungs of humans. Treating tuberculosis requires prolonged antibiotic therapy that can result in multidrug-resistant *Mtb* strains. Because the bacterium is highly infectious, grows extremely slowly, and is difficult to manipulate genetically, the discovery of new drugs to combat *Mtb* infection is challenging. Thus, identifying *Mtb* components as potential drug targets is one of the key approaches to developing new tuberculosis therapies. On page 1104 of this issue, Pearce *et al.* (*1*) report the discovery of a protein (Pup) in *Mtb* that modifies other bacterial proteins to target them for degradation. The process is similar to that in eukaryotes, in which the protein ubiquitin modifies proteins and targets them for proteolysis (see the figure). The discovery of this process in prokaryotes opens the door to further characterizing a protein regulatory mechanism that could be targeted by pathogen-specific drugs.

The proteasome is an adenosine 5′-triphosphate (ATP)–dependent protein degradation complex present in eukaryotes, as well as in several archaebacterial and eubacterial species, including *Mtb* (*2*). The *Mtb* proteasome system, however, is not well characterized, and its functions remain elusive. Nitric oxide, an important signaling molecule, slows the growth of *Mtb*; genetic inactivation of an enzyme that produces nitric oxide (inducible nitric oxide synthase) increases the susceptibility of mice to *Mtb* infection (*3*). Two *Mtb* proteins, *Mycobacterium* proteasomal adenosine triphosphatase (ATPase) and proteasome accessory factor A, were identified in screens for factors that increase susceptibility of the bacterium to the lethal effects of nitric oxide. *Mycobacterium* proteasomal ATPase forms hexamers and exhibits ATPase activity similar to that of the eukaryotic ATPases involved in proteasome function (*3*). ATPase activity is required for the recognition, unfolding, and translocation of substrates into the proteasomal core in eukaryotes. *Mtb* bacteria that are resistant to nitric oxide, and consequently exhibit increased virulence in mice, require proteasomal activity, thereby linking protein degradation to pathogenesis. Interestingly, autophagy, another form of protein degradation in eukaryotes, is linked to a mechanism that inhibits the survival of *Mtb* within host cells independent of nitric oxide (*4*).

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