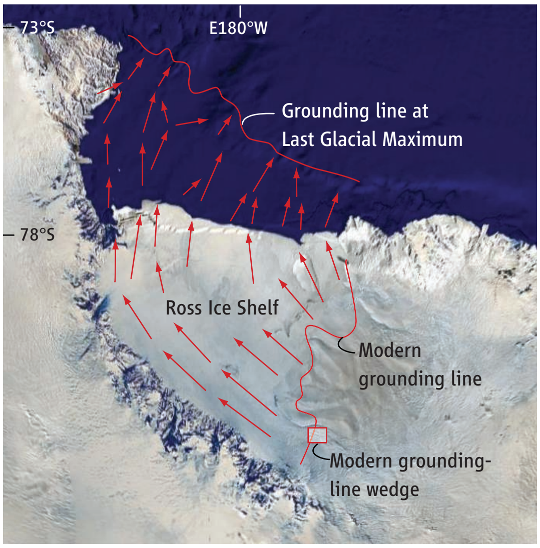
CLIMATE CHANGE

Ice Sheet Stability and Sea-Level Rise

A wedge of sediments appears to stabilize the Whillans Ice Stream, suggesting that sea-level rise may not destabilize ice sheets as much as previously feared.

John B. Anderson

The base of the West Antarctic Ice Sheet is mostly below sea level. Where the ice is thin enough to float, it spreads seaward into vast ice shelves. The grounding line is the juncture between the ice shelf and the part of the ice sheet that is thick enough to ground on the sea floor. Any increase in water depth or decrease in ice sheet thickness at the grounding line could cause the ice sheet to float off the sea floor. The grounding line will then retreat landward until the water depth decreases or the thickness of the ice sheet increases to the point where it is no longer buoyant.



The grounding line, past and present. This satellite image of the Ross Sea and Ross Ice Shelf shows the modern grounding line of the ice sheet, as well as its grounding line ~20,000 years ago (red line). Arrows show flow lines of ice streams. The location of the modern grounding-line wedge identified by Anandakrishnan *et al.* is also shown.

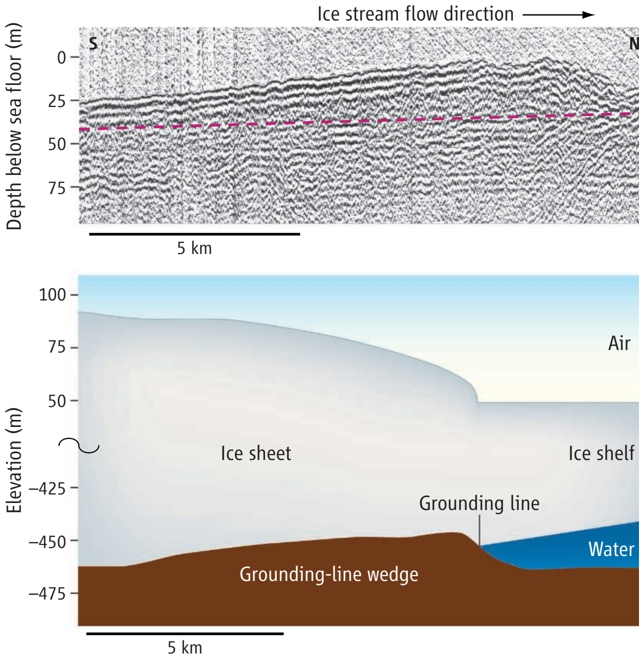
It has long been argued that a rise in sea level or a change in ice sheet thickness can result in rapid grounding-line retreat, thereby increasing the overall rate of sea-level rise (*1*, *2*). Thus, the West Antarctic Ice Sheet may be inherently unstable. The ice sheet has clearly retreated landward since the Last Glacial Maximum (~20,000 years ago) when its grounding line was located at the edge of the continental shelf (*3*) (see the first figure). Recent changes in the ice sheet have raised concern that it may be retreating again.

Two reports in this issue show that at least one threat to the ice sheet's stability—sea-level rise—may not be as serious as has been feared. Anandakrishnan *et al*. on page 1835 (*4*) and Alley *et al*. on page 1838 (*5*) provide evidence that the grounding line of the Whillans Ice Stream, one of the major drainage outlets of the West Antarctic Ice Sheet, rests on a wedge of sediments that will stabilize the ice stream during a sea-level rise of several meters. Thus, in the foreseeable future, sea-level rise should not threaten the ice sheet's stability.

Around West Antarctica, the flow of the ice sheet converges toward the coast as the ice passes through mountain and sea-floor valleys. The converging ice accelerates to form rapidly flowing ice streams, with flow velocities of typically a few hundred meters per year (compared with a few tens of meters per year in nonstreaming parts of the ice sheet). Hence, the ice streams have long been considered the unstable portion of the ice sheet (*6*). Indeed, as the technology for analyzing the behavior of ice streams has evolved, signs of their instability have also emerged (*7*). To assess West Antarctic Ice Sheet stability, it is thus crucial to understand the factors that regulate ice stream behavior over centuries to millennia.

Early discussions of ice stream stability focused on the reason for rapid and potentially episodic flow. Measured velocities of most ice streams far exceed the capacity of ice to flow internally, especially where the ice is not confined by valley walls. Hence, high flow rates must be accounted for by basal sliding. Basal sliding requires a lubricant at the base of the ice sheet, either water or a sediment/water mixture. It is now generally accepted that rapid flow of ice streams is due, at least in part, to flow across a deforming till layer produced by the mixing of basal meltwater with sedimentary material (*8*, *9*).

The deforming till concept implies high rates of sediment transport at the bed. The



Stabilizing ice sheets. (**Top**) Seismic image of an ancient ice stream wedge on the Ross Sea continental shelf. The dashed line marks an erosion surface that formed during the advance of the ice sheet onto the continental shelf. The wedge was deposited as the grounding line of the ice sheet became stationary at this location during the overall retreat. [Adapted from (*3*)] (**Bottom**) In the model presented by Alley *et al.*, the wedge elevates the grounding line and manifests itself as an abrupt change in the profile of the ice sheet at this location. It stabilizes the grounding line as sea level rises. The horizontal scale of the model has been adjusted to approximate the wedges on the continental shelf shown at the top.

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sediment that moves seaward within the subglacial conveyer belt is deposited in wedges of sedimentary material known as grounding-line wedges. Several such wedges have been identified and mapped in broad valleys on the Antarctic continental shelf with detailed images of the sea floor and high-resolution seismic data (see the second figure, top panel) (*10*). Ice streams excavated these valleys when the ice sheet advanced onto these continental shelves. The wedges were formed at locations where the grounding lines stabilized for a while during retreat.

Anandakrishnan *et al*. now provide the first documentation of a grounding-line wedge beneath a modern ice stream, the Whillans Ice Stream. The wedge is likely to have formed during a pause in the overall retreat of the ice sheet. Alley *et al*. describe the wedge in relation to the current ice stream configuration and behavior, and model the response of the ice stream to sea-level rise. The combined results show that the modern grounding line is situated over the crest of the wedge and that the ice thickness increases appreciably upstream of the grounding line (see the second figure, bottom panel). The model results indicate that the ice sheet is thick enough at that point to remain grounded, even with a sea-level rise of several meters. At the current rate of sea-level rise, it would take several thousand years to float the ice sheet off the bed.

The two reports discuss a single ice stream, but relict grounding-zone wedges are common features on the continental shelf, including the Ross Sea shelf (*3*, *10*). In addition, all ice streams of the Siple Coast have an anomalous elevation and stop at the grounding line (*11*). Thus, this mechanism for stabilization of the grounding line is likely to be widespread.

The ice sheets have changed in the past and are changing today. Yet Anandakrishnan *et al*. and Alley *et al*. demonstrate that grounding-line deposition serves to stabilize ice streams, suggesting a decreased role for sea level in explaining these changes. Future research should focus on other ice streams, especially those that currently display signs of instability, to get at the causes of this instability.

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ATMOSPHERIC SCIENCE

CO$_2$ Is Not the Only Gas

Keith P. Shine and William T. Sturges

About 40% of the heat trapped by anthropogenic greenhouse gases is due to gases other than carbon dioxide, primarily methane.

In 1971, one of the first international assessments of the role of humankind in climate change concluded that "because methane has no direct effects on climate…it is considered of no importance" [(*1*), p. 242]. How times change. By the mid-1980s (*2*), methane and a host of other non-CO$_2$ gases were together recognized to be contributing to climate change by an amount comparable to that of CO$_2$.

An increase in the concentration of a greenhouse gas causes a change in Earth's energy balance. This change, or radiative forcing, is a simple indicator of the climate change impact. The largest single contributor to radiative forcing is CO$_2$, with an estimated value of 1.66 W m^{-2} since preindustrial times—enough, on its own, to eventually raise global average surface temperatures by about 1.4°C. The non-CO$_2$ greenhouse gases contribute an additional 1 W m^{-2} (*3*, *4*).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change recognizes the importance of non-CO$_2$ greenhouse gases. Emission targets for signatories to the Convention are given in terms of CO$_2$-equivalent emissions; the signatories can choose to control emissions of several gases—CO$_2$, methane, nitrous oxide, sulfur hexafluoride (SF$_6$), the hydrofluorocarbons, and the perfluorocarbons—to meet their targets. There remain issues concerning what emissions are included and excluded in the Kyoto Protocol and the method by which emissions of different gases are placed on a common "carbon-equivalent" scale (*5*). Nevertheless, it is clear that controlling non-CO$_2$ greenhouse gas emissions can play a very important role in attempts to limit future climate change (*6*, *7*).

The contribution of a given non-CO$_2$ greenhouse gas to radiative forcing depends on its ability to absorb infrared radiation emitted by Earth's surface and atmosphere. This ability is determined by fundamental spectroscopic properties of the molecule; to be really effective, the molecule must absorb at wavelengths where the atmosphere is not already strongly absorbing. The contribution also depends on the change in the atmospheric concentration of the gas; this change is determined by the size of its emissions and by its atmospheric lifetime. The lifetimes of non-CO$_2$ greenhouse gases vary from less than a year to thousands of years.

On a per-molecule basis, many non-CO$_2$ greenhouse gases are far more effective than CO$_2$ at contributing to radiative forcing. For example, the absorption strength of heavily fluorinated molecules can be 10,000 times that of CO$_2$. CO$_2$ has a dominant radiative forcing only because the increase in its atmospheric concentration has been so large—around 100 parts per million (ppm) since preindustrial times. Methane, by contrast, has increased by only 1 ppm; other important non-CO$_2$ greenhouse gases have increased by parts per billion or even parts per trillion (ppt), yet still contribute appreciably to radiative forcing (*3*, *8*–*10*).

Determining the past and present growth of non-CO$_2$ greenhouse gases in the atmosphere is not trivial. A global network of surface measurements has only become available since the late 1970s (*8*–*10*). Unraveling earlier histories requires measurements of "firn air" pumped out of deep snow in polar regions, or analysis of tiny bubbles trapped in ice cores. Glacial records of the more abundant gases,

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