The Intergovernmental Panel on Climate Change (IPCC) this year confirmed a global mean warming of 0.6 ± 0.2°C during the 20th century and cited anthropogenic increases in greenhouse gases as the likely cause (1). However, this mean value conceals the complexity of observed climate change. If the recent past is a guide to the future, regional climate changes will have more profound effects than the mean global warming suggests.

Global maps of observed climate change reveal a complicated pattern. Trends in mean annual air temperature for 1950–98 indicate three areas of particularly rapid regional warming, all at high latitudes (2): northwestern North America and the Beaufort Sea, an area around the Siberian Plateau, and the Antarctic Peninsula and Bellingshausen Sea. The last area provides a valuable case study, remote from the complications of urban warming and sulfate aerosols.

The mean temperature trend for all Antarctic stations for 1959–96 is +1.2°C per century (3), well above the global mean. Regional responses have, however, varied widely. Annual air temperatures have cooled at Amundsen-Scott base at the South Pole since 1958 (4) but have warmed on the Antarctic Peninsula (see the first figure) since reliable records began in the 1950s (3, 5). The longest records from the peninsula (4) show a warming in the northwest Antarctic Peninsula that is considerably larger than the mean Antarctic trend. The shorter records (4, 6) suggest that the warming extends further south and east. Antarctic Peninsula records are too short to show when the rapid regional warming began. However, warming at Orcadas began in the 1930s, and annual temperatures at Orcadas correlate well with the Faraday record. Warming in the Antarctic Peninsula may thus have begun at a similar time.

The importance of this recent rapid regional warming is highlighted by its impact on the local environment, such as expanding ranges of flowering plants (7), retreat-

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**References and Notes**

5. We thank J. Murray for help with the figure.
ing glaciers (8), and shrinking seasonal snow cover (9). A reorganization of penguin distributions is now also attributed to rapid regional warming, rather than overhunting of baleen whales, as was once thought (10). Adélie penguins, which require access to winter pack ice, are declining around Faraday, whereas chinstrap penguins, which usually require open water, are increasing. The rookeries vacated by the Adélie penguins seem to have been occupied continuously for ~644 years, and there is no evidence that chinstrap penguins were present more than 20 to 50 years ago.

This evidence alone may not be strong enough to convince us that the recent warming is exceptional. But other climate proxies tell the same story. Three of the four ice cores from the Antarctic Peninsula show a rise in temperature over the past 50 years (11). There is a 99% likelihood that the recent warming is exceptional compared with any part of the 500-year period recorded in the longest of these records.

Further evidence comes from the retreat of ice shelves, long predicted to result from warming in the Antarctic Peninsula (12). Rapid regional warming has led to the loss of seven ice shelves during the past 50 years (13). The Prince Gustav Channel ice shelf collapsed in 1995. Sediment cores show that during the period from ~6000 to 1900 years ago, the ice shelf was absent and climate was as warm as it has been recently. Since 1900 years ago, the shelf was, however, continuously present until it disappeared in 1995 (14). A similar pattern was observed in undated sediment cores from the area formerly covered by the Larsen Ice Shelf (15) and in microfossils records from Lallemand Fjord (16) on the west coast of the peninsula.

The recent rapid regional warming in the Antarctic Peninsula is thus exceptional over several centuries and probably unmatched for 1900 years. It may be tempting to cite anthropogenic greenhouse gases as the culprit, but to do so without offering a mechanism is superficial.

A plausible mechanism must explain how the climatic response is amplified in this area. It must also reduce sea-ice cover around the Antarctic Peninsula, the only region of Antarctica that shows strong annual (17) and long-term correlations between sea-ice concentration and air temperatures. Sporadic observations from whaling ships provide some evidence for mid-20th century retreat of summer sea ice (18), but detailed observations are only available for the satellite era. In this period (1979–99), there was a major reduction in sea-ice duration in the Bellingshausen Sea, with a maximum change that coincided with the maximum warming trend around Faraday and Rothera (19).

At least three candidate mechanisms may explain the recent warming on the Antarctic Peninsula. First, changing oceanographic circulation may have brought relatively warm Circumpolar Deep Water onto the continental shelf (20). As melting glacial ice and tidal processes mixed the Deep Water through the water column, sea-ice production was reduced, causing warming. Second, large-scale atmospheric circulation over the Antarctic Peninsula may have changed since the 1950s (21), advecting warmer air into the area. Changing sea ice would then be simply a consequence of atmospheric warming. Third, global mean warming may be amplified by a regional sea-ice–atmosphere feedback restricted to the Antarctic Peninsula by the unique sea-ice conditions.

Because we cannot distinguish between these widely differing mechanisms, we have no basis for predicting future changes, even if we accept that the recent warming is exceptional. Can global circulation models (GCMs) help determine the mechanism?

Some GCMs do show a sea-ice–atmosphere feedback (22). However, when the atmosphere-ocean GCM HADCM3 was driven by historic CO2 trends, the results showed only slight warming on the Antarctic Peninsula over the past 50 years (see the second figure). This slight warming could be compatible with the lowest estimate of the Faraday trend, but this is unconvincing. And HADCM3 is no worse in reproducing recent rapid regional warming than other GCMs (23). Many GCMs reproduce the observed large-scale changes in surface temperature over the 20th century, but they do not yet reproduce regional changes.

The recent warming on the Antarctic Peninsula has been a profound climatic change, an order of magnitude greater than global mean warming, over an area similar in size to the mainland United Kingdom. Yet we do not know the mechanism that caused it and cannot predict whether it will continue. This suggests that we do not yet have tools to predict potentially socially significant regional climate changes in the
next 100 years. For national adaptation planning to be properly targeted, we must achieve competency in predicting regional climate changes through a better understanding of regionally specific climate processes.

References and Notes


4. For a table of trends in mean annual air temperature at selected meteorological stations in Antarctica, see Science Online at www.sciencemag.org/cgi/content/full/293/5536/1778/DC1.


15. E. Domack et al., Eos 82, 13 (2001).


19. Several studies show retreat of sea ice in the Bellings- hausen Sea, but it may be more appropriate to com- pare sea-ice duration, rather than extent, with atmo- spheric temperature trends (24).


PERSPECTIVES: PLANETARY SCIENCE

What Is the Moon Made of?

Paul D. Spudis

The Moon, long a most mysterious object, has in the past decade come under close scrutiny from orbital spacecraft. In 1994, the Clementine mission mapped its global topography and color (1). Four years later, the Lunar Prospector spacecraft mapped its chemistry and gravity from a lower orbit (2). These missions have greatly advanced our understanding of the global distribution of elements and rock types at the lunar surface. A picture of the Moon’s structure and history is emerging that challenges some long-held views and confirms others.

Before the two orbital missions, knowledge about lunar surface chemistry was largely based on samples brought back by the Apollo and Luna missions. These samples showed that the Moon’s highlands are rich in aluminum and poor in iron and magnesium (3). The new data confirm this picture on a global scale, with some subtle but important variations.

Huge regions of the highlands are extremely low in iron (see the figure). These regions are believed to be composed of an aluminum-rich rock type called anorthosite, the only low-iron rock type found on the Moon. Anorthosite forms when molten rock crystallizes slowly, allowing low-density, aluminum-rich minerals to float to the top of the magma body. The abundance of anorthosite in the highland crust strongly supports the notion that the Moon’s outermost layer was once nearly completely molten, forming a “magma ocean” (3).

The isotopic composition of lunar anorthosite samples indicates that the magma ocean must have occurred early in the Moon’s evolution, while the Clementine data show that it was a global event. The only known source of sufficient heat for such an event is very rapid accretion, as expected if the Moon formed as a result of a giant impact between Earth and a massive asteroid (4). The global iron data provided by the Clementine mission thus support both the model of the lunar magma ocean and the popular giant impact model for lunar origin.

Much of the highland surface is iron-poor, but some zones appear enriched in iron, especially the floor of the huge South Pole–Aitken basin, a 2600-km-diameter impact structure centered on the southern far side (see the figure). The basin floor material is also enriched in titanium and the trace element thorium (5). In contrast to the iron-rich basin floor, the surrounding highlands are high in aluminum and low in iron.

Recent observations suggest that the large impact stripped off the upper aluminous crustal layer, exposing iron-rich material underneath. The lunar crust may thus be stratified, with a lower crust that is richer in iron, titanium, and thorium and less anorthositic than the upper crust. Such a crustal structure, combined with evidence from the Apollo samples, supports the idea that the Moon has a complex igneous history, with crust-forming magmatic events after the magma ocean had ceased to exist.

Basaltic volcanism is responsible for the lunar maria—the dark, smooth plains that fill ancient basins on the Moon. This volcanism must have occurred after the magma ocean had solidified. Mare volcanism is caused by the remelting of iron-rich cumulate rocks, deep in the lunar mantle (below 400 km). Volcanism was active from 4.3 billion years ago to at least 3 billion years ago (the youngest basalts in the Apollo collection); unsampled lavas may date from less than 1 billion years ago (3).

Clementine and Lunar Prospector data show that the titanium content of the maria varies by over an order of magnitude. The very high-titanium mare basalts first returned from the Moon by the Apollo 11 mission over 30 years ago turn out to be rare, although they are abundant in Mare Tranquillitatis (sampled by Apollo 11). Impact craters that penetrate the iron-rich

http://www.sciencemag.org/cgi/content/full/293/5536/1778/DC1

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