(3). This test, which uses a chemiluminescent reporter group and sensitive Polaroid film, is highly accurate and suitable for use in the local pharmacy. Another diagnostic test under development by Biota Holdings (Melbourne, Australia) and BioStar (Colorado, USA) uses a silicon chip biosensor and optical immunoassay technology (3). The chip has antibodies to flu A and B nucleoproteins attached to its surface, and the refractive index changes if these antigens are present in the test sample, yielding a purple color easy to see by eye. Both of these tests give a result in no more than 20 min.

It is doubtful whether vaccination would be useful in controlling an influenza pandemic, at least in the early stages. Such an exercise was, in fact, attempted in January 1976, when a swine flu outbreak occurred among army recruits at Fort Dix, New Jersey (4). It was thought that the 1918 "Spanish influenza" virus might have returned, prompting President Ford to authorize the expenditure of $350 million to "vaccinate every man, woman, and child in the U.S.A." This mass vaccination program experienced a number of problems—low antibody titer, vaccine side effects, and litigation tangles—that could happen again if such an exercise were ever to be repeated. (The expected pandemic never materialized.)

The influenza vaccines currently in use are inactivated subunit vaccines containing hemagglutinin and neuraminidase obtained from various strains of cultured flu virus. They are reasonably effective against the strain used to make the vaccine and are cost-effective. However, it would be difficult to make, test, and safety-test enough vaccine in time to protect many people against a new virus. Vaccines currently being developed may show more promise. These include vaccines prepared by reverse genetics, DNA vaccines, vaccines against the conserved regions of the M2 ion channel of the flu virus, and even vaccine "cocktails" containing all known hemagglutinin subtypes.

But the most promising first line of defense does seem to be antiviral drugs, and of those currently available, the neuraminidase inhibitors, although expensive, appear to be the best. Use of these drugs in the face of an exploding influenza epidemic would, however, be beset with immense social, political, economic, and logistical problems. For the drugs to be of any use, huge quantities would need to be immediately available, and means for their rapid distribution would need to be in place beforehand. Supplies of these drugs at the moment are woefully inadequate. In addition, the companies producing the drugs now seem to have a diminished interest in influenza—possibly because the last flu season was the lightest for many years, and little demand for neuraminidase inhibitors meant few sales and meager profits for the pharmaceutical companies involved. The concept that it is hard to sell umbrellas in a drought seems to have escaped them!

Imagine the following: Somewhere in China, an influenza virus, subtype H9N2, suddenly acquires the ability to infect humans. The virus is highly infectious and highly transmissible, although the disease it causes is fairly mild. Because of this, perhaps, the identity of the new strain is determined only after it has infected a large number of people in China. Some of them carry the new virus into Hong Kong, others into Taiwan, and still others into a number of other countries. There is an explosive pandemic, much social and economic disruption, and a good deal of misery among the victims. Rapidly growing strains of the new virus are created, and vaccine production starts but progresses slowly. The neuraminidase inhibitors Relenza and Tamiflu are eagerly sought but are in very short supply. Who should get these new drugs? Health care workers and those in essential services, obviously, but who will identify them? Even then, there will not be nearly enough of the drugs for all those who need them in the developed world, let alone the rest of the world's population.

The answer seems to be: Stockpile these drugs now, in huge quantities. Their shelf life has not yet been determined, but they are simple chemical compounds and there is no reason to suppose they are not stable. In any case, it would be possible to replace the stockpile every 5 years or so. The cost of making the drugs, as opposed to the prices the pharmaceutical companies charge consumers, would not be exorbitant. Such an expenditure by governments would be a worthwhile investment in their defense against this debilitating and often deadly illness.

References and Notes

1. M. J. Gibbs, J. S. Armstrong, A. J. Gibbs, *Science* **293**, 1842 (2001).
2. M. Hatta, P. Gao, P. Halfmann, Y. Kawaoka, *Science* **293**, 1840 (2001).
3. Proceedings of the Royal Society meeting on "The origin and control of pandemic influenza" held at the Royal Society in London, UK, 25 to 26 April 2001.
4. W. R. Dowdle, *J. Infect. Dis.* **176**, S69 (1997).

5. We thank J. Murray for help with the figure.

PERSPECTIVES: CLIMATE CHANGE

Devil in the Detail

David G. Vaughan, Gareth J. Marshall, William M. Connolley, John C. King, Robert Mulvaney

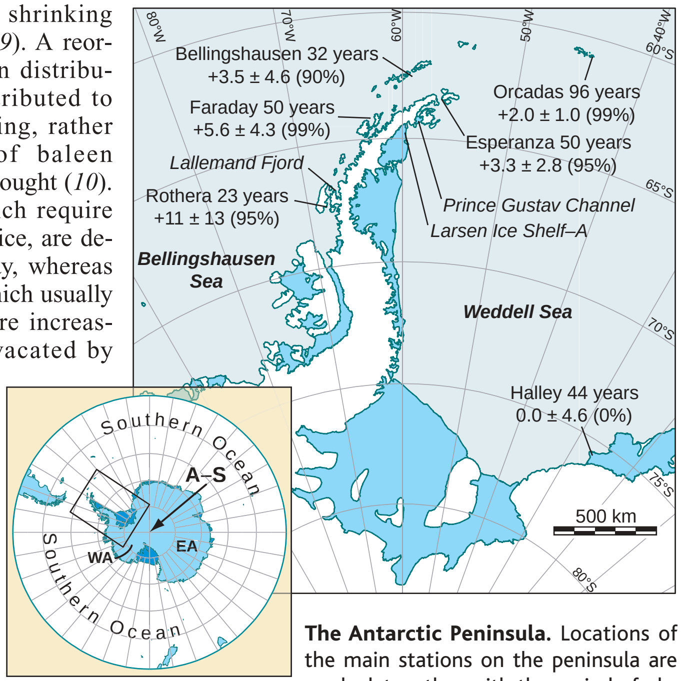
The Intergovernmental Panel on Climate Change (IPCC) this year confirmed a global mean warming of 0.6 ± 0.2°C during the 20th century and cited anthropogenic increases in greenhouse gases as the likely cause (1). However, this mean value conceals the complexity of observed climate change. If the recent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

The authors are at the British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, CB3 0ET, UK. E-mail: d.vaughan@bas.ac.uk

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), retreating 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.



The Antarctic Peninsula. Locations of the main stations on the peninsula are marked, together with the period of observation in years, the temperature trend in degrees Celsius per century, and the significance of the trend. **(Inset)** Location of Amundsen-Scott Base (A-S), East Antarctica (EA), and West Antarctica (WA).

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.

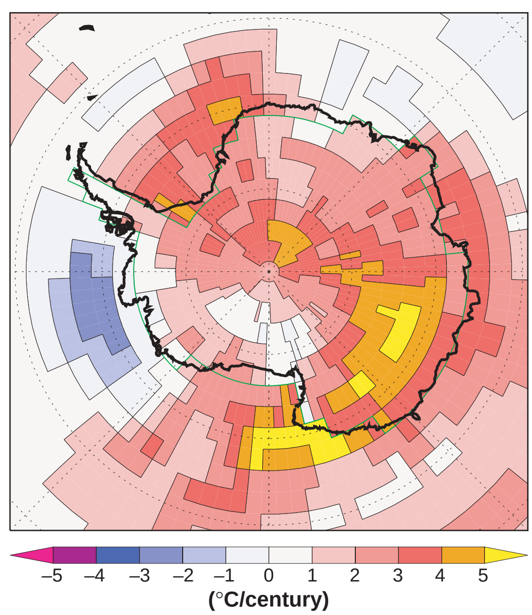
A plausible mechanism must explain how the climatic response is amplified in this area. It must also reduce sea-ice cover around the Antarctic Peninsula, the only region of Antarctica that shows strong annual (*17*) and long-term correlations between sea-ice concentration and air temperatures. Sporadic 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 CO_2 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



Spot the regional trend. Changes in mean annual temperature 1.5 m above the surface of Antarctica and the Southern Ocean from the HADCM3 model driven by observed greenhouse gases concentrations for 1950–2000. The model cannot reproduce the observed rapid regional temperature changes.

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

1. J. T. Houghton *et al.*, Eds., *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, Cambridge, 2001).
2. J. Hansen, R. Ruedy, J. Glascoe, M. Sato, *J. Geophys. Res.* **104**, 30997 (1999).
3. T. H. Jacka, W. F. Budd, *Ann. Glaciol.* **27**, 553 (1998).
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.
5. J. C. King, *Int. J. Climatol.* **14**, 357 (1994).
6. C. Shuman, R. B. Alley, *Geophys. Res. Lett.* **20**, 2643 (1993).
7. J. A. Fowbert, R. I. Lewis Smith, *Arc. Alp. Res.* **26**, 290 (1994).
8. A. M. Smith, D. G. Vaughan, C. S. M. Doake, A. C. Johnson, *Ann. Glaciol.* **27**, 113 (1999).
9. A. J. Fox, A. P. R. Cooper, *Ann. Glaciol.* **27**, 636 (1998).
10. W. R. Fraser, W. Trivelpiece, D. Ainley, S. Trivelpiece, *Polar Biol.* **11**, 525 (1992).
11. L. G. Thompson *et al.*, *Ann. Glaciol.* **20**, 420 (1994).
12. J. H. Mercer, *Science* **271**, 321 (1978).
13. D. G. Vaughan, C. S. M. Doake, *Nature* **379**, 328 (1996).
14. C. J. Pudsey, J. Evans, *Geology* **29**, 787 (2001).
15. E. Domack *et al.*, *Eos* **82**, 13 (2001).
16. E. W. Domack *et al.*, *Ant. Sci.* **7**, 159 (1995).
17. J. Weatherly, J. Walsh, H. J. Zwally, *J. Geophys. Res.* **96**, 15119 (1991).
18. W. K. de la Mare, *Nature* **389**, 57 (1997).
19. Several studies show retreat of sea ice in the Bellingshausen Sea, but it may be more appropriate to compare sea-ice duration, rather than extent, with atmospheric temperature trends (*24*).
20. E. E. Hofmann, J. M. Klinck, C. M. Lascara, D. A. Smith, in *Foundations for Ecological Research West of the Antarctic Peninsula*, R. M. Ross, E. E. Hofmann, L. B. Quetin, Eds. (American Geophysical Union, Washington, DC, 1996), vol. 70, pp. 61–80.
21. J. C. King, S. A. Harangozo, *Ann. Glaciol.* **27**, 571 (1998).
22. W. J. Cai, H. B. Gordon, *J. Clim.* **12**, 132 (1999).
23. W. M. Connolley, S. P. O'Farrell, *Ann. Glaciol.* **27**, 565 (1998).
24. C. Parkinson, *Ann. Glaciol.*, in press.

PERSPECTIVES: PLANETARY SCIENCE

What Is the Moon Made of?

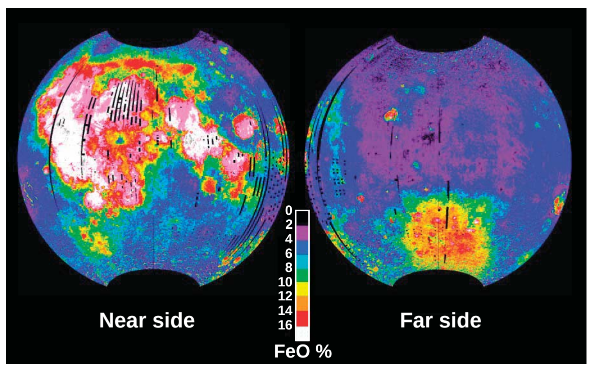
Paul D. Spudis

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.



Global distribution of iron on the Moon. These maps are derived from Clementine color images by using the ratio of the 950- and 750-nm images and empirically calibrating the results against the "ground truth" supplied by the Apollo and Luna samples (*8*, *9*). The iron distribution is expressed as percentage of FeO in weight. Large regions of the Moon are very low in iron, supporting the magma ocean model for crustal formation. The large quasi-circular area of elevated iron content on the far side is the South Pole–Aitken basin, the largest known impact crater in the solar system. The elevated iron in this area, and the corresponding low-iron zone surrounding the basin rim, suggest that the lower crust of the Moon is exposed in the basin floor and is more iron-rich than the upper crust.

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.

These 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

The author is at the Lunar and Planetary Institute, Houston, TX 77058, USA. E-mail: spudis@lpi.usra.edu