low temperatures) in adjacent kyanite quartzite (*17*).

Some of the forbidden zone garnet peridotites in the Dabie-Sulu UHP terrane may have been placed in the crust before subduction and subjected to in situ UHP metamorphism together with the subducted slab. In particular, the Bixiling and Maowu mafic-ultramafic complexes of the Dabie Mountains in central China are interpreted as layered crustal intrusions (*13*, *16*, *19*). The reasons are as follows. The primary modal layering observed in the Bixiling rocks can be attributed to fractional crystallization of basaltic magma at crustal depths. Similarly, Maowu contains layers likely derived from plagioclase (a mineral stable only in crustal rocks) and high-temperature–low-pressure inclusions in garnets that require a crustal metamorphic event before subduction. Furthermore, both have UHP metamorphic ages of ~220 million years, younger than their crystallization ages of <300 million years for Bixiling and 450 million years for Maowu. Finally, there is evidence that both have experienced crustal contamination, as indicated by high $^{87}Sr/^{86}Sr$ ratios (Maowu) and low $\delta^{18}O$ (Bixiling and Maowu) (*20–22*). If this interpretation withstands further scrutiny, these bodies would be the first evidence that continental rocks have been subducted to depths of 200 km.

The most obvious location where crust can be subducted to 200-km depth without being heated beyond 900°C is a cold, steady-state subduction zone where old lithosphere is rapidly subducted, such as beneath northeast Japan, where the 130-million-year-old Pacific Plate is foundering at 90 mm/year (*23*). As pointed out by Peacock (*24*), UHP rocks (even the aforementioned bodies from the forbidden zone) are actually hotter than the coldest conditions calculated for mature, cold subduction zones. Most UHP localities do not appear to be associated with a coeval volcanoplutonic arc, however, suggesting that they do not form in long-lived subduction zones. Crustal rocks in an incipient subduction zone that has not reached a thermal steady state (see the figure), may reach a temperature of 900°C at 200-km depth are carried to 200-km depth if subduction is rapid enough that advection dominates conduction. For example, if subduction to 200-km depth takes ~5 million years, rocks in the middle crust of the subducted slab will undergo little heating, as the characteristic diffusion distance for this time scale is 10 to 15 km.

The discovery of these ultramafic denizens of the forbidden zone confirms the cold subduction-zone models of Peacock and Wang (*23*). These cold subduction zones are clearly the sites of major recycling of H_2O into the mantle, because high-pressure experiments on mafic-ultramafic compositions (*25*) reveal that numerous important hydrous phases are stable in the forbidden zone. Research in the past 10 years on UHP rocks containing coesite and diamond has produced a dramatic restructuring of our understanding of plate tectonics. The discovery of garnet peridotites from the forbidden zone now provides a revolutionary new window into the subduction of continental margins, the thermal structure of subduction zones, and the recycling of volatiles into the mantle.

References

1. W. Schreyer, *Mineral. Mag.* **51**, 1 (1988).
2. S. Maruyama, J. G. Liou, M. Terabayashi, *Int. Geol. Rev.* **38**, 485 (1996).
3. H. K. Brueckner, *Geology* **26**, 631 (1998).
4. H. L. M. van Roermund and M. R. Drury, *Eos* **79**, F971 (1998).
5. H. L. M. van Roermund, M. R. Drury, A. Barnhoom, A. Ronde, *J. Metamorph. Geol.*, in press.
6. M. P. Terry, P. Robinson, D. A. Carswell, T. Gasparik, *Eos* **80**, S359 (1999).
7. K. N. Bozhilov, H. W. Green, L. Dobrzhinetskaya, *Science* **284**, 128 (1999).
8. L. Dobrzhinetskaya, H. W. Green, S. Wang, *Science* **271**, 1841 (1996).
9. B. R. Hacker, T. Sharp, R. Y. Zhang, J. G. Liou, R. L. Hervig, *Science* **278**, 702 (1997).
10. E. J. Krogh and D. A. Carswell, in *Ultrahigh Pressure Metamorphism*, R. G. Coleman and X. Wang, Eds. (Cambridge Univ. Press, Cambridge, 1995), pp. 244–298.
11. H. K. Brueckner and L. G. Medaris Jr., *Schweiz. Mineral. Petrogr. Mitt.* **78**, 293 (1998).
12. L. G. Medaris Jr., *Int. Geol. Rev.* **41**, 799 (1999).
13. R. Y. Zhang, J. G. Liou, J. S. Yang, T. F. Yui, *J. Metamorph. Geol.*, in press.
14. J. Yang, G. Godard, J. R. Kienast, Y. Lu, J. Sun, *China J. Geol.* **101**, 541 (1993).
15. R. Y. Zhang, J. G. Liou, B. L. Cong, *J. Petrol.* **36**, 1011 (1995).
16. J. G. Liou, and R. Y. Zhang, *Island Arc* **7**, 115 (1998).
17. R. Y. Zhang, J. F. Shu, H. K. Mao, J. G. Liou, *Am. Mineral.* **84**, 564 (1999).
18. Z. Q. Xu, W. C. Yang, Z. M. Zhang, T. M. Yang, *Continental Dynam.* **3**, 1 (1998).
19. A. I. Okay, *Contrib. Mineral. Petrol.* **116**, 145 (1994).
20. J. Baker, A. Matthews, D. Mattey, D. Rowley, F. Xue, *Geochim. Cosmochim. Acta* **61**, 1685 (1997).
21. B-M. Jahn, in *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks*, B. Hacker and J. G. Liou, Eds. (Kluwer Academic, Dordrecht, Netherlands, 1998), pp. 203–239.
22. R. Y. Zhang, D. Rumble, J. G. Liou, Q. C. Wang, *Chem. Geol.* **150**, 161 (1998).
23. S. M. Peacock and K. Wang, *Science* **286**, 937 (1999).
24. S. M. Peacock, *Island Arc* **4**, 376 (1995).
25. B. O. Mysen, P. Ulmer, J. Konzett, M. W. Schmidt, *Rev. Mineral.* **37**, 97 (1998).
26. R. Y. Zhang and J. G. Liou, *Episodes* **21**, 229 (1998).

PERSPECTIVES: CLIMATE CHANGE

Temperatures High and Low

David E. Parker

Satellite measurements of atmospheric temperatures have been available since 1979 through retrievals from Microwave Sounding Units (MSUs). These measurements show virtually no warming trend in the lower troposphere, the layer from about 1 to 5 km above Earth's surface. In contrast, measurements taken in situ at Earth's surface indicate a globally averaged warming of between 0.3° and 0.4°C over the same period. Papers in this issue by Santer *et al.* (*1*, p. 1227) and Gaffen *et al.* (*2*, p. 1242) use a combination of observations and model simulations to throw further light on these trends and bring a partial reconciliation.

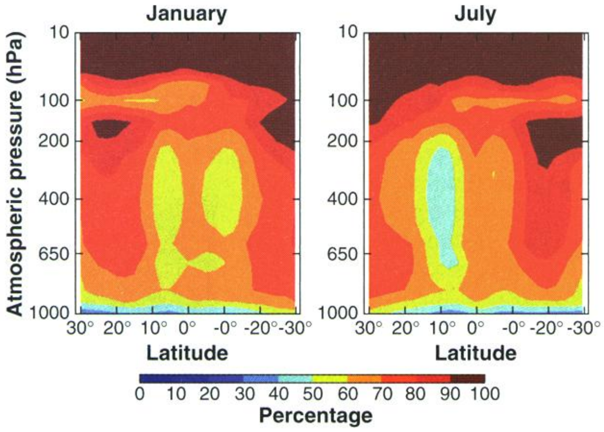
Understanding the difference between surface and tropospheric temperature trends is crucial for modeling climate, explaining and attributing climatic changes, and planning for future climate monitoring. The observed differential temperature trends between these layers may result from biases or sampling inadequacies in the observations, fluctuations caused by short-term events such as El Niño or volcanic eruptions, and/or longer term natural or human-induced changes. The vertical structure of the observed trends may differ from that predicted by models because of observational biases, spatial and temporal sampling uncertainties, and shortcomings in the models or in the human and natural forcings (such as greenhouse gas emissions and volcanic eruptions) provided to them. These possibilities were recently examined by an expert panel for the U.S.'s National Research Council (NRC) (*3*).

Santer *et al.* (*1*) use surface and MSU data to argue that a small but not negligible part of the observed differential temperature trend has arisen from incomplete surface temperature sampling. This finding lends support to the NRC panel's recommendation (*3*) that a worldwide temperature monitoring system must be implemented that ensures the continuity and quality control of critically important data sets. Santer *et al.* also use coupled atmosphere-ocean model simulations to explore the impacts of stratospheric ozone depletion and of the 1991 eruption of Mount Pinatubo. They conclude that, together, these forcings may explain a further third of the discrepancy between the observed differential trends and those predicted by models forced with changes in greenhouse gases, direct and indirect sulfate forcing, and tropospheric ozone. In the models investigated by Santer *et al.*, unforced natural climate variability cannot explain the observed lapse rate changes. Santer *et al.* recommend additional simulations that take account of the uncertainties in the forcings and allow full assessment of the space-time patterns of the mod-

The author is at the Hadley Centre, Meteorological Office, London Road, Bracknell, UK RG12 2SY. E-mail: deparker@meto.gov.uk

eled and observed temperature changes, rather than simple consideration of trends over a short (20-year) period. The NRC report draws the same conclusion (*3*).

Gaffen *et al.* (*2*) analyzed daily radiosonde data for the tropics, where the increase in lapse rate since 1979 has been most pronounced. These data, which are independent of the MSU data and almost independent of the surface data, show an increase in lapse rate since the late 1970s. Over the longer period from 1960 to 1997, however, they show a decrease in lapse rate. Brown *et al.* (*4*) obtained similar results using a different source of radiosonde data (*5*). They showed a widespread sharp decline in tropical lapse rates during the late 1970s, followed by an increase after the mid 1980s. One interpretation is that atmospheric circulation changes in the Pacific sector around the late 1970s (*6*), possibly a manifestation of the Interdecadal Pacific Oscillation (*7*), entailed changes in tropical lapse rate.



Controlling influences on air temperatures over the tropical oceans. Percentage of heating due to radiation for 1982 to 1994, based on diagnostics from (*16*). In regions colored blue, heat inputs are mainly convective. In regions colored red, they are mainly radiative. Convection dominates throughout the troposphere in the intertropical convergence zone. There is a rapid upward transition toward radiative control across the tropopause (at about 100 hPa) and, to a lesser extent, the trade wind inversions.

Gaffen *et al.* (*2*) found that lapse rate trends since 1979 have been greater on convectively more stable days, during which lapse rates are small, than on convectively less stable days, when further increases are limited by convective overturning. This is encouraging evidence for the high quality of the radiosonde data. Inversions, especially trade wind inversions, during which convection is inhibited by warmer air aloft, may respond to greenhouse gas forcing in a manner analogous to the tropopause. If so, then the air above the inversion would cool relative to the air below, because its temperature is controlled more by radiative than by convective equilibrium (see the figure). However, Gaffen *et al.* find that, for 1960 to 1997, the less stable days had the greater decrease of lapse rate. Resolution of this question requires both improved data and models that can fully simulate these inversions.

In contrast to Gaffen *et al.* (*2*), Angell (*8*) found more warming at the surface than in the troposphere since 1958, but a more limited station network was used in the study. Several recent papers (*9–12*) have stressed the need to improve radiosonde data availability and quality control and to apply physically based bias adjustments to retain valuable independence from MSU. This would improve on the method of Parker *et al.* (*5*), who used MSU as a reference. Hurrell *et al.* (*12*) lend support for the NRC panel's conclusions (*3*) by demonstrating the need for improved radiosonde and MSU data and for ongoing comparisons between analyses.

There are major physical differences between surface and tropospheric temperatures (*13*, *14*). Transport of heat by tropospheric winds ensures that variations of tropospheric temperature over continents and oceans are of similar strength. In contrast, if the winter atmospheric circulation in the Northern Hemisphere is stronger than usual, the inversions over the continents are weaker, and the continental surface can be much more anomalously warm than can occur over the oceans, where the high thermal capacity strongly damps any changes. The observation that nighttime temperatures have risen more quickly than daytime temperatures at the land surface (*15*) is consistent with a smaller tropospheric warming, because nighttime temperatures often relate to a very shallow layer (*3*, *12*, *15*).

The NRC panel considers that much of the discrepancy between surface and tropospheric temperature trends is real. Measurement errors and the effects of sampling natural variability account for the remainder of the discrepancy. The work of Santer *et al.* and Gaffen *et al.* reported in this issue made important contributions to the NRC Panel's findings. The consensus is that major advances are needed in our modeling and interpretation of temperature profiles, along with considerable improvements in data acquisition, documentation and distribution of the data, and their analysis by the scientific community worldwide.

References

1. B. D. Santer *et al.*, *Science* **287**, 1227 (2000).
2. D. J. Gaffen *et al.*, *Science* **287**, 1242 (2000).
3. National Research Council, *Reconciling Observations of Global Temperature Change* (National Academy Press, Washington, DC, 2000).
4. S. J. Brown *et al.*, *Geophys. Res. Lett.*, in press.
5. D. E. Parker *et al.*, *Geophys. Res. Lett.* **24**, 1499 (1997).
6. K. E. Trenberth, *Bull. Am. Meteorol. Soc.* **71**, 988 (1990).
7. S. Power *et al.*, *Clim. Dyn.* **15**, 319 (1999).
8. J. K. Angell, *Geophys. Res. Lett.* **26**, 2761 (1999).
9. R. E. Eskridge *et al.*, *Bull. Am. Meteorol. Soc.* **76**, 1759 (1995).
10. D. J. Gaffen *et al.*, *J. Clim.*, in press.
11. J. K. Luers and R. E. Eskridge, *J. Clim.* **11**, 1002 (1998).
12. J. W. Hurrell *et al.*, *Bull. Am. Meteorol. Soc.*, in press.
13. J. W. Hurrell and K. E. Trenberth, *J. Clim.* **9**, 2222 (1996).
14. ______, *J. Clim.* **11**, 945 (1998).
15. A. Dai *et al.*, *J. Clim.* **12**, 2451 (1999).
16. E. Kalnay *et al.*, *Bull. Amer. Meteorol. Soc.* **77**, 437 (1996).

PERSPECTIVES: ASTRONOMY

Superclusters—the Largest Structures in the Universe?

Michael Drinkwater

The last two decades have seen a remarkable growth in our knowledge of the distribution of matter in the local universe. Large galaxy surveys have revealed structure on ever-increasing scales. The largest structures identified so far are conglomerates of thousands of galaxies with sizes of hundreds of millions of light-years. These superclusters may help define the largest scale of the initial density perturbations in the early universe and elucidate the early stages of galaxy formation. Until recently, however, this potential could not be realized because existing galaxy surveys were not large enough to contain a representative sample of superclusters. Several large galaxy surveys are about to close that gap by allowing the first quantitative measurements of large-scale structure on the scale of superclusters to be made.

Enhanced online at www.sciencemag.org/cgi/content/full/287/5456/1217

Galaxy surveys are normally based on two-dimensional optical images of the sky. To measure large-scale structure efficiently from the surveys, the third dimension of distance must be measured. This is usually the limiting step because it requires a detailed measurement of the spectrum of each galaxy. The first "large" three-dimensional galaxy surveys made in the 1980s were lim-

The author is at the School of Physics, University of Melbourne, Victoria 3010, Australia. E-mail: m.drinkwater@physics.unimelb.edu.au