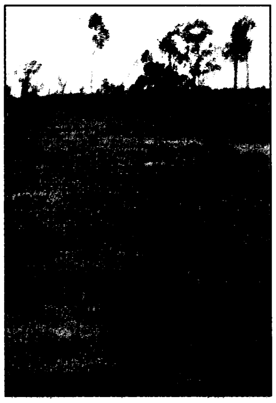
and 1998 in Asia and the Americas. Today, vast tropical rainforest areas have already been opened up by commercial and subsistence land clearing. A large swath of rainforest in South America and Southeast Asia has been affected by its first big (initiating) fire in 1998, the galvanizing event from which more violent, frequent, and destructive fires will follow.

1995. Thirteen years after the initial fire. More standing trees have died and collapsed. The undergrowth is dominated by pioneer tree species (predominantly *Macaranga* spp.). This secondary succession becomes highly flammable in extremely dry years.

1998. A second fire. The tree layer, including the postfire secondary succession, is almost completely killed by a high-intensity fire.



1998. Final stage of fire-induced savannization of the rainforest in a nearby site. The area is dominated by an aggressive invading grass species (*Imperata cylindrica*).

The last 2 years have seen an increase in the willingness of international agencies to address the fire problem. The Global Fire Monitoring Center (GFMC) was established in 1998 for continuous worldwide monitoring, archiving, and information distribution and to form a link between science, users, and policy-makers (*9*). One of the major objectives of the GFMC is to provide a balanced view on fire and to assist in the clarification of detrimental and beneficial effects of fire and their implications for fire management. The report by Keeley *et al.* (*1*), questioning one of the prime tenets in fire management policy, is an important contribution toward this end (see box on previous page). An interagency task force on fire is urgently needed to follow up on the requirements laid out by the UN Convention on Climate Change and the UN Commission for Sustainable Development. The initiative of the World Bank to establish a Consultative Group for Global Disaster Reduction in June 1999 is an important step toward a concerted global fire program.

References and Notes

1. J. E. Keeley, C. J. Fotheringham, M. Morais, *ibid.*, p. 1829.
2. M. A. Cochrane *et al.*, *Science* **284**, 1832 (1999).
3. D. C. Nepstad *et al.*, *Nature* **398**, 505 (1999).
4. A. Timmermann *et al.*, *ibid.*, p. 694.
5. J. G. Goldammer, Ed., *Fire in the Tropical Biota. Ecosystem Processes and Global Challenges* (Springer-Verlag, Berlin, 1990); the Freiburg Declaration on Tropical Fires, as released by the conference participants in May 1989, is included in Appendix I (pp. 487–489). See also P. J. Crutzen and J. G. Goldammer, Eds., *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires* (Dahlem Workshop Reports, Environmental Sciences Research Report 13, Wiley, Chichester, UK, 1993).
6. *Protecting the Earth. A Status Report with Recommendations for a New Energy Policy*, vols. I and II (German Bundestag, Bonn, 1991).
7. See the newsletter *IGACtivities* (no. 15, December 1998) for a summary of the International Global Atmospheric Chemistry (IGAC) Biomass Burning Experiment (BIBEX). The BIBEX home page is maintained at the Max Planck Institute for Chemistry (http://hermes.mpch-mainz.mpg.de/~bibex).
8. For the results of the Southern Tropical Atlantic Regional Experiment (STARE: TRACE-A and SAFARI), see *J. Geophys. Res.* **101**, 23519 (1996); B. van Wilgen, M. O. Andreae, J. G. Goldammer, J. Lindesay, Eds., *Fire in Southern African Savannas. Ecological and Atmospheric Perspectives* (Univ. of Witwatersrand Press, Johannesburg, 1997).
9. The GFMC (www.uni-freiburg.de/fireglobe) is supported by the German Foreign Office and cosponsored by the UN Food and Agricultural Organization (FAO)/Economic Commission for Europe (ECE) Team of Specialists on Forest Fire, International Decade for Natural Disaster Reduction (IDNDR), UNESCO, and the World Bank.
10. J. G. Goldammer, B. Seibert, W. Schindele, in *Dipterocarp Forest Ecosystems: Towards Sustainable Management*, A. Schulte and D. Schöne, Eds. (World Scientific, Singapore, 1996), pp. 155–185.

PERSPECTIVES: ATMOSPHERIC SCIENCE

Vertical Couplings

Michael E. Summers

The conventional approach to studying the global atmosphere is to divide the atmosphere into the troposphere, stratosphere, mesosphere, and thermosphere (see figure), horizontal layers which are defined by the temperature-altitude profile of the atmosphere (*1*). Many characteristic dynamical and chemical processes distinguish these layers, but the boundaries between them are far from impermeable. Studies over the past decade have revealed that strong chemical, dynamical, and radiative coupling exists between them. It is becoming increasingly clear that the global atmosphere must be considered as an integrated system if we are to understand the relative roles of natural and anthropogenic effects on Earth's changing atmosphere. Recent research presented at a Chapman Conference held in Annapolis, Maryland (*2*), highlighted the importance of atmospheric coupling across the stratopause (at an altitude of about 50 km), the region that marks the transition between the stratosphere and mesosphere, together known as the middle atmosphere.

It is now well established that anthropogenic pollutants such as chlorofluorocarbons (CFCs) released in the troposphere cause depletion of stratospheric ozone on a global scale (*3*). Effects attributable to other anthropogenic pollutants have also been predicted to occur but are less well established. Middle atmosphere model results presented by Guy Brasseur (National Center for Atmospheric Research) predict that increasing levels of atmospheric carbon dioxide—associated with global warming in the troposphere as a result of an enhanced greenhouse effect—should, in contrast, lead to global cooling of the middle atmosphere (*4, 5*). This is a robust prediction and is based on the fact that CO_2 is not only an efficient absorber of infrared radiation but also an efficient emitter. At stratospheric altitudes and above where infrared emission from CO_2 can "escape" to space because of the low atmospheric density at these heights, dramatic atmospheric cooling is expected. Tropospheric climate models generally predict a 1° to 4°C increase in the tropospheric temperature in a doubled-CO_2 scenario. Corresponding middle atmospheric models for the same scenario predict a 10° to 20°C decrease in middle atmospheric temperatures (*5*).

Such a large middle atmospheric signal of global temperature change suggests that the atmospheric effects of increasing lev-

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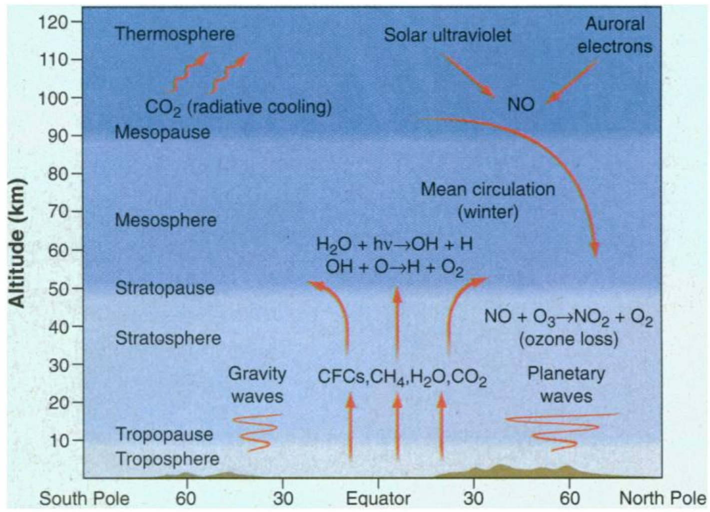
els of CO_2 may become apparent at higher altitudes before an unambiguous trend is observed in the troposphere. A large change in the middle atmospheric temperature structure would also drive significant changes in the middle atmospheric circulation. This would affect tropospheric climate because stratospheric dynamics provide the upper boundary mechanical forcing of tropospheric weather patterns. Recent results suggest that high-altitude cooling is already being observed, sooner than expected (*6, 7*). However, our ability to explain this cooling is complicated by other perturbations, including solar activity and volcanic eruptions.



Coupling between layers. Sketch of the atmospheric layers and the physical and chemical processes that couple the middle atmosphere to the troposphere below and to the thermosphere above. Middle atmospheric circulation is driven by solar heating and by momentum drag resulting from gravity and planetary waves. These waves couple tropospheric climate to the middle atmospheric circulation that in turn controls the transport of radiatively and chemically active trace gases and exerts mechanical forcing on the troposphere below.

To understand the effects of anthropogenic pollutants in the middle atmosphere, we must determine the dynamic processes by which tropospheric trace gases are transported into the middle atmosphere. Both observations and models have shown that most tropospheric trace gases enter the stratosphere through the tropical tropopause (see the figure) and are then transported through the middle atmosphere by winds and various mixing processes. For greenhouse gases like CO_2 and CH_4, which show increasing abundances and have a long atmospheric lifetime, the time difference between the appearance of a given abundance in the troposphere and the appearance of that same abundance in the stratosphere is known as the "age-of-air." In addition to providing a measure of the delay between the release of the gases at Earth's surface and their effects on the middle atmosphere, the age-of-air can be used to diagnose model descriptions of dynamics (*8*).

Darryn Waugh (Johns Hopkins University) and colleagues have compared more than 20 two- and three-dimensional middle atmosphere models and showed that all of the models significantly underpredict the age-of-air, some by as much as a factor of 2, compared with observations of the tracer sulfur hexafluoride (SF_6). These discrepancies indicate major deficiencies in chemical-dynamical models, possibly due to inadequate treatment of mesospheric chemical loss processes or of the time history of tracers in the upper troposphere. These results emphasize the effect of interlayer coupling on middle atmosphere trace gas distributions and their variation with time, and their importance for predicting, for example, long-term changes in stratospheric ozone.

In addition to its role as a greenhouse gas, methane is oxidized in the stratosphere to yield water vapor. The photochemical breakup of the water molecule in turn produces hydroxyl (OH), one of the most important oxidizing agents in the atmosphere. In the stratosphere and mesosphere, OH is a key catalytic agent for the destruction of ozone. The ozone budget in the lower and middle stratosphere is well understood, but models of upper stratospheric and lower mesospheric ozone continue to underpredict the observed ozone abundance (*9*). Robert Conway (Naval Research Laboratory) presented the first satellite observations of OH in the upper stratosphere and showed that the observed abundances are consistent with standard models of ozone chemistry. Thus, the underprediction of ozone near the stratopause continues to be a mystery.

Recent analysis of observations from the NASA Upper Atmosphere Research Satellite (UARS) (*10*), presented by Lin Callis (NASA Langley Research Center) and David Siskind (Naval Research Laboratory), has established a potentially significant chemical coupling between the stratosphere and thermosphere. Nitrogen oxides produced in the upper mesosphere and lower thermosphere by energetic electrons impacting the upper atmosphere (which also produce the visible emissions of the aurora) are carried downward by the atmospheric circulation into the polar stratosphere (see the figure) (*11*). These nitrogen oxides react with ozone, increasing the chemical loss of ozone in the polar stratosphere. However, the global impact of this effect on stratospheric ozone is uncertain and controversial.

It is well known that diurnal and semidiurnal atmospheric tides have a strong influence on mesospheric and thermospheric winds. It is also clear that dissipation of gravity waves and planetary waves, both of which are generated in the troposphere by the interaction between winds and orography (see the figure), provide momentum drag on the circulation of the stratosphere and mesosphere. Yet there are currently no dynamical models that encompass the entire atmosphere from the ground to the thermosphere. Most upper atmospheric models have a lower boundary above 90 km altitude, whereas most lower atmospheric models have an upper boundary below 50 km altitude. Ray Roble (National Center for Atmospheric Research) has coupled the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM), which has a lower boundary near 30 km altitude, with the NCAR Community Climate Model (CCM3) model. This "coupled" model was run for one model year with the CCM3 model forcing the TIME-GCM but without feedback from the TIME-GCM on the CCM3 model. Initial results show that lower atmospheric forcing affects the dynamical variability in the mesosphere and the layers above significantly. The results illustrate the need for a fully coupled ground-to-space global atmospheric model with which to study global atmospheric weather and climate, and to understand solar-terrestrial relations.

References

1. G. Brasseur and S. Solomon, *Aeronomy of the Middle Atmosphere* (Reidel, Dordrecht, the Netherlands, ed. 2, 1986).
2. American Geophysical Union Chapman Conference "Atmospheric science across the stratopause," Annapolis, MD, 19 to 22 April 1999.
3. G. Brasseur, J. J. Orlando, G. S. Tyndall, *Atmospheric Chemistry and Global Change* (Oxford Univ. Press, Oxford, 1999).
4. G. Brasseur and M. H. Hitchman, *Science* **240**, 634 (1988).
5. D. T. Shindell, D. Rind, P. Lonergan, *J. Clim.* **11**, 895, (1998).
6. G. S. Golitsyn *et al.*, *Geophys. Res. Lett.* **23**, 1741 (1996).
7. T. J. Dunkerton, D. P. Delisi, M. P. Baldwin, *Geophys. Res. Lett.* **25**, 3371 (1998).
8. D. W. Waugh *et al.*, *J. Geophys. Res.* **102**, 21493 (1997).
9. M. E. Summers *et al.*, *Science* **277**, 1967 (1997).
10. J. M. Russell III *et al.*, *J. Geophys. Res.* **98**, 10777 (1993).
11. D. E. Siskind *et al.*, *ibid.* **102**, 3527 (1997).