gene and/or p53 are directly involved. Answers to these questions may clarify the role of the TASCC in maintaining the senescent state and in tumor suppression.

References and Notes

1. S. Courtois-Cox, S. L. Jones, K. Cichowski, *Oncogene* **27**, 2801 (2008).
2. F. d'Adda di Fagagna, *Nat. Rev. Cancer* **8**, 512 (2008).
3. T. Kuilman, D. S. Peeper, *Nat. Rev. Cancer* **9**, 81 (2009).
4. F. Rodier, J. Campisi, *J. Cell Biol.* **192**, 547 (2011).
5. M. Narita *et al.*, *Science* **332**, 966 (2011); 10.1126/science.1205407.
6. J.-P. Coppé *et al.*, *PLoS Biol.* **6**, e301 (2008).
7. D. Hanahan, R. A. Weinberg, *Cell* **144**, 646 (2011).
8. J. C. Acosta *et al.*, *Cell* **133**, 1006 (2008).
9. R. M. Kortlever, P. J. Higgins, R. Bernards, *Nat. Cell Biol.* **8**, 877 (2006).
10. T. Kuilman *et al.*, *Cell* **133**, 1019 (2008).
11. N. Wajapeyee, R. W. Serra, X. Zhu, M. Mahalingam, M. R. Green, *Cell* **132**, 363 (2008).
12. C. He, D. J. Klionsky, *Annu. Rev. Genet.* **43**, 67 (2009).
13. Y. Sancak *et al.*, *Cell* **141**, 290 (2010).

10.1126/science.1207552

ATMOSPHERIC SCIENCE

Subtropical Rainfall and the Antarctic Ozone Hole

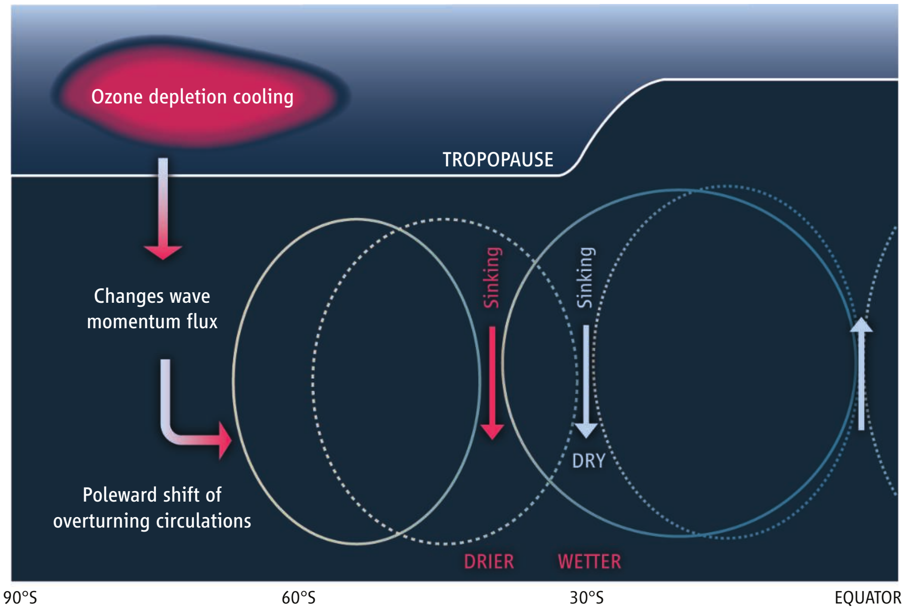
Simulations show that ozone depletion has had a large impact on Southern Hemisphere climate.

Steven B. Feldstein

For more than 100 years, researchers have understood that ozone in the stratosphere, the atmospheric layer between 10 and 50 km above Earth's surface, plays an important role in absorbing ultraviolet radiation and protecting life on Earth (*1*). In 1985, scientists and the public became alarmed when Farman *et al.* (*2*) reported that, during the Antarctic spring, stratospheric ozone concentrations over the continent were declining by as much as 50%, indicating the presence of a polar "ozone hole." Implementation of the 1987 Montreal protocol, an international agreement that phased out the use of some chlorofluorocarbons and other compounds that destroy stratospheric ozone, has led to the first stage of recovery (*3*). Researchers, however, had not widely recognized the ozone hole's impact on the climate of the troposphere (the lowest 10 km of the atmosphere) until recent observational (*4*) and state-of-the-art climate modeling studies (*5*–*8*). These studies showed that ozone depletion has a large influence during the Antarctic summer, when it drives a major air current called the mid-latitude westerly jet to a higher latitude, closer to Antarctica; this reduces sea level pressure over the continent, cooling much of the continental interior, coinciding with a warming of the Antarctic Peninsula. On page 951 of this issue, Kang *et al.* (*9*) expand our understanding of ozone depletion's impact on climate. Using a series of carefully designed climate model experiments, they show that ozone-induced climate change is not confined just to the vicinity of Antarctica but extends over much of the Southern Hemisphere, even reaching the tropics, where it appears to have resulted in increased summer precipitation in the subtropics.

To isolate the impact of reduced stratospheric ozone on tropospheric climate, recent studies have compared results from two types of climate model simulations: One specifies pre–ozone-hole concentrations of ozone; the other uses the more recent, ozone-depleted concentrations. Some studies also specify various concentrations of primary greenhouse gases in order to compare their influence on climate with that of depleted ozone. Together, such studies have provided climate modelers with strong support for the claim that stratospheric ozone depletion has been the dominant driver of climate change in the mid- and high-latitude Southern Hemisphere during the summer season. In particular, the pre-ozone-hole and depleted simulations produce differences in wind, temperature, and precipitation patterns that closely resemble changes observed in the atmosphere.

In their models, Kang *et al.* not only accounted for pre-ozone-hole and depleted ozone concentrations but also investigated the sensitivity of the model response to physical "parameterizations" (a key component of climate models that differs between models), and to the coupling of the atmosphere with the oceans and sea ice. All climate models use parameterization to represent important physical processes, such as those associated



Catching a wave. In the Southern Hemisphere, cooling related to stratospheric ozone depletion over Antarctica alters atmospheric wave momentum fluxes, which causes circulation cells (solid and dotted circles) to shift poleward, altering precipitation patterns in the subtropics. Pre–ozone-hole circulation cells are illustrated with dotted lines and blue labels; depleted ozone cells are illustrated with solid lines and red labels.

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with clouds, heat transport between the atmosphere and the Earth's surface, radiation and turbulence, that have a spatial scale smaller than the resolution of the model grid. There are important differences between the parameterizations used by various climate modeling groups. To evaluate these differences, the authors used two different climate models: the Canadian Middle Atmosphere Model (CMAM) and the National Center for Atmospheric Research/Community Atmospheric Model (CAM3). To investigate the possible impact of the ocean and sea ice, the researchers performed separate model runs in which the sea surface temperature and sea ice concentrations were either specified or allowed to vary with time through coupling with the atmosphere. All model experiments produced similar results, including increased summer precipitation in the subtropics that is very similar to the observed precipitation trend. The results indicate a lack of sensitivity to different climate models, and a limited role for the coupling of the atmosphere with the oceans and sea ice.

Kang *et al.* also addressed the question of what physical mechanism links ozone depletion with changes in tropical precipitation. Their model calculations show that the ozone decline is associated with a poleward expansion of the Hadley cell (a tropical circulation pattern characterized by air masses that rise near the equator, flow poleward in the upper troposphere, then descend in the subtropics and flow back toward the equator in the lower troposphere). What process drives the Hadley cell expansion? Previous studies have shown that an important driver of the Hadley cell is the momentum flux associated with synoptic-scale waves (the atmospheric waves that correspond to day-to-day weather) (*10*, *11*); indeed, Kang *et al.* find that the Hadley cell changes are linked to changes in wave momentum flux. This relationship between ozone depletion and wave momentum flux is tied to a fundamental question: What is the physical mechanism that connects wind and temperature change in the lower stratosphere to changes in these and other variables in the troposphere? This is an open question, and a number of researchers are actively pursuing an answer. One common factor underlying most proposed mechanisms involves changes to synoptic- and planetary-scale waves, particularly their instability (linear and nonlinear), propagation, breaking, and feedback features (*12*–*16*), all of which influence the wave momentum flux. Additional diagnostics studies with observational and model data could go a long way toward enhancing our understanding of both stratosphere/troposphere interaction in general and the linkage between the Antarctic ozone hole and tropical precipitation in particular.

References

1. S. Solomon, *Rev. Geophys.* **37**, 275 (1999).
2. J. C. Farman, B. G. Gardiner, J. D. Shanklin, *Nature* **315**, 207 (1985).
3. S.-W. Son *et al.*, *Science* **320**, 1486 (2008).
4. D. W. J. Thompson, S. Solomon, *Science* **296**, 895 (2002).
5. J. M. Arblaster, G. A. Meehl, *J. Clim.* **19**, 2896 (2006).
6. N. P. Gillett, D. W. J. Thompson, *Science* **302**, 273 (2003).
7. L. M. Polvani, D. W. Waugh, G. J. P. Correa, S.-W. Son, *J. Clim.* **24**, 795 (2011).
8. S.-W. Son, N. F. Tandon, L. M. Polvani, D. W. Waugh, *Geophys. Res. Lett.* **36**, L15705 (2009).
9. S. M. Kang *et al.*, *Science* **332**, 951 (2011).
10. H.-K. Kim, S. Lee, *J. Atmos. Sci.* **58**, 2859 (2001).
11. R. L. Pfeffer, *J. Atmos. Sci.* **38**, 1340 (1981).
12. G. Chen, I. M. Held, *Geophys. Res. Lett.* **34**, L21805 (2007).
13. P. J. Kushner, L. M. Polvani, *J. Clim.* **17**, 629 (2004).
14. Y. Song, W. A. Robinson, *J. Atmos. Sci.* **61**, 1711 (2004).
15. I. R. Simpson, M. Blackburn, J. D. Haigh, *J. Atmos. Sci.* **66**, 1347 (2009).
16. M. A. H. Wittman, A. J. Charlton, L. M. Polvani, *J. Atmos. Sci.* **64**, 479 (2007).

10.1126/science.1206834

PALEONTOLOGY

Evolving Large and Complex Brains

X-ray studies of two Early Jurassic fossils offer insight into the evolution of mammalian brains.

R. Glenn Northcutt

During the Mesozoic (~250 million to 65 million years ago), two distantly related groups of reptiles—the cynodont (or mammal-like) reptiles and the coelurosaurian theropod dinosaurs—gave rise to mammals and birds, respectively. Both mammals and birds evolved brains some 10 times as large, relative to a given body weight, as those of their ancestors (*1*). In both groups, these brains contributed to the evolution of the ability to control body temperature (endothermy) and complex social interactions, including parental care and a reliance on learning that even involves tool use (*2*, *3*). The size of most parts of the brain increased in birds and mammals, but the cerebral hemispheres and cerebellum, both of which are involved in sensory and motor integration, underwent particularly spectacular development (see the figure). Although mammals and birds evolved from distantly related groups of reptiles, the higher integrative centers and circuitry of their cerebral hemispheres are very similar, and comparative neurobiologists continue to vigorously debate whether these centers evolved from the same ancestral neural centers (*4*, *5*) or from different ones (*6*–*8*). Speculation about the evolutionary steps leading to large and complex mammalian and avian brains is equally contentious and unresolved, in part because of the rarity of fossil skulls and, until recently, the need to destroy such skulls in order to expose the endocasts (casts molded by the cranial cavity). Typically, endocasts are the only record of the brain's outward appearance in a transitional form, because brains themselves are rarely fossilized.

On page 955 of this issue, Rowe *et al.* (*9*) offer new insights into the early evolution of mammalian brains. Using high-resolution x-ray computed tomography, they reconstructed the endocasts of *Morganucodon* and *Hadrocodium*, two basal mammaliaforms from the Early Jurassic (~199 million to 175 million years ago). These data allow the authors to postulate that the evolution of these large and complex brains occurred in three major steps.

Triassic cynodont reptiles appear to have had relatively poor olfaction and vision, insensitive hearing, and a lack of fine motor coordination (*9*, *10*). Their brains were characterized by small olfactory bulbs, narrow and tubular cerebral hemispheres (exceeded in width by the cerebellum), and a dorsally exposed midbrain. The *Morganucodon* endocast reconstructed by Rowe *et al.* indicates that the brain was almost 50% larger than that of the earlier Triassic cynodonts, with the olfactory bulbs and cerebral hemispheres showing the greatest expansion, and the cerebral hemispheres now wider than the cerebellum and covering the midbrain. It is also likely that *Morganucodon* had body hair. The

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