A deep and stormy lake. Lake Tanganyika, just south of the equator in tropical Africa, is one of the world's oldest and deepest lakes. Home to many animal species that live nowhere else, such as the snail *Tiphobia horei* (**inset**), Lake Tanganyika has been profoundly affected by global climate change.

insufficient light to support photosynthesis. Photosynthetic production of new organic material is controlled by water mixing, which returns some of the nutrients from deep water to the surface.

In Lake Tanganyika most mixing is seasonal, dependent on the southeast monsoon, which drives the light surface-water north and brings deep water close to the surface at the south end of the lake. The density gradient of the stratified water column resists this mixing, and productivity of the lake is strictly controlled by the balance between mixing and stability.

Verburg and his colleagues have searched the sparse historical records for information about lake temperature, transparency, and fauna. Climate warming in the last century has raised the temperature of the lake more at the surface than in the depths. The sharper temperature gradient inhibits mixing, so productivity has fallen. The mass of planktonic organisms is now less than one-third of the mass when measurements were first made 25 years ago. Currently, the transparency is so great that a white disk can be seen in the water to a depth of 13 m instead of 6 m.

More intense stratification has led to drastic changes in water chemistry. Dissolved oxygen does not penetrate to the depth it once did, and one of the endemic snails, *Tiphobia horei*, which in 1890 was collected to a depth of 300 m, is now restricted to the upper 100 m of the water column (see the figure). Hydrogen sulfide could not be detected above 300 m in 1938; now it extends to a depth of 120 m. Soluble reactive phosphorus in the mixed layer has fallen from 0.29 µM to below the detection limit of 0.01 µM since the mid-20th century. The amount of dissolved silica in deep water has not changed, but in the upper 50 m it has trebled since 1975. Diatoms, which use silica to make their skeletons, have decreased so much that upwelling of silica, in spite of a sharpened density gradient, more than suffices for their needs.

Although Verburg *et al.* have contributed substantially to our knowledge of the modern lake, their conclusion depends on observations by many early biologists. For a hundred years, with no management goal and no scientific hypothesis to test, these pioneers used the best methods of their time to describe Lake Tanganyika. Their data, collected intermittently when war and scientific funding allowed, are sparse, but are sufficient to demonstrate to a very high degree of statistical reliability that there has been a drastic change in mixing of the lake's waters.

New techniques and conceptual advances (*5*) have rendered obsolete much of what freshwater biology students were taught 20 years ago about the annual mixing of lake waters. The National Science Foundation has no program for the physical study of inland lakes and waters, despite long-standing rumors of imminent change. A modest injection of funds might help us to understand the mixing of lake waters as well as we comprehend the mixing of ocean waters.

Verburg *et al.* show that a deep tropical lake with a very rich fauna, which seemed resistant to global climate change, has already been profoundly affected by it. The best efforts of lake-shore nations and conservationists can do little to slow the continuing alteration of Lake Tanganyika. That will take determined international action, of which enforcement of the Kyoto protocols might be a reasonable first step.

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ATMOSPHERIC SCIENCE

Climate Change at Cruising Altitude?

Brian J. Hoskins

Climate model studies are widely used to estimate whether observed changes in the climate system are likely to be related to changes in greenhouse gases or other climate forcing agents. On page 479 of this issue, Santer *et al*. (*1*) report important climate model results of this kind.

The authors consider, separately and in combination, the anthropogenic forcings (caused by greenhouse gases, aerosols, and ozone) and natural forcings (resulting from changes in solar output and volcanic aerosols) that may have influenced climate in the 20th century. However, instead of taking the surface temperature as the measure of climate—as is done in most such studies—they consider a phenomenon characteristic of Earth's atmosphere: the tropopause.

Because Earth's atmosphere is nearly transparent to solar radiation, its temperature is generally highest at the Earth surface. Atmospheric ozone, which absorbs solar ultraviolet radiation, creates another temperature maximum, near 0°C, at a height of about 50 km (see the figure). Weather systems and deep convection in the troposphere determine the rate at which the temperature falls with height (the lapse rate). Air masses in the troposphere can move substantially in height or latitude within days. In contrast, the temperature in the stratosphere generally does not change so much with height. Here, solar radiation is very important in the heat balance, motion is quasi-horizontal and less turbulent, and time scales are generally much longer.

The boundary between the troposphere and the stratosphere, the tropopause (see the figure), is generally sharp, whether viewed in terms of changes in lapse rate, potential vorticity [a fluid dynamic property measuring both stability and rotation (*2*)], or chemical characteristics (*3*). This sharpness is probably a result of mixing in

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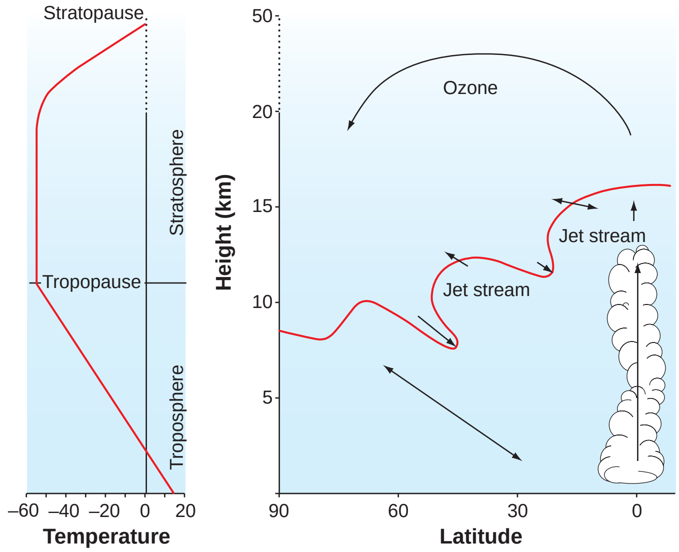
On a typical day. (Right) Schematic vertical section from equator to pole on a particular day, showing the tropopause with westerly jet streams, tropical convection, and transport and exchange. **(Left)** Typical vertical profile of atmospheric temperature.



the upper troposphere and of the different concentrations of radiatively important trace constituents on the two sides. The lower stratosphere contains much more ozone, but the troposphere is much moister.

The tropopause typically slopes from about 9 km near the poles to about 18 km near the equator. However, because it is distorted by weather systems, on any particular day and longitude the tropopause is likely to be far from smooth, with thin tongues of stratospheric air sometimes moving deep into the troposphere (*4*).

The tropopause is important on a daily basis because it puts a lid on tropospheric convection. It also plays a very active role in the development of large weather systems: One classic view of the growth of weather systems involves the interaction of waves propagating on temperature gradients at the tropopause and at Earth's surface (*5*).

Not only the amounts of trace chemicals but also the dominant chemical processes differ widely in the regions on either side of the tropopause. For these reasons, there has been much interest in the extent to which the tropopause is permeable, allowing stratosphere-troposphere exchange (*6*). Such exchange influences stratospheric ozone reduction, tropospheric pollution, and global warming.

The tropospheric air that eventually moves high into the stratosphere crosses the tropopause in the equatorial region. The extreme dryness of the stratosphere suggests that this must occur mainly over the Indonesian region, where the temperature is low enough to "freeze-dry" it. However, the winds are such that while the air crosses the tropopause it must also move a considerable horizontal distance. A picture of the three-dimensional motion in this region is starting to emerge (*7*). In the subtropics, there is two-way exchange, whereas at higher latitudes, streamers and cut-off pools of stratospheric air are produced by weather systems and later absorbed into the troposphere (*8*).

On the basis of the contrasting thermodynamic budgets of the weather-dominated troposphere and radiation-dominated stratosphere, the height of the tropopause can be estimated (*9*, *10*). More simply, assuming that the vertical temperature profile is like that shown in the figure and that the lapse rate in the troposphere does not change, tropopause height changes are related to changes in tropospheric and lower stratospheric temperatures. An increase in the former and a decrease in the latter—as expected, for example, with increases in carbon dioxide concentrations—both lead to a higher tropopause. In each case, a 1°C change leads to a rise in the tropopause by about 160 m. Stratospheric ozone reduction also leads to stratospheric cooling and, hence, a higher tropopause. In contrast, sulfate aerosols are calculated to cool the troposphere and therefore lower the tropopause. Other natural and anthropogenic forcings will also act to change its height.

The analysis of Santer *et al*. suggests that over the past 20 years, the observed globally averaged tropopause height has risen by ~200 m. Their model results show that this rise is consistent with the changes in natural and anthropogenic forcings over this period, and that greenhouse gas and ozone changes are mostly responsible for it. Continuing changes in the properties of the tropopause as a result of human activity could have wide-ranging implications because of its physical and chemical roles in the climate system.

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CHEMISTRY

Colloidal Molecules and Beyond

Alfons van Blaaderen

About a hundred years ago, Jean Perrin's experiments on colloids—particles a few nanometers to a few micrometers in diameter—convinced even the skeptics that matter consists of atoms and molecules. More recently, the analogy between atoms and colloids has led to insights into crystal nucleation and growth, the glass transition, and the influence of the range of particle-particle interactions on phase behavior. Moreover, the ability to manipulate colloid crystallization has led to advanced materials such as photonic crystals.

To date, most studies of colloids have used spherical particles or particles with simple shapes, such as rods and plates. Syntheses of nonspherical colloids generally yield a broad size distribution. On page 483 of this issue, Manoharan *et al.* (*1*) report a method for making large quantities of identical colloidal particles with complex shapes consisting of equal-sized colloidal spheres.

The authors made these particles by drying the oil out of an oil-in-water emulsion in which spherical colloids were adsorbed to the surface of the oil droplets. Subsequent centrifugation yielded an intriguing sequence of colloidal structures (including the tetrahedral tetramer in the top left panel of the figure). Each structure consists of 2 to 15 spheres. For a given particle size, the spheres are arranged identically in all particles (*1*).

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