CLIMATE CHANGE

# Cool ozone

The influence of global warming on temperature trends at higher altitudes has been hotly debated. Stratospheric ozone depletion is another piece in the remaining tropical climate puzzle.

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Climate change at the Earth's surface understandably receives the most attention from those interested in global warming. But temperature trends higher up in the atmosphere are also important, helping with the attribution of climate change and providing tests for global climate models. Debates over apparent discrepancies between observations and models in trends in the troposphere (the lower layer of the atmosphere from the surface to ~12–16 km altitude) have raged for many years, and have been used to raise doubts about the validity of climate models. Forster *et al.*[1] show that ozone depletion in the tropical lower stratosphere has contributed to recent tropospheric temperature changes in a location where discrepancies between some data and the models have stubbornly remained.

The large-scale vertical structure of temperature change in the atmosphere is an important characteristic of the forces driving climate change. Increases in greenhouse gases cause warming in the troposphere but cool the stratosphere. Greater output from the sun similarly warms the troposphere, but causes even greater warming in the stratosphere. Observations show that the troposphere has warmed in recent decades whereas the stratosphere has cooled markedly; this is clear evidence for anthropogenic warming rather than natural warming from the sun.

However, the precise structure of temperature trends with altitude is complex. Climate contrarians argued for years that models should not be trusted as they did not produce as much warming as satellite observations indicated in the troposphere. It was eventually shown that the satellite measurements were biased, and the apparent discrepancy largely vanished over most of the globe, with some problems remaining in the tropics[2,3].

Therefore, our understanding of how temperature trends vary with altitude at low latitudes is still incomplete. Warming of much of the troposphere is closely coupled to surface warming in the models, with simulated temperatures up to altitudes of ~10 km directly following the theoretical temperature change of air as a consequence of decreasing pressure and condensation of water vapour as the air moves upward — the so-called moist adiabatic lapse rate. In the tropics, however, trends derived from observations suggest less warming aloft than the models produce in both the lower and upper troposphere[3]. This discrepancy is difficult to interpret, owing to the large uncertainties in both model and observational trends results.

On the observational side, both radiosondes (balloon-borne instruments) and satellites show warming in the troposphere and cooling in the stratosphere. Whereas discrepancies between the various observational datasets are tiny near the Earth's surface, they grow steadily moving upwards to the upper troposphere and lower stratosphere[3].

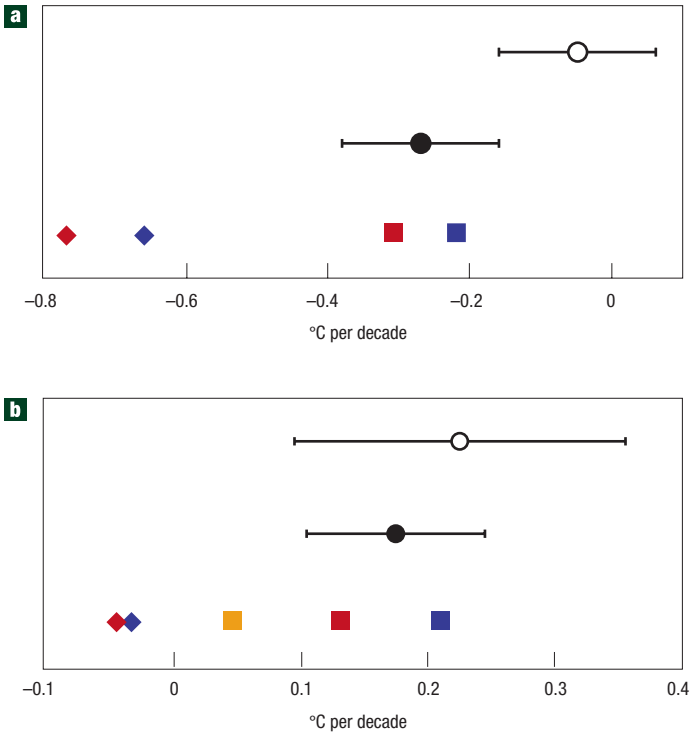


**Figure 1** Tropical temperature trends. **a**,**b** Changes in temperatures in °C per decade between 20° S and 20° N during 1979–1999 for the lower stratosphere (**a**) and the mid-troposphere to lower stratosphere (**b**). Trends[8] derived from the models used in the IPCC's fourth assessment report without ozone depletion are shown as open circles, ($n$=5), and those with ozone depletion as solid circles, ($n$=12). For the observations[3], diamonds are values from radiosonde observations, and satellite observations are shown as squares. The different colours are analyses of these data by different groups. Trends are calculated for the satellite lower stratospheric and mid-troposphere to lower stratospheric channels. Model error bar indicates the standard deviation among the AR4 models; uncertainties in individual models and datasets are not included.



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The most likely explanation for the more negative temperature trends observed in radiosonde data (see Fig. 1) is that they contain cooling biases that have not yet been fully accounted for[3] (though work continues on this topic[6]).

Forster *et al.*[1] suggest that deficiencies in the climate models' representation of ozone trends may explain the "long-standing discrepancy between modeled and measured temperature trends in the uppermost tropical troposphere". Such a discrepancy exists in comparison with radiosonde data, but many models are in fact quite consistent with the substantially more positive trends derived from satellite measurements[4,5].

Forster and colleagues make a convincing case that lower stratospheric ozone changes can have an important influence not only on local temperatures, but on the warming in the upper tropical troposphere as well. Hence models that do not take into account ozone trends will yield positively biased temperature trends not only in the stratosphere at the location of the ozone depletion, but also at the level below — the upper troposphere.

Despite the general impression that climate simulations used for assessments such as the IPCC Fourth Assessment Report (AR4) are rigorous model intercomparisons, in fact the climate models were driven by different forcings (external agents that affect the Earth's climate). Many climate models use ozone datasets that incorporate the observed depletion in lower stratospheric ozone in the tropics[7] and are fairly similar to those of Forster *et al.* However, some climate models in the AR4 ensemble did not include ozone trends at all. Looking at the lower stratosphere, models including stratospheric ozone depletion found cooling trends that are ~0.08 °C per decade greater than the average of all models[3]. Including ozone trends improves the agreement between models and observations both in the lower stratosphere and upper troposphere (see Fig. 1).

Thus part of the reason that models yield such a large range of temperature trends at these levels may be the lack of uniformity in their forcings, and part of the explanation for the model average continuing to show more positive temperature trends in the tropical upper troposphere than observations could indeed involve the ozone forcing.

The results presented by Forster *et al.* imply that projections of the expected future recovery of stratospheric ozone are important, not only for their effect on ultraviolet radiation reaching the Earth's surface, but also for their effect on the climate of the lower atmosphere.

Similar arguments could undoubtedly be made for tropospheric ozone and black carbon, which absorb solar radiation causing local heating and therefore affecting trends in the upper troposphere. Climate models need to include realistic treatments of all known climate forcing agents, not only greenhouse gases.

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PALAEOCLIMATE

# The riddle of the clays

Rising carbon levels contributed to profound climate change 55 million years ago. Where did that extra carbon come from? One proposal — a cometary impact — is rebuffed by two analyses of magnetic particles in clay sediment cores from New Jersey.

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If one wishes to draw lessons on the effects of rapid extreme changes in the carbon cycle and global climate, the Palaeocene–Eocene thermal maximum (PETM) of 55 million years ago is a good place to start[1,2]. But almost immediately we run into difficulties. We are not even sure what the root cause of this climatic turmoil was — a comet impact? Or did its origins lie closer to home? Two studies of magnetic particles in sediment cores from New Jersey published in *Paleoceanography*[3,4] address this debate. In doing so, they also expand the range of environmental consequences that stemmed from this extraordinary event.

Within a few thousand years of the start of the PETM, a huge injection of carbon dioxide depleted in $^{13}C$ into the atmosphere and oceans caused the $^{13}C/^{12}C$ ratio in carbonate and organic compounds across the Earth to drop significantly and large amounts of calcium carbonate on the deep seafloor to dissolve[5]. At more or less the same time, temperatures spanning all latitudes, both at the Earth's surface and in the deep sea, rose by 5–8 °C. The hydrological cycle changed. On the land, mammals and plants undertook great migrations; in the sea, unusual plankton appeared in surface waters and much deep-sea fauna became extinct[2]. Over the following 80,000–200,000 years, the global carbon cycle and various Earth systems slowly recovered to something approaching their former state. But certain groups of organisms, such as the mammals and the foraminifera of the deep ocean, were affected forever[2].

Where did all this excess carbon come from? One answer was suggested in 2003. Kent *et al.*[6] discovered, preserved in three sediment drill cores from New Jersey, an exceptional abundance of single-domain magnetite ($Fe_3O_4$) grains, nominally between 30 and 100 nm in size, that were deposited on a continental shelf almost precisely during the PETM. Such magnetic nanoparticles are common in shallow marine sediment. Most derive from 'magnetotactic' bacteria, which precipitate uniform bullet-sized magnetite grains, typically in chains, within intracellular vesicles known as



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