supply issues). Even with actual leakage factors taken into consideration, the machine operates with less than one-thousandth of the energy per operation of a conventional circuit implementing the same computational model.

Although all these techniques are becoming more tractable, there is still no sign of any way to break the Turing barrier. Which computational route holds the most promise for the future? In spite of profound differences — in philosophy, methodology, resources — all face a number of similar problems. How should we efficiently encode the data? What architecture should we choose? How is the architecture initially programmed? Can the architecture reconfigure itself? How should we modify the presently known algorithms to fit the new architecture? How should we efficiently read the output?

So it is a matter of some debate whether any of these models will ever leave the lab. But they have helped draw together the disciplines of computing, mathematics, physics, engineering and biology, and already produced new insight. For instance, new ideas have arisen about the evolution of genes and DNA sequences (that life may be seen as a series of complex computations) and in the field of quantum communication; and solutions have been obtained to old problems (for example, the negative solution to Maxwell's demon problem (S. Lloyd, MIT): a perfectly efficient engine is impossible not only for mortals, but even in principle). The real issue might not be the final destination, but the journey, and the understanding of natural phenomena that will necessarily occur along the way. ☐

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Ozone depletion

A greenhouse warming connection

Ross J. Salawitch

On page 589 of this issue[1], Shindell and colleagues tackle the question of how rising levels of greenhouse gases will affect ozone (O_3) depletion over the Arctic in the years to come. Their conclusion is tentative but worrisome — that despite reductions in emissions of O_3-depleting chlorofluorocarbons (CFCs), levels of O_3 will continue to fall, with especially severe declines occurring in the years 2010 to 2019.

The direct radiative effects of the build-up of carbon dioxide (CO_2) and other greenhouse gases have led to a gradual cooling of the stratosphere, with the largest changes in temperature occurring in the upper stratosphere, well above the region of peak O_3 concentrations[2]. Build-up of greenhouse gases has been associated with global warming, which occurs as more of the heat radiated from Earth's surface is trapped in the troposphere; as a consequence, less heat reaches the overlying stratosphere, which cools. Cooling of the upper stratosphere during the past several decades would lead to slightly higher concentrations of O_3 due to the temperature dependence of the rates of several key reactions. But this effect has been masked by depletion of upper stratospheric O_3 driven by the release of industrial CFCs (ref. 3). It has also been suggested that the abundance of O_3 in the lower stratosphere may be reduced on longer timescales due to changes in circulation induced by the so-called 'doubled CO_2' environment[4]. Because the greatest concentrations of O_3 exist in the lower stratosphere, this region has the strongest influence on the total column abundance of O_3 (the integrated amount of O_3 between the surface and the top of the atmosphere), which in turn affects exposure to ultraviolet radiation.

Shindell *et al.* now describe a previously unappreciated connection between greenhouse gases and O_3 for the contemporary lower stratosphere. They use a general circulation model (GCM) to show that increasing concentrations of greenhouse gases may currently be leading to colder, more stable vortex circulations in winter, accelerating the chemical removal of O_3 at high latitudes. The authors' calculations suggest that, because of the build-up of greenhouse gases, the total column abundance of O_3 in the Arctic vortex will continue to decrease for about 15 years after levels of stratospheric chlorine begin to decline.

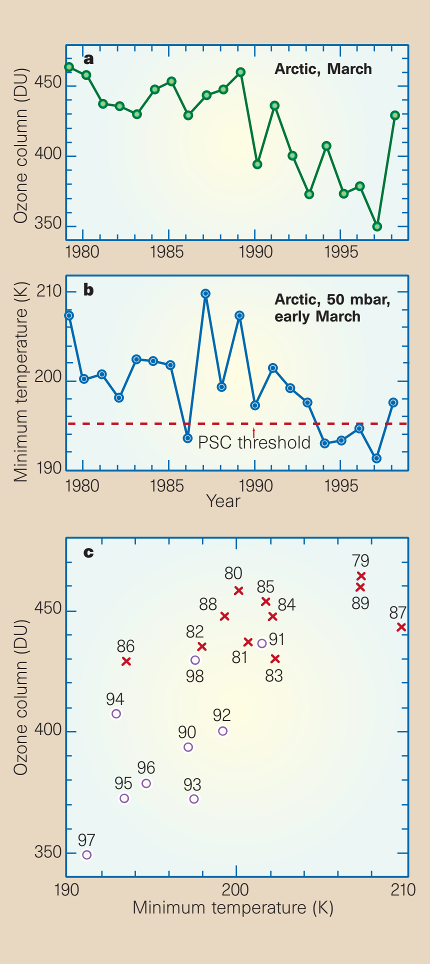

Figure 1 **Ozone levels and minimum temperature over the Arctic (63 to 90° N), 1979–98.** a, **Time series of the average total ozone column during March (from ref. 6). Column O_3 data for 1998 are from Earth Probe TOMS. (One Dobson unit (DU) is the thickness, measured in units of hundredths of a millimetre, that the ozone column would occupy at standard temperature and pressure.)** b, **Minimum temperature on the 50-mbar pressure level in the Arctic vortex during the first two weeks of March, based on data from the National Center for Environmental Prediction; the temperature threshold for formation of polar stratospheric clouds is also shown.** c, **Scatter diagram of these observations, with the data labelled according to the year of observation. Shindell *et al.*[1] show that rising concentrations of greenhouse gases may be the cause of the colder conditions in recent years, accelerating the chemical loss of O_3 by ClO derived from industrial CFCs. Observations for 1998 are preliminary and will be the subject of a future publication by P. A. Newman and R. D. McPeters. I thank them for making these observations available for inclusion in this figure.**

Rapid loss of O_3 throughout the winter polar vortices occurs under conditions of high concentrations of chlorine monoxide (ClO), low temperatures and relatively long periods of daylight. The unreactive reservoirs, HCl and $ClNO_3$, are converted to ClO by reactions on the surfaces of polar stratospheric clouds that form when temperature drops below a critical threshold. Sunlight is required for catalytic removal of O_3, but sunlight also leads to the suppression of increased concentrations of ClO. Maintenance of high concentrations of ClO until the equinox, when day and night are of equal duration and rates of O_3 loss tend to maximize in the Antarctic, requires either temperatures persistently low enough to suppress concentrations of gas-phase HNO_3, which photolyses and eventually converts ClO to $ClNO_3$, or temperatures intermittently low enough to allow repeated exposure of air to heterogeneous processing on polar stratospheric clouds. More stable vortex circulations (that is, greater isolation) typically lead to colder temperatures and a stronger association between local chemical loss and the column abundance of O_3.

Ozone concentrations in the Arctic polar vortex reached unusually low values during the early springs of 1996 and 1997 (refs 5–7). Compared to the Antarctic vortex, which experiences elevated concentrations of ClO until the equinox and massive loss of O_3 on an annual basis, concentrations of ClO in the Arctic vortex are usually too low by early March for sustained rapid loss of O_3 (ref. 8). The rapid loss of Arctic ozone during late winter and early spring of 1995–96 and 1996–97 has been associated with observations of higher levels of ClO (ref. 9), suppressed levels of HCl (ref. 5), unusually low temperatures during early March[5–7,10], and more stable vortex circulations[10]. Conditions during these two years have built upon the general (but not monotonic) trend in the Arctic towards lower abundances of total column O_3 in March and lower temperatures in late February and early March during recent years, as illustrated in Fig. 1, even though the burden of stratospheric chlorine has stopped rising because of international legislation that has phased out the use of CFCs (ref. 11).

Shindell *et al.*[1] provide a provocative explanation for the unusually cold, stable Arctic vortices during early March in recent years — a decrease in the poleward propagation of planetary waves, driven by increased concentrations of greenhouse gases. The decrease in planetary-wave activity in their model results from a decline in the latitudinal temperature gradient near the tropopause. A feedback involving decreased absorption of solar radiation due to less O_3 exacerbates the situation, leading to a nonlinear response of temperature to climate forcing. An analysis of temperature fields from the National Center for Environmental Prediction has shown that the low Arctic temperatures during March 1997 were probably due to a significant reduction in planetary-wave activity[10]. This hypothesis may also offer an explanation for the rapid acceleration in the severity of the Antarctic O_3 hole during the 1980s.

Shindell and colleagues' hypothesis must be viewed as somewhat speculative, given the difficulty GCMs have in properly simulating both temperatures in the polar region and the nonlinear wave–wave interactions that lead to poleward transport of heat and momentum[4,12]. Reliable predictions of stratospheric wave transport are critically dependent on the proper simulation of the circulation of the upper troposphere[4,12,13]. The detailed dynamical conditions that lead to low temperatures within the Arctic vortex vary from year to year[7,10,13,14] and are inherently difficult to simulate using a GCM. Indeed, the primary conclusion of Shindell *et al.* is model dependent: some but not all other GCMs find similar decreases in planetary-wave activity as the concentrations of greenhouse gases rise[1]. Nonetheless, during the past decade there has been an apparent trend towards colder conditions later in the season[6,7,10,14], lower abundances of total column O_3 (ref. 6), and more extensive chemical removal of lower stratospheric O_3 (refs 5, 6, 9) that resembles the predictions of Shindell and colleagues.

The hallmark of the Arctic vortex is large year-to-year variability in temperature, the concentration of ClO in February and March, and the degree of chemical loss of O_3. The Arctic winter of 1997–98 has been fairly warm, with considerably less chemical loss of O_3 than occurred in the previous five winters (G. L. Manney, P. A. Newman & M. L. Santee, personal communication). This behaviour is not necessarily inconsistent with the model of Shindell *et al.*[1], which predicts less frequent early warmings of the Arctic vortex but not the complete cessation of such events. However, the winter of 1997–98 certainly complicates ascribing a climatic influence to the changes in temperature and O_3 that have occurred during the previous five winters. Predicting the future course of both Antarctic and Arctic O_3 is contingent upon gaining a better understanding of the factors that regulate the temperature of the polar vortices, and it is imperative that the hypothesis of Shindell *et al.* be tested by further analyses of atmospheric observations as well as by additional theoretical studies. ☐

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Evolutionary ecology

Different routes to similar ends

Paul H. Harvey and Linda Partridge

In science, it can be all too easy to provide the public with different take-home messages from the same body of theory and data. Nowhere is that more apparent than from evolution, where different authors have championed different perspectives.

Richard Dawkins, for example, frequently emphasizes evolution by natural selection as a unifying theory for biology: his is a largely deterministic world following from the differential survival and reproductive success of genes within which there is no recombination[1]. By contrast, Stephen Gould concentrates on the evidence for biodiversity resulting from contingency — historical accidents determine disparate courses of evolution[2]. In his metaphor, if the tape of life was repeated, we should always expect a different outcome.

These perspectives leave open the middle ground: if the tape of life was repeated, just how varied would the outcome be? In a paper published in *Science* last month[3], Jonathan Losos and colleagues describe their studies of *Anolis* lizard species evolving on the Caribbean islands of the Greater Antilles to provide an illuminating test case.

Four islands constitute the Greater Antilles: Cuba, Hispaniola, Jamaica and Puerto Rico. Each of these islands has its own *Anolis* community. Working over four decades, Ernest Williams and his students demonstrated that each species on each island has a distinctive niche[4,5] to which it seems to be nicely adapted[6,7]. There are small, short-legged species that live out on fragile twigs, and large-bodied species that inhabit the crowns of trees; and there are others again on the trunk, on the ground and in bushes, and on transitional habitats. Williams called these habitat specialists 'ecomorphs'[8]. Losos has identified six ecomorphs (examples are shown in Fig. 1), most of which are present on each island; two are missing from Jamaica and one from Puerto Rico. Some islands have more than one version of a particular ecomorph.

But are the ecomorphs figments of Williams's and Losos's imaginations, or do the same ecomorphs from different islands cluster together in 'morphospace'? In the new study, a variety of morphological characters was measured on several specimens from each ecomorph on the different islands, corrected for body size, and mapped in four-dimensional morphospace, which accounted for more than 95% of variance in the data. The data were then subjected to a hierarchical classification by similarity, and each of 46 species was found to group by ecomorph,