shown[12] that plant species diversity controls the magnitude of the increase in carbon fixation as levels of atmospheric CO_2 increase.

How general is species complementarity? I suggest that the strength of this mechanism is related positively to the length of evolutionary history, and negatively to the frequency and intensity of disturbances to an ecosystem. Complementary resource use and synergistic relationships are more likely to occur among species that have had a chance to coevolve over long periods of time[13]. Frequent disturbance will prevent the evolution of tight differentiation in resource use, and will perturb or destroy symbiotic relationships. BIODEPTH was carried out using grassland species, mostly at sites where the potential natural vegetation was forest. These sites were maintained as grasslands because of frequent human intervention; if they had not been mowed once or twice a year, they would have reverted to forest. Species complementarity may act even more strongly in ecosystems that have been disturbed less often and have a longer evolutionary history.

We clearly need a better understanding of the relationships between biodiversity and ecosystem functioning. There are two ways forward. The first is to apply this new tool, the Loreau–Hector equation, to other existing data sets, to see how general the species-complementarity principle is. The second is to gather — and then likewise analyse — fresh data for other ecosystems by carrying out experiments such as BIODEPTH in other areas of the world with different evolutionary and disturbance histories. ■

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Planetary science

Climate change on Venus

Ronald G. Prinn

Earth's climate has changed significantly over the past several million years. New theoretical work suggests that the climate of our nearest neighbour, Venus, may have also changed on similar timescales.

Venus is a most inhospitable planet. Its average surface temperature of 735 K is some 435 K higher than that of Earth. It has a thick atmosphere of carbon dioxide that exerts a surface pressure about 92 times greater than Earth's. Its craters and volcanoes are completely shrouded by thick clouds of sulphuric acid, and its surface features are revealed only in radar images. Not surprisingly, it has no oceans and no known life. But has this extreme climate always been the same, or does it change from millennium to millennium? In an article in *Icarus*, Mark Bullock and David Grinspoon[1] describe a numerical simulation of venusian climate that suggests it has oscillated over the past billion years between periods of global cooling and global warming.

Bullock and Grinspoon[1] have developed a new radiative–convective model of the venusian climate. It is based on recent data from spacecraft (particularly the 1990–1994 Magellan mission) and from ground-based telescopes, which together provide information on the geology, geophysics and atmospheric chemistry of Venus. Their model is the first to use high-temperature, high-resolution spectroscopic data on the absorption properties of the major greenhouse gases found on Venus (mainly CO_2 with t race amounts of H_2O and SO_2). The authors also include data on the rates of reaction of these gases with surface minerals at high temperatures — reactions that limit their abundance in the atmosphere. They couple their climate model to models of cloud microphysics, volcanic outgassing of sulphur dioxide and water from the crust, surface chemistry, and water loss due to hydrogen atoms escaping from the high atmosphere into space.

The Bullock–Grinspoon[1] model indicates that between 600 million and 1,100 million years ago, Venus was cooler than it is today. It was cooler because sunlight was reflected by thick clouds of sulphuric acid (H_2SO_4) produced during a geologically active period when erupting lavas from global volcanic activity resulted in the build-up of SO_2 and H_2O in the atmosphere. This was followed by a period of warming as the SO_2 responsible for creating the clouds was depleted by reactions with minerals at the surface, raising temperatures to 900 K. But the contribution of water vapour to greenhouse warming was subsequently lowered by the steady loss of hydrogen into space and the loss of oxygen through oxidation of surface minerals. This helped to cool Venus down to today's temperatures.

I first became interested in climate change on Venus in the early 1980s, spurred on by the intriguing results from the Pioneer mission to Venus in 1978. My own studies were aimed at understanding the processes that maintain sulphuric acid clouds on Venus, and the possibility that the clouds, and hence climate, could change as a result of changes in the emission of sulphur gases through volcanism and thermally driven surface chemistry[2–4] (Fig. 1). Work in the laboratory indicated that SO_2, the precursor of sulphuric acid, could be removed from the atmosphere by reactions with surface minerals in 1.9 million years[5] — a relatively short timescale for geological processes. And because the removal rate of SO_2 (and hence of H_2SO_4) increases with temperature, there is also the possibility of amplifying any warming or cooling trend.

The starting point for Bullock and Grinspoon's study was the Magellan mission to Venus in the 1990s. Magellan used radar to penetrate the clouds to produce, among other things, the first extremely high-resolution spatial map of the surface of Venus. This map indicated that the density of impact craters, and hence the number of comet and asteroid collisions recorded on the surface of Venus, was fairly low, suggesting that the present surface is only 600 million to 1,100 million years old[6]. The previous surface must have been obliterated by erupting magmas from volcanic activity on a global scale.

Bullock and Grinspoon's work indicates that H_2O and SO_2 have both cooperative and competitive effects on the venusian climate. The climate on Venus today is controlled by two main processes: global warming, largely resulting from the greenhouse effect of CO_2, and cooling, owing to the reflection of solar radiation by the thick clouds of sulphuric acid. Large increases in H_2O above today's levels could amplify the greenhouse warming effect and lead to thinning of the clouds through evaporation of their lowest layers. Overall, this could increase surface temperatures by 200 K. But large increases in SO_2 could cool the planet by up to 40 K by thickening these same clouds and increasing their reflectivity.

The authors propose that global volcanic activity 600 million to 1,100 million years ago injected large quantities of H_2O and SO_2 into the atmosphere. This thickened the clouds of sulphuric acid, and the resulting cooling was greater than any warming these gases contributed through

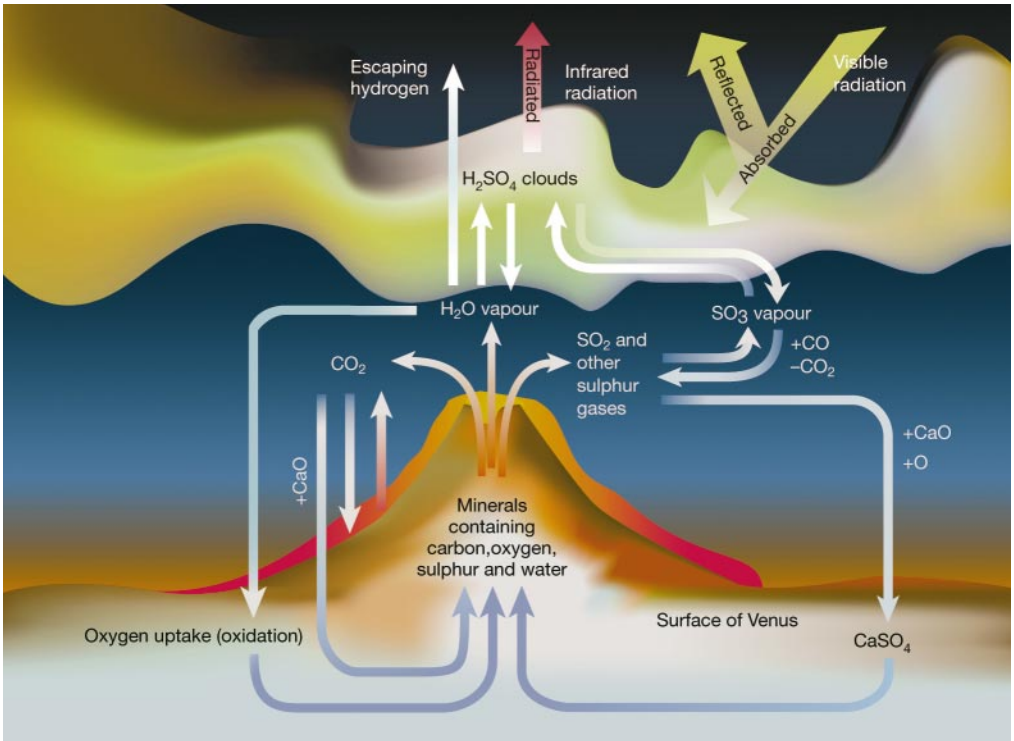

Figure 1 **Key chemical and physical processes controlling the climate of Venus over long timescales[1–5]. Venus has an atmosphere of 96.5% CO_2, which is primarily responsible for its greenhouse effect and high surface temperature. Venus also has a thick layer of sulphuric acid (H_2SO_4) clouds that reflect sunlight away from its surface, helping to cool it. The greenhouse warming is greater than the cooling effect of the clouds, making the surface of Venus much warmer than on Earth. A new numerical model developed by Bullock and Grinspoon[1] suggests that over the past 1 billion years the climate on Venus has experienced periods of both cooling and warming, largely triggered by global volcanic activity spewing out large amounts of sulphur dioxide (SO_2) and water vapour (H_2O).**

the greenhouse effect. But after this period, the Bullock–Grinspoon model indicates relatively rapid removal of excess SO_2 by reaction with carbonates and other surface rocks, so the clouds became thinner and the planet warmed by 100 K. But the warming was limited by the steady loss of H_2O as hydrogen escaped into space and oxygen was lost at the surface, allowing Venus to cool again to its current temperature.

How stable is the climate of Venus now? Maintaining current levels of SO_2, and hence clouds of sulphuric acid, requires volcanic activity. Large impacts from comets could also bring water and sulphur to Venus, but it seems that in the near future the venusian climate will be a slave to the volcanism needed to sustain current levels of H_2O and SO_2 against their loss at the surface and into space. This simple picture is complicated by the possibility that changes in surface temperature can feed back to the processes involved in volcanism, by affecting the heat flow, and hence temperatures, deep below the surface[7]. So the story will be complex.

Such models are always speculative, but Bullock and Grinspoon suggest some specific space missions and observations that could clarify the existing picture. Measurements of noble gases in the atmosphere could help quantify the flow of volatile gases from the interior into the atmosphere and space[8]. Close-up images of the surface — perhaps where the crust breaks in an impact — could reveal subsurface layers indicative of past climate change, like those seen on Mars[9]. And measurements of the flow in the atmosphere of visible and infrared radiation involved in the greenhouse effect, and the key gases involved in the chemical cycles[4], would help enormously. Stay tuned for better forecasts of the climate on Venus. ■

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Daedalus

Learning to forget

Last week Daedalus contemplated the sensitivity of the brain to microwaves. He recalled brain theory, insofar as it exists. Each brain cell has many inputs (dendrites) and one main output (its axon); these are connected to other brain cells. Very plausibly, each dendrite is potentiated or inhibited by a specific protein molecule, whose configuration turns it on or off. And the shuffling of amino acids and the re-ordering of protein chains occurs at microwave frequencies. So mobile phones and microwave towers do a lot of unintended damage.

But controlled memory loss could be very welcome in psychiatry. Many people are haunted by dire memories, which prevent them re-entering places or circumstances, or make them fearful of certain normal human activities. A simple microwave irradiation, neatly erasing the damaging memory, could be gladly accepted. So DREADCO biochemists are irradiating test organisms, hoping to find that pattern of frequency or combination of frequencies that can erase a specific memory — in rats, for example, how to run a given maze.

The extension of this scheme to human psychiatry will be fraught with hazard. Fortunately, the main complaints about mobile phones refer to the loss of short-term memory only. Psychiatrists could screen mobile-phone users for the sort of information lost, and employ subjects who do not mind losing useless short-term data (perhaps certain recent breakfast menus). Furthermore, some quite worrying methods have been accepted by psychiatrists despite their potential for memory loss (electroconvulsive therapy is an example). So careful microwave-irradiation stands a good chance.

But Daedalus's main worry is the adoption of his methods by the politicos. A wide-band high-energy microwave assault on the brain might scramble all its data long before heating set in. The most convinced capitalist or advocate of human freedom could crumble before such brain-washing. Against that, how many fierce species have their hatred of humanity stored as software rather than hardware? A DREADCO selective irradiation might produce genuinely friendly lions and tigers, cheerfully accepting crocodiles and alligators. The range of tameable, tractable species could be wonderfully extended. Even the wild cat of the Scottish Highlands, said to hate everything on sight, might be converted to a purring fireside moggy.

David Jones