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THE LIVING SKIES
Cloud Behaviour and Its Role in Climate Change

Oliver Morton

The Hybrid Vigor Institute
<http://hybridvigor.org>
<http://hybridvigor.net>
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[0.0] Overview

The clouds above have always been a worldwide source of poetic inspiration, quotidian joy and curious speculation. They are also, at the moment, central to questions of great environmental, economic and thus political importance. The behaviour of clouds and the processes that produce them in the face of increased atmospheric greenhouse gas concentrations¹ will be a crucial element in future climate change, and as yet that behaviour is not well understood. It is possible that changes in cloud formation and structure could act to reduce the climatic effects of greenhouse gases quite markedly, and thus reduce the need to abate their production. Were this the case, it would have a profound influence on the current efforts in many countries to implement the Kyoto Protocol (the global accord outlining actions to be taken to minimize climate change) and develop global successor regimes to further reduce greenhouse gas emissions. However it is also possible that clouds will not reduce the effects of increased greenhouse gases, or will do so no more than is envisioned in current predictions, or will even exacerbate them.

The problem, briefly stated, is this. It is not yet possible to have confidence in the predictions made by General Circulation Models (GCMs) — computer driven representations of the climate system — about how cloud cover will change in a world with significantly higher levels of atmospheric greenhouse gases. It is possible that these models, which make use of a physics-based understanding of the processes that govern the movement of radiation and moisture into, through and out of the atmosphere, are simply not yet detailed enough in their representation of the processes involved to capture their fundamental behaviours under changed conditions. Since they cannot model the climate raindrop by raindrop, or even cloud by cloud, these models have to simplify, and in their current form that simplification may be producing quite large errors.

Another possibility is that processes and factors not yet dealt with in the models, processes which, to the extent they are understood, are understood as topics for chemistry or biology, may play an important role. While it is with this second type of consideration that interdisciplinary issues arise most clearly, a realistic look at future directions in cloud research needs to deal with both possibilities for two reasons. The first is that it is not possible, *a priori*, to say that the solution to the problem cannot come from within the community of scientists already studying it; that is, without interdisciplinary input. The second is that it is impossible to understand the role interdisciplinary input might have without first understanding the issues within the field and the approaches being taken to address them.

While the representation of clouds in models of greenhouse-gas rich climates is a recognised research priority, and of fundamental importance to policy, this report will also discuss the fact that changes in cloud cover brought about by non greenhouse-gas processes — notably changes in the production and behaviour of aerosol particles due to a variety of human, geological, chemical, biological and even, conceivably, astrophysical factors — may lead to climate changes at the regional level as significant in some cases as the changes due to greenhouse gases. To understand clouds one needs to understand the sources of the dust they form on, the chemistry of the droplets within them, the degree of control over their environment exercised by any microbes living in the cloud water, and the role, if any, of cosmic rays that ionise the lower atmosphere. Here the need for interdisciplinary approaches is obvious from the start.

Clouds, as has been pointed out by both Hamlet and Charlie Brown, are the natural world's great Rorschach tests. What they look like depends on what you want to see in them, or what's suggested to you, or what you think other people want you to see. They can be camels or weasels or whales. They can look like an expression of purely physical processes, or the interaction of dust and dew, or a fog of chemical reactions, or the abode of life, or the result of far-off astrophysical events. The truth is that they are complex enough to be all of those things. That does not mean all approaches to studying clouds are equally valid, but it does mean that they are worth exploring and bringing together, to see if they offer insights to each other. Thus it may be that microbiology has little of use to add to the debate among climate modelers about the accurate representation of clouds, or to predictions of regional climate changes — but current understanding cannot say that for sure. The best way to find out is to explore the possible microbiology of clouds with climate issues clearly in mind. This is the sort of interdisciplinary approach that seems most likely to add to the understanding needed to help with policy formulation.

The question of how clouds behave in future climates is of primary importance to all predictions of climate change, and answering that question —and applying the answer to consequent regulatory questions about the need for control of greenhouse gases, industrial aerosols and changes in land use — will require the ability to combine an understanding of clouds gained from various different disciplinary approaches. This monograph seeks to set out how such combinations are currently developing, and to suggest paths that might fruitfully be followed in the future.

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[1.0] Introduction

This article is intended as a study of the way in which questions about the role of clouds in climate change may be elucidated through interdisciplinary approaches. It does not contain original research, nor does it aspire to the thoroughness and balance of a traditional review article. Instead it seeks to bring together current ideas from a range of different studies involving clouds in such a way as to provide a broad view of the issues and some sense of the possibility for further interactions between the various disciplines involved. It is worth noting that to some extent this is already an extremely interdisciplinary endeavour, in that it is hard to ascribe disciplinary labels to all the participants in the debate. The terms “climate scientist”, “atmospheric scientist” and such are widely used, but do not represent disciplines in any clear or traditional sense. This article thus attempts to discern disciplinary trends on the basis of ideas and approaches rather than participant credentials or job descriptions.

A note about reading this monograph: Interdisciplinary appeal requires knowledge which cannot be assumed. To ensure accessibility to the greatest number of readers, we have prepared a primer on clouds which covers the basics. We’ve placed this primer, called “Clouds 101”, in Section 7.0 (page 39) following the paper’s conclusion. We recommend readers with only a nominal familiarity with the science of clouds and climatology to read this section in advance. We will also refer to it in the text where it might be useful.

[1.1] The researchers whose work informed this journal

To prepare this report, we sought out and focused on relevant research from the following scholars. A bibliography, including additional source material, is appended.

- **Keith Shine, Ph.D.**; Department of Meteorology, University of Reading
- **Richard Linzom, Ph.D.**; Alfred P. Sloan Professor of Meteorology, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology
- **Tim Lenton, Ph.D.**; Institute of Terrestrial Ecology, Edinburgh
- **Andrew Ackerman, Ph.D.**; Atmospheric Aerosol, Chemistry & Clouds Group, NASA Ames Research Center
- **Daniel Rosenfeld, Ph.D.**, Hebrew University of Jerusalem
- **Birgit Sattler, Ph.D.**, University of Innsbruck
- **Bruce Moffett, Ph.D.**, University of East London
- **David Sands, Ph.D.**; Department of Plant Sciences and Plant Pathology, Montana State University
- **Third Assessment Report**, Intergovernmental Panel on Climate Change²

[2.0] The importance of clouds to the climate

By some accounting standards clouds seem all but negligible. At any given time only about 0.001 percent of the earth's water is suspended in its atmosphere. This means that the total water content of the atmosphere is equivalent to a layer of water over the surface of the earth of just 2.5 cm — half the amount of water in Siberia's Lake Baikal (though, to be fair, Lake Baikal is a damn big lake). A molecule of water will spend, on average, about nine days in the atmosphere before returning to the surface, and the amount of that time spent in one of the water droplets that make up clouds may be only hours. These clouds are short-lived and produced, for the most part, by local or at most regional effects. And yet despite being low on bulk and circumscribed in time and space, they are of global significance, dominating key aspects of the planet's climate.

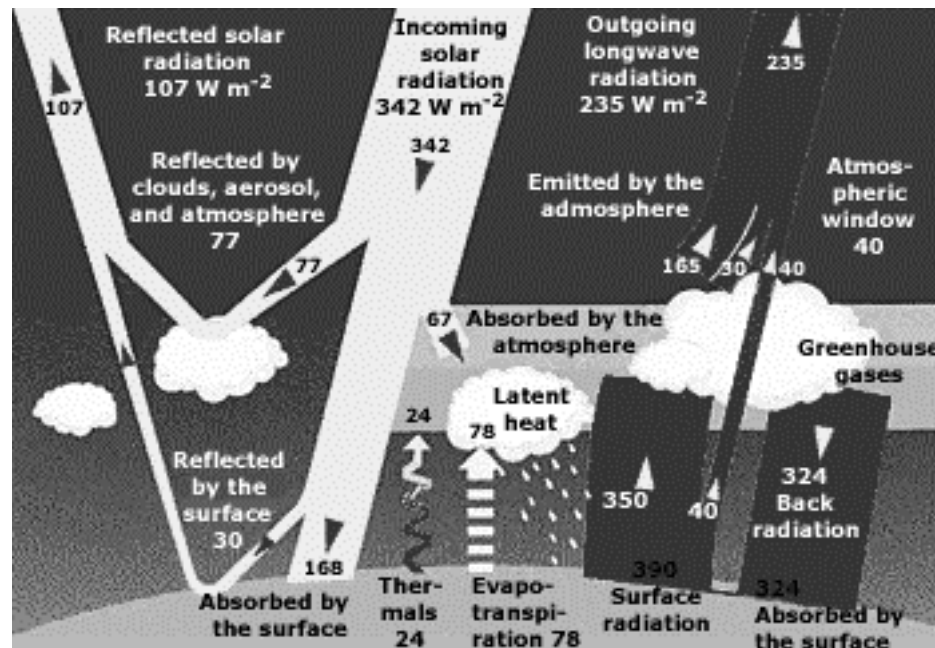
[2.0.1] The planetary perspective

The true importance of clouds is clearly seen from orbit. Looking at the earth from space, the clouds, more than the continents or oceans, are what catch our eyes. In the two most famous images of the whole earth taken from space — the pictures of the earth rising over the limb of the moon taken from Apollo 8 in 1968, and the iconic image of Africa, the Indian Ocean and Antarctica taken by Harrison Schmitt from Apollo 17 — the clouds form the dominant visual motif. In the images from the moon (and most especially in those taken on colour stock, which have less fine resolution) no surface feature is recognisable, yet the clouds can be seen in the rough edge of the line that marks day from night; in the black and white images, weather patterns form a fine white filigree. In the Schmitt image, great swirls of cloud in the southern ocean are a crucial part of the composition, as important to the peculiarly pleasing composition as the dominant descending V of Africa.

The prominence of the clouds was not much commented on at the time — the iconic value of the images depended on stressing the gestalt attributes of the represented “whole” earth, rather than its components — but it seems to have been unexpected, at least in the visual imagination. Chesley Bonestell, the extremely influential astronomical artist of the 1940s and 1950s, attempted the highest possible fidelity to the facts when imagining his images of the space age; and yet his pictures of the earth look like maps with a few clouds scattered on top. While it was obvious that clouds could be seen from space — indeed, weather monitoring was one of the first applications suggested for artificial satellites — no art prior to the 1960s seems to have imagined just how much they would dominate the face of the earth. The earth of the mind's eye, it seems, was the simplified and regularised one of the geographer's globe, not the changeable, atmospheric planet we are now used to looking down on.

To get a quantitative feeling for the importance of clouds, look at the role they play in the earth's heat budget.³ The earth receives 342 Watts per square metre (Wm^{-2}) of sunlight, most of it at

visible wavelengths and referred to as “shortwave” to differentiate it from the infrared “longwave” that the earth and its atmosphere radiate as a result of their temperatures. About 30 percent of this shortwave radiation bounces straight back into space, and about half of the reflection is due to clouds. Of the radiation that is not reflected, about 70 percent is absorbed by the surface, and the other 30 percent — 67Wm^{-2} — by the atmosphere. (The amount of absorption that can be ascribed to clouds became a matter of some controversy in the mid 1990s, when some measurements seemed to suggest that clouds were, in general, absorbing far more of the sunlight than had been expected on the basis of their physical attributes. There is now a consensus that this excess absorption was not a general effect, though there is still room for further work on specific cloud types.)



Courtesy *Bulletin of the American Meteorological Society*

Of the atmosphere’s energy inputs, though, direct solar heating is only the third biggest. The largest input comes from the surface of the earth, which emits about 390Wm^{-2} of infrared radiation. This may seem surprising — it means, after all, that the earth’s surface is radiating more energy than it is receiving from the sun. The reason for this is that much of the radiation absorbed by the atmosphere is radiated back to the surface, and vice versa. The surface is warmed by radiation from the atmosphere and the sun; the atmosphere is warmed by radiation from the surface and the sun. The atmosphere absorbs almost 90 percent of the longwave radiation from the surface, while 10 percent escapes into space. The importance of greenhouse gases is that they increase the amount absorbed in the atmosphere still further.

If the surface is the largest source of energy for the atmosphere and the sun the third largest, what is the second? The answer is cloud formation. 78 Wm^{-2} of the radiation that reaches the surface of the earth is used up evaporating water at the surface; this light-bulb's worth of energy is enough to evaporate about a metre of water over a year. All the water vapour thus produced will condense in the atmosphere, forming clouds. The process of condensation releases the same amount of energy in latent heat as was used in the original evaporation process: 78 Wm^{-2} . On a planet with a surface area of 510 trillion square metres, that's 40,000 trillion watts — equivalent to the detonation of a ten megaton nuclear bomb set every second. This is a very substantial fraction of the energy that drives the climate.

Considering their roles as reflectors of radiation (about 50 Wm^{-2}), absorbers of radiation (about 30 Wm^{-2}) and converters of latent heat (about 78 Wm^{-2}), it is clear that an understanding of clouds is crucial to models of a climate powered by a total input of just 342 Wm^{-2} . By way of comparison, the climatic effect that the Intergovernmental Panel on Climate Change (IPCC) ascribes to the increase in carbon dioxide levels since the mid-nineteenth century is put at 1.46 Wm^{-2} , and the change expected if carbon dioxide were to double is about 4 Wm^{-2} . It is thus fairly obvious that changes in the production and distribution of clouds, which are implicated in energy flows an order of magnitude larger than those expected due to increased levels of atmospheric greenhouse gases, could modify the effects of those gases quite profoundly.

These changes in energy flow are referred to as “forcings”. A forced system is normally one in which energy is being put in from outside; a child on a swing being pushed again and again by a parent is undergoing “forced oscillations”, for example, while one that just sits there after an initial push is undergoing “free oscillations”. Forcing does not actually have to come from outside, though — imagine a child pumping up the swing herself by moving her centre of mass. In an analogous way, changes in atmospheric composition can “force” the climate even in the absence of changes in the absolute amount of energy coming into the system. Forcings, like energy inputs, are measured in terms of watts per square metre. The change in forcing associated with doubled carbon dioxide is, as mentioned, about 4 Wm^{-2} . As a general oversimplification, changes in forcing below 1 Wm^{-2} can be treated as details, and those above 10 Wm^{-2} can be considered catastrophes.

The significance of the 4 Wm^{-2} associated with doubled carbon dioxide is not necessarily a simple rise in surface temperature. The effect of an increase of 4 Wm^{-2} in the amount of longwave radiation absorbed by the atmosphere will be to change the way the atmosphere

behaves. Some of these changes will act to increase the surface temperature, but some may act to decrease it. The degree to which the climate amplifies or damps down the changes in average temperature expected for a given level of radiative forcing is known as its “sensitivity”, and this sensitivity is the net effect of positive and negative feedbacks that come into play as a result of the primary longwave forcing. Estimates of climate sensitivity made from observations of past climatic change and inferred from General Circulation Models (GCMs) are in rough agreement, but there is a range in the estimates of 50 percent or so. In some models the climate amplifies the radiative forcing only mildly; in others it amplifies it strongly. Changes in the number, character and location of clouds plays a crucial part in these processes.

[2.1] Problems in the models

Some changes in cloud cover increase sensitivity, while some decrease it. For example, if increased radiative forcing means that low clouds extend over a larger area, their greater extent will tend to counteract the warming by reflecting more shortwave radiation back out to space. If the cloud tops tend to be a little higher, though, this will tend to exacerbate the warming somewhat; higher cloud tops are by and large colder cloud tops, and colder cloud tops will be less efficient radiators of the heat within the clouds, since the rate at which radiators lose heat depends on their temperature. If cloud tops are less able to radiate heat away, more heat is left in the lower atmosphere. If cirrus clouds, which are made of ice crystals rather than water droplets, increase in extent then they will exacerbate warming, because they are largely transparent to shortwave but absorbent of longwave; if they shrink, the reverse will happen. (More on cirrus clouds below.)

All these factors feed in to the climate sensitivity, and all are functions of the climate that produces them. Different climatic systems will produce different clouds: cloud structure over the Pacific, during recent El Niño events, for example, changes quite radically, with a marked increase in shortwave cooling over the warm pool of the western Pacific.⁴ It is in their prediction of such changes that current general circulation models seem poor, and their inadequacies in this respect are perhaps the greatest source of error in attempts to predict the effects of increased greenhouse gas levels through GCMs. These errors may include missing large scale feedback mechanisms in the climate.

[2.1.1] Iridology of the skies: including clouds in the model

Richard Lindzen, an atmospheric physicist and climate scientist at the Massachusetts Institute of Technology, has a history of scepticism over the climatic effects of industrially-produced greenhouse gases. In the past couple of years his criticism has taken the form of a theory of cloud behaviour in the tropics which he believes to be a major factor in world climate, and which is completely absent in the circulation models currently being used to predict climate change. If Lindzen were right about this cloud effect, it would have great significance for predictions of climate change. Whether the effect is real or not, it nicely illustrates the sort of change in cloud production and behaviour that models of the climate may have difficulty capturing.

Lindzen's idea is that rises in sea surface temperature may be correlated with decreases in cirrus cloud cover. On the basis that cirrus coverage is derived from the tops of cumulonimbus towers, where ice particles blow away to provide the broad "anvil head" familiar on the top of thunderstorms, he argues that increased efficiency in precipitation in cumulonimbus towers over warmer oceans would reduce this source, and thus reduce the total amount of cirrus coverage. Since cirrus clouds are warming, decreasing the degree to which cumulonimbus clouds produce cirrus will tend to be cooling.

Lindzen invokes a secondary mechanism that enhances this cooling effect through changes in water vapour. In data on the water-vapour content of the atmosphere over the Pacific, he finds evidence that there are patches of drier air and patches of moister air, and argues that the water vapour in the moist patches comes from the evaporation of overlying cirrus clouds. Water vapour is itself a powerful greenhouse gas, and so smaller moist patches mean less greenhousing. Lindzen talks of the dry, cirrus-free patches of atmosphere over the ocean as an "adaptive iris" through which longwave infrared radiation can leave the surface unmolested. Increases in tropical sea-surface temperature will lead cirrus coverage to decrease and the iris to expand, thus providing a counterbalancing cooling. This would mean that the climate's sensitivity was very low — a position that Lindzen held long before this model was developed.

The observational basis of this work has been criticised, as has the modelling component. Dennis Hartmann, a professor of Atmospheric Science at the University of Washington, has argued that the cloud cover changes that Lindzen points to are not physically connected to the convection associated with cumulonimbus formation, and that the water-vapour feedback, while present, is overestimated in Lindzen's work.⁵

However, whether it is in fact representative of a process that can be expected to take place or not, Lindzen's model is an interesting illustration of a counterintuitive general principle: that the same process can be stabilising or destabilising under different circumstances. If the earth faced an overall and general increase in radiative forcing, as is the case in carbon dioxide warming, the iris mechanism would minimise the climatic effects by cooling much of the globe. However, if the climate system were to start operating in a different way — if the rate at which heat flows to the poles from the equator were changed, for example, by changes in ocean circulation, as appears to be the case during ice ages — the iris could exacerbate the change. If, for example, the heat flow to the poles increased, the iris might contract, thus keeping the tropics at the same temperature even though they are exporting more heat, and so increasing the global mean temperature.

The iris model is thus consistent with some sorts of change in average global temperature and not with others. Specifically, it allows ice ages to happen through changes in the pattern of heat flow, while arresting change through increased greenhouse gas levels.⁶

Models of the current climate are broadly successful in predicting where clouds will form. But this success has to be seen as both partial and to some extent the product of ad hoc fine tuning. It is partial in that the models tend to be poor on two particular types of cloud: clouds in the boundary layer, particularly low-lying stratocumulus, and thin high-level cirrus. (The boundary layer is the lowest layer of the troposphere [see Clouds 101, Section 7.0], where conditions are dominated by the topography, temperature and moisture of the underlying surface.) The problem with boundary layer clouds is that, by definition, they form in response to very particular local conditions, both on the ground and in the air. Models of the atmosphere cut it up into a set of cells that mark the limit of the model's granularity; at the scales at which climate models operate, with individual cells hundreds of kilometres on a side and vertical resolutions of about a kilometre, it is impossible adequately to capture these conditions. As a result, current climate models tend to underestimate the prevalence of boundary layer clouds, which tend to reduce the total climatic forcing by reflecting shortwave radiation back into space before it reaches the surface.

Cirrus clouds are underestimated because of their extremely tenuous nature. It takes very little water to make a cirrus cloud, and it is hard to predict exactly the extent of such clouds. Here, the underestimation works in the opposite direction. Cirrus clouds tend to warm the earth, because they are extremely transparent to incoming shortwave radiation but somewhat less so to outgoing longwave radiation.

[2.1.2] The role of cirrus clouds

The pleasing mares' tail wispieness of cirrus clouds reflects the fact that they are mostly made of ice crystals. Clouds of water droplets are stable only within volumes of air saturated in water vapour — droplets that stray outside will quickly evaporate. Ice crystals are made of sterner stuff.

The fact that cirrus clouds can be thin, though, raises another problem — they are actually rather hard to see. It has recently been recognised that there is a great deal of easily overlooked “sub-visible” cirrus in the atmosphere, enough to have some climatic effects. Contrasting images produced by the MODIS sensor on NASA's Terra spacecraft show the effect nicely — skies that appear clear in the visible are misty in the infrared.⁷

While sub-visible cirrus is, by definition, hard to detect with the naked eye, it is not impossible. At night it has an effect on the clarity with which the stars shine, and this

effect has long been part of the weather folklore of the Andes. Observations of the brightness of the Pleiades around the winter solstice are used by Andean farmers to anticipate rainfall in the coming seasons. Comparing satellite data on sub-visible clouds, data on crop yields and records of El Niño events, researchers at Columbia University's Lamont Doherty Observatory have shown that sub-visible cirrus in June is in fact a reasonably reliable predictor of El Niño events.⁸

Overall, the study of cirrus still has a great deal of progress to make. In particular, it is not clear to what extent cirrus clouds are influenced by human activity. Sulphate aerosols may be an important factor in cirrus cloudiness, as might contrails; it is possible that cirrus induced by aviation-associated pollution may contribute 0.3Wm^{-2} of forcing in some heavy-traffic areas. One unique possibility for research into this area has been satellite coverage of the United States on September 11th and 12th 2001, when the complete cessation of normal civilian air traffic following the attacks on Washington D.C. and the World Trade Center allowed the effects of a small number of military contrails to be examined in detail. According to a report in *The New York Times* ("Briefly Empty Skies Offer Climate Clues" by Andrew Revkin, October 30, 2001) this approach is being pursued by Dr Patrick Minnis of NASA's Langley Research Center.

[2.2] Twiddling the knobs: fine-tuning models to include clouds

The problem of ad hoc fine tuning runs deeper than the problem of only partial success. The reason that models of today's climate tend to provide realistic amounts of cloud cover, realistically distributed, is that the data on current cloud cover is used to tune the models. After all, climate models of this sort, which are run at specialised research centres around the world (such as the Goddard Space Science Institute in America, the Hadley Centre in the UK, the Department of Atmospheric Research of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia and the Max Planck Centre for Meteorology in Germany) as well as in various universities, were derived in part from models meant to predict weather under today's conditions, and they carry that heritage with them. To take an analogy offered by one climate modeller: imagine a model with lots and lots of knobs which can be twiddled to change parameters within the model. At first, this model doesn't produce the cloud cover that matches the records of real cloud cover. So the modeller twiddles a few of the knobs until the model matches reality, more or less. But that doesn't mean the settings on all the knobs are now right. There may be many ways of setting the knobs that gets today's cloud cover right; but there will only be one setting that gets the underlying processes that cause the cloud cover right. That one setting is the one in which what goes on in the model actually mimics what goes on in the

climate, rather than simply producing some of the effects of that climate. And twiddling knobs to get the empirical fit is not going to find that one true match.

The point is that models make all sorts of simplifying assumptions about the world, and it is currently more or less impossible to say which are valid and which are not from an analytical standpoint. Some of the simplifications may be good ones — simplifications which accurately capture the underlying mechanism involved. Others may be bad — simplifications that reproduce today's conditions more or less by accident, without capturing how those conditions are actually caused, but which go unquestioned because they seem to work. And as long as the models show roughly what happens today there is no way of knowing whether they are good or bad, and thus whether they should be trusted in their predictions.

There are various reasons to believe that the basics of the climate's behaviour are reasonably well captured in today's models. By and large, models run under ice age conditions produce cold climates that approximate to those inferred from the geological record. Models run under the higher carbon dioxide conditions of the Cretaceous period, 145 to 65 million years ago, tend to produce warmer climates, which fits the geological record. Models developed on earth can even do a reasonable job of modelling the climate of Mars, if fed the right initial conditions and tweaked in reasonable ways (the lack of an ocean on Mars may actually make Martian climate modelling easier). But though these fits are good rough approximations, they have plenty of room for error, partly because the climate records they are being compared to are necessarily patchy, and partly because what counts as a good fit when looking across the depths of time and space is far too imprecise when looking at near term policy issues such as whether to defend or implement the Kyoto Protocol. The changes in the climate that may come about in this century, while they may be large compared to climate changes in the historical past (and will certainly be larger in impact, simply because the global population is so much larger), are very unlikely to be as great as the differences between today's climate and that of the ice ages, or the Cretaceous.

With no way of showing for sure that the models will work as predictions of future climates, there has been a considerable interest in working on ways to show that they should. Within the climate modelling field, the 1990s saw a marked shift from what are called "diagnostic" approaches to "prognostic" ones, particularly in the area of representing clouds. In diagnostic approaches, clouds were introduced into the models using empirically derived rules about the conditions of temperature and pressure under which they might appear. Though the rules

allowed such models to get cloud cover right, they made no attempt to represent the processes which one would normally require if asking for an explanation of *why* the clouds were there. They did not model the condensation of water and its precipitation as parts of the same process — indeed, they were capable under some conditions of producing precipitation without clouds, which is quite a trick. The fact that they did not model the processes behind cloud appearance coherently made it hard to believe that they would accurately capture changes in those processes when run with higher levels of greenhouse gases.

Prognostic models do try to capture the physical processes involved, at least for the production of some sorts of cloud; they model the way water cycles through clouds in such a way as to ensure that the total amount of water in a given part of the system doesn't change even as some of it moves from vapour to liquid, some from liquid to solid, some from solid back to vapour and so on. This is obviously preferable in principle to the more ad hoc approach of the diagnostic models. Unfortunately, it is not yet clear that the prognostic approach produces better — or more consistent — results. When different models are run using the same input data, no clear trend is seen in which one type of approach consistently gives one sort of an answer while the other approach does something different. While the prognostic approach has clear philosophical advantages, in its current applications it has not yet made a difference to either the average value of predictions of future temperature in an enhanced greenhouse or the range of those predictions.

Comparisons between the predictions of cloud effects in models that work in different ways have thus not, as yet, provided a great deal of guidance on which models are most reliable. While in the mid 1990s it looked as though the predictions of cloud cover under heightened carbon dioxide made by different models were converging, this was illusory. It was in fact only the net forcing due to clouds — longwave warming minus shortwave cooling — that was converging. Estimates of shortwave and longwave effects taken separately remained as varied as ever, so the fact that the average was converging had to be seen as a chance occurrence. The problem is well illustrated in a review published in 2000 and cited in the IPCC's Third Assessment Report which compares cloud predictions for ten models, five of which show a cooling effect and five of which show a warming effect. While the model operated by the CSIRO team in Australia and the model operated by the Max Planck Institute for Meteorology in Hamburg both suggested that the effect of the clouds was moderately cooling, they did so for precisely opposite reasons: the Australian model suggested a large increase in the amount of sunlight reflected while the German model suggested a marked decrease; the Australian model

showed a large decrease in the longwave effect while the German model showed a large increase. Clearly the basis on which the two models reached “agreement” was spurious; the underlying processes are not being captured.

The IPCC’s Third Assessment Report is encouraging in its discussion of recent attempts to make the way that models simulate clouds more realistic in their capturing of the processes involved in the production of clouds and the properties of the clouds produced. But it concludes that, “in spite of these improvements, there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate change simulations.”

(Iconographically, it is worth noting that the cover of the science working group’s contribution to the Third Assessment Report features a very impressive tropical ocean cloudscape as seen from the space shuttle.)

As a possible route forward, the report points to the fact that a new generation of satellites currently entering service will produce datasets on a wide range of cloud related physical properties not previously measured, including heights of cloud tops and of bases, cloud water content and cloud particle radius. By seeing which models best capture these previously unknown factors and improving on them it may be possible to produce models so convincing in their treatment of today’s climate that their predictions of tomorrow’s can reasonably be given a privileged status. The availability of new evidence on variables about which the models make predictions but which have not previously been monitored on a planetary scale is thus a hopeful development.

[3.0] Aerosols and cloud formation

Prognostic approaches to cloud formation may thus eventually solve some of the basic problems bedeviling the predictions of future cloudiness by providing reasons for increased confidence in particular models. However, other issues will remain uncertain until there are more reliable ways to build other effects into climate models, such as the effects on clouds of solid particles in the atmosphere.

Solid particles — aerosols — are necessary for cloud formation. Cloud water droplets form on aerosols, as do ice crystals. Without ice-nucleating particles in the atmosphere, ice would not normally form at temperatures higher than about -40°C . Since ice crystals are frequently crucial to the growth of cloud droplets into raindrops (see *Clouds 101*, Section 7) their absence would drastically change climatic conditions. To get a sense for the importance of this, consider the fact that one modelling experiment for the IPCC TAR found a difference in forcing of 17Wm^{-2} between a world in which all water in clouds that could possibly freeze — that is to say, all water colder than 0°C — did indeed freeze, and a world in which all the water in clouds that could conceivably remain liquid — that is to say, all water in clouds over -35°C — did remain liquid. To compare all ice clouds to all water clouds is a caricature, but the size of the effect makes it a telling one.

To understand clouds, then, it is not enough to understand the physics of atmospheric water. One must also understand the sources and sinks of the aerosols that allow that water to condense. Aerosol studies have traditionally been the province of chemists more than physicists, not least because some aerosols are produced in the atmosphere through chemical reactions and lead to chemical effects, the most noted being acid rain. In very broad terms it may be said that, before the advent of widespread concerns about global warming in the mid to late 1980s, the physics of the atmosphere was seen as a set of natural phenomena, while its chemistry was largely, though not exclusively, studied within the context of pollution.

Because aerosols are relatively short-lived, most of the early work undertaken to understand and model their effects was local or regional in extent. The first global aerosol models were not developed until the 1970s, and then it was in response to phenomena not on the earth but on Mars. The Mariner 9 space mission observed a dust storm that completely engulfed the planet, significantly cooling its surface. (Happily, the storm subsided soon after the spacecraft went into orbit, thus allowing the first detailed mapping of the Martian surface to take place.) Studies of

the effects seen on Mars led to models of the effects that stratospheric aerosols produced by volcanic eruptions could have in cooling the earth's climate; this effect was seen quite clearly in the aftermath of the Mount Pinatubo eruption in the early 1990s. The idea of aerosol cooling went on to become a part of the impact theory for the cretaceous/tertiary boundary proposed by Walter and Luiz Alvarez. The Alvarazes (physicist father and geologist son) suggested that the vast amount of dust and debris kicked up by a comet or asteroid hitting the earth 65 million years ago might have cooled the earth in the manner of a Martian dust storm, killing off the dinosaurs (and about 65 percent of all other species then living) in the process. This idea led in turn to the original aerosol model derived from the Martian studies being reapplied to the earth both to study impact events and, as a direct result of that work, the effects of nuclear war. This started the "nuclear winter" debate over the extent to which debris and soot kicked up by a large nuclear exchange might effect global temperature, thus crop production. This debate pumped a lot more money into the study of aerosol effects. (Interestingly, in early 2002 new geological work suggested that the aerosol effects of the end-Cretaceous impact could not in themselves have caused the worldwide extinctions; the debate continues.)

Thus global aerosol modelling has a profoundly interdisciplinary birth, coming out of the concerns of planetary scientists, geologists, physicists, radiation chemists, astronomers and climate modellers. (For forthcoming planetary work that might conceivably have ramifications for our understanding of terrestrial atmospheric processes, including clouds, see the Titan section in Clouds 101, Section 7).

[3.1] State of play: aerosols and cloud condensation

Today, the largest sources of aerosol particles in the atmosphere are grit from the earth's soil and sea-salt from its oceans: estimates prepared for the IPCC suggest that a couple of billion tonnes of soil particles are blown aloft every year, and a similar amount of sea salt. The same report also contains estimates from the relevant literature of other aerosol sources. The main anthropogenic sources of primary aerosol particles include industrial dust, estimated at about 100 million tonnes a year, the burning plants for land clearance and fuel, responsible for about 60 million tonnes of particles a year, and the burning of fossil fuels, responsible for about 35 million tonnes. Plant matter is also a major source of aerosol particles, with an estimated yield of 56 million tonnes. (Perhaps this is what Ronald Reagan was thinking of when he cited trees as a major source of air pollution).

Other aerosols are formed within the atmosphere due to reactions between gases. Important precursor gases include: volatile organic compounds (molecules that contain carbon and which can evaporate, such as some hydrocarbons), of which humans produce about 100 million tonnes (measured in terms of carbon content) a year, and which natural sources produce at a similar rate; oxides of nitrogen, which are produced at a rate of about 41 million tonnes (nitrogen content) every year, mostly by industrial processes, but with about 10 million tonnes produced by soil microbes and nitrogen; ammonia, which is produced at a rate of perhaps 54 million tonnes (nitrogen content) a year, again with about 10 million tonnes from natural sources; sulphur dioxide, produced at a rate of about 88 million tonnes (sulphur content), most of it industrial but some volcanic; and dimethyl sulphide, of which natural sources produce about 25 million tonnes (sulphur content) each year. Of the aerosols produced from these precursors the lion's share are particles of sulphate, produced at a rate of about 200 million tonnes (total mass) a year.

Sulphate particles are particularly good sources of cloud condensation nuclei (CCNs), since they are hygroscopic (that is, they are partial to water, and will at least partially dissolve in it). The history of their study also provides an interesting example of interdisciplinary research into the origin and behaviour of clouds. In the late 1960s and early 1970s, James Lovelock, an independent British scientist, began to think about planet-wide interactions between the earth and its biosphere, a line of thought that led to what he came to call the Gaia hypothesis. (More on Gaia in Section 4.1, below.) One of the issues that intrigued him was the sulphur cycle. Sulphur is not an abundant element on land, and is perpetually being lost from the soil to water, which carries the sulphur down to the sea. Volcanoes provide some replenishment of the sulphur, but not enough. So there must be a way of getting sulphur from the oceans back to the land. The standard explanation for this at the time was that the oceans gave off hydrogen sulphide, but Lovelock found this untenable on the theoretical basis that hydrogen sulphide has a short residence time in the atmosphere, and on the practical basis that the sea does not smell of rotten eggs.⁹ Lovelock suggested instead that the main marine source of atmospheric sulphur was dimethyl sulphide (DMS), which is produced by a wide range of plankton, and which diffuses from surface waters into the atmosphere. This has turned out to be the case; plankton pump about three times as much sulphur into the atmosphere as all the earth's volcanoes put together.

This intriguing discovery, though, was only the beginning of the dimethyl sulphide story. DMS is transformed into sulphate aerosols in the atmosphere, and these in turn form CCNs. In general,

there are relatively few CCNs over the open oceans, because most aerosol particles are produced over land (the exception is sea salt, released wherever waves are breaking) and have relatively short atmospheric lifetimes. In the 1980s work inspired and participated in by Lovelock showed that the DMS-derived particles were a major source of CCNs over much of the open ocean, and thus over much of the surface of the earth. In a way that no one had anticipated, a significant fraction of the earth's cloud cover was dependent on the activity of plankton. It was, in the words of Andrew Ackerman, a modeller who studies clouds at small scales and has made various studies of aerosol effects, the most amazing thing you could imagine — the tiniest creatures of the sea painting towers of cloud onto the sky.

[3.2] The indirect effects of aerosols

Even before the observations of the great Martian dust storm of 1971 it was clear that aerosols in the atmosphere could cool the surface by reflecting away sunlight; the IPCC currently calculates that this may provide a cooling of as much as 1.5 Wm^{-2} averaged over the world, though the uncertainties are very large and the effects will not be evenly spread. This cooling may have “masked” some of the warming effects of increased carbon dioxide over the past century. Cleaner fossil-fuel technologies, which by reducing aerosols, especially in densely populated areas, have a significant ameliorative effect on human health, will decrease the effectiveness of this masking. However, even if technologies are cleaner, the IPCC TAR suggests that increased fossil fuel use on the scale envisaged in many scenarios for the twenty-first century will in all likelihood lead to more aerosols and more aerosol cooling, especially in the first half of the century.

For the purposes of this monograph, though, it is the indirect effects of the aerosols — the ways in which aerosols change the properties of clouds — that are of most interest. In the 1970s Sean Twomey, a climate researcher, pointed out that aerosols could in principle have two indirect effects mediated through clouds. More aerosols (particularly more sulphate aerosols, a product of fossil-fuel burning) would mean more CCNs on which cloud droplets can form; more CCNs would make clouds brighter reflectors of sunlight and, seemingly paradoxically, poorer producers of rain. The reason for both effects is that the CCNs are effectively in competition with each other for the available water vapour, and when more enter the competition all end up with less. More CCNs mean more but smaller droplets in the clouds. Smaller and more numerous droplets reflect the sunlight better, making clouds brighter and thus more efficient shortwave

coolers. At the same time, smaller cloud droplets are less able to grow into raindrops, and thus reduce the clouds ability to produce precipitation.

The Twomey effects were very straightforward — indeed, some considered them too simplistic ever to be seen in the real world. However, subsequent research has found the real world, in this respect, to be quite simple. In the 1980s satellite images of low-lying stratus clouds over oceans were found to be embossed with bright lines marking the passage of ships below; the sulphates and other particles in the smoke from their funnels were adding locally to the number of CCNs, which are relatively scarce over many parts of the ocean. There has been a degree of military interest in this work, as the tracks in the cloud reveal ship movements that might not otherwise be visible. (Modern military vessels, however, which burn clean fuel in turbines rather than bunker oil, are less easily traced this way).

Later work, developed theoretically by climate modeller James Hansen and colleagues at the Goddard Institute for Space Science and observationally by Andrew Ackerman of NASA's Ames Research Center, identified a further "semi-direct" effect. Soot and other "black carbon" aerosol particles are very effective trappers of heat, and in some areas the heat that they trap will warm the atmosphere in a way that cause clouds to evaporate. In Ackerman's case, this insight came out of a close interplay between the study of climate and of aerosols as part of a co-ordinated observational campaign in the Indian Ocean. Ackerman had previously used small-scale cloud models to argue against the view, proposed in the mid 1990s, that clouds absorb more sunlight than had previously been thought. If they absorbed more sunlight, he argues, they would cause themselves to evaporate. V. Ramanathan, the climate modeller leading the Indian Ocean campaign — and one of the researchers who had previously found evidence for the purported increased absorption in clouds — turned this criticism back into an aerosol issue, pointing out that if clouds absorbing sunlight would dissipate as a result, clouds in air laced with sunlight-absorbing soot would suffer the same fate. Ackerman, part of the aerosol team on the interdisciplinary campaign — known to the rest of the project as "the dirt guys" — found that this was indeed the case.

In the second half of the 1990s, Daniel Rosenfeld, an applied meteorologist and physicist at the Hebrew University in Jerusalem, has observed the indirect aerosol effects now well known from ship tracks in a number of non-maritime settings, including Australia and the Amazon basin, where the additional CCNs are from industry and burning, and the eastern Mediterranean, where the additional CCNs are from desert dust. In all these cases, Rosenfeld uses satellite

observations to argue that the clouds produce less precipitation than they otherwise might because the high number of CCNs depresses the average radius of the droplets below the threshold at which they might start to grow by coalescence into raindrops.

Extrapolating from his regional studies to the global scale, Rosenfeld points out that this second indirect effect could have significant impacts on the climate. The sky cannot simply store up more and more water; what goes up must come down. Since total global precipitation is fixed in this way, a world in which clouds are less effective in producing precipitation will need more clouds, and will thus reflect more shortwave radiation. Modelling such changes exactly is not yet possible; analysing the indirect effects of aerosols over northern hemisphere oceans the IPCC estimates the forcing as somewhere between 0 and -2.8 Wm^{-2} . While the indirect effect that leads to brightening is now included in some models of the climate, the other indirect and semi-direct effects are not widely incorporated, and thus the magnitude of the forcing associated with them is hard to put a number to.

In Rosenfeld's view, the global forcing due to these effects might be of secondary importance. Reduced precipitative efficiency doesn't just mean longer-lived clouds. It means less rain in some areas. This is of particular interest in the eastern Mediterranean example, where the CCNs suppressing precipitation are particles of Saharan dust transported to non-desert and semi-arid areas by the wind. Rosenfeld suggest that this dust may be capable of producing a desertification feedback loop; soil disturbed by agriculture in semi-arid lands might produce dust that would then suppressed precipitation further, expanding the desert. In general, Rosenfeld believes that changes in precipitation due to aerosol effects may be similar in the scale of their human impact to changes in global average temperature due to enhanced greenhouse gas forcing. He is currently looking for further areas where precipitation records and air pollution records could be tied together to make this case.

It is possible to see the indirect effects of aerosols on clouds as a good thing, in that they can be expected to counteract any warming caused by changes in greenhouse gas forcing. Climate scientists have spent a great deal of time arguing against this perceived benefit, pointing out that aerosols (particularly sulphate aerosols) are themselves damaging (in that they promote acid rain) and that the move to cleaner fuels will reduce industrial aerosol effects. Rosenfeld's research brings home the point that making clouds less good at producing rain (and possibly moving a significant portion of the rain that currently falls over land to the oceans) could have very significant human costs.

This stress on the practicalities of precipitation seems to reflect Rosenfeld's research background, which is not the same as that of the majority of researchers in this area. Much of his work has been in the field of cloud-seeding — the deliberate addition of particles likely to produce particularly effective CCNs to clouds in order to provoke and sustain rain. It was from this area that he moved into the study of the unintentional modulation of rainfall through anthropogenic changes in aerosol levels. He brings to his work a greater interest in practical outcomes, and less stress on modelling, than is the norm for the subject.

[3.3] Future aerosol production

To some extent, future aerosol production is under human control. Since many of the sources of aerosols are industrial, they can in principle be limited — or enhanced — through regulation of various sorts. Sulphate production has been reduced throughout the industrial world as a result of concern about acid rain; the production of soot in industrial processes and in domestic settings is being reduced by improved technology, and in light of the substantial health damage due to soot particles this is clearly a good thing. However it is worth considering that these two types of aerosol reduction will have opposite effects on the climate. Reducing black carbon, which warms the atmosphere directly by suppressing clouds, has a cooling effect. Reducing sulphates, which increase the brightness and in many circumstances, it appears, the longevity of clouds, will have a warming effect. As yet there is no move to harness aerosol control policies to global climate policy — aerosols are still basically local and regional issues, and where policy on aerosols exists it is always geared to reducing them.

In the context of Rosenfeld's work, however, the possibility arises of tailoring aerosol production so as to minimise any unwanted suppression of precipitation. It might be possible to encourage the formation of particularly effective cloud condensation nuclei in factory chimneys, particles that would then win the competition for water vapour hands down and restore precipitative efficiency downwind. Ice nucleating particles might be a possibility here (discussed further in "Life in the Clouds," next section). As Rosenfeld pointed out in an interview during the writing of this report, aerosols produced as by-products of other processes vastly outnumber those that might be created by any conceivable cloud seeding programme. If the aerosols produced in this way could be tailored for even low- efficiency cloud seeding they might counteract the unwanted suppression of precipitation, and even conceivably induce precipitation where it has previously been insufficient. This may seem a long shot given that, even among the practitioners of cloud seeding, there is relatively little consensus on the question of how well deliberate attempts to

modify precipitation actually work. It might also carry risks. It is already recognised that rival national claims to water in rivers and aquifers may be a major source of conflict in the coming century. Conflicts over clouds could be just as bad.

This level of active management is currently not feasible, since not enough is known about the relevant cloud physics. It would also surely be seen as undesirable by some; the dominant ethic of environmentalism, especially as it applies to the climate, is to minimise all deviation from the pre-industrial status quo ante. This has attractions as a precautionary approach, and also in terms of equity; since climate change typically imposes losses on some people, it is only reasonable to try and minimise those losses. However, given the many ways in which mankind, as the dominant biological and geological actor on the earth, is implicated in the climate, the possibility of seeking to modulate rather than eliminate those effects, even to tailor them, must eventually be taken seriously.

There is a limit to the lightness with which six to 10 billion people can tread on the earth, and when effects can not be avoided, attempting to design them in such a way as to minimise harm and even produce benefits must be the rational response. If fine tuning, as opposed to ending, aerosol production can modulate cloud production in beneficial ways, it is a possibility that we should take seriously.

Purposeful human activity however is only one influence on the rate of aerosol production. There are also natural sources, some effectively constant (sea salt which comes from surf) or effectively random (volcanic eruptions) and some of which will themselves respond to changes in the climate. While the IPCC has looked at a few of these issues, there is clearly a great deal more to be understood here. For example, estimates in the Third Assessment Report of dimethyl sulphite production by plankton in 2100 are arrived at by seeing how changed wind patterns expected in 2100 would influence the transfer of dimethyl sulphide from the surface layer of the ocean to the atmosphere if the DMS concentrations in the ocean were exactly the same in 2100 as in 2000. No attempt was made to model the changes in phytoplankton growth patterns that might be expected in a significantly warmer world, though such plankton can in some circumstances be very sensitive to water temperature. If climate change were significantly to reduce the population of DMS-producing phytoplankton, or to change its geographic distribution, resultant changes in sulphate aerosols could greatly amplify local and possibly global warming by reducing cloud cover.

These are not the only areas where cloud cover can be expected to respond to anthropogenic changes in the climate. Changes in land use and soil moisture will also drive changes in cloud cover. A recent example has come to light in Costa Rica, where the cloud-forest of Monte Verde (an ecosystem which gets its moisture from suspended cloud droplets as much as precipitation) has been seeing considerably less cloud in recent years. While it was at first suspected that this might be because of global changes in climate, recent work has shown that in fact it is due to the clearance of lowland forest upwind of Monte Verde; this clearance means that less moisture evaporates up into the winds blowing west, and thus clouds do not form.

Some among those who regularly decry the “overselling” and “hying” of global climate change fell on this data as evidence that such change was being blamed for things which it had nothing to do with, and there is a certain truth in this. However, at the same time, the underlying cause of the decrease in cloud at Monte Verde — changed land use — is a global phenomenon. If it has local effects wherever it is felt, those effects too will add up into something global. But these effects, like the indirect effects of aerosols and changes in the rate of natural aerosol production, are not yet well enough understood to be integrated into overall projections. These areas of climate feedback are in urgent need of further interdisciplinary research, involving ecologists and human land-use specialists including agricultural scientists, geographers and demographers. These issues are much more complex and sensitive to local conditions than greenhouse gas induced climate change, and will require a far greater integration of local knowledge (such as the details of land clearance up-wind from Monte Verde) with global approaches, such as satellite databases of aerosol composition, which will become increasingly comprehensive over the coming decade.

[4.0] The living skies: Adding biology to the mix

It has become a commonplace of astrobiology — the new minted discipline which seeks to study life as a planetary phenomenon, both on the earth and elsewhere — that the basic requirements for life is water, an energy source and a carbon source. Clouds offer all this, and so it is reasonable to ask to what extent, if at all, clouds are a habitat for life. If clouds are in fact, inhabited, might this have consequences for their bulk properties and their microphysics? Should we move beyond adding chemistry and environmental science to the physics of cloud formation and add biology, as well?

One way to start investigating this question is through the link between plankton, DMS production, and clouds. In the 1980s this became one of the primary areas of concern in something that might loosely be called Gaian science (see below), its importance due to the fact that it showed a clear link between biological activity and global climate. Without the clouds over the oceans which form around DMS-derived cloud condensation nuclei (CCNs), the earth might be considerably warmer than it is today. Bob Charlson, a chemist, oceanographer and climate scientist at the University of Washington, puts the figure at as much as 10 degrees, though few other researchers may be willing to go that far.

[4.0.1] ‘Geophysiology’: the science of Gaia

Gaian science, in this context, means science either carried out by people ascribing to Jim Lovelock’s ideas about the role of life on earth or science co-opted by those people. It is the endeavour of a relatively small group of “core believers” and a considerably larger penumbra of interested fellow travellers, and is by its nature fundamentally interdisciplinary.

In this it mirrors its founder. Lovelock is, by academic and commercial training, a chemist. He spent a long time in medical research, and his doctorate is a medical one. His career as an independent researcher, begun in the 1960s, was made possible by his development and expertise in various measuring devices of great importance to environmental science (devices which played a crucial role both in the understanding of the effects of DDT and the monitoring of the spread of CFCs). The work that led him to the basic Gaian idea that the biological and non-biological parts of the earth together form a self regulating system that can lead to long term stability in a number of environmental variables (temperature, oxygen level, ocean salinity, sulphur availability) was started when he was under contract to NASA, and rests on atmospheric chemistry, physiological modelling and cybernetics.

Lynn Margulis, his partner in a great deal of the development of the Gaia hypothesis, brought a strong component of microbiology to the theory. Since then, various aspects of

earth science – climate studies, oceanographical research – have been added to the brew, as have a number of studies that could also be seen as “mainstream” biogeochemistry. Having toyed with describing the whole field as “geophysiology” (a term first introduced for the study of the earth as a living object by geologist James Hutton two hundred years before) Lovelock now tends to see the whole range of what are called “Earth Systems Sciences” as Gaia by another name. The term “geobiology”, coined as a parallel to geophysics and geochemistry to describe biological researches that reveal aspects of the development and behaviour of the earth as a planet, is close in its intent to much of what could be called Gaian science. Astrobiology’s emphasis on the idea of life as a planetary phenomenon brings it close to a Gaian perspective, and some astrobiologists have clearly been greatly influenced by Lovelock and Margulis.

Two questions follow on from this idea. One is to ask whether the plankton are actually part of a self-regulating system or just having a climatic effect — that is, is their production of DMS itself controlled by climate, so that a warmer climate leads to more DMS and thus to cooling, or is it just something that they do with no regard for the climatic consequences? The Gaian assumption would be that the first of these is the case. Either way, though, the second question remains the same: what’s in it for the plankton? A much-rehearsed problem with the Gaia hypothesis, looked at from the perspective of Darwinian evolutionary theory, is that it seems to involve inexplicable altruism, in that some creatures devote resources to regulating the climate for the benefit of others. Darwinians expect behaviours to persist only if they deliver particular benefits to the individual concerned or others that share many of his or her genes; they don’t expect plankton to start regulating the planet’s temperature unless there’s an obvious benefit to the plankton themselves.

It was this second issue that intrigued the late William Hamilton, who until his untimely death in 1999 was one of the world’s leading evolutionary theorists. Hamilton was interested in Gaia, in that he thought there was indeed some evidence that biological systems brought hard-to-account-for stability to the world. He was unwilling to accept that plankton had any interest in anything other than what was best for the plankton. However he was open to the idea that evolution might have found a way for the plankton to use DMS they produce anyway (it is a way of protecting their cells against the salinity of sea water) to affect clouds, if that effect was directly helpful to the plankton. This led him to collaborate with Timothy Lenton, a protégé of Lovelock’s working in environmental science, on a paper about what plankton might want clouds for.

Their answer was that clouds were the plankton’s equivalent of a space programme. Lenton and Hamilton suggested that by providing extra CCNs to overhead clouds, a plankton bloom could generate enhanced winds at the surface of the sea by means of increased convection in the

thickening clouds. More wind means more droplets of water lifted aloft, and some of those droplets would contain plankton that might then travel far, especially if they were within a cloud layer. (Otherwise the droplets would evaporate). Work in the 1970s by Hamilton and Bob May, a physicist with a keen interest in biological matters, had shown mathematically that being able to send viable offspring a very long way away is a trait that is normally extremely valuable. If the clouds were the plankton's way of moving a great distance, that would explain why the plankton were putting substantial effort into making CCNs in the first place.

This theory has empirical problems. Its not clear that the sorts of clouds that are thickened by DMS-derived CCNs actually do generate winds that might help in such a process, and there is as yet no evidence that plankton do in fact get lofted long distances by any process related to these ideas. It is also not clear that, if the hypothesis is true, it offers more support for Gaia — it shows planktonic self interest at work in a process that has climatic effects, but doesn't explain any regulatory process that might also be involved. But it still constitutes an intriguing suggestion that life might actually be using clouds for its own purposes.

[4.1] The possible role of ice-nucleating bacteria in cloud control

A relevant observation for anyone pursuing that possibility was provided in 2001 by studies of clouds high in the Alps undertaken by microbiologist Birgit Sattler of the University of Innsbruck and her colleagues. Cloud droplets collected at Sonnblick Observatory, perched on a 3,000 metre summit in the Austrian Alps, contained bacteria which, when fed radioactively labelled foods, immediately produced radioactively labelled by-products. This strongly suggests that the bacteria were metabolically active in the cloud itself before reaching Sonnblick (care was taken not to allow local alpine bacteria to contaminate the sample). While it has long been known that bacteria are blown around in the wind and can be found in clouds, it was always assumed that the bacteria were inert during their travels, reanimating themselves only after landing.

Though definitive proof has not yet been provided that the bacteria were in fact metabolically active while in the cloud (it is conceivable that the bacteria simply woke up very quickly), that certainly looks like the case. Nor should this necessarily be a great surprise. Though General Jack Ripper (of *Dr. Strangelove* fame) considered rainwater to be the only drink other than grain vodka that would guarantee the purity of his precious bodily fluids, rainwater is not, in terms of the amount of dissolved organic matter within it, much purer than lake water. So there is organic material in clouds for bacteria to use, and there is sunlight with which to photosynthesise, if they are that way inclined. Considering the range of far less promising places where life has been

found — extraordinarily arid deserts, sulphuric-acid from mine tailings, deep within the basalts below the Columbia River — clouds should hardly represent a problem.

A research project currently seeking funding in the UK seeks to settle this matter. Led by Bruce Moffett, a microbiologist at the University of East London (UEL), and Tom Hill, a colleague in environmental sciences, a team of researchers from a range of backgrounds and institutions is planning to use the latest molecular techniques to show that microbes in clouds are active and not just spores. Using gene amplification techniques to detect and measure the presence of specific mRNAs (the “working copies” of genes used to produce proteins) they hope to be able to demonstrate active metabolism in samples taken directly from clouds.

Whether bacteria sleep or stay awake while cruising the skies might seem a minor matter, were it not for the possibility that they could be taking an active role in the clouds' behaviour. Some types of bacteria have the ability to produce proteins which, due to their structure, are very efficient ice-nucleating particles (the proteins mimic the shape of an ice crystal's surface) and can thus serve to get such growth started. These strains of bacteria are so good at encouraging water to freeze that they have a commercial value as additives for the water used in snowmaking machines at ski resorts. Their true economic importance, though, is negative and lies elsewhere. The ice-nucleating properties of these bacteria provide them with a way of attacking plants. It is easier for bacteria to eat damaged plant tissue than healthy plant tissue, and frost is a widespread cause of damage. By encouraging frost to form on leaves, ice-nucleating bacteria cause a great deal of damage to crops in places where the temperature only occasionally falls below freezing (in colder areas frost will form without bacterial help). There is a continuing strand of industrially supported research aimed at trying to do something about this problem.

It has been established that some of the approximately one-in-a-billion aerosol particles that have ice-nucleating properties are in fact bacteria, though the proportion is unknown. It has also been established that ice-nucleating bacteria occur in places (such as Egypt) where their abilities stand no chance at all of damaging plants, which casts doubt on the idea that plant pathogenesis could be the only benefit of this adaptation: by and large, bacteria do not express genes that will do no good, and there's little opportunity for causing frost damage in Egypt. If ice nucleating properties are being found where frost cannot be encouraged, then promoting frost damage may be a secondary use for an adaptation originally evolved for some other purpose.

One possible original purpose is the creation of rain. In many cloud types ice particles are the most important factor in the creation of raindrops. Bacteria might be taking advantage of this fact by using the production of ice nucleating proteins as an exit route from clouds they have been sucked up into. Given the argument sketched above that clouds might be a benign microbial environment, it is not entirely clear why bacteria might require such an exit strategy; one possibility is that it might be a response to UV stress. If a microbe in the free atmosphere, or in a cloud droplet, found itself at a high enough altitude to experience significantly heightened UV fluxes, it would clearly be advantageous to have a way to return to earth. In this context, it is worth noting that the types of micro-organism most often recovered in high altitude sampling missions are of species that show ice nucleating capabilities. Indeed, some academic work on airborne bacteria in the 1970s and 1980s was directly attributable to an event in which a test crop was hit by a disease which could only have come from above.

[4.1.1] Aerosols and the origin of life

In the late 1990s, measurements made from high altitude aircraft showed a surprising amount of organic matter in aerosols near the top of the troposphere. Indeed, in the tropics, up to 50% of the upper troposphere aerosols were organic. One way of accounting for this unexpected finding was to imagine that what was being seen in these aerosols were particles in which a thin, greasy coating of organic matter was wrapped around a watery core. Tiny watery specks with greasy coatings are familiar to biologists – they call them cells.

While the greasy aerosols were not cells, the fact that they looked like cells was quite suggestive. Adrian Tuck, a British aerosol specialist working at the US National Oceanic and Atmospheric Administration in Boulder, working with chemists and biochemists at the University of Colorado and the University of Oxford, put forward the idea that while such particles were not alive, they might, four billion years ago, have been the precursors to the first living cells.

The question of where cells came from is a key problem in accounts of the origin of life. The boundary between the inside of a cell and the outside world seems to be a fairly crucial step in defining an individual, and in delineating biochemical processes on the inside from what goes on on the outside. However, making cell sized environments in water – normally taken as the environment in which life developed – is not easy. The “vesicles” that form in bulk water mixed with organic molecules tend to be too small. Various workers on the origin of life – notably Stanley Miller and Carl Woese – have suggested that cloud droplets might play a role, but they are large compared to bacterial cells. The greasy aerosol droplets, on the other hand, are just about the right size. They can coalesce and divide, and they can support some of the internal chemistry that life requires more easily than bulk water can. (In particular, they provide a better chemical environment for the formation of the peptide bonds required in the building of proteins.)

The essence of the argument is coincidence. In the current atmosphere, nature provides aerosols of cell-like proportions that offer “versatile chemical reactors”, and such aerosol particles being whipped off the surface of an early ocean and deposited back there would meet some of the requirements identified for the origins of life very well. Though atmospheric conditions were very different on the earth at the time of the origin of life (no free oxygen in the atmosphere and a pressure at sea level perhaps as much as 100 times greater than today) these differences do not significantly alter the prospects for such aerosols, though they do offer a longer atmospheric life for them, and allow somewhat larger dimensions. A worldwide population of such aerosols coalescing and dividing would offer a richer environment for pre-biotic processes to work in than the “warm little pond” suggested by Darwin as a potential site for the origin of life, various versions of which (most notably tidal pools) still dominate discussion of the subject. The idea also offers a plausible experimental program – the chemistry that goes on in such aerosols could be studied in laboratory settings to see if it allows or encourages the formation of simple proteins.

The idea that bacteria can colonise and at some level control clouds is an extremely intriguing one, and ripe for further research — a recent review article by members of NASA’s Astrobiology Institute in *Nature* referred to clouds as “one of the last frontiers of biological exploration on earth”. It is also of possible climatic concern. Professor Tom Choularton, a physicist the University of Manchester Institute of Science and Technology (UMIST) who works on ways of adapting what is known about cloud microphysics into forms that can be used in climate models, has joined the UEL-led team proposing studies of the activity of cloud-borne microbes. If ice-nucleating particles are created *in situ* by bacteria under certain conditions, knowledge of those conditions could effect models of cloud properties, especially in clouds below freezing but above the temperatures where ice forms through chain reactions (below -6°C ice crystals splinter as they grow, thus providing ever more seeds for further freezing). If ice nucleation is adaptive in the way described, or in some other way, it may have a significant role to play in the contributions made by clouds in models of the global climate. Whether this role is already incorporated implicitly into the models it is not yet possible to say. It is certain that changes in the role played by ice-nucleating bacteria that would result from climate change and thus amplify or damp down that change are not dealt with in current models.

The idea might have practical implications. For example it suggests the possibility that by planting crops which harbour large numbers of ice nucleating bacteria (some do, to no apparent ill effect) one might conceivably be able to influence clouds downwind, if enough bacteria are shaken off into the sky. It also suggests that one approach to frost damage which has been discussed — though not implemented — might have detrimental effects. This is the idea of spraying crops at risk with non-ice-nucleating strains of bacteria pre-emptively, as a way of denying ice-nucleating strains the niche in which they might flourish. If this approach were

widely used, it is possible that it might significantly reduce the population of ice-nucleating bacteria aloft, with meteorological consequences.

[4.2] The cosmic (ray) connection

Another factor that may be relevant to cloud formation, but which falls outside the ambit of traditional approaches to the subject, is the possible role of galactic cosmic rays — high energy particles produced in intense magnetic fields associated with collapsing stars. When these particles reach the earth they interact with its atmosphere, knocking electrons off neutral atoms to produce ions. Indeed, cosmic rays are by far the largest single source of ionisation in the troposphere, producing one or two ions per square centimetre per second. Ionisation of cloud condensation nuclei may contribute to their effectiveness.

This idea has recently become particularly interesting because of its possible role in connecting variations in the sun's behaviour to variations in the earth's climate. The sun's brightness varies on a number of timescales, the most well-known being the 11 year solar cycle. Some of these variations have been linked to various climatic phenomena — perhaps most famously, the “little ice age” of the 16th, 17th and 18th centuries corresponded with a long period of low solar activity (measured by the number of sunspots) called the Maunder minimum. However, in general, variations in the sun's energy output are very small: the difference in the sun's brightness between the maximum and minimum of an 11-year cycle corresponds to a radiative forcing of about 0.2 Wm^{-2} ; longer term trends correspond to changes in forcing of about 0.009 Wm^{-2} per year.

Such forcings seem unlikely to account for significant climatic effects. However, given the evidence of regular cycling in the climate that seems to be linked to solar output, some thought has gone into looking for subtleties that might explain what such links might be. This thinking has been heightened, and to some extent politicised, by the issue of greenhouse gas-mediated climate change. The idea that solar effects might dominate climatic change is one that exonerates industrial processes, and has thus been popular with some pro-business lobbies.

Partly as a result of this, a complex and somewhat oppositional dynamic has sprung up in research on links between the sun and climate. Some researchers looking at links between the climate and solar output feel marginalised by the “consensus science” represented by the IPCC process, which they see as dominated by climate scientists from the GCM community who

perpetuate a “not-invented-here” attitude to explanations of climate change that do not depend on the make-up of the atmosphere and well understood forcings. This view plays into a david-and-goliath stereotyping of the debate, especially as it is represented in the media. At the same time members of the mainstream climate modelling community doubt the good faith of some of the claims made about solar output on the basis of the way those claims are used in lobbying against greenhouse-gas control. Solar output effects are considered in the IPCC’s Third Assessment Report, but not found to be supported by strong evidence of causal links. However, that does not mean the links are not there.

One possible link is the fact that the shorter the wavelength of the radiation, the more it varies over the cycle. If only the ultraviolet is measured, the sun can be 7 percent brighter at solar maximum than at solar minimum. This will lead to changes in the stratosphere, where the absorption of ultraviolet light is a significant source of heat, and these changes may be linked to changes in the troposphere through circulation patterns. Another possible amplifier is the cosmic ray flux. The solar cycle is a matter of magnetic activity as well as brightness — indeed, it is the changing magnetic activity that brings about the rise and fall in the number of sunspots that defines the cycle and controls the sun’s brightness (counter-intuitively, sunspot maximum is also the time of maximum brightness, because the bright rings that surround them more than make up for the darkness of the spots themselves). At times of maximum activity, the sun’s magnetic field, its field lines embedded in the plasma of the solar wind, provides more defence against cosmic rays from elsewhere in the galaxy than it does at solar minimum). The result is that the number of cosmic rays hitting the atmosphere varies by about 15 percent over a solar cycle, though the change in the troposphere is only about 10 percent.

Since one of the things that cosmic rays do is produce light radioactive isotopes, such as carbon-14 and beryllium-10, the link between cosmic rays and solar activity has allowed scientists to use ice cores in which the presence of these isotopes can be measured to trace changes in solar activity back a quarter of a million years. It is this new record which has allowed more and more correlations to be made between solar activity and climate, including some quite significant fluctuations.

The idea that cosmic rays could actually cause the climate changes linked to the solar cycle seems initially highly unlikely: the total energy flux in cosmic rays is no more than the amount of energy that falls to the earth in starlight, and less than a billionth of the amount received as

sunshine. However, if that energy is ionising the troposphere in such a way as to produce CCNs very efficiently it is conceivable that it might make a difference.

The strongest claims for a cosmic ray connection have been made by Henrik Svensmark of the Danish Space Research Institute, who in the mid 1990s found a strong correlation between global cloud cover, as recorded in a data-set produced by the International Satellite Cloud Climatology Project called ISCCP C2, and cosmic ray levels. More cosmic rays seemed to make for more clouds, with an equivalent radiative forcing in the region of $0.5 - 1.0\text{Wm}^{-2}$ over a solar cycle. However, this correlation has been criticised on a number of grounds. Taking account of the El Niño events that took place over the time period also seemed to explain the cloudiness changes, and it could be argued that if El Niño explained the data, invoking cosmic rays to do so was redundant. And when the ISCCP revised its data-set to take account of new calibrations and produced ISCCP D2, the correlation with cosmic rays seemed to vanish. Svensmark subsequently reanalysed the data and found a correlation between cosmic rays and the D2 figures for low-level cloudiness, as opposed to the figures for total cloudiness which he had used in his first correlation. While this is not an entirely invalid approach, choosing a new variable for your correlation from a wide variety of apparently equally valid possibilities after new data rules out the old one does look a little suspicious. New data that lengthened the period for which the D2 data-set provided figures have tended to undermine this second, low-level-cloud correlation, too — prompting Svensmark to suggest that the ISCCP needs to recalibrate again. The sense of special pleading is thus reinforced. However, the correlations between solar activity (as recorded in carbon-14 and beryllium-10, which are produced by cosmic rays) and changes in the climate (as recorded in paleoclimatological data on such things as the number of icebergs in the north Atlantic) remain, and require explanation.

One route to such explanation may be an intriguing experimental approach. Jasper Kirkby, a physicist at the European particle physics laboratory, CERN, has suggested building a cloud chamber — a device in which water vapour is coaxed into condensing through drops in pressure and their associated adiabatic cooling (see *Clouds 101*, Section 7) — into which an accelerator would fire simulated cosmic rays. The ionisation effects could then be analysed quite rigorously under a wide range of conditions. This proposal, called CLOUD, is currently under examination for possible funding. It is supported by an intriguing interdisciplinary team incorporating solar physicists, cosmic ray experts, particle physicists and accelerator builders,

cloud researchers who specialise in laboratory recreations of cloud microphysics and paleoclimatologists.

If CLOUD were to go ahead, it would mark a pleasing historical closure. In the early years of the twentieth century, cloud chambers were the most important tool of visualisation in what was then becoming particle physics; Lord Rutherford, the experimentalist from New Zealand who dominated early twentieth century atomic and particle physics in Britain, went so far as to call the cloud chamber “the most original and wonderful instrument in scientific history”. However, the inventor of the cloud chamber, Charles Wilson, intended his invention to be a way of illuminating the creation of clouds as seen in nature — in particular, of reproducing the effects he had frequently seen from the meteorological observatory on top of Ben Nevis, in Scotland.¹⁰ Wilson was always convinced that electrical phenomena accounted for a great deal of what went on in clouds. Though his Nobel prize was awarded for his use of the cloud chambers he had developed to track individual subatomic particles by means of the lines of droplets their ionisation trails left in saturated water vapour, he withdrew from particle physics fairly soon after these discoveries. He wanted to concentrate again on atmospheric phenomena, and eventually developed the first modern theory of thunderstorms. The idea that his cloud chamber, adopted by the more intellectually prestigious field of particle physics and then abandoned by it, might eventually be turned back to its original purpose by particle physicists with a newfound interest in the atmosphere would undoubtedly have pleased him.

[5.0] Conclusion

From pulsars pouring out cosmic rays to plankton letting loose their protection against salt, the causes of clouds may yet prove far flung. It is because of the particularly intriguing nature of these ideas that clouds were chosen as the topic for this article. However, while the range of disciplines with some interest in clouds may be peculiarly wide, the fact that clouds are subjects of interdisciplinary interest is not in any way remarkable. In general, the earth sciences are particularly in need of interdisciplinary approaches, and even in an intellectual and academic framework that does not do anything like as much to encourage interdisciplinarity as might be possible, ways are often found to meet those needs.

To some extent, issues in earth science lend themselves to interdisciplinarity through the very nature of the topic. The earth and its phenomena are primarily studied observationally, rather than experimentally, and thus outside the controls of the laboratory. While a laboratory physicist can construct physical phenomena for study that have no relevance outside physics, as can — *mutatis mutandis*¹¹ — a laboratory chemist or microbiologist, an earth scientist must study phenomena as they are in the world, and thus with any number of messy connections to phenomena that are the subject of study in other disciplines. Thus the integration of studies of clouds and of aerosols is not an arbitrary choice; it is a necessary step towards a proper understanding. In this respect, some forms of interdisciplinarity in the earth sciences are obligate. While a climate modeller can choose in his or her own work not to deal with aerosol effects, there is no respectable way to deny the need for someone, somewhere to be studying such effects.

If this is true in the earth sciences in general, it is particularly true when these sciences are required to inform policy debates. The way that policy questions divide up the world very rarely follows disciplinary lines. One of the most impressive aspects of the massive amount of work that has gone into the IPCC has been a real effort to try and bring together data from an extremely wide range of areas in an effort to guide policy making. One of the problems with this work, though, is that it has to be largely driven by consensus. To assemble the insights of a range of disciplines necessarily involves some removal of subtlety and some narrowing of the range of opinion in all of those disciplines. This is a besetting problem with interdisciplinary research, and one of the reasons that it is so easily done badly. The product of such a process

cannot claim to be “scientific” in the way that a single paper can be; it becomes part of a debate that takes place in locales far from the desk and the lab.

It is the fact that the interdisciplinary nature of attempts to understand clouds are a particularly striking version of those necessary in the earth sciences more generally that makes them a fruitful topic for discussion in the context of Hybrid Vigor’s attempts to understand (and encourage) such processes. But there is an extra dimension to the study of clouds that makes it almost emblematic of attempts to shape the unshapable, and thus of Hybrid Vigor’s efforts. The scientific study of clouds began rather more sharply than most fields of inquiry with a truly inspired piece of systematisation. In 1802 Luke Howard, a British apothecary and scientific amateur, produced for the first time a broadly applicable vocabulary for talking about clouds. He distinguished four basic descriptive terms for types of cloud: cumulus, meaning a heap or pile; stratus, meaning a layer; cirrus, meaning filamentous; and nimbus, meaning rain-yielding. A fifth term, alto, was used to differentiate clouds at intermediate altitudes. Compounds of these terms yielded terms for 10 distinct types of clouds that are still used 200 years later.

Howard’s Classification

Three types of high level cloud:

cirrus (wispy, “mare’s tails”);

cirrostratus (a thin translucent veil; sun visible, often with halo); and

cirrocumulus (small white puffs).

Three types of mid level cloud:

altocumulus (systems of puffy clouds; individual elements about the size of a thumbnail at arm’s length);

nimbostratus (dark layer of cloud that can cover whole sky, with rain or snow);

altostratus (thinner layer of even cloud, through which watery sun may be seen).

And four types of low level cloud:

stratocumulus (low, lumpy widespread cloud; individual elements about the size of your fist at arm’s length);

stratus (low uniform gray cloud; may drizzle);

cumulus (small, fluffy, separated, flat-based);

cumulonimbus (low based but tall, often with anvil shaped top; heavy showers of rain and snow, thunder and lightning)¹²

This achievement was widely feted both in science and the arts: Goethe, a huge fan of Howard’s (he fell out with the hugely influential romantic artist Caspar David Friedrich on the issue) wrote:

“But Howard gives us with his clearer mind
The gain of lessons new to all mankind;
That which no hand can reach, no hand can clasp,
He first has gain’d, first held with mental grasp.
Defin’d the doubtful, fix’d its limit-line,
And named it fitly. — Be the honour thine!
As clouds ascend, are folded, scatter, fall,
Let the world think of thee who taught it all.”

The ability to define the doubtful and fix its limit line is a great driver of efforts to understand clouds in the sciences and beyond. It is one of the reasons that the painter John Constable was fascinated by the depiction of particular clouds on particular days — a new interest for an artist, and one that brought his work into a new sort of relationship with time, situating art with a specificity never seen before. The advent of photography led to similar attempts — the nineteenth century astronomer Piazzi Smith devoted his later years to obsessive photography of clouds, as did the great photographer Alfred Stieglitz, seeing in clouds a way of creating a photography abstract and pure, of producing work that was entirely the artist’s and the effect of which could not be put down to any intrinsic aspect of the subject.

And yet, as all these attempts end up affirming, the clouds escape. The definition of the doubtful lasts only briefly; the limit line is passed over, or shrunk back from. Any attempt to construe the cloud as a definite thing ends up foiled — because the cloud is always a process, its vapours condensing and evaporating, its droplets drifting and falling. The processes at play do not obey limits in space and time — the seemingly defined clouds just highlight those processes as they appear at particular times and places. Perhaps its not too fanciful to suggest that a discipline is something similar. Its edges seem set, and it can be categorised, and yet it does not last, nor need to. Its form seems to make sense in a particular time and place, but will soon transform itself; it will rise or fall, amalgamate into something greater, or vanish away into thin air. And all the time the underlying and undefined processes of understanding play on.

[6.0] About the author: Oliver Morton

Oliver Morton, a Hybrid Vigor Fellow, is the author of *Mapping Mars* (St. Martin's Press, 2002). He is currently a contributing editor to many publications, including the journals *Nature* and *Science*; to the magazines *New Scientist*, where he has a regular column, and *Prospect*, where he is a member of the advisory board; and to the news publications *Newsweek*, *The Financial Times* and *The Wall Street Journal*. He was the youngest science and technology editor to serve at *The Economist*. Morton writes from Greenwich in the U.K.; in deference, as you doubtless already noted, we have left the British spellings intact.

[7.0] Clouds 101: A Primer

All chemical substances can take solid, liquid or gaseous forms, depending on the temperature and pressure. For clouds to form, all that is necessary is that the temperature and pressure conditions prevalent in some parts of an atmosphere are such that a substance which is gaseous under the conditions elsewhere in that atmosphere condenses into a liquid or freezes into a solid. In the earth's atmosphere, the changeable substance is water, which typically makes up one or two percent of the atmosphere. Above Venus, the changeable substance is sulphuric acid. In the tenuous atmosphere of Mars it is mostly carbon dioxide. In the atmospheres of Jupiter and Saturn, clouds of ammonia form. It is thought that in the large, hot planets that have been discovered in close orbits around other stars there may be more exotic clouds, perhaps of magnesium silicates; the exquisite recent observation of sodium levels in the atmosphere of a planet orbiting a star called HD209458 suggest that such clouds may in fact be present there. Nor is the phenomenon restricted to planets. The faces of some small stars, relatively cool by starry standards, are mottled with clouds of molten iron.

The formation of clouds in the earth's atmosphere is brought about by the cooling of air that contains water vapour. The question of whether water is present in the atmosphere as a gas or a liquid depends on the temperature of the air and the amount of water vapour (the "partial pressure"); the partial pressure at which water vapour will naturally condense into liquid water is known as the saturation vapour pressure, and this declines with temperature. A common way of understanding this is to imagine air losing its capacity to "carry" water as it gets colder, and though this is not really accurate, it is a serviceable image.

At 30°C water's saturation vapour pressure is just over 40 millibars; at 0°C the saturation pressure is just six millibars. This means that when moist air is cooled down, the water vapour within it will at some point condense out into liquid water; the temperature at which it does so will depend on how much water vapour is present in the first place. When this condensation happens in midair, the result is a cloud. The following two sections explain the basics of cloud formation and precipitation; readers who need no illumination in these areas of basic meteorology are welcome to skip ahead.

[7.1] Coming into being: cloud formation in practice

How does cloud formation work in practice? Consider the development of scattered fair weather clouds on a summer's afternoon somewhere in the plains of America. They are caused by columns of warm air rising from close to the surface. As the air in these thermals rises it expands, and this expansion cools it — a process known as adiabatic cooling. The rate of cooling for air in which the partial pressure of water vapour is below the saturation vapour pressure is about 10°C for every thousand metres – this is known as the “dry adiabatic rate” of cooling.

At a certain height above the plains, the rising air will become cool enough for the water vapour in it to start condensing. The height of this level depends on the partial pressure of the water vapour in the rising air; drier air needs to rise higher. This is why, in general, the base of the clouds on a summer day gets higher as one travels west across America into the drier air of the continent's heart; on similar days the clouds will be higher around Denver than around Kansas City, and higher still over Nevada. Once the water starts to condense the rate at which the rising air cools adiabatically (that is, without importing or exporting heat) slows down, because the condensation releases latent heat. (Turning water vapour at a given temperature into liquid water at the same temperature releases heat into the environment; evaporating liquid water to form water vapour at the same temperature draws heat from the environment. This is very well demonstrated in the concourse of Marseilles' St Charles railway station during the summer, where a high-level misting system is used to cool the hot air down. The release of latent heat means that air saturated with water vapour cools at about 6°C per 1,000 metres, the “moist adiabatic rate”. (The moist adiabatic rate is itself temperature dependent; at relatively high temperatures it is lower than the 6°C per 1,000m average, at low temperatures it is lower.)

The warm air will keep rising and cooling until it is no longer warmer than the air through which it is passing, at which point it loses buoyancy – the top of the cloud represents the level at which the rising air has cooled to the temperature of the air around it. The height at which this happens depends on the environmental lapse rate – the way that the temperature of the air through which the thermal is rising changes with altitude in that particular place on that particular afternoon. For fair-weather summer cumulus that might typically be about 1,000 metres above the condensation level, within the part of the atmosphere, known as the boundary layer, where conditions are dominated by the surface below.

However this will not necessarily be the case. If the surrounding air gets cooler with altitude at a rate higher than the moist adiabatic rate — say at 7°C per 1,000 metres — then the rising air will keep on rising higher and higher. This condition, where the environmental lapse rate is greater than the moist adiabatic rate, is known as conditional instability. In a stable atmosphere, the lapse rate is less than the adiabatic rate; this means that if a packet of air at a given height, and at the same temperature as other air at that height, is raised up, adiabatic cooling will make it cooler than its surroundings (because the adiabatic rate is greater than the lapse rate) and it will sink back down to its starting point. In an unstable atmosphere, the lifted packet, while cooler at its new height than it was, will still be warmer than the surrounding air (because the difference in the surrounding temperature due to the lapse rate is greater than the cooling due to the adiabatic cooling) and will thus rise yet further.

If the environmental lapse rate is higher than the dry adiabatic rate of cooling the atmosphere is absolutely unstable; if it is intermediate between the dry adiabatic rate (10°C per 1,000m) and the moist adiabatic rate (6°C per 1,000m) it is conditionally unstable – unstable with respect to moist air but not to unsaturated air. This is, globally, the average condition (the average lapse rate in the lower atmosphere is about 6.5°C per 1,000m). Instability tends to depend on some mixture of cooling at high altitude and warming at low altitudes. The higher parts of the troposphere (the lowest 10km of the atmosphere in which clouds normally form) can be cooled either by high level winds bringing in cold air or by clouds emitting infrared radiation to space and cooling their surroundings. The lower levels can be warmed by warm surface winds and warm surfaces. Mixing between low and high air will also tend to increase the lapse rate, since sinking air will be warmed adiabatically and rising air cooled. And lifting a layer of air with a moist base and a dry top will also lead to instability, since the top will cool much quicker than the bottom.

In the example of the great plains on a summer afternoon, the difference between stable and unstable conditions between two and ten kilometres is the difference between a layer of fluffy little cumulus humilis and great towers of cumulonimbus, their heads reaching so high that the water vapour in the highest parts of the cloud turns almost entirely to ice, spreading out like the top of an anvil at more or less the height where the troposphere gives way to the dry, warmer and stable stratosphere. Clouds can be produced by many other mechanisms, including the passage of air over mountains and the lifting of air due to the passage of cold and warm fronts. As a warm front slides over cold air the warm air in it is forced higher, typically forming layers of high cloud that run ahead of the front's position on the ground (because the front is further

advanced at altitude). As a cold front shovels warm air away from below the clouds tend to form in air pushed up from behind the front. The basic processes, though, are the same, and the role of instability in the atmosphere often crucial in determining the cloud's nature and extent.

[7.2] Passing away: evaporation and precipitation

Once water is in a cloud in the form of droplets of water or crystals of ice, there are two ways out: it can turn back to vapour, or it can fall. For our puffy little summer cumulus, the likelihood is evaporation: as dry air from the surroundings mixes with the moist air of the cloud, the water vapour content of the cloud will eventually fall below the saturation vapour pressure, at which point the droplets of water in the cloud will quickly evaporate. The fact that water evaporates quickly once the air around it is unsaturated accounts for one of the basics of cloud classification. Warm clouds composed mainly of water droplets are quite dense to look at and have reasonably sharp edges, because when water droplets find themselves outside the region of saturated air that makes up the heart of the cloud they evaporate relatively quickly. Ice particles, on the other hand, last longer in unsaturated air, allowing ice clouds to be thin and fuzzy at the edges. The sun, and even moon, can be seen through icy clouds, but not, by and large, through watery clouds. (The exception is altostratus, a mixed ice/water cloud which is most easily distinguished from lower-lying true stratus by the fact that the sun is visible through it.) But though the process may be slow, icy clouds do evaporate and can moisten the air below them in ways that may be significant.

The formation of water droplets depends on the presence of small specks of matter floating free in the atmosphere: these "aerosol particles" act as nuclei on which condensation can take place. In the absence of condensation nuclei the partial pressure of water vapour can exceed the saturation vapour pressure. In the absence of nuclei that, through their shape, encourage water to freeze, water droplets can stay liquid at temperatures well below the freezing point; clouds of water droplets can be cooled to -40°C before the water in them spontaneously transforms itself into ice. A vapour at or above the condensation vapour pressure in which condensation is not taking place is referred to as "supersaturated"; a liquid that does not freeze even though it is below its freezing point is referred to as "supercooled". Only moderate levels of supersaturation are seen in the earth's atmosphere, because there are quite a lot of aerosols around on which condensation can take place; relative humidities of more than 102 percent (just over the saturation pressure) are hardly ever seen. However supercooling is quite common, because

only a very few aerosol particles have a surface that encourages freezing; clouds can be composed almost entirely of water droplets down to temperatures of -35° or so.

The size of the condensation nuclei on which liquid water droplets form is an important factor in the development of a cloud. At microscopic scales, evaporation and condensation become more sensitive processes than they are in the macroscopic world of freezing lakes and steaming cups of coffee. The more curved a water surface is, the higher the saturation vapour pressure above it, and while macroscopic water surfaces are pretty flat, the surfaces of microscopic droplets are strongly curved. For very small droplets the curvature raises the local saturation vapour pressure above the partial pressure of water vapour in the surrounding cloud, making the droplets unstable. However impurities in the water, such as dissolved salts, act in the opposite way, reducing the saturation vapour pressure. The effect of impurities is thus to make smaller droplets possible, and the minimum size of stable droplets is a function of the water's impurities.

The formation of cloud droplets is a necessary condition for precipitation, but not a sufficient one. Most droplets form on nuclei sizes of around a micron in radius and quickly grow to about 10 microns in radius through further condensation, a process that may take about a second. However droplets in this size range this will never precipitate; because they are so small and light, the speed at which they can fall through the air (their terminal velocity) is kept very low due to the resistance of the air. A ten-micron particle would take five days to fall 100 metres. Only when droplets get up towards the millimetre size-range does their terminal velocity become high enough for them to fall out of their cloud. And growing to such size represents a problem: a two-millimetre-radius raindrop contains four million times more water than a ten micron cloud droplet, and will take a very long time to grow to such size through condensation alone, time during which it would have to stay in saturated air.

In fact, drop growth is not dominated by condensation; it is dominated by collision. Droplets grow by bumping into other droplets and coalescing with them. Droplets that start off large (because they have coalesced on larger nuclei, or nuclei with a particular affinity for water) have an advantage in this area; the larger a droplet, the quicker it can grow by coalescence, since it falls through the cloud faster, has a larger surface area, and is more likely to coalesce with a droplet it comes into contact with. Large droplets may be rare in number in a cloud, but at the same time they can contain a large fraction of its water, since the larger droplets are so much more voluminous. Once a drop reaches a diameter of about 3 millimetres it becomes unstable and splits into smaller drops, all of them still large enough to grow quickly by coalescence.

Making raindrops by coalescence requires that the larger droplets fall through the air and in so doing sweep up smaller droplets. This means that only clouds which are relatively thick, or which contain circulating air that can lift a falling droplet back up, will produce rain. In other circumstances the drops will fall out before reaching raindrop size, and being small — and thus falling slowly — makes such drops liable to evaporate before reaching the surface. (This fate can also meet full-scale raindrops under some circumstances, producing a phenomenon called "virga" in which wisps of precipitation can be seen below clouds — and detected by weather radar — but never reaches the ground.)

The other mechanisms for producing raindrops out of clouds involve freezing. Because particles with the properties required for ice nucleation are comparatively rare compared to the range of particles that can cause droplet condensation, ice crystals in most clouds of supercooled water will be vastly outnumbered by water droplets. However, another oddity of the way things condense and freeze means that the saturation vapour pressure with respect to ice and the saturation vapour pressure with respect to liquid water are not quite the same; the saturation vapour pressure with respect to ice is, in the region between 0°C and –20°C, a couple of tenths of a millibar less than the saturation vapour pressure with respect to liquid water. So if the water vapour in a cloud is at the saturation vapour pressure with respect to water it will be supersaturated with respect to ice, and ice crystals within it will grow into snowflakes much faster than droplets condense into raindrops. So though it's harder to get started as an ice crystal, its easier to grow large once you've begun. What is more, under some circumstances the ice can effectively eat up the water droplets; if the level of water vapour in the cloud is above the saturation vapour pressure with respect to ice but below the saturation vapour pressure with respect to water, then water droplets will evaporate, freeing more vapour to freeze out onto the ice. And ice crystals can shatter, just as raindrops divide, thus providing more small ice particles. These processes mean that a large part of a moist cloud can be turned into precipitation in tens of minutes. In temperate latitudes, a great deal of what falls to the earth as rain starts off as snowflakes created this way and subsequently melted into raindrops on the way down.

[7.2.2] Titan: Clouds in the coldest of climates

On the basis that seeing familiar processes play out in unfamiliar ways can be a source of illumination, it's possible that new insights into the basic processes of precipitation and the behaviour of clouds may arise from the study of rain on Saturn's moon Titan. The first such studies *in situ* should become possible when the international Cassini mission goes into orbit around Saturn. NASA's Cassini will drop a separate European

probe — Huyghens — into Titan's atmosphere when it first arrives in 2004; during a series of encounters with Titan that should continue for years, it will also make a variety of measurements from space to reveal the atmosphere's structure.

Titan's atmosphere is very cold — 170°C or lower at the surface and through the troposphere, a little warmer in the stratosphere — and mostly nitrogen, with some argon and perhaps as much as 8 percent methane. Smoggy hazes of more complex hydrocarbons make the atmosphere opaque; when Voyager 1 flew past it in 1980, and to the cameras of the earlier Voyager missions, Titan was a featureless ball. Though measurements of Titan's upper atmosphere made by Voyager 1 revealed that large parts of it were supersaturated with methane, meaning that in principle methane clouds could form there, in practise the spacecraft saw no clouds. This led to the belief that for some reason — perhaps a lack of condensation nuclei, or extreme stability — Titan's atmosphere did not form clouds.

More recent observations from earth, though, made at infrared frequencies in which the hazy atmosphere is expected to be transparent, have shown that there are transient changes in moon's brightness which are best understood as clouds of methane, and possible also of ethane, a slightly heavier hydrocarbon.¹³ The fact that these clouds seem to come and go suggests that there may be rain on the moon as well. According to calculations by Ralph Lorenz, methane raindrops in Titan's atmosphere will be considerably larger than water raindrops on earth, perhaps up to about a centimetre in diameter. They will also be exceptionally slow, falling through Titan's thick atmosphere and its weak gravity at a languid 1.6 metres per second. And they will be quite rare; thermodynamic considerations suggest that in Titan's cold atmosphere the amount of energy available is enough to provide only 6 millimetres of precipitation a year (the same arguments, applied to earth, predict about one metre a year, which is close to what is observed). Since the atmosphere near the surface seems not to be saturated with methane, the likely fate for such drops is probably evaporation.

However, when falling raindrops evaporate close to the surface they will increase the partial pressure of methane, possibly allowing the rain that follows to get through the corridor of moisture that they create. It's conceivable that rain on Titan may be rare but heavy, with many years worth of precipitation in a single downpour.

It is not immediately clear what the study of Titan's clouds and rain might add to our understanding of such processes on the earth (where they are, after all, much easier to study). Experience suggests, though, that understanding the processes of other atmospheres can reveal insights into similar processes in the atmosphere of the earth processes which may not have been studied but may be important. The first Mars orbiter, Mariner 9, observed a dust storm that chilled the whole surface of the planet; questions about the possibility of such a thing happening on earth were one of the starting points for research into the possibility of nuclear winter. Studies carried out to help understand the behaviour of chlorine and fluorine in the upper atmosphere of Venus (where chlorine is hundreds of times more common than it is in the atmosphere of the earth) provided some of the empirical data used in Sherwood Rowland and Mario Molina's Nobel-prize winning work on the destruction of ozone by CFCs; computer programs designed to mimic the chemistry of Venus were vital to some of the modelling work that followed up on their insights. In both cases ideas needed for understanding other planet's atmospheres provided insights into possible futures of the earth's. There is

no guarantee that such insights will come from watching the walking-pace rains of Titan. But it would be foolish to rule out the possibility.

[7.3] Co-dependent behaviour: clouds and particles

Both with respect to the formation of water droplets and ice particles, the behaviour of clouds depends crucially on the presence of other particles in the air. These aerosol particles include components from the soil, from the sea, from plant matter and from man-made (anthropogenic) sources; they range in size from clusters of a few atoms up to particles measured in millimetres (wings separated from the insects that grew them, for example); it's a range of sizes, as Owen Toon of the University of Colorado points out, as extensive as that which separates baseballs from planets. The surfaces of these particles are crucial to the development of clouds, and it is in trying to understand the interactions between particles and clouds that the study of clouds becomes most open to interdisciplinary influences.

Further explanation of the role of aerosols in cloud condensation can be found in Section 3.1, page 17.

[8.0] Endnotes and Bibliography

Endnotes

¹ Greenhouse gases, like carbon dioxide (CO₂), trap heat in the atmosphere by absorbing longwave radiation while letting the sun's energy pass through. Concerns are centered about the effects on climate (i.e., global warming) of adding too much anthropogenic, or man-made, greenhouse gas to the environment.

² Recognizing the problem of potential global climate change, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The role of the IPCC is to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change, basing its assessments mainly on peer reviewed and published scientific/technical literature.

³ Image, courtesy *Bulletin of the American Meteorological Society*

⁴ <http://earthobservatory.nasa.gov/Study/CloudsInBalance/>

⁵ <http://www.atmos.washington.edu/~dennis/Papers.html>

⁶ <http://ams.allenpress.com/amsonline/?request=get-pdf&file=i1520-0477-082-03-0417.pdf>

⁷ http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=7259

⁸ <http://www.natureasia.com/japan/sciencenews/psu/psu000112/psu-000112f.html>

⁹ Lovelock, who not only has a university training as a chemist but also served a formative apprenticeship in a commercial chemistry lab, has a well trained and sensitive nose, and makes full use of it as a tool for understanding the world. It would be intriguing to know how common this mode of analysis is, and whether it is on the wane.

¹⁰ An observatory built in the same widespread fit of mountain-based meteorology that provided the Alpine observatory at Sonnblick where Birgit Sattler found her living cloud bacteria.

¹¹ "With respective differences taken into consideration"

¹² For references, consult <http://www.weather-photography.com/Clouds/>

¹³ Griffith et al. *Science* 290, p509 (2000); Griffith et al, *Nature*, 395, p575 1998

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