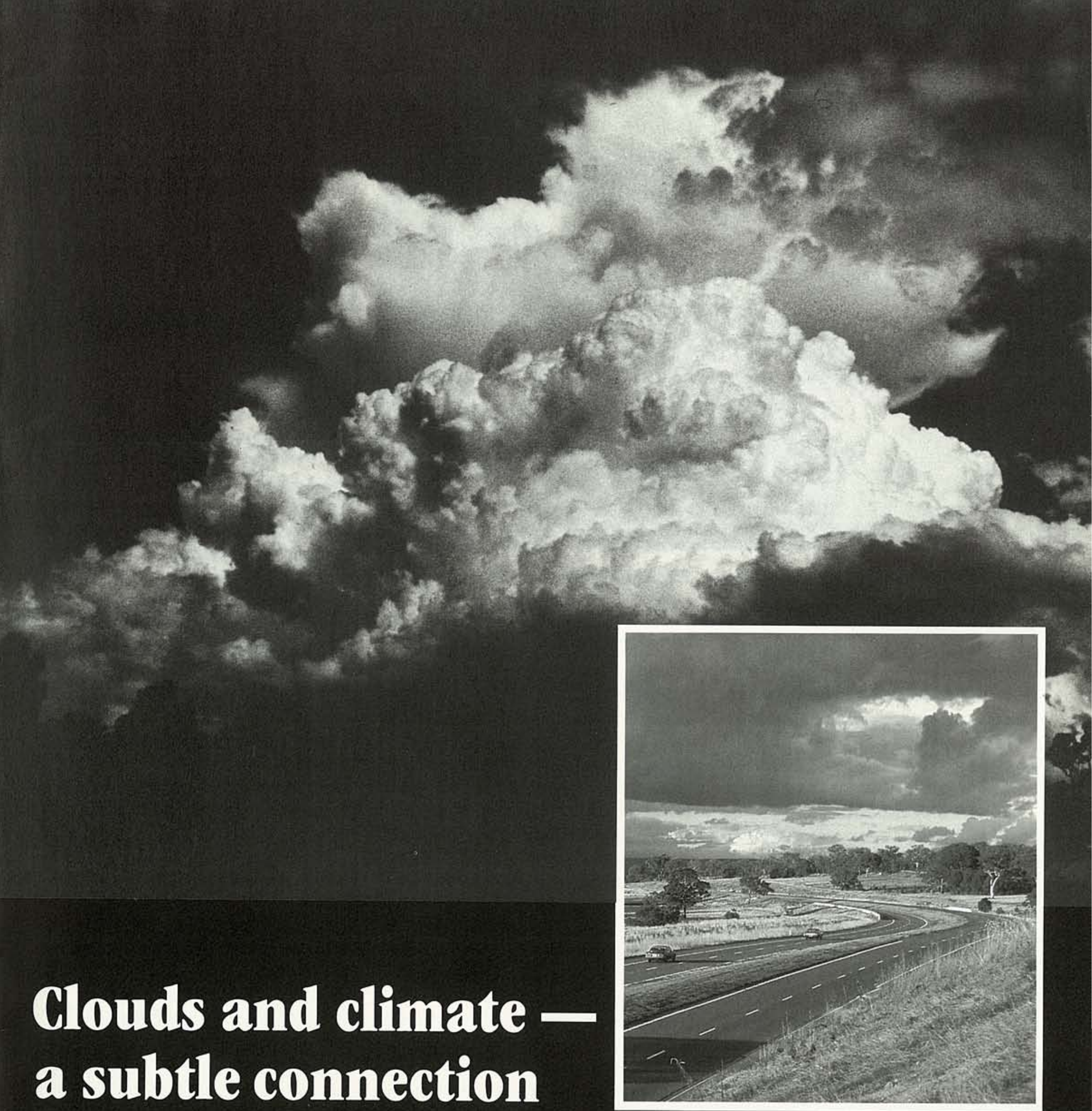


Clouds and climate — a subtle connection

Floating serenely, or boiling tempestuously, clouds roam the skies like free spirits. Although clouds cover half the world's surface, the role they play in the functioning of the earth's climate is far from clear.

Some scientists believe it is a crucial one. Others see clouds as incidental — a backdrop, albeit beautiful, to the staging of the fundamental long-term energy-exchange processes of the atmosphere.

Researchers in the CSIRO Division of Atmospheric Research and the Australian Numerical Meteorology Research Centre are trying to clarify the part that clouds play in controlling climate. The work is important for answering questions about the stability of climate, particularly in evaluating the influence of increased carbon dioxide levels, or possible lowered ozone concentrations. For example, could a change in cloud cover compensate for a warming tendency caused by a build-up in the atmosphere's carbon dioxide?

Energy in, energy out

The sun is the prime mover for the atmospheric heat engine, that conceptual machine whose ceaseless goings-on manifest as the weather. The sun's energy, mainly visible short-wavelength radiation, impinging on the earth tends to heat it up. Of course, the earth's temperature doesn't keep increasing — the gain in short-wavelength radiation is more or less balanced by loss of heat to space by long-wavelength infra-red radiation. In the middle are clouds.

They affect the radiation balance by modulating the energy flows in various ways. Considering the short-wavelength radiation, a cloud will act like a white sun-hat: it will intercept the sun's short-wavelength radiation and reflect it back to space, lowering the input of energy to the earth. (Really

hot days are the ones with cloudless skies.) The denser the cloud is, the greater the amount of visible radiation it will reflect and the whiter it will appear from space. The technical term for the fraction reflected is the 'albedo'. A jet-black cloud will have an albedo of zero, a snow-white one an albedo of 1.

At the long-wavelength end, however, a cloud will act like a blanket: it will prevent heat emitted by the earth from escaping. Instead, this long-wavelength radiation will be absorbed and re-emitted back downwards, lowering the earth's heat loss. (The hottest nights are those with an overcast sky.) The denser the cloud is, the greater the amount that, in an equilibrium situation, will be returned to the ground: this quantity is measured by scientists as the cloud's 'emittance'. Infra-red photography will show a cloud with low emittance as dark, whereas one with high emittance will appear light.

A cloud's radiative properties relate to a single quantity: the cloud's liquid water path. It is the depth of water (or ice) a cloud could be condensed to.

Liquid water path

Conveniently, these cloud properties can be tied together using a single measure, the cloud's 'liquid water path'. The accompanying graph shows these relations.

The significance of the liquid water path began to be appreciated by scientists in the 1970s after work by Dr Garth Paltridge and Dr Martin Platt, of the CSIRO Division of Atmospheric Research, pointed to its dominance in controlling the infra-red behaviour of clouds. Later, Dr Graeme Stephens of the Division demonstrated that the liquid water path played an equally vital role in influencing a cloud's exchange of visible radiation.

As the name suggests, the liquid water path is the depth a cloud would occupy if the water (and ice) that make it up were condensed flat. Its physical significance lies in the fact that it is the depth of water (or ice) through which a light beam must pass in travelling through the cloud in a line of sight.

To get a feel for how tenuous clouds are, remember that a cloud veils the sun's disc from our sight whenever its liquid water path exceeds a minute amount — just 0·01 mm! A continuous film of water this thick would be close to invisible, but broken up into tiny droplets only 10 micrometres in radius (millions of them per cubic metre) the water very effectively scatters light in all directions.

Concerning infra-red radiation, water absorbs it very strongly indeed, and a film 0·01 mm thick presents an impenetrable infra-red barrier.

The density of a typical cumulus cloud is only about 1 gram per cubic metre; a cirrus cloud is even more nebulous — about 0·001–0·01 g per cu. m. Surprisingly, considerably less water occurs as droplets in clouds than you will find in cloudless air as water vapour (some 5–10 g per cu. m).

Because water absorbs infra-red radiation so strongly, the long-wavelength properties of all low clouds are virtually the same — even thin low clouds absorb and re-emit a good fraction of the heat radiation striking them. In contrast, thin clouds let most visible radiation through — you can see through them. Only dense cumulus and stratocumulus clouds approach a snow whiteness when observed from above, and even then their albedo can increase further if the density permits. To the watcher on the ground, the darkest cloud cover appears during a thunderstorm, when towering cumulus achieve truly large liquid water paths. On such occasions we find it hard to appreciate that on the other side of that blackness it is blinding white.

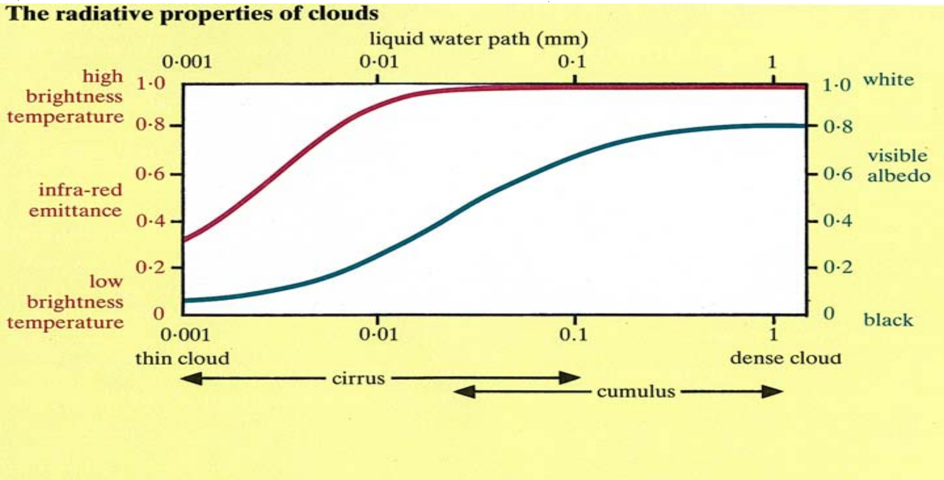
Sun-hat and blanket

The main point is that clouds act like both sun-hat and blanket. The question then is (figuratively speaking): if you wear both items of apparel, like some Arab tribespeople do, are you warmer or cooler than without them? (We must consider their effects averaged over day and night for long periods of time, for we are talking about climate.)

The answer depends on which effect — sun-hat or blanket — is larger. The heat balance depends on a great number of factors, but total cloud cover, cloud altitude, and cloud type are the main ones.

Theoretical studies by Dr Stephens with his colleague Dr Peter Webster (now in America) have added to our understanding of how these diverse factors work together. Taking cloud height first, we now know that clouds at low and middle heights in the

The radiative properties of clouds



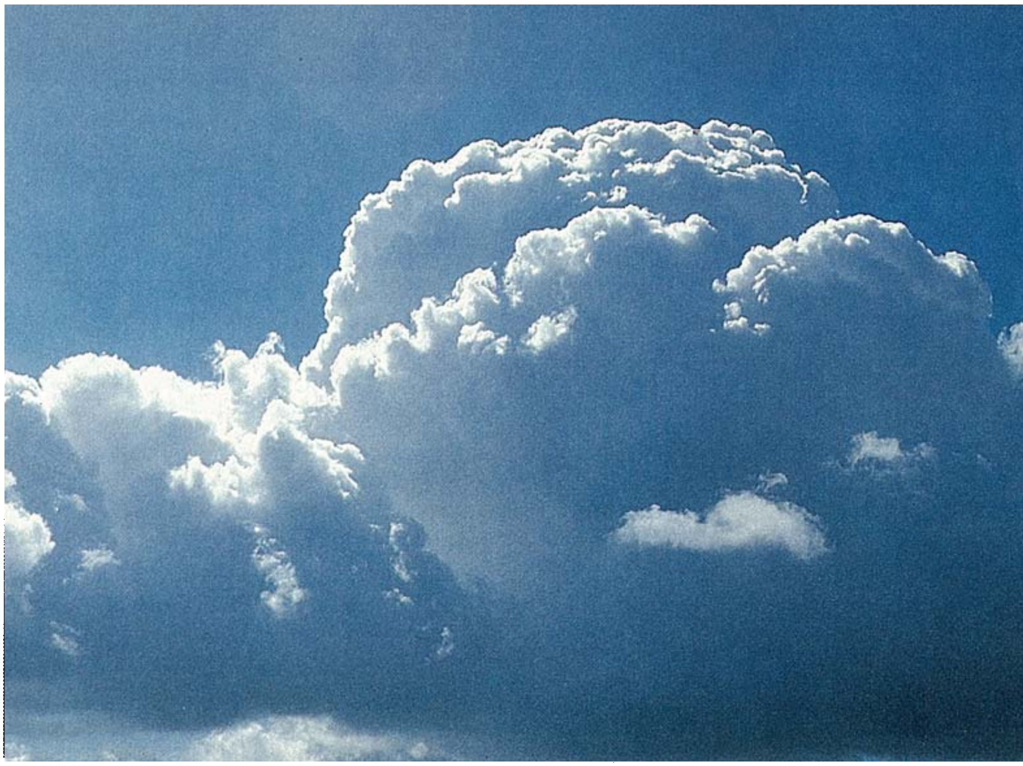
atmosphere tend to decrease the surface temperature, whereas high clouds do the opposite. Low clouds are cumulus (or stratus or stratocumulus) whereas high ones are cirrus, and the reason for their different effects lies in their nature.

Cumulus cools

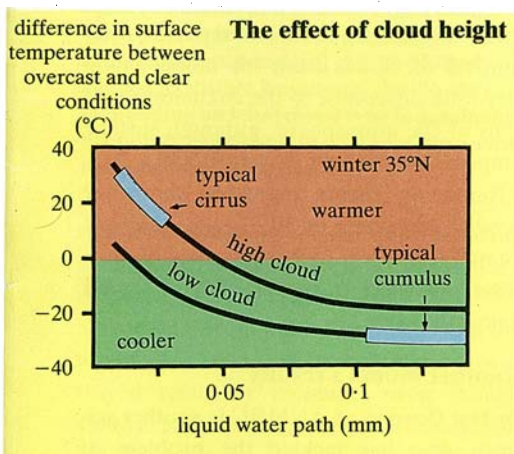
Cumulus clouds are the workhorses of the climate system. Their distinctive round tops result from a convective boiling as large quantities of water condense and release latent heat. In the tropics, particularly, they are visible manifestations of the atmospheric heat engine — indeed, its major part.

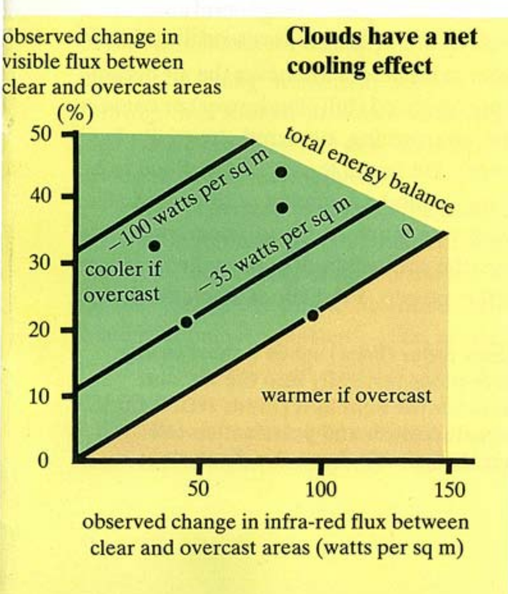
Brim-full of moisture, cumulus clouds have a high liquid water path, giving rise (as the graph shows) to a high emittance and high albedo. Because they occupy low altitudes, their temperature is not much different from that of the earth, and so they radiate heat to space at about the same rate. However, they reflect more of the sun's energy than the earth does, and so the net effect of their presence is to cool.

If something is going to restrict the predicted climatic warming induced by carbon dioxide, then the formation of extra cumulus or other types of low cloud may be it. The warming may lead to more evaporation, more cumulus, and hence a reduction in warming — a negative feedback effect.



Typical cirrus clouds warm the surface, whereas cumulus ones cool it.





The dots are the results of satellite studies comparing clear and overcast areas of the earth. They show that overcast areas lose more energy to space than clear areas.

Cirrus warms

But then the extra evaporation may lead to an increase in cirrus — a different kettle of fish. High wispy cirrus clouds are cold and composed of ice crystals. They have quite short liquid water (in this case ice) paths of about 0·001 mm. As our graph shows, this means their albedo is only about 3% that of cumulus clouds, yet their emissivity will be perhaps 20% that of cumulus clouds.

In other words, much more energy passes through them to the surface, while the blanketing effect against heat loss is not reduced by nearly as much. Cirrus tend to warm the earth.

This warming is accentuated by the low temperature of cirrus clouds, which means that less long-wave radiation is sent off to space from the top of the cloud. The higher (and colder) the cloud, the more pronounced this effect will be.

Surprisingly, then, thin wispy cloud high up in the sky can be blocking half the ground-released heat from leaving to space. During the night, thin cirrus can trap as much radiation as thick cloud lower down. To refine the analogy, cumulus acts most like a parasol (Latin: *ward off the sun*), whereas, in the same vein, cirrus might be likened more to a delicate silk shirt than to a blanket.

The heating or cooling effect of clouds is very pronounced, and Dr Stephens and Dr Webster have calculated that about a 10% increase in low cloud or 10% decrease in high cloud would reduce average global temperatures at the surface by the same amount that a doubling of carbon dioxide (without a change in cloud cover) would increase them (most predictions go for a 2–3°C rise). Unfortunately, we don't know how much change in cloud cover a carbon dioxide doubling would produce, or even whether the change would be in the wanted direction (at one or other level).

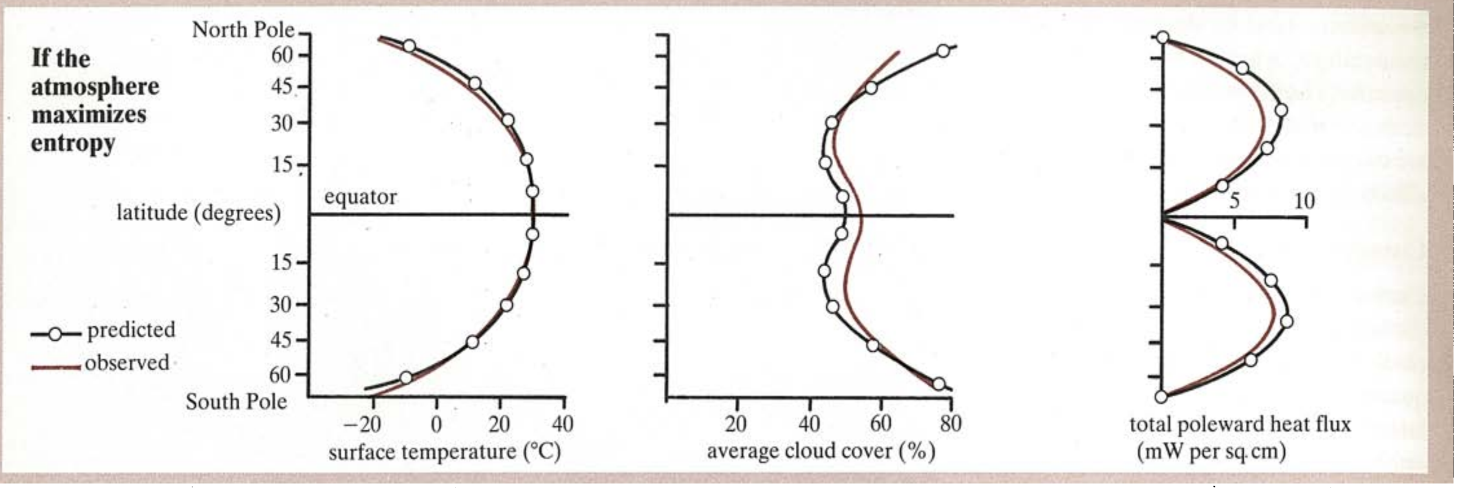
Satellites test the link

In trying to uncover experimentally the links between cloud and climate, a number of scientists have used satellite observations to measure how the radiation flux from the earth changes with cloudiness.

If cloudy areas show, on average, a greater energy flow to space than clear areas, then we would expect that increased cloud cover on a global scale (due to increased carbon dioxide, for example) would lead to a cooling effect.

In a pioneering study in 1976, an American scientist, Dr R.D. Cess, concluded that the difference in space-bound energy flux between overcast and clear areas of the earth was essentially zero. This suggested that clouds are merely incidental to the running of the climate machine.

However, other scientists have found fault with this result, and later work has pointed towards clouds exerting a total cooling effect. On average, according to a number of studies, the earth's cloud cover appears twice as effective in reflecting solar radiation as in trapping terrestrial radiation. The net result, shown in the diagram at left, is that the outwards energy flux



Dr Paltridge finds that he can predict major aspects of the atmosphere's behaviour if he assumes that the atmosphere, in distributing the sun's energy, maximizes entropy production.

differs between clear and cloudy areas by about 50 watts per square metre.

Feedback effects

This implies that an increase in cloudiness will lead to lower temperatures on the ground. But the question of feedback remains to be tackled.

Every imbalance has an effect of its own. Conceivably, lower temperatures could produce less cloud, which in turn could have a warming effect (a negative feedback effect). But is this feedback effect significant, or is it so small it can be disregarded?

The theoretical and experimental approaches looked at so far have not considered feedback. Dr Stephens calls them 'open-loop' or 'non-interactive' models that only gauge an initial tendency. We tend to get into trouble when we carve nature up into cause and effect, because ultimately effects become causes in giant interlocking loops that our linear thinking finds hard to grasp. If we are to consider feedback, then we need a 'closed-loop' model.

Because the atmosphere is so complicated, the only models capable of taking feedback into account are the numerical models run on huge computers — the stock-in-trade of weather forecasters. These 'general circulation models' start with a 'snap shot' of the atmosphere at a given time, and, using equations of motion, predict how the atmosphere will develop hours or days in the future.

Atmospheric temperature, pressure, and winds are the main variables, and a broad radiation budget of the earth and atmosphere is also introduced. However, the grid scale of the model (typically points 200 km apart in layers 2–3 km thick) is too coarse to accommodate cloud in detail. The model can be programmed to introduce cloud in an area if, say, the humidity there exceeds a pre-set level.

Ultimately effects become causes in giant interlocking loops.

Complementary

While only closed-loop models can simulate the atmosphere's activity with reasonable accuracy, open-loop models have important roles to play in climate studies. They can show the relative sensitivity of climate to various factors; for example, they can be used to estimate the immediate effects on temperature of an increase in cloud cover or a build-up of carbon dioxide levels. The results of such studies are then incorporated into more comprehensive closed-loop models.

Open-loop models are mathematically simpler, and this allows finer-scale modelling. Details such as cloud amount, height, and radiative properties can be included. The effects of changes in any one parameter can be readily observed. However, the results can be seen only as the initial changes produced by the modelled event and bear an unknown relation to what would happen in the real atmosphere.

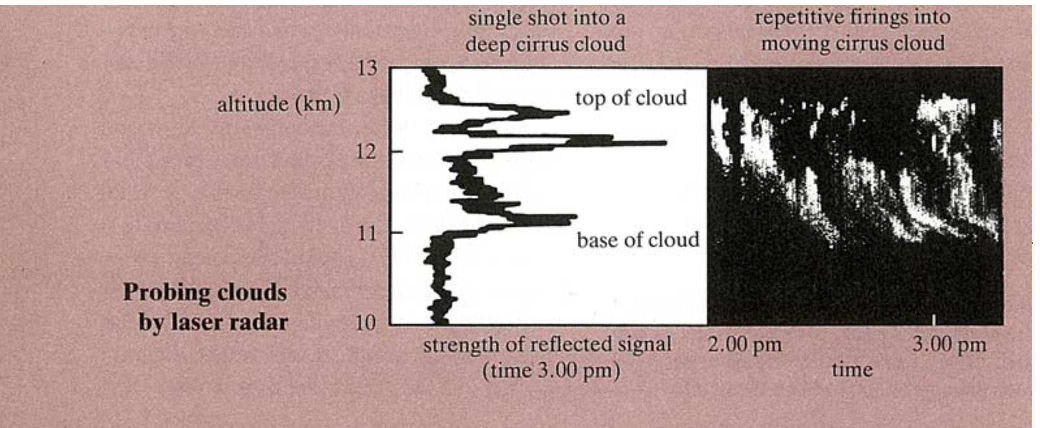
A numerical model experiment

Mr Barrie Hunt of the Australian Numerical Meteorology Research Centre (ANMRC) was one of the first scientists to test the effect of cloud in a closed-loop numerical model. In 1978 he reported that removal of clouds from his model made very little difference to the circulation patterns of the atmosphere, although surface temperatures increased by 4–10 °C.

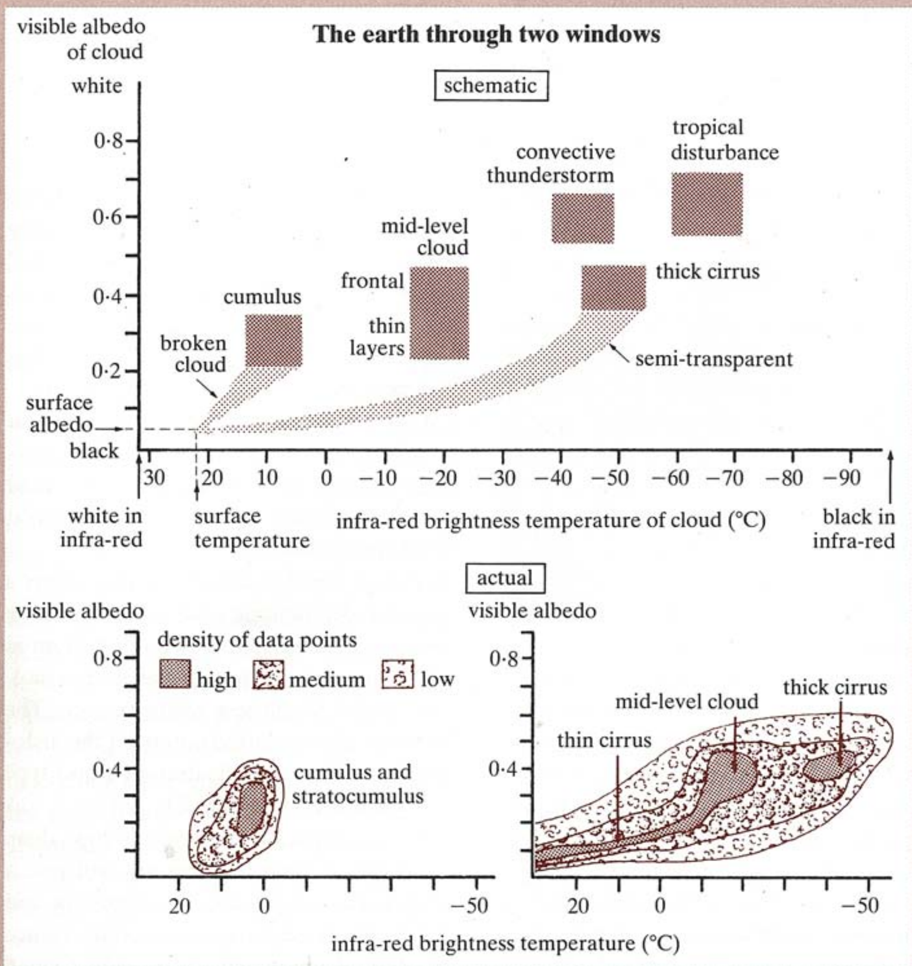
Removing clouds increased the solar input at the surface by 30%, a gain that was counteracted by a higher infra-red output. Total poleward transport of heat stayed almost the same.

Another model's results

Dr Hal Gordon of ANMRC is another scientist who has tackled the problem of accommodating cloud in general circulation models. He arranged for cloud and rain to occur in his model whenever the air became supersaturated (full cloud cover) or convective overturning occurred (partial cloud cover). He found the predicted cloud to be in quite good agreement with reality. The smaller amount of cloud cover occurring over the continents than over the oceans is well captured. Predictions of cloud at par-



Laser radar (lidar) sends a short strong laser pulse vertically into the sky and registers the light that clouds reflect back. Signal strength and polarization tell scientists much about cloud structure.



An area of satellite picture about 500 km square contains about 40 000 data points. Each point's infra-red brightness (its brightness temperature) can be plotted against its visible brightness (its albedo). Depending on what cloud type is dominant, the points will cluster in different regions of the resulting histogram.

ticular instants also appear quite realistic, even though only two levels of low cloud are considered (cirrus is ignored).

One significant point to emerge from the model was that the global cloud cover stayed relatively constant, even though cloud in each Hemisphere varied considerably.

Non-equilibrium thermodynamics

Instead of using numerical models, Dr Paltridge has looked at atmospheric processes using the relatively new discipline of non-equilibrium thermodynamics.

This has proved very useful in the analysis of linear systems such as certain chemical reactions. Its theoretical basis is the second law of thermodynamics; scientists have found that one assumption — that production of what they call entropy will be a maximum — explains much in the behaviour of linear systems. Dr Paltridge wondered whether this would also be the case with the non-linear processes that occur in the atmosphere.

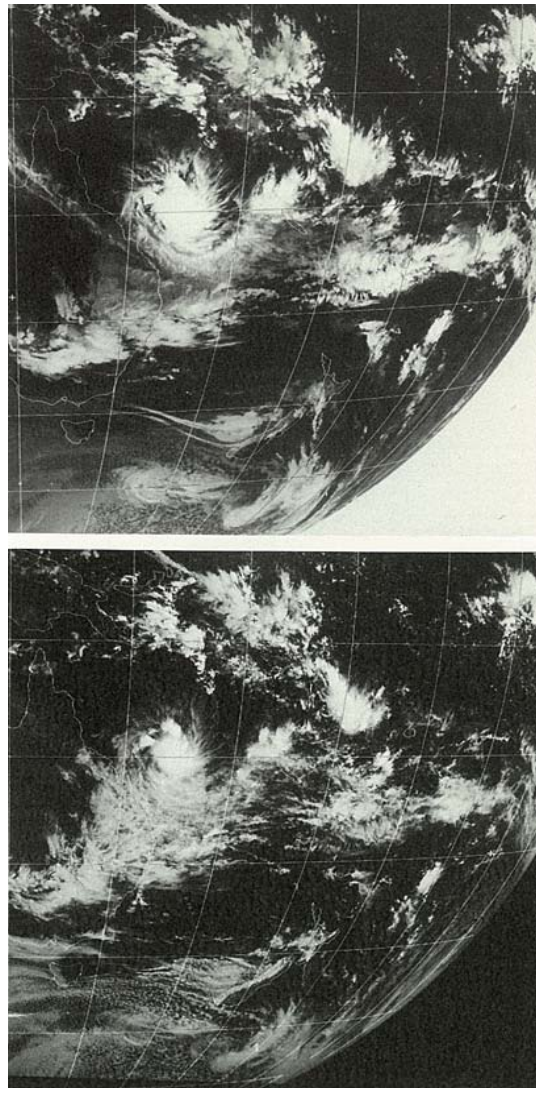
If it were, it would allow us to predict the effects of disturbances such as increases in carbon dioxide levels on global climate without needing to know the internal workings of the system. We could calculate broad geographic distributions of cloud, surface temperature, energy fluxes in the ocean and the atmosphere, radiant energy inputs, and so on, without going near a general circulation model.

At this stage it is a matter of speculation whether the condition of maximum entropy production holds true for the atmosphere, or whether this is even provable.

Be that as it may, Dr Paltridge has produced some exciting results by assuming that it is true. The graphs at the top of page 6 show that the earth's temperature and cloud cover can be predicted quite well.

Maximum efficiency

In practice, the principle of maximum entropy production means that the atmosphere maximizes the efficiency with which it turns solar energy into kinetic energy (convective energy and wind energy, essentially). This means the upward turbulent flux of heat is maximized and radiational flux is minimized.



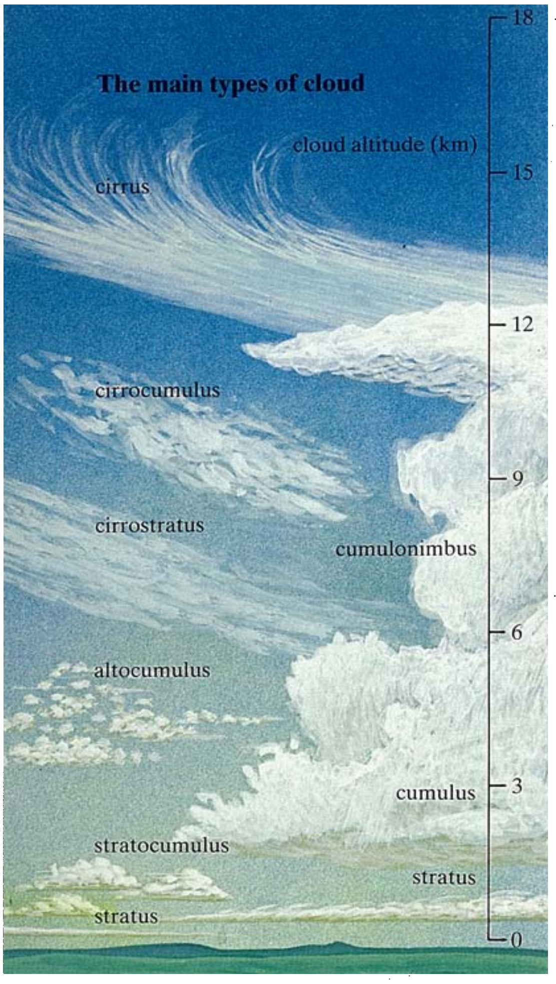
These two satellite views show the same scene as received by detectors operating in the infra-red (top) and visible wavelength bands. Comparison of the images provides information on the cloud types.

A simple feedback process in the atmosphere provides a ready physical explanation for the proposition that the turbulent flux stays at a maximum level. If it fell to less than its maximum value, the fall would tend to increase the temperature difference between the atmosphere and the earth. The atmosphere's stability would then decrease, with a resultant increase in the turbulent flux.

Interestingly, this provides an explanation for the fact that Mr Hunt's numerical model steadfastly refused to change its value for the total poleward flux of heat, even when cloud was removed entirely.

Cloud atlas

Atmospheric scientists now believe that a greatly improved knowledge of the world's cloud distribution, and its variation on monthly and annual time scales, is necessary if they are to make further progress in understanding the atmospheric processes that determine climate. Recent improvements in the abundance and accuracy of satellite observations, and techniques for



This article talks mainly about cirrus (high cloud) and cumulus (low cloud). However, clouds appear in many forms and at various altitudes.

deducing cloud properties from satellite data, now make it possible to compile a global 'cloud atlas' which should prove invaluable for climate research. Agricultural and solar energy studies will also benefit.

The object of the International Satellite Cloud Climatology Programme (ISCCP) is to record the cloud cover of the entire earth continuously for 5 years. The project began in July 1983, and it records data relating to cloud on a 32-km grid every 3 hours. Data come mainly from five geostationary meteorological satellites (GOES-E, GOES-W, GMS-1, INSAT, and METEOSAT). Two polar-orbiting satellites also contribute. Dr Paltridge and Dr Platt have been involved in organizing ISCCP internationally.

The atlas will not be a coffee-table production; rather the data will be stored on several hundred magnetic tapes. Information is coming from detectors of both visible and infra-red radiation.

The raw data from the satellites are reduced immediately to manageable proportions using a sampling procedure that averages the data over the required 32 km from an initial resolution of a couple of kilometres.

Information at higher resolutions will be retained for some areas — including south-eastern Australia. This will enable researchers to check the satellite data against ground observations. Dr Platt will be involved in this work, using the Division's laser radar (lidar) equipment, discussed later.

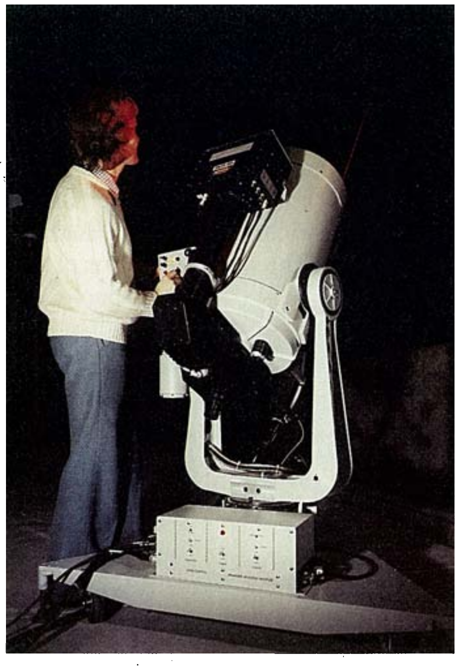
Two data channels

The infra-red information from the satellites yields what is known as 'brightness temperature', which can be interpreted as the temperature of the top of the cloud, at least for thick, low cloud. As clouds are colder than the ground, cloud patterns can be easily distinguished in infra-red images; the cloud pictures we see on our television weather reports every evening are actually infra-red images from the Japanese geostationary GMS-1 satellite.

The visible channel provides a measure of albedo, and also yields an easily discerned cloud pattern, at least during the day-time. The visible and infra-red images reveal a similar pattern of cloud cover. The discrepancies come mainly from thin, high cloud — cirrus. Scattered thick cloud can also cause problems. The reflection and absorption characteristics of clouds of ice crystals are not well known, leading to further uncertainty. It seems that the particular shape of the crystals, and even their orientation, can affect things greatly.

These complications can lead to some uncertainty in determining the precise amount of cloud cover, and can cause considerable errors in assessments of such things as the type of cloud, the height of its top and base, and its liquid water path.

The laser radar (lidar) at the Division of Atmospheric Research. It sends an intense pulse of red light into cloud directly above, and registers light reflected back.



Cloud algorithms

One of Dr Platt's major interests is to work out how to extract as much information as possible from the satellite data that will go into the ISCCP cloud atlas. He is searching for what he calls accurate 'cloud algorithms' that will make it possible to convert radiation measurements into reliable statements about the types and properties of the clouds that gave rise to them.

That the ISCCP is proceeding now is an act of faith on the part of the organizing scientists that Dr Platt, and others in this field of endeavour, can come up with improved cloud algorithms.

One of Dr Platt's methods that offers a way of understanding what the satellites are seeing involves constructing a histogram in which cloud albedo measurements are plotted against brightness temperatures. The locations of the plotted points on the histogram give a good indication of cloud type (see the diagram on page 7).

For example, an extensive low deep cloud deck with a uniform top will give a fairly uniform brightness temperature and albedo when measured by satellite. Hence the plotted points will cover only a small area. Similarly, a dense ice cloud will cover a small area in another part of the histogram. Albedo tends to rise with the depth of the cloud, and is generally higher for a water cloud than an ice cloud. Cloud brightness temperature goes down as the cloud becomes higher and cooler.

Plotting the 40 000 data points for an area of about 500 km square, Dr Platt can use the resulting histogram to assess the dominant cloud type present. However, this work is still in its early stages, and it is not yet possible to fully characterize different cloud fields by their histogram 'signatures'.

Dr Ian Barton of the Division has been able to identify cirrus cloud reliably by using data from two infra-red channels of the Nimbus 5 satellite. Water vapour and carbon dioxide both strongly absorb radiation in these bands, so only that solar radiation reflected from high (cirrus) cloud passes through a sufficiently thin absorbing layer to be detected. He has been able to map the seasonal abundance of cirrus using this approach, giving data of considerable value to numerical modellers.

Lidar and CSIDA

Important tools in use at the Division of Atmospheric Research to discover more about clouds go by the names lidar and CSIDA. Together they allow a cloud to be probed from underneath and above simultaneously. Lidar, a laser radar system, operates from the ground, whereas CSIDA (the CSIRO System for Interactive Data Analysis) allows satellite data streams to be sifted and analysed almost instantaneously, and immediately displayed on a screen. Validating one set of data against the other is a powerful approach to finding out what's really going on. And CSIRO is the only research body that has both of these facilities.

The lidar has been operating for about a decade. Over recent years its powerful beam has been predominantly aimed at high cirrus, since knowledge of such clouds is lacking because of the difficulty of using aircraft at such high (10-km) altitudes.

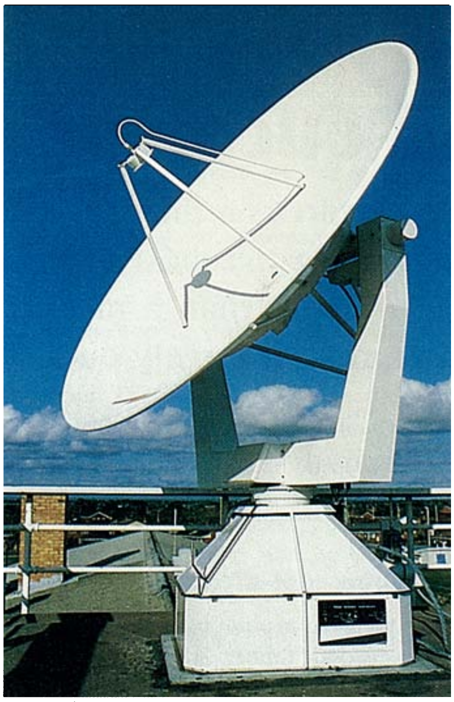
The ruby laser system sends a short (10-nsec) strong (10-MW) pulse of red light vertically into the sky, and a sensitive light detector records the reflected light as the pulse travels up through a cloud. The pulse is so strong and the detector so sensitive that the system can register a return signal after the pulse has penetrated to the top of just about any cloud that comes its way (only very thick storm clouds with low bases are too deep for the beam to penetrate). It can reach the top of an ordinary ice cloud, which may be 5 km thick.

From the lidar readout (one is shown on page 6) the scientist can determine the heights of the base and the top of a cloud. Normal routine is to fire a pulse once every minute. The polarization of the reflected signal, together with a measure of the strength of the cloud's infra-red emission obtained using a narrow-beam infra-red radiometer developed at the Division, allows the particle composition of the cloud to be determined.

Using the lidar system, Dr Platt found that cloud colder than −40°C has optical properties significantly different from those of warmer cloud. This is the lowest temperature at which super-cooled water can exist in the atmosphere. Also, we now know that the lower warmer clouds tend to be thicker than the higher ones, and that ice-crystal clouds have a greater albedo than water-droplet clouds of the same density. The reason has to do with light scattering by cylindrical ice crystals (the most common shape) instead of by spherical water droplets.

A discovery of significance to climate studies is that high thin cirrus possess infra-red properties that give rise to a maximum possible warming of the earth's surface.

Another interesting lidar finding is that the sizes and numbers of flat hexagonal ice crystals in a cloud can be worked out by looking at the polarization of the reflection, since they float horizontally and reflect like tiny mirrors.



Two views of the CSIDA system: a satellite receiving dish, and computer equipment to store and analyse the signals.

The CSIDA system was proposed by Dr Paltridge in 1980 and it has recently begun operation. It takes data from the GMS-1 geostationary satellite as well as polar-orbiting ones. A sophisticated computer system permits the incoming data (typically a million bits a second) to be manipulated according to the scientist's wishes. He can focus his attention on a particular wave band, or combination of bands, and can analyse and enhance images or overlay one set of data on another. He can take in the broad picture, or zoom in on particular features of interest.

Onward and upward

Meanwhile, scientists are already planning something better.

Another lidar, based on a tunable carbon dioxide laser that operates in the infra-red, has recently been constructed by Dr Chris Scott at the Division. Not only will this give more information on cloud properties, but it is also capable of providing data on the concentration of atmospheric constituents such as water vapour, ozone, and methane.

In America, scientists are working out the logistics of flying a lidar on a space shuttle in the next decade. No ordinary lidar, it would send out a stabilized infra-red laser beam and be capable of detecting a single photon reflected back. It would provide scientists with an avalanche of data, not only on clouds, but also on gas and particle concentrations and winds.

While they are beginning to come to terms with the role clouds play in affecting the earth's radiation balance, scientists are also starting to grapple with the reverse problem: the effect of radiation on cloud. This is an obvious gap in studies so far, and Dr Stephens is finding it an important one in attempting to understand the formation and evolution of clouds. He is finding it a difficult problem, full of non-linear effects.

Despite our most determined efforts, clouds seem certain to retain their shroud of mystery for some time yet.

Andrew Bell

More about the topic

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