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Cloud Climatology

In order to predict the climate several decades into the future, we need to understand many aspects of the climate system, one being the role of clouds in determining the climate's sensitivity to change. Clouds affect the climate but changes in the climate, in turn, affect the clouds. This relationship creates a complicated system of climate feedbacks , in which clouds modulate Earth's radiation and water balances.

- Clouds cool Earth's surface by reflecting incoming sunlight.
- Clouds warm Earth's surface by absorbing heat emitted from the surface and re-radiating it back down toward the surface.
- Clouds warm or cool Earth's atmosphere by absorbing heat emitted from the surface and radiating it to space.
- Clouds warm and dry Earth's atmosphere and supply water to the surface by forming precipitation.
- Clouds are themselves created by the motions of the atmosphere that are caused by the warming or cooling of radiation and precipitation.

If the climate should change, then clouds would also change, altering all of the effects listed above. What is important is the sum of all these separate effects, the net radiative cooling or warming effect of all clouds on Earth. For example, if Earth's climate should warm due to the greenhouse effect , the weather patterns and the associated clouds would change; but it is not known whether the resulting cloud changes would diminish the warming (a negative feedback) or enhance the warming (a positive feedback). Moreover, it is not known whether these cloud changes would involve increased or decreased precipitation and water supplies in particular regions. Improving our understanding of the role of clouds in climate is crucial to understanding the effects of global warming.

Atmospheric scientists have learned a great deal in the past many decades about how clouds form and move in Earth's atmospheric circulation. Investigators now realize that traditional computer models of global climate have taken a rather simple view of clouds and their effects , partly because detailed global descriptions of clouds have been lacking, and partly because in the past the focus has been on short-term regional weather prediction rather than on long-term global climate prediction. To address today's concerns, we need to accumulate and analyze more and better data to improve our understanding of cloud processes and to increase the accuracy of our weather and climate models.

A major effort is under way at the NASA Goddard Institute for Space Studies (GISS) under the direction of Dr. William B. Rossow , to gather better information about clouds and their radiative effects. Since 1983 the International Satellite Cloud Climatology Project (ISCCP) , as part of the World Climate Research Program (WCRP) , has been collecting observations from weather satellites to assemble a global, multi-year dataset. GISS serves as the Global Processing Center for ISCCP, in cooperation with institutions in several other countries. The datasets provide some of the key variables that determine the interaction of clouds and radiation.

There are now a number of global cloud datasets and datasets available from special field experiments . A thorough study of all these data will take many years and will lead, of course, to new experiments; but the investigations have already provided fresh insights into how clouds might change with climate and provided us with some statistics about the global distribution and character of clouds.

Data collection and model development proceed at GISS in parallel, with the goal of formulating an increasingly precise understanding of how sensitive the climate is in response to external forces and what those changes look like regionally. If we can understand these processes well enough, we may be able to predict the climate of the near-future with sufficient accuracy to be useful for societal planning.

Cloud Climatology: The Role of Clouds in Climate

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Clouds have always been signs of the weather to come. Scattered white cumulus clusters sailing across a field of blue promise a dry summer afternoon. Massive dark thunderheads portend crop-damaging wind and rain. A blanket of light gray signals a temperate winter's night. A high sheet of see-through wisps signals a change in the weather tomorrow or the next day. Today meteorologists scan the moving cloud patterns in satellite images to give daily weather forecasts with much greater accuracy than ever before. Special attention to severe weather events like tornadoes with satellite and radar networks has significantly increased the warning time, saving lives.

Thus it is ironic that when it comes to forecasting the climate several decades ahead, clouds mainly obscure our vision. Their most important roles in climate are to modulate Earth's basic radiation balance and to produce precipitation. The law of conservation of energy requires that the energy absorbed by the Earth from the sun balance the energy radiated by the Earth back into space. Clouds both reflect incoming sunlight and inhibit the radiation of heat radiation from the surface, thereby affecting both sides of the global energy balance equation. Clouds also produce precipitation from water vapor, releasing heat to the atmosphere in the process (evaporation of water vapor from the surface cools it, so that these two processes serve to transfer heat from the surface to the atmosphere). Thus, any changes in clouds will modify the radiative energy balance and water exchanges that determine the climate. The trouble is that clouds are produced by the climate, specifically the atmospheric motions (winds) that are produced by the radiative and latent heating influenced by clouds. This connected loop of relations is called a feedback loop. The ways that clouds respond to changes in the climate are so complex that it is hard to determine their net effect on the energy and water balances and to determine how much climate might change.

What makes it so important to disentangle the interactions of clouds and climate? The balance between absorbed solar radiation and emitted heat radiation sets the temperature of Earth. For example, when heat radiation from the surface slows, as caused by increasing greenhouse gas abundances, the balance can only be maintained if the temperature rises. Changing clouds can alter this relation, either increasing or decreasing the magnitude of the resulting temperature increase. Also, when clouds change, precipitation will change, which will affect the supply of freshwater to the land where we live and grow our food. Right now, we do not know how important the cloud-radiative or cloud-precipitation effects are and can not predict possible climate changes accurately.

Cloud Climatology: System of Climate Feedbacks Involving Clouds

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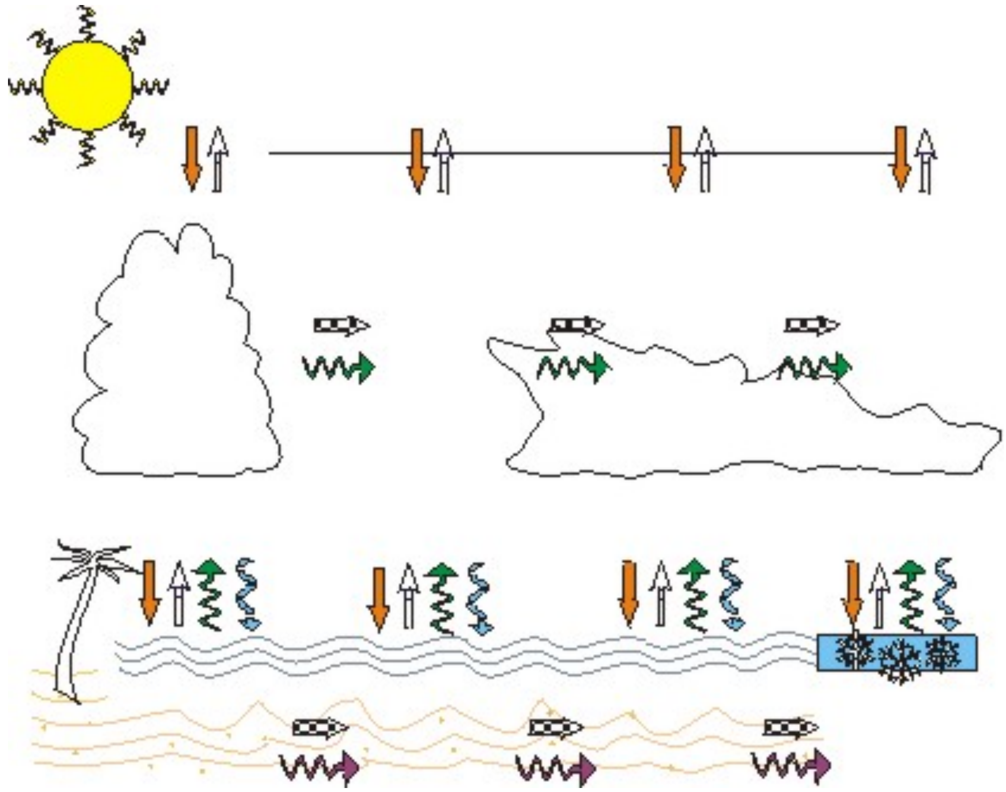
To illustrate the complex linkages that clouds are involved in, the figure below represents the climate system as a three-layer atmosphere and a one-layer ocean stretching from the equator (palm tree) to the pole (snow flake). Clouds occur in the lower two atmospheric layers that comprise the troposphere extending from the surface to about 12 km altitude. The uppermost atmospheric layer extends from about 12 - 100 km and is comprised, going upward, of the stratosphere (containing the ozone layer), the mesosphere and the thermosphere. The fluxes of radiation and water are indicated by different types of arrows: sunlight (red straight arrows), terrestrial (heat) radiation (blue-striped straight arrows), heat carried by atmospheric and oceanic circulations (checkered arrows), water evaporating from the ocean (land) surface (green wiggly arrows) and returning to the surface as precipitation (broken-blue wiggly arrows), water vapor carried by the atmospheric circulation (green wiggly arrows), and freshwater carried by the oceanic circulation (purple wiggly arrows).

ENERGY-WATER EXCHANGES



The **primary** energy exchange pathway within Earth's climate system begins withsolar heating of the ocean (and land) surface concentrated towards the equator, continues with transfer of this heat to the atmosphere by the water cycle ocean (and land) surface coolingby evaporation of water and atmospheric heating by precipitation, and ends with atmospheric cooling by emission of infrared radiation to space. Because the heating of the ocean and atmosphere is not uniform over the Earth, circulations are caused in both that transport heat and water: in particular, heat is transported by both the ocean and atmosphere away from the equator and towards the poles. Thus, the concentration of solar heating near the equator is not completely balanced by heat radiation and more heat radiation leaves Earth near the poles than arrives from the sun. The existence of these energy and water transports by the atmosphere and ocean means that the energy and water exchanges by other means do not balance locally.

The atmospheric circulation also produces clouds that modulate both the solar radiation gain and infrared radiation loss and are the locus of precipitation formation, establishing a set of intricately linked feedbacks on any forced climate change. An important consequence of these cloud effects is that time scale for the variation of the energy and water exchanges set by the atmosphere through cloud modulations has a time scale that is very different from the time scale on which the ocean can respond. Thus, the energy and water exchanges also fail to balance over shorter time periods, resulting in unforced variations ofthe climate. Storage of water on land and in ice also contributes to these variations. Study of the climate system to understand its behavior and its sensitivity to imposed perturbations necessarily entails consideration of all these energy and water exchanges, which constitute the main rapid feedbacks.

Moreover, these processes create unforced climate variability that also must be understood to separate them from climate changes that might be caused by human activities. None of these energy and water exchanges can be understood without consideration of the effects of clouds on them, so quantitative cloud data, complemented by precipitation, water vapor, and radiative flux data, are required to diagnose these exchanges and their space-time variations.

Cloud Climatology: Net Effect on Energy and Water Balances

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At the heart of the difficulty of understanding how clouds affect climatic change is that clouds both cool and heat the planet, even as their own properties are determined by the cooling and heating (current link). The cooling effect is literally visible: the minute water or ice particles in clouds reflect between 30 and 60 percent of the sunlight that strikes them, giving them their bright, white appearance. (Deep bodies of water, such as lakes and oceans, absorb more sunlight than they scatter and so appear very dark. If all of the cloud water in the atmosphere were placed on the surface, the layer depth would only be 0.05 mm on average. If all the water vapor in the atmosphere were reduced to a liquid water layer on the surface, the depth would be about 2 cm on average.) A cloudless Earth would absorb nearly 20 percent more heat from the sun than the present Earth does. To be in radiation balance Earth would have to be warmer by about 12°C (22°F). Thus, clouds can cool the surface by reflecting sunlight back into space, much as they chill a summer's day at the beach.

The cooling effect of clouds is partly offset, however, by a blanketing effect: cooler clouds reduce the amount of heat that radiates into space by absorbing the heat radiating from the surface and re-radiating some of it back down. The process traps heat like a blanket and slows the rate at which the surface can cool by radiation. The blanketing effect warms Earth's surface by some 7°C (13°F). Thus, clouds can heat the surface by inhibiting radiative heat loss, much as they warm a winter's night.

The net effect of clouds on the climate today is to cool the surface by about 5°C (9°F). One can calculate that a higher surface temperature would result from the buildup of greenhouse gases in the atmosphere and the consequent slowing of heat radiation from the surface, provided nothing else changes. But what happens to the radiation balance if, as part of the climatic response, the clouds themselves change?

If the radiative cooling effect of clouds increases more than the heating effect does, the clouds would reduce the magnitude of the eventual warming. The same result could come about if both effects decrease, but the cooling decreases less than the heating does. On the other hand, if the cooling increases less (or decreases more) than the heating, the cloud changes would boost the magnitude of eventual warming. It is also possible for the two effects to go in opposite directions, which would give rise to outcomes similar to the ones already mentioned, but much stronger. In any event, what matters is the difference between the cooling and the heating effects of clouds. For a more detailed and technical discussion, see

- Rossow, W.B., and A.A. Lacis, 1990: Global, seasonal cloud variations from satellite radiance measurements. Part II: Cloud properties and radiative effects. J. Climate, 3, 1204-1253.
- Rossow, W.B., and Y.-C. Zhang, 1995: Calculation of surface and top of atmosp here radiative fluxes from physical quantities based on ISCCP datasets, 2. Validation and first results. J. Geophys. Res., 100, 1167-1197.

and the references therein.

Clouds are also part of another important internal heat exchange process involving water phase changes. Most of Earth's "free" water is in the oceans (even more water is contained in the rocky crust of Earth), equivalent to a layer covering the whole surface about 2.5 km deep. Another 50 m of water is currently stored in the major ice sheets in Greenland and Antarctica. The atmosphere only contains about 2.5 cm of water and clouds contain only 0.05 mm. When water evaporates from the ocean and land surface, it cools the surface because it takes energy to change liquid/solid water into vapor. The atmospheric circulation transports water vapor from place to place. When the atmospheric motions include upward motions, the air cools and clouds form by condensing water vapor back to liquid/solid form. If the clouds produce no precipitation, then the energy released by the condensation of the cloud water is recaptured by the water vapor when the cloud water evaporates. However, if the clouds produce rain/snow, the energy released by the condensation heats the atmosphere. Because of the atmospheric transport of water vapor, the precipitation does not locally balance the evaporation, so the water vapor transport is equivalent to energy transport. The average evaporation and precipitation rates mean that all the water in the atmosphere is exchanged about once every 10 days. There is also a net transport of about 10% of the total water vapor evaporated from the oceans to the land, most of which is then returned to the oceans by rivers. Thus, the water cycle links the two parts of the radiation balance: the surface is heated by sunlight and cooled by water evaporation, but the atmosphere is heated by precipitation and cooled by terrestrial radiation to space. This water cycle is even more important to us because the small amount of water that is contained lakes and rivers or retained in underground water is our only supply of fresh water for drinking, agriculture and many other industrial and recreational uses.

Cloud Climatology: Greenhouse Effect and Climate Change

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Within the next half-century or so an accumulation of airborne pollutants -- notably carbon dioxide (CO2), methane (CH4), nitrous oxides (NOx), and chlorofluorocarbons (CFCs) -- will very likely cause noticeable changes in climate (noticeable changes may have already occurred but there is debate about that). Because these so-called greenhouse gases retard the flow of heat radiation from the surface into space, the whole Earth will warm . This is called the greenhouse effect . This warming is partly reduced by other pollutants that form tiny aerosol particles which reflect some sunlight back to space. The global warming will in turn lead to a variety of other changes throughout Earth's climate system: changes in heat and water transport, wind and ocean currents, precipitation patterns and clouds. Given such a profound potential for an adjustment of the basic climatic elements and the possible consequences for human society, an improved understanding of the radiation and water balance and their dependence on cloud processes is one of several crucial goals of current research.

The threat of climatic change is not primarily in the change itself but in its rapidity. The geological record is replete with climatic changes similar in magnitude to the one now contemplated, but past changes were slow enough to allow most species to adapt. What is unprecedented about the current greenhouse warming is that significant change could come to pass in only a few generations, creating human and economic dislocations. For example, since most people live fairly near oceans, a rapid rise in sea level caused by the melting of glaciers could force most people to move inland. If severe storms , such as hurricanes , became more frequent, they would interfere with airborne and waterbourne transportation of goods from market to consumer. A change in the average temperature and its seasonal variations could alter patterns of energy use and demand. A change in rainfall or snowfall could change our water supply and may alter the success of agriculture . The possible political and economic consequences of such disruptions are suggested by the global concern over maintaining an uninterrupted oil supply from the Middle East or avoiding catastrophic floods and droughts that have affected food supply recently in parts of Africa and Asia.

Yet in spite of the need to forecast climatic changes accurately, current understanding of how the climate works is not detailed enough for climatologists to predict exactly when, where, or to what extent changes will take place, only to say that there will be a certain amount of warming and that other things will likely change. The global climate is such a complex system that no one knows how even a small increase in temperature will alter other aspects of climate or how such alterations will influence the rate of warming. Moreover, changes in any of these climatic features may also affect the distribution and properties of clouds , but the understanding of clouds is so rudimentary that no one knows whether climate feedbacks involving clouds will dampen or amplify a warming trend. The possibility that clouds might accelerate global warming brings a special urgency to the ancient problem of understanding the climatic importance of clouds.

Effects of Global Warming

Cloud Climatology: How Clouds Form and Travel

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A cloud is formed when atmospheric water vapor is cooled by vertical air motions (or in the polar regions by heat loss by radiation), condensing on microscopic airborne particles - dust, sea salt, bits of organic matter, or chemical aerosol particles, the most common beingcomposed of sulfuric acid and other sulfate compounds. Between the evaporation of water from the surface and its condensation in a cloud, water vapor is carried along by winds from warmer, moister regions to cooler, drier ones. Because the atmosphere, except for clouds, is nearly transparent to solar radiation, the surface absorbs 70 percent of the total solar heat taken up by the earth-atmosphere system, making the air warmer near the surface than it is at high altitudes. Because sunlight strikes the planet most directly near the equator, the tropics are warmer than the polar regions.

Both temperature gradients - the temperature variations from low to high altitudes and from low to high latitudes - are intensified by the effects of water vapor on radiative heating and cooling and by the transformations of water from liquid or solid into vapor and back. This happens because water vapor is nearly transparent at the wavelengths of sunlight (between 200 and 3,000 nm, nm = nanometer, one billionth of a meter), so it lets virtually all the sunlight reach the surface. However, water vapor is nearly opaque at the wavelengths at which the sunlight-warmed surface radiates away its absorbed energy (thermal radiation with wavelengths between 3,000 and 100,000 nm). The absorption of most of the outgoing thermal radiation by water vapor creates most of Earth's natural greenhouse effect - an effect that is now being increased by human pollution. Without the atmospheric water vapor Earth's surface would be, on average, about 31°C (55°F) colder than it is now and the differences in temperature between high and low altitudes and between the poles and equator would be smaller.

Since cold air is denser than warm air, temperature differences give rise to atmospheric motions that work to eliminate the density differences. Winds generally move warmer, moister air upward and poleward from the tropical surface and move colder, drier air downward and toward the equator from higher altitudes and latitudes. Although some water is transported to higher latitudes at upper levels, the winds nears the equator actually transport water vapor towards the equator, concentrating it into a narrow, heavy rainfall zone there. The contrasts in heating, together with the winds, also drive ocean currents, which help reduce the temperature differences between the equator and the poles even more.

Some of the water evaporated from the surface (primarily from the oceans) condenses into clouds and eventually falls as rain or snow. These transformations not only redistribute water but also play an important role in global heat transport. When surface water evaporates, the heat required to change liquid water into vapor is absorbed from the surface and carried along with the vapor into the air. When water vapor condenses into a cloud and falls as rain, it releases that heat, known as latent heat, into the air.

The processes that control the conversion of water vapor into cloud and precipitation particles are called cloud microphysical processes. The interaction of these processesdetermines the properties of clouds that, in turn, determine the effect of clouds on the radiative energy exchanges, whether the cloud will produce precipitation, how much and what type of precipitation it will produce, and how long the cloud will last.

At temperatures above freezing (0�C), the weak vertical air motions (slow cooling) associated turbulence near the surface or with large-scale circulations lead only to the formation of rather small cloud droplets (about 5-10 um in radius, 1 micron = 1 millionth meter) covering very large areas. For typical concentrations of small aerosols on which the droplets form (from about 50-200 cm^{-3} over oceans to about 500-2000 cm^{-3} over land), the total amount of vapor converted to droplets is small, equivalent to about a layer of water about 0.01-0.03 mm deep. Such clouds, ranging from scattered fair-weather cumulus toextensive sheets of stratocumulus, produce no precipitation and last only as long as the upward motions continue (usually about 10-20 min for cumulus but days for stratocumulus) because such small droplets fall very slowly (about 3 mm s^{-1}) and evaporate within a fewminutes after the leave the cloud environment. Stronger vertical air motions (rapid cooling as in stormy weather) tends to produce somewhat more numerous and much larger droplets, about 15-30 μm in radius. These larger droplets fall more rapidly (still only about 10 cm s^{-1}) and collide. Colliding droplets merge into even larger, more rapidly falling droplets, so the collision process quickly produces very large droplets, more than 300 μm. Such clouds, ranging from stratus and altostratus to nimbostratus produce drizzle or light rain. When the vertical motions are even stronger, as happens when the heat release from the condensing water causes very rapid ascent of large parcels of air, forming cumulonimbus clouds, the cloud extends into the upper troposphere where the colliding droplets freeze. The mixing of ice and liquid droplets not only produces more rapid growth from the vapor but more efficient sticking of the colliding particles (see discussion below), leading to the growth of very large particles, more than 1 mm (1000 μm) in size, that fall so rapidly (more than 100 m s^{-1}) that they can reach the surface without evaporating. These falling large droplets are known as rainfall; rainfall rates can range from very small rates of 0.01 mm hr^{-1} to very heavy downpours of 50 mm hr^{-1}.

The situation at colder temperatures is similar to that described above, but there are some important differences that arise because of the peculiar properties of water and because of the difference between liquid and solid particle collisions. Because of the strong interactions of water molecules, some extra energy is needed to initiate the growth of very small water particles from vapor. For the growth of liquid droplets in clouds near the surface, the presence of water-containing aerosol particles greatly reduces the amount of energy needed, requiring only a small excess of vapor pressure over the saturated amount (*i.e.*, the relative humidity must only reach values of about 100.1% to form droplets). However, at higher altitudes there are not only many fewer aerosols available but they do not help initiate the growth of an ice crystal nearly as well as they can help droplet growth, so ice clouds do not begin to form until the vapor pressure exceeds saturation by a much larger amount (relative humidity with respect to ice usually must reach values as much as 101%). In fact, many ice clouds start instead by forming liquid droplets at temperatures well below freezing(down to as low as about $-30°C$) and then freezing them. The peculiar property of water is that at temperatures below freezing the saturation vapor pressure over liquid droplets is much higher than over ice crystals at the same temperature. Once these cold droplets begin growing, they quickly freeze, exposing them to a much higher vapor pressure. The consequence is that the ice crystals grow much more quickly to larger sizes in the range from 20-100 μm and they keep growing below the cloud, reaching sizes of a few hundred microns, because the relative humidity is still > 100% with respect to ice below the initial cloud base. These large particles also collide as they fall, but ice crystals have a more difficult time sticking together; nevertheless, at temperatures nearer freezing, some liquid droplets are encountered that help stick the crystals together. So when the air motions are stronger, very much larger frozen particles can be produced. In the violent vertical motions of strong thunderstorms, for example, the particles can fall and rise many times, producing large hail stones that have been known to reach sizes > 10 cm (10^5 μm).

The formation, evolution and motion of clouds is determined by the interaction of these cloud microphysical processes with atmospheric motions and radiation; this combination can be thought of as a kind of cloud dynamics. As the air moves past the particles in a cloud, there is a frictional force exerted, so that, even in very small clouds, the number of particles is sufficient to cause the air to move around the cloud rather than through it. Thus, smaller clouds are moved with the wind. However, since clouds are formed by the air motions, their actual evolution is much more complex and can involve wave as well as mass motions. Differences in the nature and behavior of cloud dynamics in different meteorological situations produces different cloud types. Researchers are now studying the behavior of these different cloud types to understand the role of each in weather and climate.

Cloud Climatology: Computer Climate Models

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Because there are so many possibilities for change, climatologists must know how clouds over the entire Earth will respond. Determining that response calls for computer models of the global climate that can explore changing conditions. Climate models are sets of mathematical equations that describe the properties of Earth's atmosphere at discrete places and times, along with the ways such properties can change. The challenge for climate models is to account for the most important physical processes, including cloud microphysics and cloud dynamics, and their complex interactions accurately enough to carry climatic predictions tens of years into the future. When contemporary models are given information about Earth's present condition - the size, shape and topography of the continents; the composition of the atmosphere; the amount of sunlight striking the globe - they create artificial climates that mathematically resemble the real one: their temperatures and winds are accurate to within about 5%, but their clouds and rainfall are only accurate to within about 25-35%. Such models can also accurately forecast the temperatures and winds of the weather many days ahead when given information about current conditions.

Unfortunately, such a margin of error is much too large for making a reliable forecast about climate changes, such as the global warming will result from increasing abundances of greenhouse gases in the atmosphere. A doubling in atmospheric carbon dioxide (CO_2), predicted to take place in the next 50 to 100 years, is expected to change the radiation balance at the surface by only about 2 percent. Yet according to current climate models, such a small change could raise global mean surface temperatures by between 2-5�C (4-9�F), with potentially dramatic consequences. If a 2 percent change is that important, then a climate model to be useful must be accurate to something like 0.25%. Thus today's models must be improved by about a hundredfold in accuracy, a very challenging task. To develop a much better understanding of clouds, radiation and precipitation, as well as many other climate processes, we need much better observations.

Cloud Climatology: Simple Early Views of Clouds

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The earliest attempts to predict how changes in cloud cover would affect greenhouse warming concluded that they would have no net effect: clouds would neither speed nor slow a change in climate. That conclusion was based on the belief that any change that made clouds better at cooling the Earth would also make them more efficient at retaining heat near the surface. For example, if cloud cover were to increase (as many thought it would, assuming that warmer temperatures would speed evaporation), the amount of sunlight reaching Earth's surface would decrease, but then the thermal radiation trapped by the cloud might increase by the same amount.

Even such a simple scenario has problems, though. Because the decrease in solar heating would affect surface temperatures, whereas the change in the emission of thermal radiation would affect air temperatures at higher altitudes, additional cloud cover would reduce the temperature contrasts between the surface and the higher altitudes that drive the winds. Any reduction of winds might in turn inhibit the formation of clouds. The early studies did not account for this possibility.

Another idea is that higher atmospheric temperatures could create denser clouds, since greater evaporation rates at higher temperatures would make more water vapor available in the atmosphere for cloud condensation. Because denser clouds reflect more sunlight, there would be an enhanced cooling effect. This would reduce the magnitude of the greenhouse warming. On the other hand, denser clouds might also lead to an increase in precipitation (rainfall and snowfall), possibly from storm clouds, whose tops are especially high and cold. Such clouds, which are particularly good absorbers of thermal radiation, could more than make up for their tendency to block sunshine. In that case the warming would be intensified. Observations have shown, however, that warmer temperatures seems to create less dense, low-level clouds instead. The evidence we have so far suggests that this effect occurs because, as temperature increases, the air near the surface becomes drier, causing the cloud base to rise and reducing the cloud layer thickness. Earlier studies did not consider this possibility.

Such "what-if" discussions can go on indefinitely. All of the changes mentioned above are physically reasonable and there are many more to be considered. The question is: How many and which ones will actually take place when the climate changes and exactly how large will they be? In all likelihood, all of these changes and more would occur together, but we don't know what the net effect would be.

Another kind of complication is that clouds come in many forms , depending on the weather conditions that create them. Low, dense sheets of stratocumulus clouds hanging just above the ocean cool more than they heat. They make efficient shields against incoming sunlight, and because they are low - and therefore warm - they radiate upward almost as much thermal radiation as the surface does. In contrast, the thin, wispy cirrus clouds, which soar at 6,000 meters (20,000 feet) and higher, reflect little sunlight, but they are so cold that they absorb most of the thermal radiation that comes their way. Hence they warm more than they cool. The net cooling effect of clouds is the sum of a large number of such specific effects, many of which cancel one another.

Atmospheric scientists have been aware for nearly two decades that the complex effects of clouds on radiation and water exchanges pose a major challenge to the understanding of climatic change. In 1974 an international conference of investigators in Stockholm highlighted the need for greater understanding of clouds as one of the two biggest obstacles to further progress in climate research. The second was inadequate knowledge of ocean currents. Recent comparisons of the predictions made by various computer climate models show that the problem has not gone away. In some models, for instance, clouds decrease the net greenhouse effect, whereas in others they intensify it.

Cloud Climatology: How Clouds Might Change with Global Warming

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Although simple relations may hold between climatic conditions and the radiative properties of certain kinds of cloud, predicting how the global distribution of various kinds of clouds would change with global warming is complicated by their interaction with regional wind systems. Consider the roles of clouds in seasonal climatic change. In the midlatitudes, winter brings a substantial decline in solar heating, yet the corresponding drop in air temperature near the surface is between 70 and 80 percent less than what the decline in solar heating would seem to imply. More abundant and thicker winter clouds, with slightly higher tops, trap heat better.

In the tropics, despite significantly greater cloud cover in the rainy season, there is only a small seasonal variation in surface temperature. In part the variation is small because the effects of tropical clouds on thermal and solar radiation nearly cancel one another, but even more important is the controlling influence of heat transports by atmospheric winds.

The quest for more data about clouds and climate continues in parallel with the refinement of climate models. It is a slow-going process: each new piece of information must be incorporated throughout. With certain findings the models themselves may have to be reformulated. But the result should be an increasingly precise understanding of how sensitive the clouds are in response to changes in external forces and what effect those changes would have on global warming. One must hope that the model building and data collection activities will lead to an understanding of climatic change before that change comes to pass.

Cloud Climatology: Global Distribution and Character of Clouds

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The new global datasets show that clouds typically cover almost two-thirds of the planet, some 10 percent more than had been thought. Oceans are significantly cloudier than continents. Slightly more than 70 percent of the sky over oceans is cloudy, but a little less than 60% of the total land area is usually covered with clouds. Almost a fifth of the continental surface is covered by large areas of clear sky, whereas less than 10 percent of the ocean surface is. Clouds on average are about 27°C (48°F) colder than the surface is, and they reflect more than twice the amount of sunlight as the surface. But far more interesting than such averages is how widely the properties of clouds can vary with location, with time of day, with changing weather, and with season).

Cloud over the ocean, for instance, are different in some ways from clouds over land. The tops of ocean clouds are generally slightly more than a kilometer (3300 feet) lower than the tops of clouds over land, but ocean clouds reflect about 3% more sunlight on average than clouds over land. Above the oceans at low latitudes, clouds are more common in the morning than in the afternoon and the morning clouds are the most reflective of the day. Over land there are more clouds, with higher reflectivity, in the afternoon. Although clouds over oceans and land contain about the same amount of water on average, the low-level clouds over oceans are composed of fewer, but larger, droplets than are low-level clouds over land.

Cloud properties also vary with distance from the equator. The cloudiest regions are tropics and the temperate midlatitude storm zones; the subtropics and the polar regions have 10-20% less cloud cover. Tropical cloud tops are substantially higher, on average extending between one and two kilometers higher than cloud tops in the midlatitudes and more than two kilometers higher than the clouds over the subtropics and the north pole (clouds are much higher on average over the south pole because the ice sheet surface is so much higher in altitude). At some places in the tropics (the western Pacific Ocean, the Amazon River Basin and the Congo River Basin), cloud tops extend up to 15 kilometers (50,000 feet), occasionally higher. High-latitude clouds are almost twice as reflective as most clouds at lower latitudes.

Any attempt to explain such variations must take into account the kinds of clouds common to a given region, which depends on the local meteorology. Consider storm clouds. In the tropics exceptionally large thunderheads often form, extending from the surface to an altitude of between twelve and fifteen kilometers (about 40,000 - 50,000 feet). Similar storm clouds occur in areas of low pressure over temperate regions, but their tops only reach altitudes of between seven and ten kilometers (about 23,000 - 33,000 feet). Elsewhere thunderheads are virtually absent. To understand clouds better, scientists are investigating the detailed behavior of many different cloud types as defined by surface weather observers and cloud types as defined by weather satellites.

Meteorologists have long associated greater cloud cover, higher cloud tops and denser, more reflective clouds with regions of more vigorous storms. Both the tropics and the low-pressure areas at midlatitudes are regions of severe weather. The frequency and strength of storms are also related to such climatic factors as average wind speed and direction, temperature, humidity, sunlight and topography. By comparing satellite observations of cloud variations with meteorological data, it may be possible to establish correlations between these conditions and the cooling and heating properties of clouds.

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Cloud Microphysics

Further Reading

ISCCP

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http://isccp.giss.nasa.gov/role.html
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