convective cloud systems, with associated large anvil clouds, are found above these ocean surfaces. These anvil clouds are efficient at both reflecting incoming shortwave radiation and absorbing outgoing longwave radiation emitted from the ocean surface. Recently, it has been hypothesized that shortwave reflection by these anvil clouds acts as a strong regulator to stabilize sea surface temperatures.[7] Sea surface temperatures can be reduced by increased reflection or increased evaporative flux from the ocean surface. Field data are currently being analyzed to see which of these processes dominates in the tropical Pacific. The relevance of this mechanism to climate change is as yet poorly understood, but it may be important to understanding the small variability of sea surface temperatures over geologic time scales.

▷ **Cloud condensation nuclei in midlatitude stratus.** Increased emission of aerosol particles from fossil fuel usage may affect cloud albedos. These hygroscopic particles may increase cloud condensation nuclei and lead to an increase in the number of cloud droplets. For constant water concentration, there will be a shift toward smaller effective drop size and an increase in cloud optical depth (see equation 11), leading to an increase in cloud albedo.[8] This phenomenon has been observed over oceans.[9] At present, the details of the highly nonlinear processes that link cloud condensation nuclei below a cloud to new cloud drop formation are poorly understood. Measurements show a link between these two quantities.[10] Also, the assumption that the liquid-water concentration remains fixed may not hold in general. The problem of linking increased aerosols to increased cloud albedo is under theoretical, modeling and observational study.

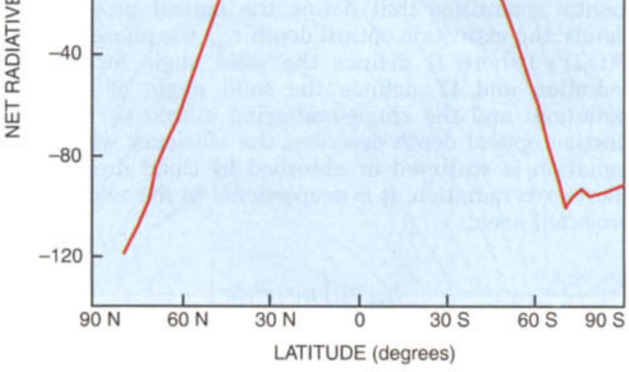
▷ **Cloud absorption.** Although cloud reflection is the major determinant of shortwave cloud forcing, shortwave absorption is non-negligible. Two recent observational studies indicate that the amount of shortwave absorption may be much larger than previous models suggest and that this effect is a global phenomenon.[11,12] These studies indicate that shortwave cloud absorption in the atmosphere is about 50% of the shortwave cloud forcing at the top of the atmosphere. This result implies that the absorption is nearly 40 W/m², instead of the 2 W/m² indicated in our energy budget analysis. If these studies are confirmed, the *NCF*(A) term in our energy budget analysis becomes a major determinant of the poleward heat transfer in equation 7.

Observation, modeling, theory

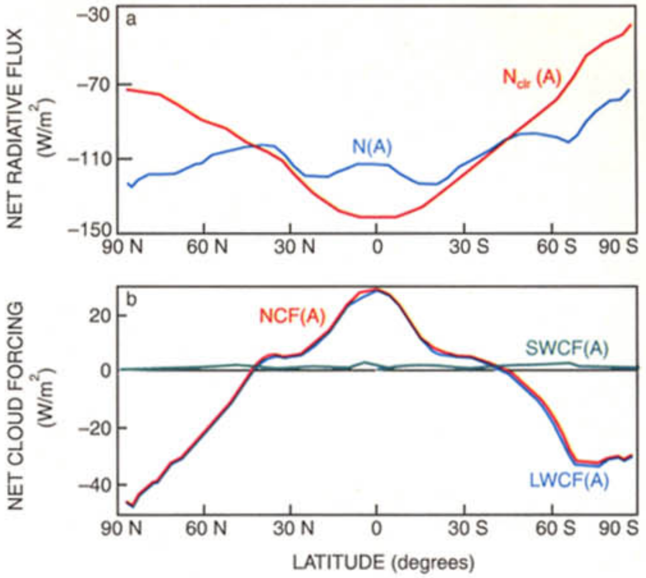
Approaches to understanding cloud–climate problems have focused on observation, numerical modeling and theory. Unlike experimental physics, observations of clouds must occur in an open, uncontrolled system—namely, the Earth's atmosphere.

Observation. Progress on many of the present cloud–climate problems is limited by sparse observational data. Observations of cloud radiation processes can be made from three locations: the Earth's surface, *in situ* and at the top of the atmosphere, via satellite remote sensing. The advantage of ground-based observations is that instruments can be calibrated and maintained over a long time period, enabling long-term observations of clouds in a number of locations; new instruments to complement existing ones can be introduced at any time. The DOE Atmospheric Radiation Measurements program is an example of a long-term ground-based program to collect data on cloud radiative processes.[13] The limitation of ground-based measurements is that certain cloud characteristics, such as microphysical properties, cannot be observed from the ground, although some information can be retrieved by remote sensing from ground-based instruments, such as microwave sensing of column-cloud water. Also, there are many regions, such as the ocean, where it is logistically difficult to base surface instruments.

In situ observations from airplanes or balloons are



Net radiative flux at the top of the atmosphere *N*(T). Plotted is the annual and zonally averaged net radiative flux, which is equal to the shortwave absorbed flux minus the outgoing longwave flux. **Figure 4**



Flux and cloud forcing. a: Annual and zonal mean net radiative flux into the atmosphere N(A) and clear-sky component N_{clr}(A). **b:** Net cloud forcing NCF(A) and its shortwave and longwave components. **Figure 5**

valuable in obtaining data on microphysical processes in clouds. For example, *in situ* instruments are needed to measure the cloud drop-size distribution $n(r)$. Aircraft instruments can also measure the radiative fluxes at the tops and bottoms of clouds, and even within a cloud. Thus these types of measurements are best suited to studying detailed microphysical processes occurring in or near a cloud system. The limitation of this approach is the difficulty in obtaining a sufficiently large data base for climate parameterization. The data are also not comprehensive, since payload and power limitations restrict the number of instruments on a given airplane. However, *in situ* data can be used to test satellite retrieval methods and microphysical models. The cost of *in situ* measurements is often prohibitive. Although *in situ* observations are important for understanding a given cloud process, they are limited in direct applications to climate research.

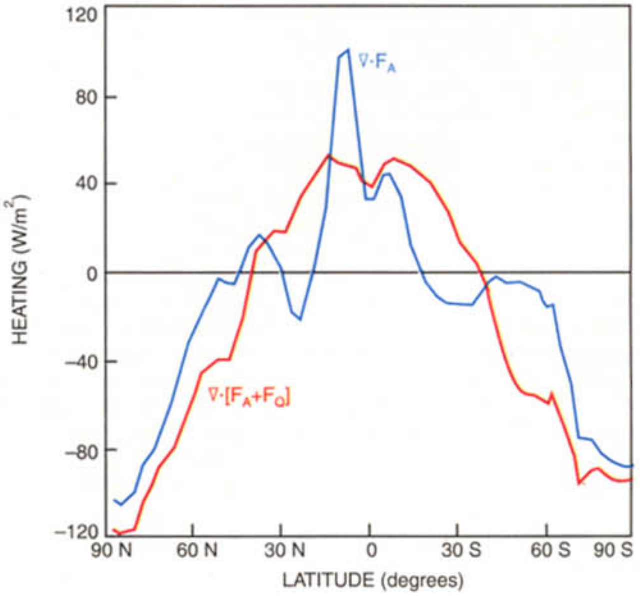
Satellites in space provide near-global coverage. Earth-radiation-budget instruments have measured fluxes on scales of roughly 30 kilometers, while other instruments, such as the Advanced High-Resolution Radiometer, can measure radiance at a specific wavelength down to a scale of about 1 km. The smallest scales observable from space using Landsat imagery are in the range of tens of meters. Hence, satellite data span a wide range of spatial scales.

Earth radiation-budget information, which measures the net radiative flux at the top of the atmosphere N(T), is extremely important for global models. Every global model must be validated against accurate Earth radiation-budget data. NASA's Earth Radiation Budget Experiment, which ran from October 1985 to April 1989, provided calibrated data (see the article by V. Ramanathan, Bruce Barkstrom and Edwin Harrison in PHYSICS TODAY, May 1989, page 22), but at present there are no observations being taken of the Earth radiation budget. Because Earth radiation-budget data yield little information about vertical distribution of radiant energy, other satellite instruments, such as radiometers aboard geostationary satellites, must be used in conjunction with radiation models. Interpreting such measurements is difficult, however, because of the need to make assumptions about cloud properties that are still poorly understood. To improve these retrieval methods requires coupling satellite observations with *in situ* and ground-based observations. Other limitations to satellite methods are cost, payload and power restrictions. NASA is planning to launch a suite of instruments for cloud research as a part of the Earth Observing System.

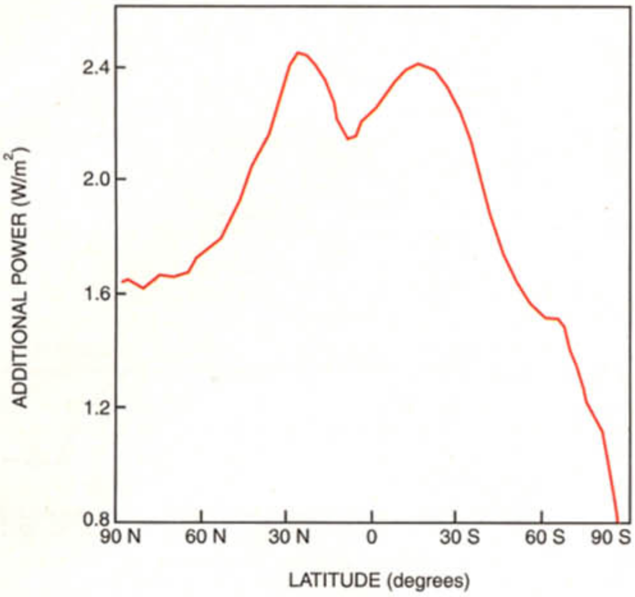
What is required for the near term is to use existing satellite instruments for cloud studies. The calibration of many current satellite instruments can be carried out with the help of *in situ* instruments. Such calibration is perhaps the highest-priority need for climate researchers.

Modeling. Numerical modeling on various scales of cloud systems is integral to a coherent research program. Present computational resources are able to represent an ensemble of clouds with scales ranging from 1 km up to 1000 km. Numerical simulations of resolved cloud systems can routinely be made in two dimensions (horizontal and vertical slices) and, in more limited cases, can be carried out in three dimensions. These models typically rely on imposed boundary conditions (such as large-scale horizontal winds) to represent the large-scale forcing from the climate system (with scales of motion greater than 1000 km). Future attempts should be made to allow for the interaction between the cloud ensemble and the large scale. Thus the smaller-scale cloud model can be forced with large-scale atmospheric conditions predicted by a climate model.

Global models need to be tested more quantitatively. At present, validation of general circulation models usually employs monthly mean satellite data on the Earth's radiation budget. Although this is important, models should be tested against time-varying data as well. Comparison



Atmospheric poleward heat transport of dry static energy (blue curve) and moist static energy (red curve). (See figure 3.) F_A represents dry static energy; F_Q represents latent energy. **Figure 6**



Greenhouse forcing. Plotted is the change in the net top-of-atmosphere radiative forcing $N(T)$ due to increases in greenhouse gases—CO_2, CH_4, N_2O, CFC_{11} and CFC_{12}—from preindustrial times to the present. **Figure 7**

of models with observations on time scales both longer and shorter than monthly means is required.

For example, tropical sea surface temperatures exhibit a variation every two to three years called El Niño. This variation of 2–3 °C in sea surface temperature forces changes in cloud cover and associated radiative fluxes. The response of models forced with the observed El Niño sea surface temperature patterns can be tested against Earth radiation-budget data.

Models should also be tested on shorter time scales, such as the diurnal scale. Comparison of modeled cloud properties with three-hourly data from the International Satellite Cloud Climatology Program are of great value.[14]

Theory. Theoretical research is needed on the fundamental questions of scale. How are the multiple cloud scales related? How does this multitude of scales affect the transfer of radiation within clouds? How can the relevant smaller-scale processes be incorporated into a general circulation model cloud parameterization? One focus of research on these questions is the study of the fractal nature of clouds.[15] But further effort is required to relate the current studies to the climate parameterization problem. Present-day general circulation models assume that clouds are geometrically plane-parallel and thus neglect radiation entering or exiting from their sides. Also, horizontal cloud–cloud radiative interactions are neglect. Monte Carlo techniques reveal significant differences in cloud radiative properties obtained from an array of finite clouds and from a plane-parallel cloud.[16]

For parameterization purposes, the question is, How do we include these finite cloud radiative effects over scales of hundreds of kilometers? Theoretical studies of cloud geometry and cloud inhomogeneity are needed, again with special emphasis on relating these theoretical findings to the large-scale (on the order of a few hundred kilometers) climate problem. Further theoretical understanding of microphysical processes is needed, in particular, the role of aerosols on cloud drop-size distributions. Finally, given the extreme lack of understanding of tropical anvils, especially with regard to the microphysical processes, further theoretical work is desperately needed.

Observation, modeling and theory cannot occur in isolation from one another. Continued progress in understanding how clouds affect the climate system relies on an active interchange among these activities.

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