Cirrus clouds and climate

Cirrus are thin, wispy clouds that appear at high altitude and consist of ice crystals. At midlatitudes, clouds with base heights above about 6 km (20,000 ft) are designated as high clouds, a category that includes cirrus (Ci), cirrostratus (Cs), and cirrocumulus (Cc). Cirrus clouds are globally distributed at all latitudes over land or sea at any season of the year. They undergo continuous changes in area coverage, thickness, texture, and position. The most striking cirriform cloud features are produced by weather disturbances in midlatitudes. In the tropics, cirrus clouds are related to outflows from tower cumulus associated with the convective activity over the oceans. The global cirrus cover has been estimated to be about 20–25%, but recent analysis using the satellite infrared channels at the 15-micrometer carbon dioxide (CO_2) band has shown that their occurrence is more than 70% over the tropics.

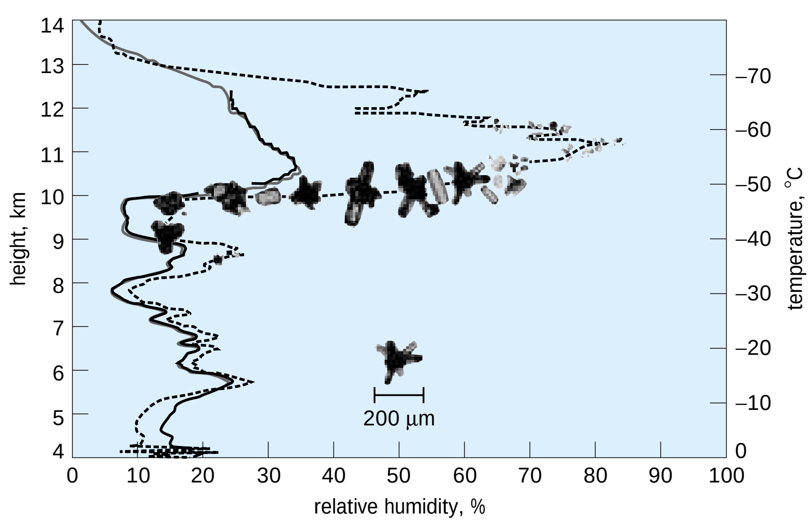
Cirrus composition. Cirrus clouds usually reside in the upper troposphere, where temperatures are generally colder than −20 to −30°C (−4 to −22°F). Because of their high location, direct observation of the composition and structure of cirrus clouds is difficult and requires a high-flying aircraft platform. In the 1980s, comprehensive information about cirrus composition became available because of the development of several airborne instruments to sample their particle-size distribution with optical imaging probes using a laser beam, high-resolution microphotography, and replicators, which preserve cloud particles in chemical solutions.

Ice crystal growth has been the subject of continuous laboratory, field, and theoretical research in the atmospheric sciences discipline over the past 50 years. It is the general understanding now that the shape and size of an ice crystal in cirrus is primarily controlled by the temperature and relative humidity inside the cloud. If ice crystals undergo collision and coalescence due to gravitational pulling and turbulence, more complicated shapes can result. In midlatitudes, where most of the observations have been made, cirrus clouds have been found to be composed of primarily nonspherical ice crystals with shapes ranging from solid and hollow columns to plates, bullet rosettes, and aggregates, with sizes spanning from about ten to thousands of micrometers. Observations in midlatitudes also revealed that at cloud tops pristine small columns and plates are predominant, whereas at the lower part of the cloud bullet rosettes and aggregates are most common (see **illusration**).

Limited measurements from high-flying aircraft in tropical cirrus clouds, which extend as high as 15–18 km (8–11mi), show that their ice crystal sizes range from about 10–2000 μm with four predominant shapes—bullet rosettes, aggregates, hollow columns, and plates—similar to those occurring in midlatitudes. In the tropics, observations reveal that large ice crystal sizes are associated with warmer temperatures or the development stage of clouds related to convection. Ice crystal data in arctic cirrus have also been collected which show their shapes to be a combination of pristine and irregular types with sizes appearing to be larger than about 40 μm. In the Antarctic, the extensive collection of ice particles at a surface station reveals the prevalence of long, needle-shaped ice crystals.

Ice crystals vary substantially in size and shape from the tropics, to midlatitudes, to the polar regions. In addition to the variety of intricate shapes and a large range of crystal sizes, the horizontal orientation of some cirrus columnar and plate crystals has been observed from a number of lidar backscattering depolarization measurements, as well as limited polarization observations from satellites. Also, the fact that numerous halos (sundogs) and bright arcs surrounding the Sun have been observed demonstrates that a specific orientation of the ice particles must exist in some cirrus. An understanding of the climatic effect of cirrus clouds must begin with a comprehensive understanding of their microscopic composition and associated radiative properties.

Cirrus radiative forcing. The amount of sunlight that cirrus clouds reflect, absorb, and transmit depends on their coverage, position, thickness, and ice crystal size and shape distributions. Cirrus clouds can also reflect and transmit the thermal infrared emitted from the surface and the atmosphere and, at the same time, emit infrared radiation according to the temperature structure within them. The ice crystal size and shape distributions and cloud thickness are fundamental cirrus parameters that determine the relative strength of the solar-albedo (reflecting of sunlight) and infrared-greenhouse (trapping of thermal radiation) effects, which are essential components of the discussion of cirrus clouds and climate. These radiative effects are determined by the basic scattering and absorption properties of the ice



Ice crystal size and shape as a function of height, temperature, and relative humidity captured by a replicator balloon sounding system in Marshall, Colorado, on November 10, 1994. The broken and solid lines denote the relative humidity measured by cryogenic hygrometers and Vaisala RS80 instruments, respectively. (*Graphic by Andrew Heymsfield, National Center for Atmospheric Research. data from K. N. Liou, An Introduction to Atmospheric Radiation, 2d ed., Academic Press, 2002*)

crystals. Unlike the scattering of light by spherical water droplets (which can be solved by Lorenz-Mie theory), an exact solution for the scattering of light by nonspherical ice crystals, covering all sizes and shapes that occur in the Earth's atmosphere, does not exist in practical terms. Recent advances in this area have demonstrated that the scattering and absorption properties of ice crystals of all sizes and shapes, which commonly occur in the atmosphere, can be calculated with high precision by a unified theory for light scattering. This theory combines the geometric optics approach for large particles and the finite-difference time-domain numerical method for small particles. Results of this theory have been used to assist in the remote-sensing and climate-modeling programs involving cirrus clouds.

To comprehend the impact of cirrus clouds on the radiation field of the Earth and the atmosphere and thus climate, the term "cloud radiative forcing" is used to quantify the relative significance of the solar-albedo and infrared-greenhouse effects. Cloud radiative forcing is the difference between the radiative fluxes at the top of the atmosphere in clear and cloudy conditions. The addition of a cloud layer in a clear sky would lead to more sunlight reflected back to space, reducing the amount of solar energy available to the atmosphere and the surface. In contrast, the trapping of atmospheric thermal emission by nonblack (-body) cirrus clouds enhances the radiative energy, or heat, available in the atmosphere and the surface. Based on theoretical calculations, it has been shown that the infrared greenhouse effect for cirrus clouds generally outweighs their solar albedo counterpart, except when the clouds contain very small ice crystals on the order of a few micrometers, which exert a strong solar-albedo effect. The relative significance of the solar-albedo versus infrared-greenhouse effects is clearly dependent on the ice crystal size and the amount of ice in the cloud. Because of the complexity of sorting cirrus signatures from satellite observations, actual data to calculate the global cirrus cloud radiative forcing is not yet available.

Cirrus and greenhouse warming. An issue of cirrus clouds and greenhouse warming produced by the increase in greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), chlorofluorocarbons (CFC), and ozone (O_3), is the possible variation in their position and cover. Based on the principles of thermodynamics, the formation of cirrus clouds would move higher in a warmer atmosphere and produce a positive feedback in temperature increase because of the enhanced downward infrared flux from higher clouds. A positive feedback would also be evident if the high cloud cover increased because of greenhouse perturbations. Climate models have illustrated that high clouds that move higher in the atmosphere could exert a positive feedback, amplifying the temperature increase. However, the extent and degree of this feedback and temperature amplification have not been reliably quantified. The prediction of cirrus cloud cover and position based on physical principals is a difficult task, and successful prediction using climate models has been limited. This difficulty is also associated with the uncertainties and limitations of inferring cirrus cloud cover and position from current satellite radiometers. In fact, there is not sufficient cirrus cloud data to correlate with the greenhouse warming that has occurred so far.

Another issue that determines the role that cirrus play in climate and greenhouse warming is related to the variation of ice water content and crystal size in these clouds. Based on aircraft observations, some evidence suggests that there is a distinct correlation between temperature and ice water content and crystal size. An increase in temperature leads to an increase in ice water content. Ice crystals are smaller at colder temperatures and larger at warmer temperatures. The implication of these microphysical relationships for climate is significant. For high cirrus containing primarily nonspherical ice crystals, climate model results suggest that the balance of solar-albedo versus infrared-greenhouse effects, that is, positive or negative feedback, depends not only on ice water content but also on ice crystal size. This competing effect differs from low clouds containing purely water droplets in which a temperature increase in the region of these clouds would result in greater liquid water content and reflect more sunlight, leading to a negative feedback.

Contrail cirrus. In addition to naturally occurring cirrus, the upper-level ice crystal clouds produced by high-flying aircraft, known as contrails, or condensation trails, have also been frequently observed. Contrails are generated behind aircraft flying in sufficiently cold air, where water droplets can form on the soot and sulfuric acid particles emitted from aircraft or on background particles and then freeze to become ice particles. Based on a number of recent field experiments, contrails were found to predominantly consist of bullet rosettes, columns, and plates, with sizes ranging from about 1 to 100 μm. Persistent contrails often develop into more extensive contrails in which the ice supersaturation is generally too low to allow cirrus clouds to form naturally. Consequently, contrails may enhance the extension of the natural cirrus cover in the adjacent areas where the relative humidity is too low for the spontaneous nucleation of ice crystals to occur, although this is an indirect effect that has not yet been quantified.

The climatic effect of contrail cirrus also includes their impact on the water vapor budget in the upper troposphere, which is important in controlling the thermal infrared radiation exchange. It has been estimated that aircraft line-shaped contrails cover about 0.1% of the Earth's surface on an annually averaged basis, but with much higher values in local regions.

An analysis of cirrus cloud cover in Salt Lake City based on surface observations revealed that in the mid-1960s a substantial increase in cirrus clouds coincided with a sharp increase in domestic jet fuel consumption. A similar increase has also been detected at stations in the midwestern and northwestern United States that are located beneath the major upper tropospheric flight paths. Satellite infrared imagery has recently been used to detect contrail cirrus, but long-term observations are needed for assessment purposes. Analysis of contrail cirrus and radiative forcing indicates that the degree and extent of net warming or cooling would depend on the cloud optical depth (a nondimensional term denoting the attenuation power of a light beam) and the ice crystal sizes and shapes that occur within them. Projections of air traffic show that the direct climatic effects of contrails could be on the same order as some tropospheric aerosol types. It appears that the most significant contrail effect on climate would be through their indirect effect on cirrus cloud formation, a subject requiring further observational and theoretical modeling studies.

Indirect effects. The indirect aerosol-cloud radiative forcing has usually been connected to low clouds containing water droplets via modification of the droplet size and cloud cover/precipitation. Recent analyses of ice cloud data, however, suggest that mineral dust particles transported from Saharan Africa and Asia are effective ice nuclei capable of glaciating supercooled middle clouds. Thus, it appears that major dust storms and perhaps minor eolian (wind) emissions could play an important role in modulating regional and global climatic processes on the formation of cirrus clouds through an indirect effect.

Currently, it is certain that, through greenhouse warming and indirect effects via high-flying aircraft and aerosols, cirrus clouds play a pivotal role in shaping climate and climate change of the Earth and the atmosphere system in connection with the solar-albedo and infrared-greenhouse effects. However, there is not sufficient global data from satellite observations to ascertain the long-term variability of cloud cover, cloud height, and cloud composition to enable the construction of a climate model to assess the impact of their changes in terms of temperature and precipitation perturbations. Moreover, many thin and subvisual cirrus clouds, with an optical depth less than about 0.1, have not been detected by the present satellite radiometers and retrieval techniques. The subject of cirrus clouds and climate is a challenging problem and requires substantial observational and theoretical research and development.

For background information *see* AEROSOL; ALBEDO; ATMOSPHERE; CLIMATOLOGY; CLOUD; CLOUD PHYSICS; GREENHOUSE EFFECT; HALO; HEAT BALANCE, TERRESTRIAL ATMOSPHERIC; INFRARED RADIATION; METEOROLOGICAL OPTICS; RADAR METEOROLOGY; SATELLITE METEOROLOGY; TERRESTRIAL RADIATION in the McGraw-Hill Encyclopedia of Science & Technology. K. N. Liou

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