

Cirrus Clouds and Climate

Cirrus clouds are clouds that have high appearance in the atmosphere. In midlatitudes, it has been conventionally classified that clouds with base heights above about 6 km are designated as high clouds, a category that includes cirrus (Ci), cirrostratus (Cs), and cirrocumulus (Cc). Cirrus clouds are globally distributed, being present at all latitudes and without respect to land or sea or 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 deep cumulus outflows associated with the convective activity over the oceans. The global cirrus cover has been estimated to be about 20 to 25 %, but recent analysis using the satellite infrared channels at the 15 μm CO_2 band has shown that their frequency occurrence is more than 70 % in the tropics.

Cirrus composition. Cirrus clouds usually reside in a region referred to as the upper troposphere where temperatures are generally colder than -20 to -30°C . Because of their high location in the atmosphere, direct observation of the composition and structure of cirrus is difficult and requires a highflying aircraft platform. It was not until the 1980s that comprehensive information about cirrus composition became available as a result of the development of several airborne instruments to sample their particle size distribution. These instruments included imaging optical probes using a laser beam, high resolution microphotographs, and replicators in which cloud particles can be preserved 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 our 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 conducted, 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, and with sizes spanning from about 10 to thousands of micrometers. Observations in midlatitudes also reveal that at the cloud top pristine and small columns and plates are predominant, whereas at the lower part of the cloud bullet rosettes and aggregates are most common.

Limited measurements from highflying aircraft in tropical cirrus clouds, which can extend to as high as 15-18 km, illustrate that their ice crystal size ranges from about 10 μm to 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 prevalence of long needle ice crystal types has been observed on the basis of the extensive collection of ice particles at a surface station. It is clear then that 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 spread in crystal size,

horizontal orientation of some columnar and plate crystals in cirrus 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 and arcs have been observed demonstrates that specific orientation of 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. Cirrus clouds reflect, absorb, and transmit sunlight the amount of which 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 so-called solar albedo (reflection 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 ice crystals. Unlike the scattering of light by spherical water droplets, which can be solved by the exact 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 term. Recent advances in this area have demonstrated that by unifying the geometric optics approach for large particles and the finite-difference time domain numerical method for small particles, referred to as a unified theory for light scattering by ice crystals, calculations of the scattering and absorption properties of ice crystals covering all sizes and shapes that commonly occur in the atmosphere can be performed with high precision. 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" has been developed to quantify the relative significance of the solar albedo and infrared greenhouse effects. It is defined as 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 and thus reduce the amount of solar energy available to the atmosphere and the surface. On the other hand, however, the trapping of atmospheric thermal emission by nonblack 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, we do not yet have actual data to calculate the global cirrus cloud radiative forcing.

Cirrus and greenhouse warming. The first issue concerning the role of cirrus clouds in the greenhouse warming produced by the increase in greenhouse gases involving CO₂, CH₄, NO₂, CFC, and O₃ is the possible variation in their position and cover. Based on the principle 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. Theoretical experiments using one- and three-dimensional climate models have illustrated that high clouds that move higher in the atmosphere could exert a positive feedback resulting in amplification of the temperature increase. However, the extent and degree of this feedback and temperature amplification have not been reliably quantified for the following reasons. First, 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. Unfortunately, we do not have sufficient cirrus cloud data to correlate with the greenhouse warming that has occurred so far.

The second issue that determines the role 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. Also, ice crystals are smaller (larger) at colder (warmer) temperatures. The implication of these microphysical relationships for climate is significant. For high cirrus containing primarily nonspherical ice crystals, illustrative results from one-dimensional climate models suggested that the balance of solar albedo versus infrared greenhouse effects, i.e., 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 region of these clouds would result in greater liquid water content and reflect more sunlight, leading to a negative feedback.

Contrail cirrus, aerosols, and indirect effects. In addition to naturally occurring cirrus, the upper level ice crystal clouds produced by highflying aircraft, known as contrails or condensation trails, have also been frequently observed. These are generated behind aircraft flying in sufficiently cold air where water droplets can form on the soot and sulfuric acid particles emitted from aircraft and/or background particles and can 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 μm to about 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, 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-shape 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 a substantial increase in cirrus clouds occurring in about 1965 coincided with a sharp increase in domestic jet fuel consumption in the mid-1960s. 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 employed for the detection of contrail cirrus but long-term observations are needed to provide time series for assessment purposes. Analysis of contrail cirrus radiative forcing indicates that the degree and extent of net warming or cooling would depend on the cloud optical depth and the ice crystal sizes and shapes that occur within them. The future projection of air traffic shows 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.

The discussion of 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 middle supercooled clouds. Thus, it appears that major dust storms and perhaps minor aeolian emissions could play an important role in modulating regional and global climatic processes through the indirect effect on the formation of cirrus clouds.

At this point, we are certain that through greenhouse warming and indirect effects via highflying 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, we do not have 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 perform climate simulations to assess the impact of their changes in term 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. Indeed, the subject of cirrus clouds and climate is a challenging problem in the atmospheric and climate sciences and requires substantial observational and theoretical research and development.

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Bibliography. K. K. Liou, Influence of cirrus clouds on weather and climate processes: A global perspective, *Mon. Wea. Rev.*, 114, 1167-1198, 1986; K. N. Liou, *An Introduction of Atmospheric Radiation, 2nd Edition*, Academic Press, Chapter 8, 2002; K. Sassen, Saharan dust storms and indirect aerosol effects on clouds: CRYSTAL-FACE results, *Geophys. Res. Lett.*, 30, 10.1029/2003GL017371, 2003; U. Schumann, Contrail cirrus, In *Cirrus*, Eds. D. K. Lynch, et al., Oxford University Press, pp.231-255, 2002.

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