High-Altitude Cirrus Clouds and Climate

S Veerabuthiran

Introduction

Clouds are aesthetically appealing. Without them, there would be no rain or snow, thunder or lightning, rainbows or halos. A cloud is a visible aggregate of tiny water droplets or ice crystals suspended in the air. Most clouds result from cooling due to lifting of moisture containing air. Those associated with strong rising air currents have vertical development and a puffy appearance, whereas those resulting from gentler lifting or other methods of cooling tend to spread out into layers. Although their method of formation is largely responsible for their appearance, clouds are classified primarily on the basis of their altitude, shape, color, and transmission or reflection of light.

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Classification of Clouds

The French naturalist Lamarck (1744-1829) proposed a system for classifying clouds in 1802. This work however, did not receive wide acclaim. One year later Luke Howard, an English naturalist, developed a clouds classification system that found general acceptance. He named sheet-like clouds as *stratus* (Latin for layers); puffy clouds as *cumulus* (heap); wispy clouds as *cirrus* (curl of hair); and rain clouds as *nimbus* (violent rain). These are the four basic forms of clouds. Other clouds can be described by combination of these basic types. For example, *nimbostratus* is a rain cloud that shows layering, whereas *cumulonimbus* is a rain cloud having pronounced vertical development. *Table* 1 lists the types of cloud and the altitudes at which they occur.

What is a Cirrus Cloud?

Cirrus clouds are high-altitude (6-18 km), thin, wispy clouds (*Figure* 1a and *Figure* 1b) and they cover about 30 to 50% of the earth's surface at any given time. In general, these clouds are

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Cloud group	Tropical region	Mid Lattitude region	Polar region
High clouds			
Cirrus (Ci)			
Cirrostratus (Cs)	8 to 18 km	5 to 13 km	3 to 8 km
Cirrocumulus (Cc)			
Middle clouds			
Altostratus (As)	2 to 8 km	2 to 7 km	2 to 4 km
Altocumulus (Ac)			
Low clouds			
Stratus (St)			
Stratocumulus (Sc)	0 to 2 km	0 to 2 km	0 to 2 km
Nimbostratus (Ns)			

Table 1. Types of clouds and their altitude.

found below the tropopause. The base of these clouds vary greatly with respect to seasons and their locations, but generally occur in the height range from 4 to 15 km with the cloud base temperature being below –20 °C. These clouds are generally composed of ice crystals but sometimes they may also have super-cooled water droplets. Cirrus clouds are classified into three categories: sub-visual, threshold-visible and thin. The distinction between sub-visual and threshold (i.e. barely visible or grayish) cirrus often depends on the solar elevation angle. The geometrical thickness of these clouds in general, varies from few hundred meters to three kilometers. They are unusually homogeneous in the horizontal direction and can extend

Figure 1. Photographs of cirrus clouds.

Credit: http://www-icpc.doc.ic.ac.uk/projets/ice-clouds.html

Credit: http://www.asp.ucar.edu/~zondlo/cirrus.html

Property	Typical	Measured range
Cloud base height*	12 km	6-18 km
Cloud thickness*	1.5 km	0.1 to 3 km
Cloud center altitude*	13 km	6 to 18 km
Crystal concentration	30 L^{-1}	10^{-4} to 10^{4} L^{-1}
Ice water content	0.025 gm^{-3}	10^{-4} to 1.2 gm^{-3}
Crystal length	250 mm	1 to 8000 mm
Extinction coefficient*	0.08 km^{-1}	0.03 to 0.3 km^{-1}
Optical depth*	0.063	0.01 to 0.2
Temperature	– 70 °C	–20 °C to – 80 °C

(* Obtained using Multiwavelength lidar system[1] located at Space Physics Laboratory, VSSC, Trivandrum)

Table 2. Typical values and measured ranges of the physical and optical properties (at 532 nm) of Cirrus clouds.

[1] Exploring the atmosphere with lidars, *Resonance*, Vol.8, No.4, pp.33-43; No.5, pp.47-51, 2003.

up to 2700 km. Their life time varies from few hours to few days. Clouds with a maximum thickness of 1 km or less are classified as *laminar* and those with thickness greater than 1 km as *deep*; deep clouds include thick cirrus, cirrus anvils, and deep convective clouds. Typical values of physical and optical properties (at 532 nm) of cirrus clouds are given in *Table* 2.

Formation Mechanism

Two mechanisms have been proposed for the formation of the cirrus clouds near the tropopause. They are: (1) Dissipation of optically thick cumulonimbus outflow anvils leaving behind an optically thin layer of small ice clouds; (2) *In situ* nucleation of the ice crystals near the tropopause due to homogeneous freezing of sulphuric acid particles. Either slow synoptic-scale uplift or shear-driven turbulent mixing may generate the super saturation required for the nucleation in this mechanism. Given the very low temperature at the tropical tropopause (~–80°C), synoptic scale uplift can generate the moderate ice super saturations (less than 10%) required for homogeneous freezing of sulphuric acid aerosols. A schematic representation of the two formation mechanisms is shown in *Figures* 2 (a) and (b). In the tropics, Inter-Tropical Convergence Zone (ITCZ) continuously pumps moisture and aerosols from the lower troposphere into the upper

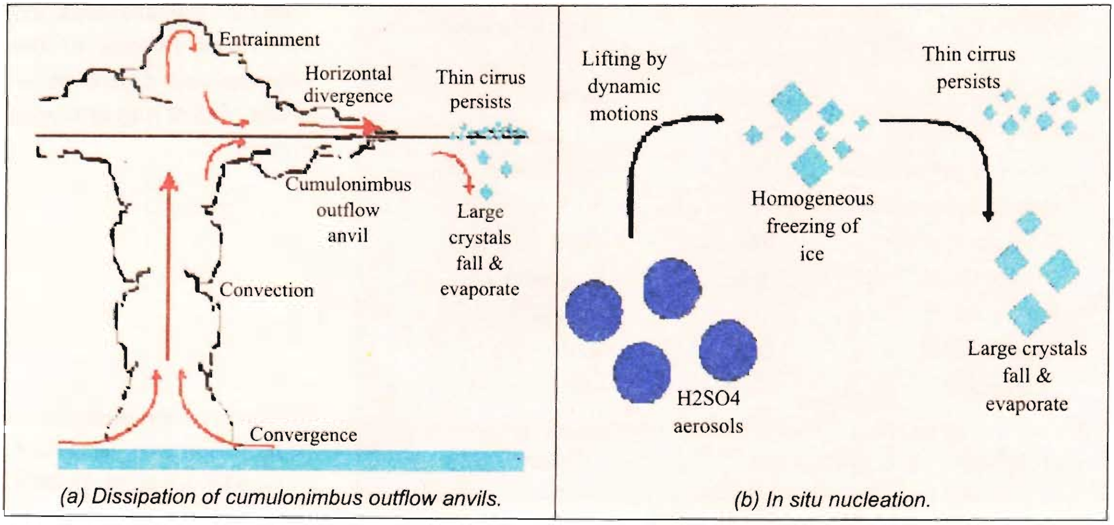

Figure 2.Schematic representation of formation of cirrus clouds.

troposphere. In the case of deep cumulus convection, water (as liquid or solid) and aerosols spread in the form of thick cirrus and cirrostratus clouds, generally below the tropopause level, but occasionally breaking through the tropopause into the lower stratosphere. At very low temperatures ($\approx -70°C$) prevailing near the tropical tropopause, aerosols and water vapour coagulate or get frozen into ice-cloud particles. When the cirrus clouds melt, water vapour and aerosols separate out, leaving large relative humidity and high aerosol content in the upper troposphere.

In the second mechanism, it is suggested that cirrus clouds form naturally in the upper troposphere when highly dilute sulphate aerosols cool and become supersaturated with respect to ice. These cloud particles freeze homogeneously when water vapour reaches ice super saturations of approximately 1.5. This super saturation required for ice nucleation may be generated by either slow, synoptic scale uplift or shear driven turbulent mixing. It has been suggested that the cirrus clouds could also form from heterogeneous nucleation on insoluble solids. A recent focus of study has been on the formation of ice clouds on soot particles, a by-product of fossil fuel combustion at the surface and from aircraft emissions throughout the atmosphere. For such heterogeneous nucleation to be efficient, soot serves as a suitable nucleus for ice.

Composition and Structure of Cirrus

Unlike water clouds, high-level cirrus, which contain significant amount of large non-spherical ice crystals, are normally optically thin with emissivity less than one. They are composed of ice crystals in the form of hexagonal plates, columns, bullets and rosettes. In cirrostratus, crystals have lengths of approximately 100 μm and a width of about 40 μm, which vary with temperature, duration of super saturation and concentration. The concentration of ice in cirrostratus cloud is about 100 - 1000 per litre and their water content is of the order of 0.01 gm^{-3} [2]. The predominant factor that controls the ice crystal size is temperature. A majority of ice crystals in cirrus clouds tend to be horizontally oriented with their longer axes parallel to ground. The size and orientation of ice crystals can be quite variable within a single cloud owing to the complex growth and evaporation environment provided by the atmospheric phenomena producing or sustaining the cirrus. Crystals with certain habits (i.e., dendrites, plates, needles, etc.) tend to fall or form with a preferred orientation. Non-random alignment of ice crystals in cirrus leads to halos, arcs, and other optical phenomena.

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How are Ice Crystals Formed in the Cirrus Cloud?

Ice particles may originate in clouds by deposition from the vapour phase and by the nucleation of super cooled water. In both cases, the nucleation is heterogeneous and involves the action of ice nuclei. Ice nuclei exist in the air as free particles as well as embedded in clouds. Ice nuclei in the air may nucleate ice in clouds by acting as deposition, freezing or contact nuclei. A deposition nucleus is one on which ice is deposited directly from the vapour phase. A freezing nucleus acts by nucleating a super cooled droplet in which it is embedded, and a contact nucleus initiates the freezing of a super cooled droplet with which it collides. The probability of the ice particles present in a cloud increases as the temperature decreases below 0°C. Clouds with tops at temperature between 0 and –4°C generally consist entirely of super cooled droplets. It is in such clouds that the aircraft is likely to encounter severe icing condition since super cooled drops freeze when they collide with an aircraft. If the temperature of the top of cloud is –10°C then there is about a 50% probability of detecting ice, and below –20°C there is better than 95 % probability.

When a super cooled droplet collides with ice particles, it freezes in two stages. In the first stage, which occurs almost instantaneously, a fine mesh of ice shoots through the droplet and freezes enough water to raise the temperature of the droplet to 0°C. The second stage of freezing is much slower and involves the transfer of heat from the partially frozen droplet (released during freezing) to the colder environment. During this stage, an ice shell first forms over the surface of the droplet and then thickens progressively inward. As the droplet freezes inward, water is trapped in its interior; as this water freezes, it expands and sets up large stress in the ice shell. This stress may cause the ice shell to explode throwing off numerous ice splinters, which may in turn grow.

Measurement Techniques

There are different kinds of techniques available for determining the altitude and thickness of the cirrus clouds. Lidar, 8.6 mm wavelength radar, balloon borne frost point hygrometer, aircraft visual observations, and satellite observations (cloud altitude only) have been used. Lidar measurements are the most accurate of these techniques. Lidar is the best for defining the position and spatial distribution of clouds. Lidar can locate cloud base (from below) and cloud top with a precision unobtainable by any other technique.

The lidar system located at Space Physics Laboratory, VSSC, Trivandrum (8° 33'N, 77° E) has been used to observe high altitude cirrus clouds during the night. A typical observation

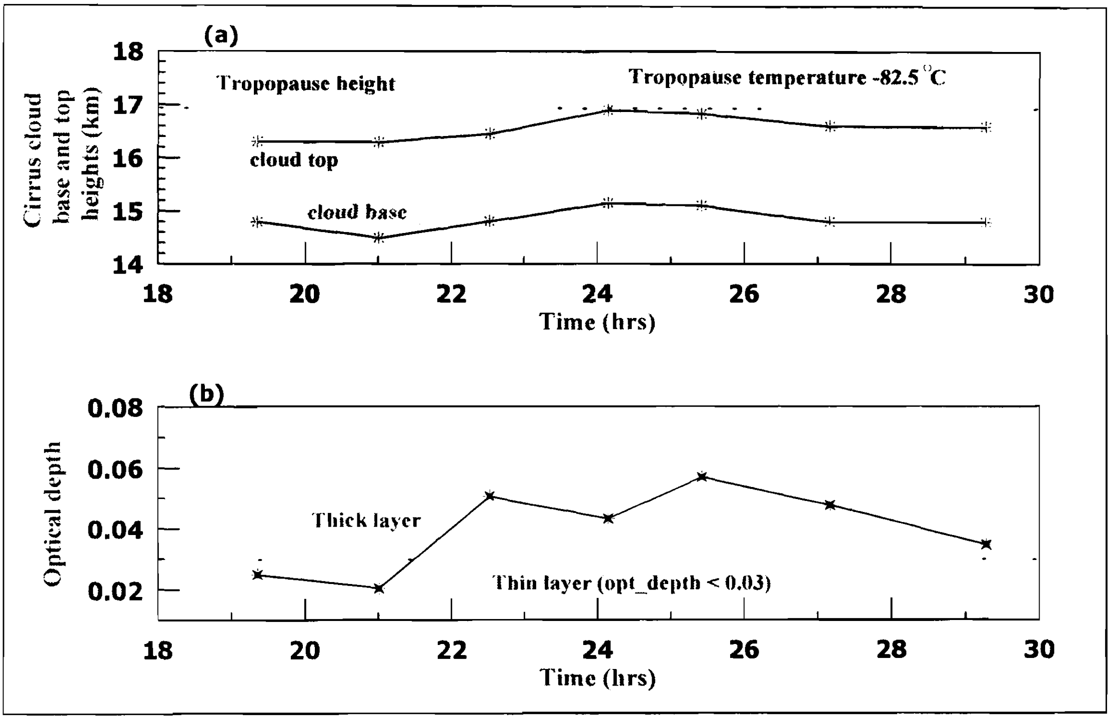


Figure 3. Analyzed lidar data for the night of December 22-23, 2000. The cirrus cloud top and base heights are shown in panel (a). The dotted line is the height of the tropopause. Panel (b) displays the optical thickness. The dotted line is sub visible cloud threshold.

showed downward falling streaks of such cloud layers on December 22, 2000 in the height range 14-17 km with thickness around 1-2 km (*Figure* 3). The profiles were obtained with an altitude resolution of 150m and were averaged for 20 minutes duration. The observations were started at 19:30 hrs and the layer with its base at an altitude of 14.57 km and geometrical depth of 1.73 km was immediately observed. The top of the layer was at 16.3 km and was just below the tropopause, which was around 16.85 km with the temperature around –82.5°C (obtained from radiosonde measurements). As time progressed, the geometrical thickness of the layer varied between 1.5 km and 2 km, with a maximum top height of 16.9 km as seen in *Figure* 3a. From *Figure* 3b, it is observed that the optical depth reached a maximum value around midnight. The layer started decaying after midnight and the optical depth values also decreased with time. These layers could be due to cumulonimbus anvil outflows [3]. They are turbulent in nature, which is due to the vertical mixing of air. Because of the turbulence, the cloud thickness decreases with time and sometimes leads to complete decay.

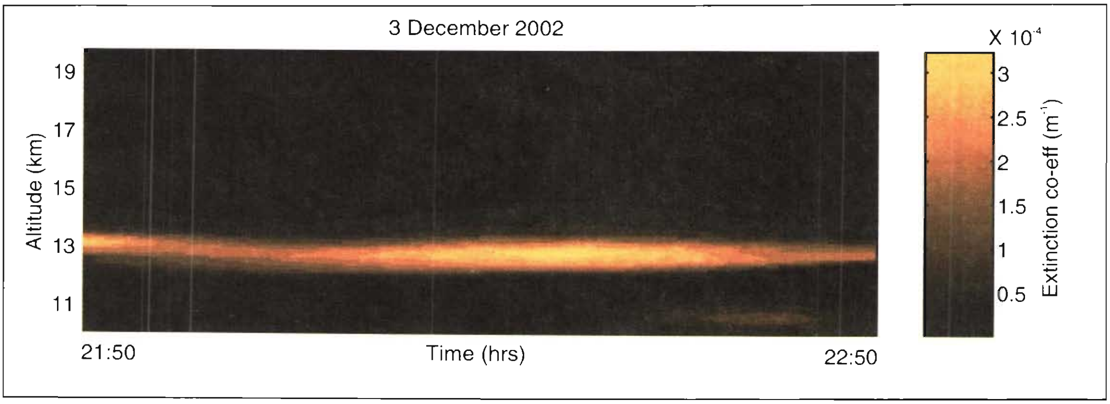
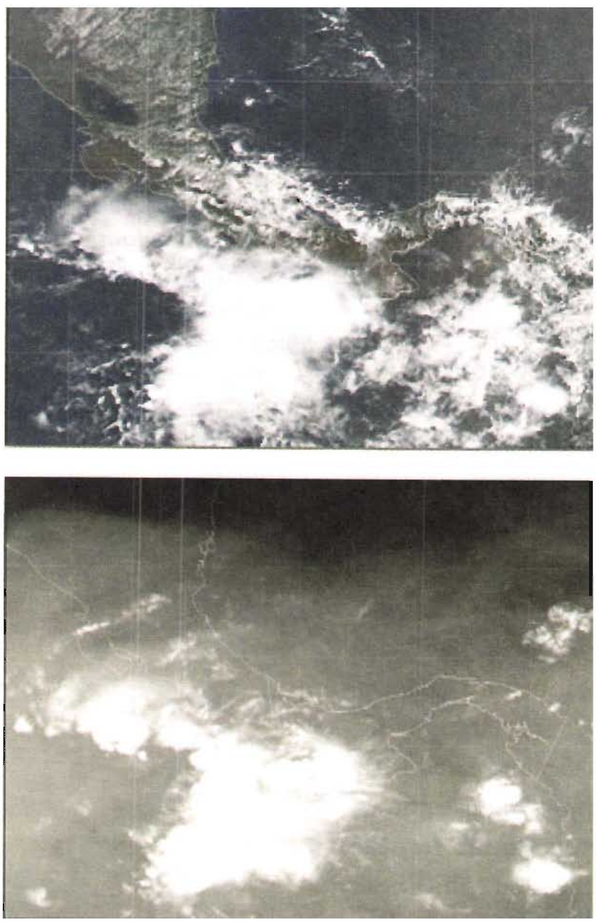


Figure 4. Cirrus cloud observed on 3 December 2002 using lidar.

Figure 4 shows another example of lidar measurements of high altitude cirrus clouds.



Several attempts have been made to identify cirrus clouds from satellite data. GOES (Geostationary Operational Environmental Satellite) IR pictures have been used to describe the formation and dissipation of cirrus clouds on a global scale. Cirrus clouds are identified based on cloud top temperature. Recently, Moderate-resolution Imaging Spectroradiometer (MODIS) has been used to detect clouds that would be invisible to the human eye (*Figure* 5). This pair of images highlights the ability of MODIS to detect what is called 'sub-visible cirrus'. The image on top shows the cloud detected by MODIS satellite using data collected in the visible part of the electromagnetic spectrum. Clouds are apparent in the center and lower right of the image, while the rest of the image appears to be relatively clear. However, data collected at 1.38 μm (lower image)

Figure 5. Cirrus cloud detected by MODIS satellite at visible and IR region.

show that a thick layer of previously undetected cirrus clouds obscures the entire scene. The 1.38 μm channel in MODIS detects electromagnetic radiation in the infrared region of the spectrum. These images were obtained from data collected on April 4, 2000.

Impact of Cirrus Clouds on Weather and Climate

Cirrus clouds control the heat budget of the earth-atmosphere system, and hence its climate. While clouds reflect a significant portion of incoming solar fluxes, they also trap the outgoing thermal infrared fluxes emitted from the earth's surface and lower troposphere. Clouds composed of water droplets are generally optically thick, and hence they act as blackbodies in the thermal infrared region. Therefore the solar albedo effect in the case of water clouds will produce greater variability in the radiative budget of the atmosphere due to changes in the cloud vertical liquid water content. High level cirrus clouds, which contain a significant amount of large non-spherical ice crystals in low concentrations are normally optically thin and non-black. Cirrus clouds reflect less solar radiation and absorb more infrared radiation from the earth than other clouds (*Figure* 6). Hence cirrus clouds suppress tropospheric cooling but significantly increase the cooling in the stratosphere.

Recent studies [4] suggest that the surface of cirrus clouds provides sites for the activation of chlorine. By increasing ClO_x abundance near mid-latitude tropopause, cirrus clouds can lead to ozone depletion. Tropical cirrus clouds spreading in the upper troposphere, are generally more widespread and thicker than midlatitude clouds.

Suggested Reading

[1] Peter V Hobbs and Arthur L Rangno, *American Meteorological Society*, pp. 2523-2549, 1985.

[2] Kuo-Nan Liou, *Mon Wea. Rev.*, pp. 1167-1199, 1985.

[3] E J Jensen and others, *J. Geophy. Res.*, Vol. 101, pp. 21361-21375, 1996.

[4] Solomon and others, *J. Geophy. Res.*, Vol. 102, pp. 21411-21449, 1997.

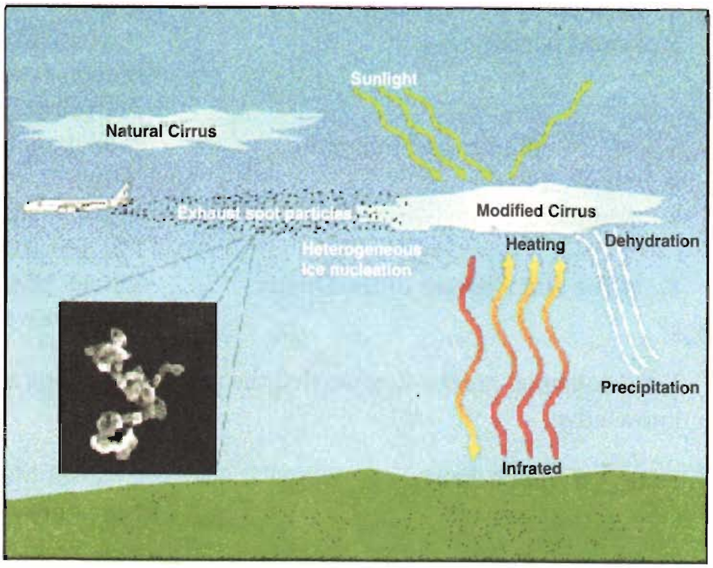


Figure 6. Impact of cirrus clouds on weather and climate.

(Credit: http://geo.arc.nasa.gov/sge/jskiles/fliers/gif_folfder/image)

Cirrus clouds also play an important role in the dehydration of the upper troposphere and lower stratosphere near the equator. The observed dryness of the lower stratosphere is due to the mean rising motion of air across the tropopause in the tropics, a poleward drift, and slow descent and radiative cooling of the air outside the tropics.

Conclusion

Cirrus clouds can have a profound impact on climate. This has lead to many major programs such as International Satellite Cloud Climatology Project (ISCCP), First International satellite cloud climatology project Regional Experiment (FIRE), Experimental Cloud Lidar Pilot Study (ECLIPS), and International Cloud Experiment (ICE) over the last decade. Observations of cirrus properties and ice content are proposed in new satellite missions such as CLOUDSAT.

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