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978-0-521-88916-2 — Light Scattering by Ice Crystals
Kuo-Nan Liou , Ping Yang
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Ice in the Earth's atmosphere

"Let there be light," and there was light.*

The fact that the Earth's sky appears blue is a consequence of the scattering of "light" by molecules according to the theory of Rayleigh scattering. The fascinating halos and arcs we see mixed within blue sky result from light scattering by ice crystals.

Our presentation of light scattering by ice crystals begins with an overview of clouds. This is followed by a global view of ice distribution in the Earth's atmosphere; formation and growth of ice crystals; ice crystal morphology, size, and distribution; and a discussion of cirrus cloud modeling with a linkage to some of these topics.

1.1 Introduction to clouds

I BRING fresh showers for the thirsting flowers,
From the seas and the streams;
I bear light shade for the leaves when laid
In their noonday dreams.
From my wings are shaken the dews that waken
The sweet buds every one,
When rocked to rest on their mother's breast,
As she dances about the sun.
I wield the flail of the lashing hail,
And whiten the green plains under,
And then again I dissolve it in rain,
And laugh as I pass in thunder.
. . .
I am the daughter of Earth and Water,
And the nursling of the Sky;
I pass through the pores of the ocean and shores;
I change, but I cannot die.
For after the rain, when with never a stain

* A quotation from Genesis 1:3 to the extent to introduce the term, "Let there be light."

The pavilion of Heaven is bare,
And the winds and sunbeams with their convex gleams
Build up the blue dome of air,
I silently laugh at my own cenotaph,
And out of the caverns of rain,
Like a child from the womb, like a ghost from the tomb,
I arise, and unbuild it again.

(Percy B. Shelley, "The Cloud" (1820))

Clouds are formed when water evaporates from oceans and other surfaces (lakes, ponds, moist land surfaces) carried by convection, orographic, or frontal lifting and rises into the upper, colder part of the atmosphere. Formation of clouds generally requires the interaction of water vapor with a type of aerosol referred to as condensation nuclei or ice nuclei. A cloud becomes visible once the water vapor has been cooled by the condition of water or ice saturation. However, some very thin clouds cannot be seen by the human eye, and are classified as subvisual clouds. Clouds are normally produced in a region referred to as the troposphere (lower atmosphere), the lowest layer of the atmosphere, where weather activities occur. Clouds are regulated by the hydrological cycle, which involves evaporation, cloud formation, precipitation, runoff, and large-scale circulation.

In accordance with the World Meteorological Organization (WMO) definition, clouds are conventionally classified in terms of their position and appearance (shape) in the atmosphere. Clouds with a base height above 6 km are designated as high clouds, a category that includes cirrus (Ci), cirrostratus (Cs), and cirrocumulus (Cc). On the basis of the U.S. 1976 Standard Atmosphere classification, 6 km corresponds to a temperature of about 249 K, which is 24 K below the freezing temperature (273 K). Thus, these clouds contain exclusively ice particles. Cirrus clouds tend to be wispy and transparent (Figure 1.1, upper left panel). In midlatitude, large numbers of this type of clouds are generally associated with an approaching storm system. The upper right panel in Figure 1.1 illustrates the appearance of Cc. Regional convective instability gives this cloud type a rolled or rippled appearance. The upper middle panel in Figure 1.1 shows the appearance of Cs, which consists of mostly continuous, wide sheets of clouds that cover a large area of sky and, when it is associated with frontal systems, is a precursor to rain or snow.

The middle group of clouds, with heights between about 2 km ($\sim$275 K) and 6 km, consists of altocumulus (Ac) and altostratus (As), in which ice particles and water droplets can coexist. The appearance of Ac, displayed in the middle left panel of Figure 1.1, is a general indication of convective instability at the level of its formation. This cloud can bring precipitation, usually in the form of virga, a type of precipitation trail that does not reach the ground. Clouds of As (Figure 1.1, middle right panel) are formed when a stable air mass is lifted to the level of condensation along a frontal system, which can produce precipitation.

Low clouds, which are classified as having base heights below 2 km, include stratus (St), stratocumulus (Sc), and fair-weather cumulus (Cu). These clouds contain exclusively

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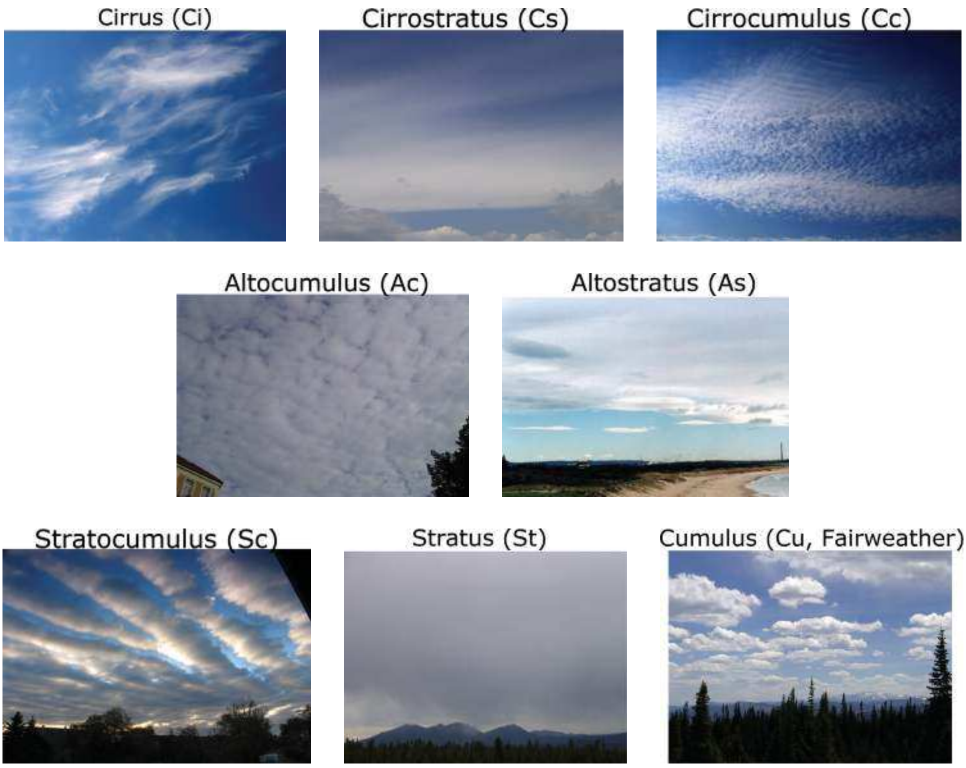

Figure 1.1 The appearance of high (Ci, Cs, Cc), middle (Ac, As), and low (Sc, St, Cu) clouds in the Earth's atmosphere. These pictures are reprinted from the cloud atlas at http://www.clouds-online.com. Copyright information: http://www.clouds-online.com/imprint.htm.

water droplets. Sc clouds have a lumpy appearance (lower left panel, Figure 1.1). They commonly form in an unstable air mass following a cold front, and can produce light rain or drizzle. St clouds (lower middle panel, Figure 1.1) form near the surface, usually over coastal oceans, have a clearly defined base, and can produce drizzle. Cu clouds (lower right panel, Figure 1.1) are the product of convective air mass instability and are often associated with fair-weather conditions.

Other cloud types are associated with substantial vertical development. Cumulonimbus (Cb) clouds are vertically developed cumulus produced by strong convectively unstable conditions, principally occurring over tropical oceans and land in the summer. They appear very dark gray with a cloud base height of about 1 km, and the cloud top can extend to the top of the troposphere and occasionally into the lower stratosphere (∼15–18 km). They generally produce thunderstorms, rain showers, and sometimes hail particles. The upper portion of these clouds may contain pure ice or a mixture of ice and water. Nimbostratus (Ns) is a type of cloud that tends to bring constant precipitation and low visibility. They normally form from altostratus clouds and can thicken into lower levels during precipitation.

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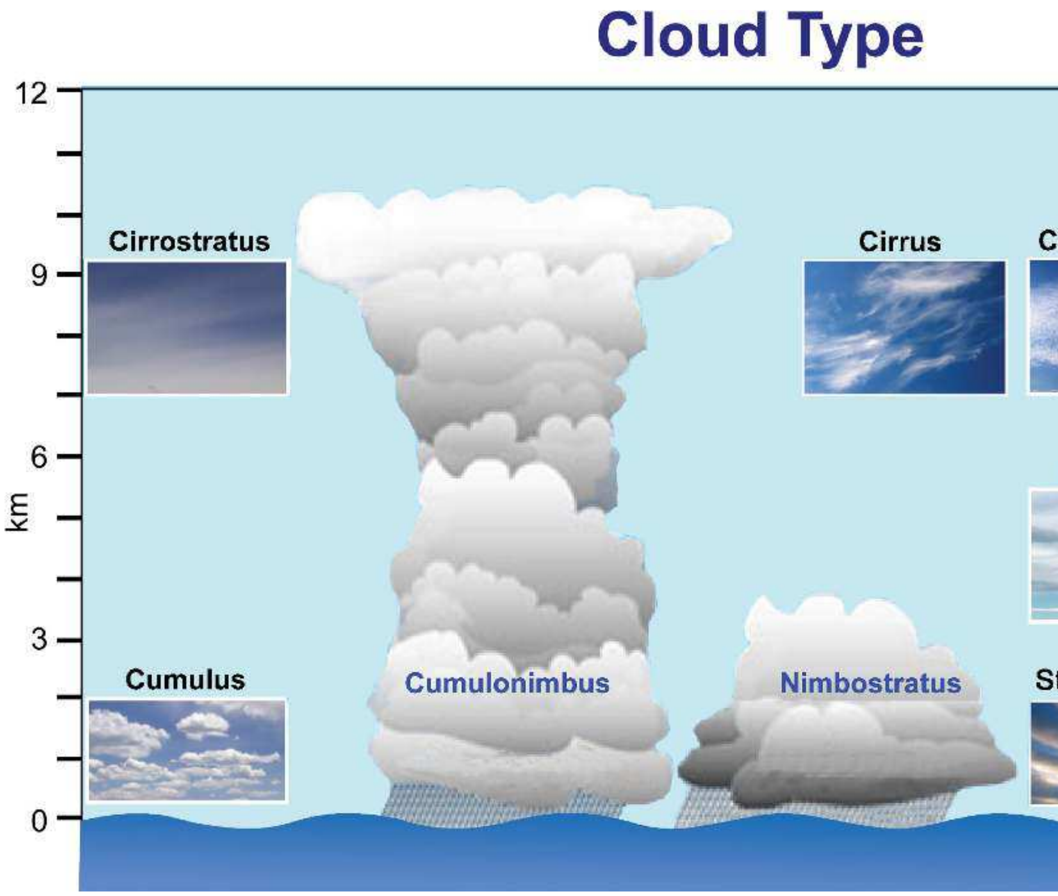

Figure 1.2 Cloud types defined in the vertical direction. High clouds have base heights above 6 km, middle c
6 km, and low clouds have base heights below 2 km. The vertically developed cumulonimbus can grow up to
normally evolved from altostratus clouds.

Figure 1.2 depicts the approximate vertical positions in the troposphere of all cloud types described above, including Cb and Ns, which produce precipitation that reaches the ground. Cb clouds generate a significant number of anvils in the tropics. Drifting with the winds, they can last for hours, and subsequently become high-level clouds before dissipating.

Upper-level ice crystal clouds produced by jet aircraft are known as contrails or condensation trails (Appleman 1953). Contrails are visible line clouds resulting from water vapor emissions that form behind aircraft flying in sufficiently cold air. Persistent contrails often develop into more extensive contrail cirrus, particularly in ice-supersaturated air masses in which ice supersaturation is generally too low to allow cirrus clouds to form naturally. Contrails may enhance the extension of the natural cirrus cover in adjacent areas where relative humidity is too low for the spontaneous nucleation of ice crystals. A comprehensive analysis of jet aircraft contrails over the United States and Europe using satellite infrared imagery has been carried out by Minnis *et al.* (1998a) and discussed in the IPCC report (IPCC Report 1999) in conjunction with their climatic impact, but see Subsection 6.5.1 for further discussion. Figure 1.3a shows an unusual spiral contrail formed by a circling aircraft observed in a NOAA-14 Advanced Very High Resolution Radiometer (AVHRR) image west of Denmark at 1236 UT, May 22, 1998. Figure 1.3b displays a typical contrail in the form of limited diffusion amidst a blue sky.

Finally, we would like to note that clouds have also been observed in the upper atmosphere. A type of ice crystal cloud known as a polar stratospheric cloud (PSC) has often been observed in the polar stratosphere between about 15 and 20 km. These clouds have frequently been detected over the Arctic and Antarctic by limb-viewing satellite instruments during the winter months when the ambient temperature falls below about 195 K. The condensation of both water vapor and nitric acid (HNO_3) results in the formation of HNO_3 trihydrates, which serve as nuclei for ice crystal growth. In the stratosphere between about 20 and 30 km, a type of thin cloud usually resembling the cirrus form, and referred to as mother-of-pearl (nacreous) clouds, has been detected. These clouds appear to be generated by ice deposition on frozen particles of sulfuric acid. In the mesosphere between about 50 and 55 km, a cloud type known as noctilucent clouds has been observed and is well known. These clouds are very tenuous and resemble cirrus.

1.2 Geographical and temporal distributions of ice in the Earth's atmosphere

1.2.1 A global perspective on clouds

Clouds are global in nature, as evidenced from satellite cloud pictures. We shall confine our discussion to the formation and dissipation of high and middle clouds based on Geostationary Operational Environmental Satellite (GOES) thermal infrared (IR) images from the perspective of large-scale weather activities, as presented in Liou (1986). Shown in Figure 1.4a is a full disk IR picture taken at 2345 GMT, February 23, 1984. Warmer areas are darker, while cooler areas are lighter. Temperature normally decreases with height in the troposphere; thus, the whitest areas can safely be assumed to be high clouds. This picture

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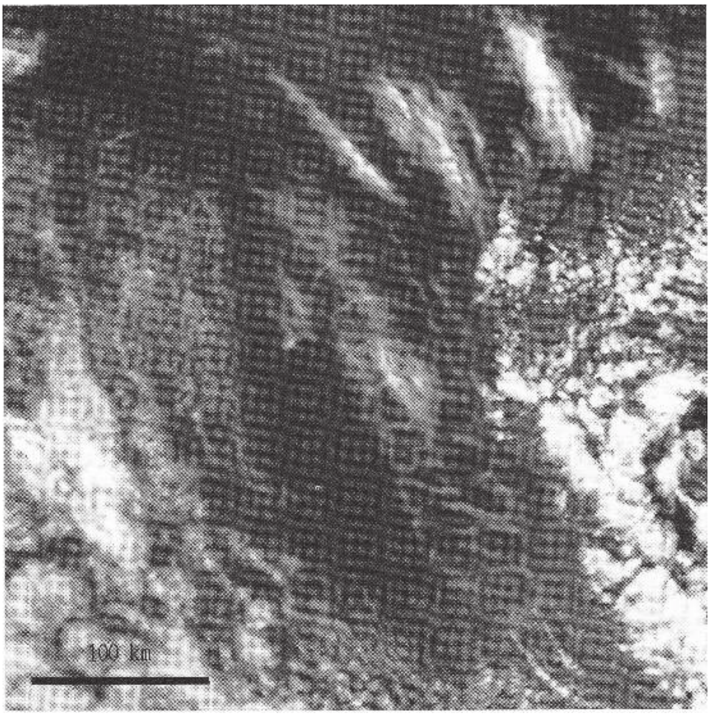

(a)

(b)

Figure 1.3 (a) An unusual spiral contrail, formed by a circling aircraft, surrounded by high clouds, observed in a NOAA-14 Advanced Very High Resolution Radiometer (AVHRR) image west of Denmark at 1236 UT, May 22, 1998 (Schumann 2002). (b) A typical contrail amidst a blue sky (Gao *et al.* 2006 and courtesy of Randall Friedl of JPL/NASA).

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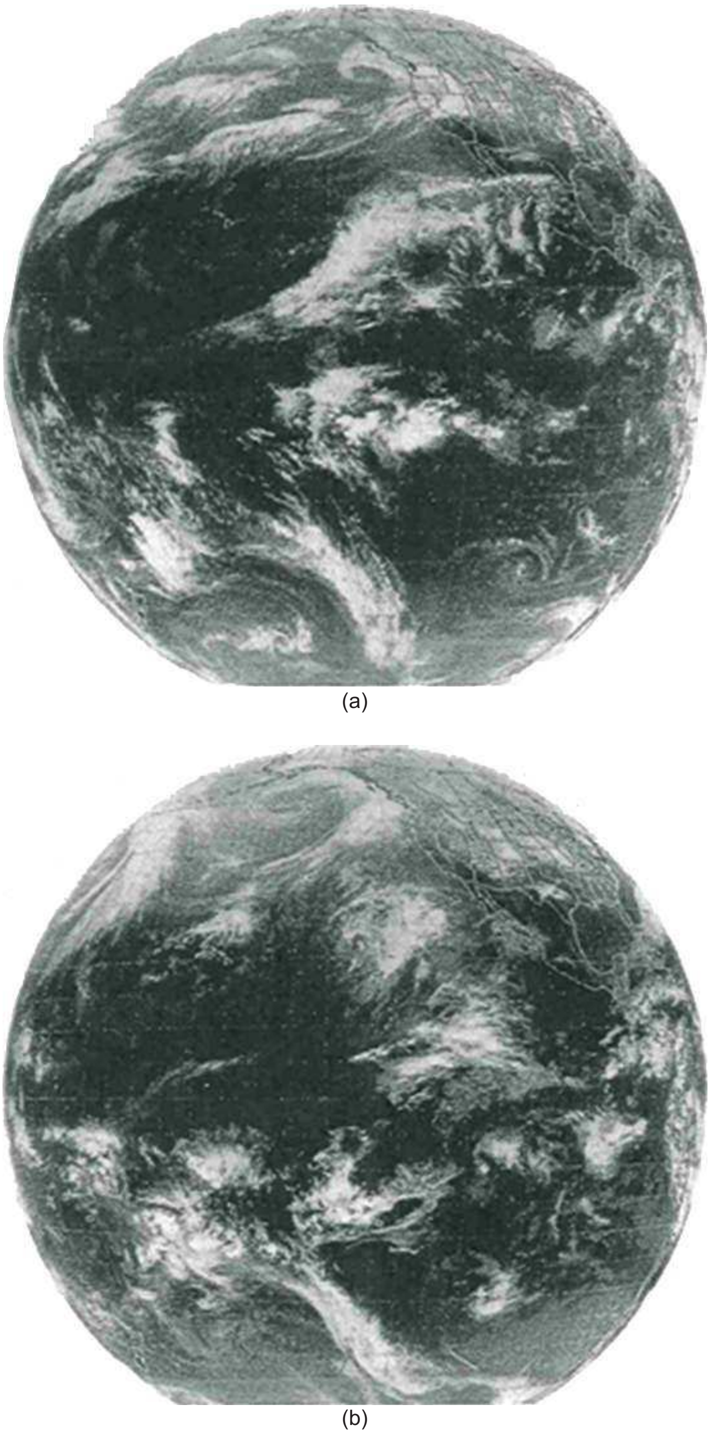

Figure 1.4 (a) Full disk thermal infrared picture at 2345 GMT February 23, 1984, illustrating globally distributed clouds in general and cirrus clouds in particular. (b) Same as (a), but for February 25, 1984 (after Liou 1986).

was taken over the Northern Hemisphere during daytime in the later part of winter, when polar regions are generally outside the frame of the satellite camera, thus minimizing the possibility that white areas may be associated with cold surface temperatures.

High-level cirrus clouds are globally distributed and present at all latitudes irrespective of land, sea, or season. These clouds undergo continuous changes in area coverage, thickness, texture, and position. The most striking cirriform cloud feature shown in Figure 1.4a is the large spiral-comma-shaped pattern west of the Washington State coastline, associated with a major surface cyclone located to the northeast of the cloud center. Lower clouds and precipitation associated with the large-scale rising motion are present under much of this high-cloud canopy. To the north of this cloud band and over the northernmost areas of the Pacific, another bright cirriform area is associated with a complex of surface lows and frontal systems. Further to the west, the leading edge of a large cirriform cloud mass is moving into the IR picture. This cloud mass represents a major storm developing off the coast of Japan.

The most impressive area of cirriform cloudiness is seen over the Pacific Ocean between Hawaii and Mexico, and is related to a huge, although rather weak, trough aloft linked to the subtropical jet stream that curves southward near about (35°N, 160°W). The brightness of these cirriform clouds coupled with light gray areas, which represent middle clouds below, indicates an active zone of weather activity. Further east, broken, largely transverse bands of cirriform clouds are spreading eastward into Mexico. The equatorial area is characterized by strong, predominantly diurnal convection over western South America, with a large production of anvil cirrus and a zone associated with the Intertropical Convergence Zone (ITCZ) that extends across the Pacific at 10°S. In the central Pacific, a collection of mesoscale and synoptic scale clusters of cumulonimbus, some imbedded in areas of middle clouds, is producing the brightest (coldest) cirriform cloudiness in the picture.

The dominant cloudiness in the Southern Hemisphere is associated with cirriform clouds produced by the strong cold front that extends north-northwestward from an occluded front anchored in an intense low centered at (57°S, 140°W). In addition, some spiral-shaped cirrus and middle clouds are shown in the vicinity of (31°S, 104°W); these are associated with a low-pressure system that has been cut off from the westerlies. On the western edge of the picture, a weak cold front with a thin cirrus band approaches New Zealand. To the north of this front, a band of cirrus stretching north-northwestward from (30°S, 165°E) is associated with a surface low at (19°S, 158°E) and a strong wind shear aloft.

In the ensuing 48 hours, the cirriform cloud pattern west of Washington State, as depicted in Figure 1.4b, changes from a well-defined spiral coupled with the original surface low to a disorganized, blotchy mass of less bright clouds in the midst of the dissipation–reformation process, and finally to a redevelopment of brighter, more organized masses coming together with a major storm development. A huge cirriform spiral, characteristic of extratropical cyclones, is seen in the north Pacific. The thin line of cirrus on the poleward side of the cold frontal band stretches from (47°N, 135°W) to (35°N, 154°W). This line occurs adjacent to the polar jet stream that cuts across the frontal zone near the west coast of central British Columbia. In conjunction with a huge cirriform frontal band and a spiral center at (43°N,

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161°E), another major storm is also evident, which was just coming into view from the west as shown in Figure 1.4b. In the Southern Hemisphere there has been relatively little change in the 48-hour period between Figures 1.4a and 1.4b, due to a large-scale dynamic blocking situation. The cirrus cloud band near (55°S, 175°W) in Figure 1.4b is associated with a strong, new cold front beginning to sweep northeastward.

The preceding discussion makes it clear that the formation, maintenance, and dissipation of high and middle clouds which contain ice particles are principally modulated by large-scale weather features and disturbances. In the tropics, these phenomena are related to deep-cumulus outflows associated with strong convection, characteristic of this region. Thin and subvisual cirrus with optical depths $\lesssim 0.1$ have not been identified in the foregoing presentation due to the limitations of IR temperature techniques. Presented in Subsection 1.2.2 are the clouds that were seen by specific satellite instruments and the associated data gathered and analyzed for cloud climatology studies.

1.2.2 An example of global cloud climatology

In what follows, we present an example of global cloud climatology derived from the NOAA High Resolution Infrared Spectrometer (HIRS) polar-orbiting satellite data from the period 1979–2001 during winter and summer (Wylie *et al.* 2005). The specific technique, called the CO_2 slicing method, which uses two channels in the 15 μm CO_2 band and a 10 μm window channel, has been developed to determine the statistics of cloud cover, height, and emissivity. Many processing procedures were required to produce a global map of cloud parameters (Wylie *et al.* 1994). Figure 1.5 illustrates the frequency of all clouds as well as high clouds above 6 km. Clouds are most frequently found in the ITCZ and the midlatitude storm belts of the North Atlantic, North Pacific, and Antarctic Oceans, as noted in Figures 1.4a and 1.4b. Clouds are less frequent between the subtropical high-pressure zones over the oceans and the subtropical deserts over land.

High clouds are observed in about one-third of the HIRS observations. Their coverage shows an annual cycle over land with the maximum occurrence during summer in each hemisphere. The ITCZ is a region of more frequent high clouds, as are the midlatitude storm belts in the Northern Hemisphere summer. The subtropical high-pressure systems are evident in the region of less frequent high-cloud cover. Over the Indonesian region, the ITCZ expands in coverage from winter to summer, whereas in the central Pacific Ocean, it shows extension during the winter months. For the Southern Hemisphere, the eastern Pacific Ocean off South America and the eastern Atlantic Ocean off Africa remain relatively free of high clouds throughout the year. The North American high-cloud cover shows little seasonal change. The high-cloud cover results derived from the CO_2 slicing method illustrate that high clouds are ubiquitous in the tropics, occurring with more than 70% frequency.

We wish to note that many past attempts have been made to classify the global distribution of clouds for climate study based on the emitted IR radiation in the 10 μm window, plus the reflected visible radiation during daytime. The classification of cloudy

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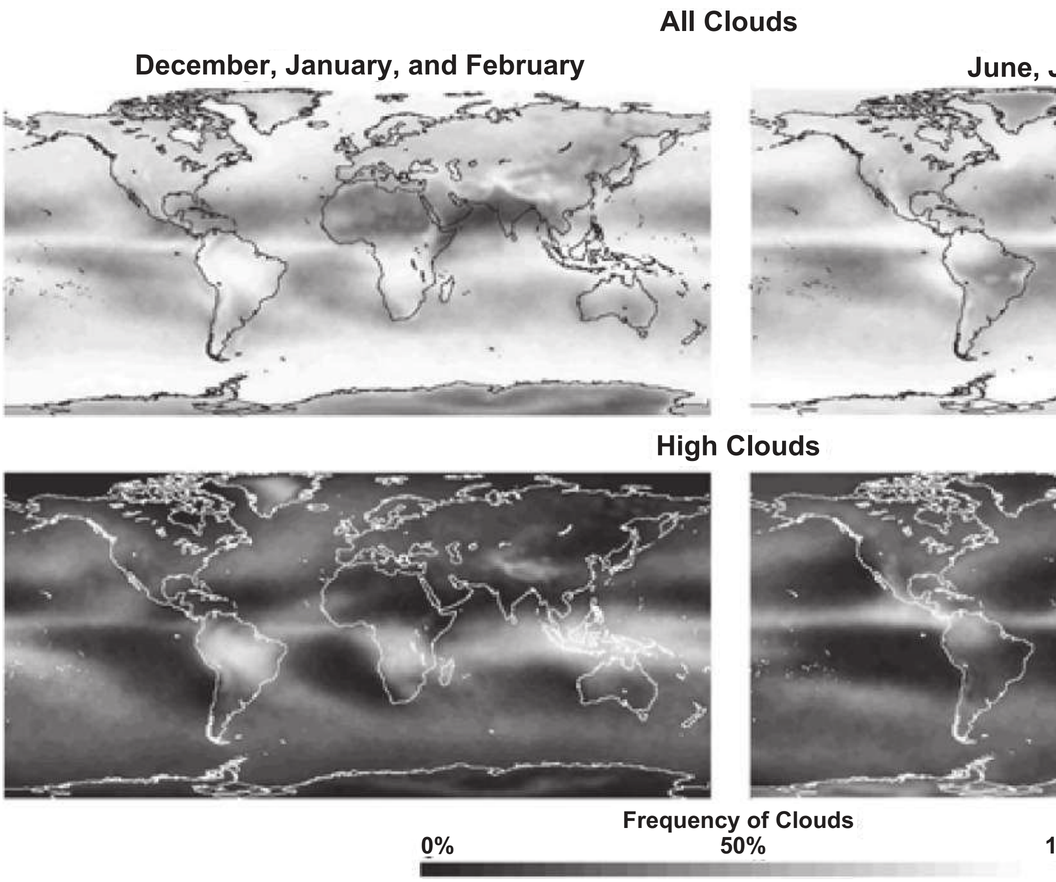

Figure 1.5 The frequency of all clouds and of high clouds above 440 hPa from 1979 to 2001, from HIRS data o
and summer [Jun–Jul–Aug (JJA)] (after Wylie *et al.* 2005; see text for further discussion).

