# Epigraph

***To all the happy ice crystals in planetary atmospheres***

**Let there be light.**

**Let there be beautiful ice crystals in the air and mountain ranges.**

**And here come the reindeers and Santa Claus carrying Maxwell's equations, and light rays are shining in the wonderlands.**

**Let the glory of Geometric Optics for ice crystals, Newton's optics, and sun's light rays rise again from the horizon.**

**Let ice crystals' old friends – black carbon and dust – be not forgot for Auld Lang Syne.**

**And ice crystals are carried by the ceaseless winds; and**

**After travelling thousands of miles up and down, the sky looks very blue.**

**Let there be space missions to tender ubiquitous light rays in the sky,**

**And all things considered, let light scattering by ice crystals in remote sensing and climate change be a delight.**

# 1

# 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 (~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