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Introduction

IN THE MORE than 30 years since the first meteorological satellites were launched, they have become indispensable for study of the Earth's atmosphere. Indeed, together with their land- and ocean-sensing cousins, meteorological satellites view the Earth from a global perspective which is unmatched and unmatchable by any other observing system. In this book we explore what has become a very broad field: satellite meteorology. As we explore, we attempt to reveal the excitement that new observing capabilities bring to science.

To begin, we present an overview of the history and important milestones of satellite meteorology. This, we hope, will give readers the background necessary to understand today's satellites and techniques. In the second section of this chapter, we offer a preview of the remainder of the book to give readers some perspective on where we are taking them.

1.1 HISTORY OF SATELLITE METEOROLOGY

Satellite meteorology predates the launch of the first meteorological satellite (*metsat*). As early as 1860, Jules Verne wrote about "Lunanauts" observing cloud systems (Vaughan, 1982). By the late 1940s, rockets carrying cameras were being launched into suborbital flights. The photographs that they returned gave rise by the early 1950s to serious scientific discussion of the possibility of observing the weather from space (e.g., Wexler, 1954). Several groups, notably the U.S. Army Evans Signal Laboratory and the University of Wisconsin, pursued the idea of launching a weather satellite. These efforts were intensified after the launch by the Soviet Union on 4 October 1957 of the first successful Earth satellite, Sputnik 1. The first successful U.S. satellite, Explorer 1, was launched 123 days later on 31 January 1958. These early days are chronicled in proceedings volumes edited by Vaughan (1982) and Vonder Haar *et al.* (1982).

Of fundamental importance to space flight, in general, and satellite meteorology, in particular, was the formation of the National Aeronautics and Space Administration (NASA) on 1 October 1958. For more than 30 years, NASA has lead the development of all types of scientific satellites used for civilian purposes. Appendix A of this book attempts to list all satellites that have made atmospheric measurements. A large fraction were developed by NASA. Involved from the first in satellite meteorology were agencies that now are components of the U.S. National Oceanic and Atmospheric Administration (NOAA), particularly the U.S. Weather Bureau (now the National Weather Service). Today operational U.S. meteorological satellites are controlled by NOAA and the U.S. Air Force.

The first satellite with a meteorological instrument was Vanguard 2, launched 17 February 1959. Developed by the U.S. Army's Evans Signal Laboratory, Vanguard 2 had a pair of photocells behind lenses that, much like today's scanning radiometers, were supposed to sweep out a visible Earth image as the satellite orbited and spun. Unfortunately, the satellite wobbled on its axis, causing the scan lines to crisscross, which rendered the data unusable.

Explorer 6, launched 7 August 1959, was the second satellite with meteorological instruments. It carried an imaging system and a Suomi radiometer (see below). It went into a highly elliptical orbit, however, and was essentially unusable, although it did return the first Earth photo.

The first successful meteorological instrument on an orbiting satellite was the Suomi radiometer, which flew on Explorer 7, launched 13 October 1959. Developed by Verner Suomi and colleagues at the University of Wisconsin, it consisted of hemispheres, painted either black or white, backed by aluminum mirrors, and mounted on the equator of a spinning satellite. The mirrors reflected the scene back to the hemispheres, such that the hemispheres acted like spheres isolated in space. Since the satellite spun, the spheres sampled solar radiation and terrestrial radiation independent of the orientation of the satellite's spin axis. The temperature of each hemisphere was monitored, and its time rate of change was related to the net gain or loss of radiative energy at the sensor. The black hemispheres absorbed all radiation; the white hemisphere reflected solar radiation but absorbed infrared radiation. The difference between the radiation balance of the hemispheres indicated solar radiation. With these data, coarse maps of the solar radiation reflected by the Earth and the infrared radiation emitted by the Earth were made for the first time.

The first satellite completely dedicated to satellite meteorology was launched on 1 April 1960. TIROS 1 (Television and Infrared Observational Satellite), the 22nd successfully launched satellite, was hatbox-shaped, about 57 cm in height and 107 cm in diameter. Its mass was 120 kg. Figure 1.1 shows a sketch of TIROS 1 along with Vanguard 2, Explorer 7, and Nimbus 1.

The image-making instrument on TIROS 1 was a vidicon camera, which was an adaptation of a standard television camera. Essentially, a lens focused the image on the light-sensitive face of a cathode ray tube (CRT) about 12.7 mm square. The bright and dark areas of the image resulted in a pattern of electrical charge on the CRT. An electron beam scanned the CRT face to measure the charge. The scanning was similar to normal television, it had 500 lines, each with 500 elements. Scanning an entire image took 2 s. The voltages measured by the vidicon camera were telemetered to the ground to be assembled into an image.

Figure 1.2 shows the first image returned by TIROS 1. Although crude by today's standards, TIROS 1 images generated immense excitement. For the first time we could view the Earth and its weather systems as a whole. Not only have satellite observations become essential for meteorology; we believe that they have fundamentally changed our perception of the Earth from a set of distant, isolated continents to an integrated, inseparable system of land, ocean, atmosphere, and living things. Nearly 23,000 images were returned in the 79-day lifetime of TIROS 1.

Nine additional satellites were launched in the TIROS series; the last, TIROS 10, was launched on 2 July 1965. Several technological improvements were introduced in the TIROS series. TIROS 2 introduced a scanning radiometer, the Medium Resolution Infrared Radiometer (MRIR), which was similar to today's imaging instruments (see Chapter 4). TIROS 3, 4, and 7 also carried improved versions of the Suomi radiometer.

The first four TIROS were launched into 48°-inclination orbits (see Section 2.2.4). Beginning with TIROS 5, they were launched into 58°-inclination orbits to expand coverage 10° toward the poles.

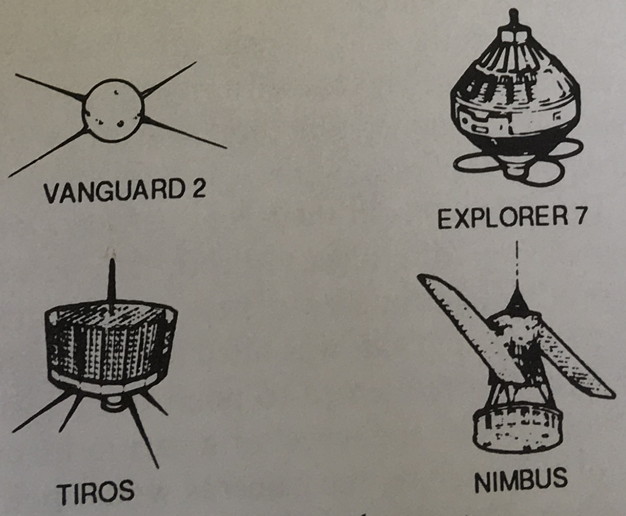

FIGURE 1.1. Four early metsats.

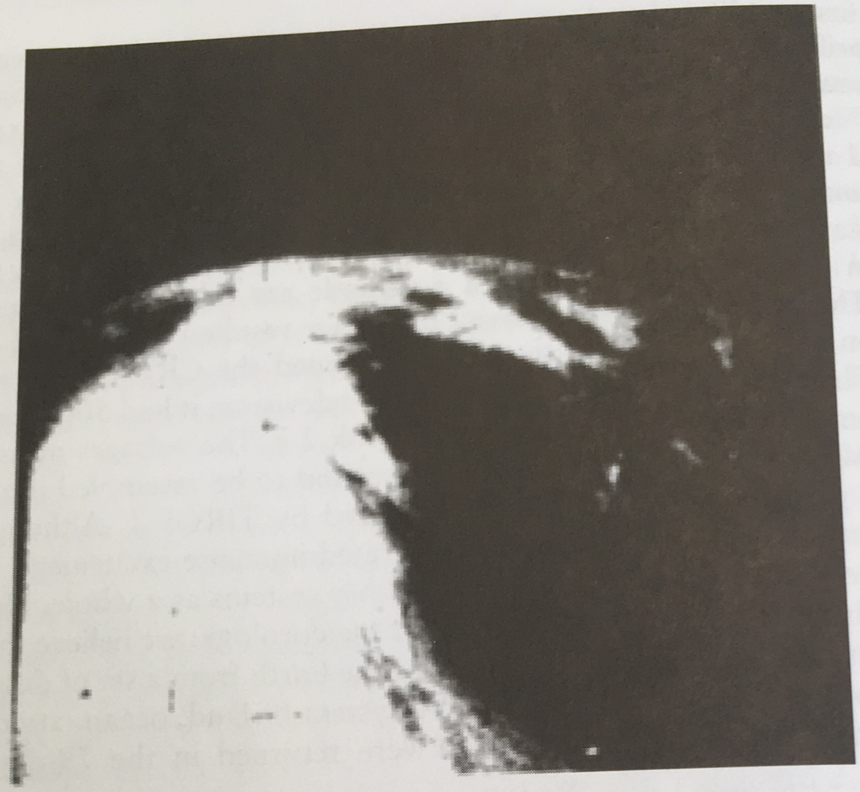

FIGURE 1.2. First TIROS 1 image. [After Rao *et al.* (1990).]

TIROS 8, launched 21 December 1963, introduced Automatic Picture Transmission (APT). A new vidicon camera with 800-line resolution was scanned at the slow rate of 4 lines per second, and the data were immediately broadcast to the Earth at VHF (very high frequency) frequencies. The slow transmission rate meant that inexpensive equipment could be used to receive and display the images. Thus anyone with the proper equipment could directly receive weather satellite images as the satellite passed by twice each day. APT is still an important function on today's polar-orbiting weather satellites.

To maintain their orientation in space, many satellites spin. In the absence of external torques, angular momentum is conserved, and the spin axis points in a constant direction in space as the satellite orbits the Earth. TIROS spun at about 12 revolutions per minute (rpm). This caused a viewing problem with the first eight TIROS, however. The vidicon cameras on these satellites were on the "bottom" of the craft; that is, they pointed parallel to the spin axis and, therefore, in a constant direction in space. The Earth was in their field of view only about 25% of the time. During the remaining 75% of each orbit, they viewed space. TIROS 9, launched 22 January 1965, introduced a new configuration, the "cartwheel" configuration. The satellite's spin axis was tilted to be perpendicular to the orbital plane, and the cameras were reoriented to point out the side of the spacecraft. Thus, the satellite "rolled" like the wheel of a cart in its orbit about the Earth. With each rotation of the satellite, the cameras would point toward Earth, and a picture could be taken. This allowed global composite images to be made; an example is shown in Fig. 1.3.

FIGURE 1.3. TIROS 9 Earth mosaic. [Courtesy of NASA and NOAA.]

In 1964 an extremely important series of experimental meteorological satellites was initiated, the Nimbus series. Nimbus 1, launched 28 August 1964 (see Fig. 1.1), had two notable firsts. It was the first *three-axis stabilized* metsat; that is, with the use of momentum wheels (flywheels inside the spacecraft) controlled by horizon sensors, it rotated once per orbit (by placing torque on the appropriate momentum wheels) so that its instruments constantly pointed toward Earth. Its APT camera was therefore much more useful than that of TIROS 8, which only viewed the Earth 25% of the time. Figure 1.4 shows a Nimbus 1 APT photo.

Nimbus 1 also was the first sunsynchronous satellite, which means that it passed over any point on Earth at approximately the same time each day (see

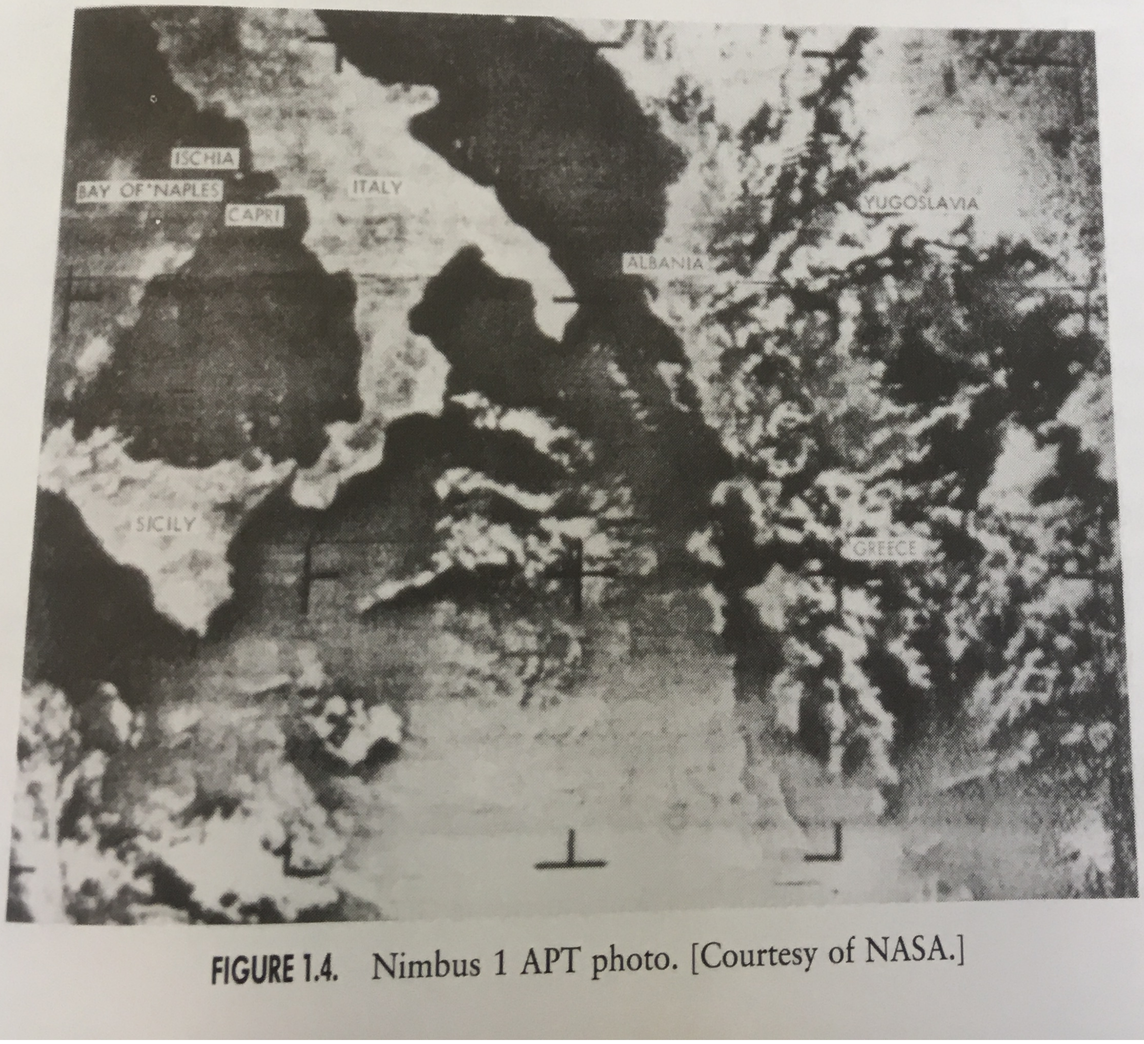

FIGURE 1.4. Nimbus 1 APT photo. [Courtesy of NASA.]

Section 2.4.1). This regularity increased its utility in operational forecasting. The sunsynchronous orbit has been used ever since for U.S. operational metsats in near-polar orbits. Nimbus 1's High Resolution Infrared Radiometer (HRIR), a scanning radiometer quite similar to those in operational use today, provided night and day coverage. Figure 1.5 shows an HRIR image of Hurricane Gladys.

An important accomplishment of satellite meteorology is that since sometime in the mid-1960s when metsat coverage became continuous, there have been no undetected tropical cyclones anywhere on Earth. These ocean-born storms, which for centuries menaced seafarers and coastal and island dwellers, can no longer surprise potential victims. Lives are still lost to tropical cyclones, but many are now saved because of the warnings that metsats make possible.

In total, seven Nimbus satellites were launched. Some experiments on the last one, Nimbus 7, launched 24 October 1978, were still operational as this book was being written! The Nimbus series tested many new concepts that have lead to the operational instruments in use today. These instruments will be discussed elsewhere in this book.

The first 5 years of satellite meteorology are also documented by Hubert and Lehr (1967), to which the reader is referred for interesting details to augment the references noted at the beginning of this section.

By 1966 the United States was ready to initiate an operational (as opposed to experimental) series of metsats. The Environmental Science Service Administration (NOAA's predecessor) commissioned nine satellites, ESSA 1 through 9, which were launched between 3 February 1966 and 26 February 1969. Each was essentially like TIROS 9; each flew in the cartwheel configuration, but in sunsyn-

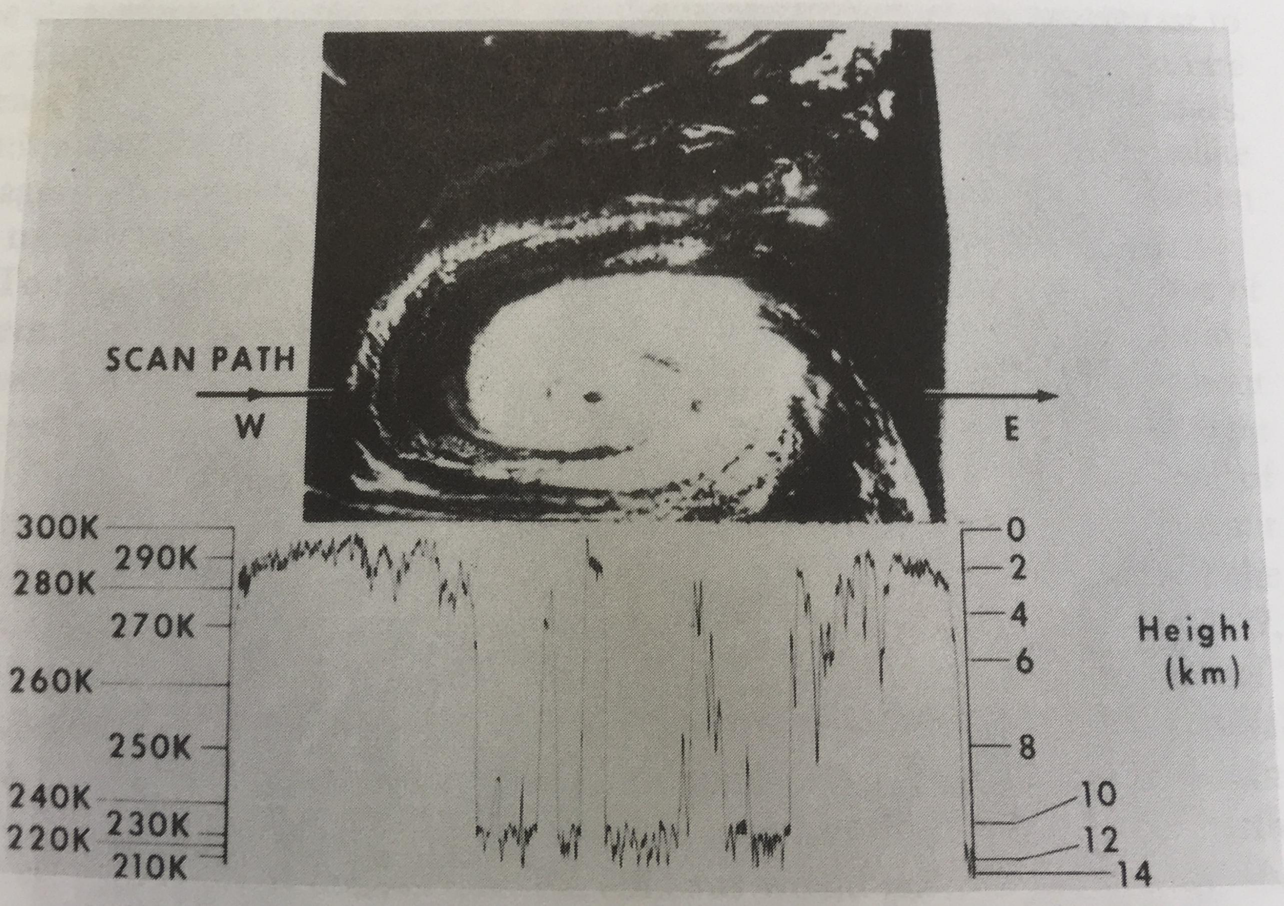

FIGURE 1.5. Nimbus 1 HRIR image of Hurricane Gladys. [Courtesy of NASA.]

chronous orbit. The odd-numbered satellites had Advanced Vidicon Camera Systems (AVCSs), which were proven on the Nimbus satellites, and which could record images for later playback to Earth receiving stations. The even-numbered satellites had APT cameras for immediate broadcast to Earth. Once again, Suomi-type radiometers measured the Earth's energy budget from some of these satellites.

On 16 September 1966 the U.S. Air Force (USAF) launched the first in a series of metsats, the Defense Meteorological Satellite Program (DMSP). This series was called DMSP Block 4. It included seven satellites; the last was launched on 23 July 1969.

On 7 December 1966 satellite meteorology took another leap forward with the launch of the first Applications Technology Satellite (ATS 1). Carrying a Spin Scan Cloud Camera, developed by Verner Suomi and Robert Parent at the University of Wisconsin, ATS 1 was placed into geostationary orbit (see Section 2.4.2) to view the Western Hemisphere in visible light. For the first time, rapid-imaging of nearly an entire hemisphere was possible. We could watch, fascinated, as storm systems developed and moved and were captured in a time series of images. Today such images are an indispensable part of weather analysis and forecasting. ATS 3, launched 5 November 1967, carried a Multicolor Spin Scan Cloud Camera, which employed a filter wheel to make the first color images of Earth (Plate 1).

Virtually all parts of the electromagnetic spectrum are useful for satellite meteorology. The microwave portion of the spectrum was first explored by the Soviet satellite Kosmos 243, launched 23 September 1968.

In 1969 the Soviets began a lengthy series of operational metsats, which, in its third generation, continues today. The first Meteor-1 was launched on 26 March 1969. The 31st member of the Meteor-1 series was launched on 10 July 1981.

Another very important event occurred on 14 April 1969 with the launch of Nimbus 3. It carried two instruments designed to provide atmospheric soundings from space. For the first time, satellite data were used quantitatively in numerical weather-prediction models. The Satellite Infrared Spectrometer (SIRS), made measurements in the 15-μm portion of the spectrum. It was the forerunner of today's operational sounding instruments. A second instrument, the Infrared Interferometer Spectrometer (IRIS), measured spectra in the infrared from about 6 to 25 μm. (See Section 4.3.1.) IRIS also flew on the Voyager spacecraft to Jupiter, Saturn, Uranus, and Neptune, and a similar instrument is under consideration for future geostationary spacecraft.

The second series of U.S. operational metsats began on 23 January 1970 with the launch of TIROS M, also called the Improved TIROS Operational System (ITOS). The NOAA 1 through 5 satellites completed the series. These satellites were three-axis stabilized and flew in sunsynchronous orbits.

An extremely long-lasting instrument, and the first ultraviolet instrument in space, was the Backscatter Ultraviolet (BUV) launched on Nimbus 4 on 8 April 1970. BUV measured ozone (see Section 6.5) for nearly 10 years.

Similar in appearance to the Nimbus satellites, the Landsat series was designed for land remote sensing. Its sensors have extremely high resolution, 80 m in the first satellite and up to 30 m in the latest satellite (Landsat 5). Landsat 1, also called the Earth Resources Technology Satellite (ERTS), was launched on 23 July 1972. Landsat data are used in meteorology primarily to study small clouds and surface features that may influence weather.

The first generation of semioperational geostationary metsats began with the launch of the Synchronous Meteorological Satellite 1 (SMS 1) on 17 May 1974. SMS 2 was launched on 6 February 1975. These satellites carried the first Data Collection Platform (DCP) repeater. Data from meteorological or other platforms on the surface (Fig. 1.6) could be relayed by the satellite to a central receiving site. Thus data from remote ground sites could be easily obtained for the first time. The cloud cameras on the ATS satellites made images in the visible portion of the spectrum only. SMS and the succeeding GOES have an infrared radiometer as well. Since 27 June 1974, when SMS 1 became operational, we have had continuous, uninterrupted, 24-hour-per-day monitoring of most of the Western Hemisphere from space.

On 11 September 1976 the DMSP Block 5D series of the USAF began. The primary Block 5D instrument is the Operational Linescan System (OLS). It is still the highest-resolution (600 m) meteorological instrument in space. OLS is interesting in another way, also. Its shortwave sensor has a broad passband, which means that it can collect enough radiation to make some images by moonlight, and it can sense city lights at night. (See Section 5.5.2.4.)

The second series of operational Soviet metsats began on 11 July 1975 with the launch of Meteor-2 1. Eighteen satellites have been launched in the series.

The first truly operational geostationary metsat, the Geostationary Operational Environmental Satellite 1 (GOES 1), was launched on 16 October 1975. GOES

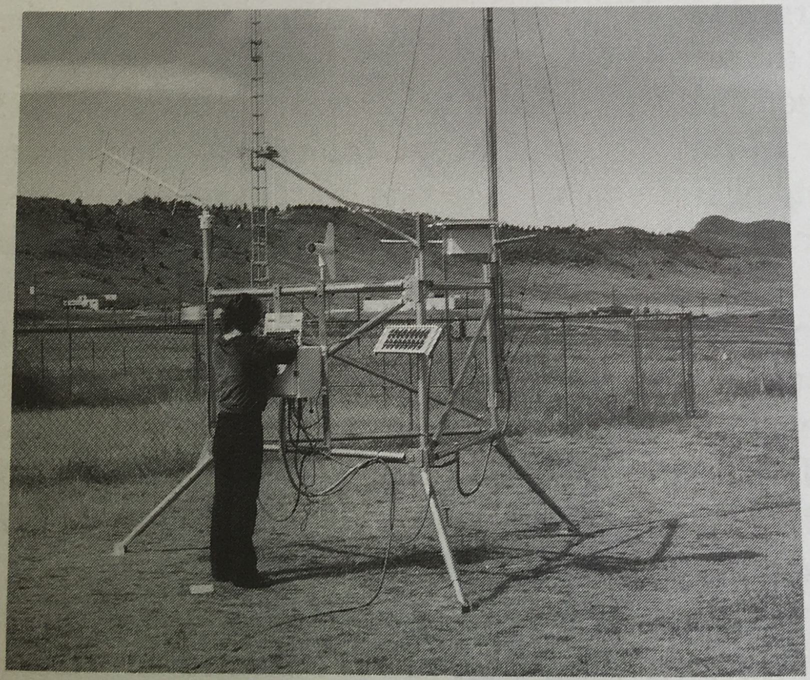

FIGURE 1.6. Data Collection Platform (DCP).

2 and 3 were similar. Since the launch of SMS 2, the United States has generally maintained two geostationary satellites in orbit, one at 75° west longitude, and one at 135° west longitude.

In 1977 and 1978 two more geostationary metsats were launched: Japan's Geostationary Meteorological Satellite 1 (GMS 1) was stationed it at 140° east longitude, and the European Space Agency's Meteosat 1 was stationed at the prime meridian. Meteosat was the first geostationary satellite to make images of mid- to upper-troposphere water vapor at 6.7 μm (Fig. 1.7) in addition to visible and 10–12-μm infrared.

The third generation of U.S. polar-orbiting metsats began on 13 October 1978 with the launch of TIROS N. This series, which continues today, is discussed in Chapter 4.

India has been quite active in satellite meteorology. Two Indian polar orbiters have been launched: Bhaskara 1 on 7 June 1979 and Bhaskara 2 on 20 November 1981. On 31 August 1983, the geostationary Insat 1B was launched from the Space Shuttle. Stationed at 74° east longitude, Insat 1B completed geostationary coverage of the tropics and midlatitudes around the Earth. (Although in 1978 and 1979, GOES 1 was temporarily stationed at 55° east longitude to provide global coverage for the First GARP Global Experiment.) Insat was also the first three-axis stabilized geostationary metsat.

On 9 September 1980 GOES 4, the first in the second generation of GOES satellites, was launched. This series of satellites is discussed in detail in Chapter 4.

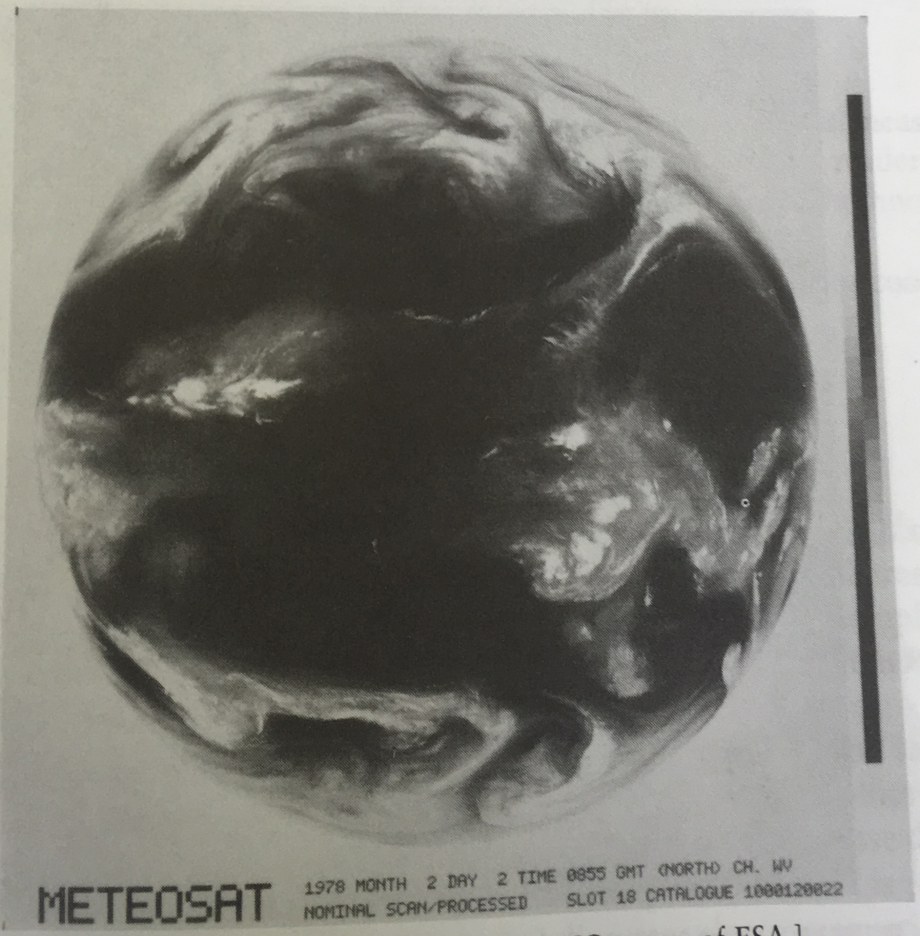

FIGURE 1.7. Meteosat water vapor image. [Courtesy of ESA.]

The first satellite dedicated to climate research was launched on 5 October 1984 from the Space Shuttle Challenger (Fig 1.8). Called the Earth Radiation Budget Satellite (ERBS), it carried two instruments: the Earth Radiation Budget Experiment (ERBE), which is discussed in Chapter 10, and the Stratospheric Aerosol and Gas Experiment II, which is discussed in Chapter 8. ERBS flies in a nonsunsynchronous orbit so that its measurements will sample all local times. It was teamed with two NOAA satellites carrying identical ERBE instruments. This sampling strategy is discussed in Section 2.6.

The final satellite series, which completes the suite of operational satellites in use as this book was being completed, began with the launch by the Soviet Union of Meteor-3 1 on 26 July 1988.

The history of satellite meteorology has many facets in addition to the hardware that has been launched into orbit. In particular, the explosion in computer and communications technology during the space age has literally made weather satellites possible. This technology has also made possible the dissemination of the satellite data and products to the operational forecasting and research sites where they are needed. Figure 1.9 shows what today seems unremarkable, a satellite image transmitted in 1980 from the Colorado State University Direct Readout Ground Station for GOES to the National Weather Service Forecast Office in Denver. Without such communications capabilities, and without the computing

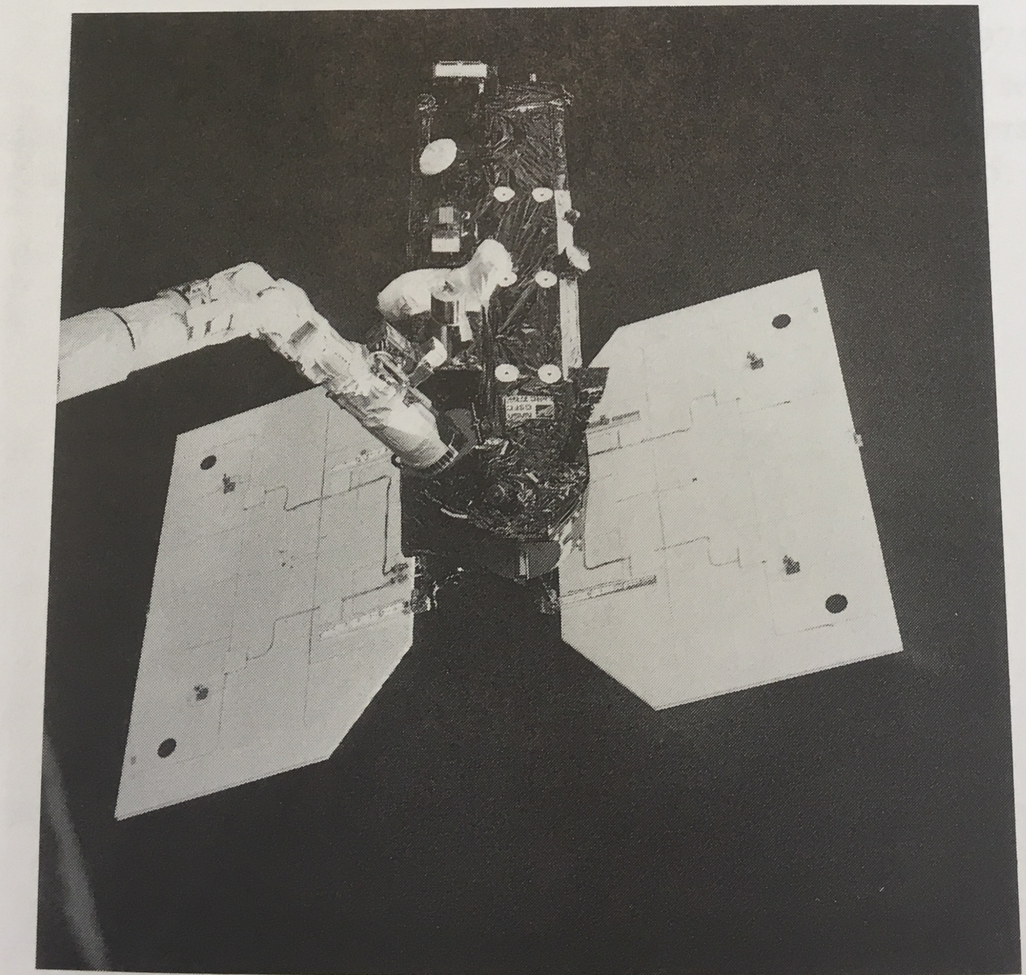

FIGURE 1.8. ERBS being launched from the Space Shuttle. [Courtesy of NASA.]

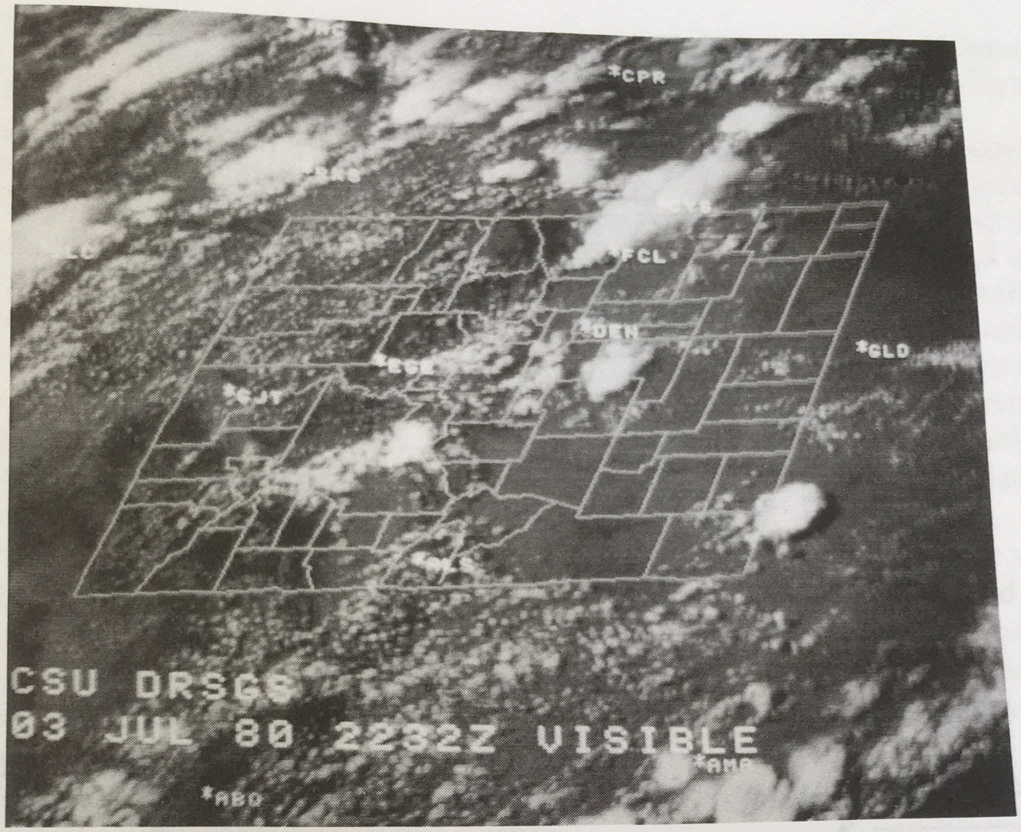

FIGURE 1.9. GOES image transmitted in near-realtime to a remote site.

power necessary to turn raw counts received from the satellite into useful measurements, satellite meteorology would still be in its infancy. Although the reader will see in this book only glimpses of the communications and computer technology that underlies all of satellite meteorology, it should not be forgotten.

In the remainder of this chapter, we offer the reader a preview of the contents and philosophy of this book.

1.2 SCOPE OF THE BOOK

Within the context of related areas of study, Fig. 1.10 denotes the scope of this basic, introductory book. As shown in the figure, the technical subareas that constitute the core of satellite meteorology are (1) time and space sampling of weather and climate features, (2) algorithms and interpretation methods, (3) satellite senors, and (4) weather and climate products and applications.

Chapters 2 through 4 present basic material necessary to understand satellites and how they can be used in meteorology. Chapter 2 discusses satellite orbits. Satellites are not free to travel any path in space, they must follow those dictated by the laws of physics. Knowledge of these laws and of possible orbits is essential to understanding satellite meteorology. Chapter 3 discusses electromagnetic radia-

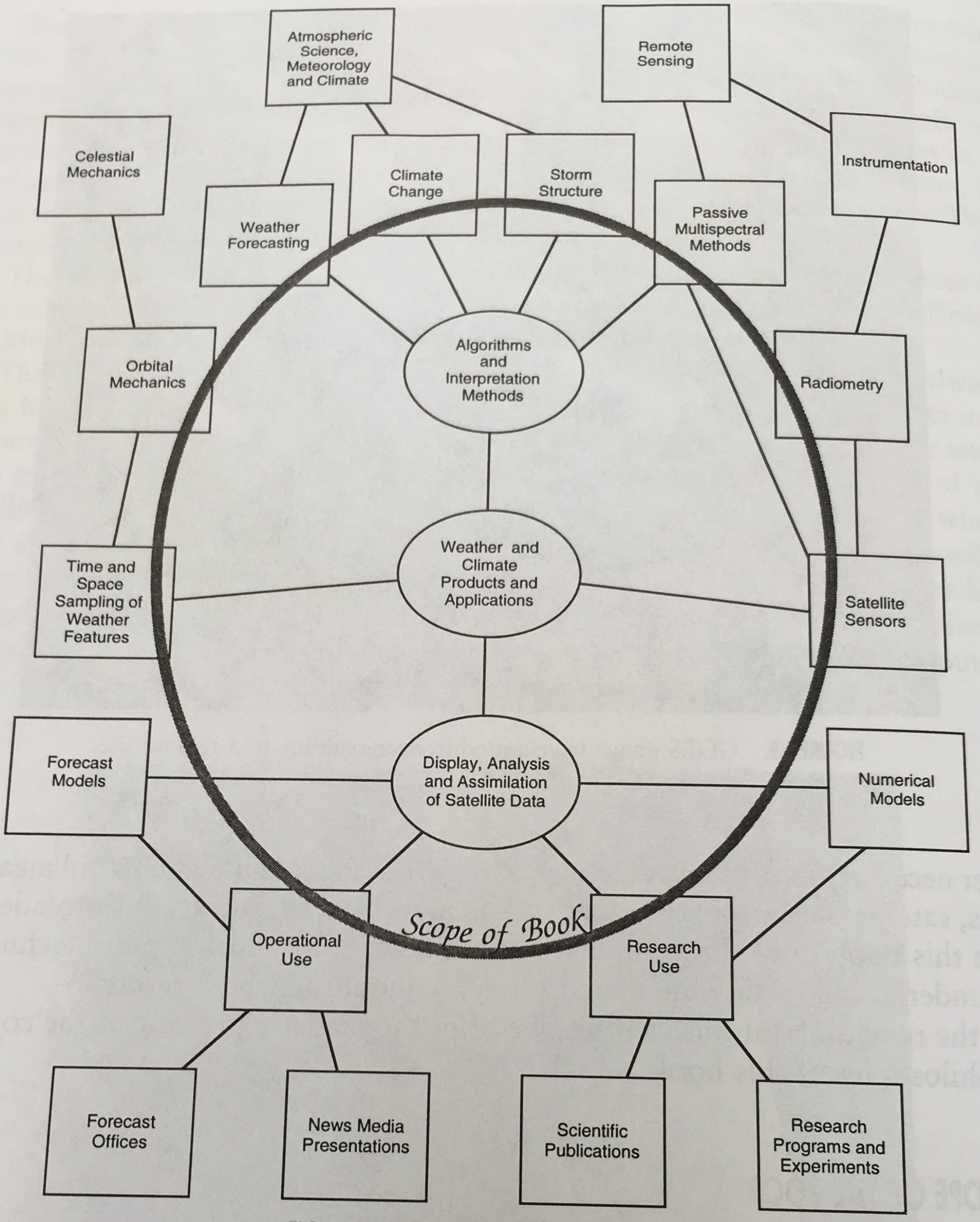

FIGURE 1.10. Scope of the book.

tion, which is the only quantity that meteorological satellites directly measure. The sources of this radiation and its interaction with the Earth's surface and atmosphere are explored. Chapter 4 discusses the instruments that make the measurements. Using instruments on current satellites as examples, the basic operation and capabilities of meteorological instruments are detailed.

Chapter 5 presents the basics of weather satellite image analysis, that is, interpreting the pictures returned by metsats. This was the first, and for many is still the only, application of meteorological satellite data. Because this subject can (and does) fill volumes, we present only what we think everyone should know about satellite images. References at the end of the chapter direct the reader to more detailed discussions.

Chapters 6 through 10 discuss the fundamental parameters that can be retrieved from meteorological satellite data. We concentrate on three issues: what meteorological parameters can be retrieved, how the parameters are retrieved from the electromagnetic measurements, and how accurate the retrieved parameters are. The parameters covered in Chapters 6 through 10, respectively, are temperature and trace-gas concentration, winds, clouds and aerosols, precipitation, and radiation budget. Many specialized applications of satellite data are not covered in this book. We have confined ourselves to the basic parameters in the interest of brevity, but also in the belief that the fundamental parameters are better able to be combined with other measurements such as rawinsonde data or radar data to further our knowledge of the atmosphere.

Finally, in Chapter 11 we look into the future as best we can to indicate what the next decade may bring to satellite meteorology. The reader is warned that the technological, political, and economic rates of change are such that making forecasts of the future of satellite meteorology is a difficult task, yet pleasant. In planning one's career, or indeed one's next project, however, it is necessary have some idea of what the future holds.

Now, dear reader, welcome to the world of satellite meteorology. We hope that you enjoy the following tour.

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