Chapter 2
History and Background

Man must rise above the Earth—to the top of the atmosphere and beyond—for only thus will he fully understand the world in which he lives.

—Socrates

A History of Weather Forecasting

It is human nature to want to find out about our surroundings, to explore our neighborhood, our planet Earth, and beyond. Until the twentieth century, viewing Earth from a space-based perspective could only be accomplished by imagination. From ancient times, astronomers have looked up at the sky, recorded their observations, and made up stories about how the universe was created and what it was like. Ancient Greeks were more aware of the truth of their surroundings than other cultures in that time period. They helped to discover that Earth was a sphere and developed observational and mathematical techniques to measure the circumference of the planet. With increasingly powerful ground-based telescopes came the discovery of the Milky Way and other galaxies and our understanding that the universe is expanding.

Space exploration has improved our understanding of Earth as a celestial object in its own right. The urge to view and explore Earth from above is perhaps also intrinsic to human nature—for example, when a mountaineer wonders how Earth appears to a hawk soaring above him, or when the first explorers tried to reach the ends of the Earth. The practice of Earth observation involves the gathering of information about the planet's physical, chemical, and biological systems, usually by remote sensing systems, which have grown technologically more and more sophisticated over time. The famous "Big Blue Marble" photograph of Earth, taken in 1972 by astronauts onboard Apollo 17, demonstrated the dramatic impact of viewing Earth from space (Fig. 2.1). This emphasized the importance of minimizing the negative impact of modern human civilization to improve social and economic well-being.

The art of weather forecasting, which began with early civilizations and was based on recurring astronomical and meteorological events, was used to monitor and predict seasonal changes in the weather. In 650 BC, the Babylonians attempted to predict short-term weather based on cloud patterns and astrological observations,

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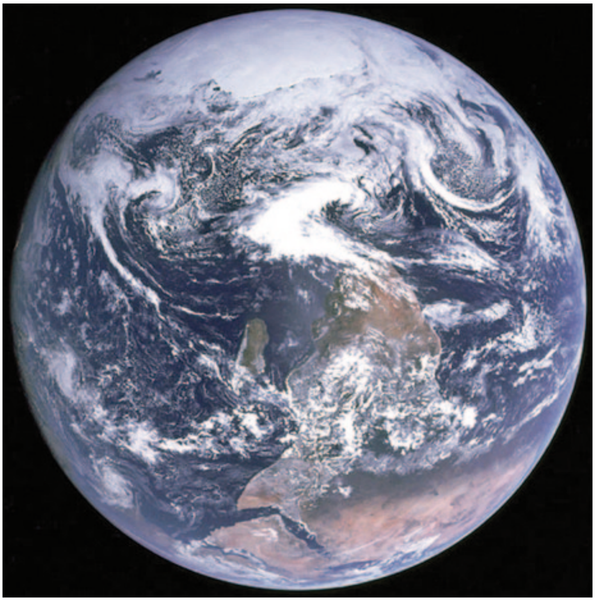

Fig. 2.1 The Blue Marble photograph taken by the Apollo 17 crew on December 7, 1972. (Courtesy of NASA) [1]

while Chinese weather prediction dates back to 300 BC, when annual calendars were developed according to repeated patterns of weather events. This experience accumulated over generations to produce weather lore. In about 340 BC, Aristotle described weather patterns in a treatise entitled *Meteorologica*. This writing contained Earth science theories, such as on cloud formations, wind, rain, and other weather phenomena. This led to his pupil, Theophrastus, compiling *The Book of Signs*, which documented weather lore and forecast signs. These texts served as definitive weather forecasting references for more than 2,000 years and helped to establish meteorology as a distinct discipline of study. Weather forecasting advanced little from these ancient times until the Renaissance, despite many of Aristotle's claims being erroneous.

Early Meteorological Instrumentation

Over the centuries, it became apparent that forecasts based on weather lore, philosophical speculations, and personal observations alone were not always reliable [2]. In order to advance knowledge and understanding of the atmosphere, instruments were needed to measure properties, such as moisture, temperature, and pressure. The first device to measure the humidity of air, called the hygrometer, was invented by Leonardo da Vinci in the fifteenth century. About 1593, Galileo Galilei, often deemed the father of modern observational astronomy, invented an early thermometer for temperature measurement using the expansion and contraction of air in a bulb to move water in an attached tube. His student Evangelista Torricelli invented

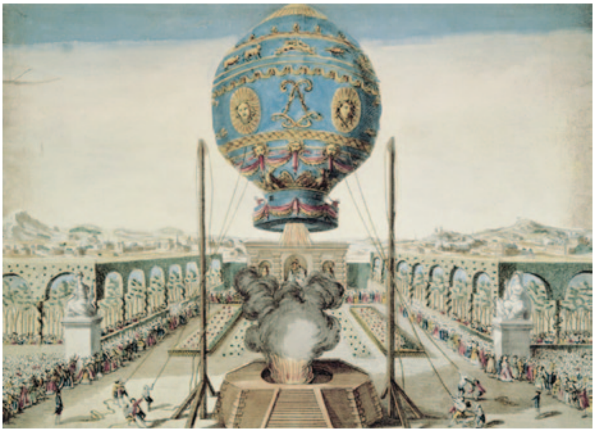

Fig. 2.2 A 1783 drawing of the first hot-air balloon, invented by the French brothers Étienne and Joseph Montgolfier. (Courtesy of *The New York Times*) [4]

the barometer for measuring atmospheric pressure in 1643. In subsequent centuries, these meteorological instruments were refined and improved, and were being applied in association with observational platforms, such as balloons and aircrafts, for taking atmospheric meteorological measurements.

The modern age of weather forecasting began with the invention of the electric telegraph in 1835, which allowed for routine and almost instantaneous transmission of weather observations. It was possible to develop crude weather maps and to study surface wind patterns and storm systems. Synoptic weather forecasting was made possible by the compilation and analysis of data collected simultaneously from weather observing stations and conveyed across the globe via telegraph in the 1860s [3]. Data collected by land locations are now conveyed worldwide via phone lines or wireless technology, enabling information to be communicated quickly for weather forecasts and studies of the atmosphere and climate.

With advancements in meteorological instrumentation in the eighteenth century came experimentation of different airborne platforms to measure physical properties of the atmospheric column, including pressure, temperature, wind speed, wind direction, and other properties. A significant historical development was the invention of the first balloon in 1783 by Étienne and Joseph Montgolfier (Fig. 2.2). They experimented with hydrogen-filled paper bags. Their experiments led to the correct notion that a buoyant force should cause ascent of the bags, if the inside gas was lighter than air. However, since gas diffused out quickly and hydrogen was produced in small quantities, they subsequently tried 'gas' produced by the combustion of a mixture of moistened straw and wool. This produced the first hot-air balloon in the world, which attained a height of about 1,950 m.

In the same year, J.A.C. Charles and the Robert brothers designed and constructed a hydrogen-filled balloon, but inflation was achieved only with great difficulty over a period of four days. Balloon flights began carrying animals and then subsequently men. Furthermore, balloons were improved to descend and ascend at will, and in time were improved with safe landing devices and better direction control. As techniques of the manned balloon evolved rapidly, it offered the possibility to investigate

Earth's atmosphere. The first manned hydrogen balloon flight conducted by J.A.C. Charles and the Robert brothers carried a barometer and thermometer to measure the pressure and the temperature of the air, making it the first balloon flight to provide atmospheric meteorological measurements above Earth's surface [5].

In 1784, the first balloon flight for the scientific purpose of studying environmental conditions was conducted by the American physician, J. Jeffries, along with J.P. Blanchard. Experiments were carried out along a flight path from London to Dartford [6]. Also in 1784, Charles rose again and measured temperature variation along with altitude in the atmosphere. After 1850, the application of balloons for measuring meteorological parameters was widely practiced. To monitor favorable weather conditions for balloon ascent, Charles also inaugurated the practice of launching a small pilot balloon prior to flight in order to determine the wind vector at different altitudes.

Thereafter, pilot balloons were superseded by free-flight sounding balloons, which carried sensors and telemetry transmitters. Sensors launched by weather balloons to measure atmospheric profiles of pressure, temperature, and relative humidity are carried in a unit commonly referred to as a radiosonde. Usually contained in a small, expendable instrument package suspended below a large balloon, the radiosonde provided an efficient way to systematically and regularly measure various atmospheric parameters to heights of over 100,000 feet, without the necessity of considering weather conditions. Nowadays, received meteorological information is transmitted to a ground-based station for data users via a radio transmitter and radiosondes are still used by national weather services for capturing high vertical resolution flight data.

Kites were frequently used for capturing meteorological observations in the second half of the nineteenth century. A meteographic device, which is a chart recorder for measuring humidity and temperature, was usually attached. However, kites were linked to the ground and highly unstable due in windy conditions. During World War I, meteorological observations from kite flights were largely substituted for by aircraft. Flying weather forecasts for aircraft were not required prior to World War I, since pilots mostly flew at low altitudes.

During wartime, however, aircraft were often required to fly in clouds, in bad weather conditions, and at high altitudes. Meteographs were often mounted on the wings of military aircraft to obtain meteorological information for monitoring flying conditions. Observations were recorded on a cylindrical chart that was retrieved after the landing of the aircraft, and meteorological parameters were read from the chart. Pilots were often required to reach a flying altitude of at least 13,500 feet, where they could black out from lack of oxygen, making this a very dangerous enterprise [7]. It was often impossible to fly in bad weather, which unfortunately was when observations were needed the most.

Subsequent advances in the use of unmanned balloons made it possible to sound the atmosphere. For example, Colonel William Blaire in the U.S. Signal Corps performed primitive experiments with weather measurements from a balloon, while the first really useful radiosonde was invented in France by Robert Bureau in 1929. This device sent precise encoded telemetry from weather sensors to the ground.

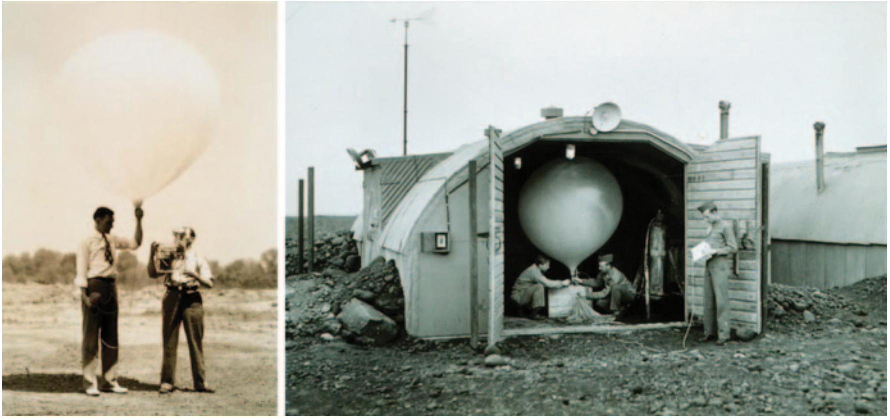

Fig. 2.3 Early launch of radiosondes developed by the U.S. Bureau of Standards in 1936 (*left*). Army Air Force meteorologists preparing a hydrogen-filled balloon equipped with a radiosonde in 1944 (*right*). (Courtesy of NOAA's National Weather Service Collection) [9]

Subsequent developments enabled radiosonde instruments to become smaller, lighter, and more accurate (Fig. 2.3). Radiosondes have also been used for exploring atmospheres of other planets, such as in the Soviet Union's Vega program, where probes dropped radiosondes to study the atmosphere of Venus. Up to present, radiosondes are still launched worldwide year-round. The National Weather Service in the United States releases about 75,000 radiosondes each year, not including soundings made by military facilities and for other specialized scientific purposes. Collective agreements have formed a global radiosonde station network worldwide (about 900 stations) that make an average of 1,209 soundings each day to support weather forecast activities [8].

The Evolution of Weather Satellites

The vast arrays of radiosonde stations, weather reconnaissance aircraft, and other newly developed observing systems have provided a vast amount of information about meteorological parameters and weather conditions. Sensors measuring atmospheric constituents directly, such as thermometers, barometers, and humidity sensors, have been sent aloft on balloons, rockets, or dropsondes for many years. Although precise in their measurements, these instruments have limited capabilities to provide regional or global coverage, which is necessary for making accurate weather forecasts. The global network of radiosonde observing stations tend to have a highly concentrated dispersion in the northern hemisphere temperate zone land masses of North America, Europe, and Asia, whereas the density of observations for the southern hemisphere, tropical regions, the Arctic, and most of the northern

Pacific is relatively sparse. Consequently, there is a high degree of uncertainty with tracking storms over the north Pacific Ocean.

Since the Earth's atmosphere is a single and closely interacting mass of air, disturbances can propagate throughout at a speed much faster than winds. Hence, real-time and synoptic monitoring of large areas of the Earth is necessary for improved meteorological data collection. Extended and long-range weather forecasts require data to be collected and distributed globally. Earth-observing satellites are able to collect meteorological data at synoptic scales and in remote locations, tracking cloud cover, relative motion of storm systems and the jet stream, and maximum heights of clouds and vertical temperature profiles. Satellite imagery can identify cloud patterns associated with different types of weather conditions and patterns (e.g., spiral cloud patterns and convective cells), which are difficult to capture and monitor using conventional weather observations alone. Developments in satellite technologies have resulted in enormous improvements in the accuracy of weather forecasting. Satellites have particularly provided routine access to observations and data from remote areas of the globe.

Polar-Orbiting Weather Satellites

Before the first meteorological satellite was launched, rockets carrying cameras were used to determine the attitude of the nose cone in space with other instruments used to photograph Earth below and to observe cloud formations. However, short-lived rocket observations proved to be insufficient for meeting meteorologists' requirements for weather information. A transition to long-duration orbiting satellite observation platforms was required. On April 1, 1960, NASA's TIROS-1 was the first successfully launched photographic weather satellite with an inclination of 48° (Fig. 2.4). As an experimental spacecraft, TIROS-1 operated for only 78 days, but it sent back nearly 23,000 pictures of Earth and its ever-shifting cloud cover from an altitude of about 700 km.

Sightings from the surface had not prepared meteorologists for the interpretation of the cloud patterns [10]. TIROS images were able to provide the visible expression of invisible air masses, frontal systems, and wind fields. After the launch, military forecasters initiated operational use of panoramic cloud images from weather satellites [11]. TIROS-9 and TIROS-10, launched in 1965, were the first two polar-orbiting meteorological satellites in the TIROS program. Previous satellites had operated at an inclination of 48 or 58°, which were not polar-orbiting.

The TIROS program not only contributed to the development of a meteorological satellite information system but also enabled testing of various design issues for spacecraft. This program thus provided tests of sensing instruments, data collection processes, and of various operational parameters. TIROS-1 through -10 were known as the first generation of American weather satellites and proved to be extremely successful. This first series of meteorological satellites paved the way for further exploration using space-borne weather prediction and monitoring devices.

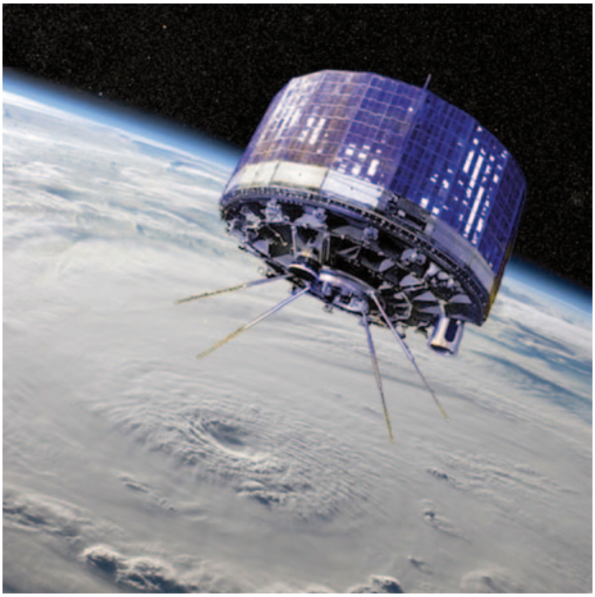

Fig. 2.4 The TIROS-1 satellite that was NASA's first experimental weather satellite. (Courtesy of NASA) [12]

After the experimental launches of the TIROS program, the ESSA satellite program was initiated. ESSA-1 launched successfully in 1966, becoming the first dedicated operational meteorological satellite. Its primary mission was to provide cloud-cover photography to the U.S. National Meteorological Center (now called the National Centers for Environmental Prediction) for the purpose of preparing operational weather analyses and forecasts [13]. This resulted in a combined effort from NASA, ESSA, the U.S. Weather Bureau, and the National Meteorological Center. This operational program consisted of nine satellites (ESSA-1 to ESSA-9) that were launched from 1966 to 1969. Similar to the TIROS satellite series, ESSA-1 also had a spin-stabilized design. Advances in technology enabled more information of a much wider scope and better resolution to be gathered. These satellites transmitted thousands of images back to Earth over a period of almost four years.

In parallel with the operational ESSA series, NASA developed and maintained a research series of seven Nimbus satellites from 1964 to 1978. One of the major goals was to serve as a test bed for future operational polar-orbiting instruments and advanced systems for sending and collecting atmospheric science data. Seven satellites were launched over a fourteen-year period and the Nimbus program became the primary research and development platform for Earth observation. This Nimbus research program formed the heritage of most NASA and NOAA satellites [14]. It carried a variety of instruments, including microwave radiometers, atmospheric sounders, ozone mappers, CZCS, and infrared radiometers, thus providing a significant source of atmospheric chemistry, physics, and climatic data. Nimbus missions contributed to significant advancements in knowledge about weather forecasting, Earth's radiation budget, ozone layer, and sea ice.

However, a demand for more accurate weather analysis meant that higher spatial and temporal resolution data was required. NASA's next step in improving the operational capability of weather satellite systems was the NOAA ITOS (Improved TIROS Operational System), and then the TIROS-N/NOAA program (Television Infrared Operational Satellite—Next-generation). This series of satellites provided higher resolution imaging, improved observations, and expanded operational capabilities. This included more day and night quantitative environmental data on local and global scales with technologically superior instrumentation than earlier TIROS satellites [15]. Moreover, the satellites carried AVHRR and the TIROS Operational Vertical Sounder (TOVS), as well as a fully digital system. A more detailed historical overview of the development of the U.S. meteorological satellite program is provided in Chap. 4.

When the more advanced TIROS-N series satellites were launched between 1978 and 1981, the name of the spacecraft constellation was changed to Polar-Orbiting Operational Environmental Satellites (POES) due to their polar-orbiting nature. POES satellites orbit Earth at an altitude of about 800 km and circle the poles once every 102 min, completing roughly 14.1 orbits per day. This type of low Earth and polar orbit is unfortunately quite popular for many applications, and thus, these orbits are becoming increasingly congested by many active and defunct satellites and various types of orbital debris.

Since the number of daily orbits is not an integer, the ground tracks do not repeat on a daily basis, although local solar time of each satellite's passage is essentially unchanged. This system includes both morning and afternoon satellites, providing global coverage four times daily. POES satellites are able to collect global data on a daily basis for a variety of environmental applications, including weather forecasting, climate research, global sea surface temperature measurements, atmospheric soundings of temperature and humidity, ocean dynamics research, volcanic eruption and forest fire monitoring, global vegetation analysis, search and rescue, and many other applications [16]. POES data offer the benefit of continuous and reliable data products that can have many human and environmental applications.

Geostationary Weather Satellites

On December 7, 1966, the Applications Technology Satellite (ATS-1) was launched—the first of six spacecrafts used to test the feasibility of placing a satellite into geosynchronous orbit (GEO). It was originally intended to be a communications satellite, but also provided a platform for meteorological and navigation equipment. The satellite was designed to test GEO orbit techniques and applications at this special orbit that circles Earth once a day (Fig. 2.5). This orbit is exactly 22,236 miles (or 35,786 km) above Earth's surface. In this GEO orbit within Earth's equatorial plane, a satellite can transmit information to surface ground stations that are constantly pointed toward the satellite without tracking. This makes the orbit excellent for telecommunications, video broadcasting, and Earth observation [17].

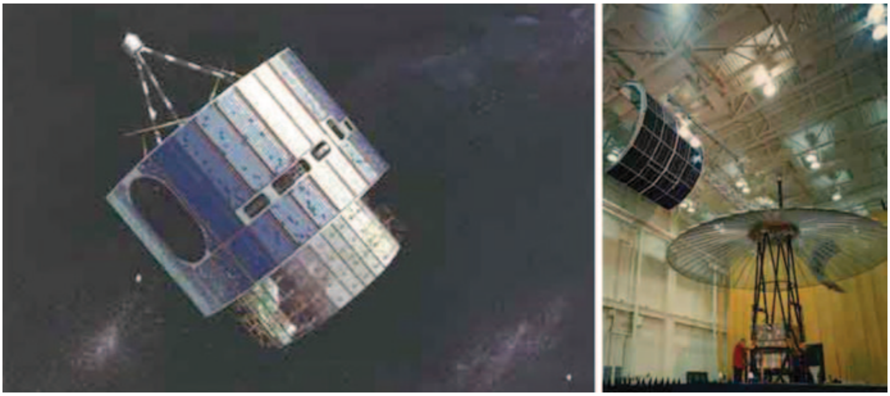

Fig. 2.5 The Synchronous Meteorological Satellite (SMS-1) was the first geosynchronous weather satellite, which later evolved into the GOES program (*left*). The sixth Applications Technology Satellite (ATS-6) undergoing prelaunch testing at Cape Canaveral, Florida (*right*). (Courtesy of NASA) [19]

Temporally continuous geostationary satellite images offer the ability to track clouds. With this information wind speeds at cloud altitude can be inferred [18]. Research into tracking clouds using image sequences began almost immediately, especially with the successful operation of the ATS-1 spin-scan camera. This imaging device provided the first high quality cloud-cover pictures and afforded a continuous watch of global weather patterns. The success of meteorological experiments carried aboard the ATS-1 and ATS-3 satellites led to NASA's development of two weather satellites designed specifically to make atmospheric observations, called the Synchronous Meteorological Satellites (SMS-1 and SMS-2). These geosynchronous meteorological satellites were launched in 1974 and 1975 (Fig. 2.5).

In 1975, the GOES program was formally initiated with the first operational spacecraft GOES launch. Its ability to orbit in sync with Earth's rotation, along with the polar-orbiting satellites and Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites enhanced NOAA's forecasting capabilities. In the following year, 1977, Japan and Europe launched their first GEO weather satellites. These were respectively, the Geostationary Meteorological Satellite (GMS-1) and the European Meteorological Satellite (Meteosat-1). Meteosat-1 provided visible imagery with a spatial resolution of 2.5 km, and infrared window band imagery and water vapor band imagery, both at 5 km spatial resolution. Its water vapor imagery provided a very different view of Earth. It primarily observed upper tropospheric humidity and high cloud features, which indicated synoptic scale circulations. In 1979, three GOES and one METEOSAT satellites were used as part of a Global Atmospheric Research Program (GARP) to define global atmospheric circulations.

Since satellite systems are beyond the resources of most individual countries, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) was established in 1986. This intergovernmental organization was governed by a council of 18 member states, 26 member states, and 5 cooperating states as of 2010, with the purpose of establishing, maintaining, and exploiting European systems for operational meteorological satellites and to contribute to the monitoring and understanding of climate change. EUMETSAT operates a system of meteorological satellites for monitoring the atmosphere and ocean and land surfaces, delivering a continuous stream of weather and climate-related satellite data, images, and products on which National Meteorological Services of member states depend. This information is critical for monitoring potentially dangerous severe weather conditions, issuing timely forecasts and warnings, and helping to protect human life and property. It is also critical to industries, including aviation, maritime, road traffic, agriculture, and construction, among others. National meteorological satellite programs are covered in detail in Chap. 4, 5, and 6, while EUMETSAT is discussed in depth in Chap. 5.

References

1. NASA: http://visibleearth.nasa.gov/view.php?id=55418. Accessed 12 Aug 2013
2. Goldstein M.: "The complete idiot's guide to weather". Alpha/Penguin Group Inc., Indianapolis, USA (2002)
3. NASA: http://earthobservatory.nasa.gov/Features/WxForecasting/wx2.php. Accessed 12 Aug 2013
4. The New York Times: http://graphics8.nytimes.com/images/2006/10/13/sports/13vecsey.1.600.jpg. (2006). Accessed 12 Aug 2013
5. Pfotzer, G.: "History of the use of balloons in scientific experiments". Space. Sci. Rev. **13**(2), 199–242 (1972)
6. Torenbeek, E., Wittenberg, H.: Flight physics: essentials of aeronautical disciplines and technology, with historical notes. Springer, New York (2009)
7. Hughes, P., Gedzelman, D.: The new meteorology. Weatherwise. **48**, 26–36 (1995)
8. Dabberdt, W.F., Shellborn, R., Cole, H., Paukkunen A., Horhammer, J., Antikainen, V.: Radiosondes. http://www.eol.ucar.edu/homes/juhong/Ecy-radiosonde/pdf (2002). Accessed 12 Aug 2013
9. NOAA's National Weather Service (NWS) Collection: http://www.photolib.noaa.gov/nws/kite1.html. Accessed 12 Aug 2013
10. NASA: Missions. http://science.nasa.gov/missions (2012)
11. Hughes, P.: The view from space. Weatherwise. **48**(60), 60–62 (1995)
12. NASA: http://eospso.gsfc.nasa.gov/missions/television-infrared-observation-satellite-program. Accessed 12 Aug 2013
13. NASA, ESSA: http://science1.nasa.gov/missions/essa/. Accessed 12 Aug 2013
14. NASA, Nimbus: http://science1.nasa.gov/missions/nImbus/. Accessed 12 Aug 2013
15. NASA, TIROS: http://science1.nasa.gov/missions/tiros/
16. NOAA—Polar-orbiting operational environmental satellites. http://www.ospo.noaa.gov/Operations/POES/index.html. Accessed 12 Aug 2013
17. NASA: ATS http://science1.nasa.gov/missions/ats/. Accessed 12 Aug 2013
18. Johnson, D.S. Development of the operational program for satellite meteorology. NASA Conference Publication. **2257**, 34–40 (1982)
19. NASA: http://history.nasa.gov/SP-4312/ch5.htm *Wallace, L.E. Dreams, Hopes, Realities:* NASA's Goddard Space Flight Center, the first forty years. (SP–4312). Accessed 12 Aug 2013

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