

# CHAPTER 1

## EVOLUTION OF SATELLITE METEOROLOGY

### 1.1 *Before satellites*

Since colonial times, the interest in today's weather and predicting tomorrow's has led to attempts at sensing the earth's atmosphere. Probing of the atmosphere before rockets and earth orbiting satellites consisted mostly of balloon and kite flights. Temperature and pressure sensing devices were attached and some method of recording the data was devised. Benjamin Franklin's kite flights are the most well known of the early meteorological observations. Early in the twentieth century, the Weather Bureau organized a regularly scheduled programme of kite observations that involved seven stations at most. In this programmed probing of the atmosphere, kites were launched for 4 or 5 hours to heights up to three or four miles. The reeling in of the kite was seldom trouble free, as witnessed in this account by a Bureau kite flyer.

There seemed to be a thunderstorm approaching... My reeler and I commenced to pull in the kite. When the kite was still 3,000 feet up...a bolt from the clouds was seen, by others, to hit the kite. We stopped reeling; we had to. I have been nearly in front of a 6-inch naval rifle at its discharge, and the noise was very mild compared to the report which we heard at the reel... Fortunately, the kite reeler was wearing rubber overshoes, but I was not, and in consequence got a burn on the sole of my foot... Several really ludicrous events can occur when a kite is behaving badly. Sometimes the operators get knocked down and dragged about by the kite in attempting to land it, while the urchins, at a distance, shout humiliating taunts.

Even with these problems, the kite was more practical than the manned balloon, and its use continued until 1933, when airplanes replaced kites.

The rapid development of the airplane during World War I stimulated new ways to obtain upper air observations. In 1925 the Bureau began an experimental programme of daily observations from sensors that were attached on the wings of the aircraft. The comparative ease of this data gathering soon saw the kite phased out completely. With the aircraft flights, observations over a relatively large local area were now possible and early attempts at depicting synoptic flow began.

In 1929, Robert Goddard launched a payload on a rocket that included a barometer, a thermometer, and a camera. The origins of the meteorological satellite programme are often traced back to this effort. Advances in rocket technology during World War II led to the first composite photographs of the top of the atmosphere. Parallel advances in the development of television cameras made the first meteorological satellites possible.

### 1.2 *Evolution of the Polar Orbiting Satellites*

On 4 October 1957 the era of satellite meteorology began as the Soviet Union launched Sputnik I. Sputnik provided the first space views of our planet's surface and atmosphere. The United States accelerated its programme to launch the first meteorological satellite TIROS-1 (Television Infrared Observational Satellite) on 1 April 1960. The great advantage of a satellite platform for meteorological measurements over a large area was realized immediately. For the first time, complete pictures of the clouds associated with large weather systems were seen. The operational meteorological satellite programme evolved rapidly thereafter. A total of ten TIROS satellites were launched (the last on 2 July 1965) which carried vidicon camera systems for daytime visible imaging and passive infrared radiometers for sensing during both day and night. Important steps in the TIROS programme included:

- (a) The Automatic Picture Transmission (APT) capability was demonstrated with TIROS-VIII; very simple ground receivers around the world could now receive real time satellite images - APT has been recognized as one of the United States' greatest "ambassadors" of goodwill (Popham, 1985);
- (b) The change to a "wheel" mode of operation with TIROS-IX, which meant that television pictures were taken when the camera was pointed directly at satellite subpoint - this allowed for ease in navigation of the imagery; and,
- (c) The introduction of sun synchronous orbits, which meant that a satellite crossed the equator at the same local solar time each orbit - this allowed for the development of worldwide mosaics of satellite images and opened the door for a number of important scientific projects, including the World Climate Research Programme.

The experimental TIROS series led to nine operational TOS satellites launched between 1966 and 1969, named ESSA-1 through ESSA-9 for the parent agency at that time, the Environmental Science Services Administration. In parallel with the operational ESSA series, NASA, developed and maintained a research series of seven NIMBUS satellites that had as one of its major goals to serve as a test bed for future operational polar orbiting instruments; in that area it was very fruitful (e.g., 3-axis stabilization, advanced vidicon camera systems, infrared imagers, microwave radiometers, and infrared sounders). Additional detail concerning the impact of NIMBUS instrumentation on the operational polar orbiting satellites may be found in Allison *et al* (1977). NIMBUS provided a number of science firsts and laid the foundation for satellite data use in "Earth Applications Science." Hass and Shapiro (1982) provide an excellent overview of NIMBUS achievements in the areas of meteorology, oceanography, hydrology, geology, geomorphology, geography, cartography, and agriculture; they point out that the roots of the Landsat programme can be traced directly back to NIMBUS.

The NIMBUS satellites also served as pathfinders for global weather experiments organized by the Committee on Space and Atmospheric Research (COSPAR). COSPAR Working Group 6 deliberations and publications served as the foundation for the general nature and detailed composition of the satellite observing system in the First Global Atmospheric Research Programme Global Experiment and of the international operational system that followed.

Significant advances with the ESSA series included routine global coverage using on board recording systems on odd numbered spacecraft, and APT on even numbered satellites. As forecast by Oliver and Ferguson (1966), the global coverage provided by the on board storage capability allowed the National Environmental Satellite Service to provide operational satellite support to forecast centres for the first time. Based on the work of Oliver *et al* (1964) jet streams, mid-tropospheric trough and ridge lines, and vorticity centres were readily located in the ESSA images. While the feasibility of using satellite imagery to locate and track tropical storms was recognized almost immediately in the satellite programme (Sadler, 1962), it was not until the ESSA series of satellites that routine surveillance was assured and techniques to estimate hurricane intensity from satellites became a regular part of weather forecasting (Dvorak, 1972). ESSA was followed by Improved TOS (ITS), which allowed the global remote coverage and APT services to be combined on one satellite. ITS-1, the first of an operational series of three axis stabilized satellites, was launched in January of 1970. Three axis stabilization allowed scanning radiometers to be flown on operational meteorological satellites and provided routine infrared window coverage both day and night. The launch of NOAA-2, on October 15, 1972, was significant to the operational cloud imaging programme: it marked the end of the vidicon era and the beginning of the era of multi-channel high resolution radiometers. The era of television cameras gave way to calibrated scanning radiometers, although initially only visible and infrared window data were available on the Very High Resolution Radiometer (VHRR). The next major step occurred in October of 1978 with the launch of TIROS-N. TIROS-N's imaging system was a four spectral channel Advanced VHRR (AVHRR). According to Rao *et al* (1990) that step "provided data for not only day and night imaging in the visible and infrared but also for sea surface temperature determination, estimation of heat

budget components, and identification of snow and sea ice." AVHRR rapidly moved to a five spectral channel system, with all channels providing imagery at 1.1 km resolution at nadir. The following channels are the backbone of the imaging system: a) 0.58-0.68 microns; b) 0.72-1.1 microns; c) 3.55-3.93 microns; d) 10.3-11.3 microns; and, e) 11.5-12.5 microns.

With the successful creation of a global picture of the earth's surface and atmosphere accomplished in 1964, the primary emphasis shifted toward measuring the atmosphere's vertical distribution of temperature and moisture to better initialize global numerical weather prediction models. King (1958) and Kaplan (1959) published works that indicated that it is possible to infer the temperature of the atmosphere or the concentration of the attenuating gas, as a function of atmospheric pressure level. King showed that measurements of the atmosphere at several tangential viewing angles could also provide information on temperature changes with altitude. Kaplan suggested this could be done through measurements in several narrow and carefully selected spectral intervals, by inverting the process of radiative transfer. Temperature profiles are derived using the emission from CO<sub>2</sub> in the atmosphere, and concentrations of moisture are then inferred with emissions from H<sub>2</sub>O in the atmosphere. Surface temperatures are estimated from observations in the spectral regions where the atmosphere is most transparent. Wark and Fleming (1966) detailed indirect measurement of atmospheric profiles from satellites.

Meteorological observations from space are made through the electromagnetic radiation leaving the atmosphere. Outgoing radiation from earth to space varies with wavelength for two reasons: (a) Planck function dependence on wavelength, and (b) absorption by atmospheric gases of differing molecular structure (CO<sub>2</sub>, H<sub>2</sub>O, O<sub>3</sub>...). Figure 1.1 shows an observed infrared spectrum of the radiance to space. Around absorbing bands of the constituent gases of the atmosphere, vertical profiles of atmospheric parameters can be derived. Sampling in the spectral region at the centre of the absorption band yields radiation from the upper levels of the atmosphere (e.g. radiation from below has already been absorbed by the atmospheric gas); sampling in spectral regions away from the centre of the absorption band yields radiation from successively lower levels of the atmosphere. Away from the absorption band are the windows to the bottom of the atmosphere. The IRIS (Infrared Interferometer Spectrometer) in 1969 observed surface temperatures of 320 K in the 11 micron window region of the spectrum and tropopause emissions of 210 K in the 15 micron absorption band. As the spectral region moves toward the centre of the CO<sub>2</sub> absorption band, the radiation temperature decreases due to the decrease of temperature with altitude in the lower atmosphere.

With careful selection of spectral bands in and around an absorbing band, it was suggested that multispectral observations could yield information about the vertical structure of atmospheric temperature and moisture. The concept of profile retrieval is based on the fact that atmospheric absorption and transmittance are highly dependent on the frequency of the radiation and the amount of the absorbing gas. At frequencies close to the centres of absorbing bands, a small amount of gas results in considerable attenuation in the transmission of the radiation; therefore most of the outgoing radiation arises from the upper levels of the atmosphere. At frequencies far from the centres of the band, a relatively large amount of the absorbing gas is required to attenuate transmission; therefore the outgoing radiation arises from the lower levels of the atmosphere. However, the derivation of temperature profiles is complicated by the fact that upwelling radiance sensed at a given wavelength arises from a rather large vertical depth (roughly 10 km) of the atmosphere. In addition, the radiance sensed in the neighbouring spectral regions arises from deep overlapping layers. This causes the radiance observations to be dependent and the inverse solution to the radiative transfer equation for temperature profiles to be non-unique. Differing analytical approaches and types of ancillary data are needed to constrain the solution in order to render temperature profiles.

The first temperature profile retrievals were accomplished with the Satellite Infrared Spectrometer (SIRS), a grating spectrometer aboard NIMBUS-3 in 1969 (Wark *et al*, 1970). Comparison with radiosonde observed profiles showed that the satellite-derived temperature

profiles were very representative overall, with detailed vertical features smoothed out. The major problems with the early SIRS observations were caused by clouds which were usually present in the instrument's 250 km diameter field of view. Also the SIRS only sampled along the sub-orbital track and consequently there were large gaps in data between orbits. In spite of these problems, the SIRS data immediately showed promise of benefiting the current weather analysis and forecasting and was put into operational use on 24 May 1969, barely one month after launch (Smith *et al*, 1970). An early example of SIRS impact on model analyses is shown in Figure 1.2. Also on NIMBUS-3 was the Infrared Interferometer Spectrometer (IRIS), a Michelson interferometer that measured the earth emitted radiation at high spectral resolution ( $5 \text{ cm}^{-1}$ ). IRIS had 100 km resolution and was nadir viewing only. The IRIS measurements of the terrestrial spectrum revealed details of the carbon dioxide, water vapour, and ozone absorption bands never seen before (Hanel *et al*, 1971).

In 1972 a scheme was devised to reduce the influence of clouds by employing a higher spatial resolution (30 km) and by taking spatially continuous sounding observations, now possible with cross track scanning on the seven channel Infrared Temperature Profile Radiometer (ITPR) on board NIMBUS-5 (Smith *et al*, 1974a). With an adjacent field of view method, clear radiances could now be inferred by assuming that the variation in radiance between two adjacent fields of view is due to cloud amount only. The ITPR concept was highly successful in alleviating the influence of clouds on the synoptic scale. In fact, soundings to the earth's surface were now possible over 95 percent of the globe with an average spacing of 250 nautical miles.

NIMBUS-5 also introduced the first microwave sounding device, the NIMBUS Experimental Microwave Spectrometer (NEMS), a nadir viewing 5-channel instrument (Staelin *et al*, 1973). The NEMS demonstrated the capability to probe through clouds, even when dense and overcast. Good comparisons of ITPR, NEMS, and radiosonde data were achieved. It was found, however, that best results were achieved from an amalgamation of infrared and microwave radiance data in the temperature profile inversion process thereby providing the maximum available thermal information, regardless of cloud conditions (Smith *et al*, 1974b).

The third satellite in the ITS series was launched in mid-October of 1972, called NOAA-2 for the parent agency renamed the National Oceanic and Atmospheric Administration. It carried the first Very High Resolution Radiometer (VHRR) and allowed operational thermodynamic soundings with its Vertical Temperature Profile Radiometer (VTPR). While input to numerical forecast models had relied on cloud image interpretation through a programme with the catchy acronym of SINAP, Satellite Input to Numerical Analysis and Prediction (Nagel and Hayden, 1971), soundings from satellites now allowed for quantitative input (Smith *et al*, 1986).

From the available results and studies in the early 1970s, it was recognized that the optimum temperature profile results would be achieved by taking advantage of the unique characteristics offered by the 4.3 micron, 15 micron, and 0.5 cm absorption bands. As a consequence, the Nimbus-6 High resolution Infrared Radiation Sounder (HIRS) experiment was designed to accommodate channels in both the 4.3 and 15 micron infrared regions and these were complimented by the 0.5 cm microwave wavelength channels of a Scanning Microwave Spectrometer (SCAMS). The HIRS also was designed with passively cooled detectors to allow for complete cross-track scanning and the SCAMS also scanned, but with lower spatial resolution. The HIRS experiment successfully demonstrated an improved sounding capability in the lower troposphere due to the inclusion of the 4.3 micron observations.

The operational implementation of these instruments was achieved on the TIROS-N spacecraft in 1978 that carried the HIRS and the Microwave Sounding Unit (MSU). The channels were carefully selected to cover the depth of the atmosphere. Infrared soundings of 30 km resolution horizontally were supplemented with microwave soundings of 150 km resolution horizontally (Smith *et al*, 1979). The complement of infrared and microwave instruments aboard each of the polar orbiting spacecraft provided complete global coverage of vertical temperature and

moisture profile data every 12 hours at 250 km spacing (Smith *et al*, 1981a). Figure 1.3 shows the global rms differences for the month of April 1980 between TIROS and radiosonde temperature profiles. The 2.5 C differences should not be interpreted literally as error; space and time discrepancies between the two types of observations contribute significantly as does atmospheric variability. Even with microwave assistance, it is evident that the sounding accuracy is degraded with increasing cloudiness.

The TIROS-N series of satellites evolved to the NOAA Advanced TIROS-N satellite series that carry:

- (a) A five channel Advanced VHRR (AVHRR) for observing cloud cover and weather systems, deriving sea surface temperature (McClain, 1979), detecting urban heat islands (Matson *et al*, 1978) and fires (Matson and Dozier, 1981), and estimating vegetation indices (Tarpley *et al*, 1984);
- (b) An improved High resolution Infrared Radiation Sounder (HIRS/2) for deriving global temperature and moisture soundings (Smith *et al*, 1986);
- (c) A low spatial resolution Microwave Sounding Unit (MSU) primarily for deriving temperature soundings in cloud covered regions;
- (d) A data collection system; and,
- (e) Search And Rescue (SAR) instruments for aiding in search and rescue operations.

The current generation of NOAA polar satellites carry improved AVHRR (addition of a channel at 1.6 microns for cloud, ice and snow discrimination) and HIRS instruments that continue to provide their basic services; and, most exciting, two Advanced Microwave Sounding Units (AMSU) that provide temperature sounding information at about 50 km horizontal resolution and moisture sounding information at about 15 km horizontal resolution. With the advent in May 1998 of this enhanced microwave sounder (more channels, better spatial resolution) and continuation of the high spatial resolution infrared (good spatial resolution, evolving to higher spectral resolution), an all weather sounding capability was established.

The TIROS-N instruments are now used routinely to measure atmospheric temperature and moisture, surface temperature, and cloud parameters. A large range of applications have been developed that are pertinent to nowcasting as well as operational short-range forecasting; they include:

- (a) Subsynoptic scale temperature and moisture analyses for severe weather monitoring and prediction;
- (b) Subsynoptic scale analysis of surface temperature;
- (c) Subsynoptic scale analysis of atmospheric stability;
- (d) Subsynoptic scale updating of aviation grid point temperature and wind fields;
- (e) Estimation of the cloud height and amount;
- (f) Estimation of tropical cyclone intensity, maximum wind strength, and central position; and
- (g) Estimation of total ozone amount.

These data have become part of the operational practices of weather services internationally (Chedin, 1989).

For details concerning scientific applications of polar orbiting satellite imagery and sounding data, the reader is referred to Rao *et al* (1990). That book contains sections on applications of satellite data in meteorology, applications of satellite data to land and ocean sciences, satellites and climate applications, and the use of weather satellite data in agricultural applications. For details in the use of polar orbiting imagery, also see Scorer (1990).

Before the end of the decade, AVHRR will transition to a more capable visible and infrared imager called the Visible Infrared Imaging Radiometer Suite (VIIRS), when the NOAA satellites become the NPOESS series, starting with a demonstration program in 2006. VIIRS will be better calibrated than the AVHRR, have higher spatial resolution (400 meters vs. 1 km at nadir), and have additional spectral capability with 22 channels. Parameters that may be derived from the VIIRS for use in operational as well as climate monitoring include sea surface temperature, aerosols, snow cover, cloud cover, surface albedo, vegetation index, sea ice, and ocean color. HIRS will be replaced by the Cross Track Infrared Sounder (CRIS), a Michelson interferometer that is designed to enable retrievals of atmospheric temperature profiles at 1 degree accuracy for 1 km layers in the troposphere, and moisture profiles accurate to 15 percent for 2 km layers. This is accomplished by the CRIS working together with the Advanced Technology Microwave Sounder (ATMS), being designed to be the next generation cross track microwave sounder replacing AMSU. Comparable sounding capability will be realized on the European METOP series by the Infrared Atmospheric Sounding Interferometer (IASI) in conjunction with the advanced microwave temperature sounding units (AMSU-A) and microwave humidity sounders (MHS / HSB). CRIS/ATMS will fly on afternoon (1330 ascending) and IASI/AMSU/MHS will fly in the morning (0930 descending) orbit. See Chapter 14 for more details.

### **1.3 The Geostationary Programme**

For meteorological applications, two types of satellite orbits have been employed. So far, we have discussed instruments on the polar sun-synchronous orbit from which global observations can be collected every twelve hours. The geostationary orbit above the equator is the other orbit; it has a period of 24 hours and thereby enables continuous surveillance of the weather. Polar orbits range from 600 to 1600 km in altitude, whereas the geostationary altitude is 38,000 km.

On 6 December 1966, a momentous day in satellite meteorology, the first Applications Technology Satellite (ATS-1) was launched. ATS-1's spin scan cloud camera (Suomi and Parent, 1968) was capable of providing full disk visible images of the earth and its cloud cover every 20 minutes. The inclusion of the spin scan cloud camera on ATS-1 occurred because of an extraordinary effort by Verner Suomi and Homer Newell, who made it possible to add this new capability to ATS-1 when the satellite was already well into its fabrication. Meteorologists were astounded by the first views of global animations of clouds and cloud systems in motion. According to Johnson (1982) "as Morris [Tepper of NASA] predicted, geostationary satellite images can be used to track clouds from which winds at cloud altitude can be inferred." Research into tracking clouds and producing winds using image sequences began almost immediately (Hubert and Whitney, 1971), and, as will be discussed in chapter 9, is still an area of intense investigation. By the early 1970s ATS imagery was being used in operational forecast centres, with the first movie loops being used at the National Severe Storm Forecast Center (NSSFC) in the spring of 1972.

As with the polar programme, NASA research and development led to the operational geostationary satellite programme. ATS was mainly a communications system test bed; however, its success in the meteorological arena led to NASA's development of the Synchronous Meteorological Satellite (SMS), an operational prototype dedicated to meteorology. SMS-1 was launched May 1974 and SMS-2 followed in February 1975: those satellites were positioned above the equator at 75W and 135W, which today remain the nominal positions of the United States' eastern and western Geostationary Operational Environmental Satellites (GOES). The two NASA prototypes, SMS-1 and SMS-2, and the subsequent NOAA GOES provided three important functions that remain central to today's geostationary satellite programme:

- (a) Multispectral imagery from the Visible and Infrared Spin Scan Radiometer (VISSR) routinely covering the earth and its cloud cover in the visible and infrared window channels. VISSR provided visible imagery at 1 km spatial resolution and infrared window channel imagery at 7 km spatial resolution.

- (b) Weather Facsimile (WEFAX) enabling transmission of low resolution satellite images and conventional weather maps to users with low cost receiving stations; and,
- (c) Data Collection System (DCS) allowing the relay of data from remote data collection platforms through the satellite to a central processing facility.

In 1977 the European Space Agency launched a geostationary Meteosat, which provided visible imagery at 2.5 km spatial resolution, infrared window band imagery at 5 km spatial resolution, and also water vapour band imagery at 5 km spatial resolution. These new images in the water vapour band gave a very different view of the planet earth. Upper tropospheric humidity and high cloud features dominated the image and indicated synoptic scale circulations. Three GOES and one Meteosat were coordinated to define atmospheric circulations as part of a Global Atmospheric Research Programme (GARP) in 1979. Organized by the Committee on Space and Atmospheric Research (COSPAR), this was the first international experiment using satellites.

By 1980, the GOES system evolved to include an atmospheric temperature and moisture sounding capability with the addition of more spectral bands to the spin scan radiometer; it was called the VISSR Atmospheric Sounder (VAS). The first GOES-VAS, GOES-4, was launched in September of 1980. The addition of spectral channels represented a major improvement in satellite capabilities (Smith *et al*, 1981b); however, imaging and sounding could not be done at the same time. Furthermore, a spinning satellite, viewing the earth only 5 percent of the satellite's duty cycle, made it difficult to attain the instrument signal-to-noise needed for either high quality soundings or the high spatial resolution infrared views of the earth needed to satisfy the increased sophistication of the data's user community. Recognizing those limitations, NOAA developed its next generation of geostationary satellites, GOES I-M (Menzel and Purdom, 1994) introduced with the launch of GOES-8 on 13 April 1994. GOES-9 through 12 followed in subsequent years and are being used to maintain a two GOES operational system, east and west.

As imagery from polar orbiting satellites helped advance understanding of synoptic scale phenomena, imagery from geostationary satellites helped advance understanding of the mesoscale. Prior to the geostationary satellite, mesoscale data were sparse; meteorologists were forced to make inferences about mesoscale phenomena from macroscale observations. Today, geostationary satellite images represent the equivalent of a "reporting station" every 1 km with visible data (every 4 km with infrared data) and hence show features that are infrequently detected by fixed observing sites. Clouds and cloud patterns in a satellite image provide a visualization of mesoscale meteorological processes. When imagery is viewed in animation, the movement, orientation, and development of important mesoscale features can be observed, adding a new dimension to mesoscale reasoning. Furthermore, animation provides observations of convective behaviour at temporal and spatial resolutions compatible with the scale of the mechanisms responsible for triggering deep and intense convective storms (Purdom, 1993). A number of important discoveries using geostationary satellite imagery (see Figure 1.4) have had a dramatic impact on mesoscale meteorology and, in turn, short term forecasts and warnings. For example:

- (a) Prior to squall line formation, organized cumulus development within a surface convergence zone is usually detectable in satellite imagery (Purdom, 1976). The ability to use satellite imagery to detect areas of incipient squall line development has aided in the location and orientation as well as the timing of severe weather watches.
- (b) The importance of thunderstorm outflow boundaries, often termed arc cloud lines, in the development and evolution of all types of thunderstorms was first recognized using animated satellite imagery (Purdom, 1976). The recognition of one such large scale boundary resulted in a very accurate, long lead time watch box for a major tornado outbreak across North and South Carolina on 28 March 1984 (NOAA, 1984). Furthermore, Doppler radar has confirmed the importance of recognizing and tracking arc cloud lines for short term convective forecasting (COMET, 1992).
- (c) The size, duration and high degree of organization of mesoscale convective complexes

were not recognized prior to their discovery using infrared satellite imagery (Maddox, 1980). These complexes, which are responsible for much of the summer rainfall in the mid-west, have since been the focus of intense investigations.

- (d) The location, tracking and monitoring of hurricanes and tropical storms has been one of the most successful aspects of the satellite programme (Rao *et al*, 1990), and a technique for using satellite data to estimate hurricane intensity (Dvorak, 1972, 1984) is used routinely at the National Hurricane Centre. According to Robert Sheets (1990) who was at the time the Director of the National Hurricane Centre: "in the estimation of the author, and many others, the development of the Dvorak technique (1972, 1984) has been the single greatest achievement in support of operational tropical cyclone forecasting by a researcher to date."
- (e) Prior to the polar satellite programme the existence of polar lows (Twitchell *et al*, 1989) was not widely recognized, and recently, geostationary satellite imagery have been used to study polar low formation near the coast of Labrador (Rasmussen and Purdom, 1992);
- (f) The influence of early morning cloud cover on the subsequent development of afternoon convection was not realized prior to the geostationary satellite era (Weiss and Purdom, 1974; Purdom and Gurka, 1974). The importance of this phenomenon has subsequently been simulated using a sophisticated mesoscale model (Segal *et al*, 1986).
- (g) Satellite imagery has had a dramatic impact on our ability to detect and forecast fog behaviour. The role of inward mixing in forecasting the dissipation of fog was not well recognized prior to the work of Gurka (1978) with geostationary satellite imagery. Polar orbiting satellite imagery has been used for a number of years to detect fog, both day and night, using a multispectral technique (Eyre, 1984), and that technique has been extended with the GOES multispectral imagery (Ellrod, 1992) to include monitoring of fog formation at night.
- (h) The GOES infrared channel at 6.7 microns is strongly affected by upper level water vapour, and is often called the water vapour channel. The ability of imagery from this channel to depict upper level flow has provided meteorologists with the ability to view atmospheric systems and their changes in time with a perspective never before possible. As has been shown by Velden (1987) and Weldon and Holmes (1991), this channel may be used for a variety of synoptic and mesoscale applications.

The advantage of continuous multispectral monitoring of atmospheric stability and moisture is demonstrated in an example from 8 July 1997. A sequence of the GOES LI DPI at two hour intervals over the western plains (Figure 1.5, top) shows strong de-stabilization in Kansas and northern Oklahoma during the afternoon (1746 to 2146 UTC) as LI values of -8 to -12 C give way to convective clouds. Radiosonde values (Figure 1.5, bottom) show generally very unstable air (LI of -5 to -6 C) across Nebraska, Missouri, Oklahoma, and northern Texas, while the GOES LI DPI emphasizes the Kansas and northern Oklahoma region within that area. Severe weather watch boxes from the Storm Prediction Center (SPC) covered Missouri and Arkansas as well as eastern Colorado (as the mesoscale vorticity center drifted southward across Missouri into Arkansas with a surface outflow ahead of it). However, storms also formed in west central Kansas by 2146 UTC and continued to develop across the state with numerous reports of hail. Although the Arkansas and eastern Colorado activity was well anticipated at the SPC, central Kansas convection did not appear within a watch area. The strong and focused de-stabilization as noted in the GOES LI DPI sequence over Kansas and northern Oklahoma presented good supporting evidence for development of strong storms in that region.

GOES data has become a critical part of National Weather Service operations, with direct reception of the full digital GOES data stream at national centres while local weather service forecast offices receive a full complement of digital imagery from the AWIPS (Advanced Weather Interactive Processing System). Additionally, quantitative products such as cloud drift winds, thermodynamic soundings and stability parameters, and precipitation amount are routinely



produced from GOES data.

Rapid interval imaging has been an important component of the GOES research programme since 1975. Research with SMS and GOES imagery included acquiring a series of images at 3 minute intervals to study severe storm development (Fujita, 1982; Shenk and Kreins, 1975; Purdom, 1982). In 1979 during a project known as SESAME (Severe Environmental Storm And Mesoscale Experiment), two GOES satellites were synchronized to produce 3 minute interval rapid scan imagery to study storm development. Fujita (1982) and Hasler (1981) used these data to produce very accurate cloud height assignments using stereographic techniques, similar to earlier work by Bristor and Pichel (1974). Other interesting studies with rapid interval GOES imagery include assessing thunderstorm severity (Adler and Fenn, 1979; Shenk and Mosher, 1987) and tracking cloud motions in the vicinity of hurricanes (Shenk, 1985; Shenk *et al*, 1987). Over the years, results from the research community filtered into satellite operations, and by the mid-1980s, five-minute interval imagery became a routine part of satellite operations during severe storm outbreaks. Recently, GOES-8 imagery at one minute intervals were taken to study a variety of phenomena including severe storms, hurricanes and cloud motions (Purdom, 1995).

The current GOES imager has 5 channels of visible and infrared measurements at 5 km resolution and is capable of full disk coverage in 30 minutes. In 2002, Europe introduced a 12 channel imager with visible and infrared measurements at 3 km resolution with full disk coverage every 15 minutes. GOES will evolve to a 16 channel imager at 2 km infrared and 0.5 km visible resolution with 5 minutes refresh in the next decade. Geostaionary sounding with high spectral resolution instruments will be added in the next decade; using an interferometer, focal plane detector arrays, and on board data processing to cover 3.7 to 15.4 microns with 2000 plus channels measuring radiation from 10 km resolution contiguous coverage of 6000 by 5000 km will be accomplished in less than 60 minutes. The trend is for more spectral channels at higher spatial resolution with faster coverage.

#### **1.4 Data Processing Capability**

Interpretation and utilization of remote sensing data requires a ground processing capability that must perform the following functions:

- (a) Downlink and reception of telemetry bit stream must yield sensor data, satellite orbit parameters, and spacecraft environment information;
- (b) Preprocessing, calibration, and earth location (navigation) of the data must transform into physical units;
- (c) Algorithms must be applied to derive geophysical parameters; and
- (d) Validation and error analyses must be performed as part of the process investigation.

Considerable effort has been focused on developing interactive processing capabilities, where satellite data can be displayed and interpreted through efficient communication between an operator and the computer. Through manual editing and enhancement of the satellite data, it has been shown that derivation of geophysical parameters (such as temperature and moisture soundings) with high quality resolution was possible on a system such as the McIDAS (Man-computer Interactive Data Access System) developed at the University of Wisconsin. Utilizing a terminal consisting of digital, video, and graphics display devices with keyboard and cursor for communication of instructions, an operator is able to rapidly interact with the data processing. For example, the operator can display images of sounding radiance data to aid in selecting important meteorological phenomena and regions of extensive cloudiness where manual intervention is needed to insure high quality sounding output. The operator can instruct the computer to zoom in on the meteorologically active area and produce soundings that can be subjectively edited and enhanced through the addition of soundings at locations selected through cursor control. The

operator can check the meteorological consistency of the satellite sounding data, for example, instructing the computer to generate 300 hPa geopotential heights and their horizontal gradient thermal winds. A sounding that is obviously erroneous and responsible for an unbalanced thermal field (and implicitly wind field) can be rapidly eliminated through cursor selection. The McIDAS application to satellite sounding data has also led to rapid improvements in the algorithms used to process the data since visual inspection of the results revealed deficiencies in the processing procedures.

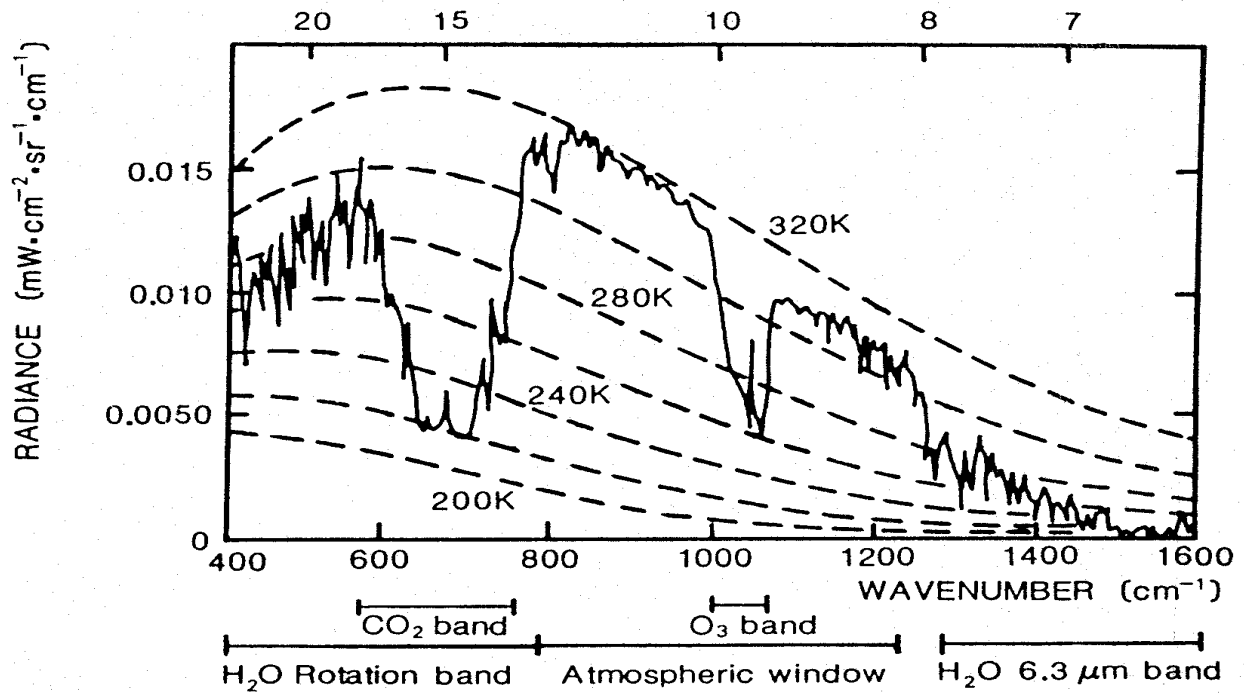
## **1.5 Summary**

In the past forty years NOAA, with help from NASA, has established a remote sensing capability on polar and geostationary platforms that has proven useful in monitoring and predicting severe weather such as tornadic outbreaks, tropical cyclones, and flash floods in the short term, and climate trends indicated by sea surface temperatures, biomass burning, and cloud cover in the longer term. This has become possible first with the visible and infrared window imagery of the 1970s and has been augmented with the temperature and moisture sounding capability of the 1980s. The imagery from the NOAA satellites, especially the time continuous observations from geostationary instruments, dramatically enhanced our ability to understand atmospheric cloud motions and to predict severe thunderstorms. These data were almost immediately incorporated into operational procedures. Use of sounder data in the operational weather systems is more recently coming of age. The polar orbiting sounders are filling important data voids at synoptic scales. Applications include temperature and moisture analyses for weather prediction, analysis of atmospheric stability, estimation of tropical cyclone intensity and position, and global analyses of clouds. The TIROS Operational Vertical Sounder (TOVS) includes both infrared and microwave observations with the latter helping considerably to alleviate the influence of clouds for all weather soundings. The Geostationary Operational Environmental Satellite (GOES) VISSR Atmospheric Sounder (VAS) was used to develop procedures for retrieving atmospheric temperature, moisture, and wind at hourly intervals in the northern hemisphere. Temporal and spatial changes in atmospheric moisture and stability are improving severe storm warnings. Atmospheric flow fields (deep layer mean wind field composites from cloud drift, water vapour drift, and thermal gradient winds) are helping to improve hurricane trajectory forecasting. In 1994, the first of NOAA's next generation of geostationary satellites, GOES-8, dramatically improved the imaging and sounding capability. Applications of these NOAA data also extend to the climate programmes; archives from the last fifteen years offer important information about the effects of aerosols and greenhouse gases and possible trends in global temperature.

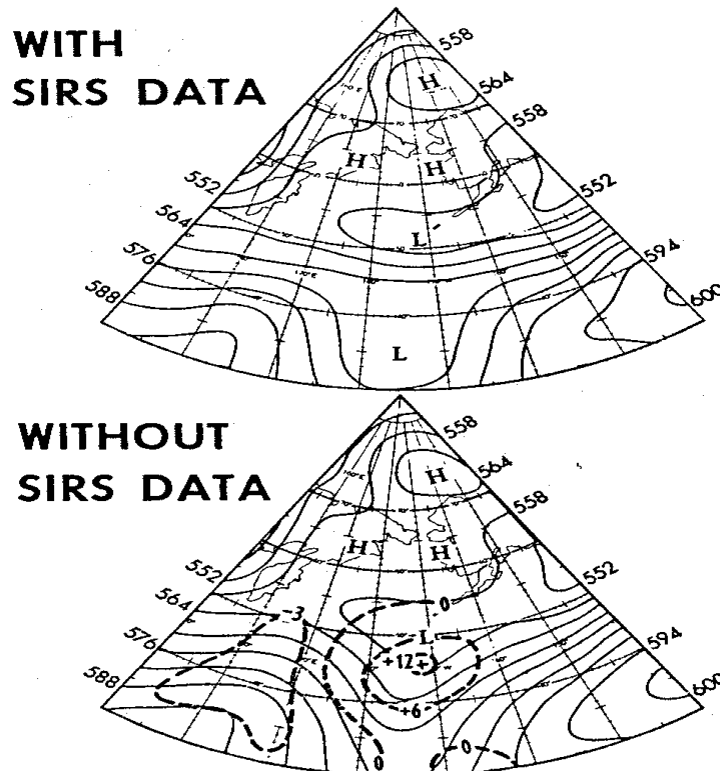
In the near future, forecasters will be able to use satellite and radar observing systems to investigate the evolution and structure of cloud systems and perform short term forecasts and warnings. Considering that convective activity ranges from air mass thunderstorms with life cycles well less than an hour to mesoscale convective systems with some aspects of their circulations that last for days, substantial benefits can be realized through correct interpretation of radar and satellite data. For example, there is obvious benefit in a forecaster distinguishing in real time between a supercell storm, associated with prolonged periods of severe weather, and a non-severe air mass thunderstorm. With the advent of improved mesoscale numerical models, the importance of interpretation of radar and satellite images and soundings is not diminished, but rather magnified as the forecaster now has the added task of using the observations critically to examine the predicted sequence of events.

The push for improved remote sensing from satellites continues. There is a need for higher temporal, spatial, and spectral resolution in the future radiometers. Higher temporal resolution is becoming possible with detector array technology; higher spatial resolution may come with active cooling of infrared detectors so that smaller signals can be measured with adequate signal to noise. Higher spectral resolution is being considered through the use of interferometers and grating spectrometers. Advanced microwave radiometers measuring moisture as well as

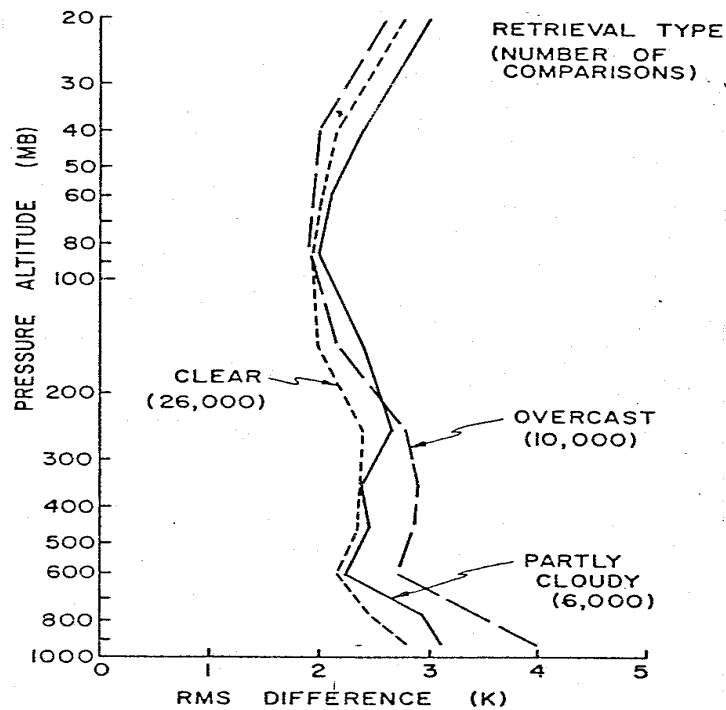
temperature profiles are flying in polar orbit; a geostationary complement is being investigated. Ocean colour observations with multispectral narrow band visible measurements are being demonstrated. The challenge of the future is to further the progress realized in the past decades so that environmental remote sensing of the oceans, atmosphere, and earth increases our understanding the processes affecting our lives and future generations.



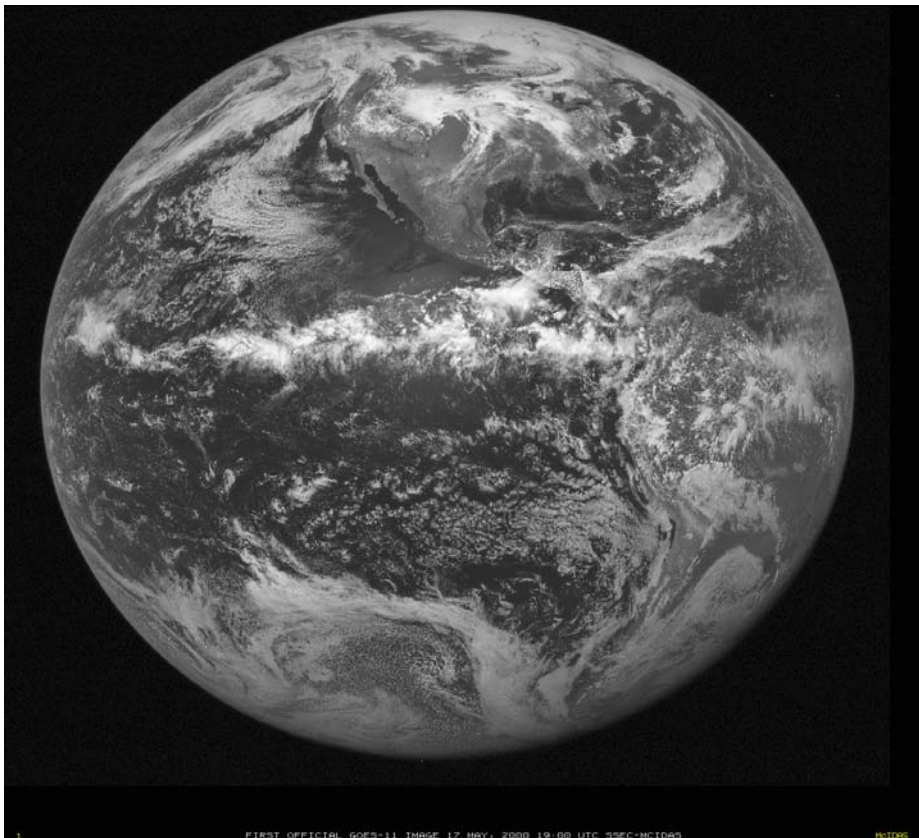
**Figure 1.1.** Infrared portion of the earth-atmosphere emitted radiation to space observed from Nimbus 4. Planck emission and line spectra are indicated.



**Figure 1.2** Comparison of objective analyses of 500 mb height for 24 June 1969 obtained with and without SIRS soundings. The differences in decameters are shown by the dashed isolines. Note the difference over the Pacific where the SIRS data indicate a cut-off low with an intense jet to the north instead of a diffusely defined trough. Extended range (72 hr) forecasts for North America displayed maximum errors based on the analyses with SIRS of only half the magnitude of those resulting without the use of the data.

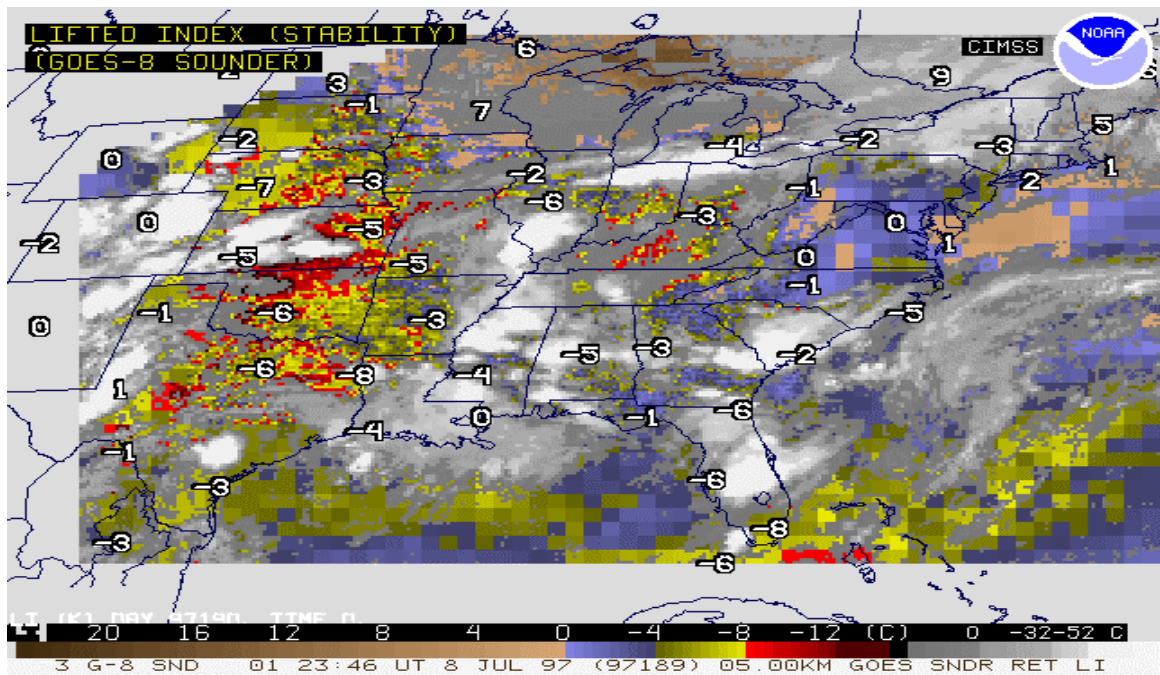
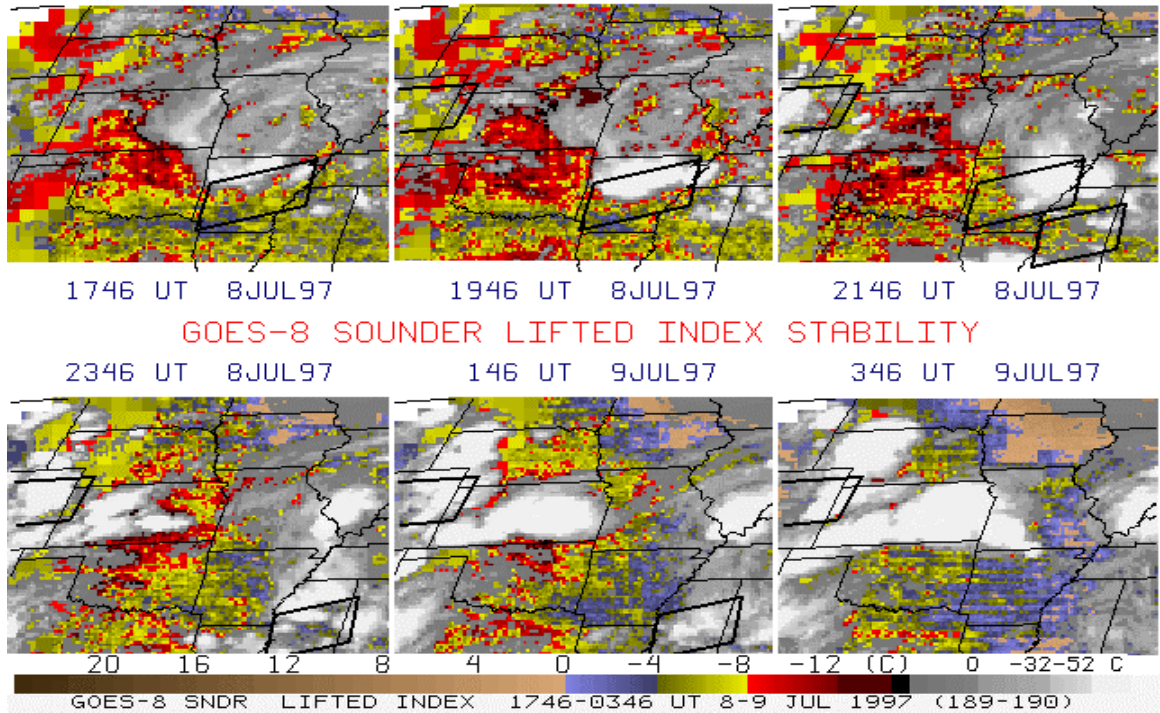


**Figure 1.3.** RMS differences between radiosonde and satellite temperature soundings for April 1980.



**Figure 1.4.** Image of visible reflectance sensed by the GOES-11, in which the light areas correspond to clouds or snow/ice regions.

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**Figure 1.5.** (top) Two hourly GOES LI DPI on 8 - 9 July 1997 showing focused strongly unstable conditions over Kansas and northern Oklahoma where severe storms subsequently developed. The severe weather watch boxes are overlaid. (bottom) The GOES-8 sounder LI DPI at 2346 UTC on 8 July 1997 along with the radiosonde values from the 0000 UTC launches.

**Table 1.1** Comparison of geostationary (geo) and low earth orbiting (leo) or polar orbiting satellite capabilities

GEO	LEO
Observes process itself (motion and targets of opportunity)	Observes effects of process
Repeat coverage in minutes ( $\Delta t = 30$ minutes)	Repeat coverage twice daily ( $\Delta t = 12$ hours)
Full earth disk only	Global coverage
Best viewing of tropics	Best viewing of poles
Same viewing angle	Varying viewing angle
Differing solar illumination	Same solar illumination
Visible, IR imager (1, 4 km resolution)	Visible, IR imager (1, 1 km resolution)
One visible band	Multispectral in visible (veggie index)
IR only sounder (8 km resolution)	IR and microwave sounder (17, 50 km resolution)
Noise of $.5 \text{ mW/ster/m}^2/\text{cm}^{-1}$ (several tenths of a degree)	Noise of $.5 \text{ mW/ster/m}^2/\text{cm}^{-1}$ (several tenths of a degree)
Constant viewing helps with clouds	Microwave helps with clouds
Filter radiometer	Filter radiometer, interferometer, and grating spectrometer