The Meteorological Satellite: Overview of 25 Years of Operation

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The first weather satellite was launched on 1 April 1960. In the 25 years since, weather satellites have contributed to improved weather analyses and forecasts worldwide. As a maturing component of a global observing system, the meteorological satellite promises even greater financial benefits and a higher quality of life to mankind.

Robert H. Goddard's original paper (*1*), from which much of the modern space program flows, was entitled "A Method of Reaching Extreme Altitudes." In 1929 he launched a payload that included a barometer, a thermometer, and a camera. It would not be inappropriate to trace the origins of the meteorological satellite program to these first steps. The advances in rocket technology during World War II led to the first pictures of clouds from high altitudes in the late 1940's. Kellogg (*2*) and Vaughan (*3*) traced the evolution of satellite meteorology from these early beginnings to the launch of the first weather satellite, TIROS-I, on 1 April 1960.

Since 1960, there has been a continuous record of improvement in sensing systems (*4*). Television cameras of the early polar-orbiting satellites have been joined by precision multispectral imaging radiometers in recent satellites. Radiometrically accurate imaging capabilities have allowed the applications to spread from meteorology and cloud pictures to oceanography and images of the Gulf Stream and biologically rich cold upwellings. But as these new applications grew, the older meteorological applications of the imaging device waned. The new focus of research and development centered on the atmospheric sounder, and the emphasis shifted from qualitative analyses of cloud patterns to quantitative contributions, including input to numerical forecasting models.

Because of image animation possibilities, the applications for qualitative weather analyses began to shift from polar-orbiting to geostationary satellites with the launches of two Applications Technology Satellites (ATS-1 and ATS-3) in 1966 and 1967. The operational applications increased with the launches of the initial Synchronous Meteorological Satellites (SMS-1 and SMS-2) in 1974 and 1975. Soon the earlier shift to quantitative analysis that had been experienced in the polar-orbiting satellites began to take place in the geostationary system as well. With the launch in 1980 of the fourth in the series of new Geostationary Operational Environmental Satellites (GOES-4), the sounding capability that had been proven with lower altitude polar orbiters was extended, on an experimental basis, to geostationary altitudes. By the late 1980's, soundings from geostationary orbit will be one of the routinely used tools of the National Weather Service.

From the first TIROS-I images of weather systems in the 1960's to today's temperature soundings of high spatial and temporal resolution gained from multispectral imagery, satellite information has provided a new means to study the earth's weather.

Cloud Imagery

The first weather satellite, launched in 1960, produced images of clouds and relayed them back to Earth (Fig. 1A). The pictures showed cloud details useful for understanding weather patterns (Fig. 1B). Early satellite pictures were particularly helpful in tracking storms that formed over tropical waters in areas for which weather data were sparse or lacking. As the satellite passed over one of these systems, it would relay the picture back to the ground and forecasters would be alerted to its existence and position. They could then place these systems on conventional maps, estimate their path and intensity, and provide necessary warnings.

The sporadic use of satellite data by forecasters continued until 1965, when a new use of satellite cameras and orbits resulted in images of cloud patterns on a worldwide basis. For the first time, all storms could be seen at least once a day, ensuring that tropical storms would never again approach land without warning.

In 1966, when the ATS-1 was launched into geosynchronous orbit (that is, a circular equatorial orbit 36,000 km above Earth with a 24-hour period of revolution), weather could be viewed continuously over an area from 70°N to 70°S and from Africa westward to the Pacific. During the following years, higher resolution visible imagery and infrared sensors, providing coverage both day and night, were added to geosynchronous satellites (Fig. 2). The ability to obtain satellite imagery at 20-minute intervals from the geosynchronous satellite allowed the meteorologist to view pictures in sequence, thereby creating a "movie" of weather developments. The availability of these movies to the weather forecaster has made a radical improvement in the prediction of local severe weather (*5*).

The latest geostationary satellites also image atmospheric temperature, water vapor, liquid water, and ice clouds (Fig. 2). The full-disk image of upper tropospheric water vapor shown in Fig. 2C delineates dry atmospheric conditions (dark regions) from moist atmospheric conditions (lighter regions). Since dry air is generally associated with descending motion or subsidence, while moist air is generally associated with ascending air, the water vapor imagery can be used to infer dynamic features of the atmosphere's circulation. Sharp boundaries of moisture in the mid-latitudes often indicate upper atmospheric jet stream boundaries, which are more easily seen

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in water vapor imagery than in liquid water and ice cloud imagery.

Satellite imagery can be used to identify cloud patterns and their distribution, storm centers, frontal bands, jet stream locations, centers of rotation (vorticity), areas of fog, the building and decay of thunderstorms, and areas of rain and snow. Pictures can be used to define snow cover and dust storms and to determine ground temperature. Over the oceans, satellite imagery can indicate warm and cold water, upwelling, and areas of ice cover. It can also yield clues to the location of clear and turbid waters and help determine areas of windy and calm conditions.

Atmospheric Motion Estimation

Frequent high-resolution satellite imagery now provides comprehensive observation of atmospheric motion through the measurement of cloud displacement. Traditionally, winds above the surface have been obtained by following a tracer drifting with the wind; weather offices routinely launch balloons over land surfaces for the tracer element. However, the three-quarters of the globe covered by oceans do not have any routine balloon wind measurements. In these regions satellite imagery is used to produce wind information (*6*). In a sequence of images from a geostationary satellite, clouds move because of the wind at cloud level. By tracking those clouds which move with the wind, it is possible to describe the motions of the atmosphere at a particular level over most of the globe. Water vapor features revealed in water vapor radiation imagery from the latest GOES instrumentation can be tracked to provide wind estimates in regions devoid of liquid water or ice clouds (*7, 8*).

Methods used to derive the "cloud drift" wind data range from fully manual tracking using movie loops to fully automatic tracking using computer correlation analysis between image segments. The procedures require a series of geostationary satellite images of good geometric fidelity with a time interval between images (generally ≤30 minutes) that is less than the lifetime of the clouds being traced. The images must be accurately aligned to remove any apparent motion due to satellite movements. Clouds that are not passive tracers of atmospheric motions need to be discriminated against. The height of a cloud is determined by using the cloud's radiating temperature observed by infrared measurement and a

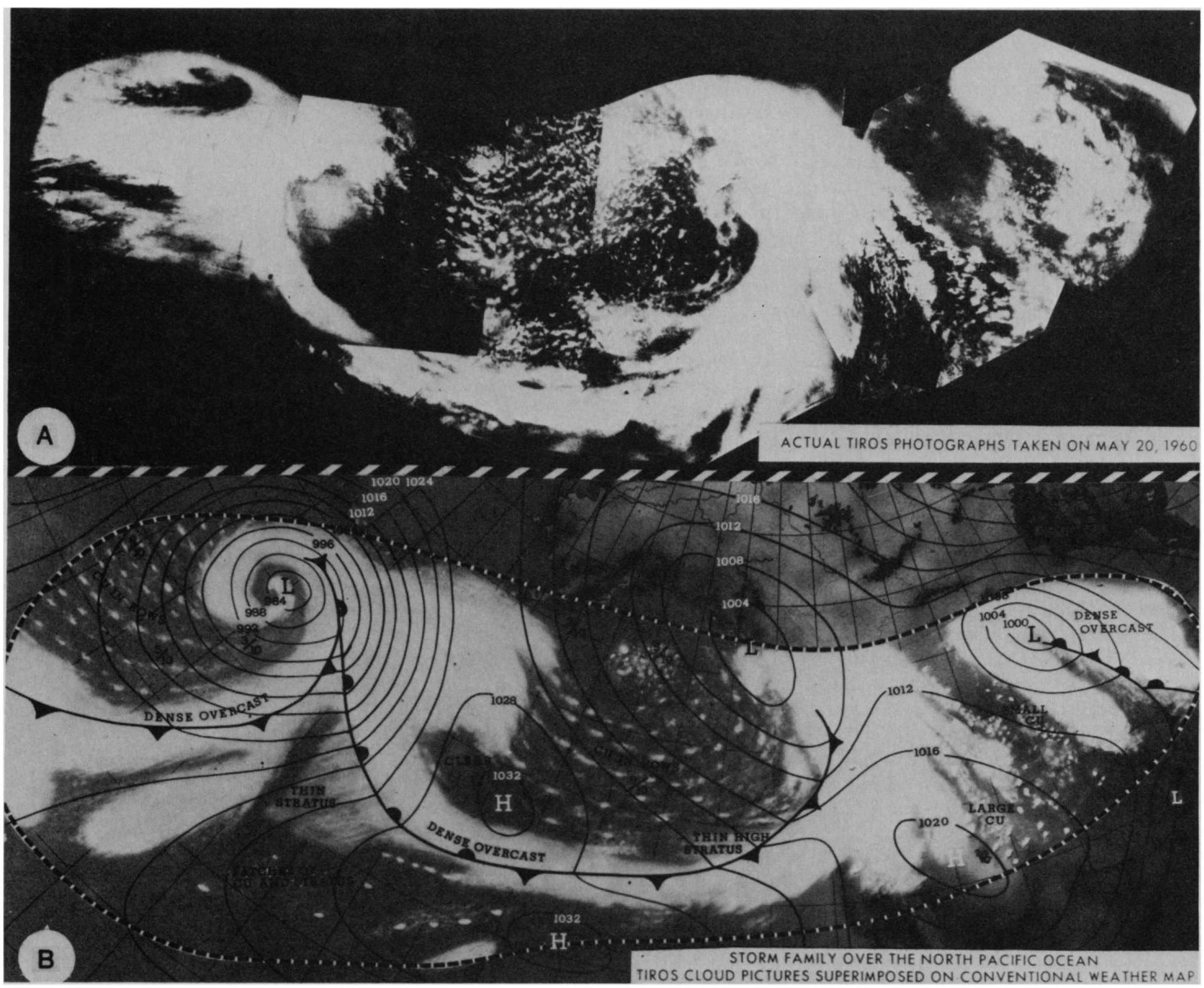

Fig. 1. Mosaic of pictures taken from the TIROS satellite. (A) Actual pictures from TIROS-I. (B) Pictures rectified for geographic distortion and superimposed on a conventional weather map.

vertical sounding of temperature versus height. The resultant "wind" data set must be controlled to eliminate erroneous measurements.

Cloud and water vapor drift wind data are slightly less accurate than balloon-derived wind data. Errors in the former originate from imprecise alignment of images, growth and dissipation of the cloud feature during the tracking sequence, the basic granularity in space and time of the images, and imprecise height measurements. Of these errors, the imprecise height assignment is generally the largest. Vector errors of 4 m/sec or greater are generally associated with operationally produced cloud drift wind data (*9*).

Liquid water and ice clouds are now routinely tracked on imagery from all the geostationary satellites around the globe at least twice per day, and the resultant wind data are fed into global weather forecast models (*10*). Geostationary satellites operated by the United States, the European Space Agency (ESA), Japan, and India are used to obtain the cloud wind data. Soon, water vapor wind data will also be obtained routinely by the United States. Figure 3 shows the coverage achievable from the GOES water vapor imagery.

Severe Storm Forecasting

The GOES has dramatically enhanced our ability to understand and predict severe thunderstorms. Before the high-resolution geostationary satellite there was a lack of information on the evolution of deep convective clouds and their local environment. This was due in large part to a gap in the meteorological observing capability: over the continental United States approximately 1000 hourly surface observation stations cover an area of 8×10^6 km^2, while a mere 126 upper air stations release balloon soundings over that same area only once every 12 hours. Satellite image and sounding data are helping to fill the gaps, in both space and time, between those routine surface and atmospheric observing sites. The GOES-VAS (Visible/Infrared Spin Scan Radiometric Atmospheric Sounder) can frequently observe atmospheric structure at a resolution of approximately 100 km^2, cloud cover at a visible resolution of 1 km^2, and thermal infrared radiation at a resolution of approximately 60 km^2. The clouds and their patterns portray the integrated effect of the dynamic and thermodynamic processes in the atmosphere. When the satellite information is combined with radar and surface and upper air observations, many of the important processes in storm development and evolution may be better analyzed and understood. This has helped lead to better forecasts of severe weather (*5*).

Major outbreaks of severe weather are normally associated with organized squall lines. Squall lines tend to form in areas of organized low-level converging air (such as exists along fronts or dry lines) that are coupled with regions of strong upward motion in the middle atmosphere and diverging air at upper levels (generally associated with a jet stream). An example of a frontal system that developed into a severe squall line is shown in Fig. 4. In this case, a Pacific front that extended from eastern South Dakota and Nebraska into central Kansas developed a line of severe thunderstorms as it moved into Minnesota and Iowa later in the day. Near the time the image in Fig. 4 was taken, large hail and funnel clouds were reported in South Dakota and a tornado injured six people in Minnesota. Later in the evening, tornado activity was reported in Minnesota and severe winds in Iowa. Thunderstorms that developed along the line in central Kansas elicited many reports of funnels and hail, and there was one confirmed tornado. Squall line developments of this type are routinely observed in GOES imagery before the development of deep convection and before their detection by radar. This ability to locate early development along squall lines and track their motion with sequential GOES images has helped in the orientation and timing of tornado and severe thunderstorm watches issued by the National Severe Storms Forecast Center in Kansas City. Once the squall line has developed, GOES infrared data may be combined with information from radar to assess storm intensity (*11, 12*).

Satellite imagery has provided valuable new observations concerning the importance of boundaries produced by prior convection and their ability to localize tornadic thunderstorm activity. In satellite imagery, such boundaries most often appear as well-defined convective cloud lines composed of cumulus congestus clouds, arc-shaped in appearance, referred to as arc cloud lines. Arc cloud lines may be thought of as miniature cold fronts produced by rain-cooled air from previous thunderstorm activity. Strong low-level convergence that exists across such boundaries can invigorate a strong thunderstorm, causing it to rotate or to increase its rotation and produce tornadic activity (*13–15*). Such interaction has recently been simulated with a numerical model of a severe thunderstorm (*16*).

Satellite imagery with an interval of 15 to 30 minutes is routinely used to observe thunderstorm-related phenomena. However, in the near future, advanced image analysis equipment and more frequent imaging (5-minute intervals) may further enhance the ability to detect and forecast severe storms, since the development of deep convection will be viewed with a temporal resolution compatible with the scale of the mechanisms responsible for its triggering.

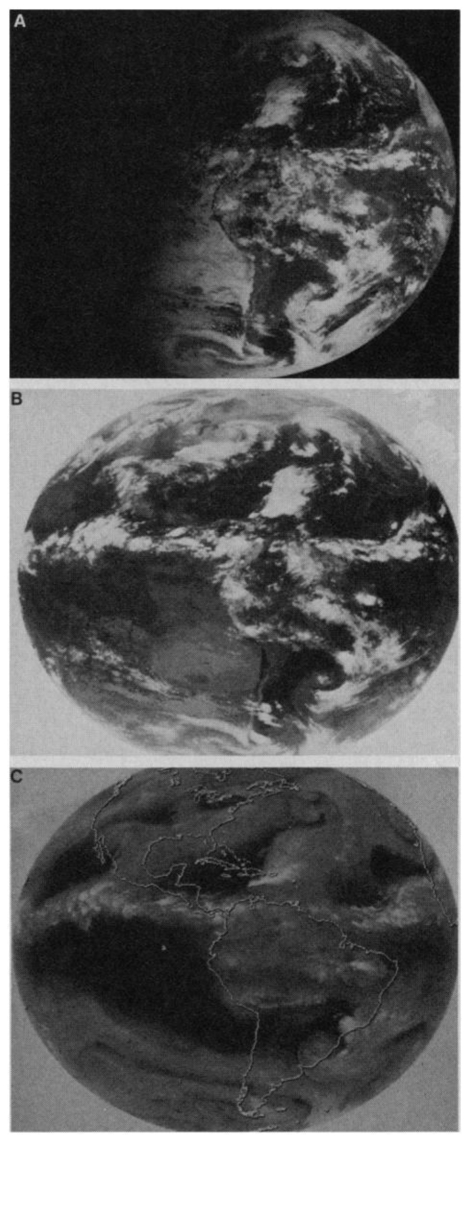

Fig. 2. Full-Earth photographs taken from GOES at sunrise. (A) Visible image showing the terminator. (B) Infrared image showing both day and night coverage. (C) Infrared image showing upper tropospheric water vapor "cloud" patterns.

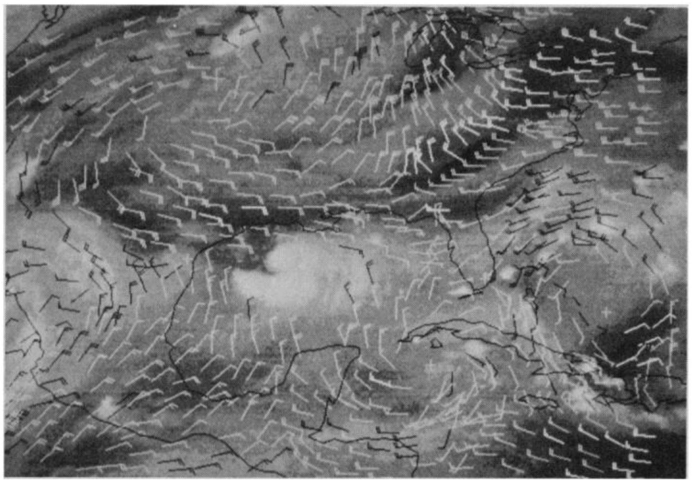

Fig. 3. Coverage of water vapor "cloud" tracer winds achieved around Hurricane Alicia in the Gulf of Mexico on 16 August 1983. Height estimates of the wind vectors are near 300 mbar (9000 m).

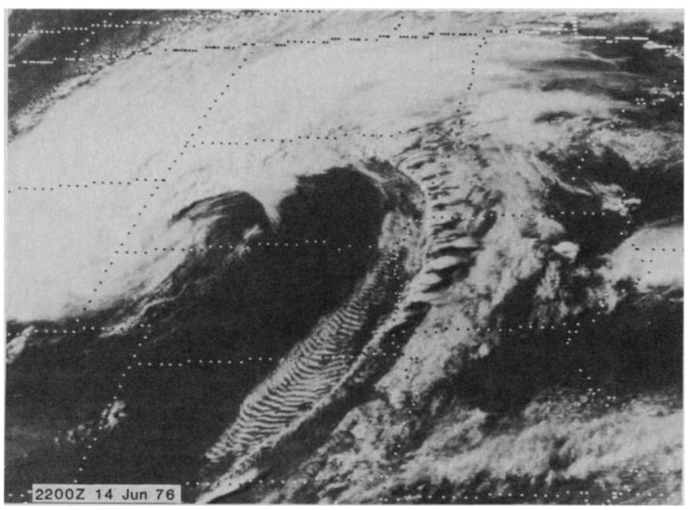

Fig. 4. Squall line viewed from GOES on 14 June 1976.

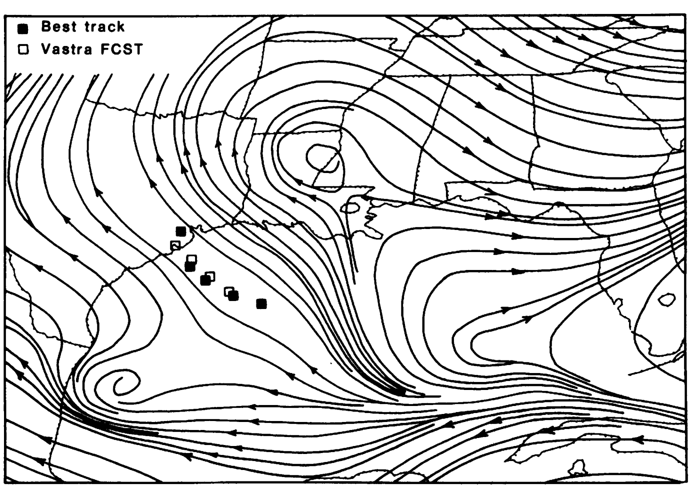

Fig. 5. Streamlines of GOES-VAS–derived deep-layer mean wind for 16 August 1983 (1200 hours GMT), with current and subsequent 12-hour positions of Hurricane Alicia's eye (filled squares) plotted together with the forecast "VASTRA" positions (open squares).

Tropical Storm Surveillance

Since the first meteorological satellite was launched, hundreds of tropical cyclones have been observed from space. The observations have provided meteorologists with a wealth of information concerning the relation between the cloud patterns of tropical cyclones and their position, intensity, and motion. Today, much of this knowledge is used in analysis and forecasting. Image interpretation techniques play a major role in the issuance of hurricane warnings.

The feasibility of using satellite pictures for tropical cyclone analysis was recognized early in the satellite program (*17*). It became apparent that the well-organized spiral structure and eye characteristics visible in pictures of these intense storms bear some relation to the high wind speed associated with them. Accordingly, methods were devised for estimating the intensity of tropical cyclones by associating certain cloud features with conventional estimates of storm strength (*18, 19*). In these methods the appearance of a storm's eye, its banding, and the size of the cloud pattern were used to estimate the intensity of the cyclone from one picture per day.

The technique currently used to estimate intensity from satellite imagery is based on an analysis of the evolution of the storm's cloud pattern. The guidance is in the form of an empirical model of tropical cyclone development. The model consists of descriptions of how a storm should appear on each successive day. Certain characteristics or features of the pattern, such as the amount of coiling of the curved cloud band, have been used for years to estimate tropical cyclone intensity. When the features are clear-cut and when they evolve in a systematic manner, they can be used to obtain reliable intensity estimates. However, because of the ever-changing nature of the clouds that form the pattern, these essential features do not always appear clear-cut and may take on a variety of appearances at each level of intensity. This complexity is dealt with in current analysis techniques through the use of systematic procedures and cloud pattern descriptions (*20*).

During the late 1970's, methods involving enhanced infrared imagery and digital infrared data were added to the technique (*21*) to provide the analyst with cloud top temperature measurements that are used in place of subjective judgments required when visible pictures are used. The infrared pictures also provide continuous storm surveillance. Because of these two advantages, the enhanced infrared and digital infrared data make the analysis simpler and more objective than it is when visible pictures are used.

The microwave radiation–sensing instrument flown on the NOAA polar-orbiting satellites since 1979 made possible a new objective technique for determining storm intensity (*22*). The method involves the microwave observation of the upper tropospheric (6 to 12 km) temperature pattern to define the intensity of the warm core of the cyclone. Since this feature is related to storm intensity, the technique monitors intensity changes by observing changes in the relative intensity of the temperature of the storm's core. Empirical relations have been developed to permit the maximum sustained wind speed at the surface to be estimated from the microwave temperature observations with an accuracy better than 10 knots.

Satellite cloud imagery is also used to forecast tropical cyclone motion. The simple extrapolation of the cloud system center, based on time-lapse motion pictures, has long been a useful forecast tool. A recently developed method is now being implemented in which satellite-derived wind data for a deep layer of the atmosphere are used to make the forecast. Cloud displacement winds, water vapor tracers, and winds estimated from satellite-observed temperature gradients are used to form a deep-layer mean wind streamline analysis that can be used as a "steering current" to forecast tropical cyclone motion (*23*). An example of the water vapor tracer wind vectors for Hurricane Alicia's environment is shown in Fig. 3. Figure 5 shows streamlines of the deep-layer mean wind for Hurricane Alicia, along with 12-hour increments of the future storm position forecast from the deep-layer mean wind, assuming steady-state motion. The actual positions observed by satellite and aircraft are also shown. As can be seen, good estimates of the wind field surrounding a hurricane, as achievable from GOES, can provide accurate forecasts of the storm's position at landfall.

There has been considerable progress in the use of satellite imagery for tropical cyclone surveillance over the past 25 years. The use of quantitative estimates of atmospheric temperature and winds made possible with the latest generation of satellite sensors has enabled more objectivity and reliability in hurricane analysis and forecasting (*24*). With a future that promises better understanding of tropical cyclones and improved videographic computer technology, the trend toward higher reliability in the forecasting of tropical storms is likely to continue.

Input to Numerical Forecast Models

Although the primary use of cloud imagery has been interpretive in terms of weather forecasting, it was logical to seek ways whereby the interpretations might be transformed for use by numerical forecast models. In theory, improvement of the initial state should enable the models to better predict the future state. The models, as they are formulated to integrate the hydrodynamic equations, require a definition of mass, motion, and moisture distributions over the domain of the model. Obviously, these quantities are related to the features observable in imagery, but the relation is not straightforward. Thus, to obtain the so-called "state" parameters, one must generally rely on conceptual and statistical relations.

Quantitative interpretation from imagery was vigorously pursued in the early years of meteorological satellites. It was generally believed that numerical predictions were seriously debilitated by a deficient initial state and that satellites offered the only economical means for describing the circulation in remote areas, especially the large ocean areas of the northern Pacific and the Southern Hemisphere.

Many "rules" were formulated to describe the state variables. The description of winds is the easiest. Calm surface winds can be specified where sun glint reveals evidence of lack of wind action on the ocean surface. Upper level winds can be estimated from the cirrus blowoff of thunderstorm tops, especially in the tropics. In addition, winds can be estimated from time-lapse imagery of evolving cloud patterns. Surface pressure can be inferred from models of the evolution of subtropical storm systems. The cloud pattern associated with a well-developed storm system is familiar to most people from television or newspaper weather information, and even a layman can locate the position, if not the magnitude, of the lowest pressure with good accuracy. This concept was expanded to include estimates of the upper atmospheric pressure distribution, which were used extensively by the U.S. and Australian weather services (*25, 26*). Finally, moisture definition from cloud imagery has been modeled to serve as input in the form of relative humidity. This practice is followed to define the moisture over the eastern Pacific, where the initial field has a strong bearing on the precipitation forecast for the West Coast. Once again, the data are deduced from conceptual models relating moisture definition to cloud morphology.

With the advent of remote soundings of temperature and moisture, more quantitative methods have been established to determine the initial state of the atmosphere. Remote soundings are now replacing these earlier estimation techniques. However, the changing of the guard will not be complete until the operational implementation of soundings from geostationary satellites in 1986.

Quantitative Measurements of Temperature and Moisture

Proposals were made as early as 1958 to exploit the details of the spectral emission by Earth's atmosphere to infer the vertical structure of its temperature and its content of water vapor. In 1969 the

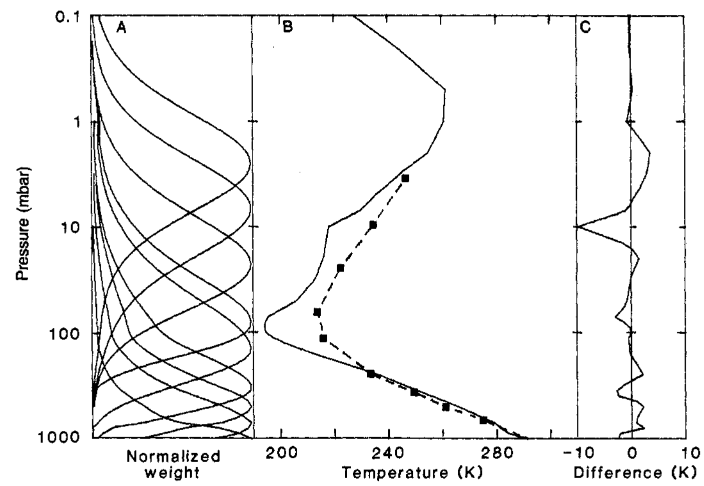

Fig. 6. (A) Normalized weights for seven TOVS channels in the 15-μm band of CO_2. (B) Sounding for Naha, Okinawa, 1200 hours GMT, 21 November 1984 (solid line) and TOVS radiance temperatures (dashed line). (C) Radiosonde minus TOVS retrieval temperatures.

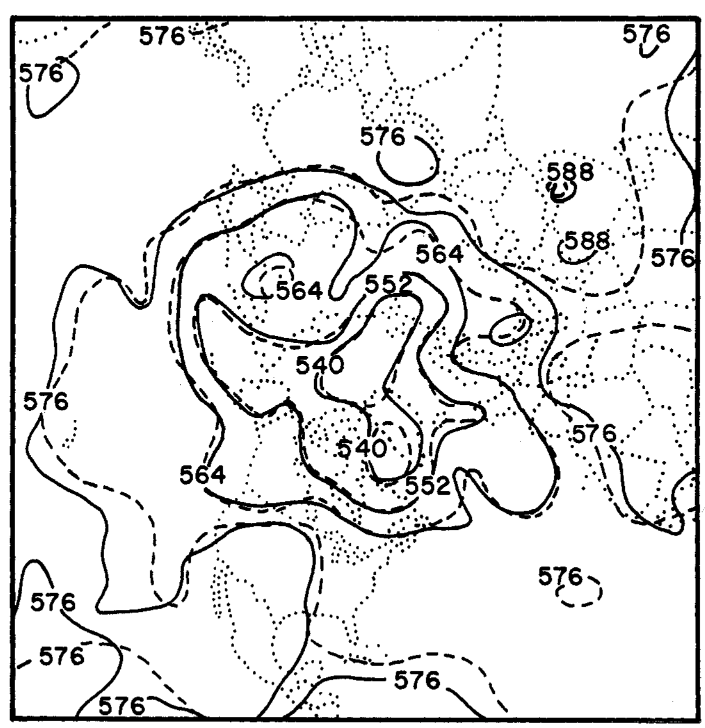

Fig. 7. Contour analysis of 1000- to 500-mbar geopotential thickness (decimeters) (proportional to 0- to 6-km mean temperature) achieved solely from TOVS satellite soundings (solid contours) and from all sources of data except TOVS over land (dashed contours).

first experiments (*27, 28*) were conducted from the NIMBUS-III satellite to test the feasibility of obtaining high-quality soundings of temperature and (later) moisture. Since that time, 18 experimental and operational instruments have been carried on the polar-orbiting NIMBUS, TIROS, and NOAA satellites, culminating in the triad of instruments now being used operationally (the TIROS operational vertical sounder, or TOVS). Also, beginning in 1980, geostationary satellites began carrying the VAS, which can provide vertical temperature and moisture profile data with high temporal frequency.

The principle of these sounding systems is the measurement of Earth's radiance (rate of flow of radiant energy through the upper boundary of the atmosphere in the direction of the observing platform) in several narrow and carefully selected spectral intervals and inverting the process of thermal radiative transfer to infer, as a function of the atmospheric pressure level, the temperature of the atmosphere or the concentration of the attenuating gas. The temperature is derived by using the emission from gases, such as CO_2 and O_2, having constant and known atmospheric concentrations. The temperature profile is used along with the observed emission to derive the variable and unknown concentrations of gases such as H_2O; interpretation can be performed simultaneously (*29*). The surface temperature and surface emission are derived from observations in spectral intervals for which the atmosphere is most transparent ("windows").

The TOVS instruments measure in 27 spectral intervals from the visible into microwave spectral regions. The stratospheric sounding unit furnished by the British Meteorological Office has three radiometers measuring in the 15-μm band of CO_2; the weights are the topmost three curves in Fig. 6A (the altitude scale is from the surface to about 60 km). The high-resolution infrared sounder, version 2 (HIRS-2), is a filter radiometer measuring in 20 spectral intervals from the visible to 15 μm; six of the spectral intervals in the 15-μm band of CO_2 have weights shown as the bottommost six curves in Fig. 6A (13 of the other spectral intervals are in windows and absorption bands of O_3, H_2O vapor, CO_2, and N_2O; the 14th is a "visible" channel at 0.71 μm). Weights of the microwave sounding unit are not shown here, but they have peaks ranging from the surface to about 17 km.

Methods for retrieving profiles of temperature and humidity may

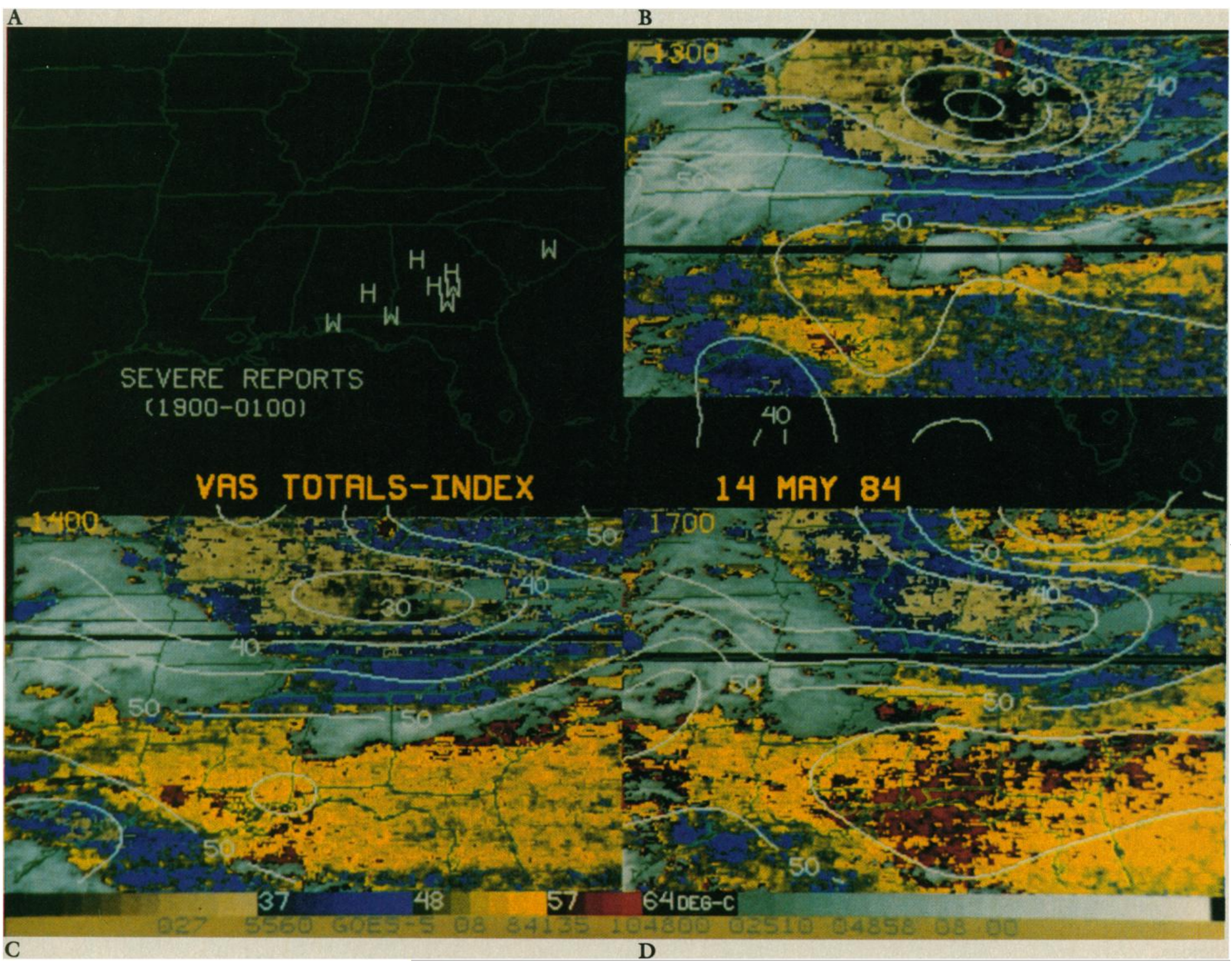

Fig. 8. (A) Severe weather reports (H, hail; W, damaging wind) from 1900 to 0100 hours GMT. (B to D) Time sequence of VAS total-totals stability and cloud imagery with contours of spatially averaged values for the southeastern United States on 14 May 1984 at (B) 1300, (C) 1400, and (D) 1700 hours GMT.

be classed as statistical (*30, 31*) and physical (*29*). The statistical method currently used in TOVS operations involves the expansion, at 40 levels of the atmosphere, of the temperature and humidity as linear combinations of the observed radiance temperatures (temperatures that yield a Planck radiance equivalent to the measured radiance in each spectral interval). Because of the limits of vertical resolution, there are considerably fewer degrees of freedom.

Figure 6B shows a radiosonde at Naha, Okinawa, at 1200 hours Greenwich mean time (GMT) on 21 November 1984 (solid line); the part above 24 km has been extrapolated from a historical data set. Also shown in Fig. 6B are the radiance temperatures from the nine measurements corresponding to the weights in Fig. 6A; heights of the radiance temperatures are at the mean levels in the atmosphere from which the observed radiances arose. The Planck radiance temperatures contain within them the general shape of the temperature profile, although each measurement by itself is a mean through a very thick layer of the atmosphere.

The retrieved profile contains errors because the measurements represent such a blurred image of the atmospheric temperature and have errors induced by instrument noise and other sources. The retrieved profile for the sounding in Fig. 6 is not shown, but the difference between the retrieval and the radiosonde is given. The root-mean-square difference from the surface to 24 km (the verified portion) is 1.44°C, which, at this stage of the processing scheme, is typical (*32*). Retrieved precipitable water for this atmosphere was 3.12 cm, compared to 2.18 cm for the radiosonde; operational water vapor retrievals are poorer than those for temperature, but the use of new mathematical procedures, such as those currently used experimentally to process VAS data, will greatly improve the situation (*29*).

Processing of satellite sounding data entails much more than simple retrieval from observation. The presence of clouds alters radiances; clouds are nearly opaque in the infrared but are transparent in the microwave except for the precipitation they may contain. In partly clouded areas the clear air infrared radiance is obtained by subjecting the measurements to an analysis of adjacent pairs having different cloud amounts, with consistency checks for clouds at different heights. The microwave measurements are used for quality control, particularly where thin cirrus clouds exist, and to improve the retrieval near the tropopause. A continuing research effort is devoted to the improvement of results, and from time to time the processing of the data is modified to reflect the benefits of this effort.

Forecast Applications

The major application of vertical soundings achieved from polar-orbiting satellites is the analysis of temperature and moisture over the oceanic regions as required to initialize global numerical weather prediction (NWP) models. The global NWP operation is focused on the long-range (2- to 5-day) forecasting of large-scale weather patterns. Short-range (0- to 2-day) forecasting of local weather elements is accomplished with limited-area, higher resolution forecast models. The First Global GARP Experiment (FGGE), initiated in January 1979 soon after the launch of the first of the current series of TIROS-N—NOAA satellites, enabled the impact of polar-orbiting TOVS data on global NWP to be evaluated.

Figure 7 presents the results of analyses of TOVS-derived 1000- to 500-mbar geopotential thickness (solid contours) and, for comparison, the National Meteorological Center (NMC) analysis (dashed contours), which is devoid of TOVS data over land areas. (This geopotential is proportional to the mean temperature of the lowest 6 km of atmosphere.) The correspondence between the "pure" satellite analyses and the NMC analysis, which did not incorporate the TOVS data over land, is striking. The agreement over the continents validates the TOVS data and shows that the results achieved over oceanic regions are accurate.

Tests on the impact of TOVS data on global NWP have been conducted by many numerical forecast centers around the world (*33*). A consensus of their results demonstrates that satellite sounding data is an absolute necessity for the conduct of fully automated NWP in the Southern Hemisphere. For the Northern Hemisphere, which is rich in other sources of weather data, the use of TOVS data extends the useful range of numerical forecasts. For example, a 3-day forecast that had the benefit of TOVS data for the initial condition will generally possess an accuracy similar to that inherent in a 2-day forecast based solely on conventional observations.

Improvements in the forecasting of local weather are being demonstrated through the use of vertical temperature and moisture profiles retrieved from VAS radiance observations from the current series of GOES satellites (*34–37*). An example of this new capability is shown in Fig. 8. Here the instability of the atmosphere (related to the probability of severe weather development), as derived from 8-km–resolution VAS temperature and moisture soundings, is shown in the false-color portions of the pictures, whereas the clouds, detected by infrared imagery, are shown in the white or gray portions for three different times on 14 May 1984. The red areas denote very unstable air, meaning that the atmosphere is highly conducive to intense convective developments. The three images show the evolution of severe weather potential during the day over an area extending from the Florida Panhandle across Georgia and into South Carolina. The instability imagery correctly locates the region where severe weather developed later in the day. As soon as this new capability of geostationary satellites to monitor atmospheric temperature and moisture changes becomes fully operational, a significant beneficial impact is expected.

Future Expectations

The next advances in the satellite instrument capabilities are already under development in aerospace contractor plants, and they will be flown before the end of the decade. The technical needs for further improvements in meteorological applications to remote sensing are well understood. Long-range development plans extend into the next century.

The launch of NOAA-9 in December 1984 realized the beginning of two entirely new measurements of the atmosphere. Two radiation measurement instruments are aboard that spacecraft as a part of the earth radiation budget experiment (*38*). A long-term set of similar measurements (beyond the "experiment") is seen by many as necessary for climate analyses and predictions. The monitoring of ozone in the upper atmosphere is a job given NOAA by the Congress. The first operational instrument to carry out that responsibility, through the use of backscattered ultraviolet radiation from the sun, is aboard NOAA-9. This is the first routine satellite measurement of a minor atmospheric constituent, and these measurements will continue for the foreseeable future.

The next generation of atmospheric soundings from the polar-orbiting satellites (aboard NOAA-K, -L and -M in 1990 through 1992) will be accomplished with an advanced microwave sounding unit (AMSU) that will replace the outdated microwave sounding unit and the stratospheric sounding unit. It will provide the first all-weather temperature soundings from space with accuracies equivalent to that achieved in clear air today (within 2.0°C of radiosonde measurements). Such soundings through clouds will allow far better analyses and forecasts in the active regions of the atmosphere. The AMSU will also provide improved water vapor measurements for three layers of the atmosphere, estimates of precipitation, and estimates of soil moisture and liquid content of the snow pack.

The next geostationary satellites (GOES-NEXT, to fly in 1989) will carry a simultaneous imaging and sounding capability. The images will be accurately registered to the ground (to within 10 percent of the instantaneous field of view) to further improve their utility in studying mesoscale weather phenomena. The soundings, while more sensitive to cloud interference than those from the polar-orbiting satellites, will be available at all times of day, not just twice a day. A new 1000–spectral channel high-resolution interferometer sounder (HIS) instrument is also under development for future geostationary satellites. This instrument, which has already been tested on high-altitude aircraft, will enable vertical temperature and moisture soundings to be achieved with greatly improved vertical resolution (*39*).

Beyond these improvements, the next major change will come in the polar-orbiting satellites. An array of improved instruments is already under study. The use of the space shuttle (*40*) will allow a large platform for the spacecraft with a large array of instruments for simultaneous measurement of several parameters.

From such an array of new instruments, a number of new or improved atmospheric measurements will be provided. Images of higher resolution (500 m compared to 1 km) and expanded spectral coverage can be anticipated. Microwave images of the sea surface and the atmosphere (to be a reality on military satellites soon and on improved NOAA satellites in the late 1980's) will have greatly improved resolution. Soundings will be of improved vertical resolution and will have a narrower field of view. These soundings may be combined with profiles from a planned array of upward-viewing ground-based sensors in order to provide better vertical resolution near the surface (*41*). A radar-scatterometer (*42*) will provide ocean surface wind data accurate to within 1.3 m/sec and 16° (*42*). Wave height data accurate to within 0.5 m will be provided by radar altimeters. Tropical storms can be analyzed in new ways with synthetic aperture radar images.

There are even more candidates for the 1990's and beyond (*43*). A pulsed-laser ("lidar") concept for measuring global wind fields by the Doppler shift of light reflected from particulates has been under study for years under the descriptive title of Windsat. It is exciting and conceptually feasible. So-called limb sounders, already flight-proven, will look at absorption or emission across the horizon to give vertical profiles of minor constituents. Limb-scanning multispectral interferometry will enable optimization of the remote-sounding technique.

The orbits of the polar platforms may be somewhat different than they are today (850 km with equator crossings of 0900 hours local time southbound and 1300 hours local time northbound), but they will still be determined by the need for special sun angles for certain instruments and the need of the numerical forecast models for data at certain times of day. A morning platform and an afternoon (near-noon) platform will still be needed. Future orbits might include one that is highly elliptical, from which some of the temporal sampling and global coverage benefits of geostationary and polar orbitors can be achieved with a single spacecraft.

High data rates and the need to combine data from several sources will drive us to new communication techniques (involving satellite links), new computer techniques, and new data management schemes. For weather forecasting, the data are perishable and must be used at once or discarded. For the scientist such data are far less perishable, but they are of little value for long-term studies if they are not well calibrated. Management of this vast quantity of data will be among the greatest challenges for the scientific use of satellite observations of the future.

Given the U.S. commitment to the development of a permanent space station and the growing participation of the world's nations in the meteorological satellite program, the next 25 years promise to bring even greater benefits to mankind through improved weather analysis and forecasting.

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