Atmospheric soundings from satellites—false expectation or the key to improved weather prediction?

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SUMMARY

Temperature and water vapour soundings from satellites have been available for more than 20 years. Because of the global nature of these data, satellite soundings were expected to improve significantly global numerical weather prediction (NWP). Indeed, experiments with the satellite soundings provided during the Global Weather Experiment (GWE) in 1979 revealed the positive impact of these data on extended-range forecasts, particularly in the southern hemisphere. Unfortunately, since the GWE, the value of satellite soundings has apparently diminished. I believe this to be due largely to improvements in the models which have surpassed the inherently poor vertical resolution of these data relative to that of the contemporary NWP models. The satellite data can even degrade the analysis/forecast operation through the aliasing of small-scale features which may be properly represented by the vertical scale resolved by the model.

This lecture addresses, from a historical perspective, the dilemma of the decreasing value of satellite soundings in the weather-forecast application (i.e., the reasons for the unfulfilled expectations of these data). Attention is then turned to the improvements in the satellite technology and the application techniques needed to reverse this trend.

1. INTRODUCTION

The expectation

George James Symons (1838–1900), whom this lecture commemorates, was a pioneer of weather observations, particularly rainfall and temperature in the British Isles (Bilham 1938). Modern-day weather predictions, almost a century after the death of this great scientist, are critically dependent upon such observations. The forecasts are achieved with computer models whose forecast skill is sensitive to the accuracy of the observations used to initialize the numerical integration of the ‘model equations’. During the past few decades, great advances in numerical prediction have been made possible by the rapidly expanding capabilities of computers. However, since a numerical weather prediction depends directly on initial values, a correct specification of the initial state is a necessary condition for an accurate prediction, regardless of the sophistication of the model or the power of the computer.

Because much of our planet is ocean, satellite sensing of the atmospheric state would appear to be crucial, both for the short-term forecast of mesoscale weather in coastal regions (e.g. the British Isles) and for extended forecasts of synoptic-scale weather on the global scale. Since its inception during the middle part of this century, the expectation was that the satellite sounding system would improve forecast accuracy. Indeed, the use of satellites to fill the large gaps of the conventional balloon observation system (Fig. 1) was the basis of the Global Weather Experiment (GWE) which it was hoped would extend the range of useful synoptic-scale forecasts to a week or more.
Figure 1. (a) Distribution of radiosonde stations, and (b) coverage of soundings from the two-satellite TOVS system during a 24-hour period (Öhring 1990).
Is the expectation that satellite remote-sensing systems can improve weather forecasts a false expectation? Ever since the launch of the world's first satellite sounding instrument (SIRS-A) in April 1969 (Wark and Hilleary 1969), meteorologists have been attempting to demonstrate whether or not these global data have a positive impact on weather predictions, with seemingly no consistent answer emerging (Ohring 1979). What was first thought to be a reasonable hypothesis, easy to verify with experimental data, has instead stimulated worldwide, and often emotional, scientific debate. The frustration of the modelling community has created the opinion that "the satellite producers have an overly optimistic attitude and have wrongly created the impression that satellite data would replace the conventional radiosonde" (Bengtsson 1979). Another opinion is that the modelers misuse the satellite profiles by treating them as if they were "observations by a very inaccurate radiosonde system" (Eyre and Lorenc 1989). After years of debate, both satellite-data producers and forecast-model users now seem to agree that both the accuracy of satellite sounding data and the methods with which the data are utilized in the analysis/forecast systems are often partially responsible for null, or even negative, impact on weather prediction.

During this past decade, significant improvement in forecast accuracy has been realized with global forecast model developments, largely inspired by the routine collection of a global data-base initiated with the GWE. It now appears that further improvement in forecast accuracy is being retarded by the inherent vertical resolution and accuracy of the current satellite sounding system, which is often poorer than that provided by the model forecast. However, this is not a call to abandon the satellite programme—quite the contrary. This review of the history of the characteristics of the satellite sounding data and their evolutionary use in the weather analysis/forecast operation is presented to support the hypothesis that satellite sounding remains the key to further improvements in global weather prediction. This improvement probably cannot be realized without the implementation of satellite sounding systems having a higher vertical resolution: but such systems are available; their feasibility has been demonstrated and planning for their implementation is underway.

2. **HISTORICAL EVOLUTION**

(a) The first results

Atmospheric sounding has been one of the main motivations of the meteorological satellite programme. Even before SPUTNIK, it was recognized that air temperature observations might best be made on a global scale using radiometric measurements from satellite (King 1958; Kaplan 1959; Houghton 1961). In the United States, two experiments were developed in the 1960s for flight on the NIMBUS-3 experimental weather satellite: (1) a Michelson interferometer, called IRIS, which measured the spectrum of infrared radiation emitted to space by the earth and atmosphere, and (2) a grating spectrometer called SIRS which measured the radiation to space in eight distinct spectral bands selected specifically for temperature sounding.

These instruments were placed aboard the NIMBUS-3 satellite, but the launch on 13 April 1968 failed and the spacecraft fell into the Pacific Ocean. NASA prepared another spacecraft with the backup instruments and it was launched successfully one year later on 14 April 1969.

The Infrared Radiation Interferometer Spectrometer (IRIS) (Conrath et al. 1970) observed earth–atmosphere radiation to space with 5 cm⁻¹ resolution within the 5–25 μm wavelength region. The Satellite Infrared Radiation Spectrometer (SIRS) (Wark et al.
Figure 2. NIMBUS IRIS brightness temperature spectrum with location of SIRS-A spectral channels.

Figure 3. 'Weighting functions' displaying the sensitivity of the observed radiance to atmospheric temperature variations for the SIRS-A spectral channels.
1969) measured the outgoing radiance in seven $5 \text{ cm}^{-1}$ intervals of the $15 \mu \text{m CO}_2$
emission band and one $5 \text{ cm}^{-1}$ channel in the atmospheric 'window' at $11 \mu \text{m}$ (Fig. 2).
The SIRS absolute radiometric accuracy of one per cent and signal-to-noise ratio of 400
to 1 was a phenomenal achievement for its time.

Even though the sensitivity of the radiance measurements to atmospheric tem-
perature variations (i.e. as displayed by the so-called 'weighting functions' shown in Fig.
3) was smeared over a vertical depth of eight kilometres or more, the SIRS-A radiance
measurements exhibited high correlation with radiosonde-level temperature meas-
urements for clear sky conditions. As may be seen in Fig. 4, the degree of temperature
variance explained by the radiances observed in SIRS channels was in excess of 80\% for
most levels of the troposphere and lower stratosphere. There was a large improvement
in the explained variance in the tropopause region (i.e. 100–400 mb) using the radiances
observed in all spectral channels relative to that achieved using only the radiance
observed in the single most sensitive channel. This result illustrates the importance of the
deconvolution (i.e., the inversion process) to define finer-scale vertical structure from
the coarse-resolution measurements.

Using various 'inversion techniques', temperature profiles were retrieved from SIRS-
A data. Radiosonde statistics were used to constrain the solution (Wark and Fleming
1966; Rodgers 1976). One example is the historic first sounding, on launch day, over
Kingston, Jamaica (Fig. 5) (Wark and Hillery 1969). The close correspondence of this
sounding with a nearby radiosonde gave good reason for celebration; however, significant
errors existed owing to the uncertainty in each channel's 'weighting function' which had
to be prescribed by theoretical calculation. As a result, it was quickly found that better
results could be achieved using empirical relations between the measured radiances and
radiosonde temperatures obtained by statistical regression (Smith et al. 1970).

Figure 6 shows two examples of comparisons between a statistical regression sound-
ing from SIRS and a radiosonde sounding over Berlin. Figure 6(a), which shows excellent
agreement, serves to illustrate how one could be misled by the satellite results. The
vertical structure of the SIRS sounding in the tropopause region is well below the vertical

Figure 4. Percentage of radiosonde temperature variance explained by the variance of SIRS-A radiance
observations.
resolution of the SIRS measurements (Fig. 3). Strong inter-level temperature statistical correlations allow the regression algorithm to produce this structure from the gross vertical-resolution measurements of the SIRS. Recent analyses show that one can distinguish the temperature of only a few broad layers of the atmosphere using the entire complement of SIRS-A channels. As a consequence, comparisons such as that shown in Fig. 6(a) wrongly misled the user into thinking that the sounding information was equivalent to that from the radiosonde and therefore could be used as such. Figure
6(b) shows clearly that the fine-scale vertical structure of satellite soundings is indeed unreliable; errors greater than 5 degC exist in the very same tropopause region retrieved so well at the same location three days earlier.

A major problem with the SIRS data was created by its large geographical field of view (~225 km square). We estimate that clouds interfered with the measurements more than 90% of the time. In order to account for the influence of cloud, a radiative correction to the measurement was calculated using a 'guess' temperature profile and the tropospheric radiances observations (Smith et al. 1970). The 'guess' profile was generated from statistical relationships with uncontaminated stratospheric-channel radiances. Although the procedure gave reasonable results for a single layer of cloud when the guess profile was close to the true profile, the cloudy-condition retrievals were in fact dangerously unreliable, and to a degree dependent on the cloud situation (Fig. 7).

![SIRS-A RMS Differentials with NMC Analysis](image)

**Figure 7.** Root-mean-square differences between SIRS-A soundings and the NMC analysis of radiosonde data for September 1969.

In spite of the poor vertical resolution and cloud contamination, the SIRS-A data immediately showed promise of benefitting the current weather analysis/forecast operation. As a result, SIRS-A was put into operational use in a guarded manner on 24 May 1969, barely one month after launch. In fact, the very first satellite-data numerical-forecast impact experiment was strongly positive. The case occurred on 24 June 1969 when the SIRS data over the Pacific Ocean (Fig. 8) revealed a cut-off low with an intense jet to the north replacing the diffusely defined trough of the forecast. Extended-range (72 h) forecasts based on analyses with SIRS, displayed maximum errors of the forecast over North America of only half the magnitude of those forecasts based on analyses without the use of the SIRS data. Unfortunately, further forecast impact tests by the United States National Meteorological Center and other numerical-prediction centres, produced negative as well as positive impacts of these data. Thus began the great debate as to whether or not these negative results were due to the deficiency of the data or to the analysis/forecast system which attempted to use them as radiosonde data. As we now understand, the issue was of no practical significance since both assertions contributed to the mixed results.
WITH SIRS DATA

WITHOUT SIRS DATA

500 MB ANALYSES JUNE 24, 1969

Figure 8. (a) Comparison of objective analyses of 500 mb height obtained with and without SIRS soundings. The differences in decametres are shown by the dashed isolines.

(b) Advances during the 70s

A series of successful NIMBUS experiments during the early 70s advanced satellite sounding instrumentation and sounding capability on several fronts. First, the SCR and PMR experiments of Oxford University (Houghton and Smith 1970; Barnett et al. 1972; Houghton 1975) pioneered the exploration of the upper atmosphere. The PMR eventually became the Stratospheric Sounding Unit (SSU) component of the TIROS Operational Vertical Sounder (TOVS) system operating today. Second, microwave instruments developed by the Massachusetts Institute of Technology (MIT) (Staelin et al. 1973, 1975) demonstrated a capability to sense atmospheric temperature within and below cloud. These experiments evolved into the Microwave Sounding Unit (MSU) component of the TOVS. Equally important, tropospheric infrared sounding instruments were developed with high spatial resolution (15 nautical miles) and a contiguous scan geometry in order to sample the clear-air interstices of a broken cloud cover (Smith et al. 1974, 1975). In addition, the spectral coverage of the tropospheric infrared sounder was expanded into the short wavelength 4.3 μm N₂O/CO₂ emission band in order to increase its sensitivity to lower tropospheric temperatures (Smith et al. 1975; Chahine 1974). The broad spectral coverage High-resolution Infrared Radiation Sounder (HIRS) which flew on the NIMBUS-6 in 1976 served as the prototype of that component of the TOVS, operational since 1978.
Figure 8. (b) Comparison of 72-hour 500 mb forecasts obtained from the initial conditions specified with and without SIRS data. The differences of each forecast with the observed 500 mb distribution are indicated in decametres by the dashed isolines.
Evolutionary changes in data processing procedures also took place during the 70s with major changes in the sounding retrieval algorithm often coinciding with an instrument change. When SIRS-B replaced the SIRS-A with the launch of the NIMBUS-4 satellite in 1970, a physical rather than a statistical retrieval algorithm was implemented in an attempt to eliminate erroneous vertical structure in retrievals not resolved by the measurements (Chahine 1968; Smith et al 1972). A 12-hour forecast was used as an initial profile which was perturbed a minimal amount in the retrieval process in order to satisfy the observed radiances through theoretical calculation. Although the apparent accuracy of the results was high, so also was the correlation of the error in the retrieval with the error in the forecast. This error correlation was due to the very same limitation noted previously for the statistical regression method, namely the lack of vertical resolution. In this case, there was a strong dependence of the vertical structure of the result on the vertical structure of the guess profile. Also, the use of the forecast guess for making cloud corrections to the data further biased the result. A question on retrieval philosophy emerged: namely, should a sounding intended for initializing a forecast model be retrieved from satellite radiances by a method which produces a retrieval error correlated with the forecast error it is intended to correct? The associated debate which dealt with the trade-off between retrieval accuracy and model-error correlation helped stimulate the use of the so-called 'optimum interpolation' objective analysis method (Gandin 1963) during the GWE as an attempt to deal with the correlated error properties of satellite-derived profiles. In any case, the physical (forecast guess) retrieval procedure was utilized throughout the 1970s for the routine processing of data from the SIRS-B on NIMBUS-4 and from the operational Vertical Temperature Profile Radiometer (VTPR) which flew on the Improved TIROS Operational Satellite (ITOS) series.

Also during the 70s, numerous satellite-data forecast impact experiments were conducted by various numerical prediction centres. The results, summarized by Ohring (1979), were disappointing for the northern hemisphere in the sense that the modest improvement of 48-hour forecasts was due to an average of forecasts with positive, negative, and no impact. In the southern hemisphere the results were more satisfying. Here the few impact studies conducted (Kelly 1977; Kelly et al. 1977) indicated consistent positive impact, particularly for the NIMBUS-6 satellite system which carried the prototypes of the advanced infrared and microwave sounding radiometers to fly during the Global Weather Experiment of 1979 (Fig. 9).

The lack of a consensus result for the various northern hemisphere impact experiments indicated that the impact of remote soundings was highly dependent upon the capability of the forecast model; the satellite sounding was more able to register a beneficial effect if the forecast it was attempting to improve was of poor quality. In spite of the inconclusive results of the 70s, the world meteorological community entered into the Global Weather Experiment with its objective to utilize a satellite-based global observing system to extend the range of atmospheric prediction to a week or more.

(c) The GWE era (1979–present)

The TIROS-N satellite, the first of the current series of operational polar-orbiting satellites, was launched into orbit on 13 October 1978, just prior to the initiation of the Global Weather Experiment. The second spacecraft in the series, NOAA-6, was launched into orbit on 27 June 1979, midway through the GWE year.

Figure 10 shows the temperature profile weighting functions for the various spectral channels of each of the three sounding instruments of the TIROS Operational Vertical Sounder (TOVS) (Smith et al. 1979), comprising: (1) the High-resolution Infrared Radiation Sounder (HIRS), (2) the Microwave Sounding Unit (MSU) and (3) the
Stratospheric Sounding Unit (SSU). The spatial resolution and scan geometry are different for each instrument, but it suffices to state that nearly complete coverage of sounding radiance data is achieved within a swath, 2250 km wide, below the spacecraft. The meteorological soundings which were produced globally by NESDIS using a statistical regression algorithm (Smith and Woolf 1976; McMillin et al. 1983) had a horizontal resolution and spacing of 250 km.

Also significant for TOVS data processing were the efforts of the International TOVS Working Group (ITWG) of the Radiation Commission of the IAMAP. Working through the ITWG, software for processing TOVS radiance data received by direct read-out was disseminated to weather service research centres throughout the world. The algorithms in the so-called 'International TOVS Processing Package (ITPP)' produced soundings with a spatial resolution of 75 km using either statistical regression or physical retrieval algorithms (Smith et al. 1983), the choice depending upon user preference. Several other high-quality processing systems for the TOVS were developed in the United Kingdom (Eyre 1984), France (Chedin et al. 1985) and Australia (Le Marshall et al. 1989).

Whether obtained from the global operational product or produced with the ITPP from direct read-out, the TOVS soundings were of sufficient quality and density to define synoptic-scale weather patterns unambiguously without the aid of conventional data. However, similar in nature to results from its operational and experimental predecessors, the TOVS sounding accuracy varied with cloudiness, being much poorer for overcast cloud conditions than for clear or partly cloudy conditions (Fig. 11). Fortunately for the TOVS, typically ten times as many relatively high-quality clear or partly cloudy soundings were achieved as compared to the lower-quality 'overcast' type of sounding. The reduced
Figure 10: Temperature profile weighting functions (normalized) for the TOVS HIRS, MSU and SSU sounding instruments.
accuracy of the 'overcast' retrievals is due to the limited number of tropospheric sounding microwave channels and their poor vertical resolution in the lower troposphere compared to their infrared counterparts (see Fig. 10).

The 'error' differences shown in Fig. 11 were again due mainly to the poor vertical resolution of the TOVS compared to that of the radiosondes. Consequently, much of the TOVS 'error' is a synoptic-scale bias. Because of the systematic nature of the error, errors in horizontal gradients are usually smaller, depending upon the depth of the atmospheric layer considered (Schlatter 1981).

Although r.m.s. differences of 2 to 3 degC may seem relatively small, a Gaussian distribution implies that differences from radiosonde observations as high as 10 degC do occur. Figure 12, from a discussion by Broderick et al. (1981), illustrates how such differences occur because of the limited vertical resolution of TOVS soundings. Shown are two NOAA-6 satellite soundings which are collocated with the Omaha, Nebraska and St. Cloud, Minnesota radiosonde soundings. These two comparisons between soundings also illustrate graphically the fact that horizontal gradients tend to be weakened through inadequate vertical resolution. The base of an upper-level front can be seen in the radiosonde soundings to be sloping from near 600 mb at Omaha up to 475 mb at St. Cloud. The surface inversion at Omaha is probably evidence of the slightly cooler and drier airmass, although it is difficult to distinguish it from a normal nocturnal inversion. At St. Cloud, this cooler airmass may be associated with the slightly stable layer just above 700 mb up to 570 mb. The intrusion of Arctic air is revealed by the lower stable portion of the radiosonde profile. At Omaha, the NOAA-6 retrieval is clearly somewhat warmer in the lower portion of the troposphere up to the upper frontal inversion and then colder above, up to nearly 300 mb. This structure shows how the satellite sounding depicts a more nearly vertical frontal zone by being warmer in the cold air below the frontal surface and colder above. The retrieval profile is definitely warmer than the radiosonde observation in the tropopause region. Near St. Cloud, the satellite retrieval, being deeper into the colder air than at Omaha, agrees with the radiosonde sounding up.
Figure 12. Comparison of NOAA-6 and radiosonde soundings at two adjacent stations on 6 May 1980.

to just above 500 mb. Above this level, up to 300 mb, the retrieval is colder with, once again, the warmer tropopause region above 300 mb. This set of retrieval comparisons shows how significant vertical temperature gradients tend to be underestimated because of the deficient vertical resolution of the TOVS sounding system. The deficient vertical resolution is responsible for both the large absolute differences with the radiosonde measurement and the reduced horizontal variance and strong horizontal error correlation of the satellite profiles as noted by Phillips (1980), Phillips et al. (1979), Koehler et al. (1983) and Schlatter (1981). The occasional large absolute temperature error and the general tendency for TOVS soundings to underestimate vertical lapse rates and horizontal gradients both serve to impair the otherwise expected large beneficial impact of these data on the numerical weather analysis/forecast operation.

Major operational forecast centres (e.g. the European Centre for Medium Range Weather Forecasts, ECMWF, and the United States National Meteorological Center, NMC), and numerical modelling research laboratories (e.g., the NASA Goddard Laboratory for Atmospheric Sciences, GLAS, and the NOAA Geophysical Fluid Dynamics Laboratory, GFDL) have investigated the impact of the TOVS data on numerical forecasts. For example, Fig. 13 taken from an ECMWF study (Uppala et al. 1984) shows the difference between an anomaly pattern correlation coefficient for forecasts conducted with and without TOVS soundings during November 1979. The coefficient describes the correlation between two difference fields: the departure of the forecast from a model-climate monthly-mean state, and the departure of the verifying analysis from the same climate monthly-mean state. The curve C represents forecasts based upon the conventional observing system (surface observations, radiosonde observations, and aircraft wind observations); the curve S represents forecasts for the total global observing system including satellite temperature soundings. As can be seen in this case, the satellite data contribute to increased forecast accuracy. Using 0.6 as an anomaly coefficient criterion for useful forecasts, one sees that the range of useful prediction was extended from 5.5
to 7 days in the northern hemisphere, and from 3.5 to 5 days in the southern hemisphere.

Other forecast impact experiments conducted with the GWE global data-set have shown smaller impact for the northern hemisphere, but consistent relatively large impacts of the satellite data on the southern hemisphere forecasts. Figure 14 shows results achieved by a GLAS study (Kalnay et al. 1985) where the number of skilful forecasts is simply a count of how many times one of the observing systems, the GWE (FGGE) or that which excluded satellite data (NOSAT), led to better forecasts than did the other. (The two forecasts were considered to differ if their S1 skill scores differed by more than two points, the S1 skill score being a measure of the accuracy of the forecast gradient of geopotential between model gridpoints—Teweles and Wobus 1954.) As can be seen, the relative value of the satellite data generally tended to be modest and to increase with the length of the forecast in the northern hemisphere and to be consistently large in the southern hemisphere. A more recent GWE observing system experiment has been conducted by the Japanese Meteorological Agency (JMA) using their global analysis/forecast system (Kashiwagi 1987) to produce 5-day forecasts. The study concluded “the space-based data are indispensable for the analyses in low latitudes and the southern hemisphere. Even in the northern hemisphere, satellite data improve the analysis over the Pacific region and thereby improve the forecast over North America downstream from that region. On the other hand, satellite data have little impact on the forecast around east Asia because sonde data basically determine the quality of the analysis upstream from that region.”

Figure 14. Number of cases of positive and negative forecast impact of GWE (FGGE) observing system during the period 5 January–5 March 1979 (Kalnay et al. 1985).
(d) Subjective use of the data

A much more distinct view of the utility of satellite soundings for forecasting arises from their use in a subjective manner. Images of satellite sounding radiances or derived sounding products have proved to be an effective forecasting tool. The most notable example is the routine use of 6.7 μm water vapour radiance imagery from the United States and European geostationary satellites (Fig. 15).

In the United States, the GOES VISSR Atmospheric Sounder (VAS) launched into orbit on 9 September 1980, began a new era during which the dynamics of temperature and moisture features of the atmosphere could be observed (Suomi et al. 1971; Smith et al. 1981; Chesters et al. 1983; Hayden 1988). The VAS radiometer is capable of observing the radiation to space in sounding spectral intervals similar to the HIRS component of the TOVS, but with nine times higher spatial resolution (8 km versus 25 km linear resolution). The higher spatial resolution, coupled with the ability to make frequent (e.g. every half-hour) observations of the same geographical area from geostationary altitude, make it a potentially useful tool for observing the short-term fine-scale features of atmospheric moisture and temperature associated with convective weather.

Figure 16 shows an example of the VAS ability to diagnose the changing thermodynamic behaviour (Smith et al. 1985) of the atmosphere antecedent to severe convective weather. Here, the instability of the atmosphere (represented by the lifted index) is shown in the false-colour portions of pictures, whereas the clouds, detected by infrared imagery, are shown in white or grey portions at three different times on 14 May 1984. The red areas denote very unstable cloudless air, where severe thunderstorms with damaging winds and hail developed later in the day. This type of ‘sounding imagery’ is now produced routinely by NOAA for daily operational use by its National Severe Storms Forecast Center in the preparation of outlooks for convective weather. However, because clouds often prohibit the sounding of the lower troposphere with the VAS infrared sounder, this product is used to supplement a more complete, but presumably less accurate, stability depiction achieved with hourly surface observations and forecast upper-air data.
Figure 16. (a) Severe weather reports (H, hail; W, damaging wind) from 1900 to 0100 hours GMT. (b–d) Time sequence of VAS total–total stability and cloud imagery with contour of spatially-averaged values for the south-eastern United States on 14 May 1984 at: (b) 1300, (c) 1400, and (d) 1700 GMT.
A major limitation of the use of VAS for mesoscale weather forecasting results again from limited vertical resolution. This precludes the detection of the very abrupt vertical changes in atmospheric temperature and moisture associated with the convective storm environment. Nevertheless, since convective storms often develop in destabilizing cloudless air, time sequences of the VAS 8 km resolution sounding imagery revealing the destabilization trend have proved to be useful.

One other well-documented forecasting use of the geostationary satellite sounder (VAS) is the prognosis of tropical cyclone motion (Velden et al. 1984). Although the simple extrapolation of a cloud system centre using geostationary satellite motion pictures has long been a useful forecast tool, the VAS permits the direct observation of the environmental circulation which steers the storm. This environmental circulation is defined from the motion of clouds and water vapour in the periphery of the storm.

It is now routine practice to use cloud displacement winds, upper tropospheric water vapour tracers, and winds estimated from satellite-observed temperature gradients to form a deep-layer (850–200 mb) mean ‘steering current’ to estimate tropical storm motion. As an example, Fig. 17 shows streamlines of the deep-layer mean wind for hurricane Alicia along with 12-hour increments of future storm positions forecast from the deep-layer mean circulation, assuming steady-state motion. The actual positions observed by aircraft are also shown. As can be seen, good estimates of the wind field surrounding a tropical storm, as achievable from a geostationary satellite, can provide accurate forecasts of the storm position at landfall.

A series of data impact tests have been conducted by the National Hurricane Research Laboratory (Velden and Goldenberg 1987) using an operational barotropic model initialized with different deep-layer mean-wind analyses. The results show a consistent 10–15% improvement in the 12–72-hour forecast of storm position using the

![Figure 17. Streamlines of GOES-VAS-derived deep-layer mean wind from 16 August 1983 (1200 GMT) with current and subsequent 12-hour positions of hurricane Alicia’s eye (filled squares) plotted together with the forecast ‘VASTRA’ positions (open squares).]
VAS enhanced wind set. It is reasonable to hope that a more effective use of the VAS cloud motion, water vapour motion, and temperature profile data used for wind estimates might be their direct input to a more complete primitive-equation forecast model for predicting tropical storm behaviour.

A major limitation of the VAS for diagnosing the deep-layer mean environmental circulation of tropical storms is that it has only two water vapour channels and these are limited to the sensing of the upper tropical troposphere. The replacement to VAS for the next series of GOES satellites beginning in 1992 will have one additional water vapour channel for seeing deeper into tropical air. This will partially alleviate the vertical sampling problem. As will be discussed below, however, it is now technologically possible to observe the water vapour within numerous distinct vertical layers (e.g. six to ten) using a high spectral resolution interferometer. If this capability were implemented on a geostationary satellite, tropical wind profiles could be constructed from water vapour tracers within these vertical layers. The resulting wind soundings could have enormous impact on defining the tropical circulation for initializing forecast models.

3. THE FORECAST IMPACT PROBLEM

Figure 18, provided by B. Norris of the ECMWF, shows that after the GWE was initiated in 1979, there was a steady improvement in the time extent of a skillful forecast until 1986 (as judged by that period where the anomaly correlation remained above 60%). Since then, the upward trend has ceased. The apparent termination of the upward trend is alarming and is believed to be due to the limitation of the global data-base, particularly the satellite sounding component.

Beginning with the GWE and continuing through the 80s to the present day the operational satellite sounding system has consisted of the TOVS temperature and humidity soundings from the NOAA polar orbiters. There has been no significant improvement in either the sounding technology or the data processing methods during this period. The upward trend during the early 80s was due in large part to the drastic improvements in satellite data assimilation methods, model resolution and physics, and numerical procedures; these improvements resulted from the intense research efforts made to optimize the use of the global data-base in order to achieve the GWE objective. As reported in the proceedings of an important workshop on this subject (Hollingsworth and Szejwach 1989) just one year ago, “the modelling and data assimilation developments which were not accompanied by developments in observing or retrieval methods have therefore tended to reduce the information content of the satellite data relative to other information sources”. Because no improved operational satellite sounding technology is planned to be implemented until the end of this decade, the retardation of significant advancement in NWP skill might be expected to continue into the next century.

4. FUTURE PROSPECTS

(a) Requirements

Because of the apparently decreasing utility of satellite soundings due to improved forecast models, it is important to reassess the requirements of future satellite sounding systems in view of current and planned forecast model characteristics. For the GWE era, these requirements were based on Observing System Simulation Experiments (OSSE) in which the numerical model was used to synthesize the ‘observations’. Errors were added and the impact of these observation errors on model forecast skill was evaluated.
Figure 18. Forecast extent to which the anomaly correlation remained above 60 per cent: (a) northern hemisphere; (b) southern hemisphere. Solid line represents a 12-month running mean of the monthly values shown by the dashed curve.

Such experiments using modern-day models to simulate the observations and study their impact on forecasts would certainly be helpful for defining the measurement requirements of future systems.

A first-order estimate of the vertical resolution and accuracy requirements of the temperature sounder can be obtained through a simple analysis of the thermal-wind equation. Here the temperature accuracy, at a given vertical resolution, required to
Figure 19. Wind error relative to temperature retrieval error as a function of horizontal to vertical aspect ratio. Aspect ratio is defined as the ratio of the horizontal spacing of the wind data to the vertical resolution of the temperature sounding retrieval.

impact the wind field is calculated as a function of the model's horizontal resolution and latitude. Figure 19 shows the result. For example, in the case of the global extended-range prediction model capable of predicting wind velocity with 4 m s\(^{-1}\) accuracy at a horizontal resolution of 400 km, the accuracy of a temperature sounder with 2 km vertical resolution (i.e. a model horizontal resolution to temperature-sounder vertical resolution aspect ratio of 200), would need to be 2 degC for useful application at temperate latitudes (45 degrees latitude). At the mesoscale extreme, one might consider the network of wind profilers being implemented in the United States to define the temperature sounding requirements. The profiles are to be spaced approximately 300 km apart. The wind measurements from this system will be, at worst, hourly with 1–2 m s\(^{-1}\) accuracy for a 1 km vertical resolution. Assuming a temperature sounder vertical resolution of 1 km (i.e. an aspect ratio of 300), the relative wind accuracy is 1 to 2 m s\(^{-1}\) K\(^{-1}\) for the 30–70 degree latitude zone. Thus, in this case, the complementary temperature sounder must be geostationary in order to achieve the hourly measurement frequency and would need to achieve 1 degC accuracy with 1 km vertical resolution for meteorological consistency with the wind data. Note that poorer temperature sounding vertical resolution coupled with higher accuracy can also satisfy the requirement. For example, if the sounder possesses 2 km vertical resolution (i.e. an aspect ratio of 150), then 0.5 degC accuracy is required at middle latitudes to achieve the same meteorological consistency with the profiler wind observations.

For the tropics, the weak coupling between temperature and wind imposes requirements on the temperature sounder which are too severe to be met with practical technology. Here the emphasis should be on providing wind profiles directly, possibly by tracking the movements of water vapour retrieved for six or more vertical layers.

(b) Available technology

Poor vertical resolution is the primary source of error which limits the utility of current satellite soundings for the weather analysis/forecast operation. In cloud-free or
partly cloudy areas, the vertical profiles from the current TOVS system benefit from the combination of infrared and microwave radiance observations. However, because of the low spectral resolution of the infrared measurements ($\lambda/\Delta\lambda \approx 50$) and the limited number of microwave observations (only four with the MSU), the vertical resolution is severely limited. In cloudy overcast areas the situation is worse, since the profiles below cloud are currently defined from only one or at best two MSU microwave channels which sense radiation from below cloud level.

Beginning in 1993, some improvement in the vertical resolution and accuracy in cloudy situations of the temperature profile is expected with the implementation of the Advanced Microwave Sounding Unit (AMSU) on the NOAA-K series of operational satellites. The AMSU will consist of twelve temperature sounding channels as opposed to four for the MSU, although only six AMSU channels sense the troposphere. A more significant contribution of the AMSU is expected to be realized in the water vapour profile retrieval, since the AMSU possesses four high-resolution channels for observing tropospheric water vapour radiance. Also, the spatial resolution of the AMSU is significantly higher than that of the MSU (50 km as opposed to 110 km in linear resolution for the oxygen emission channels), and this will provide a much greater density of atmospheric soundings than is possible with the current system, particularly under cloudy-sky conditions.

Unfortunately, the AMSU alone is not expected to satisfy the requirements of 1 km vertical resolution and 1 degC accuracy of contemporary and future NWP models. In addition to the AMSU, a much improved infrared sounding instrument is needed.

Theoretical and aircraft experimental studies conducted during the past few years show that one can approach the 1 degC per 1 km vertical resolution required with an infrared sounding instrument which achieves nearly contiguous spectral coverage throughout the 4–15 $\mu$m region. The spectral resolution ($\lambda/\Delta\lambda$) required is of the order of 1000, compared with the spectral resolution of 50 characteristic of current infrared sounding instruments (Smith et al. 1990a). The high spectral resolution is needed to isolate the high-altitude radiance contributions, coming from relatively opaque absorption line centres, from the low-altitude radiance contributions coming from the relatively transparent regions between absorption lines (Kaplan et al. 1977). Since absorption lines have an average spacing of about 1.5 cm$^{-1}$, considerable vertical smearing results with current instruments, which possess a nominal spectral resolution of 10–20 cm$^{-1}$. Contiguous spectral coverage between 4 and 15 $\mu$m with a spectral resolution of 1000 yields about 2000 spectrally independent measurements. This can be compared to the 20 or so characteristic of today’s instruments (i.e. the TOVS). Possessing 200 times as many spectral channels serves to strengthen the vertical coverage and reduce the effects of measurement noise by a factor of ten or more. The much higher vertical resolution and larger number of spectral channels both contribute to a significant improvement in vertical resolution and accuracy.

Although the required spectral coverage and resolution are beyond the capabilities of filter radiometers now flown on satellites, they can be achieved using new detector technology in the form of a Michelson interferometer or a grating spectrometer. It is interesting to note that the first atmospheric sounding instruments, IRIS and SIRS, flown in 1969 were Michelson interferometers and grating spectrometers, respectively.

Figure 20 shows the results of a theoretical analysis of vertical resolution and r.m.s. sounding error for the spectral characteristics of three sounding instrument systems: (1) the first sounder, SIRS-A, (2) the current operational system, TOVS, and (3) the University of Wisconsin High spectral resolution Interferometer Sounder (HIS) flown on the NASA ER2 aircraft. The HIS, an airborne prototype of future satellite sounding
interferometers, achieves the same performance as is planned for the Advanced Infrared Radiation Sounder (AIRS) being built for flight on the NASA Polar Platform (Chahine 1990). As can be seen from Fig. 20, the HIS/AIRS type of measurements represent a very significant improvement in vertical resolution and accuracy over that obtained with today’s operational TOVS system.

Possibly the most important meteorological advantage of future quasi-continuous high spectral resolution sounders is their capability of observing the fine-scale moisture structure of the atmosphere. To demonstrate this, Fig. 21 shows the weighting functions for the water vapour absorption channels of, (a) the HIS and (b) the TOVS sounding instruments. It can be seen that with TOVS, there are only three broad layers of moisture being sensed, whereas with the HIS there are about a dozen narrower layers being resolved. The significance of the greatly improved moisture resolution is twofold: (1) the improved definition of the stability characteristics of the atmosphere responsible for vertical motion, convection, and precipitation processes, and (2) from a geostationary satellite, moisture tracking within numerous distinct vertical layers could provide information about vertical wind profiles difficult to achieve from geostationary satellites in any other way.
(c) Experimental results

Experimental high-resolution spectral radiance data have been obtained with the airborne HIS interferometer during field programmes conducted during 1986. Results from these experiments verify that improved sounding capability is achieved with high spectral resolution measurements. An example of comparisons of a HIS and a VAS sounding retrieval with a radiosonde sounding are shown in Fig. 22. The improved capability of the HIS in resolving vertical structure in the temperature and moisture profiles is striking. (Part of the discrepancy between the water vapour profiles of the HIS and the radiosonde soundings is most likely due to the slightly different times and locations of the two measurements.)

The capability of the HIS in resolving numerous vertical layers of tropospheric moisture, as needed for wind profiling, is shown in Fig. 23. Shown is a vertical cross-section of dewpoint depression profiles spaced 2 km apart, retrieved from HIS spectra along the flight track of the ER2. The entire area sampled was free of clouds at the time of the HIS observations. The cross-section provides a vivid display of the ability to deduce the moisture characteristics of the atmosphere with the fine detail needed for
determinations of convective stability or for determining wind profiles through moisture tracking.

Finally, Fig. 24 shows, for two aircraft flight days, the error of HIS retrievals (Bradshaw and Fuelberg 1990). Comparison of the results of Fig. 24 with those of Fig. 20 demonstrates the experimental validation of the theoretical expectation of improved sounding performance.

(d) Beyond HIS/AIRS

Still further improvement in temperature and water vapour profiling accuracy can be achieved by incorporating the technology of active laser remote sensing with the HIS/
Figure 23. (a) Flight track of the NASA ER2 aircraft over northern Alabama and Tennessee on 19 June 1986. The times of various aircraft positions are denoted in hours, minutes, and seconds of central daylight time. (b) Vertical/time cross-section of atmospheric temperature (dashed) and dewpoint depression (solid) beneath the ER2 flight track as retrieved from HIS radiance spectra.
AIRS type of passive infrared spectral measurements. The very high vertical resolution water vapour emission measurements of the HIS/AIRS (Fig. 21) are used for temperature profiling, assuming that the water vapour profile is known with high accuracy and high vertical resolution from simultaneous measurements by the Differential Absorption Lidar (DIAL) (Curran 1987). In this case, the vertical resolution and accuracy of the temperature profile near the surface would be better than 1 km and 1 degC (Smith et al. 1990b)—the anticipated requirements of global soundings for NWP during the next century.

5. CONCLUSION

Thus far, the impact of atmospheric sounding from satellites on numerical weather forecasting has been somewhat disappointing, particularly in the northern hemisphere. During the 70s, the lack of consistent positive impact was due both to the poor reliability of the data, particularly in cloudy regions, and to the improper use of the profiles as if they were from inaccurate radiosondes.

During the early 80s, the situation improved because the sounding retrievals were more reliable—a result of improved operational satellite instrumentation implemented just prior to the GWE. Improved methods of data assimilation due to the unique volume sampling characteristics of the satellite soundings also contributed to the achievement of positive impact. During the past decade, when there has been a significant improvement in forecast skill due to model improvement, the technology of satellite observation has remained stagnant. This fact appears to be responsible for a reduction in the relative importance of the satellite data. I believe that the deficiency of the current satellite data relative to those of the improved model forecast is due to the poor vertical resolution of the retrieved soundings. It now appears that further improvements in forecast skill must await the implementation of instruments with higher spectral and vertical resolution on polar orbiting satellites planned for near the end of this century. The implementation of
the technology of higher vertical resolution from geostationary satellites should permit
the deduction of wind profiles through the tracing of the moisture displacement within
numerous distinct vertical layers. The application of the technology of higher vertical
resolution satellite sounding could potentially benefit numerical weather prediction
through a much improved initial wind field, particularly in the tropics. Regrettably, the
implementation of this may have to wait until the next century.

Beyond the improvement in passive infrared sensing, active lidars which can sense
the water vapour profile with very high vertical resolution might be used with high
spectral resolution water vapour radiances to provide a vertical temperature profile
resolution and accuracy even closer to that of the radiosonde.

In conclusion, I retain the belief that atmospheric soundings from satellites are the
key to improved weather forecasts. Unfortunately, it appears that further improvements,
using modern-day models, must wait for the implementation of higher vertical resolution
sensors at the end of the century. Can we change this?

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to recognize several of the ‘pioneers’ of the satellite sounding technology:

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(3) Dr John Houghton for pioneering the probing of the upper atmosphere from
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(4) Professor David Staelin for pioneering the important development of the micro-
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(6) Dr John Gille for implementing the ‘limb sounding’ technique used for sensing
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If it were not for the innovations and perseverance of these individuals, the subject
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