# APPLICATION OF GOES-8/9 SOUNDINGS TO WEATHER FORECASTING AND NOWCASTING

W. Paul Menzel<sup>1</sup>, Frances C. Holt<sup>1</sup>, Timothy J. Schmit<sup>1</sup>, Robert M. Aune<sup>1</sup>,

Anthony J. Schreiner<sup>2</sup>, Gary. S Wade<sup>1</sup>, and Donald G. Gray<sup>1</sup>

<sup>1</sup>Atmospheric Research and Applications Division Office of Research and Applications, NOAA/NESDIS

<sup>2</sup>Cooperative Institute for Meteorological Satellite Studies University of Wisconsin - Madison

Corresponding author address:

W. Paul Menzel, NOAA/NESDIS, 1225 W. Dayton St., Madison, WI 53706

email: paulm@ssec.wisc.edu

## ABSTRACT

Since April 1994 a new generation of geostationary sounders has been measuring atmospheric radiances in eighteen infrared spectral bands and thus providing the capability for investigating oceanographic and meteorological phenomena that far exceed those available from the previous generation of Geostationary Operational Environmental Satellites (GOES). Menzel and Purdom (1994) foreshadowed many of the anticipated improvements from the GOES-8/9 sounders. This article presents some of the realizations; it details the inflight performance of the sounder, presents both validated operational as well as routinely available experimental products, and shows impact on nowcasting and forecasting activities.

For the first time operational hourly sounding products over North America and adjacent oceans are now possible with the GOES-8/9 sounders. The GOES-8/9 sounders are making significant contributions by depicting moisture changes for numerical weather prediction (NWP) models over the continental United States, monitoring winds over oceans, and supplementing the National Weather Service's (NWS) Automated Surface Observing System (ASOS) with upper level cloud information. Validation of many sounding products has been accomplished by comparison with radiosondes and aircraft measurements. Considerable progress has been made toward assimilation of soundings from clear skies and cloud properties in cloudy regions in operational as well as research forecast models; GOES-8/9 moisture soundings are now being used in the operational Eta regional forecast model.

# 1. Introduction

#### a. Role of the Geostationary Sounder

The new Geostationary Operational Environmental Satellites (GOES) system significantly advances the United States atmospheric sounding capability. GOES-8/9 sounders on board the three axis stabilized spacecraft are more efficient in gathering data and have a much improved signal to noise ratio over the previous GOES Visible and Infrared Spin Scan Radiometer Atmospheric Sounder (VAS). The dedicated 19 spectral band sounders enable more frequent and more accurate thermodynamic soundings over North America and the adjacent oceans. In the infrared region, longwave carbon dioxide (CO2) sensitive bands define cloud heights and amounts and enable clear sky temperature profile retrievals; midwave water vapor (H2O) sensitive bands improve the depiction of vertical and horizontal gradients of moisture; shortwave CO2 sensitive bands enhance boundary layer investigations; and split windows provide atmosphere corrected views of the earth surface.

The role of the geostationary sounders is to a) provide simultaneous hourly observations over extended regions, especially measurements over data poor oceans; b) complement the twice daily international suite of balloons by filling in space and time gaps; c) depict rapid changes in regional temperature, water vapor, and cloud cover for nowcasting severe weather; and d) infer wind profiles by detecting thermal gradients and tracking H2O features which are particularly useful for aviation and tropical storm forecasts. Near continuous monitoring from geostationary orbit enhances the likelihood of clear sky observation of the total atmospheric column for a given location.

The improved capabilities of the GOES-8/9 sounders have a growing number of practical applications which are listed here; most of these will be discussed in more detail later in this article. Sounder data has improved monitoring of:

\* hourly temperature and moisture changes over the eastern Pacific, the Gulf of Mexico, and the western Atlantic Oceans that are critical for numerical weather prediction in North America and for local aviation and marine forecasts;

\* cloud cover that is supplementing the Automated Surface Observing System (ASOS) with accurate delineation of clouds above 12,000 feet (4 km); this is very important to aviation and weather outlooks;

\* atmospheric stability and boundary layer thermodynamics that is proving useful for nowcasting in weather service forecast offices and improved severe weather watch box determination;

\* atmospheric changes conducive to microbursts and precipitation, allowing better depiction of areas where heavy rains are likely;

\* mid tropospheric motions by tracking water vapor features and calculating thermal gradient winds that are important for hurricane trajectory forecasts; and

\* ozone (O3) fields so that diurnal, seasonal, and annual changes in total ozone content can be inferred.

#### b. GOES-8/9 Sounder Performance

The GOES-8/9 sounders measure radiances from 8 km footprints (with a spacing of ten km) in one visible and eighteen infrared spectral bands, many of them sensitive to atmospheric CO2, O3, and H2O (Menzel and Purdom 1994). Figure 1 indicates the regions of the spectrum

that are measured by the GOES sounders from 3.7 to 14.7 micrometers compared to an Earth emitted spectra (measured by the High resolution Interferometer Sounder (HIS) flying at 20 km (Revercomb et al. 1988)). The GOES window bands are located in spectral regions where the atmosphere is relatively transparent; the GOES sounding bands are selected so that the atmosphere becomes progressively more opaque from one spectral band to the next. As the atmosphere becomes more opaque, the sensed signal comes from higher up in the atmosphere. Figure 2 shows the radiances measured by four of the sounder CO2 sensitive bands from 1800 UTC 18 March 1997; the sounder sees progressively deeper into the troposphere as the spectral band wavelength moves further from the CO2 absorption band center at 15 microns. Thus, the sounder spectral bands probe the atmosphere at different depths enabling measurement of vertical variations of temperature, moisture, and ozone. Figure 3 shows the weighting functions of the sounder spectral bands; the weighting function is an indication of the layer of the atmosphere contributing the most energy to the satellite sensor in a spectral band for a given atmospheric condition. The longwave (midwave) bands show promise for discerning three layers of tropospheric temperature (moisture). The shortwave bands are very sensitive to boundary layer temperatures. The midwave band weighting functions depend strongly on the water vapor content of the troposphere and thus fluctuate in height from region to region.

The GOES-8/9 sounders are exceeding their specified radiometric noise requirements in the shortwave and midwave bands, but they are below requirements in the longwave bands. Good separation of signal from noise is critical for profile retrieval. Table 1 shows the GOES-8/9 sounder signal to noise performance compared to GOES-7 VAS and the NOAA-12 High resolution Infrared Radiation Sounder (HIRS). In the longwave bands, GOES-9 noise equivalent

temperatures (NEDT) range from 0.1 to 0.8 C as the wavelength increases and the weighting functions peak higher in the atmosphere; in the midwave and shortwave bands noise equivalent temperatures are almost all less than 0.1 C. GOES-8/9 are performing better than the previous GOES-VAS in all spectral bands, especially in the midwave or water vapor sensitive bands. GOES-8/9 are measuring water vapor radiances with the best signal to noise ratio ever, even 2 to 8 times better than that measured from the HIRS on the NOAA polar orbiters.

Calibration is accomplished using space looks (every 2 minutes) and blackbody looks (every 20 minutes) with random drifts in the sounder's infrared signal suppressed by frequent looks at the filter wheel housing (performing the function of beam chopping). The calibration algorithm and postlaunch enhancements are found in Weinreb et al. (1997). Validation of the GOES-8 sounder radiances was accomplished in January 1995 through comparison with radiances measured by the HIS, an interferometer of proven calibration, in high altitude flights on a NASA ER-2 aircraft over uniform sea surface temperatures (Smith et al. 1996). After corrections for sensor altitude and viewing angle, the HIS radiances were integrated over the spectral response functions of the GOES sounder bands. Table 2 shows the resulting brightness temperature differences. GOES-8 sounder ozone band 9 was omitted from the analysis because most of the total ozone burden is above the ER-2 flight altitude, and hence no meaningful comparison can be made. The GOES-8 sounder shortwave infrared band results do not include the effects of aerosols, the water vapor continuum contribution, and reflected solar radiation. It can be seen that most of GOES-8 sounder bands exhibit brightness temperature differences of less than 1.0 K, meeting the design specification for absolute accuracy of 1.0 K. These GOES-8 comparisons with HIS data included correction for the sounder scan mirror emissivity variations as a function

of viewing angle, which produce a bias of up to 1.0 K for some spectral bands between west and east space views. This bias was removed operationally from the sounder spectral band calibration in June (April) 1996 for GOES-8 (9) (Weinreb 1996).

The GOES-8/9 sounder pointing accuracy requirements are not as stringent as those of the imager, but are being met by the same high precision methods used with the imager (Kelly et al. 1996). Navigation of sounder images has been found to be better than 3 km. Band-to-band registration has been difficult to achieve in the GOES-8/9 sounder's multi-beam design; however, it is better than 2 km (25% of one field of view (FOV)).

## 2. GOES sounding products

# a. Soundings

There are several GOES products that come under the category of soundings. In clear sky conditions, they include the clear FOV brightness temperatures and the retrieved temperature and moisture profiles, as well as the associated layer mean values, stability indices, and thermal wind profiles. In cloudy skies, sounder products consist of cloud top height and cloud amount.

In July 1995, the National Environmental Satellite, Data, and Information Service (NESDIS) began producing operational hourly GOES-8 temperature and moisture soundings over the continental United States, the western Atlantic Ocean, and the Gulf of Mexico. Hourly GOES-9 soundings over the eastern Pacific Ocean and the western United States were added in February 1996. Typical sounder coverage is shown in Figure 4a in a combined GOES-8/9 water vapor 7.0 micrometer image from 1800 UTC on 18 March 1997 (GOES-8 and -9 sounders require about one hour to measure radiances from the indicated segments). Retrieval coverage is

shown in Figure 4b in the corresponding infrared window 11.0 micrometer image; small white squares are superimposed to represent the locations of GOES-8/9 profile retrievals. Retrievals in clear regions typically have a separation of about 50 kilometers, depending on cloud cover. Between 2000 and 3000 retrievals are made each hour. This should be compared with the radiosonde coverage (Figure 4c) of about one or two balloon launches per state every twelve hours or the polar orbiter sounding coverage at 100 kilometer resolution four times per day (including some soundings in cloudy regions). The two GOES sounders provide 24 times the number of soundings over North America that are available from polar orbiters and 150 times those available from radiosondes. They are well positioned to fill in the observing system gaps in space and time.

Clear sky vertical profiles from sounder radiance measurements are produced every 50 kilometers in the horizontal. Atmospheric temperature and moisture (including surface skin temperature) are determined at 40 pressure levels from 1000 to 0.1 hPa using a simultaneous physical algorithm (Smith 1983; Hayden 1988; Ma et al. 1998). Also, estimates of surface temperature and cloud pressure and amount are obtained as by-products. Figure 5 shows a flow chart of the sounder processing system. The processing involves several steps: a) identify clear versus cloudy FOVs by intercomparing brightness temperatures in adjacent CO2 bands and comparing the window band to surface observations (Hayden et al. 1998); b) establish a first guess by performing radiative transfer calculations using a National Centers for Environmental Prediction (NCEP) numerical model forecast (6 to 18 hour) and surface observations as boundary conditions; c) average radiances for the clear sky FOVs within a 5 x 5 FOV sounding area (approximately 50 km on one side) and apply a radiance bias adjustment; d) perform a

simultaneous physical retrieval of temperature and moisture profile deviations from the first guess for clear FOVs and assign retrieval location to the mean position of the clear FOVs ;and e) determine cloud top properties for all cloudy FOVs.

Figure 6 shows a typical comparison of a GOES profile retrieval with an Omaha, NE radiosonde measurement for 1200 UTC on 2 July 1997. The GOES retrieval has less detail but captures the vertical profile in the mean very well. The radiosonde indicates a low level temperature inversion that eludes the GOES retrieval; this sometimes compromises the ability of GOES to detect incipient convection. The GOES dewpoint temperature profile is drier than that of the radiosonde (the total column precipitable water vapor is 2 mm less), but typically the GOES moisture retrievals indicate more moisture by approximately 1 mm.

The comparison of GOES retrievals to radiosonde measurements is not ideal due to differing measurement characteristics (point versus volumetric), co-location errors (matches are restricted to 0.25 degrees), time differences (within one hour), and radiosonde errors (Pratt 1985; Schmidlin 1988). However, it has become the standard approach for GOES sounding validation. A study of the GOES retrievals for eleven months (April 1996 to February 1997) indicates that they are more accurate than the NCEP short-term, regional forecasts, for both temperature and moisture, even in the vicinity of the radiosonde where they must necessarily be verified (Schmit 1996). These temperature comparison results at individual levels are graphed in Figure 7a. Bias and root mean square (RMS) of 1488 comparisons with respect to radiosondes are shown for both the retrieval and the forecast. The retrieval RMS differences from 1000 to 200 hPa are only slightly, though consistently, better than the forecast values. In general, the retrieval does not significantly change the temperature profiles of the forecast guess, due to the high quality of the

forecast over the United States. Changes to the bias are also small. Corresponding RMS differences for moisture at individual levels are shown in Figure 7b. The improvements to the moisture profile are more substantial than those to temperature; there is skill in differentiating the vertical distribution of moisture. For dewpoint temperature, RMS is reduced for all levels, by as much as 1 K at 500 hPa. The bias is reduced by up to 0.3 K between 960 and 650 hPa.

Since the GOES sounder measures moisture content over broad layers in the troposphere, it is more meaningful to compare layer mean and total column values rather than single level values (see Table 3). The total column water vapor RMS difference with respect to radiosondes for this eleven month period in 1996-97 has been reduced from 3.3 mm for the forecast first guess to 2.6 mm for the GOES retrievals, roughly an improvement of 20%. It is found that GOES is drier than the radiosonde in the mean by 0.7 mm in the lowest layer (surface to 900 hPa) and more moist in the mean by 0.3 mm in the middle (900 to 700 hPa) as well as the upper (700 to 300 hPa) layers; GOES improves upon the model first guess in all layers in the RMS difference by 0.1 to 0.4 mm.

The atmospheric stability inferred from these eleven months of profiles has also been evaluated. GOES lifted indices (LI) of air parcels elevated to 500 hPa are found to be less stable in the mean by 0.6 C from those inferred from radiosondes with a RMS difference of 2.2 C. The numerical model first guess is 0.4 C less stable in the mean and shows an RMS difference of 2.4 C with respect to radiosonde determinations. In the vicinity of radiosondes, the GOES depiction of atmospheric stability is improving upon the first guess information from the forecast model.

More significant is the fact that much larger differences (greater than 100%) between GOES soundings and model forecasts often occur over oceanic regions where radiosondes are

unavailable; this indicates a much larger potential for GOES soundings to influence the forecast model in data sparse regions. Figure 8a shows the difference of the GOES sounder total precipitable water vapor field minus that inferred from the Nested Grid Model (NGM) at 1200 UTC 20 May 1997 (Hoke et al. 1989). Larger changes of 4 to 8 mm of moisture are evident over the oceans while changes over land are 1 to 2 mm. Figure 8b shows the microwave estimate of precipitable water vapor at 1255 UTC 20 May 1997 from the Special Sensor Microwave Imager (SSM/I) (Alishouse et al. 1990) indicating a relatively moist band over the Gulf of Mexico in agreement with the GOES retrievals. Root mean square differences (RMSE) with respect to the SSM/I are smaller for the GOES retrievals (5 mm) than the NGM (7 mm). These results are based on a version of the GOES retrieval algorithm that was implemented operationally by NOAA/NESDIS on 7 February 1997.

# b. Clouds

In cloudy conditions, the sounder infers cloud top pressures and effective cloud amounts using the CO2 absorption technique (Menzel et al. 1983; Schreiner et al. 1993; Schreiner et al. 1995). An indication of the height of clouds is useful for many applications such as aviation forecasting, initializing numerical forecast models, inferring atmospheric motion, and supplementing ASOS ground based observations of cloud cover. The ground ASOS equipment detects clouds up to 12,000 feet (roughly 4 km or 650 hPa) and the GOES detects the higher clouds. The cloud top pressure (height) is generated from measurements in the different spectral bands that see progressively deeper into the atmosphere (see Figure 2). For example, band 3 (14.1 micrometer) can only see the highest of clouds, while sounder bands 4 (13.9 micrometer)

and 5 (13.3 micrometer) can see progressively lower clouds. So the height of the cloud is bounded if it is observed, for example, by band 4 but not band 3. The satellite cloud information is generated for a given surface site using radiances from the overlying 5 x 5 FOVs to infer cloud height and amount and compositing those 25 cloud estimates into a single report of cloud cover (i.e., high, scattered clouds); these reports are being generated hourly at some 800 continental United States sites. Figure 9 shows an example GOES cloud report for Syracuse, NY at 1746 UTC on 18 March 1997 as it appears to the National Weather Service (NWS). The individual GOES cloud reports for each FOV are indicated on the left; a key is provided that defines the cloud top pressure (CTP) as low (> 650 hPa), mid (> 400 hPa), and high (< 400 hPa) and the effective cloud amount (ECA) as thin (< 50%), thick (< 95%), and opaque (> 95%). The small box on the right shows the location of the Syracuse area on the GOES-8 infrared window image. The ground station reports high and mid level broken clouds, while the GOES composite report indicates scattered clouds between 9000 and 38000 feet. These GOES cloud reports are being used by the NWS in their hourly roundups; in addition the composite GOES / ASOS report is archived at the National Climate Data Center (NCDC) as the climate record.

The quality of the satellite derived cloud product has been documented in the literature (Menzel et al. 1983; Wylie and Menzel 1989); the GOES cloud properties were found to be within 50 hPa in height and 20% in amount of other determinations. The GOES composite reports have been verified independently by the National Weather Service. In their tests, the ASOS only cloud determination and the ASOS plus the satellite observation were compared to ground observations. Results show a decrease in error in estimating cloud cover from 17% (ASOS only) to 6% (satellite data plus ASOS) compared to ground observations (Schreiner et al.

1993). While these studies were conducted with GOES-VAS, the GOES-8/9 performance has been found to be comparable.

c. Winds

In mid latitudes, using the assumption of a balanced atmosphere, thermal wind profiles have been used successfully to estimate atmospheric motions in clear sky situations. The thermal wind profiles are derived from a field of soundings, using horizontal temperature gradients to infer vertical motion gradients (Hayden and Schmit 1994). Modelers often prefer this form of the sounding product over the geopotential height fields. In combination with features tracked in sequences of sounder water vapor images, these sounder thermal winds have proven to be valuable in depicting near mid-tropospheric motions. Figure 10 shows the 500 hPa thermal gradient wind field associated with Hurricane Felix on 2316 UTC 15 August 1995 giving a good depiction of the flow. Such information, especially in the northwest sector of the near hurricane environment, has proven to be very useful. Improvements in the total suite of GOES wind field estimations have reduced the average 72 hour forecast error for a given storm feature of 360 nautical miles (670 km) by about 20% in a variety of research and operational models (Velden et al. 1997).

#### d. Derived product images

An effective display of the sounding information is the derived product image (DPI) wherein a product such as total column precipitable water vapor (PW) is color coded and clouds are shown in shades of gray (Hayden et al. 1996). Routinely, three DPIs are generated by NESDIS every hour depicting atmospheric stability, atmospheric water vapor, and cloud heights. Each FOV thus contains information from the GOES sounder with the accuracy discussed in the

previous sections, but the time sequences of the GOES DPI make the information regarding changes in space and time much more evident.

Figure 11 shows an example of a total water vapor DPI. The left panel of Figure 11 is a total water vapor image generated without any sounder data; it is generated from surface observations and the NGM. In the color scheme, brown values represent dry air, while red indicates moist air (see color bar at the bottom of the image). Two moist pockets are apparent, over Louisiana and southeast of Florida. The radiosonde (balloon) measurements are plotted in white and show agreement in the broad moisture distribution. The right panel of Figure 11 shows the total water vapor image after the inclusion of the GOES sounder data. There is no sounder derived product in cloudy regions; they are displayed as gray clouds. Comparing the two images, one notes that the broad moisture patterns are fairly similar over the continental United States on this day (20 September 1995) but that there is considerably more detail in the sounder water vapor image. The good agreement over land lends confidence to the sounding information over the data sparse Gulf of Mexico. The sounder has better depiction of a moisture ridge across the Gulf of Mexico and the circulation evident off the east coast of Florida. Small scale moisture features and measurements in data void regions from the sounder enable numerical weather prediction models to improve forecasts for six hours and beyond. These GOES sounder DPI also help the forecaster discern when the model forecast is going awry so that he/she can provide a subjective correction.

Imager DPI have also been tested. While the 4 km and 15 minute resolution of the imager provides more detail, the accuracy of the product (stability or water vapor) is degraded considerably; this is not surprising considering that the sounder has many more CO2 and H2O

sensitive spectral bands than the imager. In a two week test, the RMS difference of the imager total column water vapor with respect to radiosondes was found to be about 2 mm worse than that of the sounder and no better than the forecast guess. Tests like these have indicated that the sounder DPI is more accurate and more useful than the imager DPI. Thus over North America and the adjacent oceans, the sounder DPI is preferable; however, in other regions where sounder data is unavailable, the imager DPI provides useful information.

The sounder cloud product can also be displayed as a DPI. An example from 18 March 1997 (Figure 12) is shown with varying colors used to denote cloud top pressures at 100 hPa increments (low clouds are colored orange and the highest clouds are blue or white). The cloud free areas are shown in gray shades.

One example of an atmospheric stability DPI is shown in Figure 13. The GOES-8 lifted index (LI) image (bottom panel) indicates very unstable air over central Wisconsin at 2046 UTC on 18 July 1996. Generally unstable air (LI of -3 to -7 C) is evident along the synoptic scale cold front which ran just south of the Minnesota and Iowa border. However, the most unstable air is indicated as small local pockets in central Wisconsin (LI of -8 to -10 C). These localized regions stand in sharp contrast to the stable air (positive LIs) seen entering Wisconsin from Minnesota. Three hours later a tornado devastated Oakfield, WI. The GOES visible image clearly shows the associated cloud features (top panel). A timely tornado warning by the NWS helped to prevent any loss of life, in spite of heavy property damage. This stability information from the GOES sounder was available and supported the warning decision.

Another example of the atmospheric stability DPI from 8 July 1997 is shown in Figure 14. A sequence of the GOES LI DPI at two hour intervals over the western plains (Figure 14a) 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 14b) 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. As these examples demonstrate, the sounder is often providing new information to the nowcasting arena.

#### e. Model assimilation of GOES sounder products

There are several ways to determine the amount of information sounders are providing beyond that already available from other sources. In section 2a comparisons with radiosondes and numerical model forecasts were made. Numerical model assimilation provides another way to assess the quality of the sounder products; if the forecast improves, then the sounder data likely is adding useful information.

The sounder derived three layers of moisture have improved numerical weather prediction. For 18 days in May-June 1996, GOES-8/9 soundings were evaluated by NCEP in the operational Eta numerical weather prediction model (Rogers et al. 1996). Clear sky moisture soundings (at 50 km resolution) were inserted into the model every 3 hours; the coverage included the Pacific Ocean, continental United States, the Gulf of Mexico, and the Atlantic Ocean regions from 175 to 45 W longitude and 50 to 10 N latitude. Three layers of precipitable water vapor (PW) plus total column PW were assimilated into the Eta analysis using Optimum Interpolation (Lin et al. 1996). The results for the forecast initialized at 1200 UTC 28 May 1996 are shown in Figure 15. Figure 15a shows where the GOES influenced the Eta model (the PW field with GOES data minus that without GOES data) at 1200 UTC 28 May 1996 after assimilation of the GOES-8/9 moisture soundings from the previous twelve hours. Over the continental United States the influence of the GOES data is small as the model already has reliable information from the radiosonde network; however over the data sparse ocean and gulf regions, GOES makes modest adjustments (for example, drying by 5 to 7 mm along the 145th meridian in the Pacific Ocean, drying by 3 mm in the Gulf of Mexico, and moistening by 3 mm in the Gulf of California). Figure 15b shows the impact of the GOES moisture information on the 24 hour forecast of precipitation valid at 1200 UTC 29 May 1996; major adjustments (greater than 10 mm) in precipitation amount and location are evident in northern Kentucky and in the Gulf of Mexico. Validation with a raingauge network indicates that the GOES data improved the 24 hour Eta forecast of precipitation; in Figure 15c the entry for May 29 indicates that there was a reduction in the number of grid boxes predicting precipitation but not verifying (false alarms). False alarms of light precipitation were avoided in roughly 20 grid boxes (each at 80 km resolution) with GOES data; this equates to an area

improvement in the experimental forecast of 128,000 km2. This one day improvement was sustained for most of the 18 day test period (Figure 15c). Uniform positive impact was also found in forecasts of relative humidity at all levels (850 to 300 hPa) in the 12 hour forecast; inclusion of the GOES data improved the RMS differences with respect to radiosondes by 3 to 4 % in the western United States and by about 1 % in the western plus eastern United States. The uniformity of the improvement at all levels remained in the 24 hour forecast, at about half the 12 hour values. While these improvements are small, the consistency of improvement at each level of the troposphere is considered to be significant. The greater improvement in the western United States is likely due to GOES-9 providing information upstream over the data sparse western Pacific Ocean.

These positive Eta test results prompted operational use of GOES-8/9 three-layer precipitable water retrievals every three hours beginning October 22, 1997. The initial results have been gratifying. The equitable threat scores and threat biases (Rogers et al. 1996) for the accumulated 24 hour forecast precipitation from the operational Eta model showed improved performance through the last quarter of 1997 (see Figure 16). The threat score improved from about 0.2 to about 0.3. Two verification areas are attached: 48 states, and a western region focusing on the impact of GOES-9. Scores were computed using rain-gauge data from the River Forecast Center network as validation.

Another example of positive impact of GOES sounder data has been demonstrated with the research CIMSS (Cooperative Institute for Meteorological Satellite Studies) Regional Assimilation System (CRAS) (Raymond and Aune 1998). Sounder total column PW in clear skies and cloud heights in cloudy regions have been used to improve the forecast of water vapor

and clouds (Aune 1996). Validation of the improved forecast is possible with the subsequent GOES infrared window and water vapor images; clouds and water vapor gradients provide easily distinguishable features with which the CRAS forecast must compare. Figures 17 and 18 provide an illustration for a case study on 10 February 1997. The coverage of the sounder data at 0000 UTC is found in Figure 17a; cloud heights in cloudy regions and moisture retrievals in clear skies assure that the sounder provides input over almost the complete domain. Validating the cloud forecast with the 0300 UTC GOES-9 sounder infrared window cloud image (Figure 17d), it is obvious that the CRAS model 3 hour forecast does not resolve the low clouds off the California coast without the satellite data (Figure 17b), but does when using the GOES sounder data (Figure 17c). The better definition of the initial cloud field has helped the CRAS to produce a better 3 hour cloud forecast. In a similar manner, better definition of the initial moisture field with the GOES sounder enables a better forecast of mid-tropospheric moisture (Figure 18). Here the 0300 UTC GOES-9 water vapor image confirms that the moisture structure forecast is improved by using GOES data in the CRAS; there is clearly better depiction of the narrow dry subsidence region with GOES in the CRAS 3 hour forecast.

Recently the sounder data has been used to improve forecasts of the minimum and maximum diurnal temperatures as part of a NASA program called Timely Satellite Data for Agricultural Management (Nelson et al. 1997). Using the sounder estimates of cloud heights and amounts, the 24 hour CRAS forecast of hourly changes in surface temperature can be adjusted significantly. Figure 19 shows an example from 20 April 1997 at Madison, WI. The forecast without sounder data indicated a maximum temperature of 64 degrees F should be expected at 2100 UTC (9 hours after 1200 UTC). With sounder data this was changed to 59 degrees F

expected two hours earlier at 1900 UTC (7 hours after 1200 UTC). The surface observations in Madison, WI reported a maximum temperature of 58 degrees F at 2000 UTC. This information is being produced daily for agricultural applications in various locations throughout Wisconsin; early feedback has been very positive (Diak et al. 1998).

# **3.** Applications and benefits

The improved GOES sounder is beginning to have a positive impact on numerical weather forecasting, which in turn will have positive impact throughout the economy. In addition, the enhanced remote sensing in many spectral bands with continuous surveillance possible from geostationary orbit will enable NOAA to provide other greatly improved services to the nation. In no particular order, the following paragraphs list some examples of services that are beginning to benefit from a geostationary sounder.

\* In the area of disaster mitigation, hurricane trajectory forecasts are benefiting from better definition of mass and motion fields. Recent improvements in GOES wind field estimations helped the Navy prevent unnecessary fleet movements in 1996; Atlantic fleets were correctly ordered to stay in port for nearby but not threatening hurricanes. More generally, considerable savings are realized for every mile of shoreline (and the associated coastal region) that is not unnecessarily evacuated; a 20% improvement in 72 hour trajectory forecasts is projected to be valued at about \$70M per land falling hurricane.

\* Improved knowledge of the moisture and thermal field will provide better data for agricultural forecasting and nowcasting. It has been estimated that improvements in three day forecasting of location and timing of rain events (on the order of 500 miles and 12 hours) would enable

considerable savings in the reduction of pesticide use over one growing season, as well as mitigate the environmental impact of nitrates leeching into our ground water (important to the United States Department of Agriculture in their program of integrated pest management). Improved forecasts of three day low temperatures would enable more mitigation of crop damage to or loss of temperature sensitive crops (frost warnings). Improved monitoring of ground wetness and temperature for tractability, planting, germination, crop stress, and harvesting, would benefit daily decision making (whether to spray, harvest, plow, etc.).

\* In the area of transportation by air, ocean, or land there are many weather phenomena that are monitored by geostationary remote sensors. The improved wind, moisture, and temperature information from GOES provides a number of benefits. Better information regarding conditions leading to fog, icing, head or tail winds, and development of severe weather including microbursts en route can be used to make air traffic more economical and safer. Better depiction of ocean currents, low level winds and calm areas, major storms, and hurricanes (locations, intensities, and motions) can benefit ocean transportation in the same way. Information regarding major ice storms, fog, flooding and flash flooding, heavy snowfall, blowing snow, and blowing sand already assist train and truck transportation; improved services should result from the GOES sounder multispectral, high spatial, and high temporal resolution measurements.

\* Power consumption in the United States can be regulated more effectively with real-time assessment of regional and local insolation as well as temperatures. Power services can be maintained more reliably with information for allocation of disaster crews (e.g., for restoration of power) to locations of potential lightning damage. These are associated with thunderstorms which are found in areas of convectively unstable air often delineated by GOES soundings. Local

scale forecasts of ice, snow, and flooding will also improve with hourly assimilation of GOES sounder data.

\* General weather announcements affecting public health need improved forecasting and monitoring of surface temperatures in urban and metropolitan areas during heat stress (and subzero conditions). GOES sounder data in regional models are demonstrating skill in this application.

The potential impacts of GOES sounder can be many and great. Early applications presented in this article are an indication that the promise of the GOES sounders is beginning to be realized.

## 4. Summary

GOES sounder performance has mostly been meeting or exceeding expectations with regard to signal to noise, calibration, and navigation; noise in the longwave bands is greater than specified. The GOES sounder data and products are produced on a higher space and time scale than conventional observations. The overall quality of the GOES sounder measurements and the added information from the products have been verified by comparison to independent observations. Sounder products from both GOES-8 (at 75 W) and GOES-9 (at 135 W) are being used operationally by the National Weather Service.

GOES soundings are available hourly to help assist the NWS produce accurate forecasts/nowcasts of severe weather, as demonstrated by examples of satellite derived atmospheric instability evolution (such as for the Wisconsin tornado and Kansas hail situations). GOES-8/9 moisture impact on numerical weather prediction (NWP) is positive. Eta model impact tests for three weeks in May-June 1996 showed that the 24 hour precipitation false alarm

rate was reduced by 10% to 20%. Operational use in the last quarter of 1997 lifted equitable threat scores of 24 hour precipitation forecasts by 0.1. These improvements are expected to increase as direct assimilation of GOES sounder radiances becomes a reality in late 1998. The GOES sounder cloud information is complementing ASOS at middle and high levels of the troposphere; also the cloud top heights are being used to initialize numerical weather prediction models.

Real-time examples of both retrieved noisture and stability information as well as cloud top pressures can be seen on the CIMSS web page at http://cimss.ssec.wisc.edu. Another site with real-time GOES sounder products supported by the NOAA/NESDIS Forecast Products Development Team is http://orbit7i.nesdis.noaa.gov:8080/goes.html. Additionally sounder retrievals and hourly cloud reports are available from the National Climate Data Center (NCDC) at http://www.ncdc.noaa.gov.

# 5. Acknowledgments

The development and testing of the GOES-8/9 sounder products have been possible only with the help of many individuals who pioneered the concept of sounding from geostationary orbit and shepherded it into operations. Professors Verner Suomi and William Smith contributed tremendously to the work presented here; Professor Suomi had the vision of the original GOES sounding instruments and Professor Smith developed many of the algorithms for temperature and moisture profile retrievals. Dr. Christopher Hayden lead the team that tested and implemented many of the algorithms being used operationally today. Dr. Ma Xia Lin improved the efficiency of the retrieval algorithm using better numerical approaches for solution of the radiative transfer equation. Hal Woolf did many of the radiative transmittance model calculations. Dr. Paul van Delst provided much of the GOES to HIS calibration work. Jamie Daniels and Gary Gray worked effectively to make the research algorithms function in the operational environment. Dr. Kevin Schrab facilitated distribution of the GOES products to the many NWS weather forecast offices that have been most diligent in providing feedback to evolve the algorithms and products into more useful form.

# 6. References

- Alishouse, J.C., S. Snyder, J. Vongsathorn, and R.R. Ferraro, 1990: Determination of oceanic total precipitable water from the SSM/I. *IEEE Trans. Geo. Rem. Sens.*, **28**, 811-816.
- Aune R. M., 1996: Initializing cloud predications using the GOES-8 sounder.*Proceedings of the Eighth Conference on Satellite Meteorology and Oceanography*, January 28 - February 2, 1996, Atlanta, GA, Amer. Meteor. Soc., 408-412.

- Diak, G. R., M. C. Anderson, W. L. Bland, J. M. Norman, J. M. Mecilkalski, and R. A. Aune,
  1998: Agricultural management decision aids driven by real time satellite data. Submitted to *Bull. Amer. Meteor. Soc.*
- Hayden, C. M., 1988: GOES-VAS simultaneous temperature-moisture retrieval algorithm. J. Appl. Meteor. 27, 705-733.
- Hayden, C. M. and T. J. Schmit, 1994: GOES-I temperature and moisture retrievals and associated gradient wind estimates *Proceedings of the Seventh Conference on Satellite Meteorology and Oceanography*, June 6-10, 1994, Monterey, CA, Amer. Meteor. Soc., 477-480.
- Hayden, C. M., G. S. Wade, and T. J. Schmit, 1996: Derived Product Imagery from GOES-8. J. Appl. Meteor., 35, 153-162
- Hayden, C. M., T. J. Schmit, and A. J. Schreiner, 1998: The cloud clearing for GOES product processing. Submitted as a *NOAA/NESDIS Technical Report*.
- Hoke, J. E., N. A. Phillips, G. J. DiMego, J. T. Tuccillo, and J. G. Sela, 1989: The regional analysis and forecast system of the National Meteorological Center *Wea. Forecasting*, 4, 323-334.
- Kelly, K. A., J. F. Hudson, and N. Pinkine, 1996: GOES-8 and -9 image navigation and registration operations. *Technical Proceedings of the Society of Photo-Optical Instrumentation Engineers International Symposium on GOES-8 and Beyond*. August 4-9, 1996. Denver CO, Int. Soc. for Optical Eng., **2812**, 777-788.
- Lin Y., E. Rogers, G. J. DiMego, K. E. Mitchell, and R. M. Aune, 1996: Assimilation of GOES-8 moisture data into NMC's Eta model.*Proceedings of the Eighth Conference on Satellite*

*Meteorology and Oceanography*, January 28 - February 2, 1996, Atlanta, GA, Amer. Meteor. Soc., 518-520.

- Ma, X., T. J. Schmit, and W. L. Smith 1998: A non-linear physical retrieval algorithm Its Application to the GOES-8/9 sounder. Accepted by *J. Appl. Meteor*.
- Menzel, W. P., W. L. Smith, and T. R. Stewart, 1983: Improved cloud motion wind vector and altitude assignment using VAS. J. Appl. Met., 22, 377-384.
- Menzel, W. P. and J. F. W. Purdom, 1994: Introducing GOES-I: The first of a new generation of Geostationary Operational Environmental Satellites. *Bull. Amer. Meteor. Soc.*, **75**, 757-781.
- Nelson, A., A. Hasler, D. Chesters, D. Jones, G. Diak, P. Hunter, B. Bland, J. Norman, and K.
  Palaniappan, 1997: A NASA internet-based cooperative agreement outreach effort using
  NOAA-GOES data. Submitted to *Bull. Amer. Meteor. Soc.*
- Pratt, R. W., 1985: Review of radiosonde humidity and temperature errors *J. Atmos. Oceanic Techn.*, **2**, 404-407.
- Raymond W. H., R. M. Aune, 1998: Improved precipitation forecasts using parameterized precipitation drag in a hydrostatic forecast model.*Monthly Wea Rev*, **126**, 693-710.
- Revercomb, H. E., H. Buijis, H. B. Howell, D. D. LaPorte, W. L. Smith, and L. A. Sromovsky,
  1988: Radiometric calibration of IR Fourier transform spectrometers: Solution to a problem with the High spectral resolution Interferometer Sounder. *Appl. Opt.*, 27, 3210-3218.
- Rogers, E., T. L. Black, D. G. Deaven, G. J. DiMego, Q. Zhao, M. Baldwin, N. W. Junker, andY. Lin, 1996: Changes to the operational "early" Eta analysis / forecast system at theNational Centers for Environmental Prediction. *Wea. Forecasting*, 11, 391-413.

- Schmidlin, F. J., 1988: WMO international radiosonde comparison, phase II final report, 1985. Instruments and observing methods report, No. 29 WMO/TD No. 312, WMO, Geneva, Switzerland.
- Schmit, T. J., 1996: Sounder bias correction of the east-west gradient. *Technical Proceedings of the Society of Photo-Optical Instrumentation Engineers International Symposium on GOES-8 and Beyond*, August 4-9, 1996, Denver CO, Int. Soc. for Optical Eng., **2812**, 630-637.
- Schreiner, A. J., D. Unger, W.P. Menzel, G. Ellrod, K. Strabala, and J. Pellet, 1993: A comparison of ground and satellite observations of cloud cover. *Bull. Amer. Meteor. Soc.*, 74, 1851-1861.
- Schreiner, A. J., T. J. Schmit, C. M. Hayden, and W. P. Menzel, 1995: Images of satellitederived cloud top pressure for the contiguous United States. *Proceedings of the National Weather Association Conference*, December 3-8, 1995, Houston, TX, 35pp.
- Smith, W. L., 1983: The retrieval of atmospheric profiles from VAS geostationary radiance observations. *Jour. Atmos. Sciences.*, **40**, 2025-2035.
- Smith, W. L., R. O. Knuteson, H. E. Revercomb, W. Feltz, H. B. Howell, W. P. Menzel, N. Nalli,
  O. Brown, J. Brown, P. Minnett, and W. McKeown, 1996: Observations of the infrared radiative properties of the ocean Implications for the measurement of sea surface temperature via satellite remote sensing. *Bull. Amer. Meteor. Soc.*, 77, 41-51.
- Velden, C. S., C. M. Hayden, S. J. Nieman, W. P. Menzel, S. Wanzong, and J. S. Goerss, 1997:
  Upper-tropospheric winds derived from geostationary satellite water vapor observations.*Bull. Amer. Meteor. Soc.*, 78, 173-195.

- Weinreb, M., 1996: Real-world calibration of GOES-8 and -9 sensors *Technical Proceedings of the Society of Photo-Optical Instrumentation Engineers International Symposium on GOES-8 and Beyond*, August 4-9, 1996, Denver CO, Int. Soc. for Optical Eng., 2812, 572-586.
- Weinreb, M., M. Jamieson, N. Fulton, Y. Chen, J. X. Johnson, J. Bremer, and J. Baucom, 1997:Operational calibration of the imagers and sounders on the GOES-8 and -9 satellites. *NOAA Technical Memorandum NESDIS 44*, pp. 32.
- Wylie, D. P. and W. P. Menzel, 1989: Two Years of Cloud Cover Statistics Using VAS. Jour. Clim., 2(4), 380-392.

**Figure Captions** 

1. Location of the GOES sounder spectral bands, from 3.7 to 14.7 micrometers, with an Earth emitted spectra. Molecular absorption band centers are superimposed in microns. GOES sounder spectral band centers and bandwidths are indicated below in wavenumbers placed at the approximate altitude from which the radiation is emanating. Temperature sounding bands are blue, moisture sounding bands are red, the ozone band is yellow, and atmospheric windows are green.

2. Four spectral bands of the sounder sensitive to CO2 absorption. Shown are bands 3 at 14.1 microns (top left), 4 at 13.9 microns (top right), 5 at 13.4 microns (bottom left), and 8 at 11.0 microns (bottom right) for 1800 UTC 18 March 1997.

3. The GOES sounder longwave (a), midwave (b), and shortwave (c) band weighting functions (in arbitrary units on the x-axis) plotted as a function of pressure (in hPa on the y-axis) for the standard atmosphere. Band numbers (see Table 1 for wavelengths) are indicated with associated weighting function. A weighting function depicts the layer of the atmosphere where the radiation originated.

4a. An example of the hourly sounder coverage of North America and nearby oceans for the 7.0 micrometer band from both GOES-8 and -9 on 18 March 1997. The data have been remapped into a Lambert Conformal projection.

4b. The GOES-8/9 sounder retrieval coverage (white boxes) is plotted over the infrared window image for 1800 UTC 18 March 1997. Each white square represents a retrieved profile over a 5 x 5 FOV sounding area (approximately 50 km on a side).

4c. Radiosonde locations plotted over the infrared window image for 1800 UTC 18 March 1997.

5. A flow chart of the GOES sounder processing system which shows that temperature and moisture retrievals are generated in clear regions and cloud information is determined in cloudy regions.

6. Temperature (solid) and dewpoint temperature (dashed) profiles from GOES (black) and radiosonde (gray) over Omaha, NE on 2 July 1997 at 1200 UTC. The radiosonde temperature profile shows more vertical structure, but the GOES agrees in the mean. On this occasion, the radiosonde dewpoint temperature is somewhat wetter than the GOES.

7a. Temperature profile comparison results for 1996. Bias (left) and RMS (right) estimates with respect to radiosondes are shown for both the retrieval (solid) and the forecast guess (dashed).The sample size of 1488 was collected between April 1996 and February 1997.

7b. Corresponding bias (left) and RMS (right) differences for dewpoint temperature profiles. 8a. GOES sounder total precipitable water vapor field minus that inferred from the Nested Grid Model for 1200 UTC 20 May 1997. The larger changes of 4 to 8 mm of moisture are evident over the oceans while changes over land are 1 to 2 mm.

8b. DPI of 1255 UTC SSM/I precipitable water vapor with superimposed contours of 1200 UTC GOES retrieval minus NGM guess estimate of precipitable water vapor for 20 May 1997.

9. A GOES cloud report for 1752 UTC on 18 March 1997 over Syracuse, NY. The ground station reports high and mid level broken clouds, while the GOES reports scattered clouds between 9000 and 38000 feet. The individual reports for each FOV are indicated on the left; cloud top pressure (PCT) and effective cloud amount (ECA) characterize the cloud. A small box on the upper right shows the location of Syracuse on the GOES-8 infrared window image.

10. 500 hPa thermal gradient wind field associated with Hurricane Felix on 2316 UTC 15 August1995. Radiosonde (from 0000 UTC) measurements are indicated in black.

11. An example of a water vapor DPI from 20 September 1995. The left panel is a total water vapor image generated without any sounder data; it is generated from surface observations and the Nested Grid Model. In the color-code, brown values represent dry air and red represents moist air (see color bar at the bottom of the image). The radiosonde (balloon) measurements are plotted in white and show agreement in the broad moisture distribution. The right-hand-side panel shows the total water vapor image after the inclusion of the sounder data.

The combined GOES-8/9 sounder cloud product image from 1800 UTC 18 March 1997.
 The colors denote the cloud top pressure, low clouds are colored orange and the highest clouds are blue or white. Color changes every 100 hPa.

13. An example of the atmospheric stability DPI from 18 July 1996. The GOES-8 lifted index image (bottom panel) indicates very unstable air over central Wisconsin at 2046 UTC. Three hours later a tornado devastated Oakfield, Wisconsin. The GOES visible image from 2345 UTC clearly shows the associated cloud features (top panel).

14a. 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.

14b. The GOES-8 sounder LI DPI at 2346 UTC on 8 July 1997 along with the radiosonde values from the 0000 UTC launches.

15a. GOES influence on the Eta model (the PW field with GOES data minus without GOES data) at 1200 UTC 28 May 1996 after assimilation of the GOES-8/9 moisture soundings from the previous twelve hours.

15b. The impact of the GOES moisture information on the 24 hour forecast of precipitation valid at 12 UTC 29 May 1996. Dashed red contours indicate drying due to the inclusion of GOES data; solid blue contours indicate moistening. Units are in mm of rain.

15c. False alarm reduction using GOES for the 18 days of the impact tests. For 29 May 1996 false alarms were avoided in 20 grid boxes for light precipitation (less than 0.1 mm) and 5 grid boxes for heavy precipitation (greater than 12.0 mm). GOES reduced the number of grid boxes predicting precipitation but not verifying (false alarms). A reduction of 20 false alarm grid boxes (80 km resolution) equates to an areal improvement in the experimental forecast of 128,000 km2. 16. Equitable threat scores (lower panel) and biases (upper panel) for the accumulated 24 forecast of precipitation from the operational Eta model for the last four months of 1997. Assimilation of three layers of moisture derived from GOES-8/9 sounders every three hours started October 22. Scores were computed using rain gauge data from the River Forecast Center network. Verification for the continental United States as well as the western states are indicated. 17a. (upper right) The coverage of the sounder data, both the retrieved water vapor and cloud heights, at 0000 UTC 10 February 1997; b (upper left) The simulated infrared window from the CRAS model without the satellite data at 0300 UTC; c (lower left) The simulated infrared window from the CRAS model with the satellite data at 0300 UTC; d (lower right) The validating 0300 UTC infrared window image from the GOES-9 sounder.

18a. (upper right) The coverage of the sounder data, both the retrieved water vapor and cloud heights, at 0000 UTC on 10 February 1997; b (upper left) The simulated water vapor image from the CRAS model without the satellite data at 0300 UTC; c (lower left) The simulated water vapor image from the CRAS model with the satellite data at 0300 UTC; d (lower right) The validating 0300 UTC water vapor image from the GOES-9 sounder.

19. Maximum temperatures forecast with and without GOES sounder data for 20 April 1997 in Madison, WI. Without sounder data the CRAS forecast a maximum temperature of 64 degrees F at 2100 UTC (9 hours after 1200 UTC, top panel) and with sounder data 59 degrees F at 1900 UTC (7 hours after 1200 UTC, middle panel); the surface observations report a maximum temperature of 58 degrees F at 2000 UTC (bottom panel).

Table 1. GOES-8/9 sounder noise performance compared to GOES-7 VAS and NOAA-12

HIRS. NEDR is the inflight measured noise equivalent radiance in mW/m2/ster/cm-1; spec is the prelaunch specified value. NEDT is the corresponding inflight measured noise equivalent temperature at 290 K; GOES-8 NEDT can be inferred by multiplying GOES-9 NEDT by NEDR(G-8)/NEDR(G-9). Improvements over GOES 7 and NOAA-12 include adjustments for

| Wavelength | Ch | NEDT   | NEDR  | NEDR              |        |        | Improvement    |  |
|------------|----|--------|-------|-------------------|--------|--------|----------------|--|
| (um)       |    | G-9    | G-8   | G-9               | (spec) | G9/G7  | G9/N12         |  |
|            |    | (290K) | (mW/m | (mW/m2/ster/cm-1) |        | (FOV a | (FOV adjusted) |  |
| Longwave   |    |        |       |                   |        |        |                |  |
| 14.7       | 1  | 0.75   | 1.63  | 1.20              | (0.66) | 7.7    | 1.2            |  |
| 14.4       | 2  | 0.49   | 1.41  | 0.80              | (0.58) | 5.6    | 1.3            |  |
| 14.1       | 3  | 0.36   | 0.94  | 0.56              | (0.54) | 2.5    | 1.2            |  |
| 13.9       | 4  | 0.28   | 0.65  | 0.46              | (0.45) |        | 1.0            |  |
| 13.4       | 5  | 0.27   | 0.74  | 0.45              | (0.44) | 3.1    | 0.9            |  |
| 12.7       | 6  | 0.12   | 0.32  | 0.19              | (0.25) | 5.9    |                |  |
| 12.0       | 7  | 0.08   | 0.21  | 0.13              | (0.16) |        |                |  |
|            |    |        |       |                   |        |        |                |  |
| Midwave    |    |        |       |                   |        |        |                |  |
| 11.0       | 8  | 0.07   | 0.15  | 0.10              | (0.16) | 1.3    | 2.1            |  |
| 9.7        | 9  | 0.07   | 0.20  | 0.11              | (0.33) |        | 2.9            |  |
| 7.5        | 10 | 0.09   | 0.091 | 0.076             | (0.16) |        | 5.6            |  |

FOV differences.

| 7.0       | 11 | 0.07 | 0.091 | 0.047 | (0.12)  | 25.0 | 8.3 |
|-----------|----|------|-------|-------|---------|------|-----|
| 6.5       | 12 | 0.15 | 0.119 | 0.086 | (0.15)  | 3.0  |     |
|           |    |      |       |       |         |      |     |
| Shortwave |    |      |       |       |         |      |     |
| 4.57      | 13 | 0.09 | 0.012 | 0.008 | (0.013) |      | 1.6 |
| 4.52      | 14 | 0.08 | 0.011 | 0.007 | (0.013) | 7.7  | 1.1 |
| 4.45      | 15 | 0.08 | 0.012 | 0.006 | (0.013) | 11.1 | 1.4 |
| 4.13      | 16 | 0.08 | 0.004 | 0.003 | (0.008) |      |     |
| 3.98      | 17 | 0.10 | 0.005 | 0.003 | (0.008) | 4.8  | 1.4 |
| 3.7       | 18 | 0.05 | 0.002 | 0.001 | (0.004) |      | 2.1 |
|           |    |      |       |       |         |      |     |

FOV sizes: GOES-8/9 at 8 km; GOES-7 at 7 km (14 km for the more extreme longwave and shortwave); HIRS at 17 km

| GOES-8 Sounder | Brightness Temperature |
|----------------|------------------------|
| Band           | Difference (K)         |
| 1              | 1.1                    |
| 2              | 1.3                    |
| 3              | 1.6                    |
| 4              | -0.3                   |
| 5              | 0.1                    |
| 6              | -0.7                   |
| 7              | -1.2                   |
| 8              | -0.9                   |
| 9              | na                     |
| 10             | 0.1                    |
| 11             | -0.4                   |
| 12             | 0.8                    |
| 13             | -0.1                   |
| 14             | 0.1                    |
| 15             | 0.3                    |
| 16             | 0.2                    |
| 17             | 0.4                    |
| 18             | na                     |

Table 2. Brightness temperature differences for HISminus GOES-8 sounder bands withcorrection for viewing geometry.

Table 3. Verification of the NGM forecast first guess and the GOES-8 three layer moisture retrievals for April 1996 to February 1997. Only 00 UTC retrievals are included. The bias and root-mean-square (RMS) scatter about the bias are compared to radiosondes (in mm). The collocation distance within 0.25 degrees. Sigma is the ratio of the pressure over the surface pressure. Sample size is 1488.

|                           | Guess |     | Retrieval |     |  |
|---------------------------|-------|-----|-----------|-----|--|
|                           | Bias  | RMS | Bias      | RMS |  |
| Total Water Vapor         | -0.3  | 3.3 | -0.1      | 2.6 |  |
| WV1 (Surface to .9 sigma) | -0.9  | 1.6 | -0.7      | 1.5 |  |
| WV2 (0.9 to 0.7 sigma)    | 0.2   | 2.1 | 0.3       | 1.7 |  |
| WV3 (0.7 to 0.3 sigma)    | 0.3   | 1.4 | 0.3       | 1.1 |  |

# FIGURES



1. Location of the GOES sounder spectral bands, from 3.7 to 14.7 micrometers, with an Earth emitted spectra. Molecular absorption band centers are superimposed in microns. GOES sounder spectral band centers and bandwidths are indicated below in wavenumbers placed at the approximate altitude from which the radiation is emanating. Temperature sounding bands are blue, moisture sounding bands are red, the ozone band is yellow, and atmospheric windows are green.



2. Four spectral bands of the sounder sensitive to CO2 absorption. Shown are bands 3 at 14.1 microns (top left), 4 at 13.9 microns (top right), 5 at 13.4 microns (bottom left), and 8 at 11.0 microns (bottom right) for 1800 UTC 18 March 1997.



( a )



(b )



# ( c )

3. The GOES sounder longwave (a), midwave (b), and shortwave (c) band weighting functions (in arbitrary units on the x-axis) plotted as a function of pressure (in hPa on the y-axis) for the standard atmosphere. Band numbers (see Table 1 for wavelengths) are indicated with associated weighting function. A weighting function depicts the layer of the atmosphere where the radiation originated.



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4b. The GOES-8/9 sounder retrieval coverage (white boxes) is plotted over the infrared window image for 1800 UTC 18 March 1997. Each white square represents a retrieved profile over a 5 x 5 FOV sounding area (approximately 50 km spacing).



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5. A flow chart of the GOES sounder processing system which shows that temperature and moisture retrievals are generated in clear regions and cloud information is determined in cloudy regions.



6. Temperature (solid) and dewpoint temperature (dashed) profiles from GOES (black) and radiosonde (gray) over Omaha, NE on 2 July 1997 at 1200 UTC. The radiosonde temperature profile shows more vertical structure, but the GOES agrees in the mean. On this occasion, the radiosonde dewpoint temperature is somewhat wetter than the GOES.



GOES-8 Temperature Verification April 1996 - Feb. 1997

7a. Temperature profile comparison results for 1996. Bias (left) and RMS (right) estimates with respect to radiosondes are shown for both the retrieval (solid) and the forecast guess (dashed). The sample size of 1488 was collected between April 1996 and February 1997.



# **GOES-8** Dewpoint Verification

April 1996 - Feb. 1997

7b. Corresponding bias (left) and RMS (right) differences for dewpoint temperature profiles.



Total Precipitable Water 12UTC 20-May-97 GOES Sounder minus NGM Forecast

8a. GOES sounder total precipitable water vapor field minus that inferred from the Nested Grid Model for 1200 UTC 20 May 1997. The larger changes of 4 to 8 mm of moisture are evident over the oceans while changes over land are 1 to 2 mm.



8b. DPI of 1255 UTC SSM/I precipitable water vapor with superimposed contours of 1200 UTC GOES retrieval minus NGM guess estimate of precipitable water vapor for 20 May 1997.



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10. 500 hPa thermal gradient wind field associated with Hurricane Felix on 2316 UTC 15 August 1995. Radiosonde (from 0000 UTC) measurements are indicated in black.



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12. The combined GOES-8/9 sounder cloud product image from 1800 UTC 18 March 1997. The colors denote the cloud top pressure, low clouds are colored orange and the highest clouds are blue or white. Color changes every 100 hPa.



13. An example of the atmospheric stability DPI from 18 July 1996. The GOES-8 lifted index image (bottom panel) indicates very unstable air over central Wisconsin at 2046 UTC. Three hours later a tornado devastated Oakfield, Wisconsin. The GOES visible image from 2345 UTC clearly shows the associated cloud features (top panel).





14a. 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.



14b. The GOES-8 sounder LI DPI at 2346 UTC on 8 July 1997 along with the radiosonde values from the 0000 UTC launches.



15a. GOES influence on the Eta model (the PW field with GOES data minus without GOES data) at 1200 UTC 28 May 1996 after assimilation of the GOES-8/9 moisture soundings from the previous twelve hours.



15b. The impact of the GOES moisture information on the 24 hour forecast of precipitation valid at 12 UTC 29 May 1996 (bottom panel). Blue contours indicate moistening and red contours indicate drying due to the inclusion of GOES data. Numbers indicate mm of rain.



15c. False alarm reduction using GOES for the 18 days of the impact tests. For 29 May 1996 false alarms were avoided in 20 grid boxes for light precipitation (less than 0.1 mm) and 5 grid boxes for heavy precipitation (greater than 12.0 mm). GOES reduced the number of grid boxes predicting precipitation but not verifying (false alarms). A reduction of 20 false alarm grid boxes (80 km resolution) equates to an areal improvement in the experimental forecast of 128,000 km2.



# 24HR ETA WEEKLY PRECIP BIAS (VERIFIED AGAINST RFC RAIN DATA, 1-600MM)

16. Equitable threat scores (lower panel) and biases (upper panel) for the accumulated 24 forecast of precipitation greater than 1 mm from the operational Eta model for the last four months of 1997. Assimilation of three layers of moisture derived from GOES-8/9 sounders every three hours started October 22. Scores were computed using rain gauge data from the River Forecast Center network. Verification for the continental United States as well as the western states are indicated.



More realistic moisture forecasts with GOES Sounder Cloud and Water Vapor data NOAA/NESDIS/ASPT

17a. (upper right) The coverage of the sounder data, both the retrieved water vapor and cloud heights, at 0000 UTC 10 February 1997; b (upper left)The simulated infrared window from the CRAS model without the satellite data at 0300 UTC; c (lower left) The simulated infrared window from the CRAS model with the satellite data at 0300 UTC; d (lower right) The validating 0300 UTC infrared window image from the GOES-9 sounder.



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