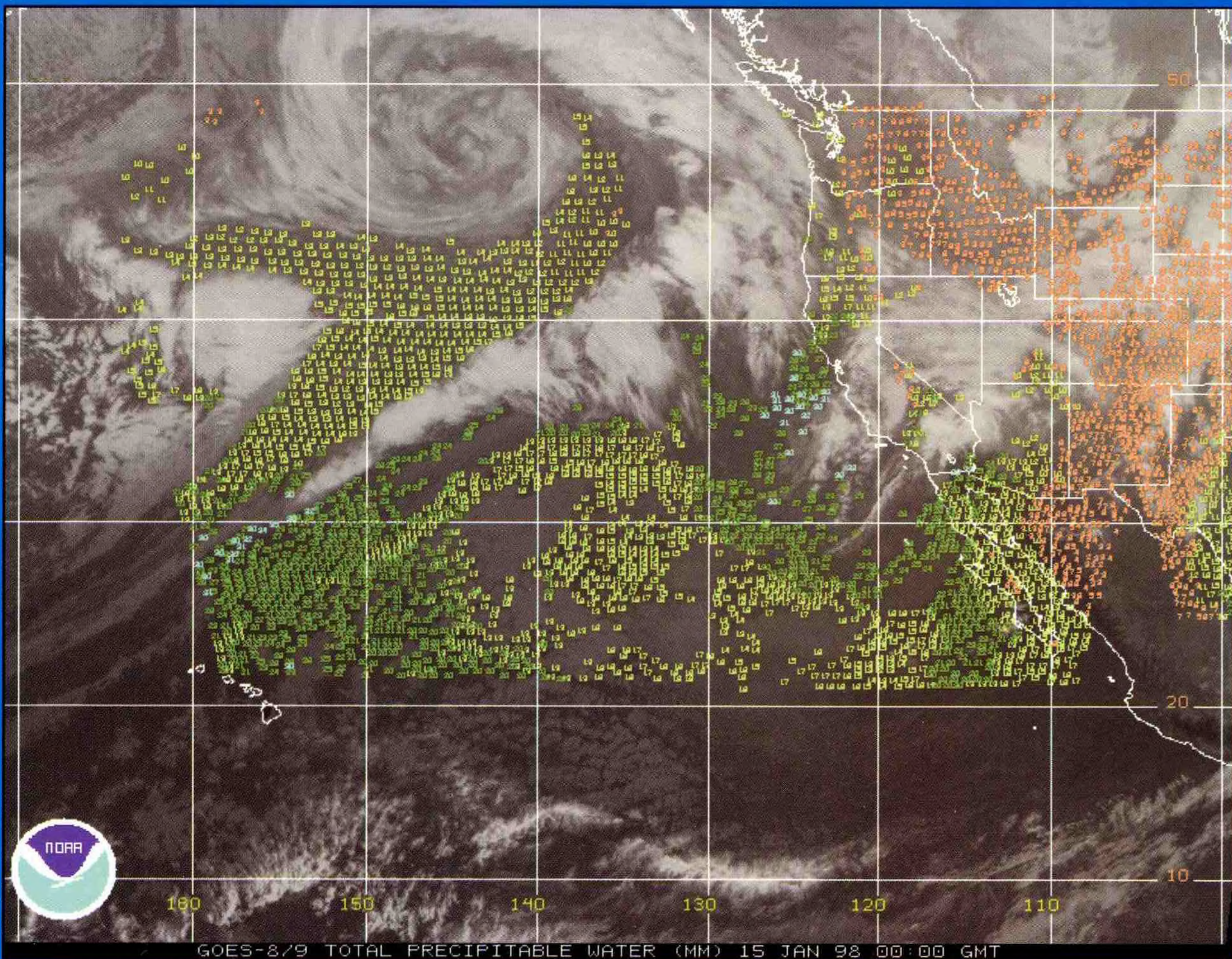
Geostationary Satellite Soundings
New Observations for Forecasters



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data and Information Service

COMMENTS FROM FORECASTERS

"The Derived Sounder Products…have been a great help to some of our offices. The La Crosse, Wisconsin, office has used the data…to determine when severe convection would develop in their County Warning Area. This has helped them make office staffing decisions for expected peak severe weather times and provide Emergency Managers with a more detailed time frame of expected severe convection"

"I have been monitoring the products as well and have found that they tend to highlight the areas where convection will initiate. This was the case on July 1 3….During the early and middle portions of the afternoon Total Precipitable Water (TPW) values were noted across central Nebraska and south central Kansas. Other values such as the Convective Available Potential Energy (CAPE) and lifted Index (LI) were also pinpointing these areas as being the most unstable. The initial thunderstorms developed in these two areas."

J. Bunting, NWS Central Region

"The Chicago [NWS] office is comparing the [satellite] data to the Aircraft Communications, Addressing and Reporting System (ACARS) data and has found the [GOES] sounder data to be pretty accurate although the lowest levels are the least accurate."

"We have been watching and learning how best to use the sounder products over the last few days….Interestingly, the sounder matched ALL of the surrounding raob sounding 500mb temperatures within 1° C." D. Baumgardt, NWS LaCrosse, WI

"I have been looking at the GOES -9 soundings from 20Z yesterday [May 29, 1997]… and it showed how useful this data can really be….You will see …that at about the time flooding was occurring in the town of Pilot Rock the ETA model forecast indicated a Lifted Index of -2, K Index of 28, and precipitable] water of 27 mm. The GOES sounding however, showed the actual Lifted Index was -7, K Index 36 and the precipitable] water 30mm (about 1.4 inches)!"

B. Schneider, NWS, Portland, OR

"We at the Sioux Falls forecast office really appreciate the satellite derived sounding data especially since there are no raob sites close to us"

R. Holmes, NWS, Sioux Falls, SD

Front Cover - GOES-9 Precipitable Water productfor 0000 UTC, January 15, 1998, showing high moisture values associated with a California winter storm.

GEOSTATIONARY SATELLITE SOUNDINGS:

NEW OBSERVATIONS FOR FORECASTERS

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APRIL 1998

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary

National Environmental Satellite, Data, and Information Service
Robert S. Winokur, Assistant Administrator

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GEOSTATIONARY SATELLITE SOUNDINGS: NEW OBSERVATIONS FOR FORECASTERS

INTRODUCTION

The new meteorological Geostationary Operational Environmental Satellites (GOES), GOES-8 and GOES-9 (Figure 1) launched in 1994 and 1995, respectively, are providing meteorologists with an vast array of new atmospheric observations and products. Key satellite improvements include more frequent imaging of weather systems, at a higher resolution, and in more spectral bands (Menzel and Purdom 1994). Another major advancement is the ability to independently image and sound or make profiles of atmospheric temperature and water vapor. For the first time, forecasters have a continuum of atmospheric sounding or temperature and moisture information. These hourly observations that cover the Continental U.S. (CONUS) and adjacent ocean areas are critical to monitoring changing weather conditions and providing improved weather services to the nation.

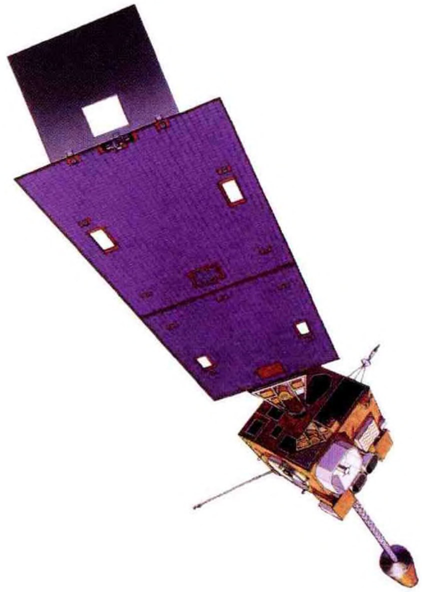


Figure 1. GOES I-M Spacecraft

Conventional upper air or radiosonde observations taken at 12 hourly intervals at 75 stations in the U.S. (figure 2a) have been the basic observational data set for numerical weather prediction (NWP) models. Now vertical temperature and moisture profiles from the GOES sounders are available at more frequent intervals (hourly versus every 12 hours) and at higher spatial resolution, 30 kilometers (km), than radiosondes. Between 2,000 and 3,000 retrievals or soundings are made **each hour**. Atmospheric temperature measurements are inferred for 40 levels of the atmosphere from the surface to 0.1 millibars (mb) (about 18 km or 55,000 feet (ft.)) in cloud-free areas. Positioning of the GOES satellites at 75° W and 135° W allows soundings to be acquired over the U.S. and adjacent data sparse ocean areas such as the eastern Pacific, Gulf of Mexico, and western Atlantic. Figures 2b and 2c illustrate the amount of information that the GOES satellite sounders add to the weather forecaster's observational set. Product examples and selected applications are presented in this report.

GOES soundings are poised to meet the data and monitoring needs of the modernized National Weather Service's (NWS) improved regional models and the weather watch and warning programs. Utilization of these products in NWS forecast models began in the fall of 1997. A number of NWS Forecast Offices are also participating in the evaluation of these products. Early results have been positive. Comments and evaluations are included on the inside covers of this report.

GOES SATELLITE SOUNDINGS

The GOES sounders are 19-band instruments that sense different layers of the atmosphere. This information can be assembled into a vertical observation profile of atmospheric temperature and moisture (figure 3), or a field of radiances that then can be utilized by numerical weather prediction models and local forecasters.

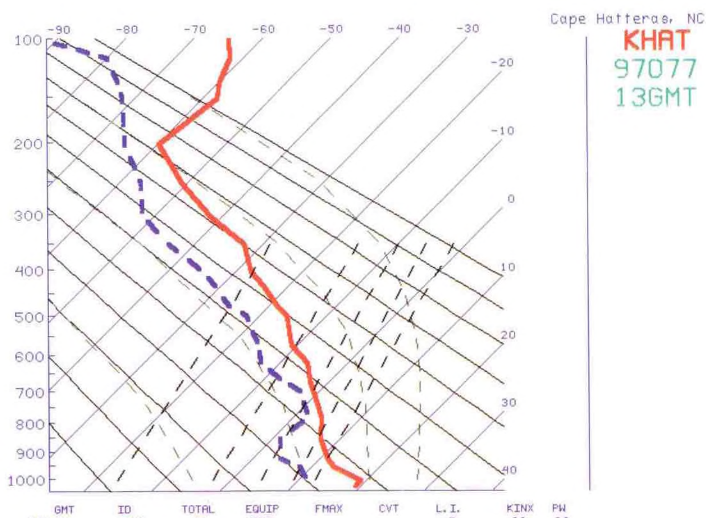


Figure 3. A GOES temperature and moisture profile. Solid line temperature; dashed line dewpoint temperature.

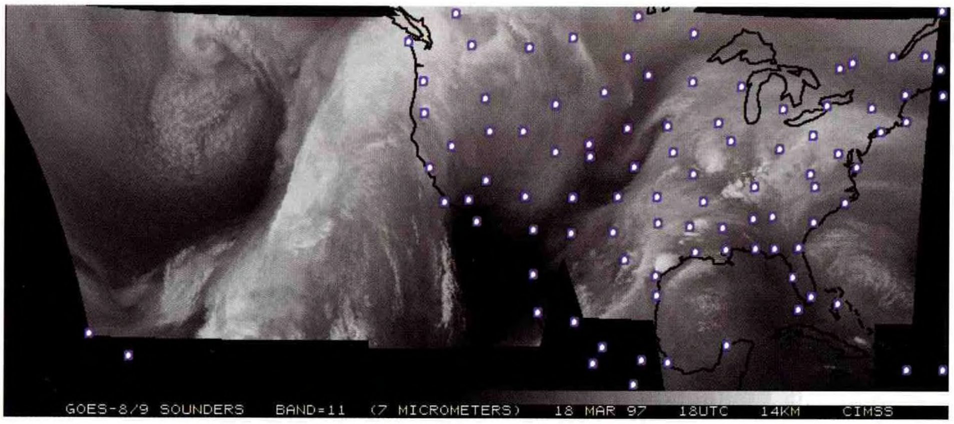


Figure 2a. Radiosonde locations plotted over the infrared window image for 1800 UTC March 18, 1997.

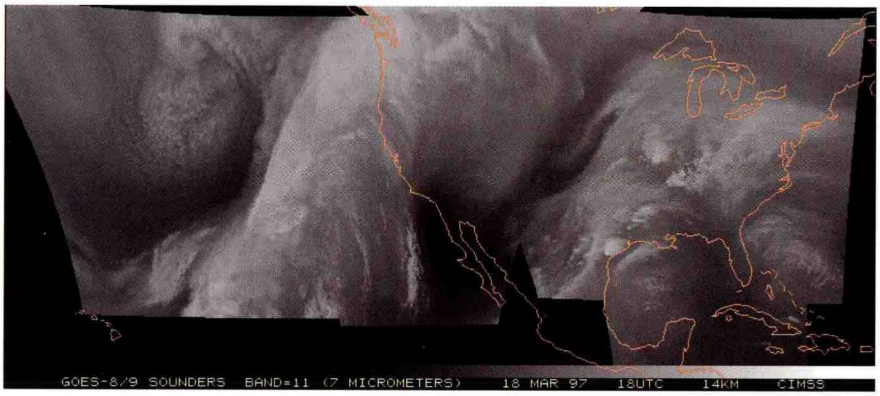


Figure 2b. An example of the hourly sounder coverage of North America and nearby oceans for the 7.0 micrometer channel from both GOES-8 and -9 on March 18, 1997. The data have been remapped into a Lambert Conformal projection.

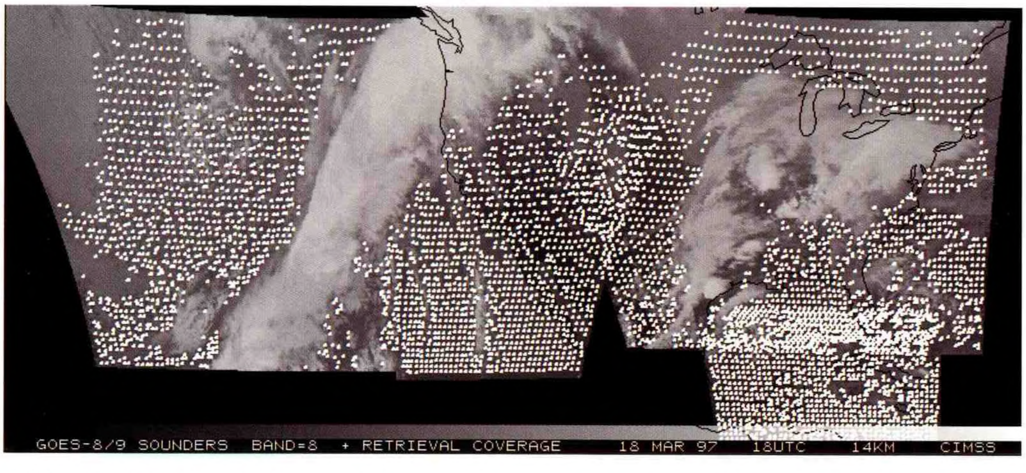


Figure 2c. The GOES-8 and -9 sounder retrieval coverage (white boxes) plotted over the infrared window image for 1800 UTC March 18, 1997. Each white square represents a retrieved profile spaced approximately 30 km apart.

Soundings are produced hourly primarily over the U.S. and adjacent waters. Because of the oblique view, and increasing atmospheric path, no soundings are done north of 50° N. Soundings are only computed for clear sky conditions.

The 19 channel sounder includes eight carbon dioxide channels, four water vapor channels, four infrared window channels, plus an ozone, a nitrogen, and a visible channel. Each channel measures radiances at different levels of the atmosphere. Figure 4 shows the weighting functions for the water vapor channels. Note that channel/band 10 captures the lowest, band 11 the middle level and band 12, the highest levels of moisture.

Discussion of products produced from the GOES sounders follows. Many of these products can be viewed on the Internet homepages at these addresses:

http://cimss.ssec.wisc.edu, and
http://orbit7i.nesdis. noaa.gov:8080/, and
http://orbit-net.nesdis.noaa.gov/ora/ht/ff/

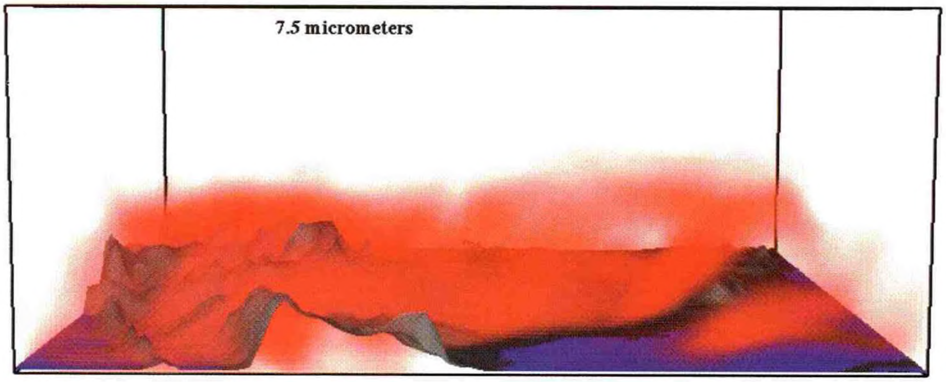


Figure 4a. Band 10 weighting functions for the GOES sounder water vapor channel in three dimensions for 1200 UTC October 23, 1996. Altitude ranges from 0 to 12 km. United States topography is indicated.

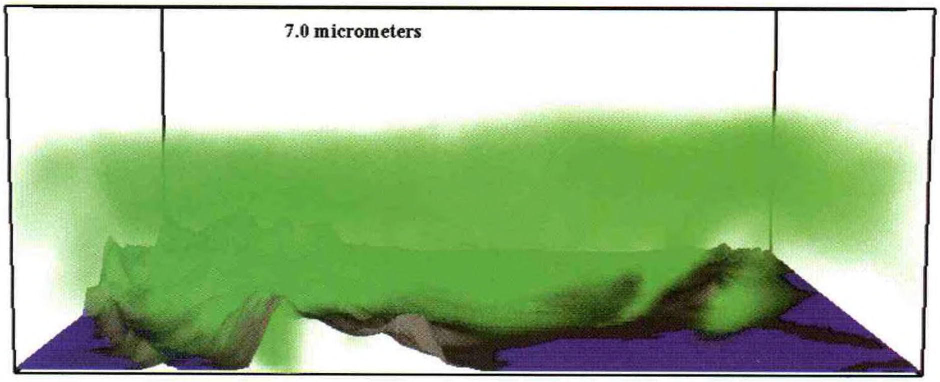


Figure 4b. Band 11 weighting functions for the GOES sounder water vapor channel in three dimensions for 1200 UTC October 23, 1996.

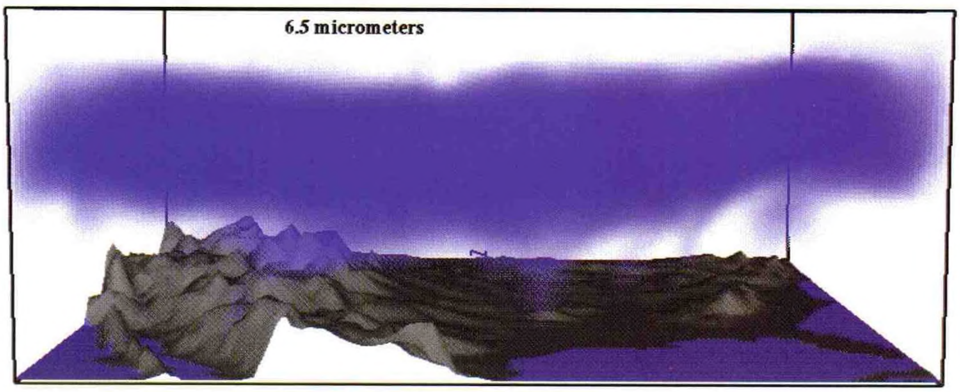


Figure 4c. Band 11 weighting functions for the GOES sounder water vapor channel in three dimensions for 1200 UTC October 23, 1996.

GOES SOUNDING PRODUCT SUITE

Sounding Profiles

The hourly sounding is computed using an iterative technique with the following input: radiance observations from 15 of the GOES-8 and -9 sounder channels, forecast information or a first guess of temperature and moisture profiles from the NWS' ETA model, hourly surface observations, and an estimate of the surface skin temperature and emissivity from the satellite (Ma, Schmit, and Smith 1998). The calculated or retrieved sounding contains temperature and moisture values for 40 levels in the atmosphere from the surface to .10 mb (about 18 km or 55,000 ft). Retrievals are attempted for an area of 3 x 3 field-of-view (fov) each 10 km in size for a horizontal resolution of $(30\ km)^2$. Each of the 9 fov sites are tested for clouds; the cloud clearing tests seek to identify thin cirrus, low level stratus, reflected sunlight and variable surface emissivity. Finally, each fov is classified clear, possibly clear, or not clear. If at least 4 fovs are clear, they are averaged and a retrieval or sounding profile (Figure 2) is made. If less than 4 fovs are clear then a retrieval is not made, unless the cloud tops are within 100 mb (1 km or 3,300 ft) of the surface, in which case an "overcast" retrieval is made. Data from cloudy areas is used to produce the Satellite Cloud Product (SCP) and cloud height and amount products.

Satellite Cloud Product

One of the earliest uses of GOES soundings was for the development of a Satellite Cloud Product of cloud top height and cloud amount. This is produced to complement the NWS Automated Surface Observation System (ASOS) (Schreiner, Unger, and Menzel 1993). ASOS, one of the new technologies of the NWS modernization effort has a maximum observing limit of 12,000 ft. for cloud detection. However, mid and high clouds occur at heights exceeding this threshold. Thus, GOES-8 and -9 sounder radiance information is used to determine the presence of clouds above 12,000 ft (3.6 km). The ASOS observation and the SCP are merged into a composite observation and a text message (figure 5) is prepared and sent through the NWS communications network. It is available hourly to the NWS, private forecasters, and radio and TV broadcasters. It also becomes part of the climate record for the site. Cloud top height and cloud top amounts are calculated each hour for 800 ASOS sites in the CONUS. The SCP is the only source of mid- and hi-cloud information at most of these sites.

The calculated SCP cloud heights and cloud amounts can also be superimposed on the coincident GOES images as shown in figures 6 and 7. This product is useful for aviation forecasting. Current text message and cloud height and amounts can be viewed on the Internet homepage at http://orbit7i.nesdis.noaa.gov:8080/.

TCUS40 KWBC 102333
SATELLITE-DERIVED CLOUD INFORMATION FOR MID (CLD TOPS 631-400 MB) AND HIGH LEVEL (CLD TOPS ABOVE 400 MB) (AUG)

STA	DA/TIMEZ	MID	HIGH	CLD TOP	ECA
K22G	10/2253	CLR			0
K2G6	10/2253		OVC	180-440	19
K2I8	10/2255	CLR			0
K5B5	10/2252	CLR			0
K7G2	10/2253	OVC		120-330	11
KABE	10/2254	BKN		120-260	21
KACY	10/2256	CLR			0
KAFN	10/2252	CLR			0
KAGC	10/2255	MCLR		150-330	8
KAKH	10/2300	SCT		180-180	2
KALB	10/2252	SCT		180-180	1
KAND	10/2301	CLR			0
KAOH	10/2254	OVC		120-300	40
KAOO	10/2255	OVC		120-210	38
KAQW	10/2252	CLR			0
KART	10/2250	CLR			0
KAUG	10/2250	CLR			0
KAVL	10/2300	CLR			0
KAVP	10/2253	CLR			0
KBDL	10/2253	SCT	SCT	150-330	3
KBFD	10/2253	OVC		120-230	27
KBGM	10/2253	MCLR		150-180	9
KBJJ	10/2254	MCLR		150-180	9
KBKL	10/2253		SCT	300-380	1
KBKW	10/2258	CLR			0
KBLF	10/2258		SCT	260-260	1
KBML	10/2250	CLR			0
KBOS	10/2252	CLR			0
KBUF	10/2252	CLR			0
KBUY	10/2259		BKN	150-380	4
KBWI	10/2256	CLR			0
KCAE	10/2302		BKN	180-300	50

Figure 5. A portion of the SCP text message for August 10, 1997, sent out through the NWS communication network to all NWS regions. It consists of the station four letter identification, satellite scan line time over the site, cloud top level (Clear-CLR, Mostly Clear-MCLR, Middle-MID, and High-HI) cloud amount (Scattered-SCT, Broken-BKN, and Overcast-OVC), range of cloud tops in feet, and average cloud amount for the 25 fovs.

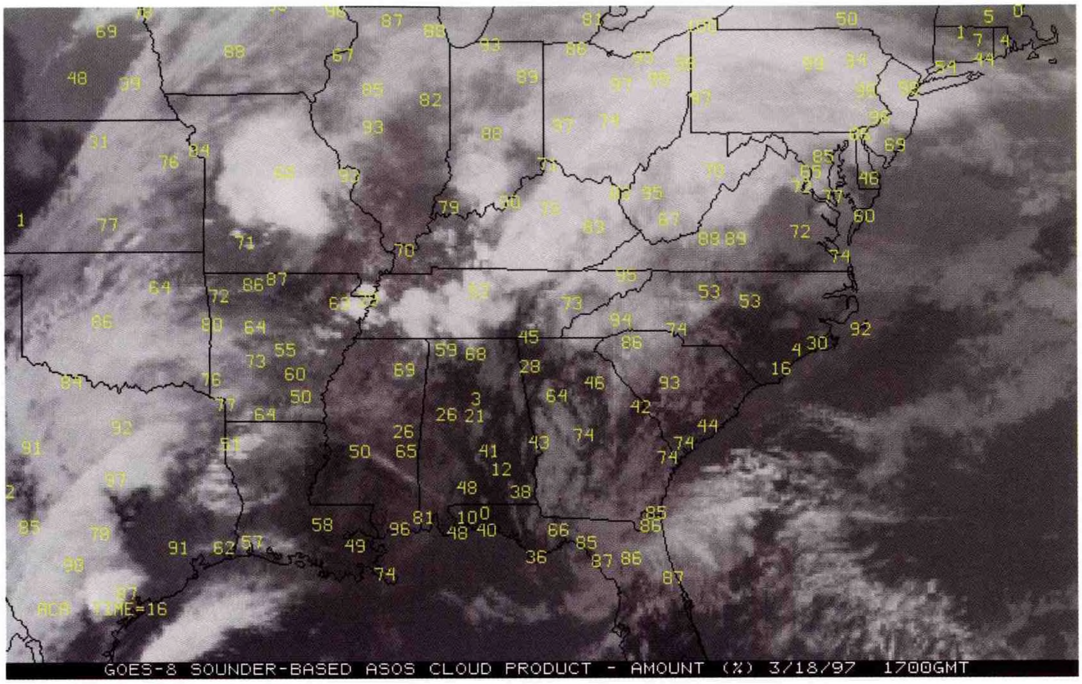


Figure 6. ASOS cloud amount (percent covered) superimposed on a GOES-8 infrared image at 1700 UTC, March 18, 1997.

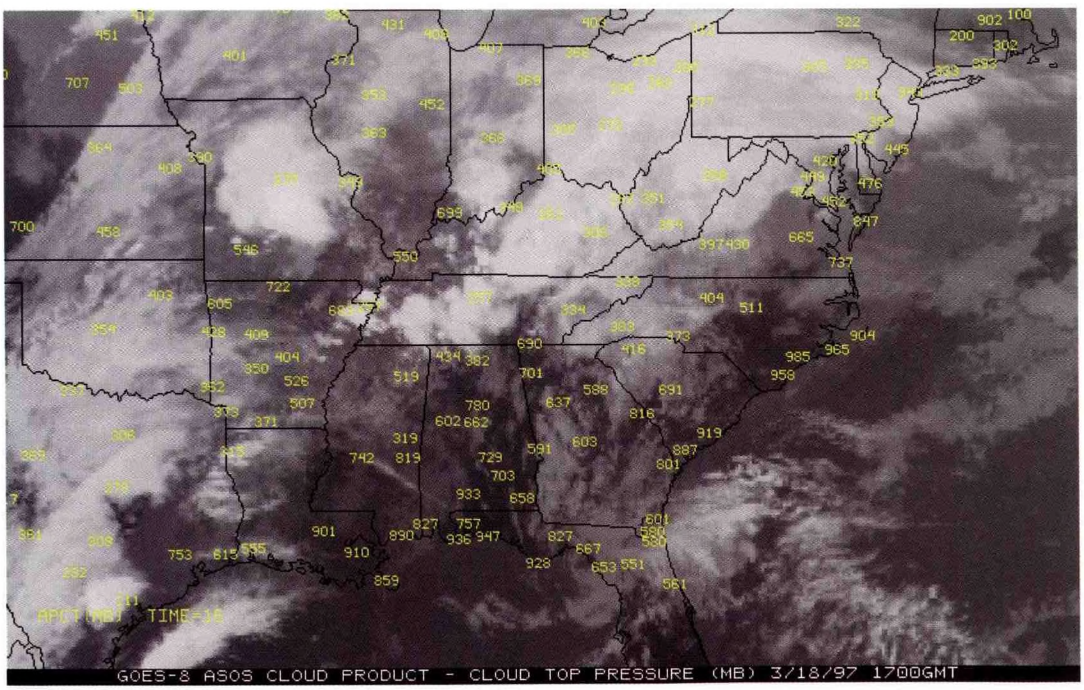


Figure 7. ASOS cloud top height superimposed on a GOES-8 infrared image at 1700 UTC March 18, 1997.

The quality of the satellite derived cloud product has been verified independently by the NWS. In their tests, the ASOS only cloud determination and the ASOS plus the SCP were compared to ground observations. Results show a decrease in error from 17% (ASOS only) to 6% (SCP plus ASOS) compared to ground observations (Schreiner, 1993).

Derived Product Imagery

Derived Product Imagery (DPI) are depictions of quantitative meteorological information that are color-coded and displayed as images (Hayden, Wade and Schmit, 1996). In some cases numerical values may also be overlaid on the imagery. Animation of these images allow forecasters to quickly locate changes in atmospheric stability, areal extent of moisture inflow, and surface heating and cooling. Currently the family of DPIs includes: cloud top pressure, total precipitable water, Lifted Index, Convective Area Potential Energy (CAPE) Index, and surface skin temperature.

Total Precipitable Water

The Total Precipitable Water (TPW) DPI represents the total atmospheric water vapor, in millimeters, contained in a vertical column extending from the Earth's surface to the "top" of the atmosphere. This information is particularly valuable for the short-term forecasting of fog, thunderstorms and precipitation. The amount of precipitable water or moisture available in the atmosphere for a storm system determines whether it will be a light rain event or a flash flood situation. Hourly updates of this information assist the forecaster in determining the timing and intensity of a rain event, the onset of fog, and even can be used to fine-tune local temperature forecasts. This product has been very useful in identifying moisture influx from data sparse offshore areas along the west coast of the U.S. and along the Gulf of Mexico coast by providing observations thousands of miles beyond the range of radars. This can be seen in Figure 8 where the moisture field associated with a storm system approaching the west coast of the U.S. is illustrated.

Lifted Index

The Lifted Index (LI) is an estimate of atmospheric stability. It represents the buoyancy which an air parcel would experience if mechanically lifted from the earth's surface to the 500 mb (about 5.5 km or 18,000 ft) level. The lifted index expresses the difference in the temperature between the ambient temperature at 500 mb and the temperature of the lifted parcel. A negative value (warmer than the environment) suggests positive buoyancy (continued rising); whereas a positive value suggests stability (descent).

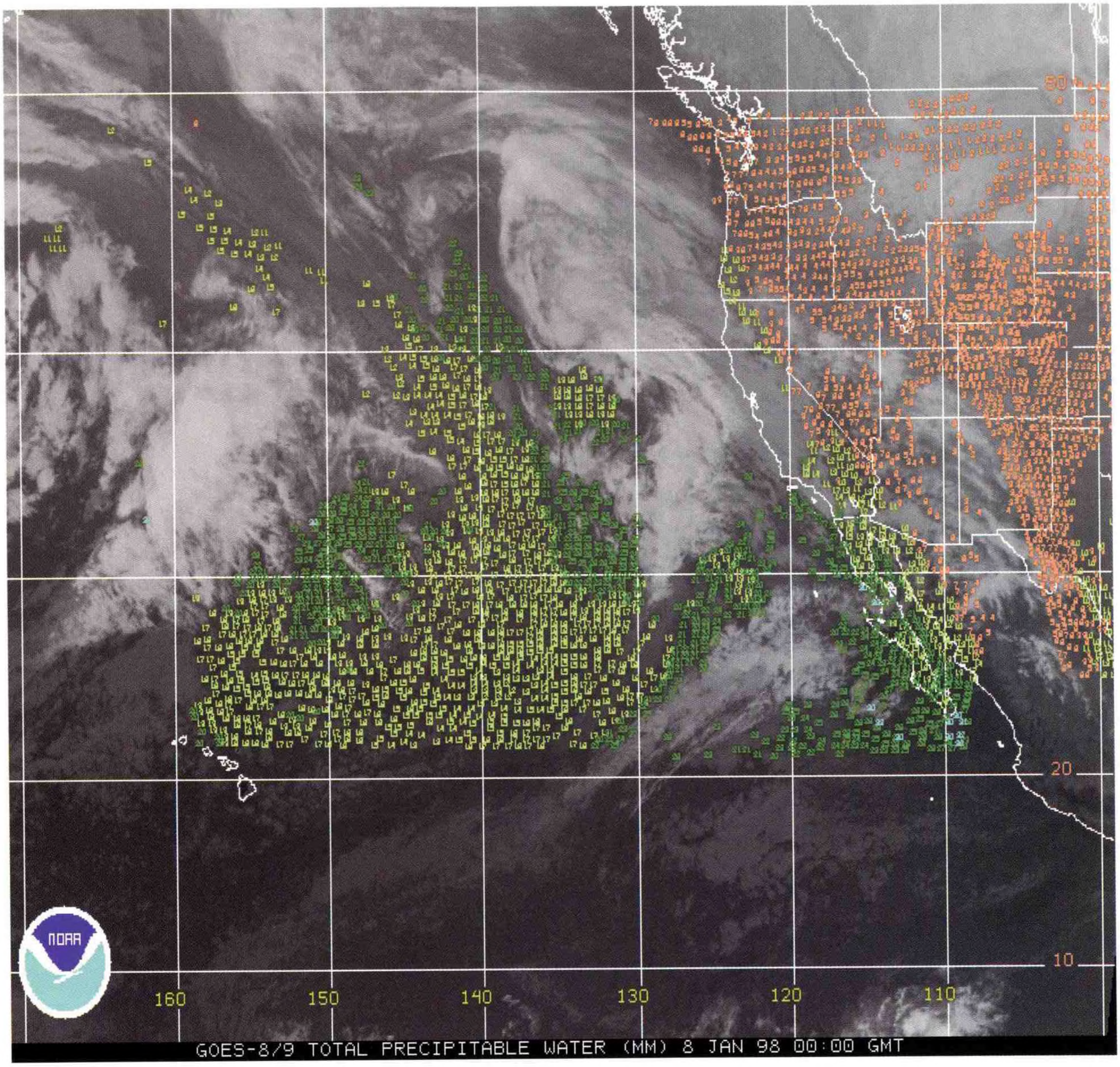


Figure 8. Total Precipitable Water from GOES-9 taken at 0000 UT January 8, 1998. Green and blue numbers represent moist areas (20mm, 30mm+ respectively), while yellow (10 to 20mm) and orange (less than 10mm) numbers indicate a drier atmosphere.

Since it is produced hourly, sequential maps of LI clearly show the diurnal and dynamic changes associated with weather events. It is particularly valuable for the short-term forecasting of thunderstorms, particularly severe storms, because it provides a dense array of atmospheric sampling that is not available from any other source.

A six hour (1446 to 1946 UT) time series of the Lifted Index product for central Texas on May 27, 1997, is shown in Figure 9. The red and yellow areas represent the most unstable air or the areas where severe thunderstorms are most likely to form. Note the high negative values over central Texas during the morning hours (1446 and 1546 UT) and the rapid development of severe thunderstorms (white areas) between 1746 and 1946 UT. Several tornadoes, most notably the tornado in Jarrell, Texas, and hail occurred with these storms.

Convective Area Potential Energy (CAPE)

Convective Area Potential Energy (CAPE) is another measure that is used by forecasters to determine the stability of the atmosphere. It measures the buoyancy of a rising parcel of air. CAPE values larger than 1000 Joules per kilogram (J/kg) indicate moderate amounts of atmospheric potential energy. Values exceeding 3,000 J/kg are often associated with severe weather. This parameter is also produced from the GOES sounding data.

Surface Skin Temperature

The temperature of the Earth's surface is another important measurement for numerical models and local forecasting. Hourly estimates of surface temperatures can be used, for instance, to monitor the onset of freezing conditions and can provide continuity in temperature trends between conventional observing stations.

Additionally, weather prediction models could utilize these data to calculate the diurnal changes in surface heat transfer or loss into the lowest levels of the atmosphere. Areas of wet ground from previous rain events can be determined and forecasters can infer the pace of drying and evaporation (Figure 10). Severe weather forecasters can animate these images and see trends in heating and further focus on the locally preferred areas of thunderstorm development.

Geostationary Winds

In 1996, a new experimental product, high density winds, was introduced to support tropical storm forecasting (Velden, et. al., 1997). Production of high density winds is similar to the traditional cloud-tracking and water vapor winds (Nieman, et. al., 1997) from the GOES images, but include far more vectors. In addition, data from two sounder channels, channels 10 and 11 (7.0 and 7.4 micrometers) are imaged and motion vectors are computed from sequential views. These sounder channels add more information in the middle levels of the atmosphere where clouds or tracers in the visible, water vapor, and infrared images are lacking. Figure 11 shows a set of winds produced from the sounder channels of GOES-9.

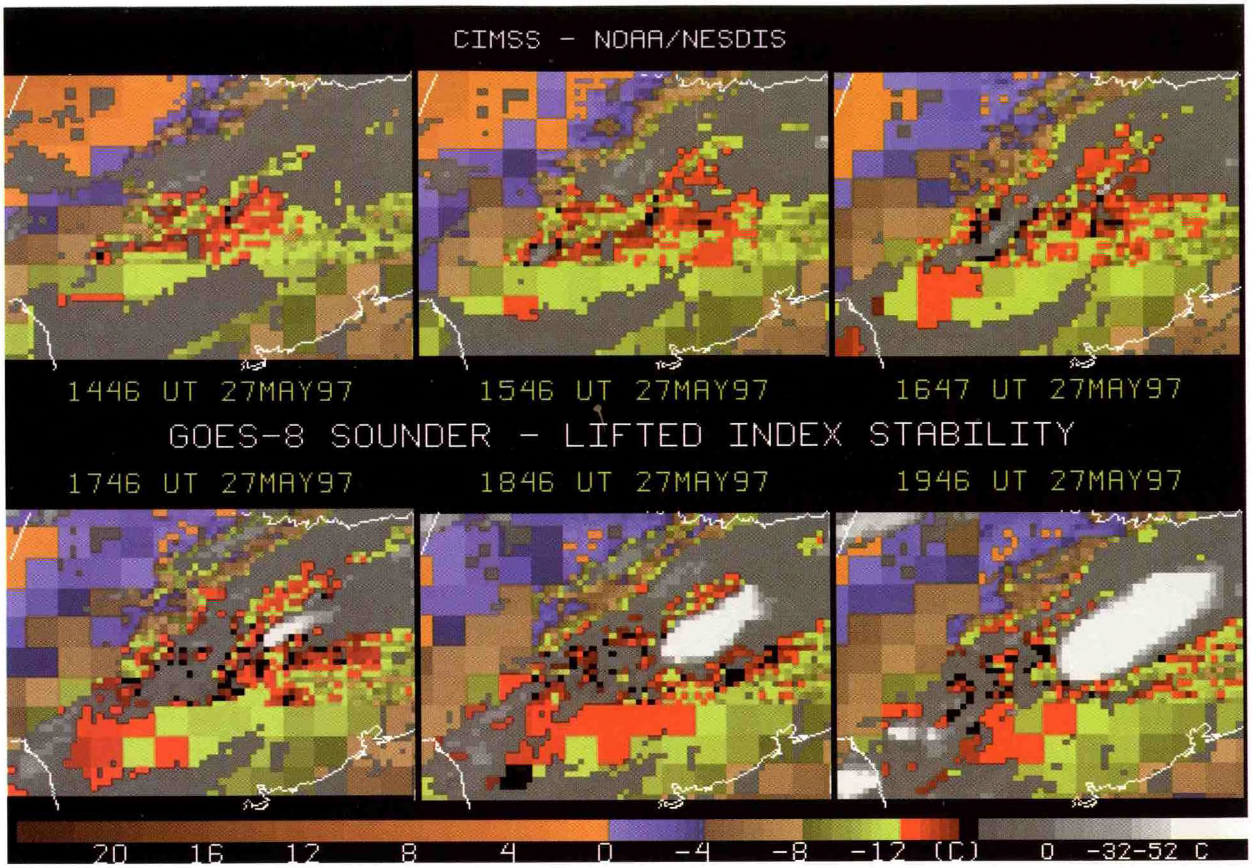


Figure 9. A six hour (1446 to 1946 UT)time series of the Lifted Index product for central Texas on May 27, 1997. Increasing unstable atmospheric conditions (greater negative values) are indicated by pink, yellow, red and black. Stable conditions appear as increasingly darker shades of orange. Low clouds are light gray and thunderstorms are white.

These four wind sets are merged together to produce the high density wind product. Nearly five times more vectors are produced daily. Most of these winds are computed for the data-sparse oceanic areas (Figure 12).

The U.S. Navy has used high density winds in their Navy Operational Global Atmospheric Prediction System (NOGAPS) model with significant improvement in their tropical storm and hurricane forecast storm tracks. As a result, the Navy has realized significant savings in ship operations.

High density winds became operational in the NWS models late in 1997. They are produced every six hours and plans are to increase this to every three hours. These winds are expected to improve track and intensity forecasts of all storms allowing residents, utilities, and local officials to better plan emergency response activities.

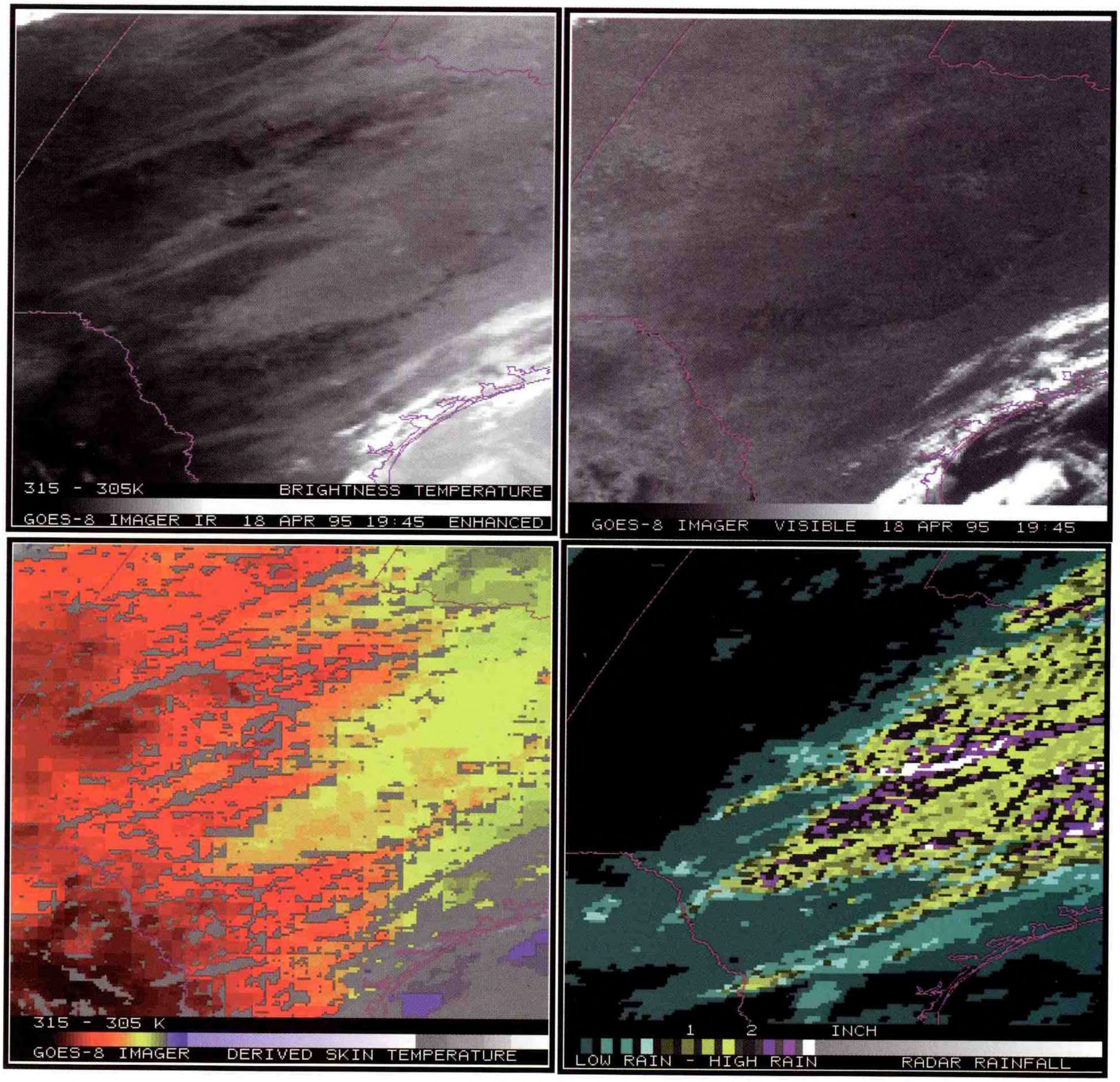


Figure 10. This four panel image illustrates the detection of wet ground in central Texas on April 18, 1996. Bottom right is the accumulated 24 hour radar estimate of rainfall with totals of 1 inch or more in yellow gray and pink tones. To the left is the GOES-8 surface skin temperature product for 1945 UTC; yellow shades are cooler and present a pattern similar to the heavier rain areas in the radar map. In the upper left is the infrared image where the rain area appears as cooler ground (lighter gray) and in the visible image to the right, this area appears as a less reflecting, darker gray area.

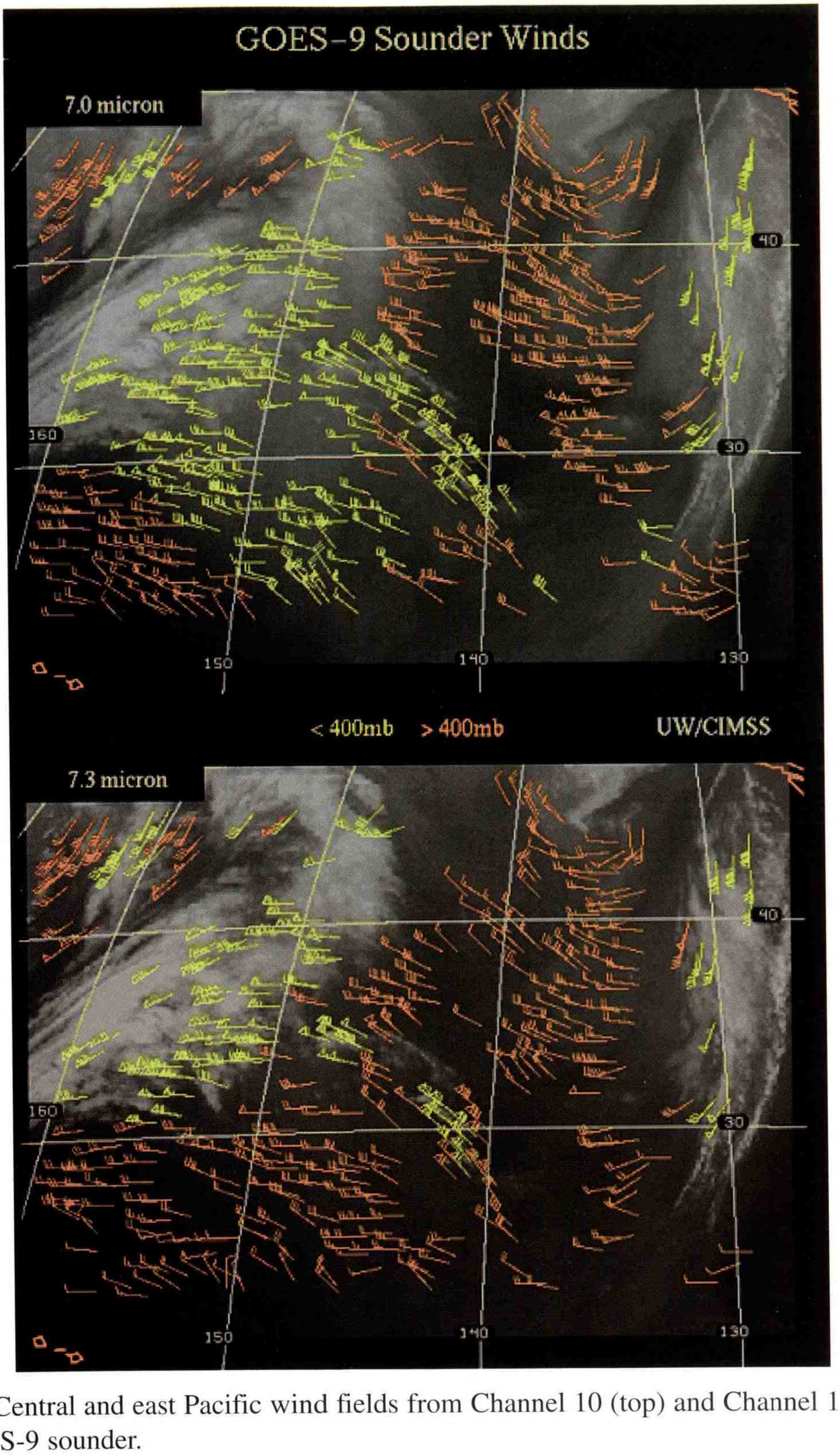


Figure 11. Central and east Pacific wind fields from Channel 10 (top) and Channel 11 (bottom) of the GOES-9 sounder.

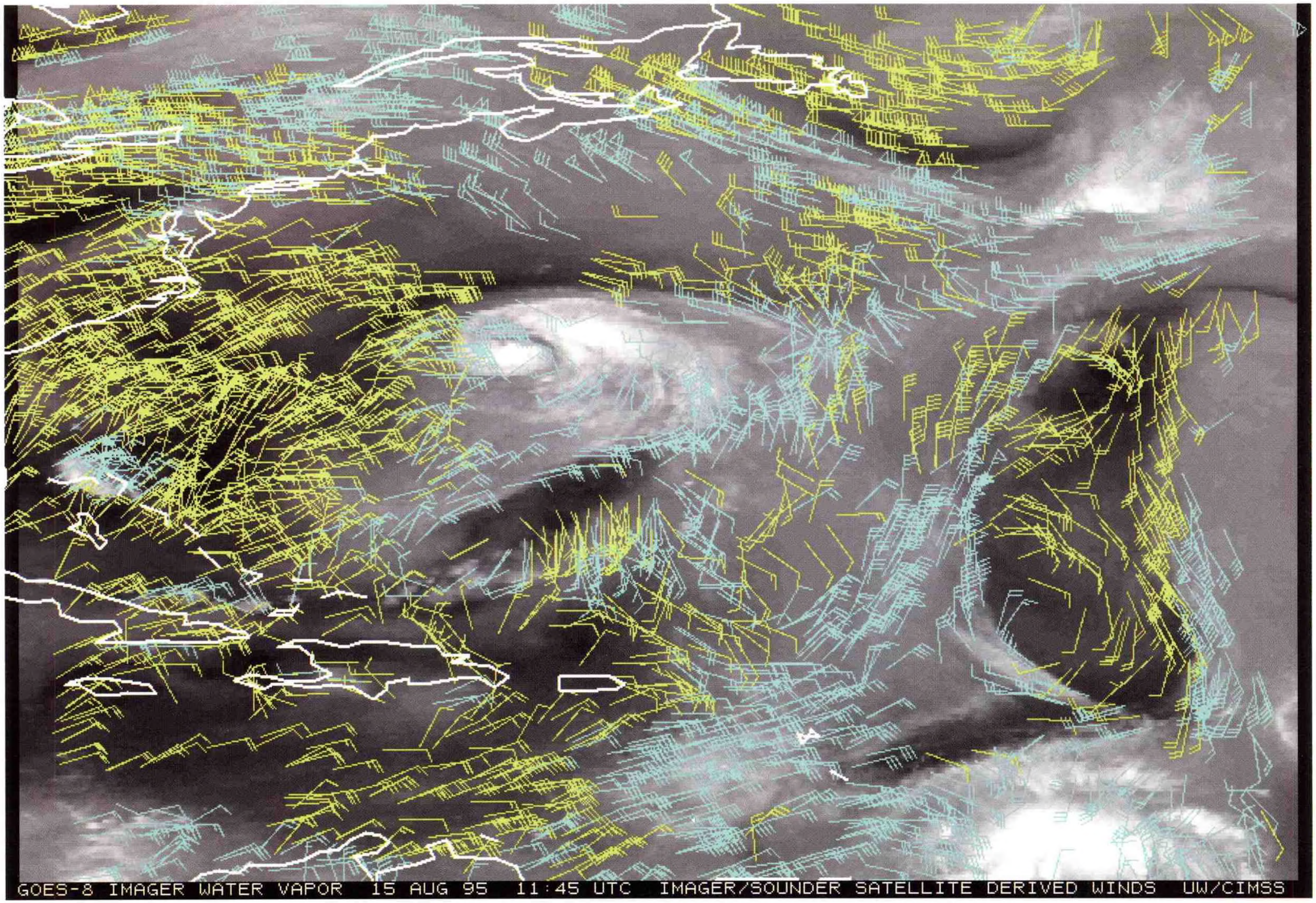


Figure 12. High density (imager and sounder) derived winds over the Atlantic Ocean for 1200 UTC August 15, 1995. Blue vectors are winds above (higher than) 400 mb, yellow vectors are winds below (lower than) 400 mb. Remnants of Hurricane Felix appear as the circular cloud mass in the center of this picture.

Numerical Weather Prediction

Before GOES sounder products were included in numerical weather prediction (NWP) models their accuracy was assured. A number of comparisons and tests were conducted. Figure 13 shows one such comparison of the GOES sounder 3-layer precipitable water (PW) with radiosonde observations and the ETA model forecast of PW. The GOES PW (dashed line) is closer than the Eta forecast PW (solid line) to the actual radiosonde observations. The GOES tends to be more moist than the radiosonde observation. GOES PW is useful in the forecast of clouds and rainfall. A study in the spring of 1996 by the University of Wisconsin found that the GOES sounder 3-layer PW reduced false alarm rates (where precipitation was predicted but not observed) in the 24 hour forecast of precipitation by 10 to 20%.

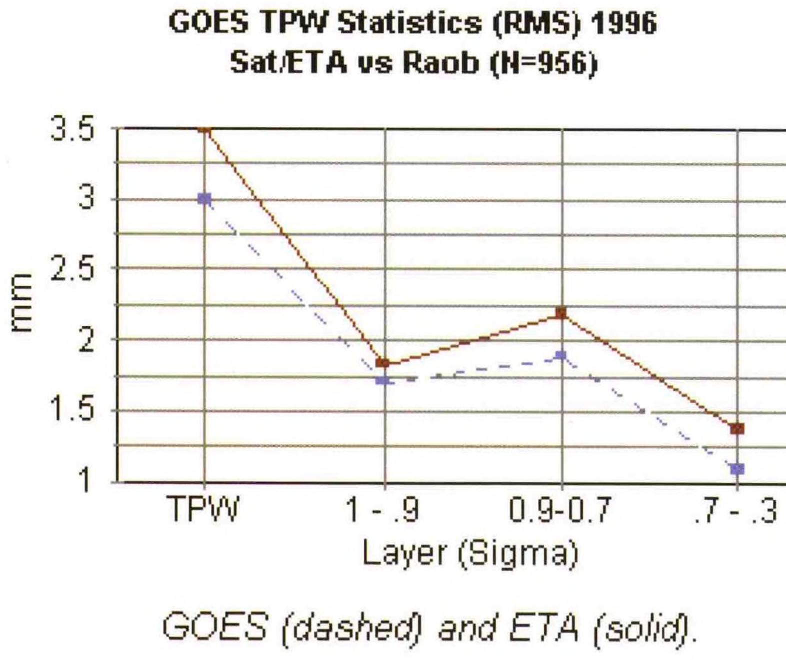


Figure 13. Comparison in millimeters of the GOES sounder TPW and the ETA model forecast of TPW with radiosondes. Statistics are for the total TPW column and for layers at 1000 to 900 mb; 900 to 700 mb; and 700 to 300 mb. The GOES TPW (dashed line) is closer than the Eta forecast TPW (solid line) to the radiosonde observations.

Another example of forecast improvement is shown in Figure 14. Here the GOES cloud cover information and clear sky TPW were included in the experimental forecast run. The results were a more realistic distribution of clouds in the storm system approaching the west coast of the U.S.

Use of the GOES sounder TPW in the NWS models began in October 1997. Figure 15 illustrates a GOES 3-layer PW field used by the ETA model (white boxes) on January 12, 1998, and the changes resulting from the GOES sounder information. Equitable threat scores that measure the accuracy of forecasts of the probability of precipitation have improved from September to December 1997 with the addition of the GOES sounder information. These cold and typically drier fall and winter weather statistics are very encouraging. Greater improvements are expected during the warmer and moister spring weather regimes.

To date the impact of GOES-8 and -9 sounder data on NWP is positive. Additional improvements should be realized as more detail is provided to the models through the three-layer temperature, cloud top pressure, and high density wind information. Further improvements are expected when assimilation of GOES radiances becomes a reality.

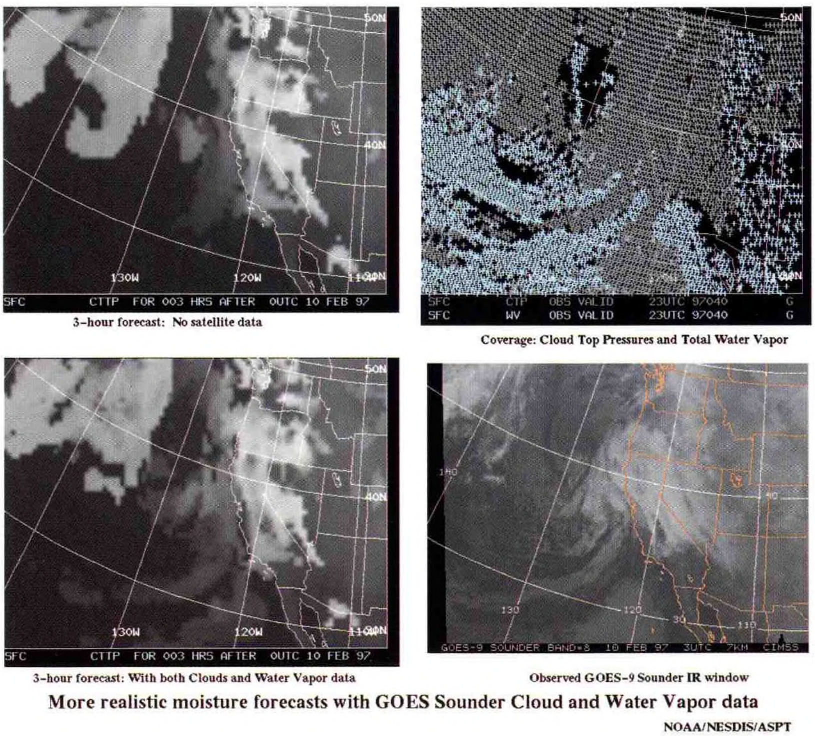


Figure 14. (upper left) Model 3-hour forecast of cloud distribution without GOES cloud heights and retrieved total water vapor; (upper right) the GOES sounder cloud heights and retrieved water vapor coverage for 0000 UTC February 10, 1997; (lower left) the same model's 3-hour forecast of cloud distribution with the GOES observations; and (lower right) the validating 0300 UTC infrared window image from the sounder. Note the additional detail and accuracy of the cloud field especially southwest of the California coast when GOES sounder observations are included in the forecast model.

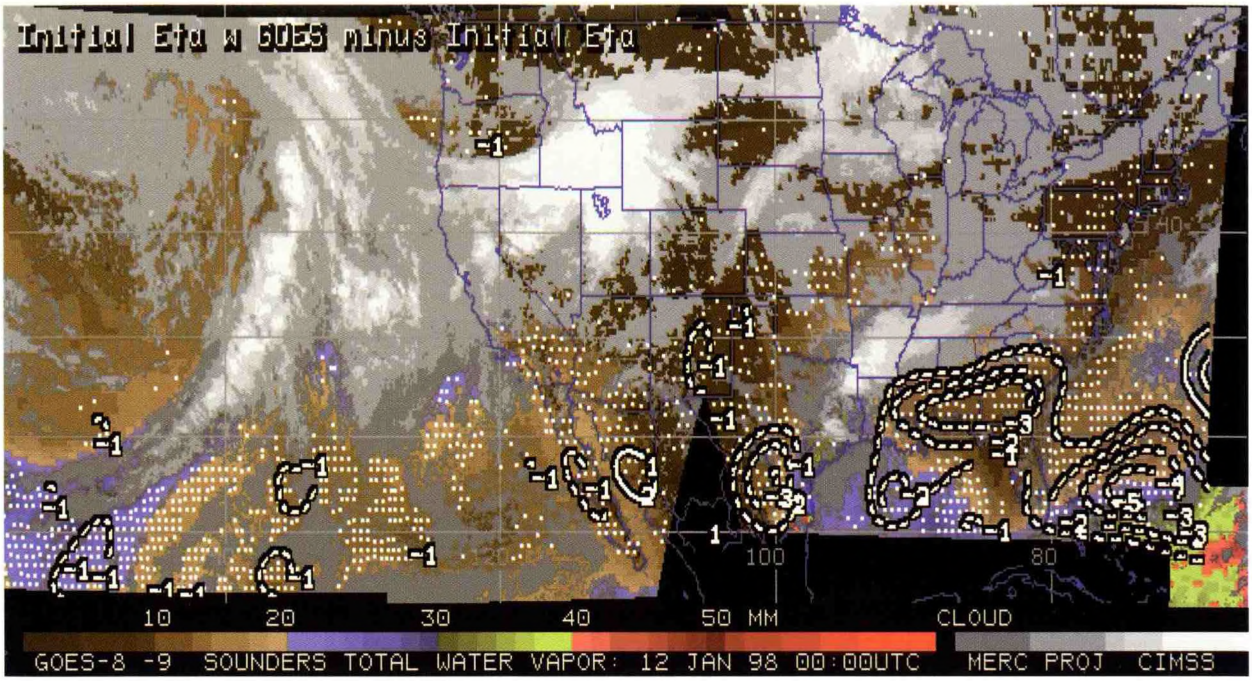


Figure 15. A GOES-8 and -9 composite of TPW (in mm) for 0000 UTC January 12, 1998. White dots indicate the locations of operational retrievals. Difference plots are shown between the initial ETA TPW and the 0000 UTC retrievals. There is confirmation of the GOES sounder moisture data being assimilated into the ETA model system by noting the small differences over most of the domain.

Regional and Local Forecast Applications

NWS forecasters have been assessing (NWS GOES Assessment Plan, 1997) and utilizing the information from the GOES sounders to improve local and regional forecasts for sometime. The applications vary according to the weather event and the region of the U.S. Comments from forecasters using the GOES sounder data in their local prediction activities are included on the inside covers of this report. Several examples of GOES sounder product utilization ranging from the forecasting of temperatures to severe weather are discussed in this section.

Temperature Forecasting

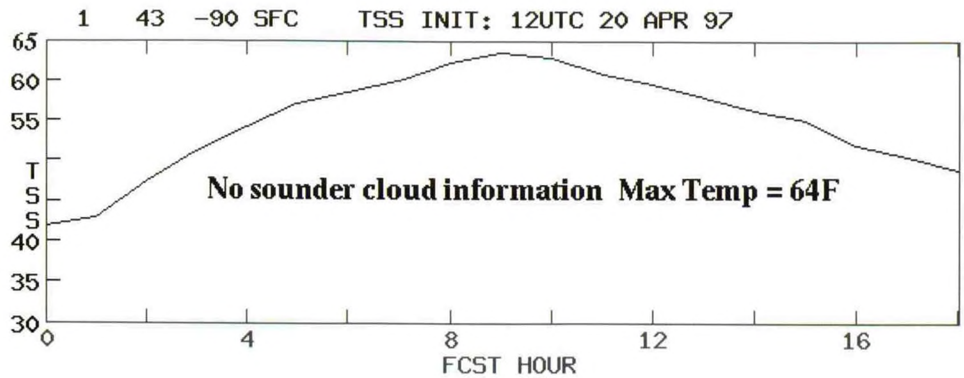
Using GOES sounder data to improve the forecast of maximum and minimum temperatures is a joint project of the University of Wisconsin and the NWS in Madison, WI. Sounder estimates of total column moisture in clear skies and cloud heights in cloudy regions, are inserted in the University's forecast model. These have adjusted the 24 hour forecast of hourly changes in surface temperature significantly. Figure 16 shows an example from April 20, 1997, at Madison, WI, where the hourly changes, forecast without sounder data (top panel), indicated a maximum temperature of 64^{o} F would occur at 2100 UT or 9 hours into the 1200 UTC forecast period. Adding the sounder data changed the temperature forecast (middle panel) to only a maximum of 59^{o} F at 1900 UT or 7 hours into the 1200 UT forecast period. The actual surface observations in Madison, WI, reported a maximum temperature of 58^{o} F at 2000 UTC (bottom panel); temperatures did not reach 60^{o} F that afternoon. This information is being produced daily for agricultural applications in various locations throughout Wisconsin; early feedback has been very positive (Diak et al., 1998).

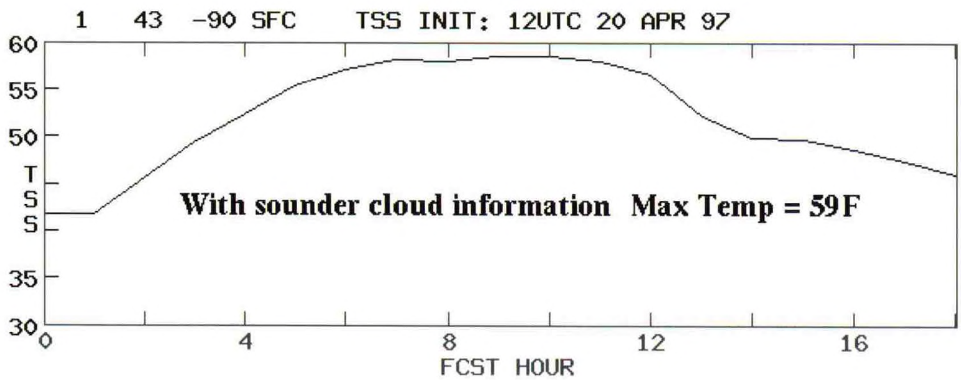
Accurate forecasts of low temperatures are just as critical for agriculture, public works, and utilities. A forecast of nighttime freezing temperatures starts a cycle of preventive measures in these business sectors. Influx of clouds, even the thinnest of cirrus, or a layer of moisture can in some cases significantly modify the amount of cooling overnight and negate the need for mitigation activities. Hourly sounder data and products can help meteorologists adjust such forecasts and help alleviate the need for costly preparedness activities.

Precipitation Forecasting

Forecasting how much rain will fall, and when it will begin and end is a major challenge. A number of products are being developed using both the GOES imager and sounder information.

For nearly 20 years, an analysis technique known as the Interactive Flash Flood Analyzer (Scofield and Achutuni, 1996) has been operational. It uses cloud top temperature from infrared imagery and conventional data to estimate hourly rainfall rates. Currently this product is being automated and enhanced to include data from multiple channels to more accurately estimate the rain and no rain areas and to correct for low cloud precipitation. GOES sounder data is also being used to help determine the amount of atmospheric water vapor that is available to storm systems. This is developed into a precipitation efficiency factor that provides guidance regarding the amount of rain that can be expected. For example, a storm system that has developed in an area of low precipitable water may have a large cloud shield, but little rain will fall because of the dry atmosphere. On the other hand, a storm with a strong connection to the tropics (high precipitable water values) will produce copious amounts of rainfall, or be precipitation efficient. The precipitation efficiency factor is calculated from the blended precipitable water product. This product is a composite of precipitable water observations for: cloud-free areas from both the GOES-8 and-9 sounders, cloud covered ocean areas from the microwave instrument of the polar orbiting Defense Meteorological Satellite Program (DMSP) satellite, and the ETA model in areas where no satellite sounding data is available.





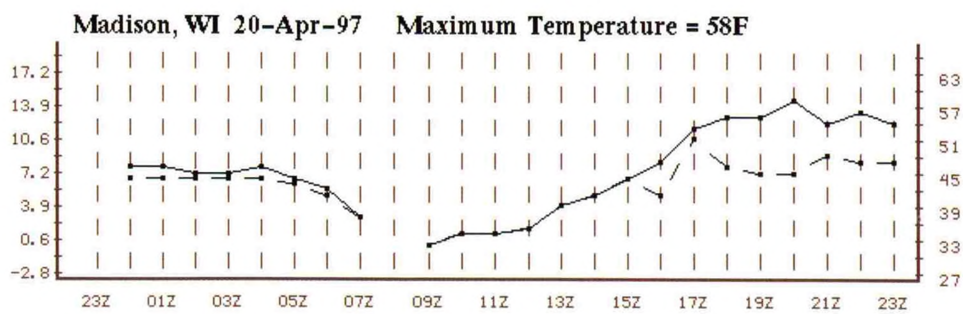


Figure 16. Maximum temperature forecast with and without GOES sounder data for April 20, 1997, in Madison, WI. Without sounder data (top panel)the maximum temperature forecast was 64$^{\mathrm{O}}$ F at 2100 UTC, 9 forecast hours after the model initialization. With GOES sounder data in the model, a maximum temperature of 59$^{\mathrm{O}}$ F at 1900 UTC, 7 hours into the forecast period (or two hours earlier) was predicted (middle panel). The actual high temperature (solid line) at Madison was 58$^{\mathrm{O}}$ F at 2000 UTC (bottom panel).

Figure 17 shows a sample product for January 15, 1998. In this case, precipitation estimates for the storm in the southeast and Mid-Atlantic states where the moisture is originating from warmer subtropical latitudes, would be increased by factors ranging 5 to 15. Rainfall with the storm entering the California coast is not being fueled by a tropical air mass, thus the correction factor or precipitation efficiency is 10 or less. This experimental product is updated four times a day. The satellite data provides critical observations, especially over data sparse offshore areas where moisture originates and fuels subsequent precipitation over the CONUS.

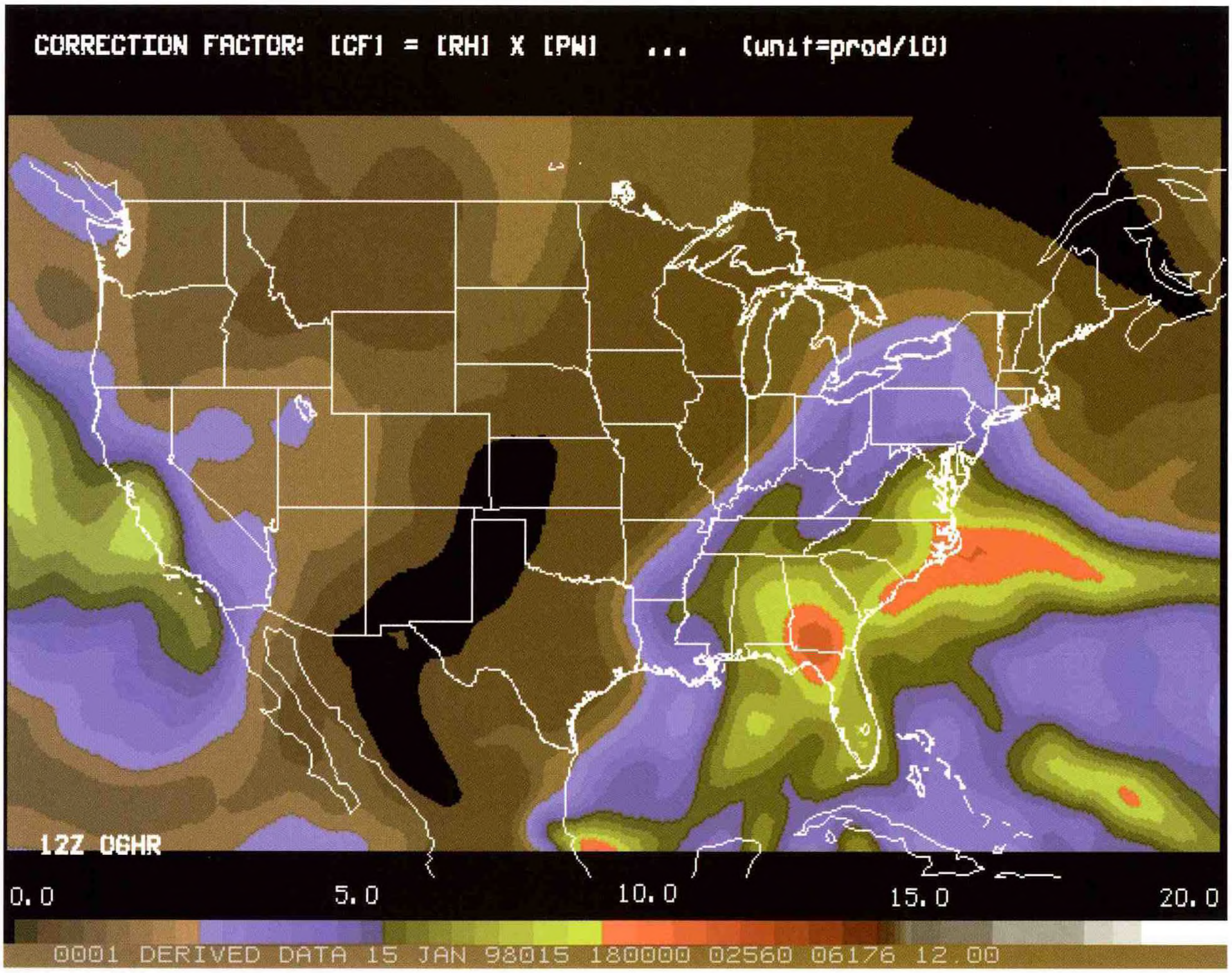


Figure 17. Precipitation efficiency for estimating rainfall. Higher units indicate more efficient (higher precipitable water) environments and the possibility of heavier rainfall.

Aviation Weather

Commercial, military, and general aviation is very weather sensitive. Fog, thunderstorms, heavy rain and snow often result in major delays at our nation's airports. Wind gusts and microbursts or downbursts associated with showers and thunderstorms are particularly dangerous during take-offs and landings and have resulted in numerous accidents. Research has characterized the atmospheric elements critical to the development of these hazardous weather situations. Radiosonde measurements have traditionally been used to compute the WIND INDEX (WINDEX), however as noted earlier, the number of observations and the distribution of stations is limited. Nelson and Ellrod (1997) have developed a new experimental product that utilizes hourly GOES sounder observations in the computation of the potential of microbursts and surface wind gust potential.

Figure 18 shows the WINDEX product, computed from the GOES-9 soundings, for the southwestern U.S. on the afternoon of August 14, 1996. The maximum potential surface wind gusts are indicated by colored boxes. The strongest wind gusts, exceeding 70 knots, were expected across the desert regions of southeastern California and southwestern Arizona. Early that evening a severe thunderstorm moved across south central Arizona. Winds of 115 mph were observed north of Phoenix. Extensive property damage exceeding more than $300 million and one fatality were reported.

The GOES microburst product is currently being evaluated by the Air Force. The wide geographic coverage and continual updates of the satellite observations are unique to making this product useful for not only aviation interests, but power companies, mariners, sports and special event managers, construction crews, and emergency response teams.

Severe Weather

On days when severe weather is expected, constant vigilance to changing conditions of temperature, moisture, and atmospheric stability is the primary job of the forecaster. The hourly GOES sounder products (LI, CAPE, PW) described earlier can play a key role in providing updated observations in support of this critical and often volatile short-range forecasting or nowcasting situation. On the afternoon of May 27, 1997, very strong tornadoes occurred near Jarrell, TX. Early that morning, Figure 9, the GOES-8 LI product indicated an extremely unstable atmosphere (red areas) across central eastern Texas. This LI sequence of images shows an axis of persistent and remarkably unstable values (red - LI values in excess of -12° C, and black in excess of -15° C) along which the Jarrell storm developed. The trend and horizontal gradient in the LI field computed from the GOES sounder observations were not available from any other measurement (e.g., radiosonde) source.

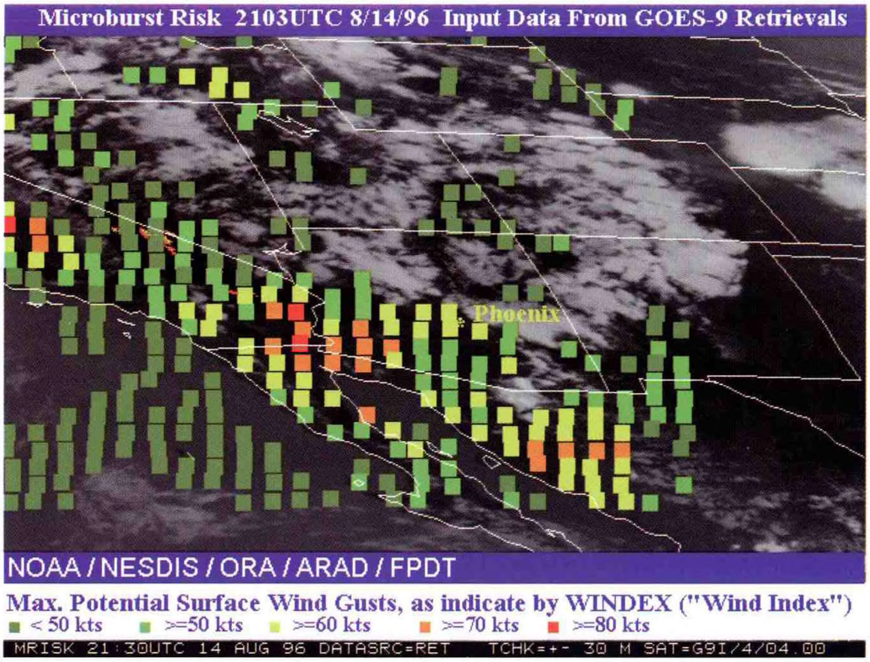


Figure 18. WINDEX product computed from the GOES-9 sounder temperature and moisture retrievals for the southwester U.S. on the afternoon of August 14, 1996. Colored boxes show the potential for surface wind gusts exceeding 50 knots. Wind gusts exceeding 80 knots were expected in areas along the southern border of California and Arizona.

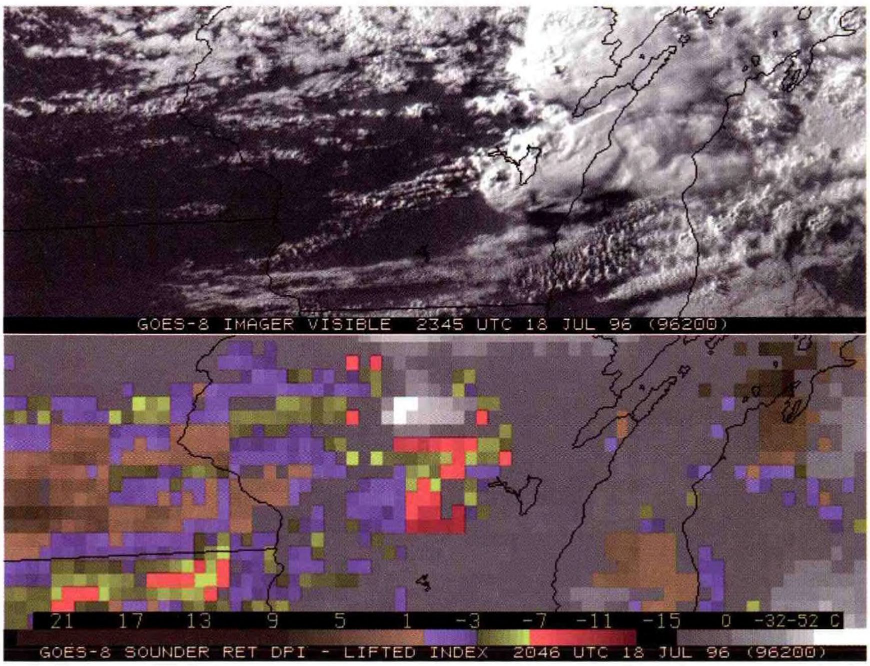


Figure 19. The GOES-8 LI image (bottom) for 1046 UT July 18, 1996, showing very unstable air over central Wisconsin. Three hours later the severe thunderstorms shown in the visible image (top panel) produced a tornado that devastated Oakland, WI.

In another case, the GOES-8 LI image, bottom panel Figure 19 indicated very unstable air over central Wisconsin at 2046 UTC on July 18, 1996. Generally unstable air (LI values of -3 to -7° C) lay along a cold front located just south of the Minnesota-Iowa border. Small localized pockets of more unstable air (with LI values of -8 to -10° C) can be seen in central Wisconsin. 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, Wisconsin. The GOES visible image (top image) clearly shows the thunderstorms associated with this event. A timely tornado warning by the NWS helped to prevent any loss of life, in spite of heavy property damage. Stability information from the GOES sounder supports the warning decision.

Severe weather, including large hail, damaging winds and three small tornadoes occurred in central and eastern Kansas between 2300 UT July 13 and 0600 GMT July 14, 1997. Gray, Daniels, and Gray, 1997, analyzed the ETA model forecast fields and the GOES-8 LI and TPW for the event. Shown as figures 20 and 21 are TPW tendencies for the four hours prior to the outbreak of severe thunderstorms. Data from the GOES sounder (which does not sample in the same location each hour) was collocated with the information from the NWS ETA model and analyzed. Four hour changes or tendencies in the TPW field prior to the onset of the thunderstorms were calculated and can be seen in Figures 20 and 21. The ETA model (figure 20) showed moistening (increasing values of TPW) in eastern Oklahoma, eastern Kansas and western Missouri and a drying tendency in northwestern Kansas and southwestern Nebraska. Data from the GOES-8 sounder is displayed in Figure 21. This field is significantly different from the model forecast with a much narrower axis of positive values from Oklahoma to Nebraska, and a large area of significant drying in from eastern Kansas to northwestern Missouri. A drying in northwestern Kansas can be seen in both analyses however the magnitude and extent of this trend is larger in the GOES sounder product.

The GOES TPW clearly shows the axis of moisture available to fuel these thunderstorms, and indicates an increasing moistening of the atmosphere along this north south line from northern Oklahoma to southeast Nebraska prior to the development of the storms. The ETA model predicted a moisture axis, and precipitation extending generally east west from northeast Kansas to north central Missouri. The only precipitation that occurred that afternoon was with the line of thunderstorms shown in Figures 20 and 21.

These examples demonstrate that the GOES sounder products are beginning to have impact on the severe weather watch and warning decision process and they support the goal of the NWS modernization program to reduce the area of unnecessary warnings in critical weather situations.

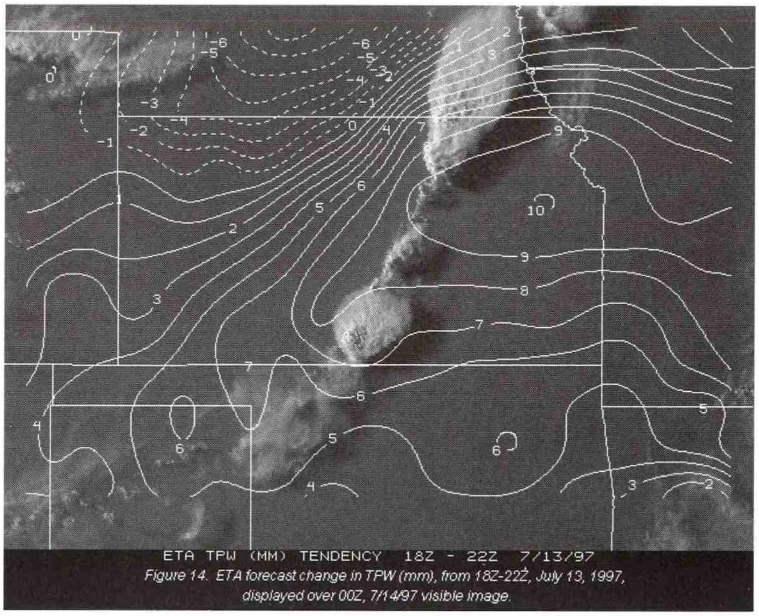


Figure 20. ETA model forecast change in TPW (mm) from 1800 to 2200 UTC, July 13, 1997, displayed over the GOES visible imagery taken at 0000 UT July 14, 1997. Solid lines are increasing values of TPW; dashed lines are decreasing values.

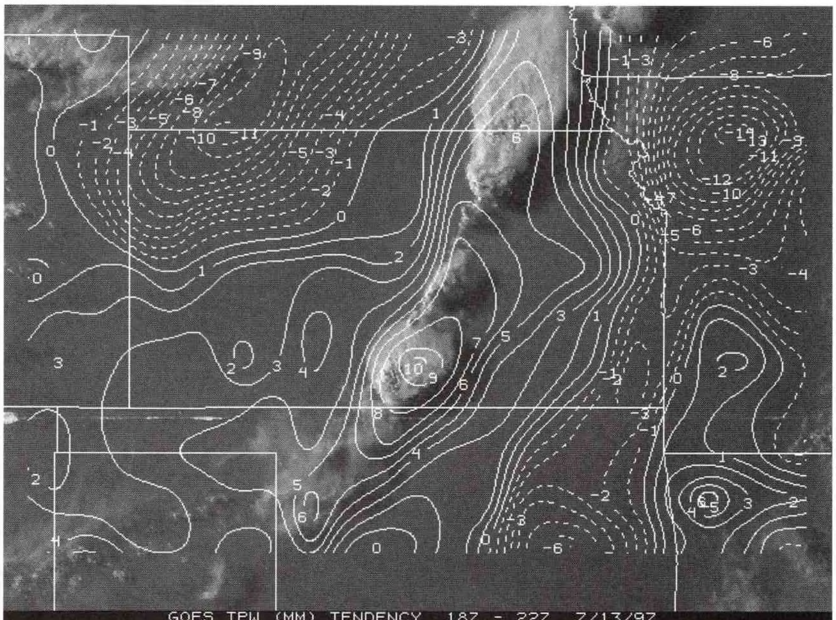


Figure 21. Change in TPW (mm) from the GOES sounder TPW product from 1800 to 2200 UTC, July 13, 1997, displayed over the GOES visible imagery taken at 0000 UTC July 14, 1997. Solid lines are increasing values of TPW; dashed lines are decreasing values.

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. Some of these benefits are listed below.

* In the area of disaster mitigation, better definition of mass and motion fields should results in more accurate hurricane trajectory forecasts. This was demonstrated when 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. Experimental forecasts using high density winds have shown the potential for improving hurricane track forecasts (Figure 22). More generally, considerable savings are possible 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.

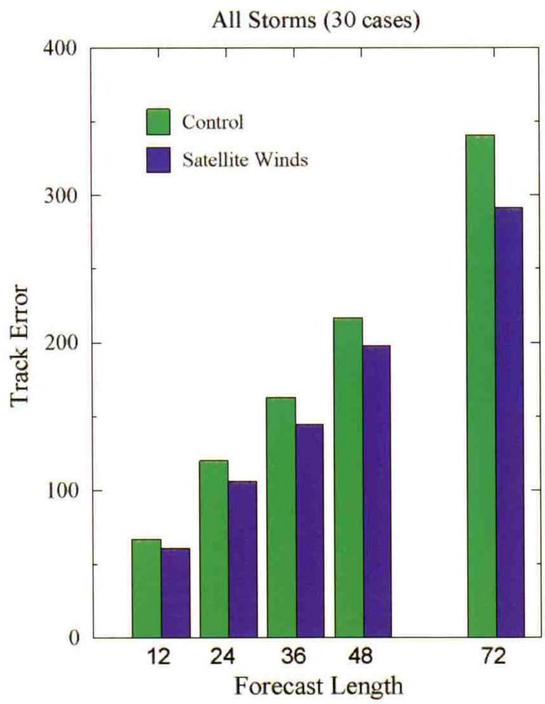


Figure 22. Results of experimental use of high density winds in hurricane track forecasts show that the GOES data reduces the error (is more accurate) in all time periods from 12 to 72 hours.

* Estimates of precipitation and continuing rainfall potential are improved by using the hourly measurements of precipitable water from the GOES sounder. Information especially for data sparse offshore areas improves the forecast for coastal areas. Emergency preparedness managers and citizenry can be better prepared especially for flash floods that are the major cause of weather-related fatalities.

* 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 USDA in their program of integrated pest management). Improved forecasts of three day low temperatures would enable more mitigation of crop damage or loss for 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 will provide a number of benefits. Better information regarding fog, icing, head or tail winds, turbulence, surface wind gusts, and development of severe weather 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.

* Power consumption in the USA 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) on locations of lightning 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 multispectral GOES data.

* General weather announcements affecting public health need continuous monitoring of the variability of surface temperatures in urban and metropolitan areas during heat stress (and sub-zero conditions). Detection and monitoring of pollution, atmospheric particulate and aerosols, and their transport (flow behind fronts often seen to take NE USA pollution into Florida and the SE USA) are important also for respiration and allergy alerts.

The potential impacts of GOES sounder can be many and great. Some of the early applications presented in this article are an indication that the promise of the GOES sounders is already being realized and are enabling NOAA to provide improved services to the nation.

SUMMARY

GOES sounder performance is meeting or exceeding expectations. The GOES sounder data and products are produced on a higher space and time scale than conventional observations thus providing a continuum of observations not available from any other observation system today. 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 living up to expectations within the research community and are being used operationally by the National Weather Service.

GOES soundings are available to help assist the NWS produce accurate forecasts/nowcasts of severe weather, as demonstrated by examples such as for the Phoenix, Arizona wind event, and the Oakfield, Wisconsin and Jarrell, Texas tornado situations. 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 and provide the climate record for more than 800 stations in the U.S.

Additional applications are under study. These include: monitoring ozone concentrations, observing the diurnal change in sea surface temperatures, and identification of "hot" or "cold" land locations for input to numerical models and for forecasting thunderstorms, fog, or temperatures at regional and local levels.

The GOES sounder has begun an exciting new era of observations that provide more frequent and more complete coverage than was previously available from conventional upper air and surface observations. More importantly these observations provide a quantum jump in the meteorological data previously available from just satellite images alone. Today, the GOES sounder provides quantitative observations both vertically and horizontally of temperature, moisture and winds that are the major ingredients of weather forecasting. The increased temporal and spatial sampling, and continuum of these satellite observations will continue to help meteorologist better understand atmospheric changes and continue to bring improvements to weather forecasts for the nation.

Acknowledgments

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ACRONYMS

ACARS - Aircraft Communications, Addressing and Reporting System
ASOS - Automated Surface Observing System
CAPE - Convective Available Potential Energy
CONUS - Continental United States
DMSP - Defense Meteorological Satellite Program
DPI - Derived Product Imagery
fov - field of view
ft - feet
GOES- Geostationary Operational Environmental Satellite
km - kilometer
LI - Lifted Index
mb - millibar
mm - millimeters
NOGAPS - Navy Operational Global Atmospheric Prediction System
NWS - National Weather Service
NWP - Numerical Weather Prediction
PW - Precipitable Water
SCP - Satellite Cloud Product
TPW - Total Precipitable Water
UTC - Coordinated Universal Time
WINDEX - WIND INDEX

COMMENTS FROM FORECASTERS (CONTINUED)

"We have looked at the plotted instability data on the web site on several occasions in real forecast situation; and it seems to be most useful (for severe storms purposes) in tracking trends in instability. This is where that great time resolution and fine horizontal gridding becomes a huge advantage. It gives us quasi-observational upper air information between raob sites and synoptic release tomes where there currently is none."

R. Edwards, NWS Storm Prediction Center, Norman , OK

The Cheyenne, WY forecast office is using GOES satellite soundings for winter weather forecasting, an example follows. "Middle and upper level moisture continues to increase over central WY this evening...snow has also begun to develop over western CO....02Z satellite derived soundings also show mid level stable layer still exists...will remove probability of precipitation from most of central WY for tonight." The forecast of no snow verified.

D. Moore, NWS, Cheyenne, WY

"This [GOES temperature and moisture soundings] is great stuff. I am an aircraft dispatcher for Delta Air Lines in ATL [Atlanta] and I use this data daily for TSTM [thunderstorm] guidance."

S. Caisse, Delta Airlines

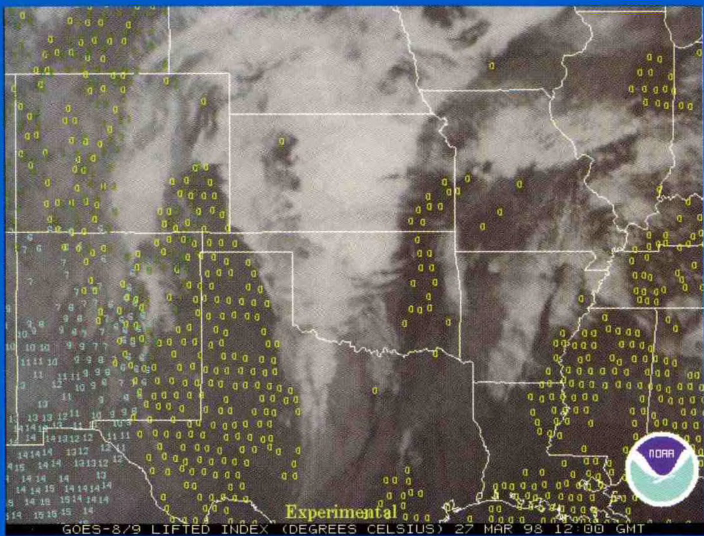
"One of our forecasters used the GOES soundings to update a tricky freezing rain forecast....Precipitation moving into western NY and across Lake Ontario at 01Z...GOES soundings at 23Z show very shallow layer slightly above zero around 850mb across northern areas. Warm layer a little deeper and warmer at Rutland. Very dry air noted below 700mb...good evaporative cooling likely in lower levels so precipitation should start as snow or snow/sleet across much of the region." P. Sisson, NWS, Burlington, VT

"What's particularly nice is how well the Sounder clearly defined the narrow tongue of high moisture ....through this narrow corridor [Gulf of Mexico to Gila Bend, AZ]. ....The forecaster in Tucson monitored the Sounder data and increase in low-level moisture and made appropriate changes to the forecast prior to any convection." Thunderstorms did develop along the edge of the moisture gradient...with severe storms....(reports of winds 66 to 75 mph). ...The modifications to the forecast...would not have been possible without the GOES-9 sounder data"

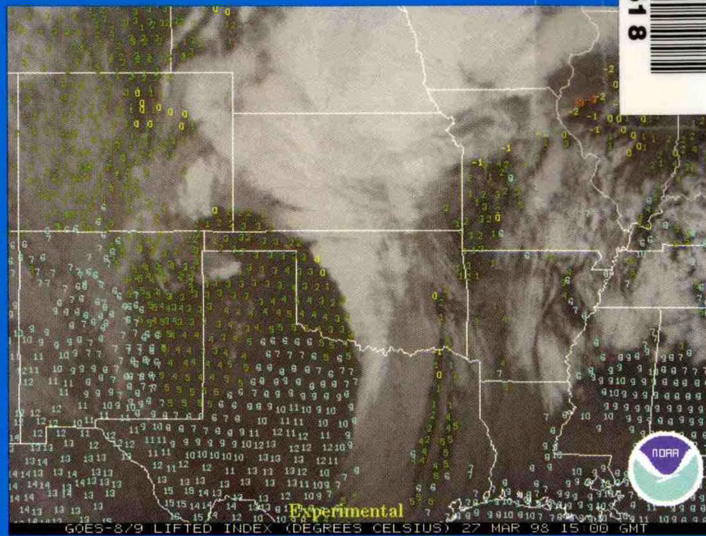
D. Bright, NWS, Tucson, AZ

Back Cover - Four panel display of GOES-8 Lifted Index for 1200 UTC, 1500 UTC, 1800 UTC, and 2100 UTC March 27, 1998.

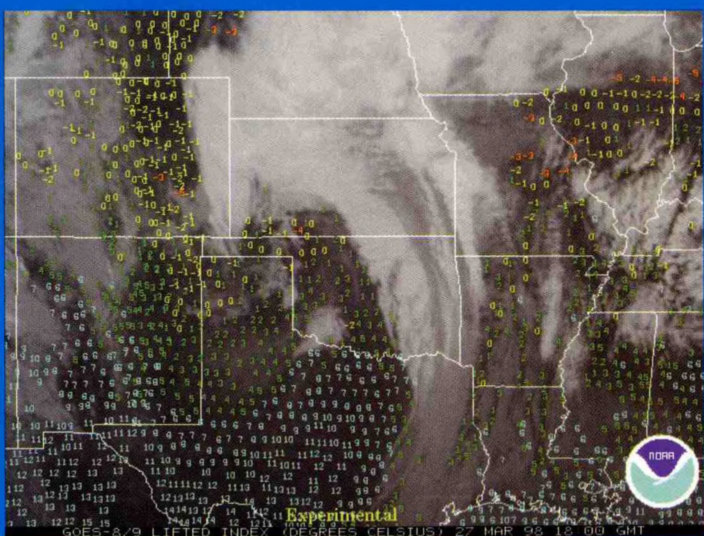
GOES 8 LIFTED INDEX



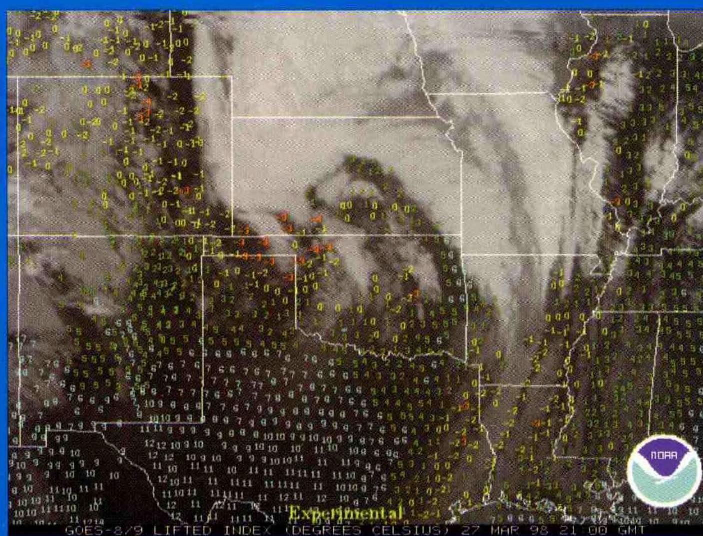
1200 UTC MARCH 27, 1998



1500 UTC MARCH 27, 1998



1800 UTC MARCH 27, 1998



2100 UTC MARCH 27, 1998