NOTES AND CORRESPONDENCE

Validation and Use of GOES Sounder Moisture Information

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ABSTRACT

The Geostationary Operational Environmental Satellite (GOES) sounders have provided quality hourly radiances and derived products over the continental United States and adjacent oceans for more than five years. The products derived from the radiances include temperature and moisture profiles; total precipitable water vapor (TPW); atmospheric stability indices, such as convective available potential energy (CAPE) and lifted index (LI); cloud-top properties; total column ozone; and midlevel motion. This paper focuses on validation and use of moisture profiles derived in clear regions. Validations are made with respect to collocated radiosondes, a microwave radiometer, and parallel runs of the regional Eta Model system. The ground-based microwave radiometer enables comparisons throughout the day, instead of only at conventional radiosonde launch times (0000 and 1200 UTC). The validations show that the sounder products provide unique information about the state of the atmosphere. The GOES sounder moisture data add information with considerably higher spatial and temporal resolution than is available from conventional radiosondes. Assimilation of three layers of moisture information retrieved from GOES sounder measurements has improved Eta Model precipitation forecasts even out to 48 h. Moreover, National Weather Service (NWS) forecasters are using GOES sounder products for a range of applications, with positive results.

1. Introduction

In April 1994, a new generation of geostationary sounders began measuring atmospheric radiances in 18 infrared (IR) spectral bands (Fig. 1) (Menzel and Purdom 1994; Menzel et al. 1998). The quality of these radiance measurements was improved over those possible from the earlier generation geostationary Visible and Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) and the polar-orbiting National Oceanic and Atmospheric Administration (NOAA) High-resolution Infrared Radiation Sounder (HIRS) instrument (Menzel et al. 1998). Weinreb et al. (1997) detailed the calibration procedure. The IR bands detect radiation emanating from layers as high as the lower stratosphere [e.g., band 1 (14.7 μm)] and down to the surface [e.g., band 8 (11.0 μm)] (Fig. 2), allowing the sounder to probe the atmosphere at different layers. This enables measurement of vertical variations of temperature, moisture, and total column ozone (Smith 1983; Hayden 1988; Li et al. 2001). Hourly temperature and moisture profiles from Geostationary Operational Environmental Satellite (GOES) sounder data have been generated routinely for clear (noncloudy) conditions over the continental United States and adjacent oceans since July 1995.

To generate these profiles, clear fields of view (FOV) are distinguished from cloudy FOVs (Schreiner et al. 2001). Temperature and moisture profiles are then calculated simultaneously from clear sky GOES sounder radiances with a physical retrieval algorithm (Smith 1983; Hayden 1988; Li and Huang 1999; Ma et al. 1999) that adjusts initial (or ''first guess'') atmospheric profiles of temperature and moisture. These guess profiles are derived using a National Centers for Environmental Prediction (NCEP) numerical model forecast (6–18 h) and surface observations. Currently forecasts from the Eta Model 0000 and 1200 UTC runs are used. Forecast profiles are interpolated in space and time to GOES retrieval locations. (On 22 May 2001 the operational retrievals began to use forecasts based on the NCEP Aviation Model.) The first guess profiles are adjusted until the associated calculations of brightness temperatures agree,

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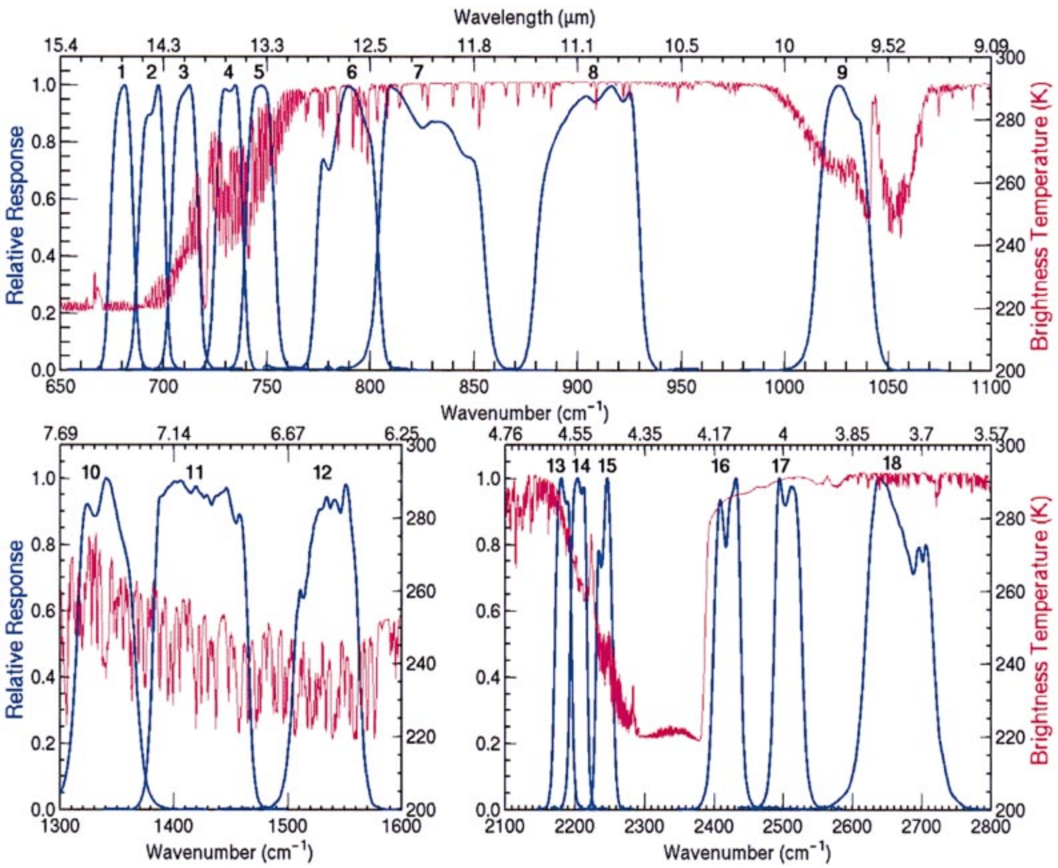

FIG. 1. Locations of the *GOES-8* sounder IR spectral response functions (blue) superimposed over a high spectral resolution earth-emitted spectrum (red). The central wavenumbers (wavelength) of the spectral bands range from 680 cm^{-1} (14.7 μm) to 2667 cm^{-1} (3.75 μm).

within some threshold, with the observed brightness temperatures. The observed brightness temperatures have been bias corrected and averaged over several FOVs to improve the signal to noise ratio. The operational GOES retrieval algorithm uses a 5 × 5 FOV average, while a 3 × 3 FOV average is used for experimental retrieval algorithms. In the retrieval process, over the continental United States, the moisture profile is adjusted more than the temperature profile (Ma et al. 1999). This is due to the high quality of the NCEP temperature forecasts. However, the moisture forecasts are less accurate and hence have more room for improvement. Given the importance of correctly analyzing the atmospheric moisture distribution, this paper focuses on the validation and use of moisture information derived from the GOES sounder.

Several methods were employed to validate the quality of the GOES sounder retrievals. In section 2, the traditional comparison of GOES retrievals collocated with radiosonde profiles (Rao and Fuelberg 1998) is presented. Recently, measurements with a microwave radiometer (MWR) at the Department of Energy Atmospheric Radiation Program (DOE ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site (Stokes and Schwartz 1994) enabled a more accurate assessment of moisture data at high temporal resolution. Comparisons of GOES sounder derived total precipitable water vapor (TPW) with the same derived from the CART site microwave radiometer are discussed in section 3. In addition, moisture retrievals from GOES in conjunction with an upward-looking high spectral resolution infrared instrument are presented. The impact

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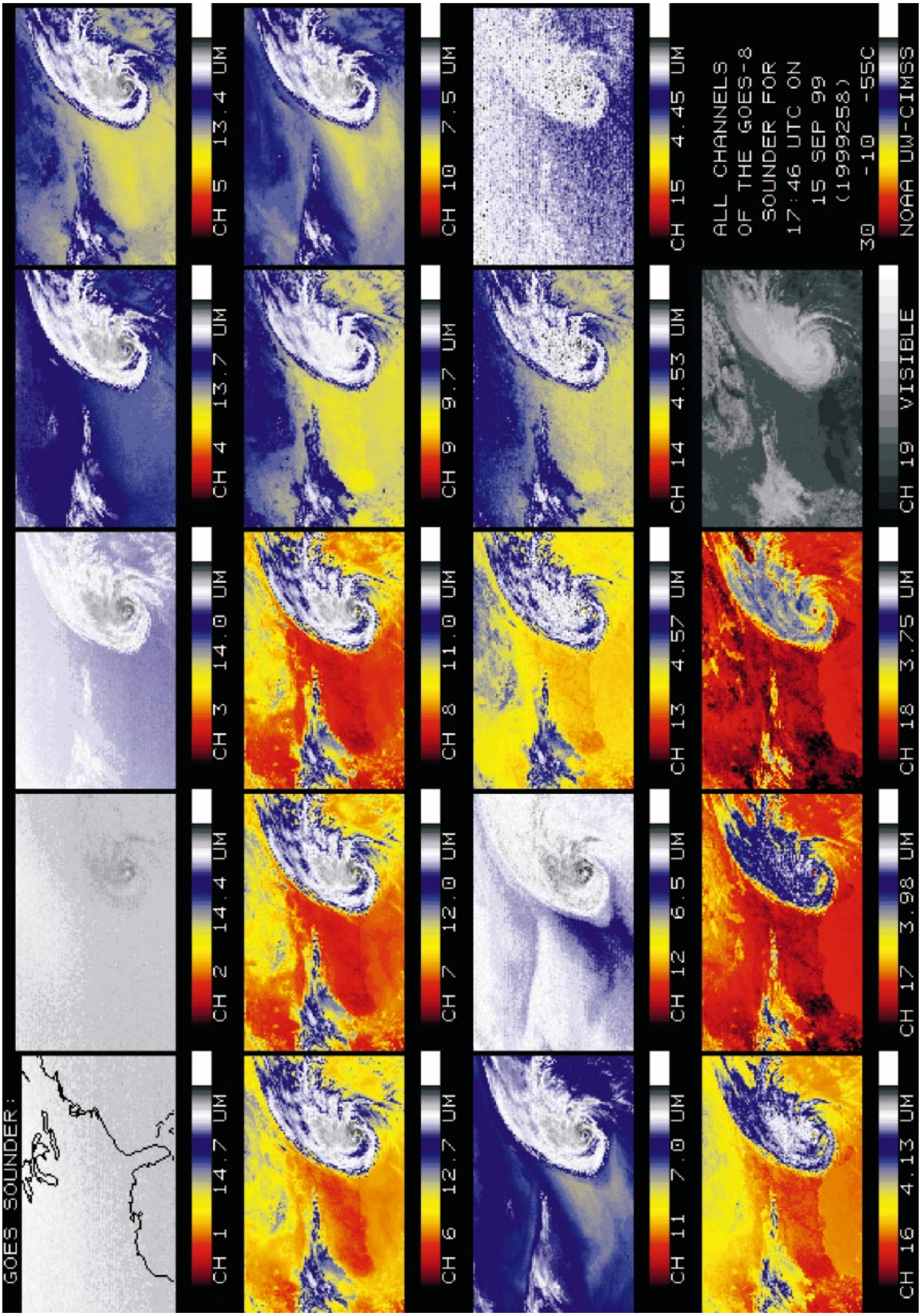
FIG. 2. The 19 *GOES-8* sounder bands for Hurricane Floyd at 1800 UTC on 15 Sep 1999. The bands are displayed beginning with band 1 in the upper left and increase to the right. All the sounder IR bands are displayed with the same color enhancement. Note the hurricane high clouds are seen in sounder band 2, which usually does not sense clouds. Window bands (7, 8, 17, and 18) are located in spectral regions where the atmosphere is relatively transparent. The sounder bands sensitive to CO_2 absorption (1–5) sense progressively deeper into the troposphere as the spectral band wavelength moves farther from the CO_2 absorption band center at 15 μm.


GOES SOUNDER:
CH 1 14.7 UM
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CH 8 11.0 UM
CH 9 9.7 UM
CH 10 7.5 UM
CH 11 7.0 UM
CH 12 6.5 UM
CH 13 4.57 UM
CH 14 4.53 UM
CH 15 4.45 UM
CH 16 4.13 UM
CH 17 3.98 UM
CH 18 3.75 UM
CH 19 VISIBLE
ALL CHANNELS
OF THE GOES-8
SOUNDER FOR
17:46 UTC ON
15 SEP 99
(1999258)
30 -10 -55C
NOAA UW-CIMSS

TABLE 1. Comparison of moisture (mm) for several layers from *GOES-8/10* retrievals and first guess from Eta Model forecasts from Apr 1998 to Mar 1999 with respect to collocated radiosonde observations. The bias (retrieved or first guess value minus radiosonde value) and standard deviation (std dev) are indicated. The next column, the rmsd, is the square root of the sum of the bias squared and the standard deviation squared. Collocation is within 0.25°.

	Guess			Retrieved		
	Bias	Std dev	Rmsd	Bias	Std dev	Rmsd
GOES-8 at 0000 and 1200 UTC. The number of samples is 6568.						
TPW	−0.67	3.60	3.66	−0.69	3.46	3.52
WV1	−0.72	1.60	1.76	−0.69	1.53	1.67
WV2	−0.16	2.00	2.00	−0.08	1.93	1.93
WV3	0.20	1.40	1.42	0.06	1.22	1.22
GOES-10 at 0000 and 1200 UTC. The number of samples is 1290.						
TPW	−0.45	2.95	2.98	−0.50	2.52	2.57
WV1	−0.96	1.20	1.54	−0.95	1.17	1.51
WV2	0.18	1.51	1.52	0.28	1.46	1.49
WV3	0.31	1.20	1.24	0.17	0.87	0.89

of moisture information on numerical model forecasts provides another means of assessing the quality and applicability of the sounder moisture profiles and is discussed in section 4. Finally, in section 5, the increasing use of GOES sounder products by forecasters is summarized.

2. Radiosonde comparisons

Typically GOES retrievals are compared to radiosonde observations. However, these comparisons are compromised because radiosonde point measurements (advected by the mean flow) are different than retrieved volumetric measurements from the GOES; additionally there are often collocation and time differences (Pratt 1985; Schmidlin 1988). Also, most radiosondes are land based, and collocation sample sizes may be small if only a short time range is considered. Table 1 shows bulk moisture validation statistics for the period April 1998–March 1999, comparing both the 12-h Eta forecast (first guess) and the GOES retrievals to collocated radiosondes. Four parameters are listed: TPW, and precipitable water vapor from approximately the surface to 900 hPa (WV1), 900–700 hPa (WV2), and 700–300 hPa (WV3). The bias (retrieved or first guess value minus radiosonde value) and standard deviation (std dev) are indicated. The next column, which is the rms difference (rmsd), is the square root of the sum of the bias squared and the standard deviation squared.

All four *GOES-8* retrieved quantities in Table 1 show improvement over the Eta Model forecast first guess in terms of the standard deviation. *GOES-10* TPW and WV3 std dev improvements are larger than those for *GOES-8*, possibly a result of the improved detectors on *GOES-10*. The *GOES-10* sounder instrument noise decreased by an average of 25% for spectral bands near 7 μm compared to *GOES-8*. Almost all of these radiosonde comparisons were made over land. Larger improvements to the first guess are generally made over oceanic regions (Menzel et al. 1998; Ma et al. 1999); this may be due to larger model errors over regions void of conventional (land based) data.

Differences from the first guess may have been larger if the *GOES-8* and *-10* moisture data were not operationally assimilated every 3 h by the Eta Data Assimilation System (EDAS) during this time period. GOES PW data were assimilated into the operational Eta Model during the model spinup period (the 12 h prior to the analysis time). So the *forecast* fields, which are used for the retrieval first guess, already contain prior GOES PW information. Thus these retrievals, compared to the forecast, may show less of an impact. To investigate this hypothesis, statistics from Ma et al. (1999) for a period prior to the assimilation of GOES sounder data into the EDAS, April 1996–March 1997, show the first guess TPW rmsd indeed improved by a larger amount (3.4–2.7 mm). Forecast model changes between the two time periods may have also caused the retrieval and model forecast differences to become smaller.

The hourly GOES sounder retrievals can reveal temporal changes and spatial gradients with greater detail than is possible from radiosondes. Time changes of moisture estimates from the GOES sounder were investigated by Dostalek and Schmit (2001) who compared the time change of moisture for radiosondes and retrievals. They reported a correlation coefficient of 0.71 (and a bias of 0.02 mm) for 12-hourly changes between TPW retrievals and those of collocated radiosondes. The first guess from the forecast model had a correlation coefficient of 0.59 (and a bias of 0.28 mm) for the same set of collocated radiosondes. A 1-yr period consisting of 2384 samples was examined in that study.

The improved spatial resolution is evident in the depiction of a moist plume that originated over Lake Michigan on 20 August 1999, as shown in Fig. 3. A pool of relatively dry air was found across the western Great Lakes region (TPW less than 20 mm is colored blue). This large-scale pattern was correctly forecast by the Eta Model (the contours are a 6-h forecast of total precipitable water from the 1200 UTC Eta Model). During the late morning and early afternoon hours, *GOES-8* sounder TPW imagery showed an elongated moist plume (TPW greater than 20 mm is colored green) forming across Illinois within this dry pocket of air. Cumulus formation was enhanced within the moist plume (Fig. 4). The *GOES-8* sounder moisture pattern depicted in Fig. 3 agrees with the observed cloud features in Fig. 4. With a low-level ridge of high pressure over Iowa and Wisconsin, the northeasterly flow within the boundary layer moved parcels of air across Lake Michigan into northeastern Illinois. The three trajectory end points shown in Fig. 4 were selected for air parcels arriving at the 1000-m level: one trajectory within the cloudy plume, and one trajectory within each of the adjacent drier regions. The 24-h backward trajectories suggest that air arriving within the cloudy plume experienced a

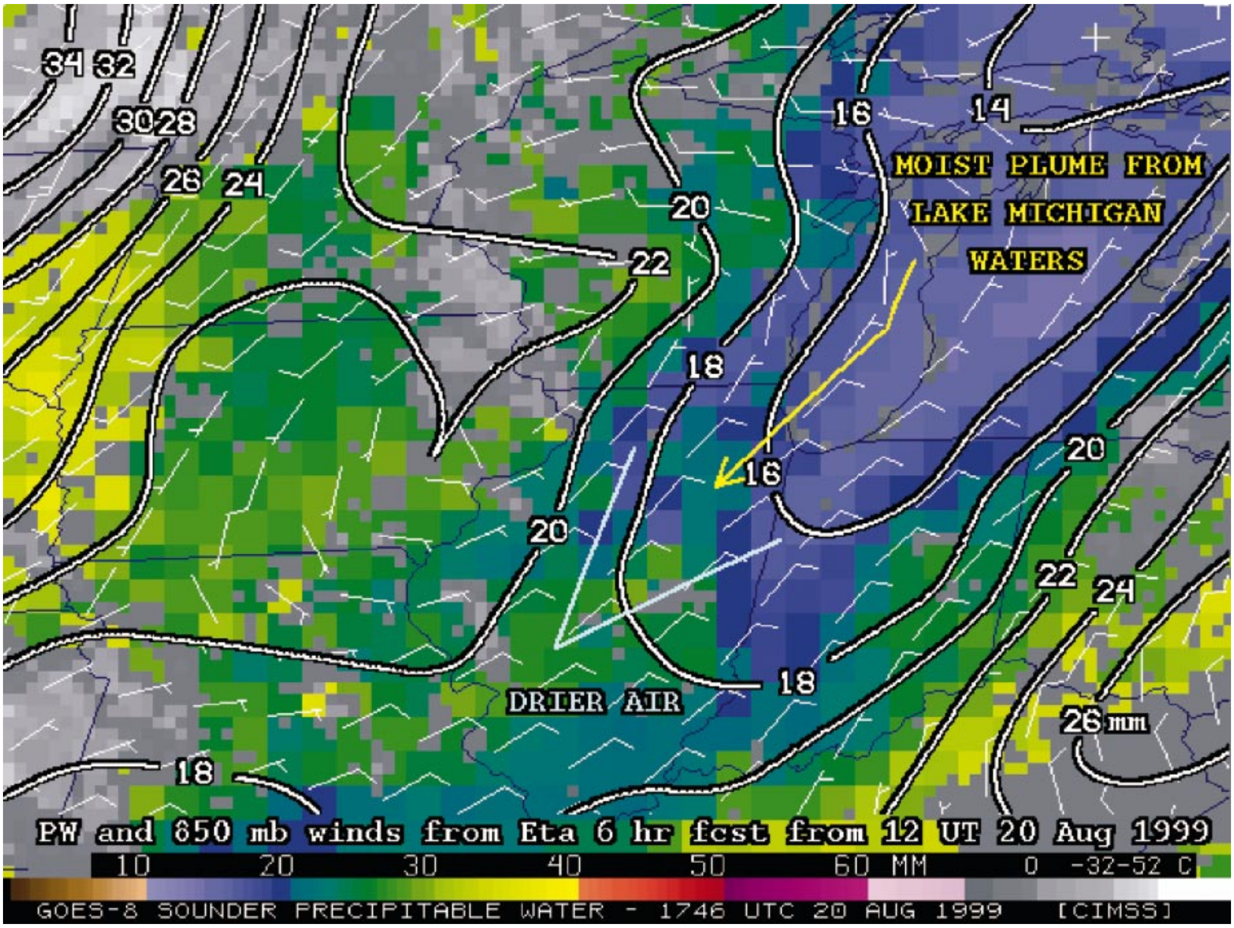

FIG. 3. *GOES-8* sounder TPW DPI at 1746 UTC 20 Aug 1999. The contours are a 6-h forecast of total precipitable water (mm) from the 1200 UTC Eta Model. Model wind barbs at 850 hPa are also plotted.

significant fetch across Lake Michigan, where it likely acquired additional moisture in the boundary layer. Backward trajectories arriving within the adjacent dry regions suggest a transport path entirely over land, helping this air maintain lower TPW values during the previous 24-h period. Air parcel backward trajectories were calculated using the NOAA Air Resources Laboratory (ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT4; Draxler and Hess 1997).

3. Validations with the SGP CART site microwave radiometer

a. Comparisons with GOES retrievals

The SGP CART site offers TPW measurements that allow for more precise validation of GOES retrievals than is possible with radiosondes. An operational MWR, located at the central CART facility near Lamont, Oklahoma, has demonstrated an accuracy of 0.7 mm under clear sky conditions (Liljegren 1995). All comparisons reported here are for clear sky cases. The MWR is tuned to the microwave emissions of the water vapor molecules in the atmosphere (Liljegren 1994) and measures TPW vapor every 5 min. The MWR measurements are completely independent of those from the GOES sounder or radiosondes. These high temporal resolution MWR measurements enable validation of the GOES retrievals at times other than the conventional radiosonde launches (0000 and 1200 UTC). Of course, the MWR and GOES retrievals still differ in that one is a point measurement (although with an improved accuracy compared to radiosondes) and one a volumetric measurement.

TPW values computed from *GOES-8* and *-10* retrievals and their corresponding Eta first guess profiles were compared to the MWR TPW for a 29-day period between 20 March and 17 April 1998. *GOES-10* retrievals were obtained at 15-min intervals; *GOES-8* was scheduled for routine hourly profiling. Figure 5 shows a 1-day comparison of TPW on 12 April 1998 between the MWR and *GOES-8* (Fig. 5a) and *GOES-10* (Fig. 5b). While the first guess (diamonds), which was interpolated from 6-hourly forecasts, is relatively flat throughout the period, the GOES retrieval algorithm (pluses) produces

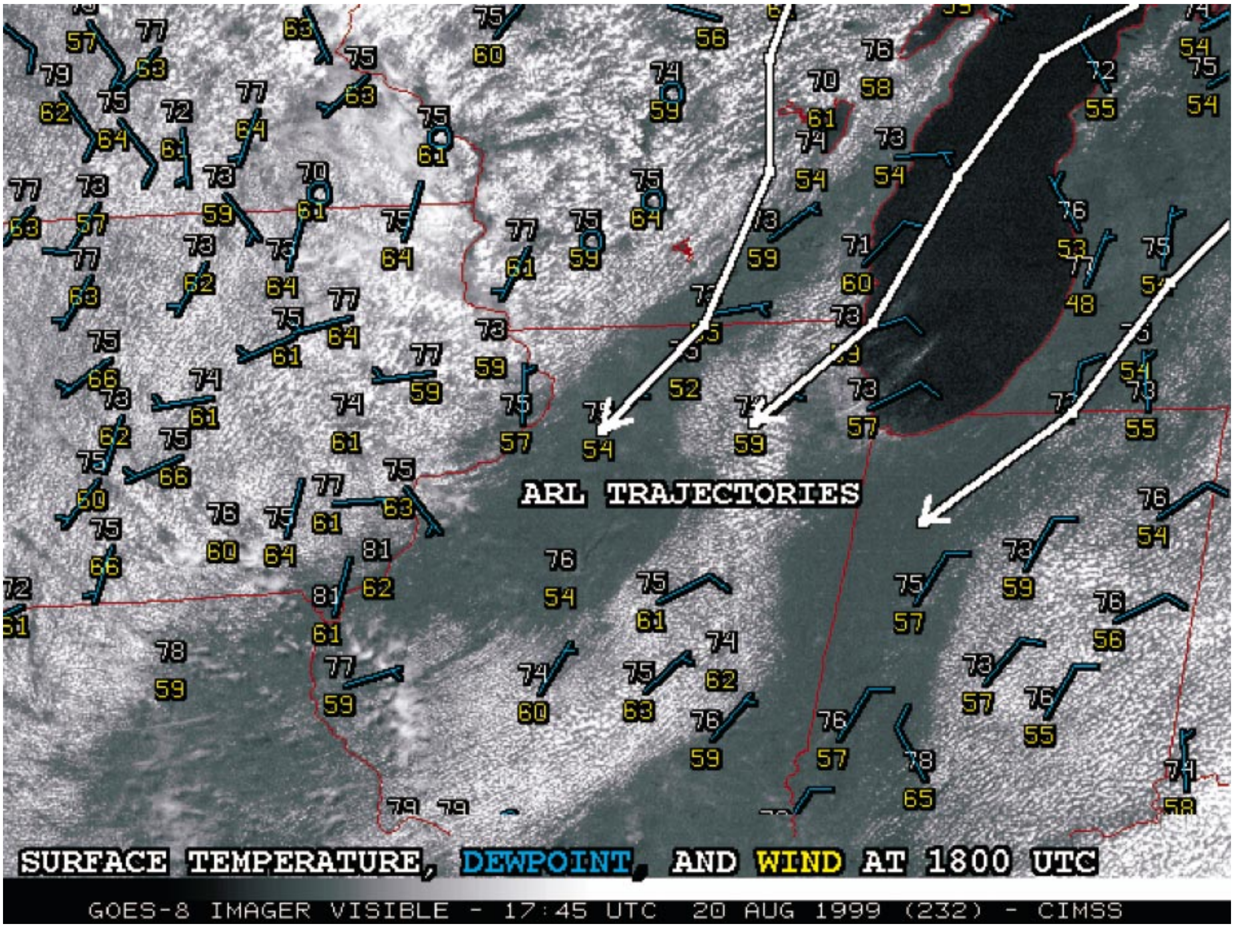

FIG. 4. *GOES-8* imager visible imagery at 1745 UTC 20 Aug 1999. Surface temperature, dewpoint, and wind data are plotted, along with the 24-h backward trajectories. The air parcel backward trajectories were calculated using the NOAA/ARL HYSPLIT4 model.

nearly the same water vapor tendency patterns as measured by the MWR (dashed line). Recall that the satellite retrieval, using a 3 × 3 FOV matrix (equating to a 36 km × 45 km box at this geographic location), represents a volumetric profile over a larger horizontal area than the MWR (which represents the atmosphere directly above the instrument). Smooth temporal changes are generated by the GOES physical retrieval algorithm, even when the first guess experiences a discontinuity when switched from using forecasts from the 0000 to the 1200 UTC model initialization times (e.g., near 1800 UTC). These discontinuities could be minimized if the forecasts from the 0600 and 1800 UTC initialization times were also used to build the first guess profiles for the GOES retrievals. The GOES retrievals follow the water vapor fluctuations between a local minimum of approximately 13 mm at 1130 UTC and a maximum of approximately 24 mm at 14 UTC; the temporally and spatially coarse radiosonde network did not capture these changes. Overall, GOES demonstrates skill in resolving the mesoscale water vapor fluctuations on this day. As further evidence of the ability of the GOES sounder to monitor the temporal variation of atmospheric water vapor, Fig. 6 shows a time series plot for the following three days (13–15 April 1998). Collocated radiosonde data (triangles) were available on these days. The known dry bias of these Vaisala radiosondes is evident (Guichard et al. 2000). Turner et al. (2000) have compared *GOES-8* retrievals, the CART site microwave radiometer, a Raman lidar, and Vaisala radiosondes with similar results.

Figures 7 and 8 show the improved agreement of the GOES physical retrieval algorithm (stars) versus the first guess (diamonds) when compared to the MWR measurements during the period 20 March–17 April 1998. These data were derived by comparing all possible matches between *GOES-8*/*GOES-10* retrievals and the MWR instrument. For the 364 matched values of MWR and *GOES-8* shown in Fig. 7, the physical retrieval improves the first guess of TPW rms from 2.21 to 1.80 mm and the bias from 0.83 to 0.40 mm. Even at greater TPW values, the GOES retrieval values compared better with microwave radiometer values (perfect agreement indicated by the diagonal line). Figure 8 shows similar results for the *GOES-10* retrievals, except with more MWR matches due to the higher 15-min temporal res-

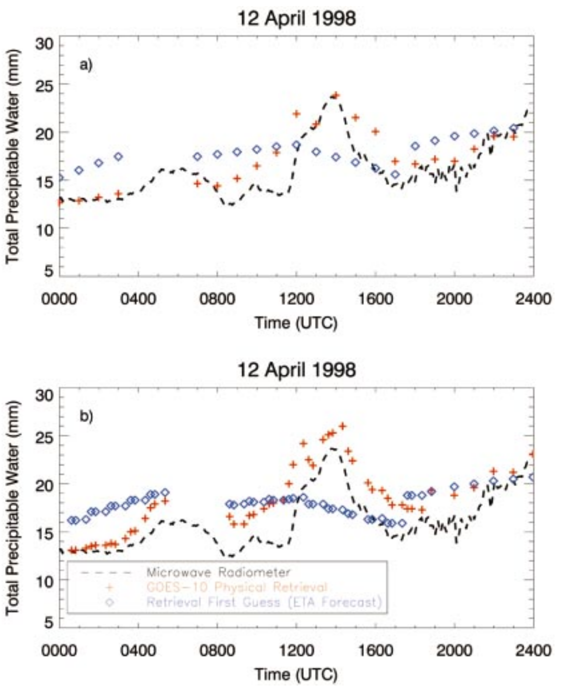

FIG. 5. Microwave radiometer (dashed line), Eta Model forecast (diamonds), and *GOES-8/10* physical retrieval (plus signs) TPW comparisons near Lamont, OK, on 12 Apr 1998: (a) *GOES-8* and (b) *GOES-10* comparisons.

olution of *GOES-10* during this period. The rms was improved, from the first guess value of 2.45 mm to the retrieval value of 1.99 mm; and the bias was reduced from 0.77 to 0.57 mm.

b. Comparisons with combined AERI plus GOES retrievals

A ground-based Atmospheric Emitted Radiance Interferometer (AERI; Revercomb et al. 1993) is also located at the SGP CART site facility; the AERI measures high spectral resolution infrared radiances emanating from the atmosphere above. These data, combined with collocated GOES data, were used to produce another set of retrievals. The GOES plus AERI retrievals produced additional improvements in TPW rms and bias over the GOES-only retrievals. Within the planetary boundary layer, high-resolution AERI radiances provide detailed information for temperature and moisture profiling. The GOES profiles were used as the first guess for the AERI retrievals from the upper planetary boundary layer to the tropopause while an AERI statistical first guess was used in the planetary boundary layer. The AERI first guess is based on a regression of 1159 clear sky radiosondes and calculations from the AERI forward model. An optimal hybrid first guess was created by linearly blending these two profiles between 2 and 3 km. The AERI radiances were then used to perform a physical retrieval of temperature and moisture in the atmosphere from the surface to 3 km at 10-min temporal resolution (Feltz et al. 1998; Smith et al. 1999; Turner et al. 2000).

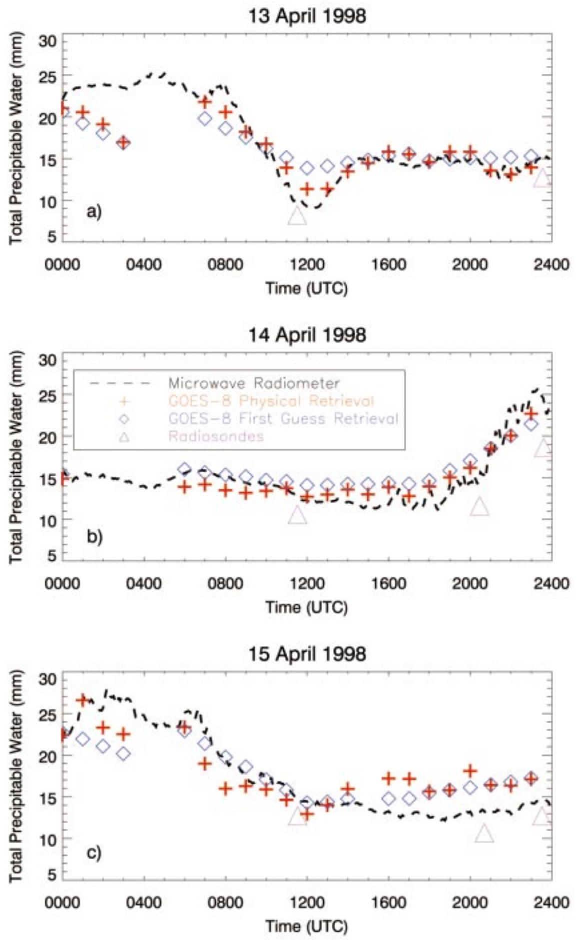

FIG. 6. Microwave radiometer (dashed line), Eta Model forecast (diamonds), and *GOES-8* physical retrieval (plus signs) of TPW comparisons near Lamont on 13–15 Apr 1998. Radiosonde values (triangles) are also plotted.

Figure 9 indicates that the rms differences for TPW with respect to the MWR of AERI plus GOES retrievals (diamonds) at 0.78 mm are less than half those of GOES alone (stars) at 1.80 mm; the bias was dramatically reduced from 0.40 to 0.05 mm. The increased sample size of the AERI plus GOES as compared to the GOES alone was due in part to the 10-min versus hourly time resolution. The AERI plus GOES retrievals and the MWR measurements of total water vapor were completely independent. These comparisons testify to the significant improvement in water vapor profiling possible by combining ground-based interferometeric measurements with GOES measurements. (Near-real-time AERI plus GOES retrievals and derived meteorological parameters can be found online at http://cimss.ssec.wisc.edu/aeriwww/aeri/aeri.html.)

To show that the GOES is adding information to the

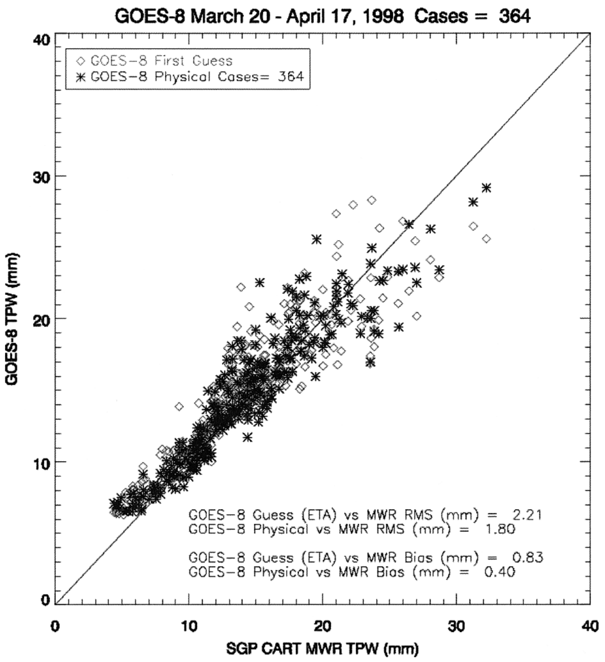

FIG. 7. A scatterplot comparing MWR total water vapor values to the Eta Model forecast (diamonds) and the *GOES-8* physical retrieval (stars) values. Rms and bias for all matches are quantified in the lower-right-hand corner.

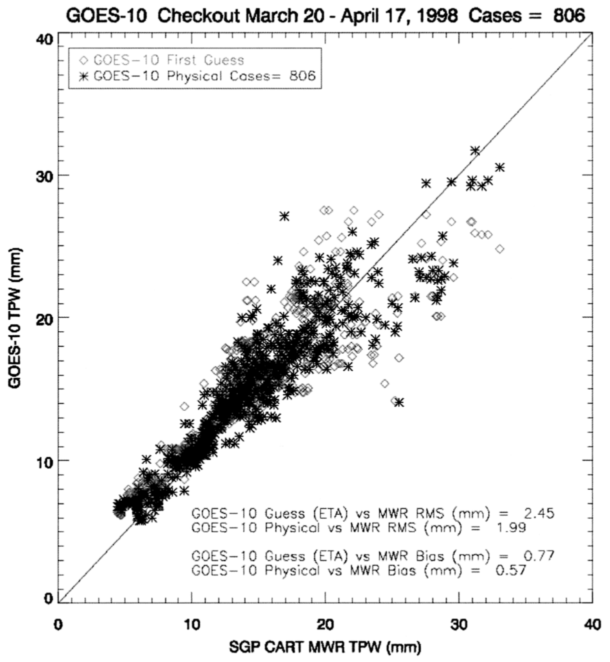

FIG. 8. A scatterplot comparing MWR total water vapor values to the Eta Model forecast and the *GOES-10* physical retrieval values. Rms and bias values for all matches are quantified in the lower-right-hand corner.

AERI-alone profile results, retrieval rms differences for GOES only (dashed line), AERI only (×), and AERI plus GOES (solid line) are plotted for temperature and water vapor mixing ratio for the 1997 Water Vapor Intensive Operational Period (WVIOP) at SGP CART. During this period a radiosonde was launched once every 3 h, which provided relatively high temporal profile validation. The standard deviations of the radiosonde temperature and mixing ratio are plotted (dash–dot line) as a measure of atmospheric variability of these two parameters. Rms differences, with respect to radiosonde observations, for AERI plus GOES temperature retrievals were shown to be approximately 1 K from the surface to 200 hPa from 72 concurrent radiosonde launches during the September/October 1997 WVIOP (Fig. 10a). Notice that the combined product is an improvement over the AERI retrievals above approximately 860 hPa and over the GOES temperature retrieval between the surface and 800 hPa. The combined product also improved the water vapor mixing ratio product of the GOES by greater than 1 g kg^{-1} during the WVIOP (Fig. 10b). In summary, the GOES retrievals add information to the AERI-alone profiles, and also vertically extend the AERI-alone profiles above 2.5 km (Smith et al. 1998).

4. Impact of GOES sounder data within numerical models

Another measure of the GOES sounder quality is to compare numerical weather prediction model performance with and without the GOES data. Such parallel model runs reveal how much information the GOES data add beyond what is already provided by numerous other data types. If the forecast is improved when a given dataset is assimilated, the dataset is deemed to have value.

The GOES sounders provide not only retrieved atmospheric profiles in clear skies, they also provide cloud information (Schreiner et al. 2001). The sounder cloud-top pressure and effective cloud amount for cloudy FOVs complement the Automated Surface Observing System (ASOS), a system not capable of detecting clouds higher than ∼4 km (12 000 ft) above ground (Schreiner et al. 1993; Menzel et al. 1998). These data have been used to initialize numerical forecast models (Diak et al. 1998; Bayler et al. 2000; Kim and Benjamin 2000).

There are two basic approaches to assimilating satellite information into numerical models. The first approach incorporates the radiances directly after being filtered for the presence of clouds (Derber and Wu 1998; McNally et al. 2000). The NCEP/Environmental Modeling Center (EMC) began assimilating clear sky radiances over oceans measured with the *GOES-8* sounder in their global data analysis system during June 1998. In late September 2000, *GOES-8* and *-10* sounder radiances over water were introduced into the regional model data assimilation system. The layers of PW are still assimilated over land. In other work, inclusion of GOES sounder radiances in the Pennsylvania State Uni-

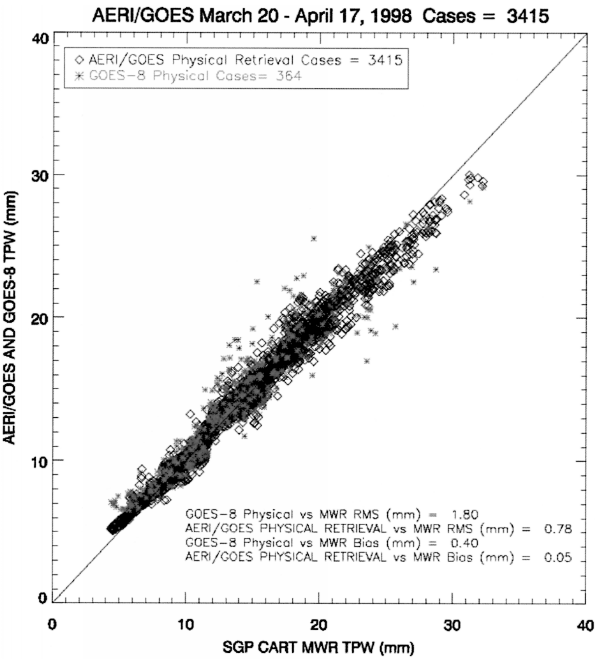

FIG. 9. A scatterplot comparing *GOES-8* only (stars) and *GOES-8* plus AERI (diamonds) retrievals to microwave radiometer TPW at the Southern Great Plains Cloud and Radiation Testbed near Lamont.

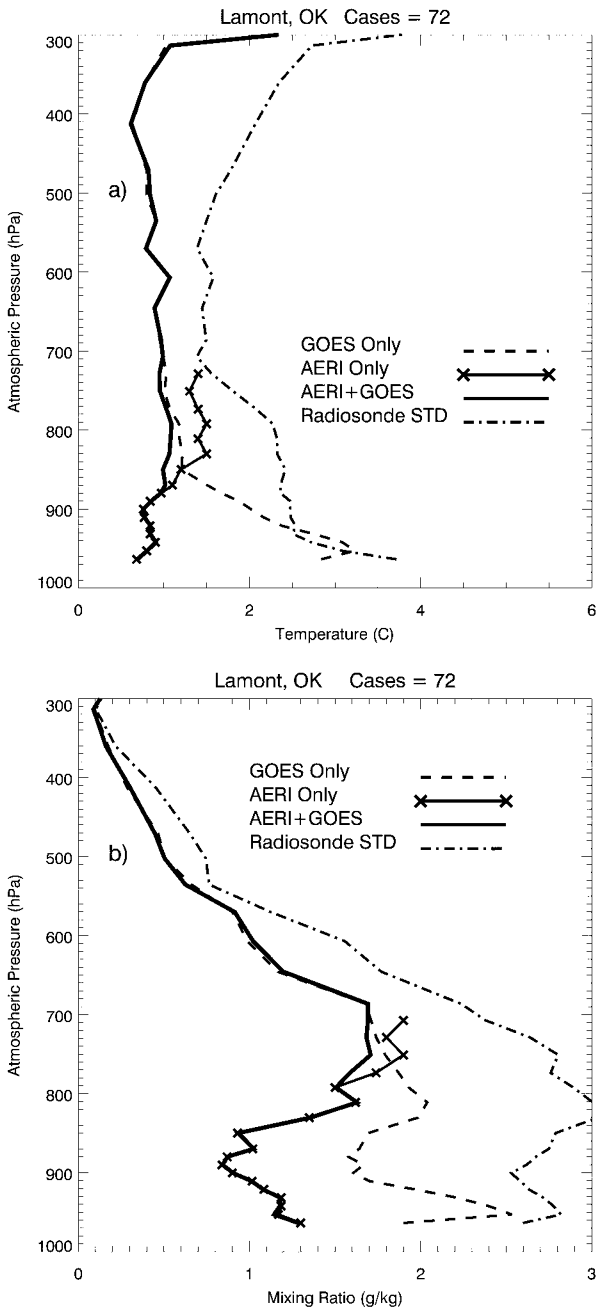

FIG. 10. (a), (b) Rms differences from 72 radiosondes for AERI retrievals (×), GOES retrievals (dashed), and AERI plus GOES retrievals (solid black) for temperature and mixing ratio, respectively, during the 1997 WVIOP. A measure of the meteorological variability of the temperature and water vapor is indicated by the dot–dash lines.

versity–National Center for Atmospheric Research (Penn State–NCAR) fifth-generation Mesoscale Model (MM5) improved both hurricane position and intensity forecasts for Hurricane Felix (Zou et al. 2001).

The second approach, and the focus of this section, involves assimilating meteorological parameters that have been derived from the satellite radiance measurements. Clear sky TPW and cloud parameters from the GOES sounder were first assimilated into the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Regional Assimilation System (CRAS) in July 1995 (Aune 1996; Raymond and Aune 1998). These two parameters were assimilated independently. The first step in the TPW data assimilation was to remove the vertical moisture perturbations from the model profile. Then the mean model moisture profile was adjusted to agree with the satellite value; thereafter, the model vertical perturbations were restored. In the assimilation of cloud data, three primary cases are addressed. In the first case, the sounder reports no cloud, yet the model indicates cloud. In this case the model cloud is removed from that grid box. In the second case, the sounder reports a sufficiently thick cloud, yet the model indicates no cloud. In this case cloud is added in the clear model grid box by increasing the amount of moisture in the appropriate layer to support cloud. The model vertical motion profiles are not adjusted. In the third case, both the model and the sounder report cloud. In this case the model moisture is modified to reflect the level of sounder cloud (Bayler et al. 2000). Synthetic IR images derived from CRAS forecasts with GOES retrieved parameters revealed improvement over those images derived from forecasts without GOES satellite data, using the actual image as validation (Menzel et al. 1998). This demonstrated the improvement possible when GOES sounder data in both clear and cloudy regions were assimilated.

The impact of GOES data was studied in a worksta-

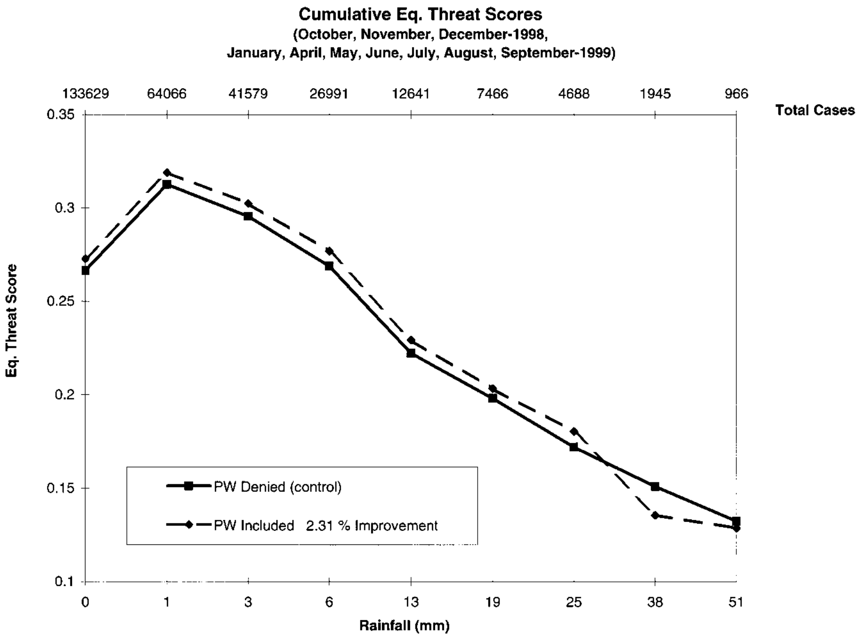

FIG. 11. Cumulative ETS for accumulated precipitation for 80-km Eta parallel runs without the GOES sounder PW data (control, solid line) and with the GOES sounder PW data (dashed line). Two weeks out of each of the 10 months listed were used in this study. A larger ETS indicates the forecasts compared more favorably to verifying 24-h rain gauge precipitation totals. The number of cases for each rainfall bin is plotted along the abscissa at the top of the graph.

tion version of the operational EDAS (Black 1994). A vital component of the EDAS is the three-dimensional variational analysis procedure (3DVAR; Parrish et al. 1997). 3DVAR assimilates many types of data into the model environment prior to the forecast. An 80-km version of the EDAS with 38 levels assimilated three layers of PW from the National Environmental Satellite, Data, and Information Service (NESDIS) operational GOES 5×5 FOV retrievals every 3 h during the model's 12-h spinup period. GOES three-layer PW was assimilated when at least 10 of the 25 FOVs were clear. This study used data from 2 weeks out of each of the 10 months from October 1998 through September 1999. The dates were chosen on the basis of data availability (all necessary model and data files had to be present for a given 2-week period to be used); on some days the required 80-km parallel model runs were either not generated, not able to be accessed, or not successfully archived. The data were assimilated, in a fully cycled mode, every 3 h during the 12-h period prior to the final analysis time, after which the forecast model was executed. Fully cycled means the initial background field (at the analysis time minus 12 h) is derived from a previous Eta Model run.

Forecasts from model runs with and without GOES sounder data were compared to rain gauge data. Forecast times of 0–24 and 12–36 h are included in the following statistics. Figure 11 shows the improvement realized when GOES sounder retrieved three-layer PW data are assimilated, over both land and water. A larger equitable threat score (ETS) indicates the forecasts compared more favorably to verifying 24-h rain gauge precipitation totals (Rogers et al. 1996); the rain gauge data are from the National Weather Service (NWS) River Forecast Centers database comprising more than 6000 stations nationwide. The ETS ranges from 0 to 1 and increases for grid points with a correct forecast of precipitation and decreases for either a missed or a false alarm precipitation forecast. The ETS was tabulated for nine ranges of precipitation (bins). The seven bins with the greatest number of matches showed an improvement due to the inclusion of the retrieved GOES sounder layer moisture data. The two bins with the highest rain amounts (where the number of samples was relatively small) were degraded. It could be that the rain gauge data of high rain amounts are less representative for an 80-km grid. Overall, precipitation forecasts were improved approximately 2.3% (when the ETS was weighted by the total number of cases) by inclusion of the GOES sounder moisture information.

The precipitation threat bias (or bias score) is defined as the total number of model grid points where precipitation was forecast, divided by the total number of model grid points where precipitation was observed (Rogers et al. 1996). Thus the threat bias indicates whether the model overproduces or underproduces precipitation over the entire model domain. It does not account for collocation of the forecast versus observed precipitation. Figure 12 shows the cumulative (entire test period) threat bias scores for precipitation amounts from a trace

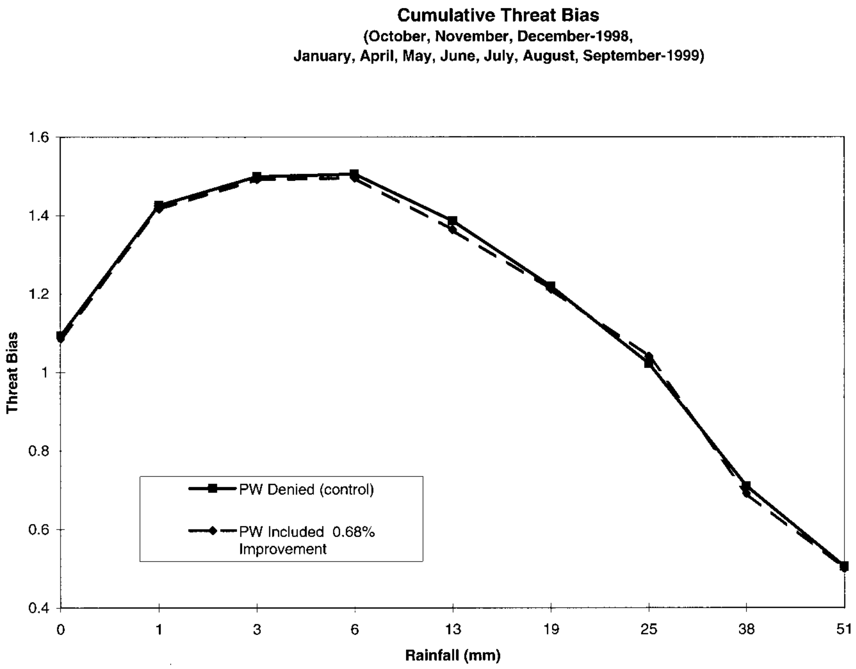

FIG. 12. Cumulative (entire test period) threat bias scores for accumulated precipitation for 80-km Eta parallel runs without the GOES sounder PW data (control, solid line) and with the sounder PW data (dashed line). A threat bias of 1 is ideal. Overall there is a slight improvement when the GOES data were included.

(0 mm) to 51 mm (2 in.). Overall there is a slight improvement. For both the model runs with and without GOES sounder data, the threat bias for precipitation amounts of 25 mm (approximately 1 in.) were nearly 1—a perfect threat bias score. Thus the model was best suited for precipitation events of such magnitude. The threat biases for precipitation amounts less than 25 mm (1 in.) are all greater than 1, which indicates the model overproduced events with low precipitation amounts. For these precipitation amounts, the threat biases of the model run with GOES sounder data were always slightly closer to 1, so the GOES PW runs were slightly better. These improvements for precipitation amounts of 25 mm or less are significant, based on the large sample sizes. For precipitation amounts greater than 25 mm, the threat biases were less than 1 (underproduction), with the GOES PW denied runs always slightly closer to 1. Thus both ETS and threat bias indicate GOES PW data slightly degrade precipitation forecasts for amounts greater than 25 mm.

TABLE 2. GOES sounder PW cumulative ETSs as a function of forecast time. The months represented are Oct–Dec 1998, and Jan and Apr–Sep 1999. There are approximately 150 000 total points for each forecast time.

Forecast time (h)	Analysis times (UTC)	Improvement (%)
0–24	1200	2.2
12–36	0000	2.5
24–48	1200	2.0

In a study by Kalnay et al. (1998), threat scores (TSs) were calculated and showed an average 11-yr (1987–97) improvement of 0.06 for 24-h forecasts at the 12.7-mm (0.5 in.) precipitation threshold. ETS differs from TS in that the chance of correctly forecasted precipitation events in a random forecast is removed. To allow comparison, TSs were computed for our study and correspond to an improvement of 0.007 when GOES sounder data are included. This value is based on over 12 000 rain gauge comparisons. Therefore, the impact of including the GOES sounder moisture data is of the same order of magnitude as the yearly historical average improvement. Considering the four summer months only (May–Aug 1999), the improvement in ETS increases to 4.5%. The positive impact of the GOES sounder three-layer PW on the precipitation forecasts (compared to 1200 UTC rain gauge readings) is sustained out to 48 h (Table 2).

Additional experiments with the 80-km EDAS have corroborated the positive impact of the retrieved GOES sounder three-layer moisture over oceanic regions, for both the analysis and forecasts (Zapotocny et al. 2000, 2002). The operational NCEP Eta Model system first began assimilating retrieved layers of moisture from the *GOES-8* sounder in October 1997 (Lin et al. 1996; Menzel et al. 1998).

5. Use of sounder products in forecasting

The use of GOES sounder derived products by forecasters has been increasing. Forecasters from the West-

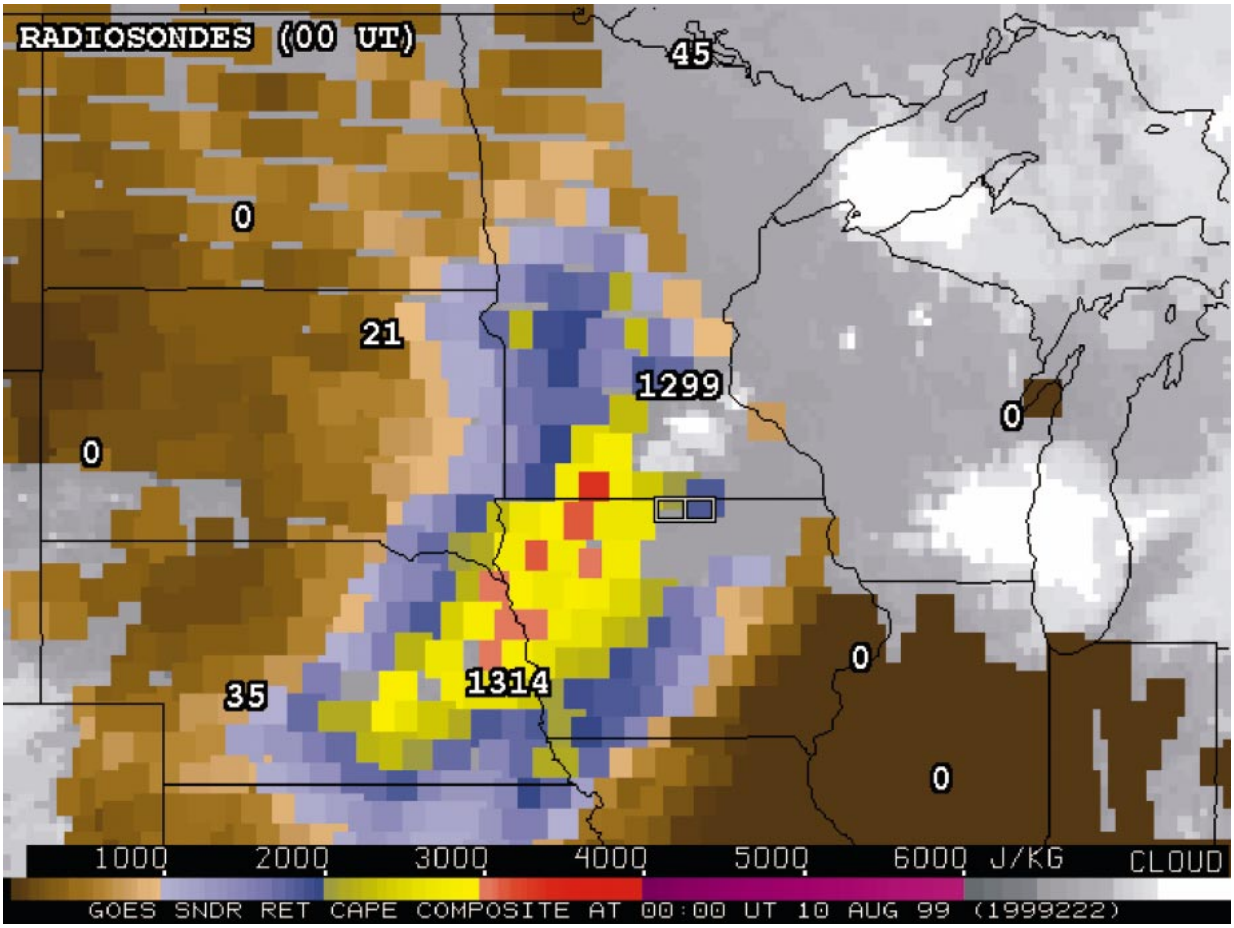

FIG. 13. *GOES-8* sounder CAPE values at 0000 UTC on 10 Aug 1999. The axis of CAPE values greater than 2500 J kg^{-1} extended from eastern NE into southern MN. CAPE values calculated from the 0000 UTC radiosondes were too sparse to capture this feature. The two counties outlined in northern IA show the location where an F2 tornado occurred just after 0200 UTC.

ern Region of the NWS have used sounder products experimentally since 1996. Schrab (1998) has documented several cases where the sounder derived product images (DPI) of TPW and LI were very useful in real-time nowcasting and forecasting. Currently, some of the products are being introduced into the Advanced Weather Interactive Processing System (AWIPS; Schrab 2000). These data include total precipitable water vapor, lifted index, CAPE, cloud-top pressure, and a select number of the sounder radiance fields.

Experimental sounder products were first displayed on the CIMSS Web site in late 1995 (http://cimss.ssec.wisc.edu/goes/goes.html). On 29 October 1999, NOAA/NESDIS began operational production of the sounder DPI. Several examples illustrating the use of atmospheric instability parameters are highlighted in Menzel et al. (1998). As mentioned in Hayden et al. (1996), the DPI can be used to detect a timing or phase error in a numerical model forecast. Ellrod et al. (2000) developed experimental products derived from the GOES sounder retrievals to assess the potential for downbursts.

From 19 July through 30 August 1999, the NWS Office of Meteorology conducted daily assessments of the operational value of the *GOES-8* and *GOES-10* sounder products. Thirty-seven NWS forecast offices, four national centers, and the NESDIS Satellite Analysis Branch participated in the evaluation, providing a total of 635 responses primarily via the World Wide Web. Forecasters used the sounder products to heighten their awareness of the potential of a wide variety of weather events, including severe thunderstorms, monsoon precipitation, and flash floods.

As an example, Fig. 13 shows the *GOES-8* sounder CAPE values at 0000 UTC on 10 August 1999. The axis of CAPE values greater than 2500 J kg^{-1} was clearly depicted, extending from eastern Nebraska into southern Minnesota. CAPE values calculated from the 0000 UTC radiosondes (plotted values) were too sparse to capture this feature. Just after 0200 UTC, an F2 scale tornado (winds between 182 and 253 km h^{-1}) was reported in northern Iowa (NCDC 1999). An NWS forecaster in Minneapolis, Minnesota, had this to say about the use of the GOES sounder data that evening:

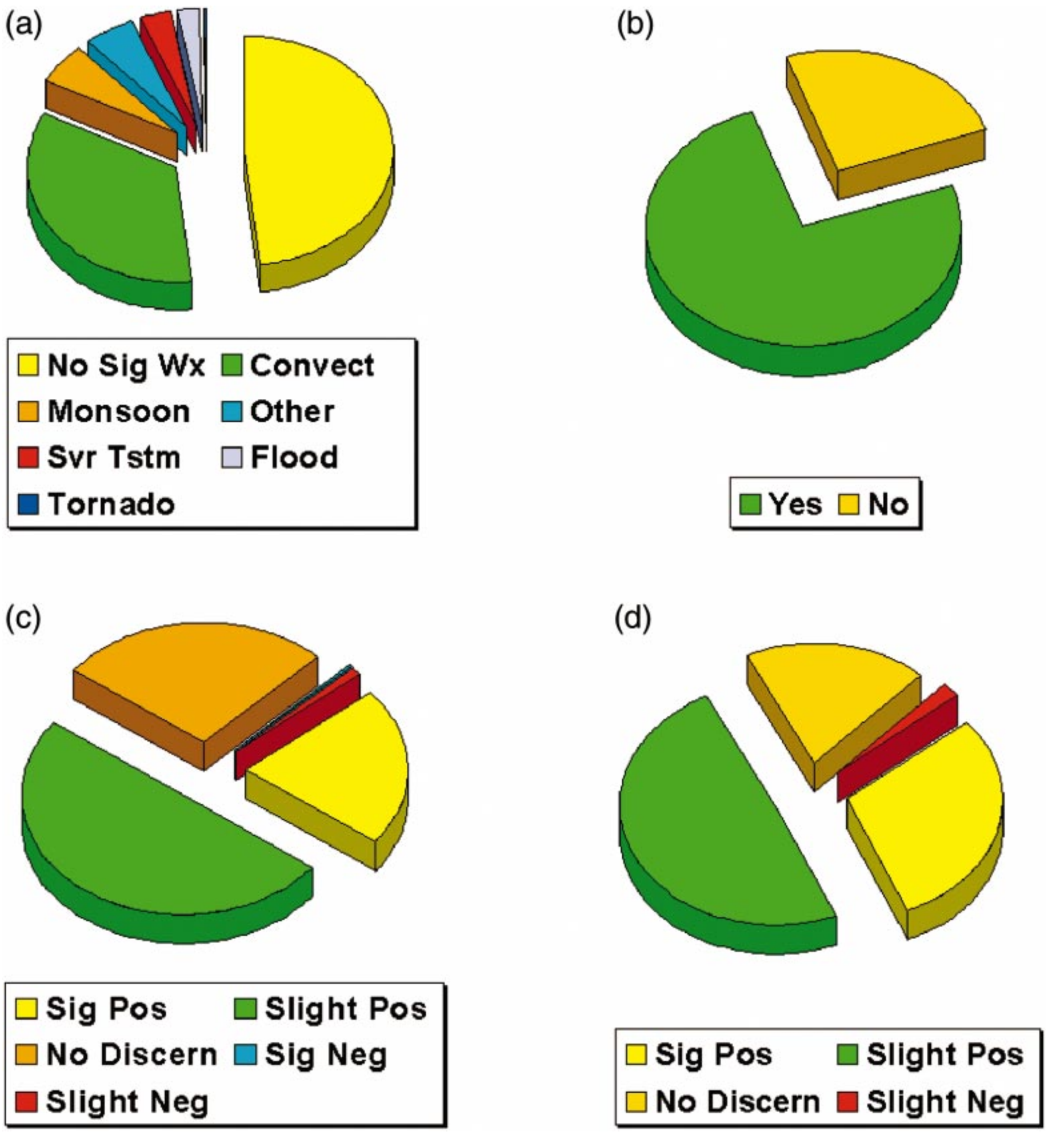

FIG. 14. (a) During the GOES sounder assessment there were several different weather situations evaluated (635 total): tornado warning (2), flash flood watch/warning (16), severe thunderstorm watch/warning (21), other (34), monsoon (37), convection expected (218), and no significant weather (307). (b) Forecast responses to the question, ''Did the GOES sounder products increase your confidence convection would/would not develop?'' There were 250 valid weather cases: 188 responded yes, and 62 responded no. (c) Forecast responses to the request, ''Rate the usefulness of TPW (changes in time/axes/gradients in the hourly product) for your precipitation program.'' There were 207 valid weather cases: significant positive impact (44), slight positive impact (104), no discernible impact (56), slight negative impact (2), and significant negative impact (1). (d) Forecast responses to the request, ''Rate the usefulness of LI, CAPE, and CINH (changes in time/axes/gradients in the hourly product) for location/timing of thunderstorms.'' There were 248 valid weather cases: significant positive impact (74), slight positive impact (122), no discernible impact (47), slight negative impact (5), and significant negative impact (0).

The Sounder Derived Product Imagery (DPI) helped a lot anticipating convective development over southern MN this evening. I looked through the DPI's over a few hours and saw a definite decreasing trend in the CINH (Convective Inhibition) from 19-21Z [1900–2100 UTC]. It was only a matter of time before the convection fired into southern MN. Impressive CAPE values (3500–4500 J/kg) and LI's −10 to −12 pointed to the possible severity of the convection. We received many reports of funnels/brief tornado touchdowns across south central MN as the convection went through. These products overlayed on surface maps/satellite/radar displays on AWIPS would be invaluable to the mesoscale forecaster.

When forecasters were asked which GOES sounder products were most useful for increasing their confidence that convection would or would not develop, the three top products were lifted index, CAPE, and total precipitable water. Figure 14 summarizes some of the National Weather Service forecast responses obtained during the assessment period. Overall, forecasters found that the sounder products provided valuable information, especially with regard to moisture distributions. The products indicated temporal and spatial gradients unavailable from any other source. The forecasters indicated that in over 79% of all active weather situations, the use of GOES sounder products led to the issuance of improved forecasts.

However, forecasters also noted several limitations of the current sounder: (a) IR sounders cannot penetrate cloud cover; (b) the scanning rate is relatively slow, which limits coverage; and (c) the vertical resolution from the current generation GOES radiometers is limited. Advanced geostationary sounders are planned to improve both the scan rate and the vertical resolution.

6. Conclusions

Moisture retrievals from the GOES sounders, obtained via the simultaneous physical retrieval algorithm, have been shown to add information defining the current state of the atmosphere by virtue of their relatively high horizontal and temporal resolution. In comparisons with high quality microwave radiometer data, the GOES sounder moisture retrievals of TPW demonstrated a bias of less than 1 mm and an rms of less than 2 mm. In addition, combining information from the operational GOES sounders with an upward-looking high spectral resolution instrument, such as the AERI, allows improvement of the final moisture retrieval over either method alone (Smith et al. 1998; Feltz et al. 1999).

The GOES sounder profiles are available only in clear sky conditions and are limited by coarse vertical resolution. Nonetheless, Eta Model precipitation forecasts are significantly improved through 48-h forecasts when assimilating retrieved layer PW data from the GOES sounders. The operational NCEP Eta Model system is currently assimilating retrieved layers of moisture from both the *GOES-8* and *-10* sounders over land. The radiance values are now used over water.

Data and products from the GOES sounders are being used in many forecasting situations. Forecasters are responding favorably to the improved depiction of moisture gradients in space and time. However limitations of the current sounders are also noted.

The need for high spectral resolution sounders from space has been repeatedly discussed in the literature (Hanel et al. 1970; Kyle 1977; Smith et al. 1979; Hayden and Schmit 1991; Ackerman et al. 1993; Huang and Purser 1996). Potential uses have been demonstrated with data collected by high spectral resolution instruments on research aircraft (Smith et al. 1990; Bradshaw and Fuelberg 1993; Strow et al. 1998). High spectral resolution will soon be a reality for polar-orbiting satellites with the Atmospheric InfraRed Sounder (AIRS), the Infrared Atmospheric Sounding Interferometer (IASI), and the Crosstrack Infrared Sounder (CrIS) instruments (Aumann and Pagano 1994; Amato et al. 1995). Observing system simulation experiments (OSSEs) have demonstrated the positive impact a geostationary interferometer will have on numerical weather prediction. The impact of such satellite data is evident even when the current observing network is included (Aune et al. 2000). While we look forward to the day of high-resolution geostationary sounders, the radiometers currently available are adding information for both numerical weather prediction and forecasting applications.

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