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## **REPORT ON THE NEED FOR HIGH TIME AND SPECTRAL INFRARED MEASUREMENTS**

In response to Recommendation 35.13: CGMS members are encouraged to present papers demonstrating the possibilities of advanced sounding for analysing convective instability of the atmosphere, particularly utilising information from the hyperspectral sounders AIRS and IASI

NOAA WP-15 reports that retrieval simulations have shown that temperature and moisture information retrieved with high spectral and temporal resolution IR instrument far exceed those from the broadband Sounders on current GOES. A high spectral resolution IR sensor has a much greater vertical resolving power of temperature and moisture than broad band sensors.

High spectral and temporal resolution observations benefit nowcasting and NWP applications by providing spatially and temporally continuous measurements of temperature, water vapor, and the wind profile. With high spectral resolution IR geostationary sounding capabilities, forecasters and regional models will have sufficient information (e.g., meeting user requirements) regarding the fine-scale three dimensional structure of atmospheric water vapor and capping inversions and how these structures vary in time. A high spectral (and hence vertical) resolution IR sounder with faster scanning will be able to monitor the evolution of important low-level information about the atmosphere and thus substantially improve the capability to forecast severe weather

# REPORT ON THE NEED FOR HIGH TEMPORAL AND SPECTRAL INFRARED MEASUREMENTS

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## 1. INTRODUCTION

The first of the next generation series of Geostationary Operational Environmental Satellite (GOES-R) is scheduled for launch in 2015. The new series of GOES will not have an infrared (IR) sounder dedicated to acquiring high vertical resolution atmospheric temperature and humidity profiles with time continuity. High spectral resolution IR sensors have a much greater vertical resolving power of temperature, moisture and trace gases than broad band sensors. These observational improvements are required by a number of user communities. Due to coarse vertical resolution, slow scan rate and limited accuracy in the legacy sounding products from the current GOES Sounders, placing a hyperspectral resolution IR sounder with high temporal resolution and fast scan rate in the geostationary orbit can provide nearly time continuous three-dimensional moisture and wind profiles which will allow substantial improvements in monitoring the mesoscale environment for severe weather forecasting and other applications. Application areas include nowcasting (and short-term forecasts) and numerical weather prediction (NWP), that require products such as atmospheric moisture and temperature profiles and derived parameters, clear-sky radiances, atmospheric motion vectors, sea surface temperature (SST), cloud-top properties, and surface properties. Other application areas include trace gases/air quality, dust, inter-instrument radiance calibration and validations.

## 2. POTENTIAL APPLICATIONS OF GEO HYPERSPECTRAL IR SOUNDER

The current U.S. GOES Sounders (Menzel and Purdom, 1994, Menzel et al. 1998) measure emitted radiation in 18 broad spectral bands and reflected solar radiation in one visible band. The spectral measurements have broad spectral widths that are on the order of tens of wavenumbers. This includes the GOES-8 through -13 Sounders, and continues through GOES-O/P (Plokhenko et al. 2003, Hillger and Schmit 2007). Operational uses by the National Weather Service (NWS) from the current GOES Sounders include: clear-sky radiances, profiles of temperature and moisture, atmospheric stability indices, layer and Total Precipitable Water (TPW), cloud-top retrievals (pressure, temperature, effective cloud amount), surface skin temperature, and water vapor atmospheric motion vectors (Schreiner et al. 2001, Velden et al. 1998). Experimental products from the current sounders include total column ozone, upper-level Sulfur dioxide (SO<sub>2</sub>) detection and additional atmospheric stability parameters (Li et al. 2001, Ackerman et al. 2008). High spectral resolution sounders have hundreds or thousands of channels with spectral widths less than a wavenumber. This finer spectral resolution is required to meet the observing requirements for weather forecasting in the 2015 to 2030 timeframe, including requirements on the accuracy of the vertical profiles of atmospheric moisture and temperature, trace gas concentrations, cloud-top pressures and surface emissivity and temperature.

There are many advantages of high spectral resolution data over that of broad-band instruments from a geostationary orbit. The key improved product is the atmospheric temperature and moisture profiles with high vertical resolution and accuracy along with the derived products such as TPW, atmospheric instability indices and moisture motion wind profiles. The derived products are used to monitor forecast model performance (e.g.,

moisture distribution, timing, etc.) and 'nowcast' the severe storm development and movement.

Numerous studies have demonstrated the value of satellite-based high spectral resolution measurements. For example, Schmit et al. 2008 used radiosonde observations and radiative transfer models for the GOES-12 broad-band Sounder and simulated high spectral resolution IR radiances. After adding appropriate noise estimates, they retrieved temperature and moisture profiles from the simulated observations, clearly demonstrating that the high spectral resolution solution provided the best profiles, with much better accuracies than the forecast, or the ABI plus the forecast. Research has also shown the benefits of combining high spectral resolution IR sounder measurements with high spatial resolution imager data (Li et al. 2004b; 2005a). A Hyperspectral Environmental Suite (HES) type sounder (Wang et al. 2007) with faster scanning and high spectral resolution remains essential for regional (and potentially global) NWP. The quality of the high spectral resolution data has been demonstrated with data available on low earth orbit (LEO) or polar orbiting satellites. This includes the IMG (Interferometric Monitor for greenhouse Gases, Ogawa et al. 1993), the AIRS (Chahine et al. 2006) on the EOS-Aqua and the IASI (Infrared Atmospheric Sounding Interferometer) on MET-OP (Siméoni et al. 1997). While these measurements provide a wealth of information for global applications they do not have the fine temporal resolution necessary to monitor quickly changing weather and environmental phenomena. In addition, sounders onboard LEO satellites have orbital gaps (e.g., sometimes provide no data at the location of storm development). A key advantage of a geostationary advanced sounder is that it can provide high vertical resolution and accurate soundings hourly (or better) over most of the full disk. The experience (science and processing technique) with high spectral resolution measurements from LEO platforms has resulted in a high level of maturity for the processing of these type data from a geostationary orbit.

### ***Nowcasting Applications***

With a high spectral resolution sensor on a geostationary orbit, the "nowcasting" and short-term forecasts (0-6 hours) for severe weather will be improved due to low-level layer moisture/temperature information and rapid scan capabilities. These enhanced capabilities will allow improved monitoring of atmospheric instability and inversions. Several potential applications from high temporal and high spectral resolution IR data were discussed by Sieglaff (2007). They showed how temporal differences of the spectral 'on-line' and 'off-line' absorption features in the IR window region of the spectrum are related to low-level temperature and moisture.

The application of current GOES Sounder on severe storm nowcasting has been demonstrated (Smith and Woolf 1985; Petersen and Aune 2006; Li et al. 2008). With replacement of advanced IR sounder on geostationary orbit, the improvement in sounding capability is significant (Smith et al. 1990, Huang et al. 1992). Here we provide further demonstration by comparing collocated AIRS and GOES Sounder soundings with the dropsonde measurements from an aircraft. Figure 1 shows a GOES Sounder comparison beginning at 18:46 UTC on 29 April 2007, the dropsonde site is indicated by a small star over the Gulf of Mexico. The time of the AIRS overpass is approximately 19 UTC (AIRS granule 193). Three Relative Humidity (RH) soundings are plotted; GOES (red) has reasonable accuracy in the mean but lacks vertical structure when compared with dropsonde (blue) while the AIRS single field-of-view (SFOV) sounding (green) depicts the fine moisture structure, and is similar to the dropsonde. In order to show the independent sounding information, the forecast is not used in either the GOES or the AIRS retrieval.

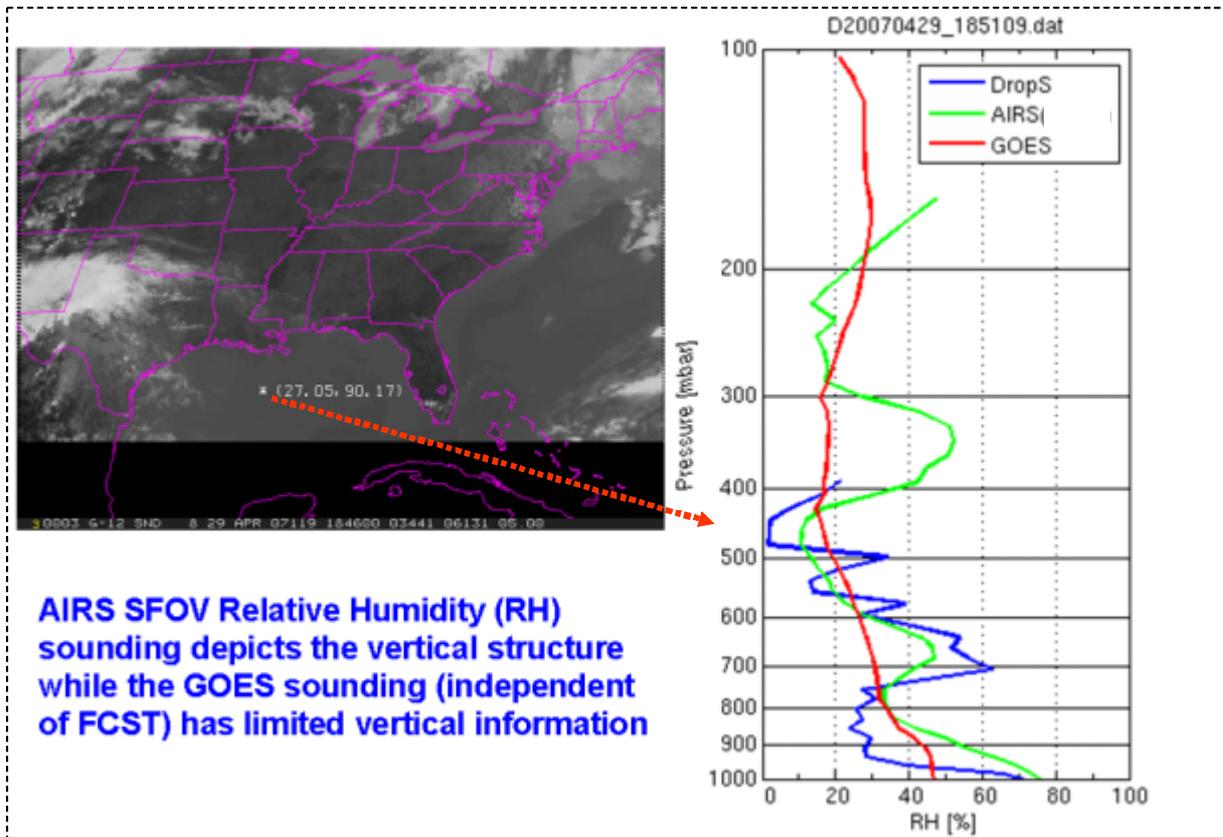


Figure 1. AIRS (granule 193), GOES Sounder and dropsonde RH profiles at approximately 19 UTC on 29 April 2007, over the Gulf of Mexico.

Current GOES observations and numerical simulations of future systems were used to demonstrate the impact on NWP. Approximately 650 simultaneous radiosonde observations (RAOBs), GOES Sounder radiance measurements, and NCEP (National Centers for Environmental Prediction) GFS (Global Forecast System) forecasts were collected over continental United States (CONUS). Current GOES soundings were derived from the GOES radiance measurements only, which are therefore independent of a forecast. The hyperspectral resolution IR radiances (e.g., HES) were then simulated from RAOBs through an appropriate radiative transfer model (RTM, Hannon et al. 1996) along with an assumed nominal instrument noise. The inverse algorithm (Li et al. 2000) was used to convert the HES radiances into a retrieved atmospheric sounding. The actual GOES soundings and simulated HES soundings were then compared with the independent collocated RAOBs to determine a root measure square error (RMSE). Figure 2 shows the temperature (left) and water vapor mixing ratio percentage (right) RMSE for forecasts (black), current GOES soundings (blue), and HES simulated soundings (red). The HES outperforms both the forecast and the current GOES moisture capabilities. For temperature, the forecast has a relatively smaller RMSE over CONUS, while the RMSE from the current GOES Sounder is larger than the forecast. These relationships are consistent with the results of Ma et al. (1999). The hyperspectral resolution IR soundings provide a much improved temperature profile, with a smaller RMSE than both the forecast and the current GOES Sounder.

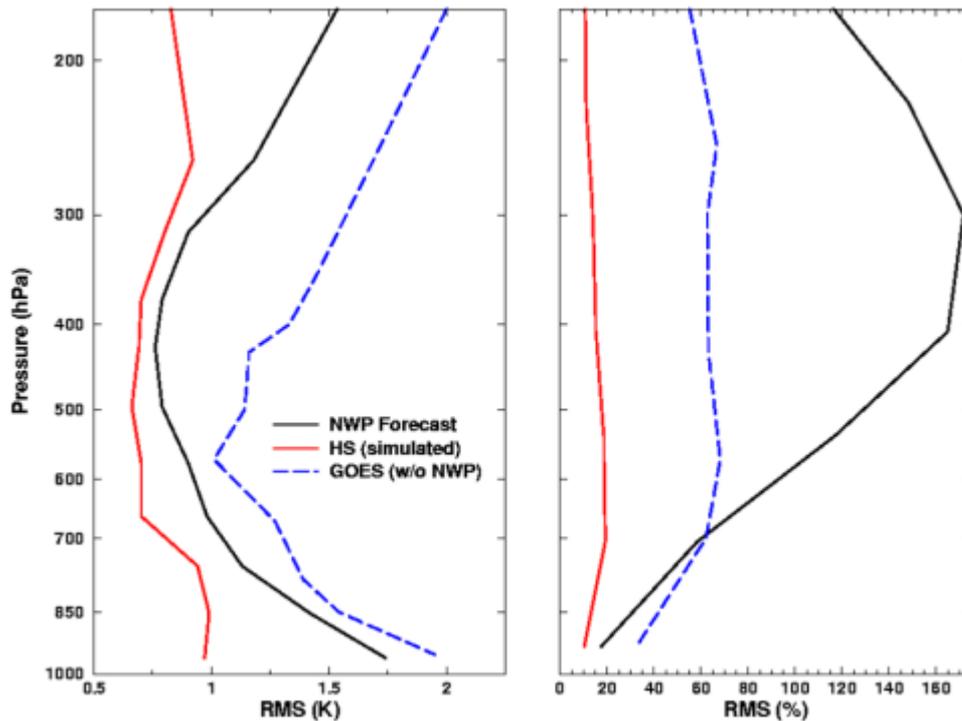


Figure 2. The temperature (left) and water vapor mixing ratio percentage (right) RMSE for forecasts (black), GOES real soundings (blue), and HS (High Spectral resolution) simulated soundings (red).

High spatial resolution regional forecast model during the International H<sub>2</sub>O Project (IHOP) (June 12, 2002) were used to demonstrate the potential for improving nowcasting with a geostationary hyperspectral resolution IR sounder. Output from the mesoscale model (MM-5), at 2 km grid spacing and 5-minute intervals, is used to simulate the ABI and HES IR radiances by using an appropriate RTM and including the expected instrument noise characteristics. The MM5 output fields serve as the truth field, while the simulated ABI and HES IR radiances are converted to atmospheric temperature and moisture profile retrievals (Li et al. 2000).

The equivalent potential temperature ( $\theta_e$ ) differences between 800 and 600 hPa are indicative of thunderstorm potential. In Figure 3, the upper left panel shows the “truth” field of  $\theta_e$  (difference between 800 and 600 hPa); the upper right panel shows the simulated  $\theta_e$  from HES while the lower right panel shows the  $\theta_e$  from ABI at 15 UTC for 12 June 2002, and the lower left panel shows the difference image between HES and ABI. HES depicts an unstable region similar to the “truth” field while ABI has weak instability with no indication of pre-storm development. Equally important is that the HES derived field clearly shows the region of stable air. This is important for reducing false alarms for convective events. The lower set of four-panel image in figure 2 is five hours later, when the convective storms started to develop. The GOES Imager data (not shown) indicated a similar pattern of the storm development as the MM-5 modelled conditions. This case demonstrates that:

- Rapid storm growth in the ‘truth’ fields begins when the storm enters the area of convective instability, and is indicated by strong vertical gradients of temperature and moisture;
- HES shows the development of the unstable region several hours earlier than the ABI alone, and;
- ABI can under-estimate the convective instability by 20-30% compared to HES, for this case.

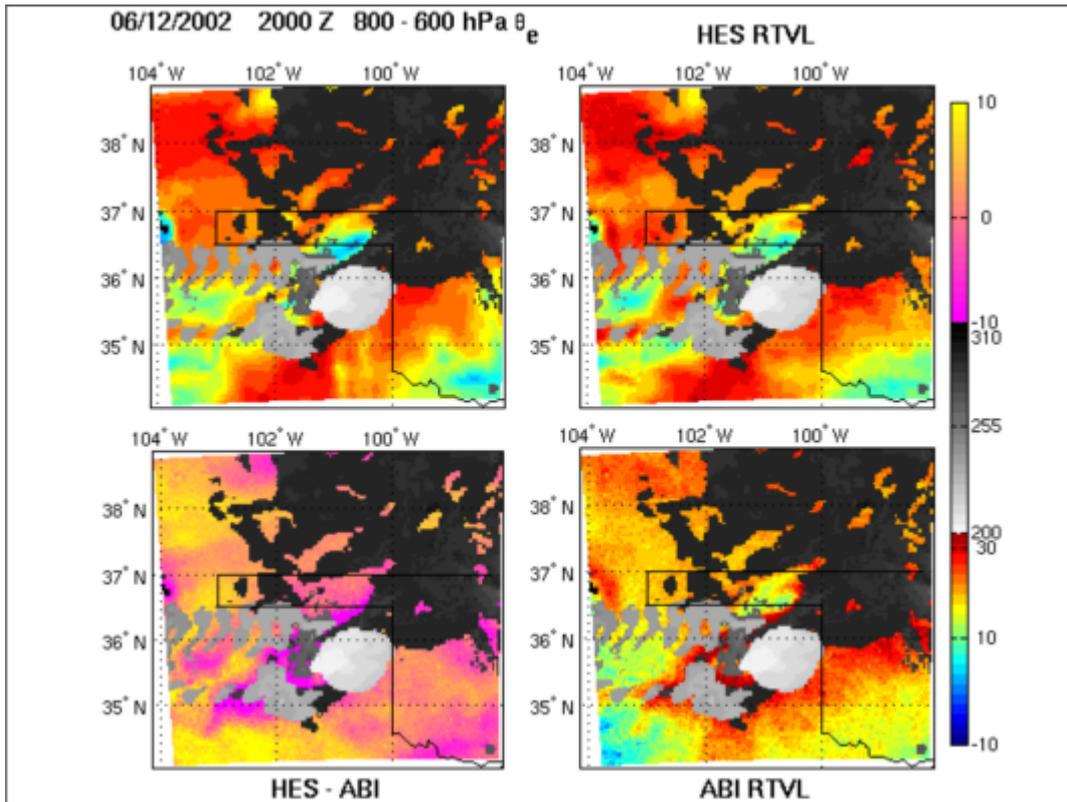
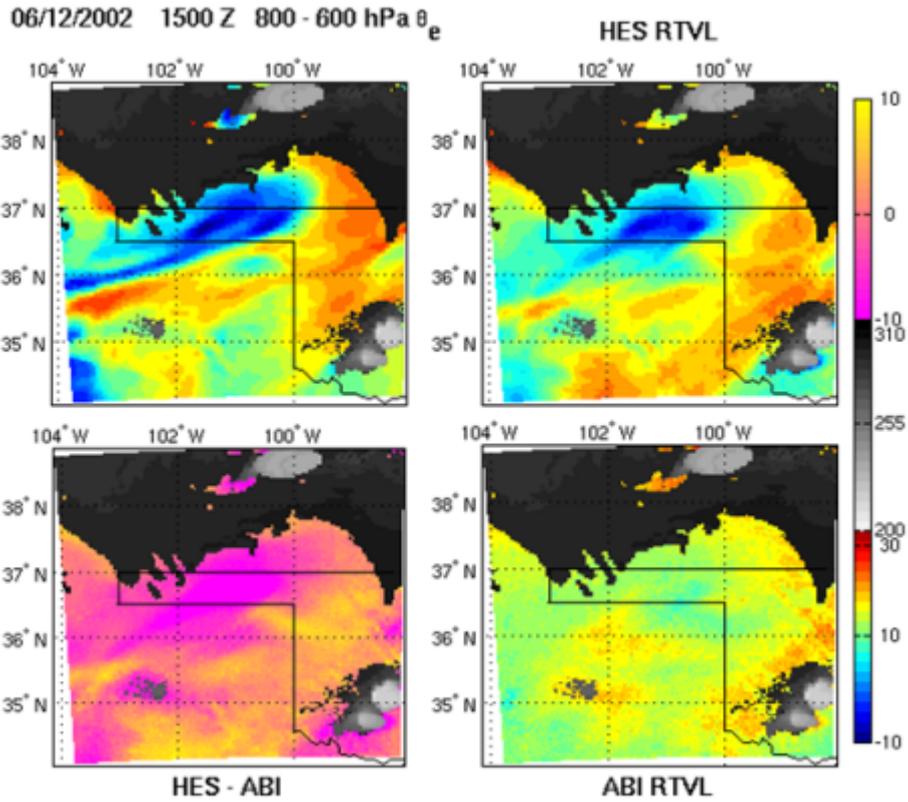


Figure 3. True field of Theta-E (upper left), Theta-E from HES (upper right), Theta-E from ABI (lower right). The top panel of images are at 15 UTC for 12 June 2002, along with the difference image between HES and ABI (lower left). The lower panel of images are from 20 UTC.

In figure 4, the lower left panel shows the TPW from HES (blue) and ABI (green), along with the “truth” at the indicated location. The lower right panel is the same as lower left panel but for Lifted Index (LI). Grey colors in the upper panels denote cloud-top temperature. The significant LI and TPW improvements can be seen from HES over ABI in the potential of estimating the convective instability that results in the formation of severe weather/storms. For example, HES depicts the atmospheric instability 2 hours earlier than ABI.

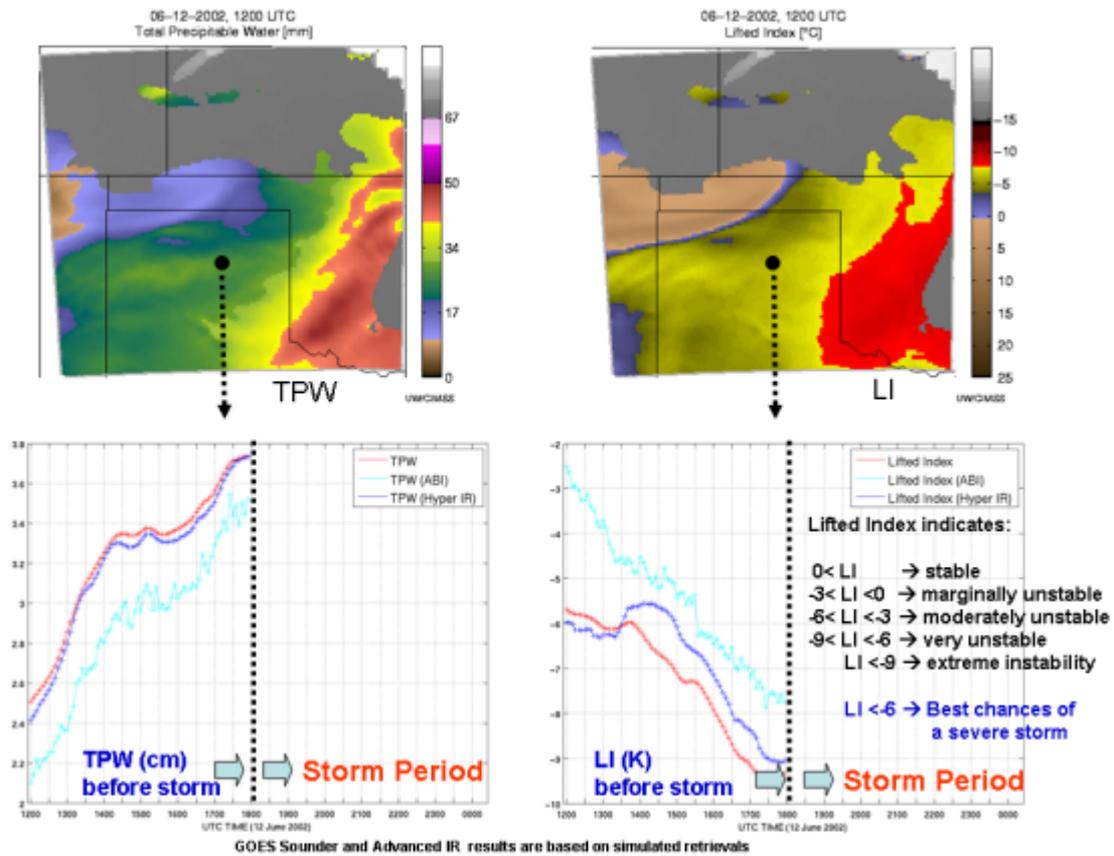


Figure 4. TPW (upper left panel) and LI (upper right panel) from IHOP (June 12, 2002) model output (MM5, 2 km, 5 minutes). Lower left panel shows the TPW from simulated HES (blue) and ABI (green), along with the “truth” at the indicated location. The Lower right panel is the same as lower left panel but for LI Grey colors in the upper panels denote cloud-top temperature.

### NWP Applications

Satellite observations are the backbone of the observing system for today’s NWP on both the regional and global scales (Zapotocny et al. 2005a, Zapotocny et al. 2005b, Zapotocny et al. 2007). High spectral/temporal data will improve both regional and global-scale numerical models via improved measurements that will help initialize the fields of moisture, winds and temperature. A rapid refresh of the data will better guide regional forecast models. The particular advantage of HES to NWP is the improved vertical temperature and moisture resolution, better definition of clouds, and more accurate surface emissivity estimates (which is critical to achieving accurate temperature and moisture profiles from radiance data assimilation over land).

A number of papers have already documented the various applications of hourly GOES sounding data and its impact on NWP. Menzel et al. (1998) described the applications, Zapotocny et al. (2002) and Zapotocny et al. (2005) provide examples of the impact of satellite and other observations on NWP). OSSEs (Observing System Simulation Experiments) with the RUC (Rapid Update Cycle) model have shown that two polar orbiting

high spectral resolution sounders do not provide the temporal coverage to sustain forecast improvements out to 12 hours, while, simulated hourly Geostationary high spectral resolution sounder observations depict moisture changes for improved forecasts (e.g., smaller S1 score) (Aune et al. 2000). Both satellite solutions improved forecast scores over data only from conventional observations.

Current GOES Sounder clear-sky radiances over the water are used in the assimilation for both regional and global forecast models (D. Keyser, personal communication). Moisture information (three layers of precipitable water), cloud heights and/or radiances from the current GOES Sounders have demonstrated positive impact on NWP (e.g., Aune 1996, Bayler et al., 2001, Zou et al. 2001, Schmit et al. 2002), including regional models such as the CRAS (CIMSS Regional Assimilation System), RUC, Eta and MM-5.

### ***Other Applications***

The high spectral resolution sounder observations will also improve derived products currently planned with the Advanced Baseline Imager (ABI) data (Li et al. 2004b, Schmit et al. 2005, Li et al. 2005b, Ackerman et al. 2008). These include: volcanic ash, cloud detection, cloud top properties, atmospheric motion vectors (Wanzong et al. 2008), dust detection, land and sea surface temperature and surface emissivity. In this section we briefly discuss the advantages of high spectral resolution in observing clouds, aerosols, surface emissivity and the height assignment of atmospheric motion vectors (AMV).

High spectral resolution IR data can retrieve a number of trace gases, depending on the instrument details regarding spectral coverage, spectral resolution and signal-to-noise ratio. These include ozone, SO<sub>2</sub>, water vapor (H<sub>2</sub>O), CO<sub>2</sub>, and carbon monoxide (CO). High spectral resolution data are able to spectrally resolve the absorption lines of these various species. Other possible species include methane (CH<sub>4</sub>) and nitric acid (HNO<sub>3</sub>) (Barnet et al. 2004, Chahine et al. 2006), although impossible to retrieve from broad band measurements.

With geostationary hyperspectral resolution IR radiances, hemispheric surface emissivity spectra could be derived hourly. Algorithms for retrieving hyperspectral resolution IR emissivity spectra have been developed by Li et al. (2007). Studies have shown that the global emissivity spectra derived from AIRS depict surface type properties very well (Li et al. 2008). The surface emissivity spectrum product is very important for deriving other products with IR radiances, for example, the temperature and moisture profiles, land surface temperature, cloud-top pressure, dust and aerosol properties, and trace gasses.

Large positive impacts have been demonstrated from GOES Atmospheric Motion Vectors (AMVs) in the forecasts of hurricane tracks (Goerss et al. 1998, Zapotocny et al. 2007) and the model wind field depiction. One of the largest sources of error with the current GOES AMV product is the height assignment (Velden et al. 1998). Research has shown promising results with respect to the height assignment when tracking the moisture in a profile derived from high spectral resolution sounding data. The traditional method of tracking features is to match features in the radiance-domain and then assign the tracers height using NWP temperature profiles or a semi-transparency correction (Velden et al. 1998). High spectral resolution IR measurements will reduce this uncertainty by enabling feature tracking in the retrieved profile fields, as opposed to the radiance fields (Wanzong et al. 2008). The more direct use of AMVs for nowcasting would also be noteworthy.

Finally, high spectral resolution IR data can provide unique data for diurnal monitoring of radiances. Regional climatologies can be generated for a number of products. High spectral resolution IR data, ideally with complete spectral coverage across the infrared region, can be used to cross-calibrate polar-orbiting sensors. It is very difficult to know the precise in-flight

spectral response characteristics of a broad spectral band instrument. But high spectral resolution measurements can resolve absorption features, and thus the instrument response can be much better validated in-flight. The utility of high spectral resolution instruments, such as AIRS for spectrally calibrating the broad band MODIS (Moderate Resolution Imaging Spectroradiometer) measurements, has been demonstrated by Tobin et al. (2006a; 2006b).

### 3. CONCLUSIONS

Retrieval simulations have shown that temperature and moisture information retrieved with high spectral and temporal resolution IR instrument far exceed those from the broadband Sounders on current GOES. A high spectral resolution IR sensor has a much greater vertical resolving power of temperature and moisture than broad band sensors.

High spectral and temporal resolution observations benefit nowcasting and NWP applications by providing spatially and temporally continuous measurements of temperature, water vapor, and the wind profile. With high spectral resolution IR geostationary sounding capabilities, forecasters and regional models will have sufficient information (e.g., meeting user requirements) regarding the fine-scale three dimensional structure of atmospheric water vapor and capping inversions and how these structures vary in time. A high spectral (and hence vertical) resolution IR sounder with faster scanning will be able to monitor the evolution of important low-level information about the atmosphere and thus substantially improve the capability to forecast severe weather.

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