High-Spectral- and High-Temporal-Resolution Infrared Measurements from Geostationary Orbit

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ABSTRACT

The first of the next-generation series of the 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. High-spectral-resolution sensors have a much greater vertical-resolving power of temperature, moisture, and trace gases than low-spectral-resolution sensors. Because of coarse vertical resolution and limited accuracy in the legacy sounding products from the current GOES sounders, placing a high-spectral-resolution IR sounder with high temporal resolution in the geostationary orbit can provide nearly time-continuous three-dimensional moisture and wind profiles. This would 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, which require products such as atmospheric moisture and temperature profiles as well as derived parameters, clear-sky radiances, vertical profiles of atmospheric motion vectors, sea surface temperature, cloud-top properties, and surface properties. Other application areas include trace gases/air quality, dust detection and characterization, climate, and calibration. This paper provides new analysis that further documents the available information regarding the anticipated improvements and their benefits.

1. Introduction

The next-generation geostationary environmental satellite series will enable many improved and new capabilities for imager-based products. Although the Advanced Baseline Imager (ABI) (Schmit et al. 2005) on the next-generation series of Geostationary Operational Environmental Satellite (GOES-R) will provide a good horizontal representation of the atmosphere, the critical vertical dimension needed for weather forecasting will remain grossly undersampled (Schmit et al. 2008). Determining the vertical structure of the atmosphere from passive sensors requires high-spectral-resolution infrared (IR) observations. The current GOES sounders only have 18 IR bands with low spectral resolution to profile the atmosphere, which severely limits their ability to resolve vertical features (Wang et al. 2007). The spectral resolution is on the order of 10–100 cm^{-1} for a single band of current GOES sounders, whereas advanced IR sounders have spectral coverage on the order of 0.5 cm^{-1} for a single channel. The finer spectral resolutions enable measurements of important changes that result from vertical structures in the atmosphere and other phenomena. Many aircraft observations have demonstrated the value of high-spectral-resolution IR data (e.g., Smith et al. 1990). In addition, high-vertical-resolved water vapor profiles are accurately retrieved in order to drive atmospheric wind profiles; this was first demonstrated and

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documented with real data by the aircraft hyper-spectral-resolution National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Test bed-Interferometer (NAST-I) measurements similar to the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS; Zhou et al. 2002; Velden et al. 2005).

A high-spectral-resolution IR sounder, originally called the Advanced Baseline Sounder (ABS) and more recently called the Hyperspectral Environmental Suite (HES), was slated to be on GOES-R as a companion to the ABI. In 2006, predominately because of budgetary pressure, the HES was removed from the GOES-R/S series. The many HES-related validation requirements remain unmet.

Advanced IR sounder technology has been demonstrated by the GIFTS measurement concept (Smith et al. 2006), which was developed by the National Aeronautics and Space Administration (NASA) and others during the late 1990s for improving weather prediction. The GIFTS measurement concept has been demonstrated by a ground-based measurement experiment conducted during the fall of 2006 (Zhou et al. 2007).

A geostationary advanced IR sounder would provide breakthrough measurements on the time evolution of horizontal and vertical water vapor and temperature structures. These measurements would be an unprecedented source of information on the dynamic and thermodynamic atmospheric fields, an important benefit to nowcasting and numerical weather prediction (NWP) services. High-spectral-resolution measurements can also support forecasting air quality and monitoring atmospheric minor constituents through its capability to provide estimates of diurnal variations of tropospheric contributions of atmospheric trace gases like ozone and carbon monoxide. The purpose of this paper is to demonstrate the important aspects (high temporal and spectral resolution) of a geostationary advanced IR sounder and their potential applications on severe weather forecasting.

Schmit et al. (2008) has demonstrated that ABI IR radiances can be used together with forecast information to continue the current GOES sounder products (legacy temperature and moisture profiles, total precipitable water, layer precipitable water, and instability indices). Information content analysis was also conducted to demonstrate that both the current GOES sounder and ABI have limited vertical information and accuracy for atmospheric profiling when compared with advanced IR sounders. This paper outlines the potential applications of high-spectral-resolution IR observations that have led many research and satellite user groups, both national and international, to recommend that a fully capable advanced sounder be flown on U.S. geostationary satellites. The focus is on providing new studies that demonstrate the value of high-spectral-resolution IR and high temporal and vertical information on storm nowcasting. Section 2 briefly describes what is meant by high-spectral-resolution observations in support of atmospheric temperature and moisture retrievals and outlines the validated user requirements that can only be met with a high-spectral-resolution sounder in geostationary orbit. Section 3 presents several applications in nowcasting, whereas section 4 discusses potential applications in NWP, on both global and regional scales. Section 5 discusses the benefits of using high-spectral-resolution information for other applications, such as atmospheric motion vectors, trace gases, air quality, sea surface temperature (SST), clouds, surface emissivity, and calibration. Potential economic benefits are summarized in section 6, and conclusions are given in section 7.

2. High-spectral-resolution observations

Several Global Earth Observations System of Systems (GEOSS) member states are considering a geostationary high-spectral-resolution sounder. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) plans to fly a high-spectral-resolution sounder called the Infrared Sounder (IRS) on the geosynchronous Meteosat Third Generation (MTG), which will be launched in 2018. China also has plans for high-spectral-resolution IR sounders on both polar-orbiting and geostationary orbits, although the first few in the series may be demonstration units. The World Meteorological Organization (WMO) has stated the need for advanced sounders in the geostationary orbit. This is consistent with the recommendations from a National Research Council (NRC) decadal study report to ‘‘develop a strategy to restore the previously planned capability to make high temporal- and vertical-resolution measurements of temperature and water vapor from geo orbit’’ and to achieve ‘‘essential sounding capabilities to be flown in the GOES-R time frame’’ (NRC 2007). The geostationary perspective will complement the global view from the polar orbiters and offer much improved monitoring of rapidly changing phenomena (Fig. 1).

The current U.S. GOES sounders (Menzel and Purdom 1994; Menzel et al. 1998) measure emitted radiation in 18 IR spectral bands and reflected solar radiation in one visible band. The spectral measurements have spectral bandwidths that are on the order of tens of wavenumbers. This includes the *GOES-8* through *GOES-14* sounders and continues through GOES-P (Plokhenko et al. 2003; Hillger and Schmit 2007). Operational uses by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) from the current GOES

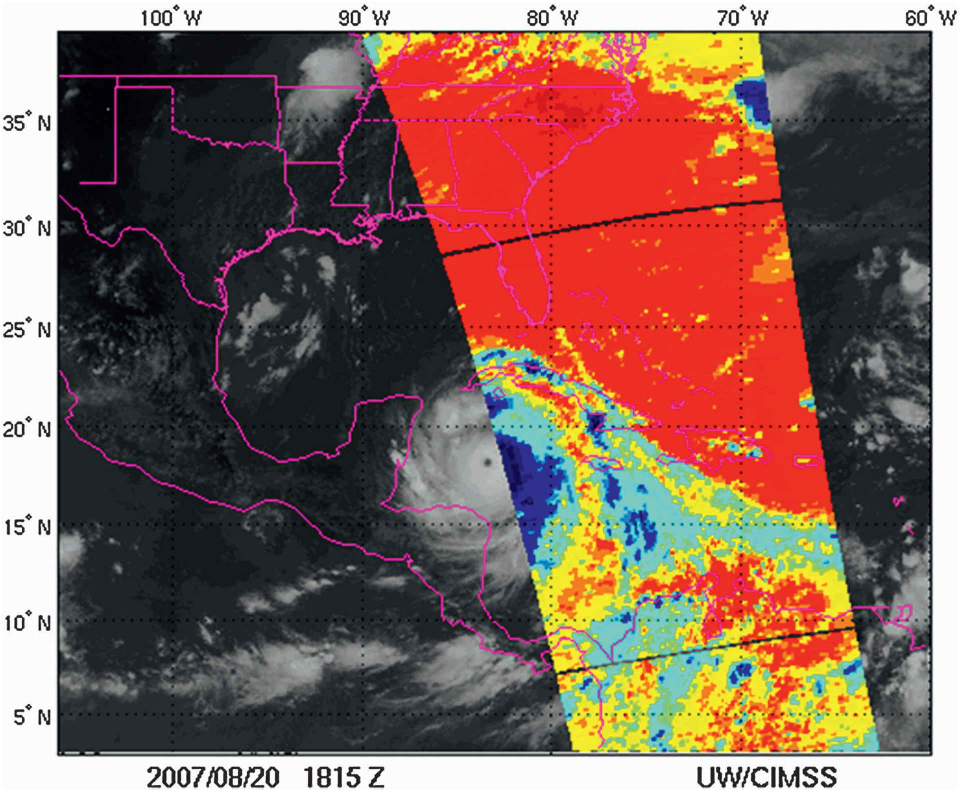

FIG. 1. Sample coverage of Hurricane Dean from the geostationary perspective (gray-shaded IR window image) and that from a polar-orbiting satellite (color coded). The coverage shown of the storm from AIRS was the best coverage for this entire day (20 Aug 2007), whereas GOES can offer rapid updates to monitor rapidly changing events.

sounders include the following: clear-sky radiances, profiles of temperature and moisture, atmospheric stability indices, layer and total precipitable water (TPW), cloud-top retrievals (pressure, temperature, and effective cloud amount), surface skin temperature, and water vapor atmospheric motion vectors (Schreiner et al. 2001; Dostalek and Schmit 2001; Velden et al. 1998). Experimental products from the current sounders include total column ozone, upper-level sulfur dioxide (SO_2) 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 of less than a wavenumber (Fig. 2, Table 1). This finer spectral resolution is required to meet the observing requirements for weather forecasting, including requirements on the accuracy in the retrieval of the vertical profiles of atmospheric moisture and temperature, trace gas concentrations, cloud-top pressure (CTP), surface IR emissivity, and surface temperature (T_s).

The challenge of higher data rates associated with high-spectral-resolution sounders can be met through improvements in the area of data compression. For example, ''lossless'' compression ratios on sample Atmospheric Infrared Sounder (AIRS) data are approaching the 4:1 range (Huang et al. 2005). The realized compression ratio value depends on the scene type, detector characteristics, and bit depth.

3. Applications

There are many advantages of high-spectral-resolution data over low-spectral-resolution data. These include more precise spectral calibration, improved vertical resolution and accuracy of retrieved temperature and moisture profiles, nowcasting and short-term forecasting applications, the retrieval of several trace gases, and wind products derived from water vapor profiles. Table 2[1] lists the NOAA-validated required products that would be greatly improved with an advanced high-spectral-resolution sounder in the geostationary orbit. High-spectral-resolution IR measurements would also improve many ABI-only products, including cloud height, total

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[1] Compiled for the NOAA Mission Requirements Document 2B (MRD-2B) for the GOES-R Series, Version 2.1, 4 March 2005.

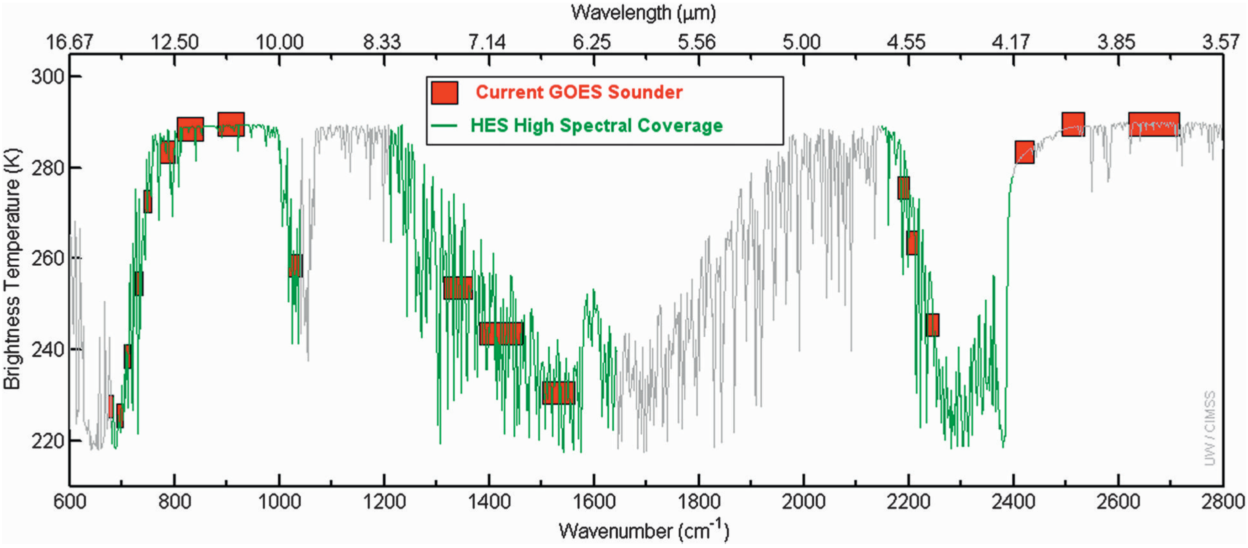

FIG. 2. The spectral coverage of the current filter-wheel radiometer (GOES sounder bands) and a high-spectral-resolution spectrum. The current sounder is at low spectral resolutions (15–100 cm^{-1}), whereas a HES-like instrument could have spectral resolutions on the order of 1 cm^{-1}. The full high-spectral-resolution coverage is similar to IASI, whereas the highlighted spectral regions were of the options at the end of the HES formulation phase.

ozone, and land and sea surface temperatures (Li et al. 2004a).

High-spectral-resolution IR observations are primarily used to determine atmospheric temperature and moisture profiles. The ill-posed nature of the retrieval of temperature and moisture profiles from IR radiances is often resolved through the addition of background data from short-term forecasts. Retrievals generated from variational methods provide an optimal method of combining observations with a background from a short-term forecast numerical weather prediction model, which accounts for the assumed error characteristics of both the observation and background. The greater information content of high-spectral-resolution sounders means that the retrieved profiles are much less sensitive to the background. This would greatly increase the value of many products, such as TPW, lifted index (LI), and other atmospheric stability parameters that are used to monitor forecast model performance (e.g., moisture distribution and timing, regions of interest with respect to convection, etc.).

Numerous studies have demonstrated the value of both land-based (Feltz et al. 2003; Knuteson et al. 2004b,c) and satellite-based high-spectral-resolution IR measurements. For example, Schmit et al. (2008) used radiosonde observations and radiative transfer models for simulating

TABLE 1. Advanced hyperspectral sounders have hundreds of channels with spectral widths of less than one wavenumber. This table shows the type of measurement requirements needed to meet future geosounding missions/weather forecast needs as specified by the International Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Working Group. Note that the spectral resolutions are on the order of 1 cm^{-1} in the longwave region.

Channel (cm^{-1})	Wavelength (μm)	$\delta\upsilon$ (cm^{-1})	Purpose	Geostationary δt (min)	Geostationary δS (km)	Remarks
680–800	12.5–14.70	0.6	Tropospheric temperature	30	5	Fundamental band
800–1000	10.0–12.50	0.6	T_s, H_2O, cloud	15	5	Fundamental band cloud, surface, and H_2O
1000–1100	9.09–10.00	0.6	O_3	3	5	O_3, stratospheric wind
1100–1590	6.29–9.09	1.2	T_s, H_2O, aerosol/dust	15	5	Water vapor flux tropospheric wind profiles
1590–2000	5.00–6.29	1.2	H_2O, T_s, cloud	15	5	Water vapor flux tropospheric wind profiles
2000–2200	4.54–5.00	0.6	CO, T_s, cloud	60	5	Trace gas/air quality
2200–2250	4.44–4.54	2.5	Tropospheric temperature	15	5	Clear ocean day and land/ocean night utility
2250–2390	4.18–4.44	2.5	Stratospheric temperature	—	—	Nighttime utility
2386–2400	4.17–4.19	2.5	Tropospheric temperature	—	—	Nighttime utility
2400–2700	3.70–4.17	2.5	T_s, cloud	—	—	Clear ocean and night land utility

TABLE 2. Observational requirements for 7 NOAA-validated user products. The mission criticality values of the products included in the table range in value from 1 to 3 (noted in parentheses in left column). A value of 1 is considered mission critical, a value of 2 is considered mission enhancing, and a value of 3 indicates lower priority to the NOAA mission but valuable to other agencies.

Observational requirement (product criticality)	Science needs	Measurement thresholds (goal)	Science requirement
Atmospheric vertical temperature profile (1) Atmospheric vertical moisture profile (1)	Atmospheric soundings of temperature and moisture are optimum repeat cycle of 1 h of sounder coverage for global NWP	Range: 180–320 K Accuracy: 1 K (0.5 K) Range: 0%–100% RH Accuracy: Sfc-500 hPa: 10% (5%) 500–300 hPa: 10% (5%) 300–100 hPa: 20% (10%)	Vertical resolution: Surface–500 hPa; 0.3–0.5-km layers 500–300 hPa; 1–2-km layers 500–300 hPa; 1–2-km layers Above 100 hPa; 2–3-km layers
Capping inversion (1)	Identify boundary layer signatures that indicate the development of severe weather	Range: CONUS: T and Td: 210–300 K Hgt: Sfc-650 hPa MESO: 0–20 K (delta T and delta Td) Accuracy: T and Td: 10 K Hgt: 150–250 hPa	Need temporal sampling of less than 5 min in clear or partly cloudy conditions to monitor conditions favorable of severe weather development
Moisture flux (1)		Range: 0–20 g kg^{-1} h^{-1} Accuracy: 10% (5%)	ABI contributes to wind determination, and HES yields needed vertical resolution
Cloud-base height (1)		Range: 0–30 km Accuracy: 2 km (0.1 km)	TBD* (±5%)
Moisture flux (1)		Range: 0–20 g kg^{-1} h^{-1} Accuracy: 10% (5%)	ABI contributes to wind determination, and HES yields needed vertical resolution
Surface emissivity (2)		Range: 0.85–1.0 (0.7–1.0) Accuracy: 0.05 (0.02)	
CO concentration (3)		Range: TBD*	

* To be determined.

the *GOES-12* sounder and high-spectral-resolution IR radiances. After adding appropriate noise estimates, the retrieved temperature and moisture profiles from the simulated radiances clearly demonstrate that the high-spectral-resolution sounder could provide 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).

The quality of the high-spectral-resolution IR data has been demonstrated with data available on polar-orbiting satellites. This includes the Interferometeric Monitor for Greenhouse Gases (IMG), the AIRS on the Earth Observing System (EOS) *Aqua*, and the Infrared Atmospheric Sounding Interferometer (IASI) on *MetOp-A* (Ogawa et al. 1993; Chahine et al. 2006; Siméoni et al. 1997). Although these measurements provide a wealth of information for global applications, they do not have the fine temporal information necessary to monitor quickly changing phenomena. In addition, polar orbiters such as AIRS and IASI [and the to-be launched NPOESS Preparatory Project (NPP) high-spectral-resolution Cross-track Infrared Sounder (CrIs)] have orbital gaps that sometimes provide no data at the location of storm development (see Fig. 1). A key advantage of a geostationary advanced sounder is that it can provide high vertical resolution and accurate soundings hourly (or better) over much of the Western Hemisphere. The experience with high-spectral-resolution measurements from the various polar orbiters has resulted in a high level of maturity for the processing of these types of data.

4. Applications in forecasting

The bird's-eye view from a satellite helps weather forecasts in two ways: trained expert forecasters interpret the satellite images or products and the measurements are assimilated into NWP models to improve numerical forecast performance by providing useful independent information about the initial state. Image/product analysis by experts plays an important role in ''nowcasting'' (short-term forecasts that predict the weather within approximately a 6-h window). Assimilation of observations into numerical weather prediction forecast models impacts the 12–72-h forecasts and beyond.

The ability to sense water vapor in the troposphere is crucial for monitoring and predicting certain hazardous weather conditions. Water vapor is the ''key player'' in severe thunderstorms. Large variations in atmospheric water vapor occur over a scale of 10 km in the horizontal and hundreds of meters in the vertical. Thunderstorms, which form mostly over land, have a life span of tens of minutes. The current GOES sounder-derived products, such as TPW and atmospheric instability, are used in a number of nowcasting applications (Smith et al. 1985; Schmit et al. 2002). A survey of NWS forecasters in 1999 demonstrated the usefulness of the current GOES sounder products. For example, when asked to ''rate the usefulness of Lifted Index (LI), Convective Available Potential Energy (CAPE), and Convective Inhibition (CINH) (changes in time/axes/gradients in the hourly product) for location/timing of thunderstorms,'' the responses[2] ranged from positive [significant (30%) or slight (49%)] to no discernible impact (19%) to slight negative impact (2%). Although the current GOES sounder is being used for a number of applications, these are constrained by limited spatial coverage and spectral resolution (e.g., vertical resolution) and the inability to penetrate cloud cover (Schmit et al. 2002). These limitations can be mitigated with an advanced IR sounder in a geostationary orbit. For example, in regions of thin clouds or low clouds, above-cloud retrievals can be generated (Zhou et al. 2007; Weisz et al. 2007b). An advanced IR sounder could also be designed to scan faster (Smith et al. 2002), and the vertical resolution can be improved with finer-spectral-resolution IR data (Wang et al. 2007).

This section demonstrates how current research assesses the impact of high-spectral-resolution IR observations on nowcasting and data assimilation applications.

a. Nowcasting applications

With a high-spectral-resolution sensor, the nowcasting and short-term forecasts (0–6 h) for severe weather would be improved because of low-level layer moisture/temperature information and rapid scan capabilities. These enhanced capabilities would allow improved monitoring of atmospheric instability and inversions. Several potential applications from high temporal and high-spectral-resolution IR data were discussed by Sieglaff et al. (2009). They showed how temporal differences of the spectral ''online'' and ''offline'' absorption features in the IR window region of the spectrum are related to low-level temperature and moisture.

The improvement in sounding capability with a high-spectral-resolution IR instrument has been well documented (Smith et al. 1990; Huang et al. 1992). Here, we provide further demonstration by comparing collocated AIRS and GOES sounder profiles along with aircraft dropsonde measurements. Figure 3 shows the GOES sounder 11-μm brightness temperature (BT) image (top panel) beginning at 1846 UTC 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 1900 UTC (AIRS granule 193). Three relative humidity (RH) soundings are plotted (bottom panel); GOES (red) has reasonable accuracy in the mean but lacks vertical structure when compared with dropsonde (blue), whereas the AIRS single field of view (SFOV) sounding (green; physical retrieval with regression as first guess) depicts the fine moisture structure and is close to the dropsonde. To show the independent sounding information, the forecast is not used in the GOES or AIRS retrieval.

Observations from the International H_2O Project (IHOP; 12 June 2002; Weckwerth et al. 2004) were used to demonstrate the potential for improving nowcasting with a geostationary high-spectral-resolution IR sounder. The observations were used with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5; Chen and Dudhia 2001) to investigate the capability for depicting the atmospheric conditions during this severe weather day. Output from the MM5, at 2-km grid spacing and 5-min intervals, was used to simulate the ABI and HES IR radiances by using an appropriate radiative transfer model and including expected instrument noise characteristics. The model output fields serve as the ''truth field,'' whereas the simulated ABI and HES IR radiances are converted to atmospheric temperature and moisture profile retrievals (Li et al. 2000). Atmospheric instability index parameters, such as LI; equivalent potential temperature; and TPW are generated from true fields and compared with those derived from the simulated ABI and HES radiances. In Fig. 4, the bottom left and right panels show the time sequences of TPW and LI, respectively, from simulated HES (blue) and ABI (light blue) radiances, along with the truth at the indicated location. Significant LI and TPW improvements from HES relative to ABI are evident. HES has a much better potential for estimating the convective instability that sparks the formation of rapid convection.

To analyze further the ABI and HES sounding performances, we selected two observation times and compared the soundings from simulated HES and simulated ABI with true profiles at the location indicated in Fig. 4. Figure 5 shows the temperature profile (top left) errors of HES and ABI, the LI errors of HES and ABI (top middle), and the RH profile errors of HES and ABI (top right). The bottom panel shows the simulated BTs

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[2] There were 248 valid weather cases relating to this question.

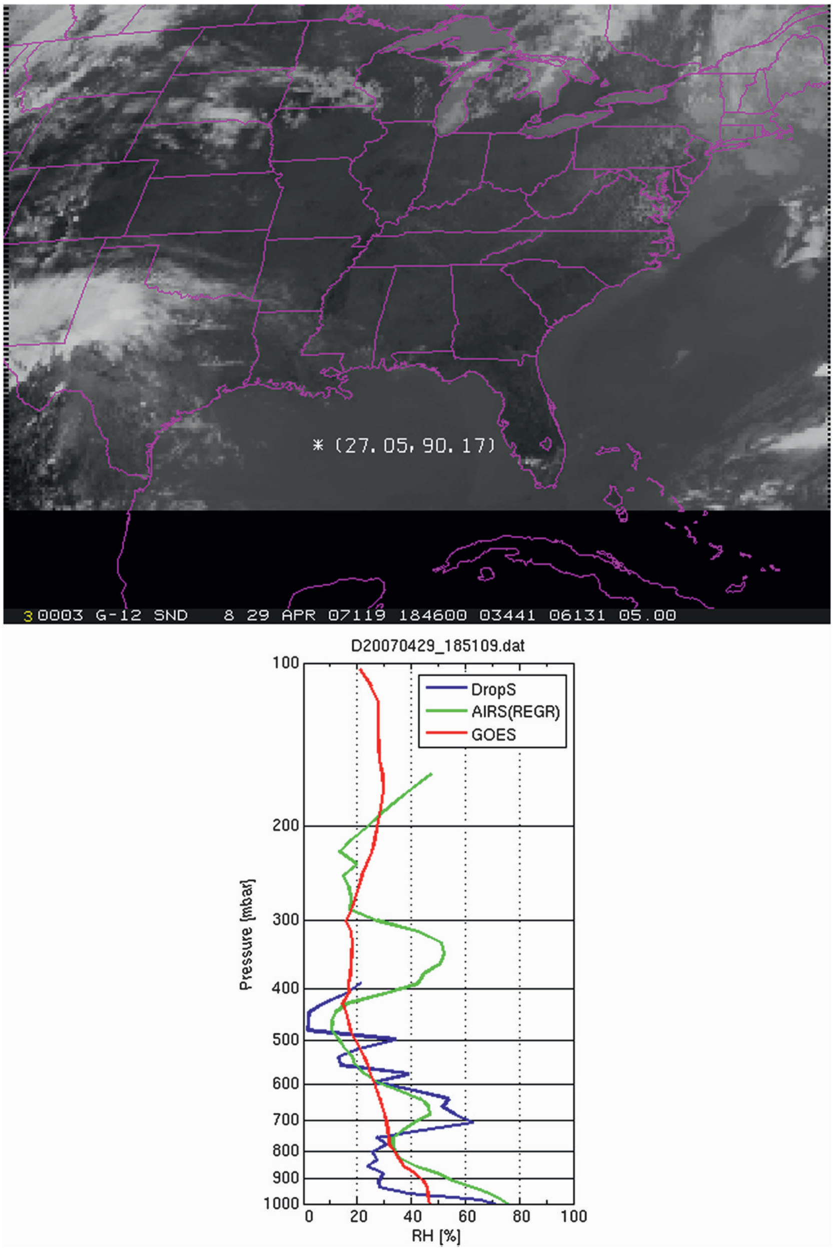
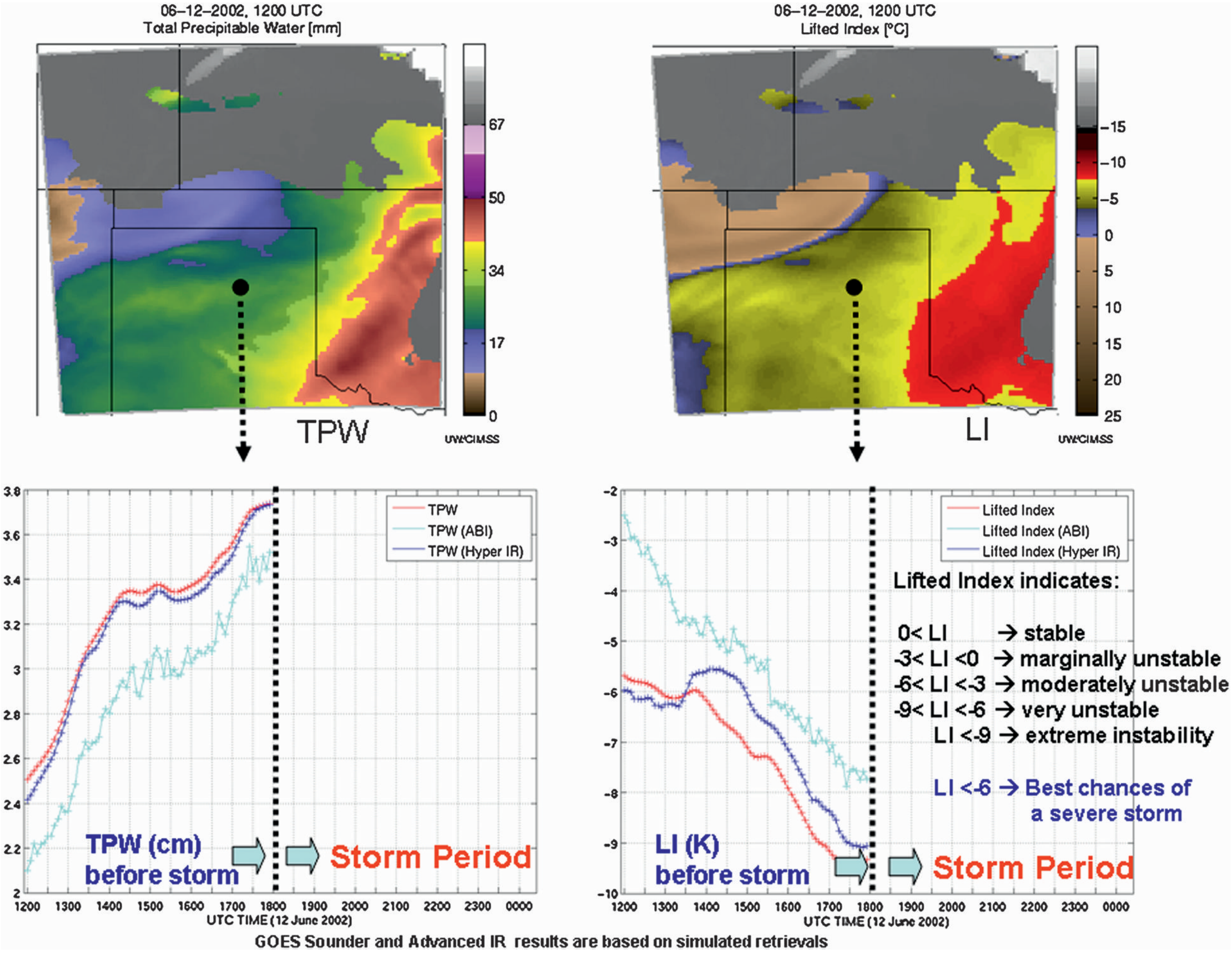


FIG. 3. (top) Satellite image of the GOES sounder 11-μm BT image at 1846 UTC 29 Apr 2007, with the dropsonde location indicated by small star over the Gulf of Mexico. The time of AIRS overpass is approximately 1900 UTC (AIRS granule 193). (bottom) Three RH soundings. Although GOES (red) has reasonable accuracy in general, it lacks vertical structures when compared with dropsonde (blue). The high-spectral-resolution observations of AIRS SFOV sounding (green) better depicts the fine structures in this case, which are close to those from the dropsonde.

for the high-spectral-resolution HES and low-spectral-resolution ABI IR bands. The ABI has large temperature errors in the upper and lower atmospheric levels because of the lack of temperature sounding information. Note that this figure is only for a single profile at a single time. In this particular case, ABI retrievals tend to cool the atmosphere in the boundary layer while warming the upper troposphere. Although the ABI provides moisture information using its three water vapor absorption bands, the retrieved errors in moisture are relatively large, especially in lower atmospheric levels. HES dramatically reduced the errors of temperature in the lower



GOES Sounder and Advanced IR results are based on simulated retrievals

FIG. 4. (top left) TPW and (top right) LI from IHOP (12 Jun 2002) model output (MM5; 2 km, 5 min). Gray colors denote cloud-top temperature. (bottom left) TPW and (bottom right) LI from simulated HES (blue) and ABI (light blue) along with the ''truth'' at the indicated location.

layers and RH profiles, indicating that HES has an unprecedented capability for capturing the atmospheric changes with high accuracy and high vertical resolution. More ABI retrievals simulations, as well retrievals from Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiances, have been compared to collocated radiosondes (Jin et al. 2008).

It is very important to note that ABI can only provide very limited profile information; retrieval simulations also have been done using a set of hemispheric profiles, with results (Schmit et al. 2008) showing that ABI SFOV provides very limited temperature information; and averaging the radiances slightly improves the temperature profile information, especially between 400 and 700 hPa. However, even 5 × 5 ABI radiance averages provide worse retrievals than the current GOES sounder SFOV radiances if no forecast data are included; despite three water vapor bands to provide some temperature information, the ABI has only one CO_2 absorption band. For relative humidity, the 3 × 3 retrievals provide a considerable improvement over the SFOV retrievals. The 5 × 5 retrievals provide better moisture information than the SFOV or 3 × 3 retrievals.

The equivalent potential temperature Θ_e differences between 800 and 600 hPa (Θ_e-diff) are indicative of thunderstorm potential. In Fig. 6, the top left panel shows the truth field of Θ_e-diff; the top right panel shows the simulated Θ_e-diff from HES; the bottom right panel shows the Θ_e-diff from ABI at 1500 UTC 12 June 2002; and the bottom left panel shows the difference image between the HES and ABI simulations. HES depicts an unstable region similar to the truth field, whereas ABI has weak instability with no indication of prestorm development. Equally important is that the HES-derived field clearly shows the region of stable air. This is important for reducing false alarms when

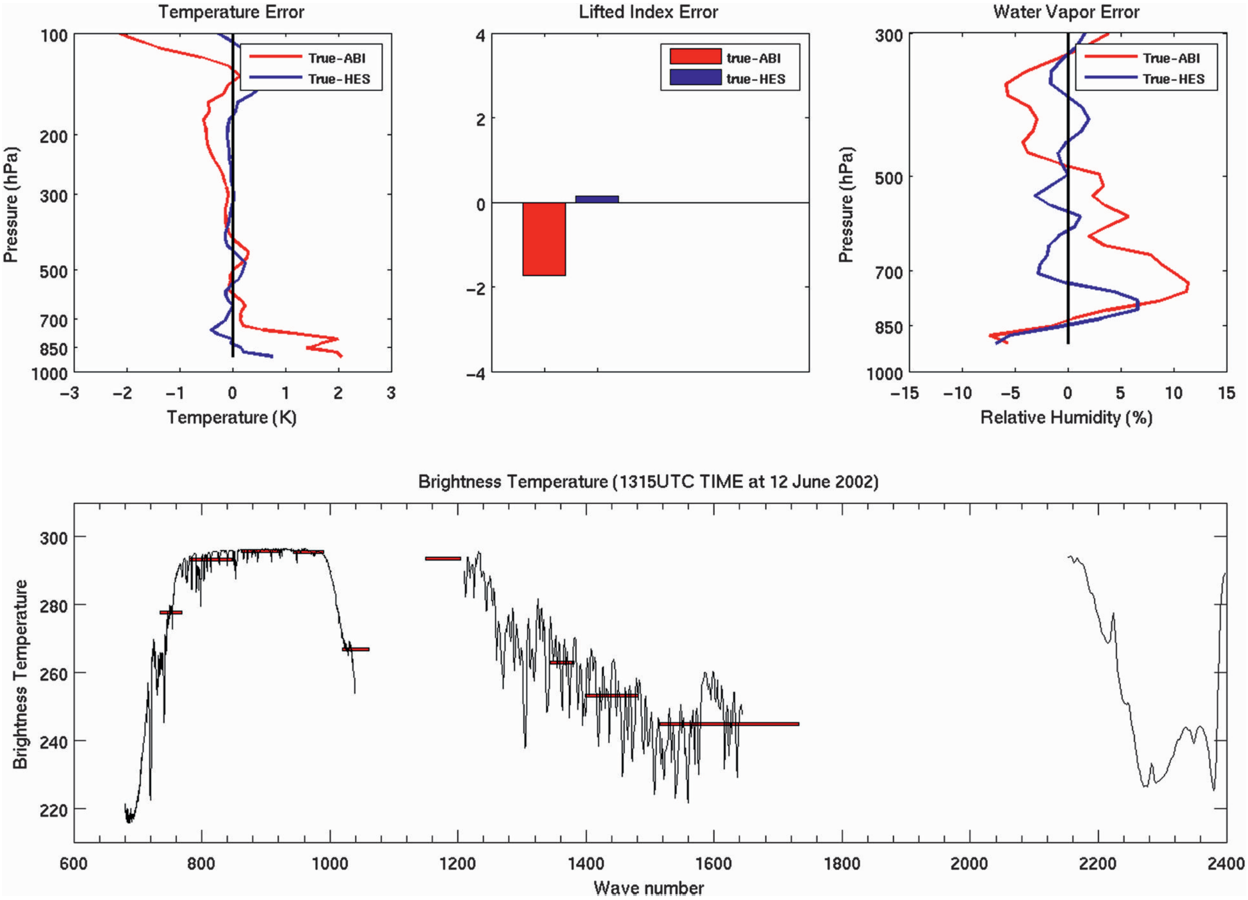


FIG. 5. (top left) Temperature errors of HES and ABI, (top middle) LI errors of HES and ABI, and (top right) RH errors of HES and ABI for the location indicated in Fig. 4, along with (bottom) the simulated BT for high-spectral-resolution HES and low-spectral-resolution ABI.

forecasting convective events. Figure 7 is the same as Fig. 6 but 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 MM5 modeled conditions. This case demonstrates the following:

- 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 underestimated the convective instability by 20%–30% compared to HES.

For a case with tornadic development, Schmit et al. (2008) showed that using upward looking high-spectral-resolution radiances made significant improvements over low-spectral-resolution sounding data in depicting important low-level moisture.

Improving the ability to identify regions of convective initiation has commercial benefits, especially in the aviation industry. More than half of the air-traffic delays at U.S. airports are due to weather, and many of those delays are a response to convective weather. Aircraft dispatch decisions are typically made between 1 and 5 h prior to take-off, depending on the flight time. The initiation of convective weather along the original flight path can cause delays on the ground as flights are either not allowed to take-off or once in the air are rerouted to avoid the weather hazard. These delays can have a ripple effect and impact airports across the country. Improvements in monitoring atmospheric instability, along with other improvements, would enable forecasters to reduce convective weather watch areas. This in turn would lead to avoiding delays due to better weather information during the flight planning process. Benefits are estimated to be larger than U.S. $25 million a year (in 2002 dollars) in savings due to improved flight planning (Bard et al. 2008; NOAA/NESDIS 2002).

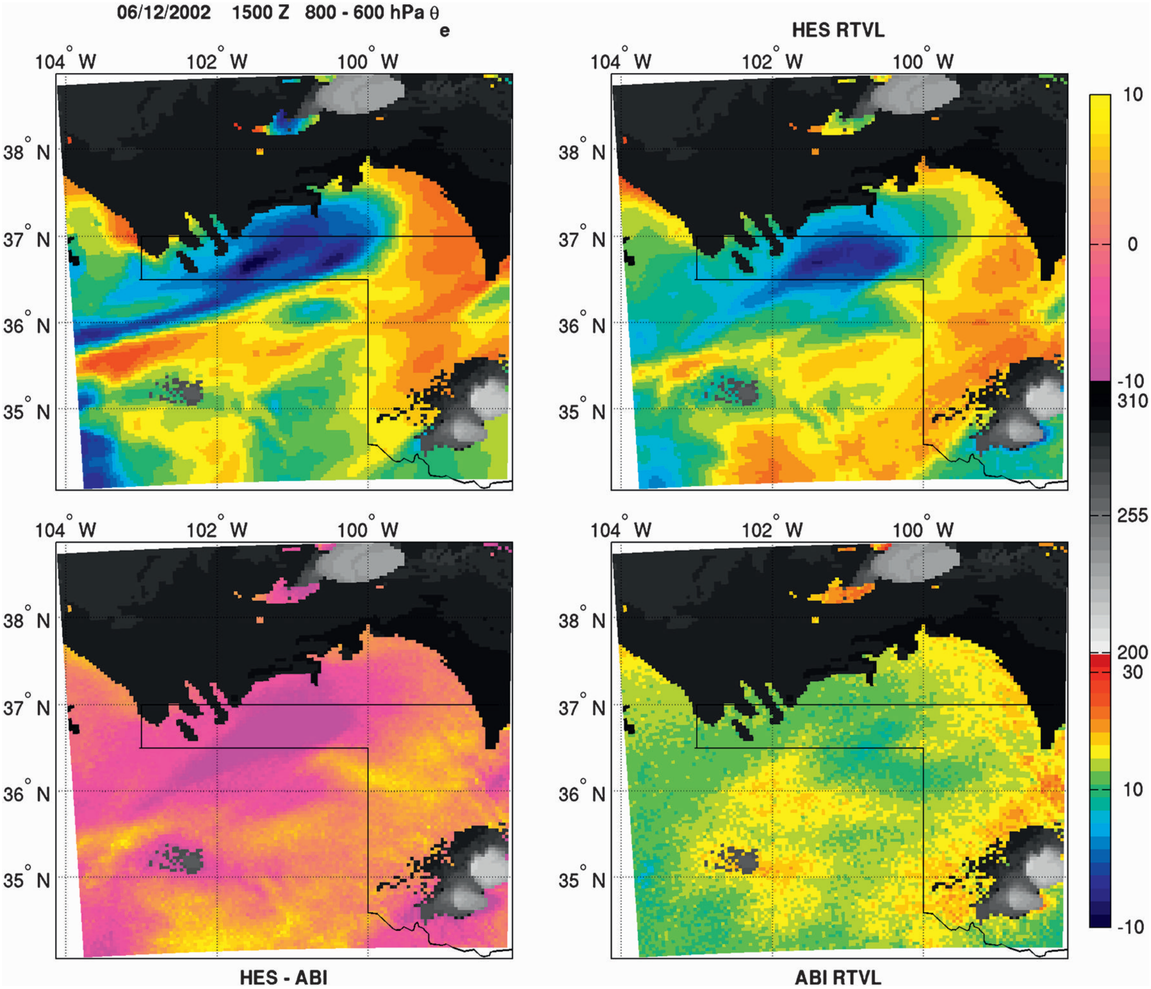


FIG. 6. True field of (top left) Θ_e, (top right) Θ_e from HES, and (bottom right) Θ_e from ABI at 1500 UTC 12 Jun 2002, along with (bottom left) the difference image between HES and ABI.

Monitoring hurricanes and their environment from a geostationary platform with high vertical and spatial resolution soundings should lead to improved hurricane forecasts (Li and Liu 2009). Moisture and temperature structures can be obtained for the hurricane eye and its environment. This was demonstrated using observations from the AIRS instrument for hurricane Isabel on 13 September 2003 with the retrieval method described by Weisz et al. (2007a). The hurricane eye temperature difference (and that of the ambient temperature) can be as large as 15–20 K from AIRS (see Fig. 8). This temperature difference is an indication of the hurricane intensity. The global analysis does not depict this difference due to coarser spatial resolution.

b. Numerical weather prediction 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,b, 2007). High spectral/temporal data can improve both regional and global-scale numerical models via improved measurements that help initialize the fields of moisture, winds and temperature. A rapid refresh of the data can better guide regional forecast models. The particular advantage of high-spectral-resolution IR measurements to NWP would be 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 measurements and assimilating radiances in NWP over land).

Zapotocny et al. (2008) and Le Marshall et al. (2006b) show that the impact at 5 days on the 500 hPa height anomaly correlation for NCEP's (National Centers for Environmental Prediction) global model is much greater with high-spectral-resolution AIRS data, than from the

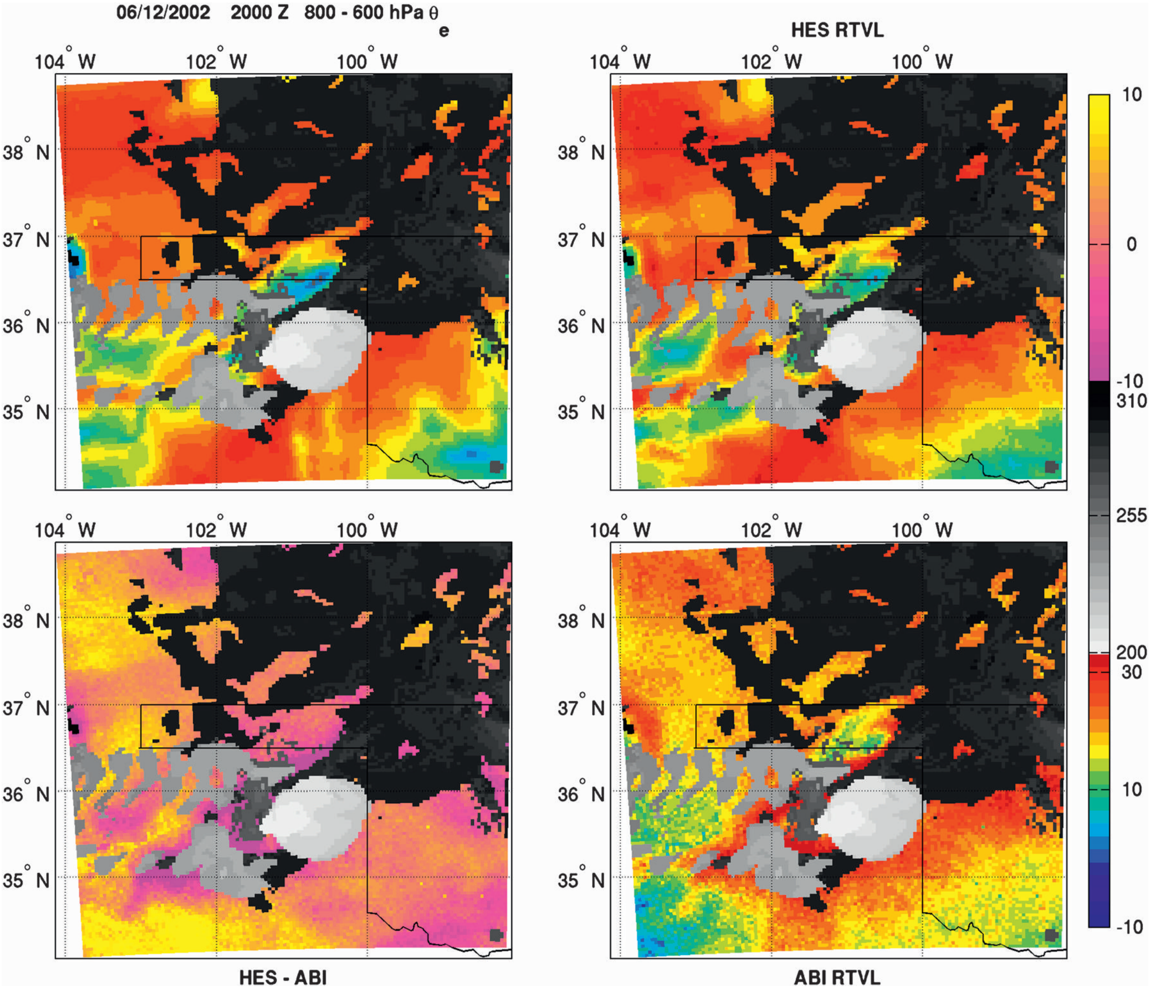


FIG. 7. As in Fig. 6, but for 2000 UTC.

High-resolution Infrared Radiation Sounder (HIRS), a 20-channel IR sounder flown on the NOAA polar-orbiting series. Although different years (2003 versus 2004) for the month of January were investigated, AIRS shows approximately a 1.8% improvement (over the control run) at both 500 and 1000 hPa. This impact is much greater than from the HIRS, which was generally neutral for this time period. Also, after taking into account the greater number of AMSU (Advanced Microwave Sounder Unit) sensors assimilated, the AIRS impact is on the same scale as that from the AMSU data. Given that the height fields reflect the temperature more than moisture, and the greater variability of moisture, it is postulated that high spectral resolution would have even more relative impact on moisture fields (Huang et al. 1992; Wang et al. 2007).

A number of papers have documented the various applications of hourly GOES sounding data and its impact on NWP. For example, Menzel et al. (1998) identified and described these applications and Zapotocny et al. (2002, 2005a,b) provided examples of the impact of satellite and other observations on NWP. Observing system simulation experiments (OSSEs) with the Rapid Update Cycle (RUC) model have suggested that two polar-orbiting high-spectral-resolution sounders do not provide the temporal coverage to sustain forecast improvements out to 12 h, whereas the 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 only conventional data.

Current GOES sounder clear-sky radiances have been used in the assimilation for both regional and global forecast models (Schmit et al. 2002). Moisture information (three layers of precipitable water), cloud heights, and/or radiances from the current GOES sounders have demonstrated positive impact on NWP (Bayler et al.

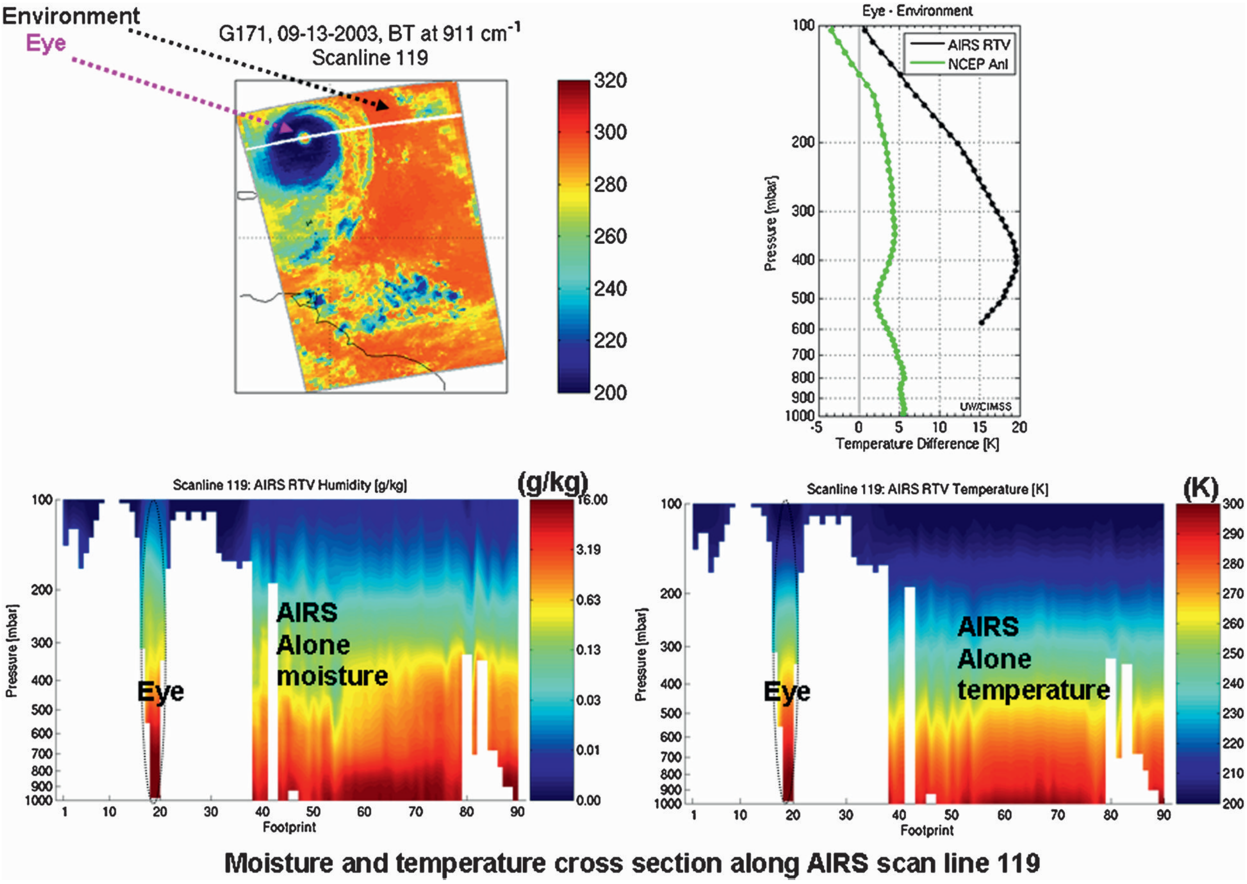


FIG. 8. (top left) BT image at 911 cm^{-1} of Hurricane Isabel made by AIRS. AIRS retrieved (bottom left) moisture and (bottom right) temperature profiles. White regions are cloudy scenes. (top right) The temperature profile differences (black) between the two pixels indicated in (top left). The temperature differences from NCEP analysis are also shown (green).

2001; Zou et al. 2001; Schmit et al. 2002), including regional models such as the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Regional Assimilation System (CRAS), RUC, Eta, and MM5.

The AIRS high-spectral-resolution infrared sounder clear-sky radiance data have provided a 6-h improvement in a 5-day forecast (Le Marshall et al. 2006a). Similar improvements are expected with an advanced geostationary sounder, with higher spectral resolution, finer temporal refresh, and higher spatial resolutions. This expectation is consistent with the recent experiments with AIRS data in the Weather Research and Forecasting (WRF) model (Chou et al. 2007; Zavodsky et al. 2007).

Experiments by NCAR with a regional numerical model [NCAR WRF/Data Assimilation Research Test bed (DART)] with 36-km grid spacing demonstrated significant track forecast improvements for Hurricanes Dean and Ike when using the full-spatial-resolution (13.5 km at nadir) AIRS sounding retrievals developed at CIMSS. For example, for a 72-h assimilation, the track error was cut in half, and the hurricane intensity forecast is also substantially improved by 10 to ~20 hPa after 24 h, when the AIRS full spatial resolution soundings are assimilated; the control runs used a host of data, including radiosondes, atmospheric motion vectors, aircraft data, hurricane position data, and Quick Scatterometer (QuikSCAT) winds (Li and Liu 2009).

Current GOES observations and numerical simulations of future systems were used to demonstrate the potential impact on NWP. Approximately 650 simultaneous radiosonde observations (RAOBs), GOES sounder radiance measurements, and NCEP Global Forecast System (GFS) forecasts were collected over the conterminous United States (CONUS). Current GOES soundings were derived from the GOES radiance measurements only, which are therefore independent of a forecast. The high-spectral-resolution IR radiances (e.g., HES) were then simulated from RAOBs through an appropriate radiative transfer model (Hannon et al. 1996) along with

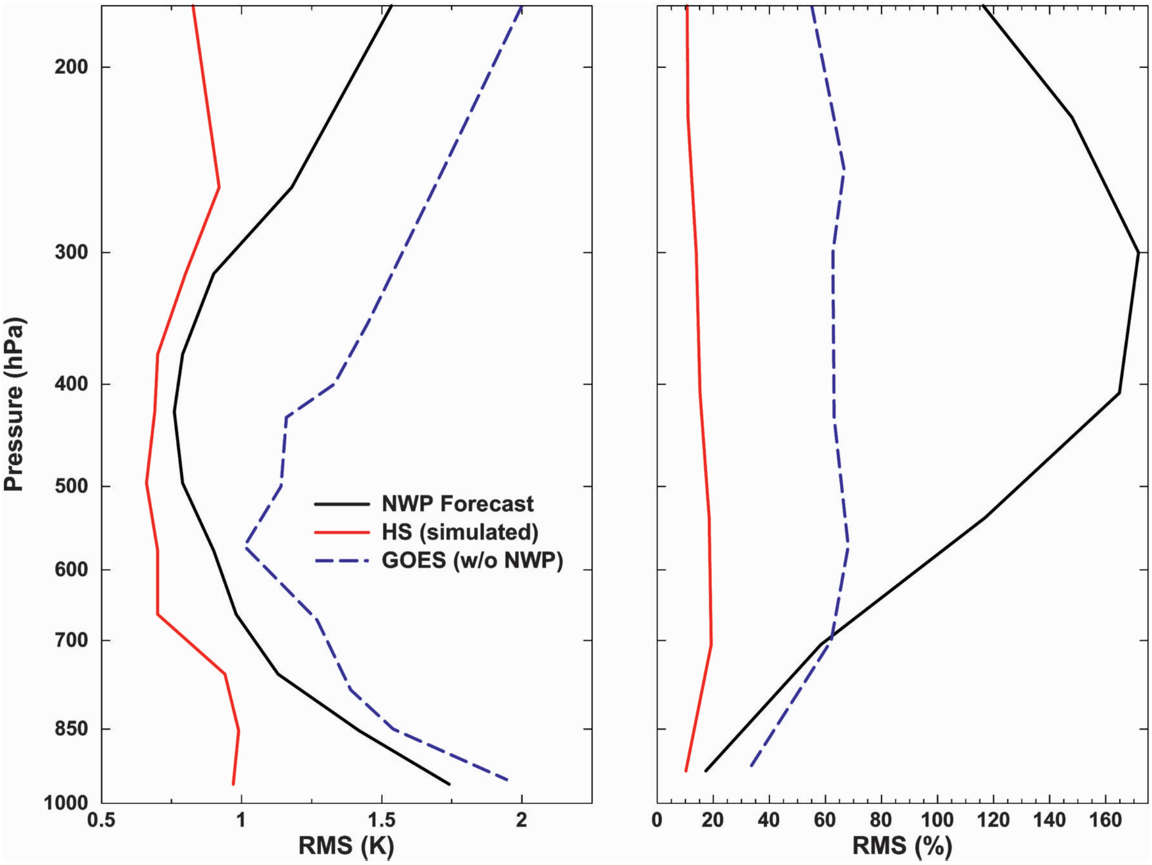


FIG. 9. The (left) temperature and (right) water vapor mixing ratio percentage RMSEs for forecasts (black), GOES real soundings (blue), and HS (e.g., HES like) simulated soundings (red).

an assumed nominal instrument noise. Ideally, AIRS and IASI should be used in the study; because it is difficult to collocate AIRS (or IASI), GOES sounder, and RAOB both temporally and spatially, the simulated hyperspectral sounder (HS) radiances are used. The physical retrieval algorithm (Li et al. 2000) was used to convert the HES radiances into a retrieved sounding. The GOES soundings and simulated HES soundings were then compared with the independent collocated RAOBs to determine a root-mean-square error (RMSE). Figure 9 shows the temperature (left panel; in K) and water vapor mixing ratio (right panel; in %) RMSEs for forecasts (black), current GOES soundings (blue), and hyperspectral sounder (HES like) 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, whereas 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 high-spectral-resolution IR soundings provide a much improved temperature profile, with a smaller RMSE than both the forecast and the current GOES sounder. For water vapor mixing ratio, the forecast does well in the boundary layer over CONUS because of the dense array of surface moisture observations used in the NWP model; however, the forecast is much worse in the atmospheric layers above 700 hPa. The GOES soundings provide much better water vapor information than the forecast model above 700 hPa, which explains why the current GOES sounder moisture product is useful for NWP.

The high-spectral-resolution data would show the variations in IR region of the surface temperature and emissivity necessary for accurate temperature and moisture profiles and radiance data assimilation over land. High-spectral-resolution data can resolve transparent microwindow channels (regions between strong absorption lines) and contain the information needed to separate the skin temperature from the effective surface emissivity within the instrument field of view (Knuteson et al. 2004a). These microwindow channels provide the maximum observed surface thermal signal and contain the information to retrieve surface temperature and emissivity by optimizing the potential for water vapor continuum corrections while averting errors resulting from the presence of trace gases [i.e., carbon dioxide (CO_2), ozone (O_3), chlorofluorocarbons (CFCs); Nalli and Smith 2003].

5. Additional applications

The high-spectral-resolution sounder observations would also improve derived products currently planned with the ABI data (Huang et al. 2004; Li et al. 2004b; Schmit et al. 2005; Li et al. 2005b; Weisz et al. 2007c; Ackerman et al. 2008). These include the following: volcanic ash, cloud detection, cloud-top properties, atmospheric motion vectors, dust detection, land and sea surface temperature, and surface emissivity. In this section, we briefly discuss the potential advantages of high spectral resolution in observing clouds, aerosols, surface emissivity, and the height assignment of atmospheric motion vectors (AMVs).

For many years, researchers have developed algorithms for detecting clouds and aerosols using high-spectral-resolution infrared measurements from aircraft (Ackerman et al. 1990; Smith et al. 1993) and polar-orbiting satellites (e.g., Holz et al. 2006; Kahn et al. 2005; DeSouza-Machado et al. 2003). Cloud detection approaches rely directly on the radiance measurements, comparing observed radiances with expected clear-sky radiances. Cloud detection is a function of the contrast between cloud and clear scenes. Contrast variations can be in space, time, or spectral domains. The high-spectral- and high-time-resolution capabilities improve the spectral and temporal contrast and thus improve the detection and characterization of clouds. This is particularly true for distinguishing low-level clouds from cold ground temperature associated with a surface temperature inversion, where online and offline absorption features clearly indicated the clear-sky temperature inversion.

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_2, water vapor (H_2O), CO_2, 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_4) and nitric acid (HNO_3; Barnet et al. 2004; Chahine et al. 2006). Most of these species are impossible to retrieve from low-spectral-resolution band measurements (e.g., the current GOES sounder or the GOES-R ABI).

With geostationary high-spectral-resolution IR radiances, hemispheric surface emissivity spectra could be derived hourly. Algorithms for retrieving high-spectral-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 and Li 2008). The surface emissivity spectrum product is very important for deriving other products with IR radiances, for example, the temperature and moisture profiles (Li 1994; Plokhenko and Menzel 2000; Seemann et al. 2003, 2008), land surface temperature (Yu et al. 2008), cloud-top pressure (Li et al. 2005b), dust and aerosol properties (Zhang et al. 2006), and trace gasses (Ho et al. 2005). Although conventional imagers such as ABI can detect dust events, a high-spectral-resolution instrument can better characterize the plume. Information can be retrieved regarding the height, loading, and possibly the composition (Sokolik 2002; Sokolik et al. 2001; Hong et al. 2006).

As mentioned earlier, the surface emissivity spectra are also important for assimilating IR spectra over land into the NWP. They can also be used to improve climate modeling and prediction (Jin and Liang 2006). High-spectral-resolution IR measurements, especially if they have full spectral coverage, can be used to generate climate-related products, such as outgoing longwave radiation (Ciren and Cao 2003; Ellingson and Ba 2003).

The potential climatic applications have been noted in a recent National Academies report (NRC 2008):

> Geostationary sounders provide the capability of observing diurnal variation of climate variables including cloudiness, surface (sea and land) temperature, and atmospheric temperature and humidity. Although limited to regional (rather than global) coverage, the environmental space-time scales sampled by geostationary sounders strongly relate to climate change, including the frequency and intensity of severe weather (e.g., severe thunderstorms, flash flooding, hurricanes, winter storms). Spatial scales of 25 km or less and temporal scales of minutes to hours, best achieved from geostationary orbit, are needed to, for example, capture the evolution of the pre-convective environment as circulations develop and as low-level moisture is advected into a region. Further, by monitoring spectrally resolved radiances for the same location, local zenith angle, and local time every day, regional water vapor budgets in the western hemisphere can be determined.

Large positive impacts have been demonstrated from GOES 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 retrieved profiles from

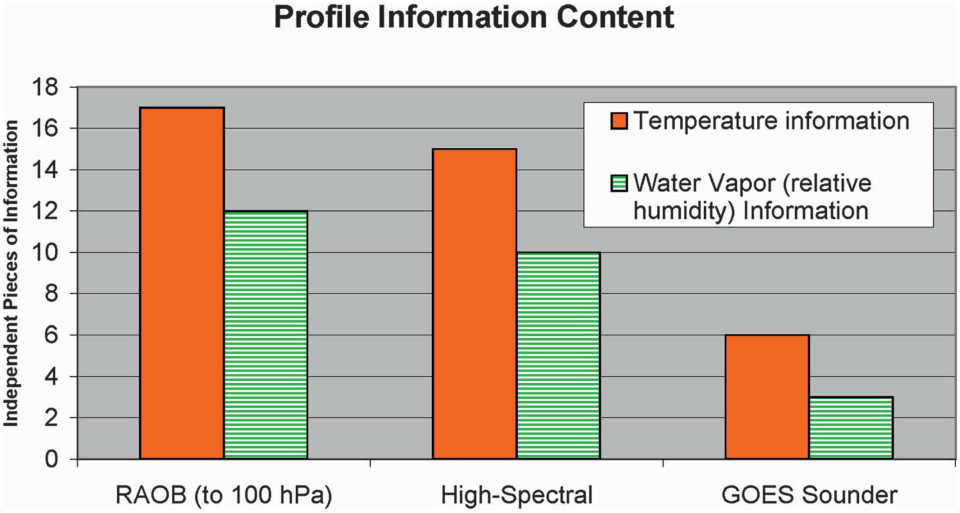


FIG. 10. The relative vertical information is shown for radiosondes, a high-spectral-infrared sounder, and the current GOES sounder. The high-spectral-resolution sounder is much improved over the current sounder. This information content analysis does not account for any spatial or temporal differences.

high-spectral-resolution sounding data. The traditional method of tracking features is to match them in the radiance domain and then assign the tracers height by using NWP temperature profiles or a semitransparency correction (Velden et al. 1998). High-spectral-resolution IR measurements could reduce this uncertainty by enabling feature tracking in the retrieved profile fields as opposed to the radiance fields (Otkin et al. 2007). 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-resolution IR data, ideally with complete spectral coverage over the IR spectrum, can be used to cross-calibrate polar-orbiting sensors (Gunshor et al. 2009). It is very difficult to know the precise in-flight spectral response characteristics of a low-spectral-resolution 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 Moderate Resolution Imaging Spectroradiometer (MODIS) measurements, has been demonstrated by Tobin et al. (2006a,b).

6. Economic impacts

It is very difficult to quantify the economic impact of future sensors. The limitations include unknown instrument performance, product quality, product applications, subsequent research, and user base. Furthermore, the impact of any sensor depends on which other sensors may be measuring the same parameters and the quality of their measurements. For example, the impact of an 18-band IR sounder would be reduced if information from a high-spectral-resolution IR sounder with the same observational coverage was introduced. Estimates have been made regarding potential impacts of a high-temporal- and high-spectral-resolution IR sounder by MITRE Corporation (available online at http://www.mitre.org/), who explored the potential economic benefits of improved information from GOES-R satellites in four specific sectors of the economy: aviation, energy (both electricity and natural gas), irrigated agriculture, and recreational boating. These studies concluded that the benefits of high-temporal/spectral data are expected to be several billions of dollars (NOAA/NESDIS 2002, 2004). More recent results show that the potential additional socioeconomic benefits for an advanced (high spectral resolution) sounder are estimated to be $4.2 billion (U.S. dollars net present value; Bard et al. 2008). The Centrec Consulting Group, LLC conducted the analyses, commissioned by the NOAA National Climatic Data Center. The $4.2 billion (U.S. dollars) estimate may be conservative because only five economic sectors (the previous four, plus tropical cyclone impacts) were included. These values change if less conservative assumptions are used for the discount rate and/or inflation rate. In addition, the benefits to a host of users or application areas were not included in the studies, such as the Department of Defense or international users, nor were applications related to human health or other agricultural sectors.

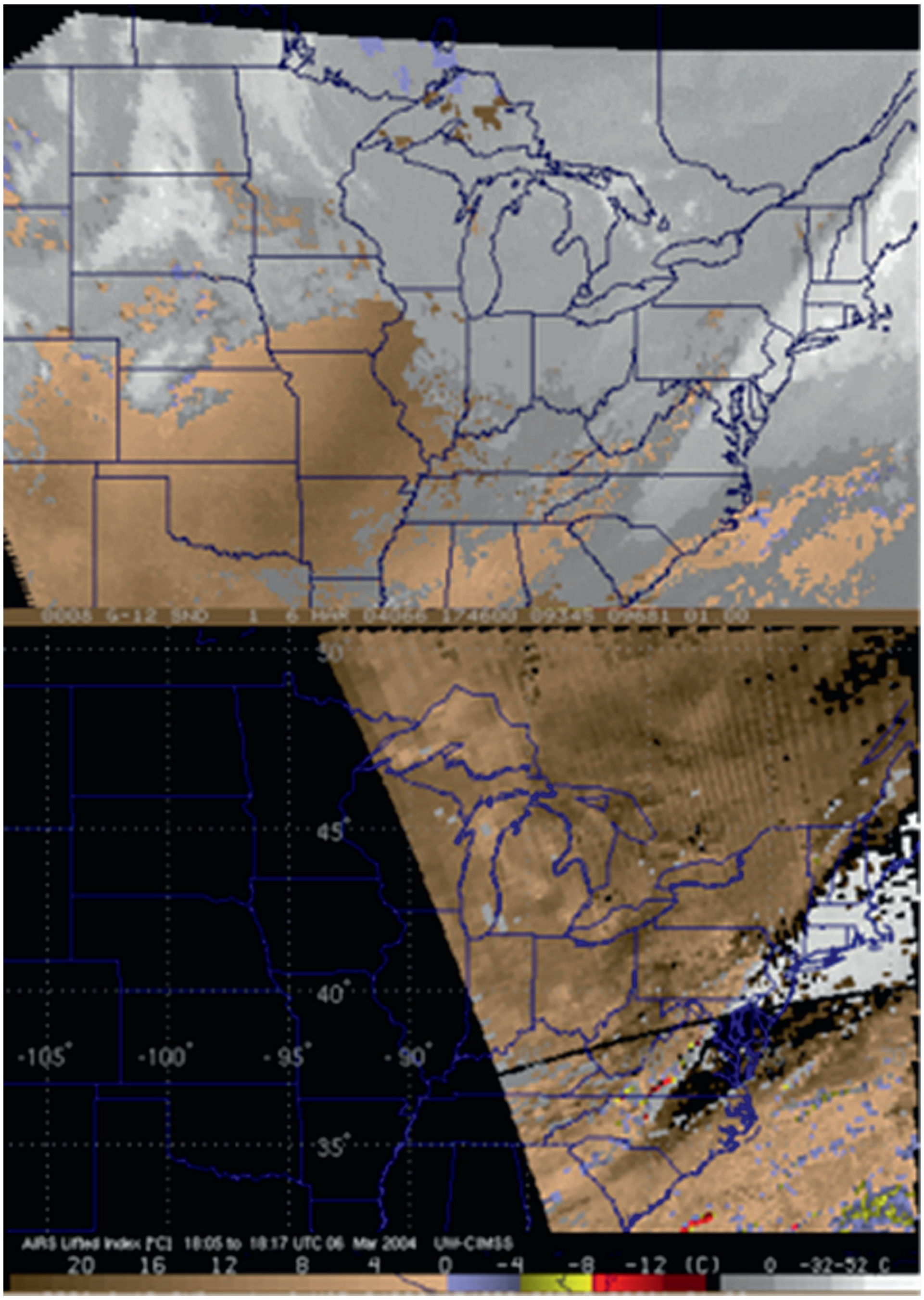


FIG. 11. LI DPI current GOES sounder and AIRS DPIs of LI from 6 Mar 2004. Note that the high-spectral-resolution data were able to retrieve a small region of instability compared to the current GOES sounder data.

7. Summary

Analyses and retrieval simulations have shown that temperature and moisture information retrieved with a high-spectral- and high-temporal-resolution IR instrument far exceed those from the current low-spectral-resolution GOES sounder. A relative vertical information analysis (Fig. 10) demonstrates that a high-spectral-resolution IR sensor has a much greater vertical resolving power (Huang et al. 1992) of temperature and moisture than low-spectral-resolution sensors. Although the in situ nature of radiosondes enables their high vertical information content, these twice a day measurements primarily over land do not meet the temporal and spatial sampling requirements to monitor rapidly changing phenomena.

High-spectral- and high-temporal-resolution observations benefit nowcasting and NWP applications by providing spatially and temporally continuous measurements of temperature, water vapor, and the wind profile. In addition, retrievals from high-spectral-resolution data exhibit much less dependence on the first guess information. An example of a derived product image (DPI) of LI from both AIRS and current GOES demonstrates the benefit of high-spectral-resolution data for nowcasting applications (Fig. 11). In this example, the current GOES sounder showed a stable atmosphere and there is no profiling in the presence of thin clouds. The high-spectral-resolution AIRS provided profiles in the presence of thin clouds and showed unstable regions not detected by the current GOES. The instability resulted in an influx of cool dry air at middle levels, which dispersed cloud cover enough for solar heating of the surface and a warming of the lower levels (Johnson 2005). The resulting convection generated severe weather. High-spectral-resolution sounders with mesoscale sounding coverage could have provided updated profiles, enabling detailed monitoring of the atmospheric destabilization to aid forecasters. With high-spectral-resolution IR geostationary sounding capabilities, forecasters and regional models would have sufficient information (e.g., meeting user requirements) regarding the finescale three-dimensional structure of atmospheric water vapor and capping inversions and how these structures vary in time. Models have shown the benefits of high-spectral-resolution IR AIRS data (Le Marshall et al. 2006a,b).

A high spectral (and hence vertical) resolution IR sounder with faster scanning would be able to monitor important low-level information about the atmosphere and thus substantially improve the capability to forecast severe weather. The potential uses (atmospheric profiling, surface characterization, cloud information, total ozone, and atmospheric motion vector winds) of high-spectral-resolution IR data have been amply documented (Smith 1983; Smith et al. 1990; Hayden and Schmit 1991; Leslie et al. 2002; Knuteson et al. 2004a).

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