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EVALUATION OF HYPERSPECTRAL INFRARED SOUNDINGS IN TROPICAL CYCLONE ENVIRONMENTS

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1. INTRODUCTION

Tropical cyclones (TCs) form and develop over the tropical and subtropical oceans. In these areas, in situ observations tend to be rather sparse, so that data assimilation systems for operational forecast models rely heavily on satellite observations such as feature-tracked winds, scatterometer measurements, and infrared and thermal radiances. Over the past several years, forecasts of TC tracks have improved considerably (e.g., Goerss et al 2004) due to numerical model and data assimilation advances.

Beginning in 1997, NOAA began operational synoptic surveillance missions into TCs that have the potential to affect the continental U.S., Hawaii or U.S. territories. In these missions Global Positioning System dropwindsondes (hereafter GPS sondes) are dropped from the NOAA Gulfstream IV-SP (G-IV) jet aircraft in the storm environment, providing wind, temperature and moisture soundings from about 200 hPa to the surface. Aberson (2004) has shown that when the wind observations from the GPS sondes are carefully assimilated into numerical models, the TC track forecasts improve considerably. The fact that these in situ observations from the G-IV jet improve the track forecasts suggests that the TC environment is not being adequately observed by satellite and other routinely available observations.

A major limitation of the GPS sondes is that they are typically available only for a very limited portion of the tropical oceans and for a small number of storms. It would be highly advantageous if the environments of TCs could be more adequately sampled from satellites. As mentioned above, there are three basic methods for measuring the TC environment from space. In the first method, features such as cloud patterns or water vapor structures are used as tracers to directly estimate winds. Soden et al (2001) have shown that these observations can lead to improvements in hurricane model forecasts. In the second method, passive or active microwave instruments provide wind measurements at the ocean surface (e.g., Smith et al 2004). A limitation of the ocean surface winds is that they do not provide information about the vertical structure of the atmosphere. In the third method, the mass field of the atmosphere (temperature and moisture structure) is measured by extracting information from satellite radiance measurements, primarily in the infrared and microwave part of the electromagnetic spectrum. At operational forecast centers, the radiance information is included in sophisticated data assimilation systems. Because of dynamical relationships between the atmospheric mass and momentum fields, the radiance assimilation indirectly provides information about the wind field.

An alternate method for determining the atmospheric mass field is through satellite retrieval schemes that use inverse techniques to provide profiles of atmospheric temperature and moisture. Retrieval techniques have been extensively applied to IR and microwave data for the last several decades (e.g., Rogers 2000).

Regardless of whether data assimilation or retrieval techniques are utilized, current satellite radiance data have spectral, spatial and temporal limitations. For example, the Advanced Microwave Sounder Unit (AMSU) on the NOAA KLM-series polar satellites includes 15 channels for temperature retrievals (AMSU-A) with a horizontal resolution of about 50 km near nadir (Kidder et al, 2000), and samples the globe about twice per day. The vertical resolution of the temperature information from AMSU-A is limited by the number of available channels. The IR sounder on the current series of NOAA geostationary satellites (GOES I-M) has increased temporal and spatial resolution (10 km) relative to the polar orbiter data, but has about the same number of channels (18), which again limits the vertical resolution. Additional limitations of the IR sounder include the inability to provide information below cloud tops and limited geographic coverage.

The next generation GOES satellite (beginning with GOES-R to be launched in the early 2010s) will include an advanced IR sounding instrument (the Hyperspectral Environmental Suite, HES). The HES will include about 2000 channels with a horizontal resolution of up to 4 km. It is anticipated that the HES will provide vertical temperature and moisture soundings in relatively cloud free regions with much higher vertical resolution than is currently available, due to the large increase in the number of channels.

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To help prepare for the use of the HES for TC analysis, temperature and moisture soundings retrieved from the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite will be evaluated in the environment of Hurricane Lili (2002) while it was in the Gulf of Mexico. Although AIRS does not have the spatial and temporal resolution of the HES, it does have comparable spectral resolution. The GPS sondes from the G-IV jet will be used for ground truth, and the results will also be compared to co-located soundings from the first guess field from the NCEP Eta model. The Eta model assimilates most currently available observations, so that a comparison will help determine if the AIRS observations have the potential to provide new information. The Eta analysis does not include the thermodynamic information from the GPS sondes, which simplifies the comparison. Hurricane Lili is briefly described in section 2, and the datasets and AIRS retrieval technique are summarized in section 3. Preliminary results from the sounding evaluations are described in section 4 and conclusions and future plans are presented in section 5.

2. HURRICANE LILI

Figure 1 shows the track of Hurricane Lili (2002). The storm formed from a tropical wave on 21 September and moved through the Caribbean as a tropical storm. It became a hurricane in the western Caribbean, and intensified to a category four hurricane in the central Gulf of Mexico. Fortunately, Lili weakened to a category one storm before striking the Louisiana coast on 3 October.

There were six G-IV flights for Lili on 25 September, 30 September, 01 October (2 flights) and 02 October (2 flights), dropping a total of 161 GPS sondes. The Aqua satellite was in a checkout mode during this period, but arrangements were made to save the AIRS data. Preliminary results will be presented for AIRS/GPS comparisons on 02 October. Additional cases from Lili and from other storms with G-IV flights will be added later.

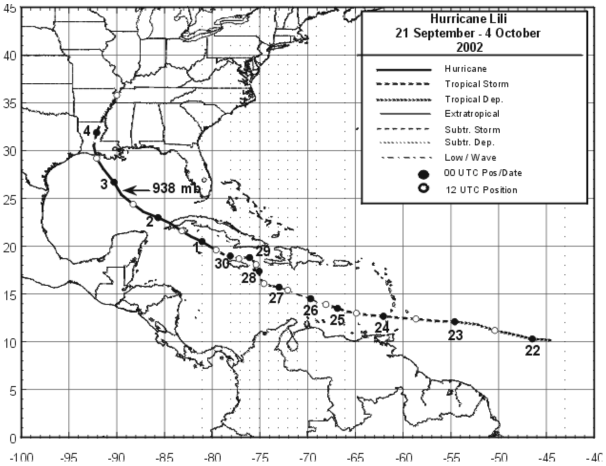

Figure 1. The track of Hurricane Lili (2002) (from www.nhc.noaa.gov).

3. DATA AND METHODOLOGY

The AIRS instrument has 2378 channels from 3.7-15.4 μm, with a footprint size of about 13.5 km near nadir. Because of the relatively large volume of information it provides, the AIRS data from 6-minute intervals are stored in granule files, which contain 135 lines by 90 elements. For each pass of the Aqua satellite over Hurricane Lili on 2 October, the two granules closest to the storm center were obtained. A total of four granule files were obtained on this day.

The temperature and moisture soundings for each granule were determined by the retrieval method described by Barnet et al (2004). The method uses the AIRS IR data in combination with microwave data from an AMSU instrument that is also on the Aqua satellite. The diameter of the AMSU footprint is about three times as large as that of AIRS. For the combined retrievals, AIRS data from the nine points with each AMSU point are combined. The retrieval algorithm includes three major components: a microwave-only retrieval, a first infrared product, and a final infrared/microwave product. In this study, only the final combined product was evaluated.

Once the AIRS temperature and moisture soundings were obtained for each granule, match-ups between with the GPS sondes were determined. For each GPS sonde, all available AIRS soundings within 5 hours and 100 km were located. Using these criteria, there were multiple matching AIRS soundings for some of the individual GPS sondes, but none for others. For the cases with more than one match, the AIRS sounding closest in space to the GPS sonde location was chosen. Using this method, 22 matching pairs were found on Oct. 2nd. These 22 AIRS soundings came from three granules which began at 0711, 0717 and 1947 UTC. The average time difference between the AIRS and GPS soundings was 2 hours, and the average distance between them was 29 km.

Figure 2 shows the locations of the 22 AIRS soundings plotted on a color enhanced GOES channel 4 (10.7μm) imagery. The GOES image in each case was within a few minutes of the AIRS observation times. This figure shows that many of the soundings near 0715 UTC were likely influenced by cloud contamination. The soundings near 1945 UTC tended to be less affected by clouds.

In most data assimilation systems, observations are combined with a “background” field, which is often obtained from a short-term model forecast. The influence of the observations on the final analysis depends on the error characteristics of the data relative to the background field. To get an idea of the utility of the AIRS data compared to what is available from other data sources, soundings from the background field from the NCEP Eta model analysis system were obtained at the same 22 locations as the AIRS and GPS sondes. For the Lili case, the Eta analysis system used a 3 hour model forecast for the background field. The background field for the 0600 (2100) UTC Eta analysis was used for the AIRS soundings at 0715 (1945) UTC in

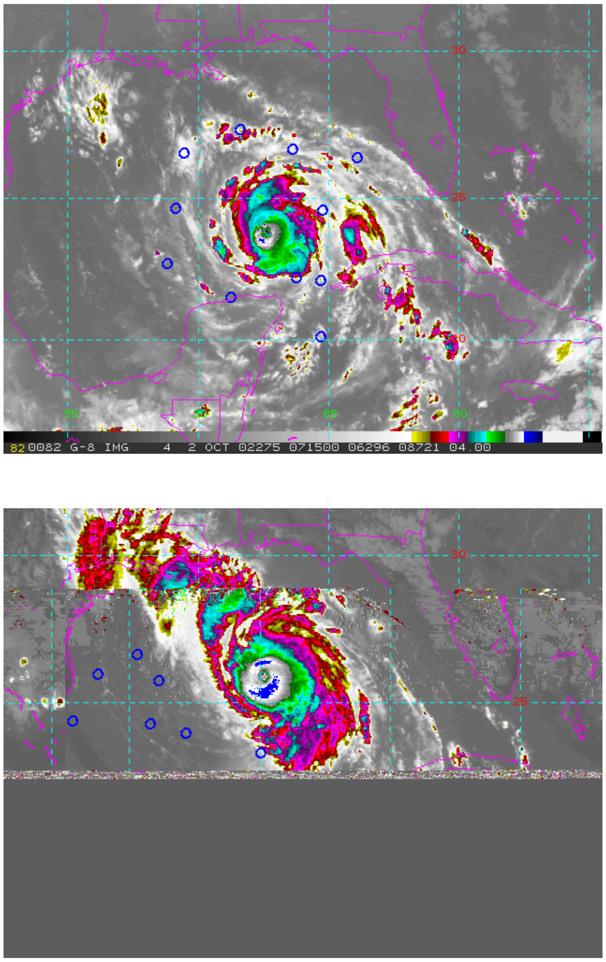

Figure 2. The 22 locations (blue dots) of the AIRS soundings in the environment of Hurricane Lili at about 0715 UTC (top) and 1945 UTC (bottom) plotted on color enhanced GOES IR imagery.

Fig. 2. Further details of the Eta data assimilation system are described by Roger et al (2001).

The GPS sondes provide temperature, moisture and wind profiles with very high vertical resolution (Hock and Franklin 1999). The soundings used in this study were post-processed to provide data at about 1600 vertical levels from flight level to the surface. The AIRS retrieval method provides temperature and moisture at 100 unequally spaced pressure levels from the surface to the top of the atmosphere. The Eta soundings were available at 25 hPa intervals from 1000 to 50 hPa. To compare the soundings from the three sources, each sounding was linearly interpolated to equally spaced (25 hPa interval) pressure levels from 1000 to 200 hPa. The typical flight level of the G-IV is a little above the 200 hPa level, so that the data from all three soundings was normally available up to 200 hPa. For the moisture comparison, the dew point temperature was used.

Figure 3 shows an example of the temperature and dew point temperature from the GPS, AIRS and Eta. The GPS sounding shows considerably more structure due to the high vertical resolution of this instrument. The differences between the dew point temperatures for each sounding type are much greater than those for the temperature, which was typical of all 22 cases.

To quantify the sounding comparisons, three error statistics were calculated as follows: 1) The mean absolute error (MAE) of the AIRS or Eta relative to the GPS sonde temperatures, 2) The mean temperature difference between the AIRS or Eta and GPS sonde soundings (bias), and 3) the variance of the GPS sonde temperature soundings explained by the AIRS or Eta temperatures that results from a linear correlation between the two (r^2). These error statistics were also calculated for the dew point temperatures. The error values were calculated for the total sample (all pressure levels for all 22 soundings), and for low (1000-750 hPa), middle (750-500 hPa) and upper (500-200 hPa) tropospheric layers. The error statistics for the total layer were also calculated for each of the 22 cases.

4. SOUNDING EVALUATIONS

Table 1 shows the error statistics for the temperature soundings. For the total layer, the MAE for the AIRS soundings is slightly less that than of the Eta, and the bias for AIRS and Eta are both fairly small. The variance explained is very close to one for both AIRS and Eta. However, the high r^2 values for the total layer are a little misleading, because both soundings reproduce the mean temperature decrease through the troposphere, which is larger than the smaller scale variations seen in the GPS sonde temperature soundings (see Fig. 3). An examination of the individual layers in Table 3 shows that the AIRS MAE are much smaller than the Eta MAE in the lower troposphere, but are larger in the middle and upper troposphere. Similarly, the r^2 values for AIRS are larger than those for Eta in the lower troposphere, but smaller in the other two layers.

Table 1. The error statistics for the AIRS and Eta temperature soundings using the GPS sondes as ground truth.

	MAE (K)		Bias (K)		r2	
Layer (hPa)	AIRS	Eta	AIRS	Eta	AIRS	Eta
1000-200	1.35	1.48	-0.04	0.22	.989	.991
1000-750	1.37	2.51	-0.80	1.39	.748	.661
750-500	1.47	0.93	0.54	0.17	.832	.962
500-200	1.22	1.06	0.17	-0.69	.987	.993

Table 2. Same as Table 1 for dew point temperature.

	MAE (K)		Bias (K)		r2	
Layer (hPa)	AIRS	Eta	AIRS	Eta	AIRS	Eta
1000-200	6.48	6.50	6.20	-2.24	.972	.915
1000-750	7.12	2.01	7.11	-0.47	.764	.766
750-500	5.08	6.22	4.95	-4.65	.871	.612
500-200	7.06	10.41	6.42	-1.80	.891	.635

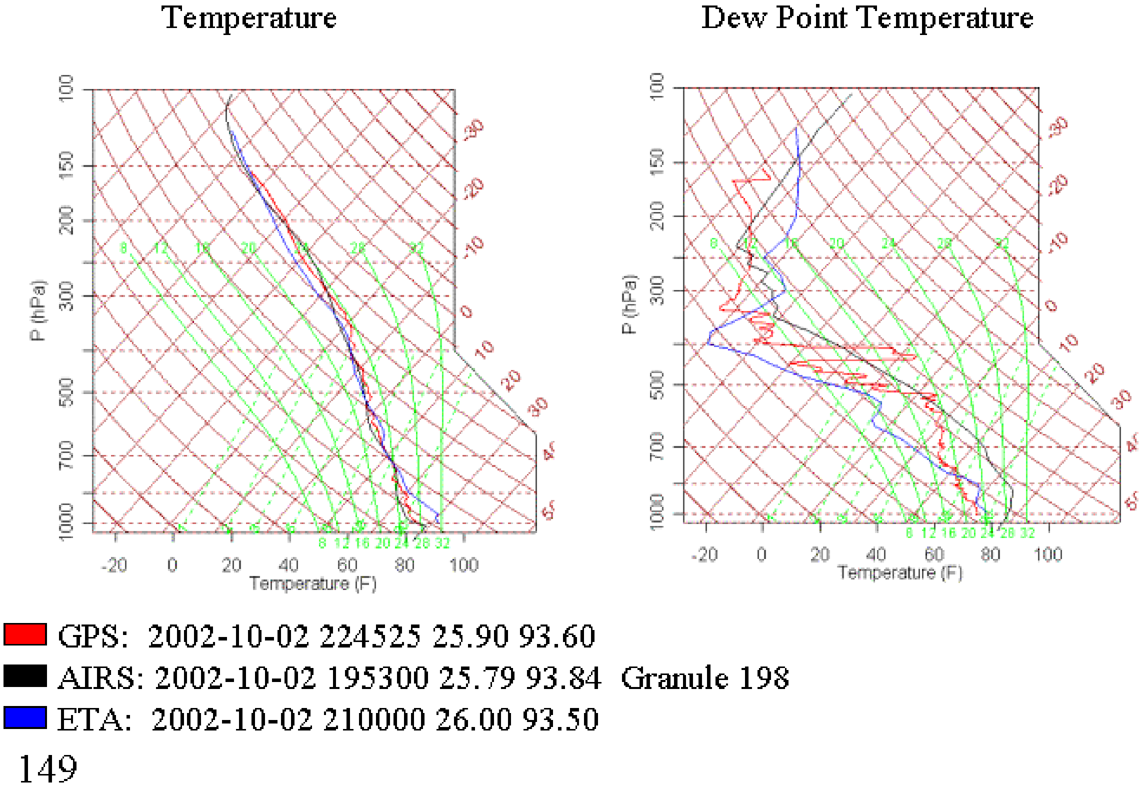

Figure 3. Examples of GPS, AIRS and Eta first guess temperature (left) and dew point temperature (right) soundings in the environment of Hurricane Lili.

Table 2 shows the error statistics for the dew point temperatures. For the total layer, the MAE are comparable for the AIRS and Eta. However, the AIRS soundings have a large moist bias, while the Eta soundings have a slight dry bias. This bias pattern is apparent in the example show in Fig. 3. In the version of the AIRS retrieval algorithm used here, the temperature and moisture are determined independently. In fact, the lower troposphere was often super-saturated in AIRS soundings. A constraint can be added to retrieval algorithm to help reduce the moist bias.

Despite the moist bias of the AIRS soundings in Table 2, the AIRS MAE is smaller than the Eta MAE in the middle and upper troposphere. Also, the variance explained by the AIRS dew point temperatures is much larger than that for Eta. The bias does not affect the correlation coefficient of the linear regression. The r^2 value becomes larger when the shape of the two profiles is similar. Thus, the AIRS dew point soundings are resolving more of the structure of the GPS soundings, even though they have an offset towards more moist values.

As shown in Fig. 2, some of the AIRS soundings were likely affected by cloud contamination. Figure 4 shows the temperature MAE for each of the 22 cases. The first (last) 11 cases are at the locations shown in the top (bottom) of Fig. 2. This figure shows that the AIRS MAE is much larger for cases 2, 3 and 5 than for the other cases. It is possible that cloud contamination affected the retrievals for these cases. The Eta MAE also varies from case to case. It appears that the Eta temperature errors tended to be larger for the relatively cloud free regions in the SW Gulf of Mexico shown at the bottom of Fig. 2.

Figure 5 shows the dew point temperature MAE for each of the 22 cases. Similar to the temperature, there is considerable case to case variability in the AIRS errors, although perhaps not quite as much as for the temperature soundings. This variability suggests that the AIRS error statistics can probably be further improved by stratifying the sample by the cloud coverage information that is determined as part of the profiles. Also, because the AIRS retrievals combine the hyperspectral IR data with the microwave data, the influence of each type of observation on the retrieval varies from case to case. As part of the future work, the cases will be stratified by the relative importance of each data source in the retrievals.

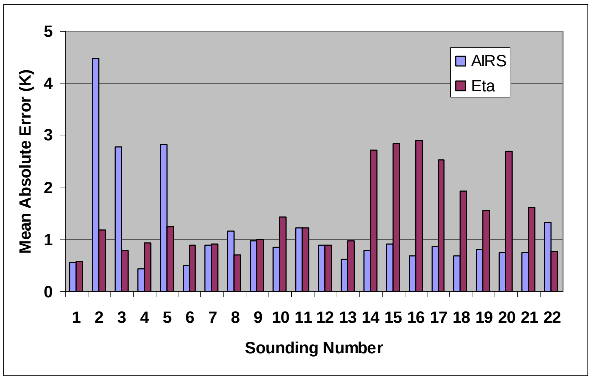

Figure 4. The temperature MAE (K) for each of the 22 sounding cases for the total layer (1000-200 hPa).

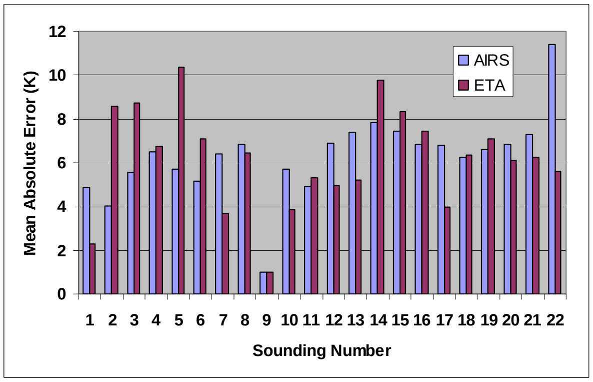

Figure 5. Same as Fig. 4 for dew point temperature.

5. CONCLUSIONS AND FUTURE PLANS

A preliminary evaluation of AIRS temperature and moisture soundings in the environment of Hurricane Lili was presented, where GPS sondes from the NOAA Gulfstream Jet were used as ground truth. This initial comparison included 22 match-ups of the AIRS and GPS soundings on 02 October 2002, when Lili was in the Gulf of Mexico. Temperature and moisture soundings from the first guess for the Eta model were also included as a benchmark. The Eta model provides a measure of the accuracy of the background fields used in current data assimilation systems.

Results show that AIRS temperature soundings are more accurate than the Eta model soundings in the lower troposphere. The AIRS moisture soundings were more accurate than the Eta soundings in the middle and upper troposphere. The AIRS soundings showed a large moist bias throughout the troposphere. Despite the moist bias, the AIRS moisture profiles generally had a higher correlation with the GPS sonde profiles than the Eta. This result suggests that the AIRS data may help to better analyze features in the moisture fields in the tropics, such as the Saharan Air Layer (SAL), which has been shown to have a significant impact on TC intensity forecasting (Dunion and Velden 2004).

Evaluation of the errors from individual soundings shows considerable case to case variability, which might be caused by cloud contamination. Future work associated with this study will include stratifying the results by the cloud flags that are determined as part of the retrieval method. Additional cases will also be added to the sample. AIRS and GPS soundings are currently being analyzed for additional cases from Hurricane Lili, as well as from Hurricanes Fabian and Isabel from the 2003 hurricane season.

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