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TROPICAL CYCLONE APPLICATIONS OF NEXT-GENERATION OPERATIONAL SATELLITE SOUNDINGS

Mark DeMaria* and Donald W. Hillger
NOAA/NESDIS/ORA, Fort Collins, CO

Christopher D. Barnet
NOAA/NESDIS/ORA, Camp Springs, MD

Robert T. DeMaria
CIRA/Colorado State University, Fort Collins, CO

1. INTRODUCTION

The next generation U.S. polar orbiting and geostationary satellite systems (NPOESS and GOES-R) will include hyperspectral infrared (IR) sounders with several thousand spectral bands. This represents a two order of magnitude increase in the number of bands relative to the current operational sounders, and will provide vertical temperature and moisture profiles in relatively cloud free areas with much greater vertical resolution. NPOESS will also include an Advanced Technology Microwave Sounder (ATMS) that can be used in cloudy regions. In the future, the radiances from these new instruments will be assimilated into numerical forecast models to help improve tropical cyclone track, intensity and rainfall forecasts. Temperature and moisture retrievals from these advanced instruments also have a number of potential applications for tropical cyclone analysis and short term forecasting.

DeMaria et al (2004) used retrievals from the Atmospheric Infrared Sounder (AIRS) in the combination with the Advanced Microwave Sounder Unit (AMSU) on the Aqua satellite as a proxy for the next generation temperature and moisture retrievals. These soundings were obtained in the environment of hurricane Lili and were compared with in situ soundings from the NOAA Gulfstream jet. Results showed that the soundings were more accurate than those from the first guess field of the National Centers for Environmental Prediction eta model (Rogers et al 2001), which indicates that the soundings provide information not available from existing data. In this paper, the AIRS/AMSU soundings in the eyes of three hurricanes (Hurricanes Lili (2002), Isabel (2003) and Fabian (2003)) are analyzed to determine the possibility of tropical cyclone intensity monitoring from the next generation operational satellites. An algorithm for estimating the wind structure from the retrievals in the inner core is also described.

2. AIRS/AMSU RETRIEVALS

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. The granules closest to the storm centers were obtained for all of the times during Hurricanes Lili, Fabian and Isabel for which corresponding in situ data from the NOAA Gulfstream jet were also available. Although the jet does not fly in the center of the storm, this dataset will be used to continue the validation study of AIRS/AMSU retrievals in the storm environments. In this paper, the retrievals near the storm centers will be evaluated.

The temperature and moisture soundings for each granule were determined by the retrieval method described by Susskind et al (2003). The method uses the AIRS IR data in combination with microwave data from the 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 within each AMSU footprint 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.

3. HURRICANE EYE SOUNDINGS

The AMSU/AIRS soundings closest to the storm center were obtained for all cases from Lili, Fabian and Isabel with corresponding Gulfstream jet data. There were 16 granule files that corresponded to the times of the jet flights. In some cases the nearest sounding was not very close to the storm center, depending on where the hurricane was located in the granule file. To ensure that the soundings were in the eye, the sample was restricted to the six cases where the AIRS/AMSU sounding was within 30 km of the storm center. Table 1 lists the dates and times of these six cases. None of the six cases were from Fabian. The maximum winds and minimum sea-level pressures from the National Hurricane Center best track interpolated to the granule times are also shown in Table 1.

Figures 1-6 show GOES IR imagery for cases from Lili and Isabel with the AMSU/AIRS eye soundings. The GOES data is within a few minutes of the AIRS/AMSU sounding. In two of the Isabel cases the eyes are fairly clear, which indicates that the AIRS observations are

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* *Corresponding author address*: Mark DeMaria, NOAA/NESDIS/ORA, CIRA/Colorado State University, W. Laporte Avenue, Foothills Campus, Fort Collins, CO 80523-1375; e-mail: Mark. DeMaria@noaa.gov

providing supplemental information to the AMSU. For the other four cases the eye is cloudy so the retrievals primarily rely on the AMSU input.

The AIRS soundings at the four corners of each granule for each of the cases in Table 1 with an eye sounding were also obtained. The four corner soundings were averaged to provide a storm environment T profile. The environment profile was subtracted from the eye profile to determine the T anomaly. Figures 7 and 8 show the eye T anomaly versus pressure for the six cases from Lili and Isabel. The warm anomaly in the upper troposphere is apparent in all cases. However, there is a significant cold anomaly in the lower troposphere for the two Lili cases, which is not realistic. This cold anomaly is probably due to cloud contamination. The Isabel cases do not show the cold anomaly in the lower troposphere, which is more realistic. The more realistic soundings for Isabel are probably due to its much larger eye size which can be seen by comparing Figs. 3 and 4 with Fig. 2. The warm anomaly for the Isabel cases extends all the way to the surface, which is also not realistic. The surface pressures for the retrievals are estimated from the NCEP global model, which are too high for the hurricane eyes. This introduces some error close to the surface. As will be described in section 4, the unrealistic structure in the lower troposphere will be corrected by extrapolating the soundings below a specified level to the surface using a constant lapse rate.

As described above, there are no in situ soundings from the Gulfstream jet in the storm centers to directly evaluate the satellite eye soundings through the depth of the troposphere. However, there were additional reconnaissance aircraft monitoring these storms which provided accurate estimates of the minimum surface pressure and maximum sustained winds. The satellite temperature and moisture soundings in the eye can be used as input to the hydrostatic equation which can be integrated down to the surface to provide an estimate of the minimum sea level pressure (MSLP). The satellite intensity estimates can then be compared to those from the reconnaissance aircraft to provide an indirect evaluation of the AIRS eye soundings. This technique would also be of considerable value for operational intensity monitoring.

Table 1. The cases with AIRS/AMSU eye soundings.

Storm	**Granule Date (mmddyy)**	**Granule Time (UTC)**	**Max Wind (kt)**	**Min Sfc Pres. (hPa)**
Lili	100202	0717	102	960
Lili	100302	0759	97	959
Isabel	091303	1705	139	933
Isabel	091403	1753	140	933
Isabel	091603	1741	95	959
Isabel	091703	1823	90	955

4. SATELLITE INTENSITY ESTIMATES

Methods for estimating tropical cyclone intensity from IR and visible satellite imagery (the Dvorak techniques) have been used for decades in operational forecast centers around the world (e.g., Velden et al, 2006). However, these methods are indirect and rely on pattern recognition and cloud top structure to estimate storm intensity. More recently, methods have been developed to estimate intensity from the AMSU instruments on the current operational series of NOAA polar orbiting satellites (e.g., Demuth et al 2004; Brueske et al 2004). Although these methods utilize the upper level warm core information from AMSU, which has a more direct physical relationship to surface pressure, the methods are still partially statistical in nature due to the fairly coarse horizontal resolution of the AMSU data (48 km near nadir). For storms with fairly clear eyes, the AIRS data may provide more accurate soundings and make the direct estimation of MSLP possible.

To determine the utility of the AIRS/AMSU retrievals for hurricane intensity monitoring, the hydrostatic equation given by

$$dP/P = -g/(RT_v)dz \qquad (1)$$

where P is pressure, T_v is virtual temperature, z is height, g is the gravitational constant and R is the ideal gas constant for dry air, is integrated from 100 hPa to the ocean surface. At the present time the moisture retrievals, which are available in the AIRS retrieval files, have not been analyzed for this study, so an idealized vertical profile of relative humidity for a typical hurricane eye was used to calculate the virtual temperature adjustment. The temperature as a function of pressure was obtained directly from the AIRS/AMSU eye soundings. The downward integration of equation (1) requires an upper boundary condition for the value of z at 100 hPa, which is obtained from the NCEP global model analysis closest in time to the AIRS granule.

As described in section 3, the AIRS/AMSU temperature soundings become less reliable in the lower troposphere. Fortunately, because of the dP/P term in (1), the largest contributions to the surface pressure estimate come from the upper-level temperature data. To correct for the problems in the lower troposphere, the hydrostatic integration was performed in two steps. First, (1) was integrated from 100 to 850 hPa using the NCEP upper boundary condition and the AMSU/AIRS soundings. Then, the surface pressure was estimated by a second integration of (1) from 850 hPa to the surface assuming a constant lapse rate (dT_v/dz = constant) from 850 hPa to the surface, where the surface temperature was set to the observed sea surface temperature (SST). This procedure was repeated with the layer from 100 to 700 hPa from the AIRS/AMSU sounding and extrapolation to the surface from 700 hPa, and similarly with 100 to 500 hPa and 500 hPa to the surface.

Table 2 shows the observed MSLP and those estimated from the hydrostatic integration of the

AIRS/AMSU soundings for the six storm cases in Table 1. There are three estimates for each storm case, where the lower pressure level that the AIRS/AMSU data was used was 850, 700 or 500 hPa. The corresponding errors of the hydrostatic MSLP estimates are shown in Table 3, where a positive (negative) error indicates that the hydrostatic MSLP estimate was too high (low). These tables show that the errors for the two Lili cases are very large, and the MSLP estimates were too high (the intensity was under-estimated). These errors are consistent with the temperature anomalies shown in Fig. 7 which were unrealistically cold in the lower troposphere. It is likely that Lili was too small to be resolved by the AIRS/AMSU instruments. In contrast, the MSLP estimates for the much larger Isabel were quite accurate. The mean absolute errors for the four Isabel cases were 4.3, 3, and 4.5 hPa for the method with the lower level of 850, 700 and 500 hPa, respectively. The horizontal resolution of the future IR and microwave instruments planned for NPOESS and GOES-R will be greater than what is currently available from AIRS and AMSU on Aqua. Thus, the direct monitoring of storm intensity may be possible in the future for many tropical cyclones.

Table 2. The observed and estimated MSLP (hPa) for the six storm cases with eye soundings. The estimates use the AIRS/AMSU input from 100 hPa to a specified lower level of 850, 700 or 500 hPa.

Storm	Obs	850 hPa	700 hPa	500 hPa
Lili 1002	960	998	993	981
Lili 1003	959	1030	1017	997
Isabel 0913	933	932	931	934
Isabel 0914	933	943	941	942
Isabel 0916	959	960	959	957
Isabel 0917	955	960	958	949

Table 3. The MSLP errors of the AIRS/AMSU estimates in Table 2.

Storm	850 hPa	700 hPa	500 hPa
Lili 1002	38	33	21
Lili 1003	71	59	38
Isabel 0913	-1	-1	1
Isabel 0914	10	8	9
Isabel 0916	1	0	-2
Isabel 0917	5	3	-6

5. WIND STRUCTURE ESTIMATES

The AIRS/AMSU retrievals are available over the entire granules with a horizontal spacing of about 50 km. These soundings can be used to provide the geopotential height field at each pressure level by the downward integration of (1). This procedure would provide the mass field, which could then be used to estimate the balanced wind field. This technique has been applied by Bessho et al (2006) to temperature retrievals from the AMSU data on the current series of NOAA satellites. In that study, the nonlinear balance equation described by Charney (1955) was used to estimate the winds from the geopotential field. Although the inner core is not adequately represented due to the limited horizontal resolution of the AMSU instrument, the wind estimates away from the radius of maximum have an accuracy comparable to the surface wind estimates from QuikSCAT. This same technique will be applied to the AMSU/AIRS data to determine the improvement provided by the IR contribution to soundings. Because the outer portion of the storm is less cloudy, the AIRS data have the potential to make the outer wind retrieval method more accurate than that from AMSU alone.

6. FUTURE PLANS

The intensity and wind structure algorithms described in this paper will applied to real-time AIRS/AMSU retrievals to obtain a larger validation sample. The contrasting accuracy of the MSLP estimates for Lili and Isabel suggest that the quality control indicators that are available with the retrievals can be used to provide a confidence measure for the intensity estimates. This possibility will be investigated in the future. The temperature and moisture soundings in the storm environments will also be verified against additional cases with ground truth from the NOAA Gulfstream Jet to expand the study of Hurricane Lili by DeMaria (2004). The real-time testing and evaluation of the temperature and moisture retrievals and derived wind products will allow the algorithms to be refined and to be ready for adaptation to NPOESS and GOES-R as soon as that data becomes available.

ACKNOWLEDGMENTS

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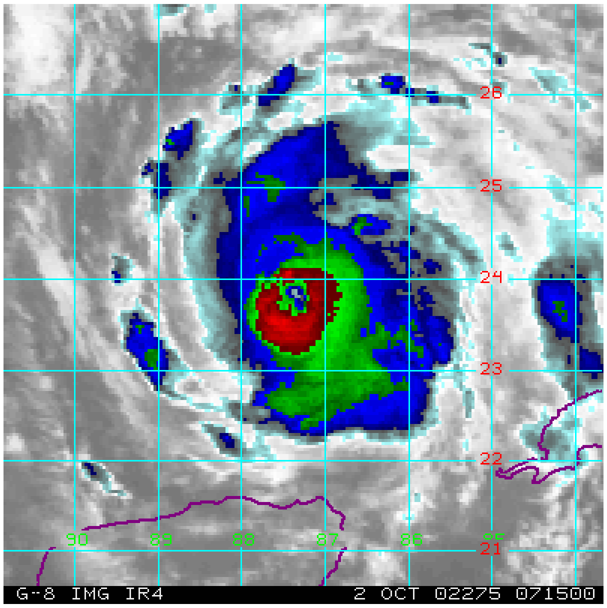

Figure 1. GOES IR (channel 4) image of Hurricane Lili at 0715 UTC on 2 Oct 2002.

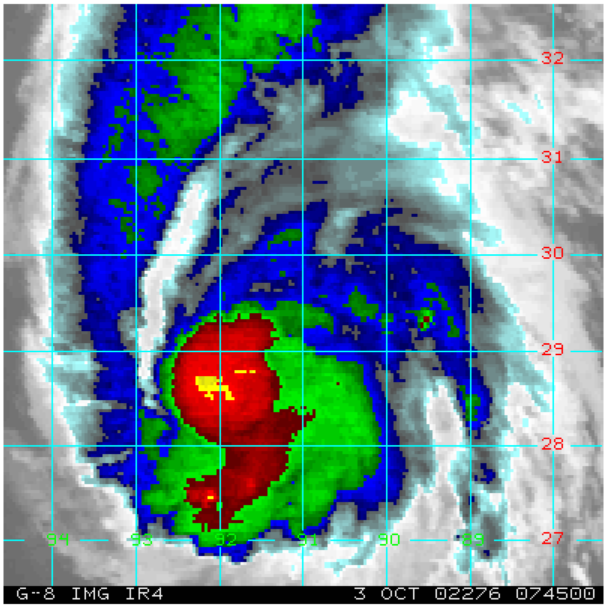

Figure 2. GOES IR (channel 4) image of Hurricane Lili at 0745 UTC on 3 Oct 2002.

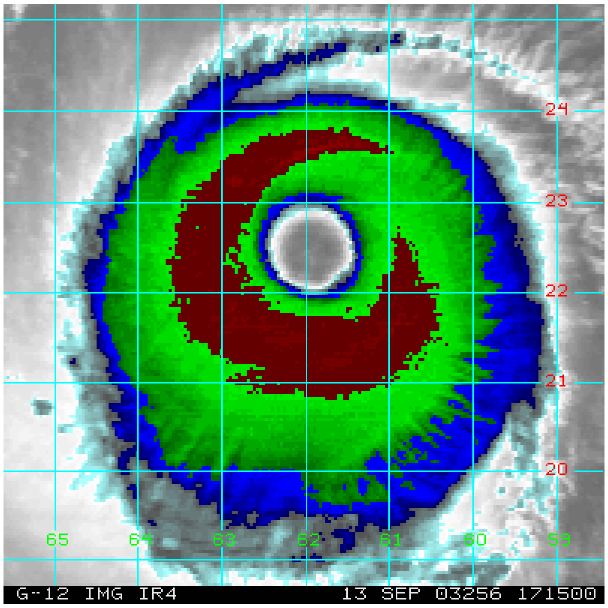

Figure 3. GOES IR (channel 4) image of Hurricane Isabel at 1715 UTC on 13 Sep 2003.

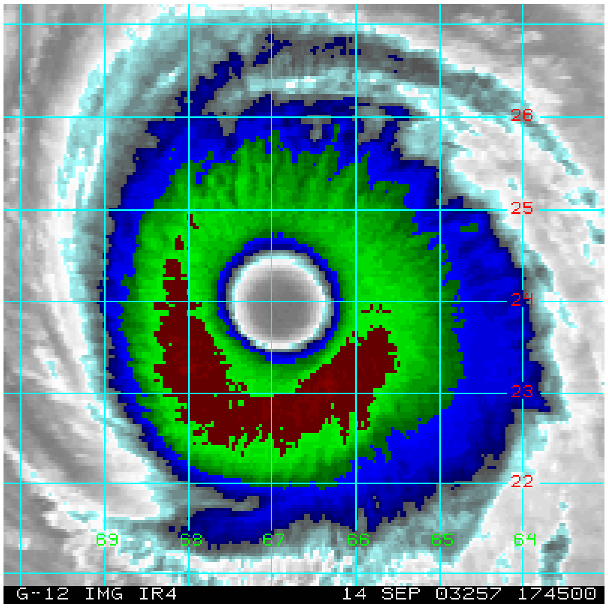

Figure 4. GOES IR (channel 4) image of Hurricane Isabel at 1745 UTC on 14 Sep 2003.

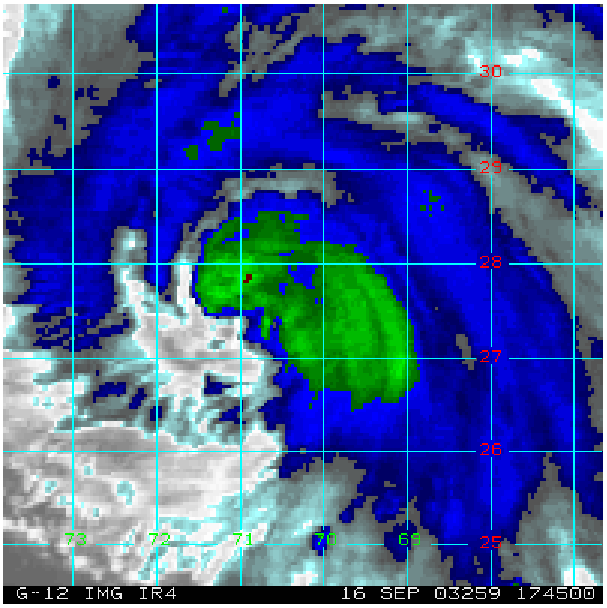

Figure 5. GOES IR (channel 4) image of Hurricane Isabel at 1745 UTC on 16 Sep 2003.

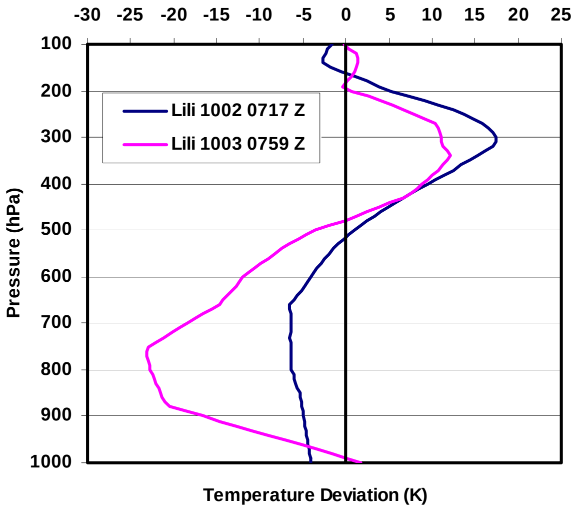

Figure 7. The temperature anomaly versus pressure for the AIRS/AMSU eye soundings of Hurricane Lili.

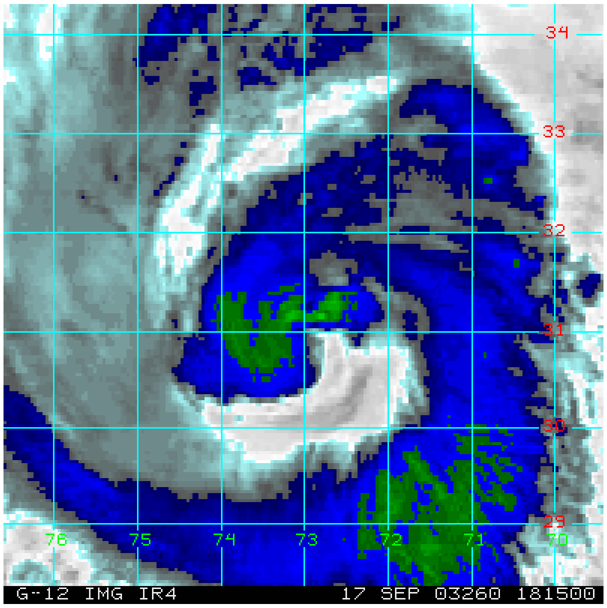

Figure 6. GOES IR (channel 4) image of Hurricane Isabel at 18155 UTC on 17 Sep 2003.

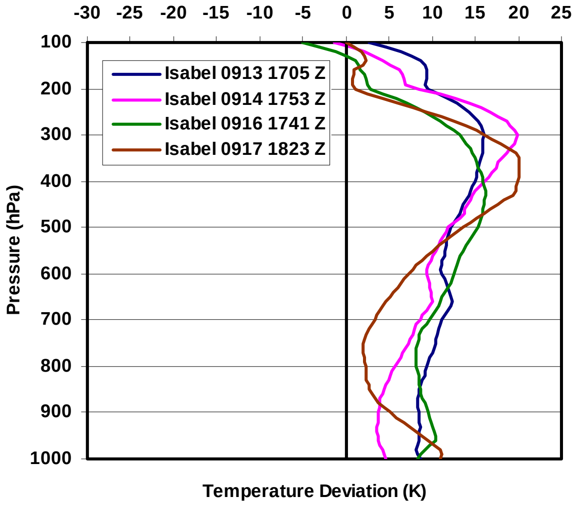

Figure 8. The temperature anomaly versus pressure for the AIRS/AMSU eye soundings of Hurricane Isabel..