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Key Points:

- The application of AIRS subpixel cloud detection with 1 km MODIS cloud
- The analysis fields with assimilation of accurate clear radiances are improved
- The forecasts are substantially improved with the AIRS subpixel cloud detection

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Advanced infrared sounder subpixel cloud detection with imagers and its impact on radiance assimilation in NWP

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Abstract Accurate cloud detection is very important for infrared (IR) radiance assimilation; improved cloud detection could reduce cloud contamination and hence improve the assimilation. Although operational numerical weather prediction (NWP) centers are using IR sounder radiance data for cloud detection, collocated high spatial resolution imager data could help sounder subpixel cloud detection and characterization. IR sounder radiances with improved cloud detection using Atmospheric Infrared Sounder (AIRS)/Moderate Resolution Imaging Spectroradiometer (MODIS) were assimilated for Hurricane Sandy (2012). Forecast experiments were run with Weather Research and Forecasting (WRF) as the forecast model and the Three-Dimensional Variational Assimilation (3DVAR)-based Gridpoint Statistical Interpolation (GSI) as the analysis system. Results indicate that forecasts of both hurricane track and intensity are substantially improved when the collocated high spatial resolution MODIS cloud mask is used for AIRS subpixel cloud detection for assimilating radiances. This methodology can be applied to process Crosstrack Infrared Sounder (CRIS)/Visible Infrared Imaging Radiometer Suite (VIIRS) onboard Suomi-NPOESS Preparatory Project (NPP)/Joint Polar Satellite System (JPSS) and Infrared Atmospheric Sounding Interferometer (IASI)/Advanced Very High Resolution Radiometer (AVHRR) onboard the Metop series for improved radiance assimilation in NWP.

1. Introduction

Reliable forecasts of tropical cyclones (TCs), such as Isaac and Sandy which made landfall on the continental U.S. during 2012, are critical for decision making and timely preparation. Obtaining good TC intensity forecasts remains one of the most challenging tasks in operational forecasting. Observations of atmospheric thermodynamic variables in the TC environment, as well as in the inner core, are very important to the prediction of the storm evolution and hence landfall. The optimal assimilation of this information into operational numerical weather prediction (NWP) models is a vital step to improve forecasts. Satellite advanced infrared sounders (i.e., the Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), or Crosstrack Infrared Sounder (CrIS)), along with advanced microwave sounders (i.e., the Advanced Microwave Sounding Unit (AMSU) or Advanced Technology Microwave Sounder) provide valuable thermodynamic information over the oceans. In particular, AMSU-A temperature information has been demonstrated to be very useful for hurricane forecast improvements [*Zapotocny et al.*, 2008; *Liu et al.*, 2012]; while positive impacts of advanced IR sounder information have been shown [*Le Marshall et al.*, 2006; *McNally et al.*, 2006], the moisture information is yet to be fully realized.

One of the challenges in assimilating advanced IR sounder radiances is cloud detection. Improved cloud detection could reduce the incorrect detection of clear fields of view (FOVs) and improve the assimilation of IR radiances. Although operational centers are using IR sounder data for clear pixel detection or clear channel detection (e.g., by comparing observations and forward calculations from the background), they are not using the collocated high spatial resolution imager data that could help sounder subpixel cloud detection and characterization [*Li et al.*, 2004]. By applying spatially and temporally collocated high spatial resolution imager cloud mask, the thermodynamic information and cloud properties at the IR sounder subpixel level can be well separated. For example, the clear IR sounder FOVs can be used for deriving atmospheric vertical temperature and moisture profiles [*Li et al.*, 2000], while the cloudy IR FOVs can be used for obtaining cloud properties [*Li et al.*, 2005a] and cloud-clearing [*Li et al.*, 2005b]. In addition to improved sounder cloud detection with collocated imager information, assimilating cloudy radiances will be very important in order to take full advantage of IR sounder thermodynamic information in the tropical cyclone (TC) inner core region. Usually only clear IR channels (not affected by clouds) are used in most data assimilation systems; cloud-contaminated channels have not been used effectively due to difficulties in modeling clouds in both forecast and radiative transfer models. The discussion of using cloudy radiances in NWP is beyond the scope of this article. The focus of this study is to investigate the impact of cloud detection on TC forecasts and to improve the use of advanced IR sounder (AIRS, IASI, and CrIS) thermodynamic variables.

2. Methodology

Moderate Resolution Imaging Spectroradiometer (MODIS) on the Earth Observing System Terra and Aqua satellites provides multispectral broadband radiance measurements and cloud products with high spatial resolution not seen before. MODIS 1 km cloud products (information available online at http://daac.gsfc.nasa.gov/MODIS/products.shtml) include, but are not limited to, the cloud mask (confident clear, probably clear, confident cloudy, and probably cloudy) [*Ackerman et al*., 1998], the cloud-phase mask (water clouds, ice clouds, and mixed phase) [*Strabala et al*., 1994; *Baum et al*., 2000], the cloud classification mask [*Li et al*., 2003; *Li et al*., 2007], the cloud particle size (CPS), and the cloud optical thickness [*King et al*., 2003; *Platnick et al*., 2003]. With a collocation methodology developed by *Nagle* [1998], AIRS subpixel cloud detection and characterization can be derived by taking advantage of high spatial resolution MODIS cloud products. For example, the MODIS cloud mask can be used for AIRS subpixel cloud detection, and the 1 km MODIS cloud-phase and cloud-type mask can be used for AIRS subpixel cloud characterization, both of which are useful for quality control in assimilating cloudy radiances. In recent experiments with Weather Research and Forecasting (WRF)/Gridpoint Statistical Interpolation (GSI), it is found that some clear pixels are identified as cloudy while cloudy pixels are identified as clear in the GSI system. While the data assimilation suffers from these misclassifications [*Hu and Xue*, 2006], a better cloud detection could reduce the cloudy data mismatch and improve the assimilation. The impact of cloud detection on AIRS radiance assimilation has been investigated, and the collocated high spatial resolution (1 km) MODIS cloud mask product is used for AIRS subpixel cloud detection.

3. Assimilation Method and Experimental Design

Developmental Testbed Center (DTC) Gridpoint Statistical Interpolation (GSI) is a three-dimensional incremental variational system with a homogeneous background covariance matrix [*Wu et al*., 2002]. It was developed by the National Centers for Environmental Prediction (NCEP) as a next-generation analysis system based on the operational Spectral Statistical Interpolation analysis system. DTC transitioned the operational GSI system into a community system that is widely used in the research environment [*Kleist et al*., 2009; *Ma et al*., 2011]. The system is capable of assimilating various kinds of observations: from surface to upper air to radar to satellite observations. The U.S. Joint Center for Satellite Data Assimilation (JCSDA) community radiative transfer model [*Saunders et al*., 1999; *Chen et al*., 2010] is implemented into GSI for calculations of satellite radiances and the derivatives under different atmospheric and surface conditions.

Hurricane Sandy (2012) was a late-season hurricane in the southwestern Caribbean Sea. It formed as a tropical storm at 12.7°N, 78.8°W at 18 UTC on 22 October 2012 and then became a hurricane with a maximum wind speed of 51.4 m/s in eastern Cuba. After a weakening process when the storm passed the central and northwestern Bahamas, it again strengthened while moving northeastward at 12 UTC on 27 October 2012 and then reached a secondary peak while turning northwestward toward the Mid-Atlantic states [*Blake et al*., 2013].

In this study, experiments are carried out to study the impact of AIRS radiance assimilation using the MODIS cloud mask on the Hurricane Sandy forecast. The assimilation is run at 6 h cycles with a ±1.5 h assimilation window followed by a 72 h forecast. The assimilation period started at 18 UTC on 25 October 2012 (5 days before Sandy's landfall) to 00 UTC on 27 October 2012 and the forecast from 00 UTC on 27 October 2012 to 00 UTC on 30 October 2012. The initial and boundary conditions are from the NCEP Final Operational Global Analysis data at every 6 h [*Li and Liu*, 2009; *Liu and Li*, 2010; *Wu et al*., 2014; *Zheng et al*., 2013]. The data assimilated in this paper include the Global Telecommunication System (GTS), AMSU-A, AIRS (GSI), and AIRS MOD. GTS represents all the conventional data including the surface observations, radiosondes, wind profile, and aircraft data. AMSU-A is the Advanced Microwave Sounding Unit data on NOAA-15, NOAA-18, and Metop-A. Hereafter, AIRS (MOD) denotes the AIRS clear footprint (pixel) detection with MODIS, while AIRS (GSI) denotes AIRS

Table 1. Data Used in the Experiments[a]

	GTS	AMSUA	AIRS (GSI)	AIRS (MOD)
GTS + AMSUA + AIRS (GSI)	Yes	Yes	*Yes*	
GTS + AMSUA + AIRS (MOD)	Yes	Yes		*Yes*

[a] Italics indicate the AIRS radiance data with different cloud detection method.

clear footprint detection with GSI. It can be seen that the locations of clear AIRS (GSI) radiances are quite different from those with the AIRS (MOD) [*Li et al.*, 2004].

The Advanced Research Weather Research and Forecasting Model (WRF-ARW) version V3.2.1 is used as the NWP model. The horizontal resolution is 12 km with a number of grid points of 400*350. The analysis domain covers the southeastern part of North America, northern part of South America, and the southern and western Atlantic Ocean. The microphysics scheme is the WRF Single_Moment six-class scheme [*Hong and Lim*, 2006], and the cumulus parameterization is the Kain-Fritsch scheme [*Kain*, 2004]. Two experiments are carried out (Table 1) to compare the impacts of the AIRS radiance under the GSI stand-alone AIRS cloud detection and the AIRS/MODIS cloud detection method.

4. Experiments and Results

4.1. Data Assimilation

The coverage of AIRS radiance data assimilated under clear-sky conditions is shown in Figure 1 for AIRS channel 210 (709.5659 cm^{-1}) with the weighting function peaking around 450 hPa; Figure 1 (bottom left)

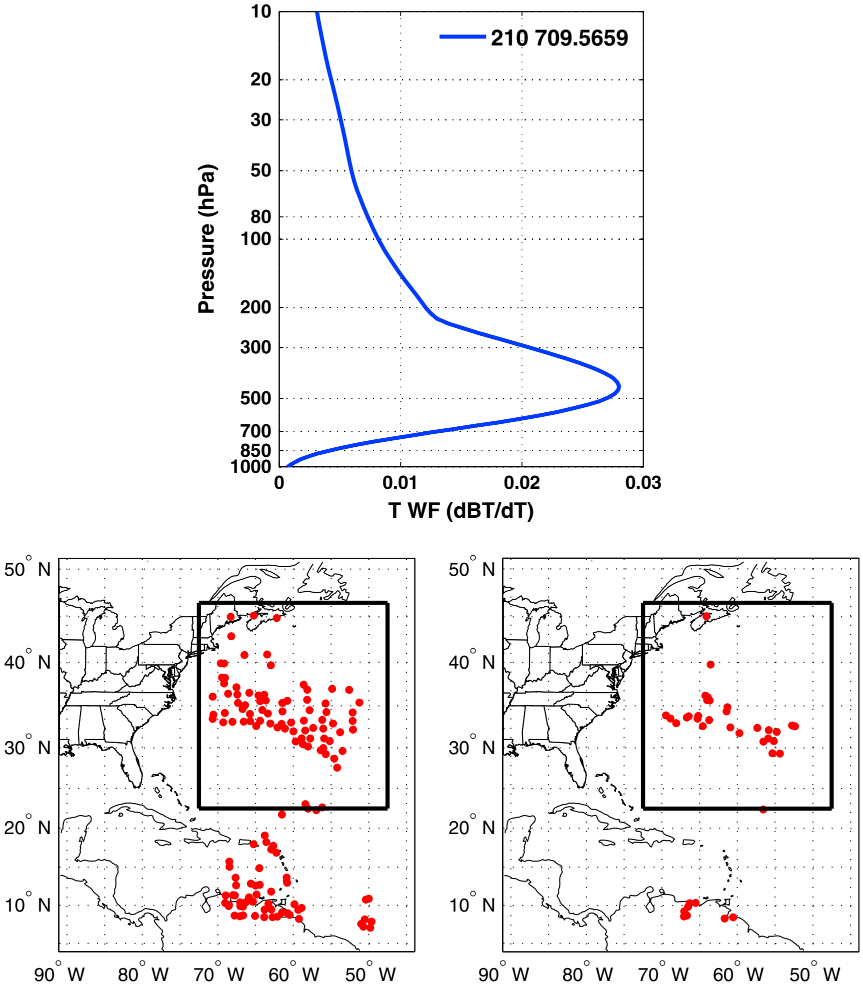

Figure 1. (top) The weighting function of AIRS channel 210 (709.5659 cm^{-1}), (bottom left) AIRS-alone cloud detection (GSI), and (bottom right) AIRS cloud detection with MODIS for AIRS channel 210.

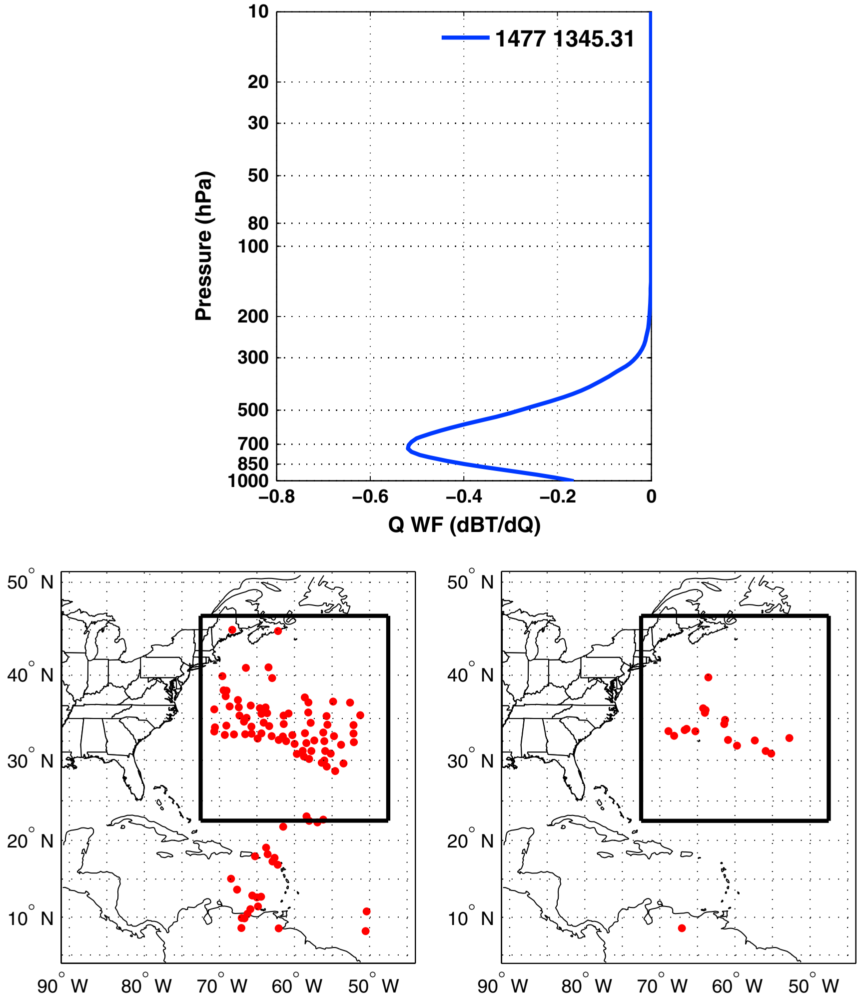

Figure 2. (top) The weighting function of AIRS channel 1477 (1345.31 cm^{-1}), (bottom left) AIRS-alone cloud detection (GSI), and (bottom right) AIRS cloud detection with MODIS (lower right) for AIRS channel 1477.

shows the GSI stand-alone AIRS cloud detection, while Figure 1 (bottom right) shows the AIRS/MODIS cloud detection. Similarly, the data coverage of AIRS channel 1477 (1345.31 cm^{-1}) with the weighting function peaking around 700 hPa is shown in Figure 2. There are some mismatched observations in the West Atlantic and north of South America between AIRS (MOD) and AIRS (GSI); the AIRS (MOD) sees much less clear footprints than the AIRS (GSI). As mentioned, only channels detected as cloud free are assimilated by GSI; therefore, the reduced amount of data is due to more accurate cloud detection with the MODIS high spatial resolution cloud mask product. The mismatched areas are the cloudy regions according to the MODIS cloud mask. The GSI cloud detection failed to reject them and assimilated them as clear-sky radiances, which could potentially degrade the analysis field due to the cloud contamination.

To better understand the advantage of AIRS subpixel cloud detection with the MODIS cloud mask, one granule of AIRS brightness temperature and collocated MODIS high-resolution cloud mask are shown in Figure 3. Figure 3 (right) reveals the collocated MODIS cloud mask for a small area outlined in Figure 3 (left). The AIRS subpixel clear mask can be easily derived based on the MODIS cloud mask; there are four possible categories for each MODIS pixel: confident clear, probably clear, uncertain, and cloudy. Only the AIRS subpixels filled with the MODIS confident clear mask are considered clear footprints for assimilation and forecast experiments.

To see the impact of different cloud detection methods on the assimilation, the difference between the temperature and relative humidity of the analysis field between AIRS (MOD) and AIRS (GSI) at 06 UTC on

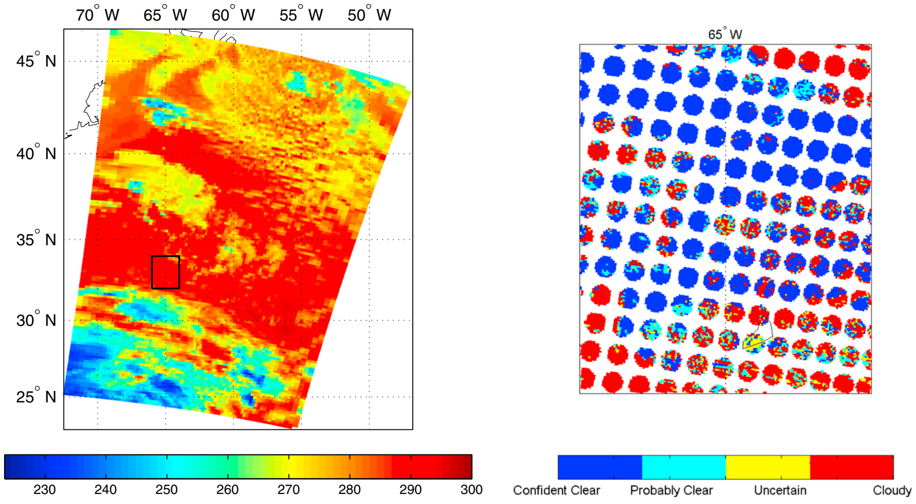

Figure 3. (left) The brightness temperature (unit: K) for one AIRS granule indicated in Figure 2 at 06 UTC on 25 October 2012 and (right) the collocated MODIS cloud mask for the small box area outlined by the rectangle in Figure 3 (left).

25 October 2012 is shown in Figures 4 and 5. In general, unsuccessful cloud detection results in more cloud contamination in the radiance assimilation. Consequently, the analysis could either be colder or wetter than it should be, or some combination of them. In this case, for the 500 hPa in Figure 4, the analysis change is dominated by temperature; the AIRS (MOD) analysis is warmer than AIRS (GSI) due to less cloud contamination. The impact of moisture field is subtle. For 700 hPa in Figure 5, the analysis change is visible in both temperature and moisture fields. The temperature of AIRS (MOD) is about 1 K warmer than AIRS (GSI) in the northwest of Atlantic Ocean and 0.6 K warmer in the east of Hurricane Sandy. The relative humidity of AIRS (MOD) is nearly 30% drier in the northwest of Atlantic Ocean and around 10% drier in the east of Hurricane Sandy. The different behaviors in 500 (Figure 4) and 700 hPa (Figure 5) are determined by the assimilation method, which is closely related to the background covariance matrix [*Derber and Bouttier*, 1999]. No attempt is made to validate as to whether the analysis changes in Figures 5 and 6 are reasonable or not. Instead, WRF-ARW is used to conduct forecasts for Hurricane Sandy. We believe better analyses should lead to better hurricane forecasts, which will be shown in section 4.2.

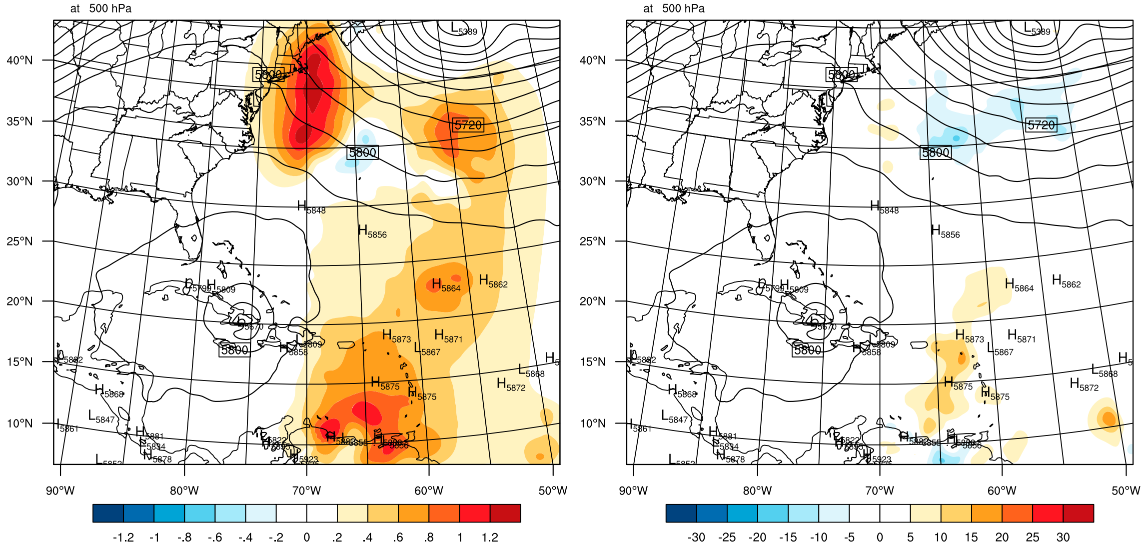

Figure 4. (left) The difference in temperature (unit: K) and (right) relative humidity (unit: %) analysis between the two experiments (AIRS (MOD) and AIRS (GSI)) with the geopotential height (solid, unit: m) of AIRS (MOD) at 500 hPa at 06 UTC on 25 October 2012.

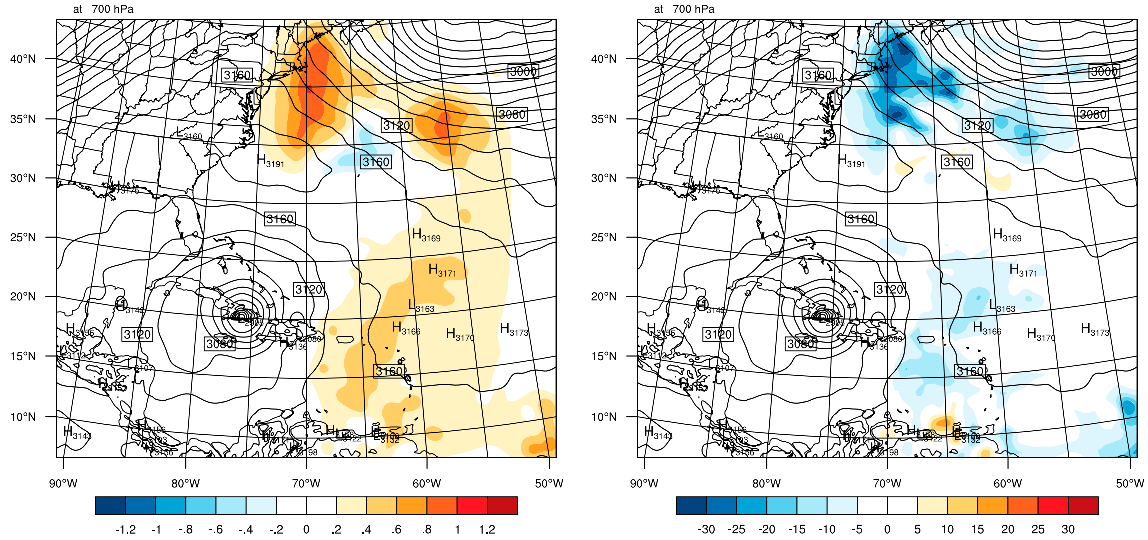

Figure 5. (left) The difference in temperature (unit: K) and (right) relative humidity (unit: %) analysis between the two experiments (AIRS (MOD) and AIRS (GSI)) with the geopotential height (solid, unit: m) of AIRS (MOD) at 700 hPa at 06 UTC on 25 October 2012.

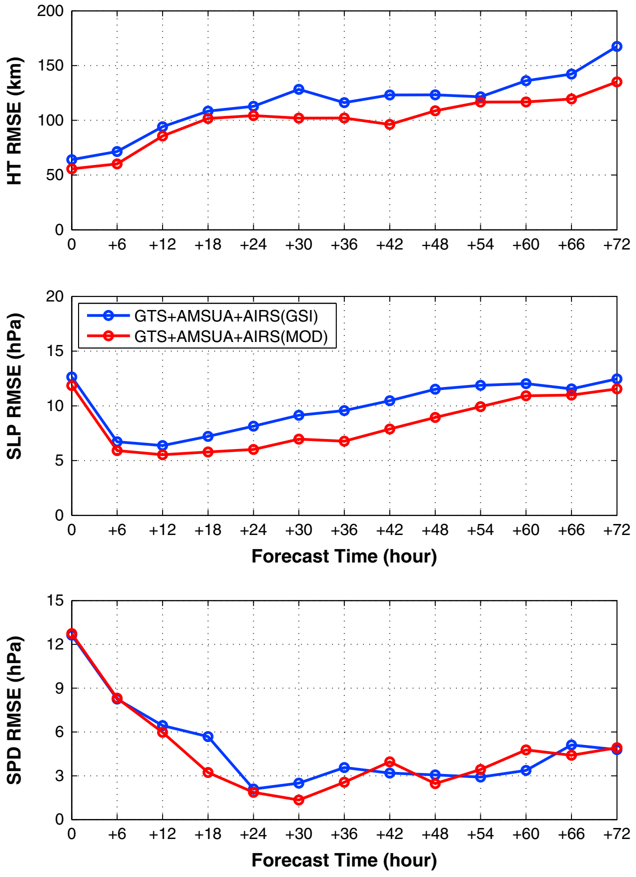

Figure 6. The (top) track, (middle) central sea level pressure (SLP), and (bottom) maximum wind speed forecast RMSE with the AIRS-alone cloud detection (blue) and AIRS subpixel cloud detection with MODIS (red). Data are assimilated every 6 h from 06 UTC on 25 October to 00 UTC on 27 October 2012, followed by 72 h forecasts for Hurricane Sandy (2012).

4.2. Forecast Results and Discussion

Hurricane track and intensity (characterized by minimum sea level pressure and maximum wind speed) are two important parameters for hurricane forecasts. Figure 6 shows the root-mean-square-error (RMSE) of the hurricane track (top), minimum sea level pressure (middle), and the maximum wind speed (bottom) of the 72 h forecasts. The GTS + AMSUA + AIRSrad (GSI) (blue) uses the AIRS stand-alone cloud detection, and the GTS + AMSUA + AIRSrad (MOD) (red) uses the AIRS/MODIS cloud detection method. For the hurricane track, the RMSE is smaller with the AIRS/MODIS cloud detection, especially after 30 h. The average improvement of the hurricane track RMSE from the GSI cloud detection to the MODIS cloud detection is obvious. For the minimum sea level pressure, the results with the AIRS/MODIS cloud detection are better during the whole 72 h forecast, although the improvement in the first 12 h forecasts is smaller. For the maximum wind speed, the forecasts with MODIS cloud detection are comparable to the forecast with MOD (GSI) cloud detection, with only a slight advantage. So for wind speed, the impact of the AIRS/MODIS cloud detection is neutral.

5. Summary

To investigate the impacts of the cloud detection from advanced IR sounders on the forecasts of hurricane track and intensity, the AIRS stand-alone cloud detection and AIRS subpixel cloud detection with MODIS high spatial resolution cloud mask product are compared. The stand-alone cloud detection is plugged into the GSI system, and the subpixel cloud detection is based on the 1 km MODIS cloud mask. The data locations of the assimilated AIRS radiances with the stand-alone cloud detection generally agree with the MODIS cloud detection; however, there are some mismatched areas that the stand-alone cloud detection failed to reject and assimilated as clear radiances. As a result, the stand-alone cloud detection allows more cloud-contaminated radiances into the GSI, causing a cold bias in the temperature field and a wet bias in the moisture field. This bias affects the forecasts of hurricane track and intensity. The 72 h forecasts of Hurricane Sandy (2012) indicate that both hurricane track and intensity forecasts are improved when the collocated high spatial resolution MODIS cloud mask product is used for the AIRS subpixel cloud detection. The RMSE of the hurricane track is improved on average over the 72 h forecast period. This improvement is more evident after 30 h in the forecasts. The minimum sea level pressure also improves during the whole forecast period. These results indicate that the AIRS/MODIS cloud detection algorithm could benefit the hurricane forecast by reducing the cloud-contaminated radiances into the assimilation system. This methodology can be applied to process CrIS/VIIRS onboard Suomi-NPP/JPSS and IASI/AVHRR on board the Metop series for radiance assimilation in the future.

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