Report on "CIMSS Participation in the Utility of GOES-R Instruments for Hurricane Data Assimilation and Forecasting"

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CIMSS Task Leader(s): Jun Li
CIMSS Support Scientist(s): Jinlong Li
NOAA Collaborator(s): Sid Boukabara
CIRA Collaborator(s): Milija Zupanski

NOAA Strategic Goals:

- Serve society's needs for weather and water
- Provide critical support for the NOAA mission

CIMSS Research Themes:

- Satellite Meteorology Research and Applications
- Environmental Models and Data Assimilation

1. Proposed Work

This is a collaborative proposal with the Cooperative Institute for Research in the Atmosphere (CIRA) at the Colorado State University entitled "Utility of GOES-R instruments for hurricane data assimilation and forecasting" with PI Milija Zupanski. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison will develop a full spatial resolution advanced sounding dataset from the Atmospheric InfraRed Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) to emulate the future geostationary sounding system on spectral and spatial characteristics, and demonstrate the advantage of a combined GOES-R imaging and sounding system on hurricane data assimilation and forecasting. CIMSS scientists will collaborate with CIRA scientists to examine the utility of the GOES-R ABI and GLM, and of the advanced IR sounder, for hurricane data assimilation and prediction, using ensemble data assimilation with the NCEP operational Hurricane WRF (HWRF) modeling system.

2. Summary of Accomplishments and Findings (06/01/2010 - 05/31/2014)

2.1 Develop the full spatial resolution advanced infrared soundings for hurricane assimilation experiments

The wealth of information that will be brought by launching the next-generation series of Geostationary Operational Environmental Satellites, starting with the GOES-R mission, offers an opportunity of using multi-channel multi-instrument data in new ways. One of the new instruments on the GOES-R satellite is the Advanced Baseline Imager (ABI). The ABI is a 16-channel imaging radiometer that will sample nine infrared (IR) wavelengths, and have a footprint about 75 % smaller than current GOES. The ABI will observe water vapor and clouds with the potential for improvement in the analysis of these fields and their forecast. However, due to no advanced IR sounder on the GOES-R series, the vertical resolution of water vapor measurements from ABI is very limited. The advanced IR sounders onboard the polar-orbiting satellites will bring additional information related to high vertical resolution of temperature and moisture profiles along with cloud microphysical properties. Assimilation of measurements from the GOES-R ABI and JPSS (Joint Polar-orbiting Satellite System) advanced IR sounder will help in improving the assessment of water vapor, clouds, and storms. The combined impact of these observations via data assimilation can be especially beneficial for the prediction of tropical storms. This CIMSS/CIRA collaborative proposal is to answer one of the important questions: what is the impact on hurricane forecast if we combine GOES-R ABI and advanced IR sounding products? With full spatial resolution advanced IR soundings from the Atmospheric InfraRed Sounder (AIRS) onboard the NASA Earth Observing System (EOS) Aqua platform, the Infrared Atmospheric Sounding Interferometer (IASI) onboard the EUMETSAT Metop-A satellite, and in future the Cross-track Interferometer Sounder (CrIS) onboard the NOAA JPSS series included in the assimilation system, the unique value of high spatial and high vertical resolution aspects of advanced IR soundings can be demonstrated. CIMSS scientists have collaborated with CIRA scientists on identifying typical tropical cyclone case for this study, Hurricane Fred in 2009 was selected for assimilation experiments. The Meteosat Second Generation (MSG) SEVIRI is used as GOES-R ABI proxy data which covers Europe, Eastern and Central Atlantic. The time period for this experiment is from 05 September 2009 at 00Z to 14 September 2009 at 00 Z, which covers a good spin-up of the system. We have processed the AIRS data for this time period, AIRS sub-pixel cloud detection was performed using the collocated MODIS 1 km spatial resolution cloud mask products (Li et al. 2004, Journal of Applied Meteorology). The AIRS full spatial resolution or single field-of-view atmospheric temperature and moisture profiles are derived using a variational methodology (Li et al. 2000), and the atmospheric temperature and moisture profiles are retrieved with an iterative approach.

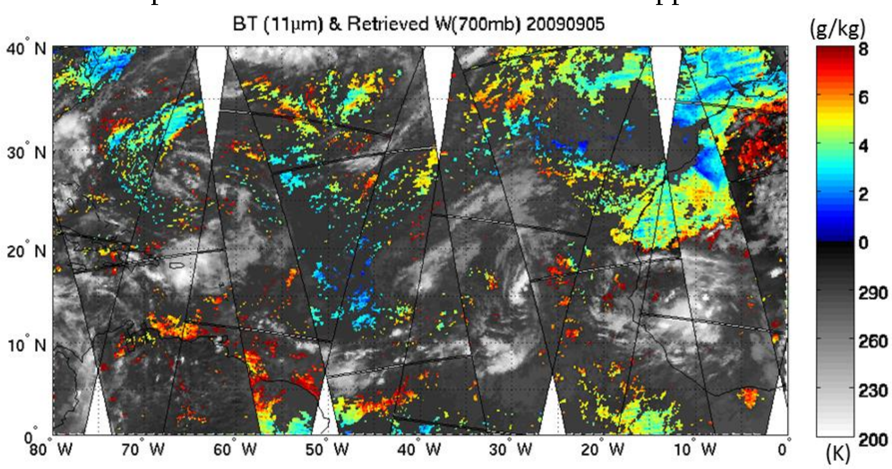

Figure 1. The 700 hPa water vapor mixing ratio retrievals (color) in clear skies from AIRS overlaying on an AIRS 11 μm channel brightness temperature (black/white) for 05 September 2009.

Figure 1 shows the 700 hPa water vapor mixing ratio retrievals in clear skies (color) from AIRS overlaying on an AIRS 11 µm channel brightness temperature (black/white) for 05 September 2009. Each pixel in the color region presents an atmospheric sounding. There are fluent soundings retrieved in the pre-convection environment, all the soundings in other days are also processed, and the full spatial resolution temperature and moisture profiles derived from AIRS have been provided to CIRA collaborator Milija Zupanski for assimilation experiments. CIMSS sounding team has also implemented the WRF/3DVAR for assimilation studies, Hurricane Ike (2008) is used for assimilation experiments, AIRS SFOV soundings are used in the WRF/3DVAR assimilation and forecast system. Results show that the AIRS SFOV temperature soundings improve the 48-hour track forecasts (Zheng et al 2014), which is consistent with that from the WRF/DART assimilation and forecast system (Li and Liu 2009; Liu and Li 2010).

2.2 A near real time regional satellite data assimilation system for high impact weather research and applications

CIMSS scientists have recently developed a near real time (NRT) regional Satellite Data Assimilation system for Tropical storm forecasts (SDAT) (http://cimss.ssec.wisc.edu/sdat) with a purpose to use it as an application demonstration on the utilization of JPSS/GOES-R observations to improve the high impact weather forecasts.

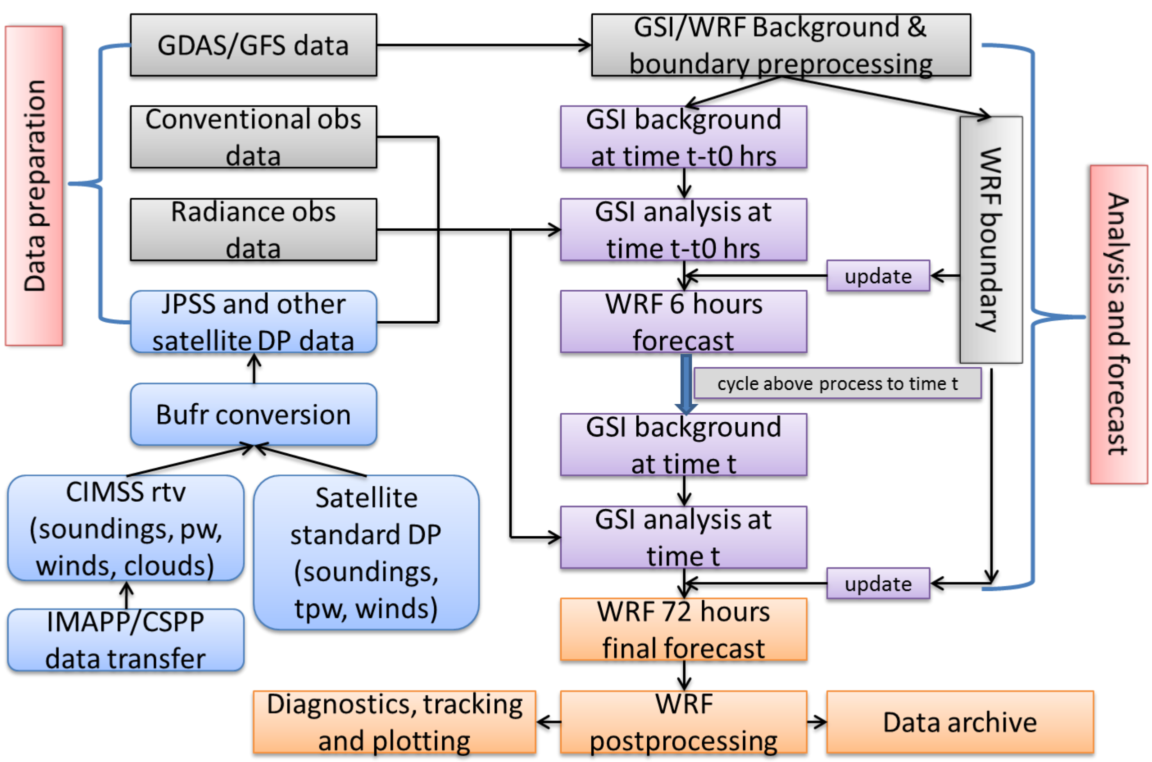

Figure 2. CIMSS SDAT system flowchart.

The core of SDAT system is the community Gridpoint Statistical Interpolation (GSI) assimilation system and the advanced Weather Research Forecast (WRF) model. Figure 2 shows the system flowchart. SDAT system mainly consists of data preparation and assimilation/forecast parts. Real time NOAA National Centers for Environmental Prediction (NCEP) global forecast system (GFS) outputs are used as SDAT background and initial/boundary input. The system runs a 6-hour cycling assimilation followed by a 72-hour forecast. In addition to assimilate regular conventional and satellite radiances obtained from NCEP bufr files which contain GOES, AMSUA/AMSUB, HIRS, MHS, ATMS, AIRS and IASI radiances, the system is also able to assimilate satellite derived products such as hyperspectral IR temperature and moisture profiles, total precipitable water (TPW). We are also working on adding GOES Sounder layer precipitable water (LPW) and GOES Imager atmospheric motion vector (AMV) products. So both satellite observed and derived data (radiance/retrieval) can be assimilated in the system.

A webpage (see Figure 3) has been preliminary designed for accessing the forecasts results: http://cimss.ssec.wisc.edu/sdat

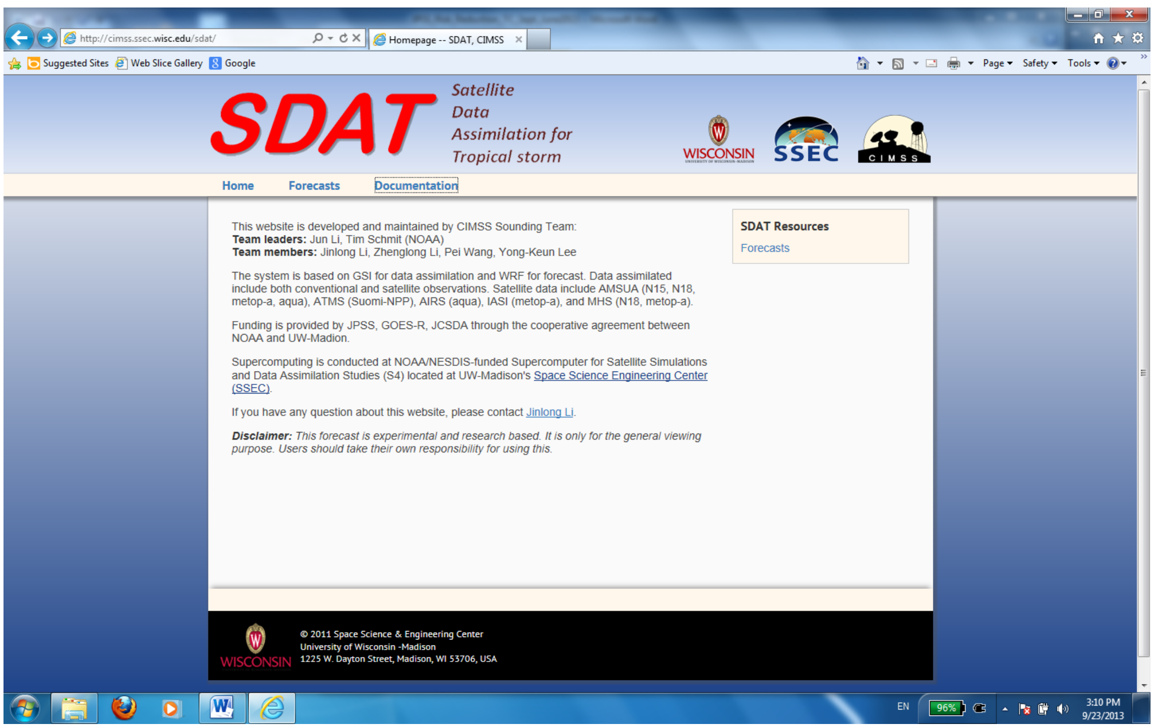

Figure 3. CIMSS near real time SDAT webpage.

2.3 Research on improving assimilation of satellite advanced IR sounder radiances conducted with SDAT

Using SDAT as a research testbed, studies have been conducted on improving the utilization of satellite data in NPW models. One of them is how to do better cloud detection for hyperspectral IR sounder radiance assimilation. Improved cloud detection could reduce the incorrect detection of clear fields-of-view (FOVs) and hence improve the assimilation of IR radiances. In hyperspectral IR radiance assimilation, currently most operational numerical weather prediction (NWP) centers are using IR sounder alone data for clear pixel detection or clear channel detection (e.g., by comparing observations and forward calculations from the background), which could result in treating some cloudy footprints as clear in the assimilation and therefore cause bias in the analysis. We have studied the synergistic use of high spatial resolution imager (e.g., MODIS) and high spectral resolution sounder (e.g., AIRS) data for improving the assimilation of sounder radiance in NWP model. Based on the spatially and temporally collocated high spatial resolution (1 km) MODIS cloud mask, the AIRS clear FOVs can be accurately derived (Li et al. 2004). There are four possible categories for one MODIS pixel: confidently clear, probably clear, uncertain and cloudy. Only the AIRS sub-pixels filled with MODIS confidently clear mask are considered clear footprints. After the sub-pixel cloud detection with collocated 1 km MODIS cloud mask product, the AIRS clear radiances are then assimilated in the GSI system. By comparing with AIRS stand-alone cloud detection, forecast experiments for hurricane Sandy in 2012 indicated that both hurricane track and intensity are substantially improved when the collocated high spatial resolution MODIS cloud mask is used for AIRS sub-pixel cloud detection for assimilating AIRS radiance. This is mainly due to that the stand-alone cloud detection method failed to reject some cloudy pixels and assimilate them as clear radiances. As a result, these cloudy contaminated radiances cause a cold bias in the temperature field and a wet bias in the moisture field, and further affects hurricane track and intensity forecasts. The major results are recently published in Geophysical Research Letter (Wang et al., 2014). Also see section 2.5 for more details.

Another research is the comparison between radiance assimilation and retrieval assimilation. Due to the development of variational data assimilation techniques, operational NWP centers like NCEP and the European Centre for Medium-Range Weather Forecasts (ECMWF) have been successfully assimilate radiance directly. However, it is still very hard to utilize full spectral information from advanced sounder due to the complexity and nonlinearity of radiance assimilation. The theoretical study suggests that there is equivalence between the radiance and retrieval assimilation (Migliorini, 2012), and the assimilation of transformed retrievals may be particularly advantageous for hyperspectral IR sounders that have the very high number of channels. Our preliminary study confirmed the equivalence to some extent. A pair of experiments was designed for this: one assimilated AIRS radiance, while another assimilated the single field of view AIRS retrieved temperature and moisture profiles from CIMSS (Li et al., 2007). In addition the conventional data and AMSU radiances from four satellites (NOAA 15, NOAA 18, Aqua and Metop-A) were also included. Using hurricane Sandy in 2012 as a case study, data were assimilated every 6 hours from 06 UTC 25 to 00 UTC 27 October 2012 and then 72-hour forecasts were followed after each assimilation step.

Figure 4 shows the RMSE of hurricane Sandy track (upper) and maximum wind speed (lower) forecasts with AIRS radiance and retrieval assimilation, respectively. The conventional data (GTS) and AMSU radiances from four satellites are also included in the simulation. It can be seen that AIRS radiance and retrieval assimilation has the similar impact on intensity forecasts, while retrieval assimilation provides better track forecasts than radiance assimilation, this might be due to the fact that more AIRS channels are used in sounding retrieval than in radiance assimilation.

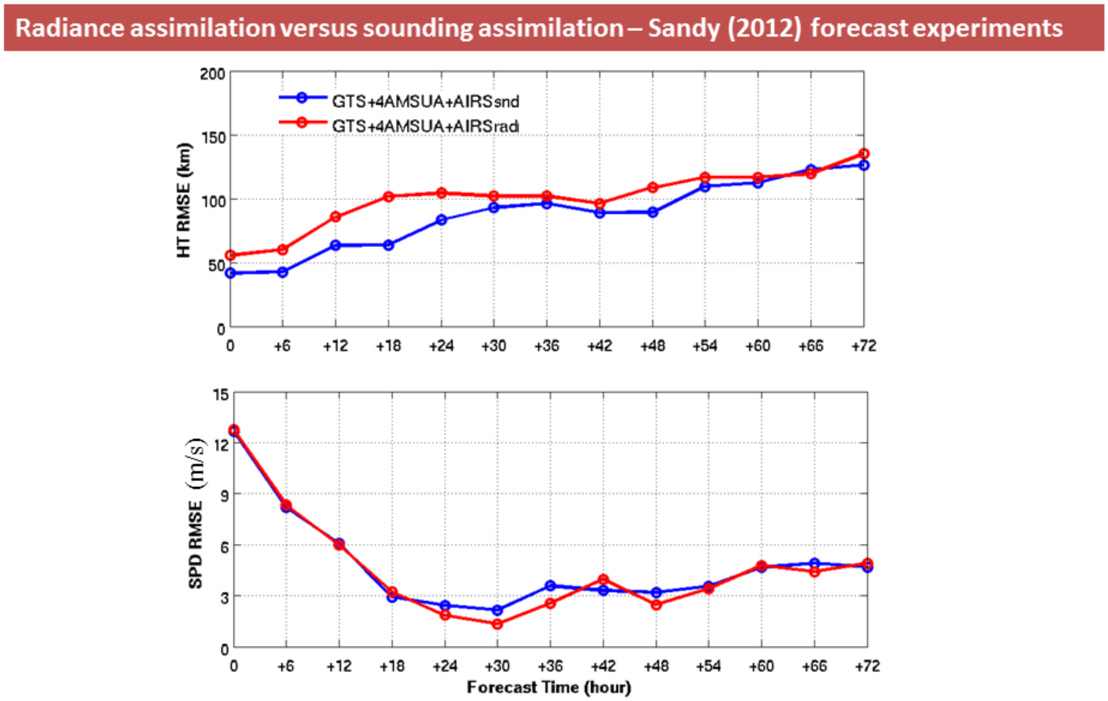

Figure 4. RMSE of hurricane Sandy track (upper) and maximum wind speed (lower) forecasts with AIRS radiance and retrieval assimilation, respectively. Forecasts start from 12 UTC 25 October 2012 and valid 18 UTC 30 October 2012.

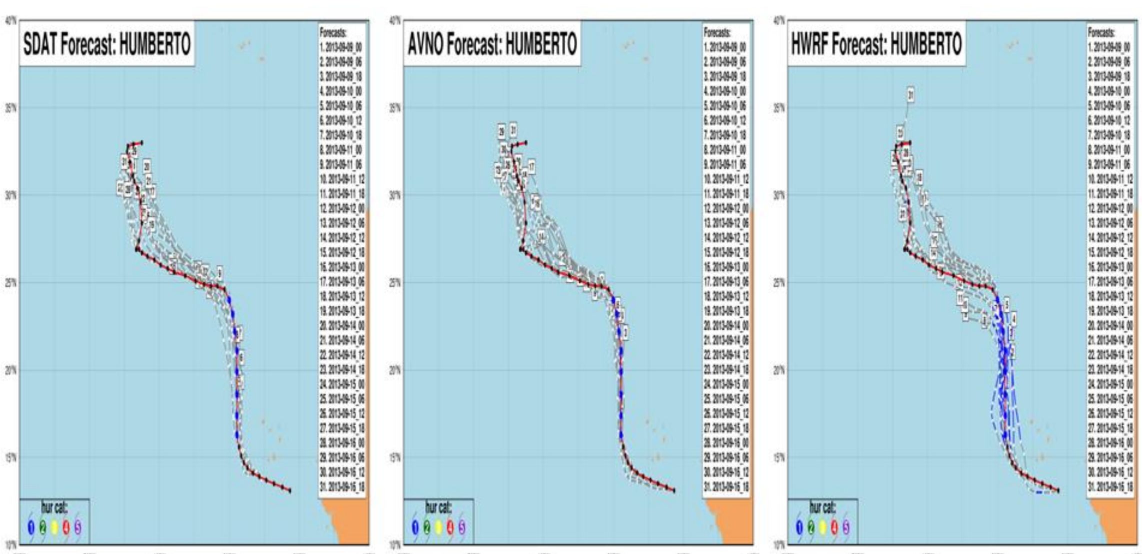

Figure 5. The life-cycle track forecasts for hurricane Humberto from 00 UTC 09 September 2013 to 18 UTC 16 September 2013: SDAT (left), GFS (middle) and HWRF (right).

Since August 2013, SDAT system has been running in near real time over a domain covering CONUS and North Atlantic Ocean. Supercomputing is conducted at NOAA/NESDIS-funded Supercomputer for Satellite Simulations and Data Assimilation Studies (S4) physically located at UW-Madison's Space Science Engineering Center (SSEC). Due to the dependence on GFS data, SDAT system generally starts no earlier than 4 hours after analysis time. We are working on latency issue now in order that SDAT forecast products can be available on line no later than 6 hours after analysis time for applications. Standard GFDL vortex tracker program has also been installed into the system. During the hurricane season the hurricane track and intensity will be automatically calculated in the same way as National Hurricane Center uses. A dedicated website (http://cimss.ssec.wisc.edu/sdat) has been designed for users to access the forecast results. In 2013, there were no many hurricanes over Atlantic Ocean. Figure 5 shows the life-cycle track forecasts from SDAT (left pane), GFS (middle) and HWRF (right). It indicates that SDAT has the similar track forecasts capability of GFS, while better intensity forecasts than GFS. HWRF has the best intensity forecasts but the track forecasts are not as good as GFS and SDAT in this case. The forecasts from SDAT for other storms (such as Gabrielle, Karen) are also very promising. For example, Karen was the only hurricane landed onto CONUS in 2013, it is found that SDAT forecasts are closer to the observations than other dynamic models, and are very close to the official guidance (see Figure 6).

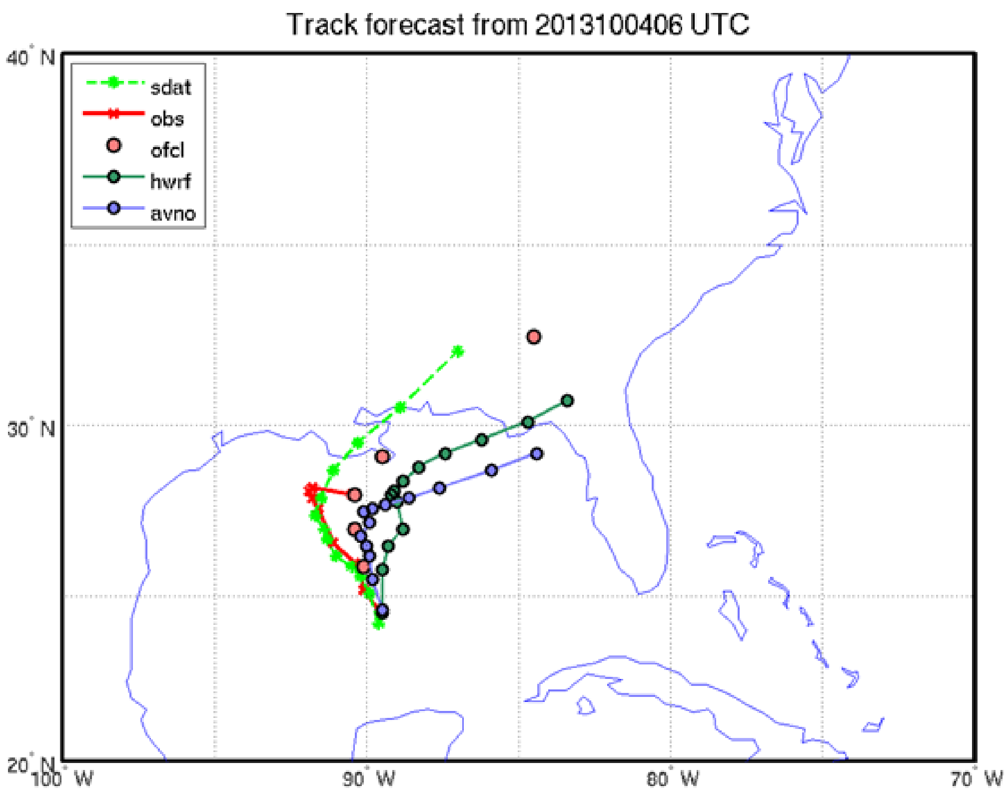

Figure 6. The track forecasts of storm Karen are from SDAT (light green), NHC official guidance (pink), HWRF (dark green) and GFS (purple) along with the best track data (red). The forecasts started at 06 UTC 04 October and are valid until 06 UTC 07

October 2013. The observations (best track) are only available until 06 UTC 06 October 2013.

2.4 Forward operator for layer precipitable water has been developed for assimilating GOES-R water vapor information

Due to the challenge on assimilating high temporal resolution moisture information in the current GSI system, it is worthwhile to study the assimilation of layer precipitable water (LPW) instead of the direct use of radiances. In addition, assimilating 300 – 700 hPa LPW can avoid this NWP model top issue. The 300 – 700 hPa LPW has the best moisture information sensitivity from GOES Sounder and GOES-R ABI infrared radiances; it has been demonstrated to improve the GFS forecasts when compared with radiosondes, ground-based microwave radiometer and ground-based GPS-Met (Lee et al. 2014, JTECH). In order to assimilate the current GOES Sounder and GOES-R LPW information, a forward operator has been developed and implemented within GSI assimilation system, which will help us understand the difficulties in using water vapor channel radiances and to find possible solutions for better use of moisture information (radiances or LPW) with GSI.

2.5 Research on handling clouds for radiance assimilation

Investigation on better cloud detection for radiance assimilation

In hyperspectral infrared (IR) radiance assimilation, currently the sounder alone method is used by most operational numerical weather prediction (NWP) centers, which might result in treating some cloudy footprints as clear in the assimilation and cause bias in the analysis. How to detect cloud accurately in sounder sub-pixel is a very important question in this project in order for better assimilating the hyperspectral IR radiances in NWP models. We have studied the synergistic use of high spatial resolution imager (e.g., MODIS) and high spectral resolution sounder (e.g., AIRS) data for improving the assimilation of sounder radiances in NWP models. The AIRS sub-pixel clear detection can be easily derived based on the collocated MODIS cloud mask, there are four possible categories for one MODIS pixel with 1 km spatial resolution: confident clear, probably clear, uncertain and cloudy. Only the AIRS sub-pixels filled with MODIS confident clear mask are considered clear footprints for assimilation and forecast experiments. After the sub-pixel cloud detection with collocated 1 km MODIS cloud mask product, the AIRS clear radiances are then assimilated in the GSI system, it is found that accurate AIRS clear radiances improve the atmospheric temperature and moisture analysis, and hence results in a better forecast.

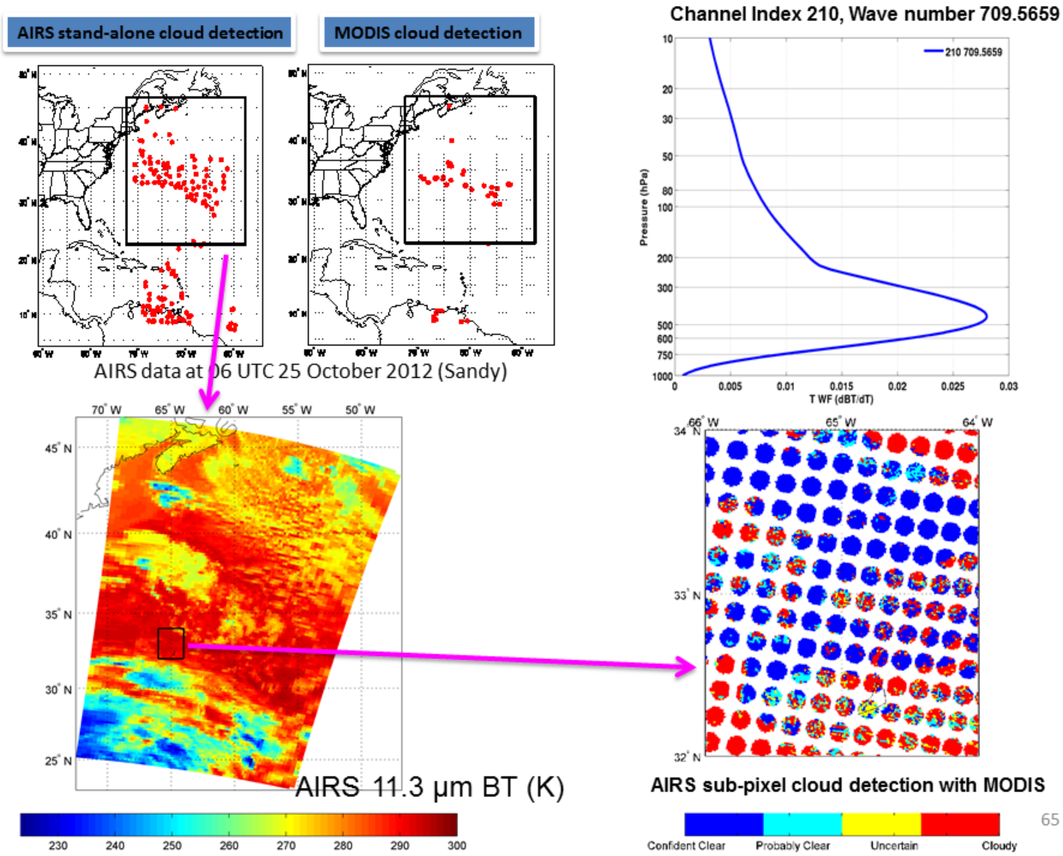

Figure 7. The GSI cloud detection (upper left) and MODIS cloud detection (middle left) for AIRS radiance assimilation. The AIRS sub-pixel cloud detection with MODIS 1 km cloud mask is illustrated in lower right panel for a small box in one AIRS granule (lower left panel).

As an example, the coverage of AIRS radiance data assimilated under clear sky conditions are shown in Figure 7 for AIRS channel 210 (709.5659 cm^{-1}) with weighting function peaking at about 450 hPa, in which upper left panel indicates the GSI AIRS stand-alone cloud detection while the middle left panel shows the sub-pixel cloud detection with MODIS 1 km cloud mask. It can be seen that the locations of clear AIRS radiances with stand-alone cloud detection are in general close to that from MODIS cloud detection. However, there are some mismatched areas in the West Atlantic and north of South America. As mentioned, only channels detected as cloud-free are assimilated by GSI, therefore, the reduced data amount is due to the more accurate cloud detection with MODIS high spatial resolution cloud mask product. The mismatched areas are the cloudy region according to the MODIS cloud mask, while the GSI cloud detection failed to reject them and assimilated them as clear sky radiances, which would bring inaccurate environmental information into the analysis.

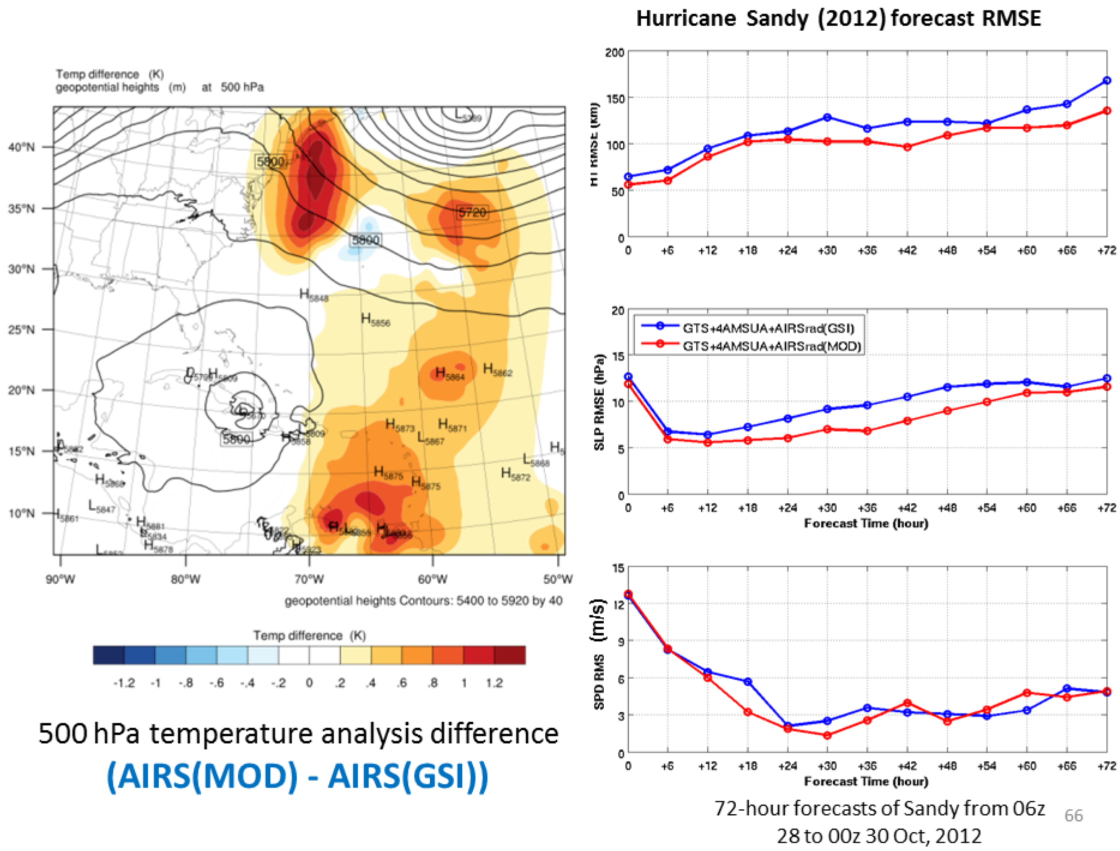

Figure 8. The difference of temperature analysis field between AIRS (MOD) and AIRS (GSI) at 06 UTC on 25 October 2012, and the RMSE of the hurricane track, minimum sea level pressure and the maximum wind speed of 72-hour forecasts with GTS+4AMSUA+AIRSrad (GSI) (blue) and GTS+4AMSUA+AIRSrad (MOD) (red).

The difference of temperature analysis field between AIRS (MOD) and AIRS (GSI) at 06 UTC on 25 October 2012 are shown in the left panel of Figure 8. At 500 hPa the AIRS (MOD) is warmer and the temperature difference at 500 hPa is more than 1.2 K at the east coast of the continent. It appears that the GSI AIRS stand-alone cloud detection failed to reject some cloudy pixels and assimilated them as clear radiances. The impact of the cloudy radiances on the analysis could result in colder temperatures than that from AIRS (MOD) since the cloudy radiances are usually colder than that of clear skies. The right panels of Figure 6 show the root mean square error (RMSE) of the hurricane track (top), minimum sea level pressure (middle) and the maximum wind speed (bottom) of 72-hour forecasts. The GTS+4AMSUA+AIRSrad (GSI) (blue) is using the AIRS stand-alone cloud detection, and the GTS+4AMSUA+AIRSrad (MOD) (red) is using the MODIS sub-pixel cloud detection method. Here GTS represents all the conventional data and 4AMSU represents AMSU data from four satellites (NOAA15, NOAA18, Aqua and Metop –A). From the hurricane track, it indicates that the RMSE of hurricane track is smaller with the MODIS cloud detection method, especially after 30-hours, the difference between GSI cloud detection and MODIS cloud detection is obvious. For the minimum sea level pressure, the results with MODIS cloud detection is slightly better in the first 12-hour forecasts, while after 18-hour forecasts, the RMSE of minimum sea level pressure with MODIS cloud detection is smaller. For the maximum wind speed, the forecasts with MODIS cloud detection are better after the 12-hour forecasts, but worse at 42-hour and 60 hour. So for wind speed, the results of the two experiments are competitive.

Investigation on radiance assimilation in partial cloud cover

Besides better cloud detection for infrared radiance assimilation, assimilating cloudy radiances will be very important in order to take full advantage of IR sounder thermodynamic information. Usually only clear IR channels (not affected by clouds) are used in most of data assimilation systems, and cloud contaminated channels have not been used effectively due to difficulties in modeling clouds in both forecast and radiative transfer models. An optimal MODIS/AIRS cloud-clearing technique has been developed at CIMSS (Li et al. 2005), this method can retrieve clear column radiances through combining collocated multi-band MODIS IR clear radiances and the AIRS cloudy radiances, and no background information is needed in MODIS/AIRS cloud-clearing. It is found that only ~13% of the AIRS footprints are clear and additional 21% of the AIRS footprints can be cloud cleared successfully (Rienecker et al. 2008). Global NWP assimilation experiments at NASA GMAO indicated that the cloud-cleared AIRS radiances provide useful sounding information beneath clouds and improve forecast skill in the troposphere (Rienecker et al. 2008; http://www.jcsda.noaa.gov/documents/seminardocs/GMAO_JCSDA_20080416.pdf).

We have investigated the assimilation of radiances in cloudy regions by imager/sounder cloud-clearing techniques (Li et al. 2005). The imager/sounder cloud-clearing is similar to AMSU/AIRS cloud-clearing for deriving the clear equivalent radiances, but retains the original IR sounder resolution, which is ideal for regional NWP applications. We have used AIRS in Sandy (2012) forecast experiments which are similar to that for better cloud detection.

Three experiments are conducted:

Exp 1 (GTS+AMSUA+AIRSrad (GSI)): assimilating conventional data, 4 AMSU-A from NOAA-15, NOAA-18, Aqua and Meteop-A, GSI stand-alone method is applied for AIRS cloud detection, only clear AIRS radiances are assimilated;

Exp 2 (GTS+4AMSUA+AIRSrad (MOD)): same as Exp1 but the collocated MODIS high resolution cloud mask is applied for AIRS cloud detection, only AIRS clear radiances are assimilated;

Exp 3 (GTS+4AMSU+AIRSrad (clrcld)): same as Exp2, but MODIS/AIRS cloud-cleared radiances over ocean are included in the assimilation.

Figure 9 shows the root mean square error (RMSE) of the hurricane track (HT) maximum wind speed (SPD) of 72-hour forecasts with GTS+AMSUA+AIRSrad (GSI) (blue), GTS+AMSUA+AIRSrad (MOD) (red), and GTS+AMSU+AIRSrad (clrcld) (green). It can be seen that the track forecast RMSE is reduced with addition of MODIS/AIRS cloud-cleared radiances assimilated for Sandy forecasts.

The impact from including cloud-cleared radiances on intensity forecasts is neutral for this particular case, those are preliminary results on using imager/sounder cloud-cleared radiances, and more investigations are ongoing. The GSI version 3.1 was used in the three experiments.

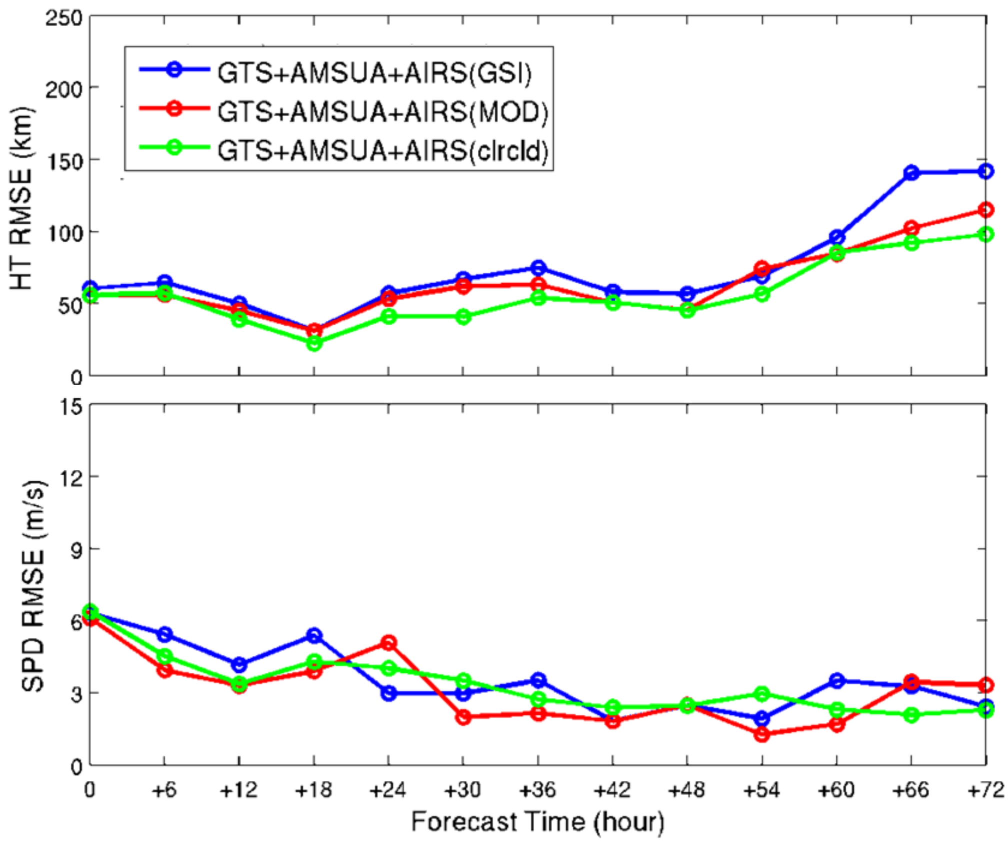

Figure 9. The RMSE of the hurricane track (HT) maximum wind speed (SPD) of 72-hour forecasts with GTS+AMSUA+AIRSrad (GSI) (blue), GTS+AMSUA+AIRSrad (MOD) (red), and GTS+AMSU+AIRSrad (clrcld) (green).

4. Relate Peer-reviewed Publications

Li, Jinlong, Jun Li, Pei Wang, 2014: A Near Real-Time Regional Satellite Data Assimilation System for High Impact Weather Research and Forecasts, *JCSDA Newsletter*, No. 46, March 2014 (http://www.jcsda.noaa.gov/documents/newsletters/201403JCSDAQuarterly.pdf).

Wang, Pei, Jun Li, Jinlong Li, Zhenglong Li, Timothy J. Schmit, and Wenguang Bai, 2014: Advanced infrared sounder subpixel cloud detection with imagers and its impact on radiance assimilation in NWP, *Geophysical Research Letters*, 41,1773- 1780, doi:10.1002/ 2013GL059067.

Zheng, J., Jun LI, Timothy J. SCHMIT, Jinlong LI, and Zhiquan LIU, 2014: The impact of AIRS atmospheric temperature and moisture profiles on hurricane forecasts: Ike and Irene, *Advances in Atmospheric Sciences* (accepted).