CIMSS near real time satellite data assimilation and forecast system for improving JPSS and GOES-R applications

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20 June 2016

JPSS/GOES-R Science Seminar

Acknowledgement:
JPSS PGRR, GOES-R HIW for funding support
Mark DeMaria, Jack Beven , Andrew Collard, and Vijay Tallapragada for guidance and feedback
Tim Schmit, Jinlong Li, Chris Barnet, Pei Wang, Agnes Lim, Zhenglong Li, Chris Velden, and Yong-Keun Lee for contributions

Outlines

- CIMSS real time SDAT (satellite data assimilation for tropical cyclone forecasts) system as research testbed for improving the utilization of satellite data in regional NWP
- Research progress on IR/MW sounder radiance assimilation with SDAT for tropical cyclone forecasts – JPSS applications
- Research progress on high temporal resolution water vapor information assimilation with SDAT for local storm forecasts – GOES-R applications
- SDAT real time demonstration and applications
  - Performs on 2015 hurricane season (evaluation and recommendation from NHC)
- Future plan

Motivation

- Most IR sounder data assimilation are limited in clear skies or clear channels, which limits the application in tropical cyclone (TC) and local storm forecasts with regional NWP, how to expand radiance assimilation into cloudy skies?
- High temporal resolution water vapor measurements from GOES-R are valuable source of information, how to better use such information in NWP for TC and local storm forecasts?

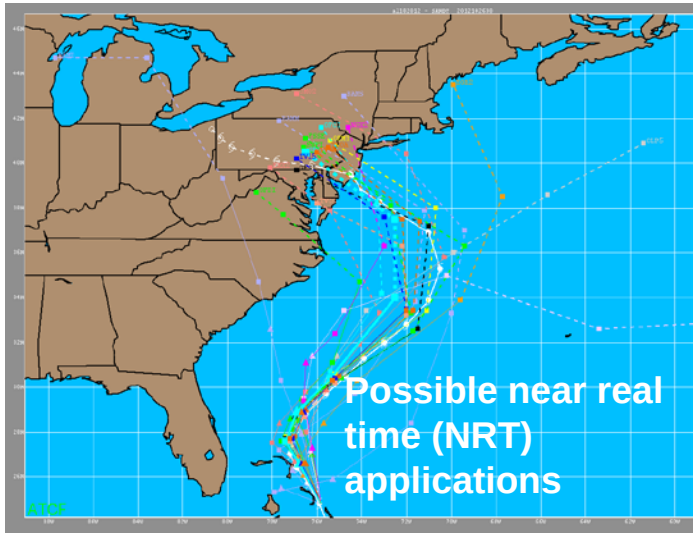
Satellite Data Assimilation for Tropical storms (SDAT)
(http://cimss.ssec.wisc.edu/sdat)

Real time SDAT
(http://cimss.ssec.wisc.edu/sdat)

Research path (R2A)

SDAT forecasts at CIMSS

Improving utilization of satellite data



Research testbed
for improving the utilization of GOES-R/JPSS data (Sounder and ABI, radiances, TPW, AMVs, Clouds)

R2O Research

Potential for operational NWP models:

GFS
HWRF
RAP/HRRR

Refining the Operational Path

Assimilation System and NWP Model for SDAT

Gridpoint Statistical Interpolation (GSI) v3.3:

- Unified variational data assimilation system for both global and regional applications
- Developed by NOAA NCEP based on the operational Spectral Statistical Interpolation analysis system.
- The core of the NDAS for NAM, GDAS for GFS at NOAA, and various operational systems.

Weather Research and Forecasting Model (WRF) v3.6:

- Next-generation mesoscale numerical weather prediction system
- Developed by NCAR, NOAA, AFWA, NRL, OU, and FAA.
- Applicable for both meteorological research and numerical weather prediction.
- 27 km for online real time SDAT (4 - 12 km for offline experiments). 18 km for SDAT is under testing

Community Radiative Transfer Model (CRTM) for DA:

- Fast radiative transfer model for calculation of radiances and Jacobians for satellite IR or MW radiometers.
- Developed by JCSDA as an important component in the NOAA/NCEP data analysis system.
- Implemented into GSI system as its radiative transfer model.

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- Research progress on IR/MW sounder radiance assimilation with SDAT for tropical cyclone forecasts – JPSS applications
  - Better IR/MW sounder sub-pixel clear detection for radiance assimilation with collocated imager cloud products
  - Assimilation of IR sounder thermodynamic information in partially cloudy skies
- Research progress on high temporal resolution water vapor information assimilation with SDAT for local storm forecasts – GOES-R applications
- SDAT real time demonstration and applications
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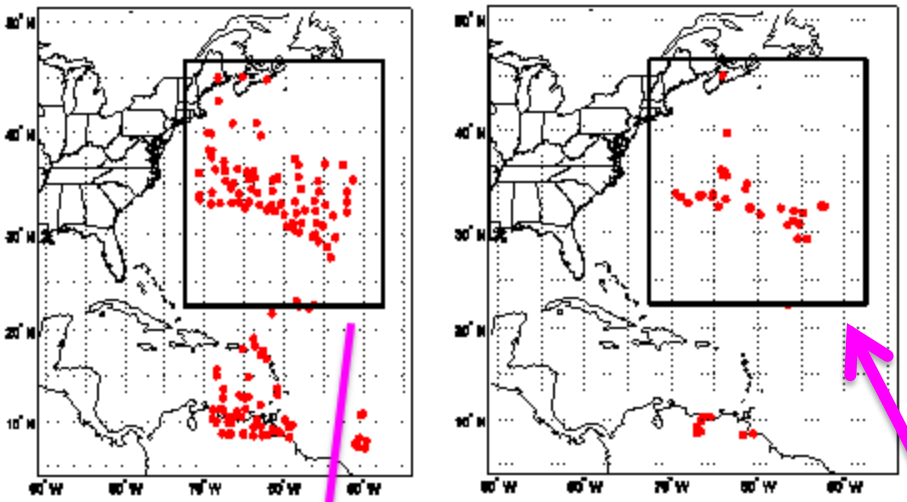
Research finding 1: IR/MW sounder sub-pixel cloud detection with collocated imager cloud mask improves radiance assimilation

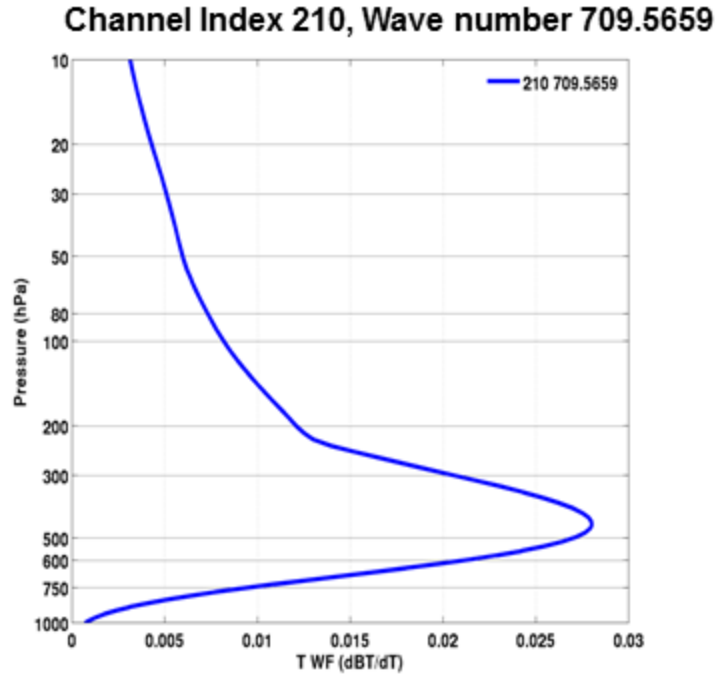
AIRS, AMSU with MODIS
CrIS, ATMS with VIIRS
IASI, AMSU with AVHRR

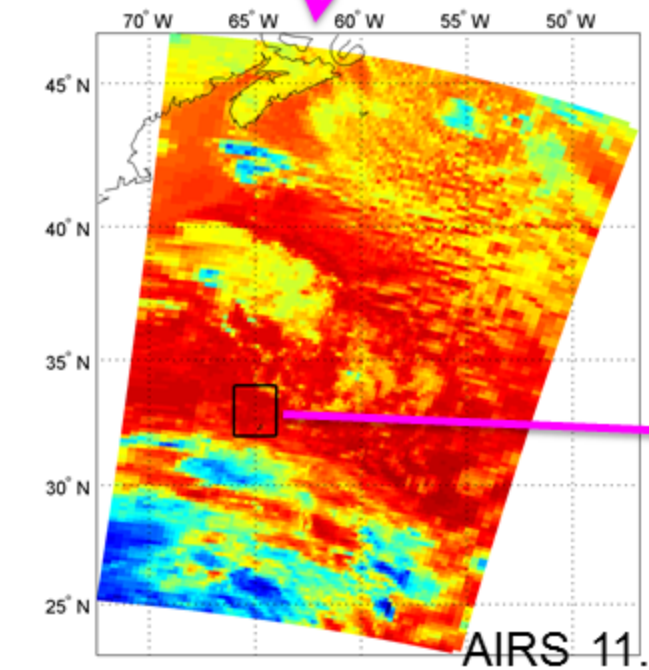
GSI cloud detection

MODIS cloud detection

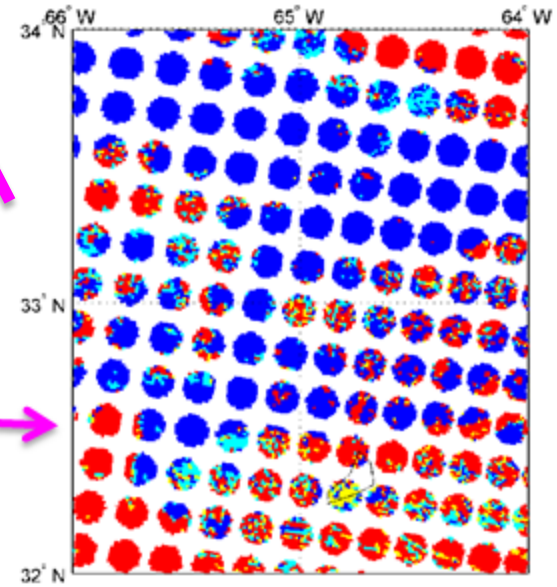


AIRS data at 06 UTC 25 October 2012 (Sandy)

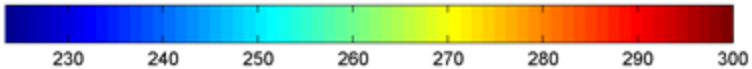




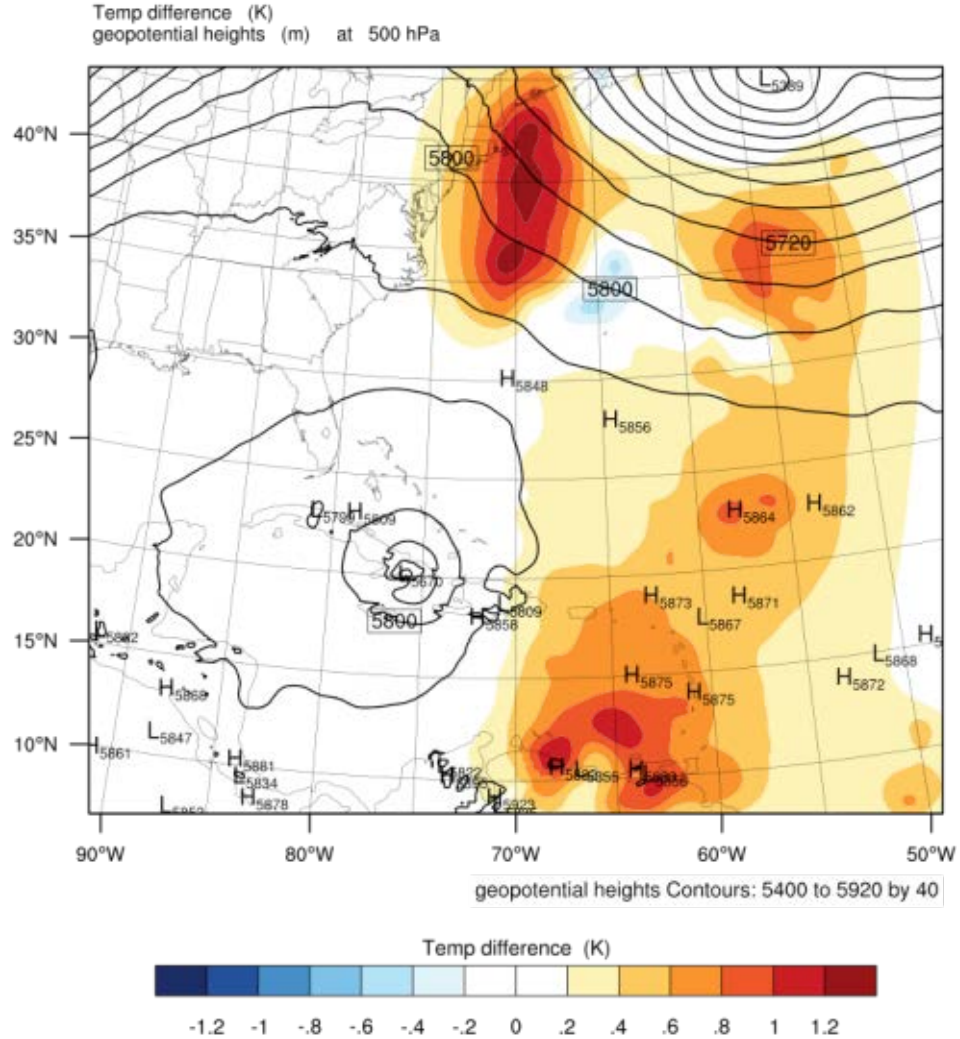
Wang et al. (2014, GRL)



AIRS 11.3 μm BT (K)



AIRS sub-pixel cloud detection with MODIS



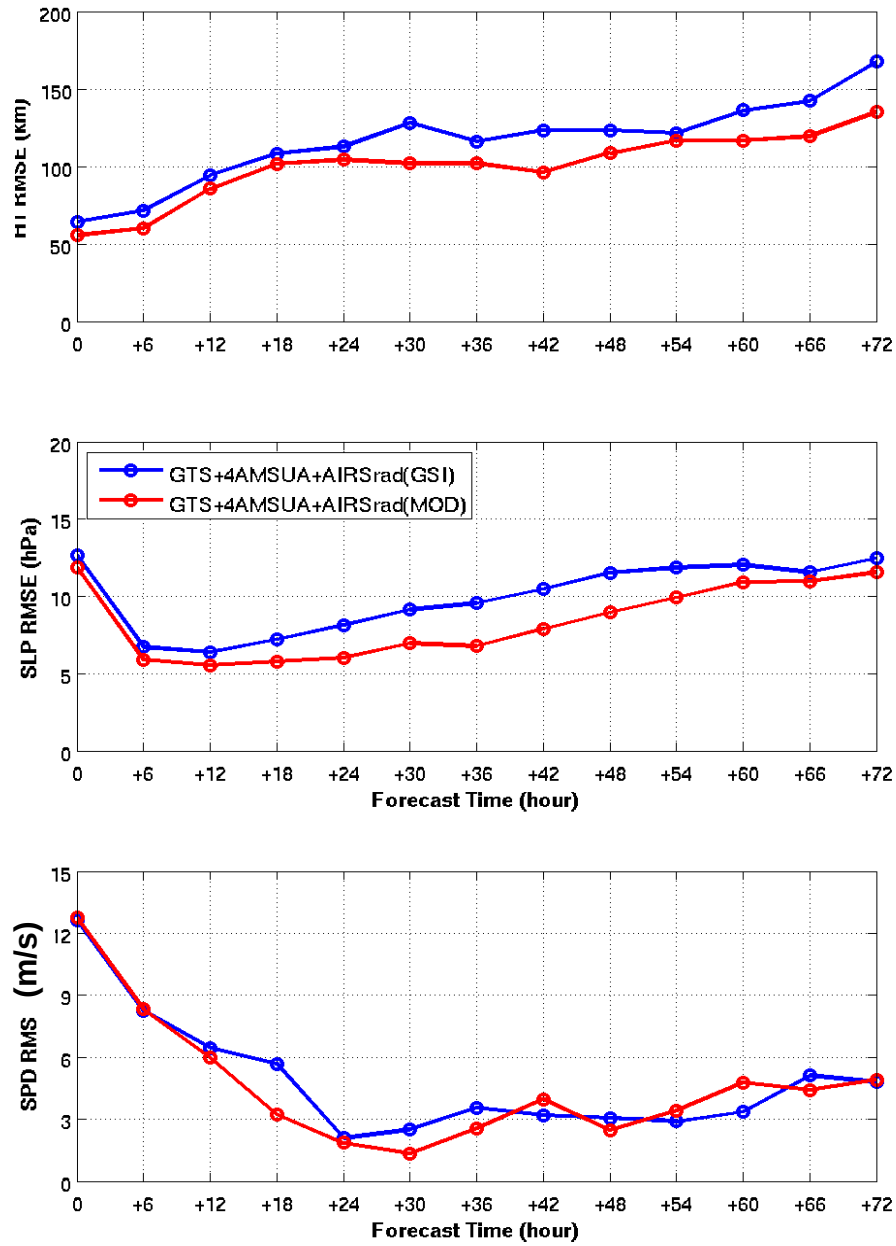
500 hPa temperature analysis difference

(AIRS(MOD) - AIRS(GSI))

Hurricane Sandy (2012)

- Assimilation : Oct 25 06z to Oct 27 00z, 2012
- Forecasts: Oct 25 06z to Oct 30 00z, 2012
- Assimilation every 6 hour

Hurricane Sandy (2012) forecast RMSE

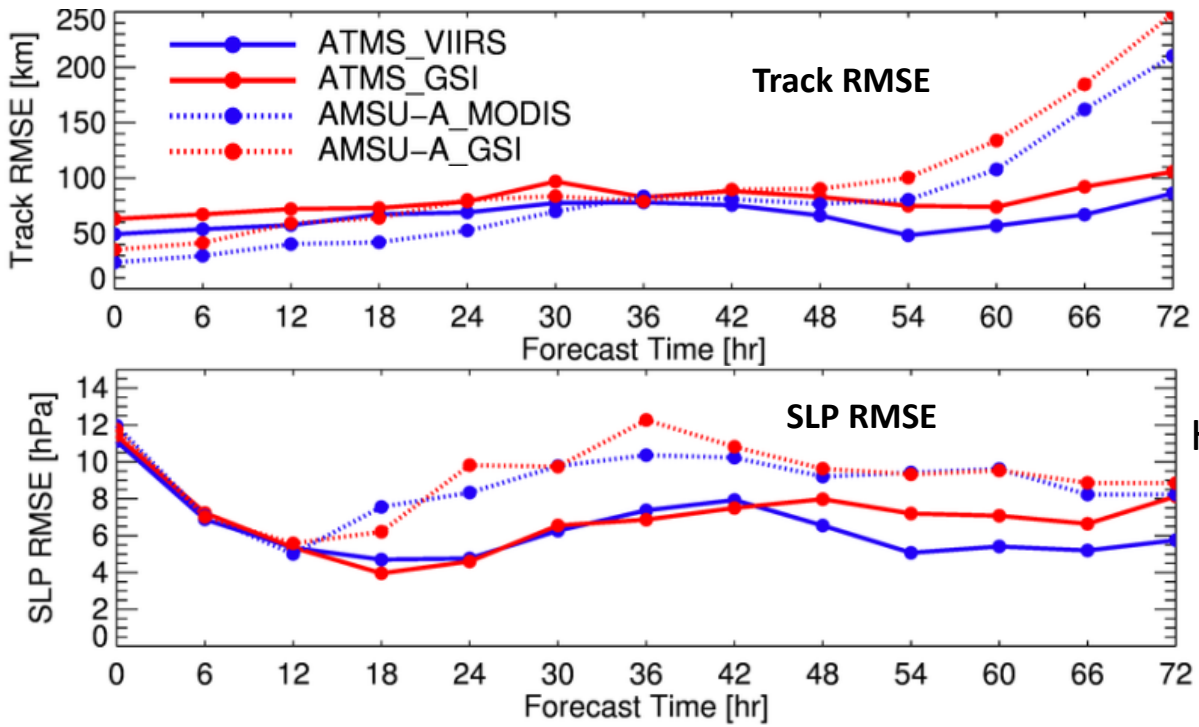


72-hour forecasts of Sandy from 06z 25 to 00z 30 Oct, 2012

Microwave sounder sub-pixel cloud detection with imager – a little complicated

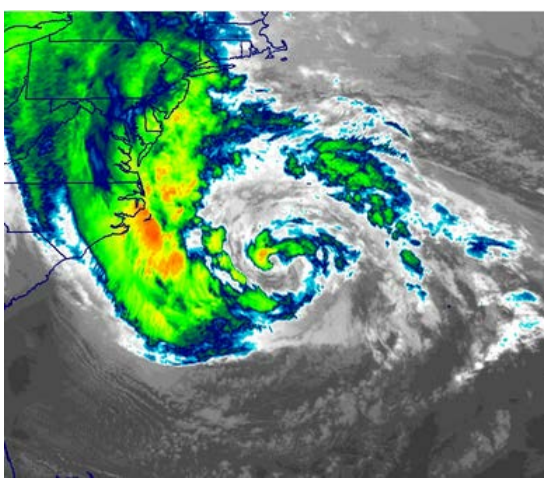
- Unlike IR sounder and imager, MW sounder and IR imager see clouds differently;
- Possible imager (e.g., AVHRR, MODIS, VIIRS) cloud products for MW sounder (e.g., AMSU-A, ATMS) sub-pixel cloud-screening
  - Cloud-top height
  - **Cloud cover (30% for AMSU-A, 70% for ATMS) (Han et al. 2016, MWR)**
  - Cloud optical thickness

Microwave sounder sub-pixel cloud characterization with imager cloud product



Han et al. 2016 - MWR

Hurricane Sandy (2012) forecast RMSE from 8 forecast groups.



GOES-13 10.7 μm

(1) ATMS (solid lines) performs better than Aqua/AMSU-A (dashed lines) for Hurricane Sandy (2012) forecasts; (2) MW sounder sub-footprint cloud characterization with imager cloud products (blue lines) improves GSI cloud detection (red lines) for radiance assimilation, which has the potential for operational use.

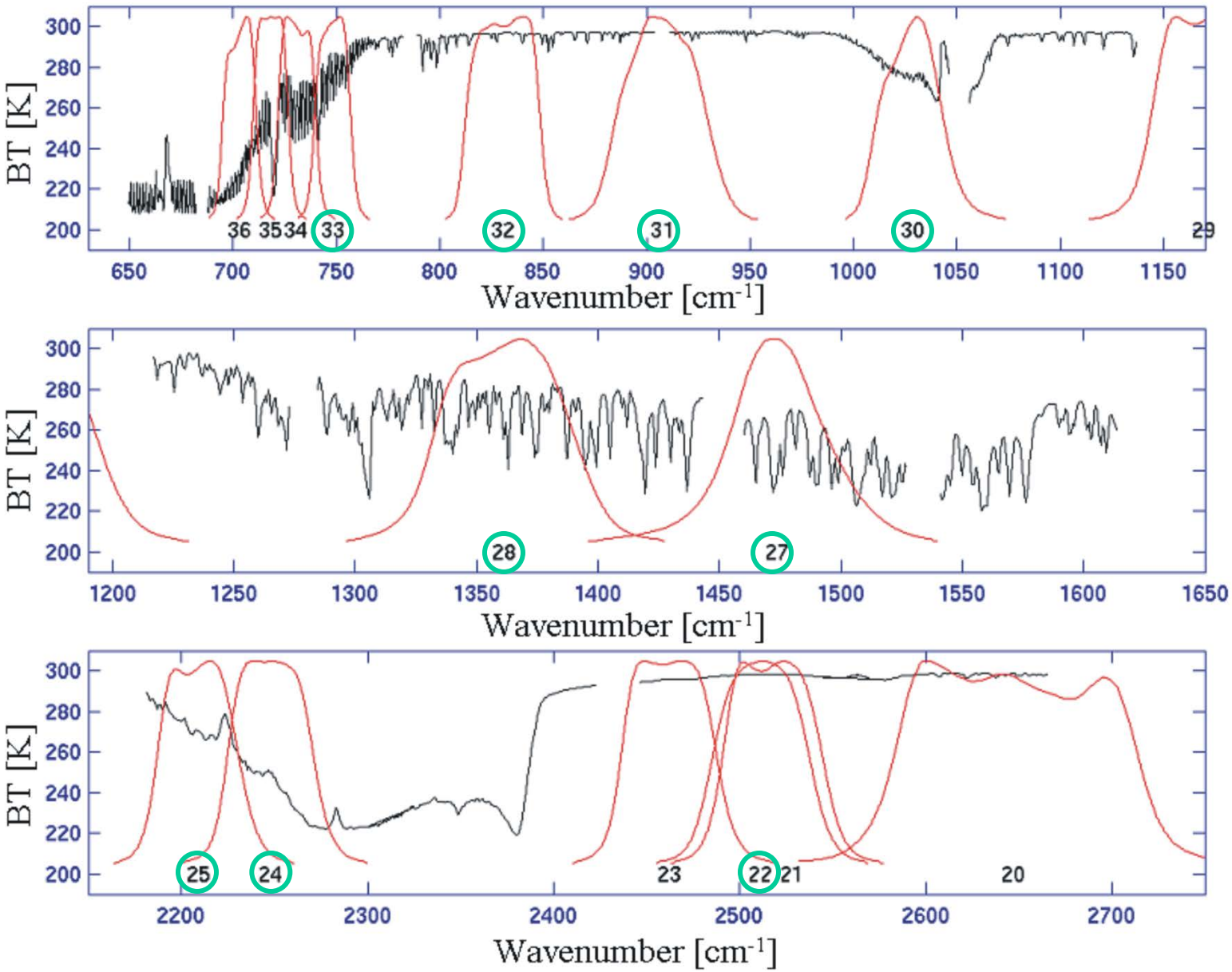
Research finding 2: Cloud-clearing can be an alternative approach for assimilating IR sounder thermodynamic information in partially cloudy skies:

(1) Based on accurate clear location detection

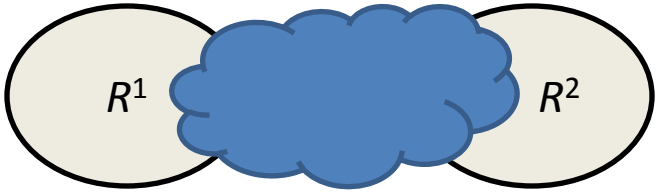
(2) Needs additional information to help. Three cloud-clearing approaches ongoing:

- Imager-based IR sounder CCRs (CIMSS approach, keep IR sounder single FOV)
- MW-based CCRs (NUCAPS approach, degraded to MW footprint)
- Background-based CCRs (EMC approach, relies on background)

Aqua MODIS IR SRF Overlay on AIRS Spectrum



Direct spectral relationship between IR MODIS and AIRS provides unique application of MODIS in AIRS cloud_clearing !



AIRS/MODIS cloud-clearing (Li et al.2005)

$$J(N^*) = \sum_i \frac{1}{\sigma_i^2}[(R_{M_i}^{clr} - f_i(R_\nu^{cc}))]^2 = \min$$

$$J(N^*) = \sum_i \frac{1}{\sigma_i^2}[(R_{M_i}^{clr} - f_i(\frac{R_\nu^1 - R_\nu^2 N^*}{1 - N^*}))] = \min$$

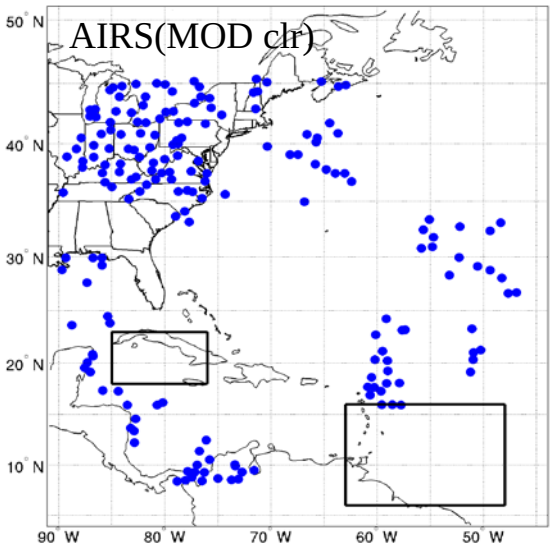
σ_i is NEdR for MODIS band

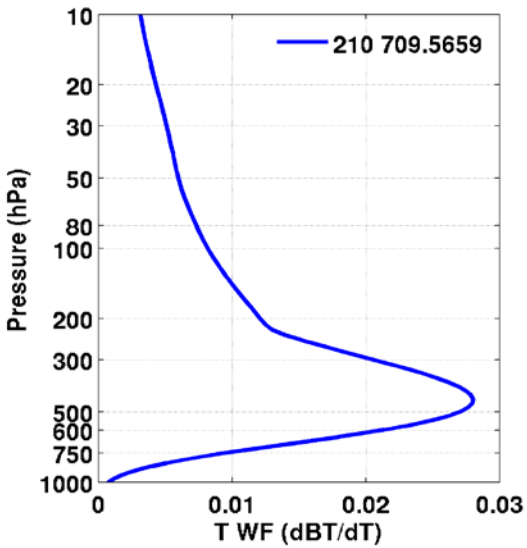
solve $\frac{\partial J(N^*)}{\partial N^*} = 0$ ⇒

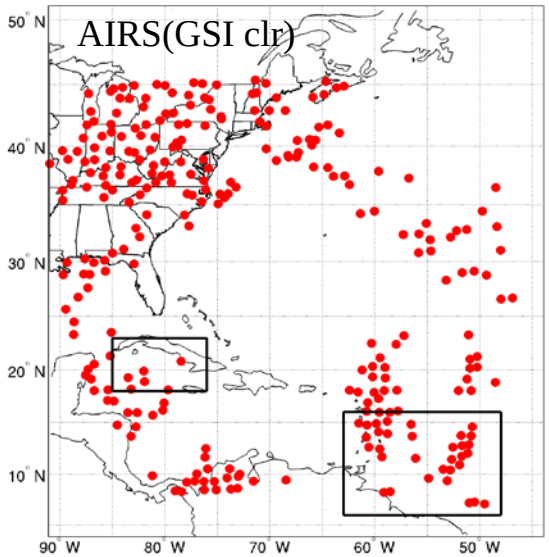
$$N^* = \frac{\sum_i \frac{1}{\sigma_i^2}[f_i(R_\nu^1) - R_{M_i}^{clr}][f_i(R_\nu^1) - f_i(R_\nu^2)]}{\sum_i \frac{1}{\sigma_i^2}[f_i(R_\nu^2) - R_{M_i}^{clr}][f_i(R_\nu^1) - f_i(R_\nu^2)]}$$

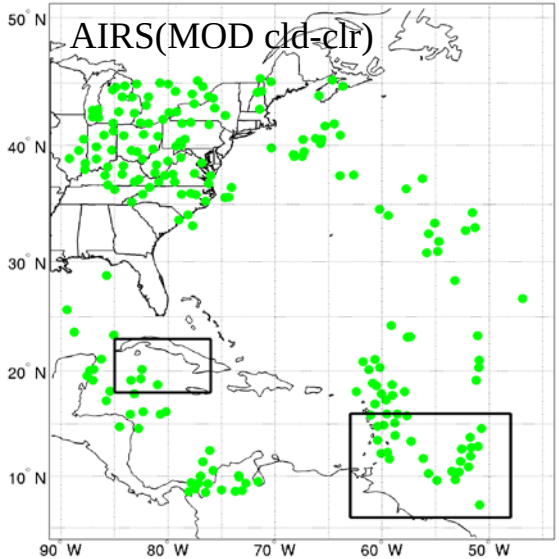
$$R_\nu^{cc} = \frac{R_\nu^1 - R_\nu^2 N^*}{1 - N^*}$$

Using cloud-cleared radiances for assimilation







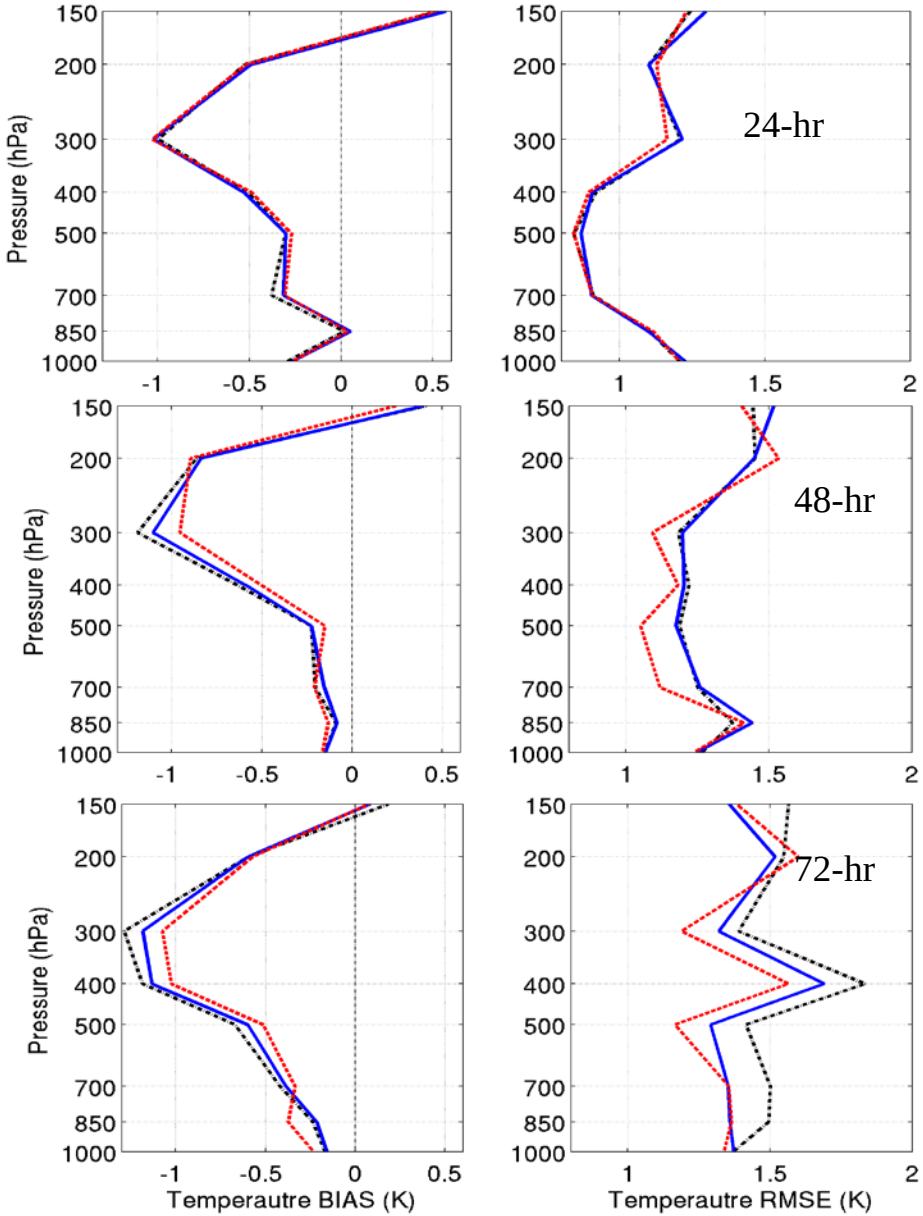


AIRS data locations at 18z 25, Oct 2012

- Data in cloudy regions according to MODIS cloud mask are assimilated as clear-sky in GSI, which contains cloud contamination.
- Cloud-clearing method generates clear equivalent radiances for assimilation in partially cloudy regions.
- Cloud-cleared radiances removes the cloud contamination and provides more clear equivalent radiances.

Wang et al. 2014 - GRL

Impact of assimilating cloud-cleared radiances on forecasts



BIAS and RMSE for 24-hour forecasts, 48-hour forecasts and 72-hour forecasts of temperature profiles between the AIRS (GSI clr) and radiosondes, AIRS (MOD clr) and radiosondes, and AIRS (MOD cld-clr) and radiosondes

- At 24-hour forecast, the difference of temperature BIAS among the three experiments is less than 0.1K.
- At 48-hour forecast, from 500 hPa to 200 hPa, the BIAS of AIRS (MOD cld-clr) is 0.2K smaller than that of AIRS (MOD clr) and AIRS (GSI clr).
- At 72-hour forecast, BIAS and RMSE of AIRS (MOD cld-clr) is smallest.
- The RMSE also increased with forecast hours, which is consistent with the model errors growing over time.

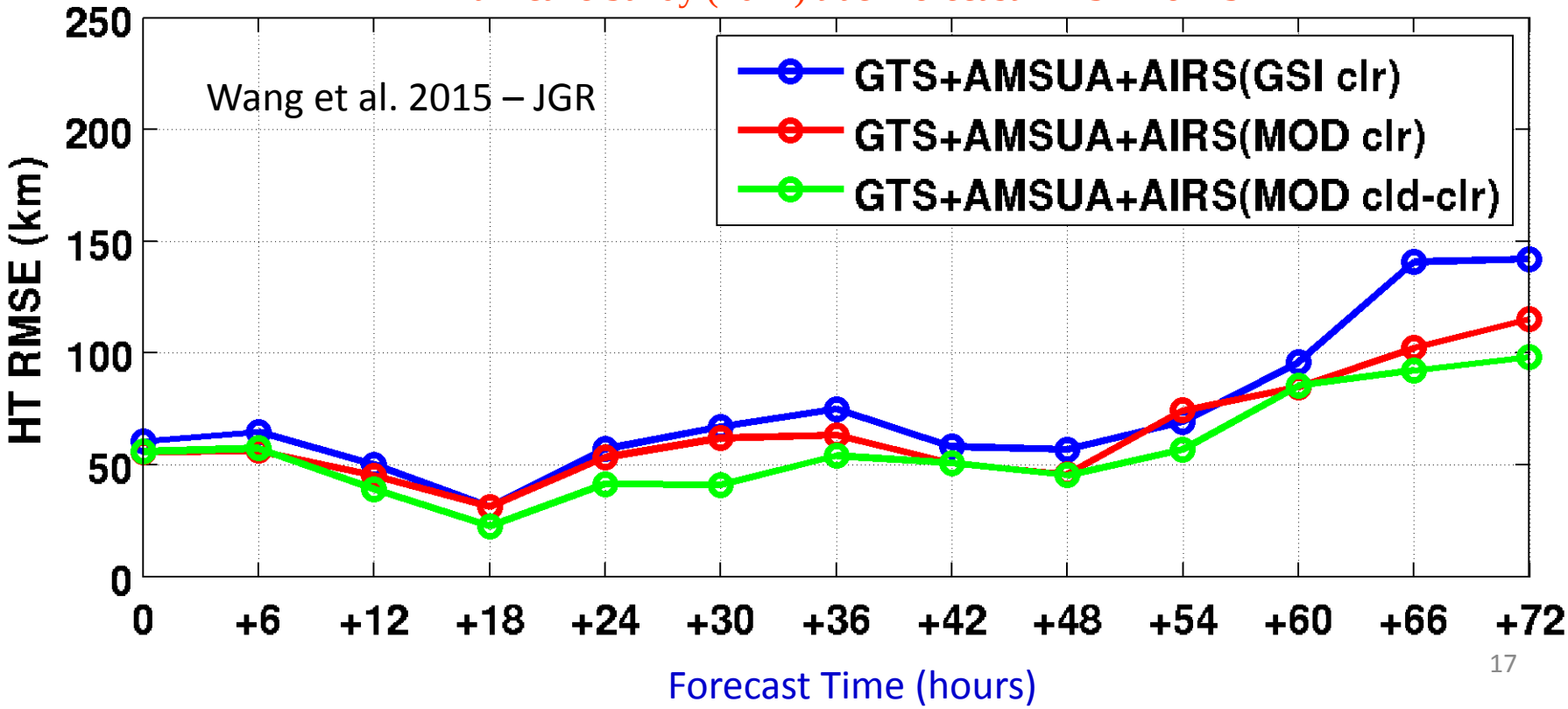
Wang et al. 2015 - JGR

Impact of assimilating imager based cloud-cleared radiances (CCRs) on forecasts

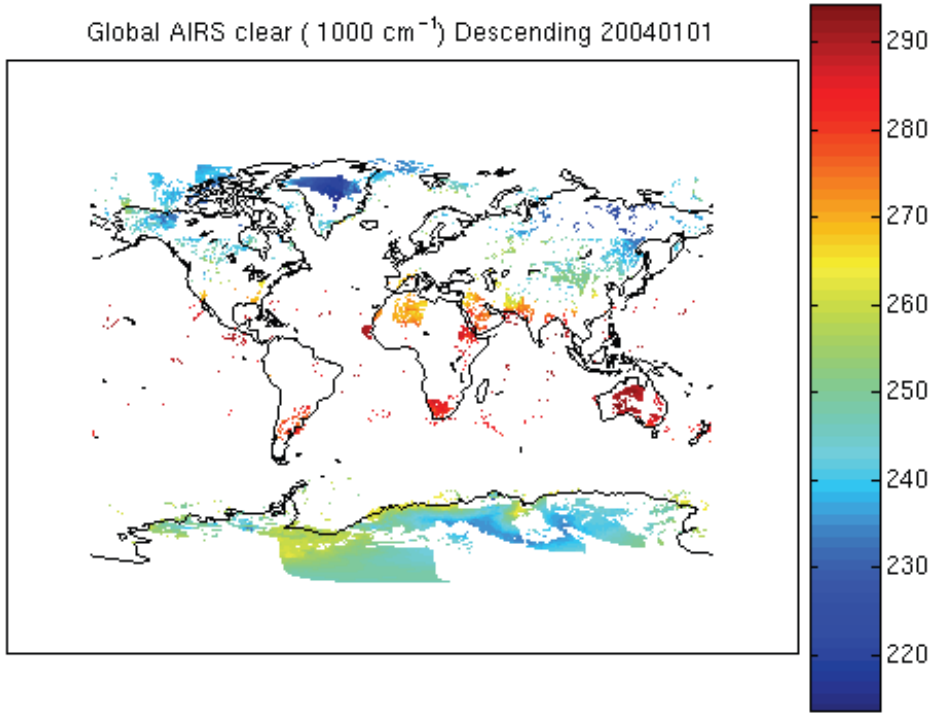
GTS: Conventional data
AMSUA: 4 AMSU-A radiances from NOAA-15,-18, Metop-A and Aqua

AIRS (GSI clr): AIRS clear location radiances detected from GSI
AIRS (MOD clr): AIRS clear location radiances detected by MODIS
AIRS (MOD cld-clr): AIRS clear location radiances detected by MODIS, plus AIRS cloud-cleared radiances (imager based)

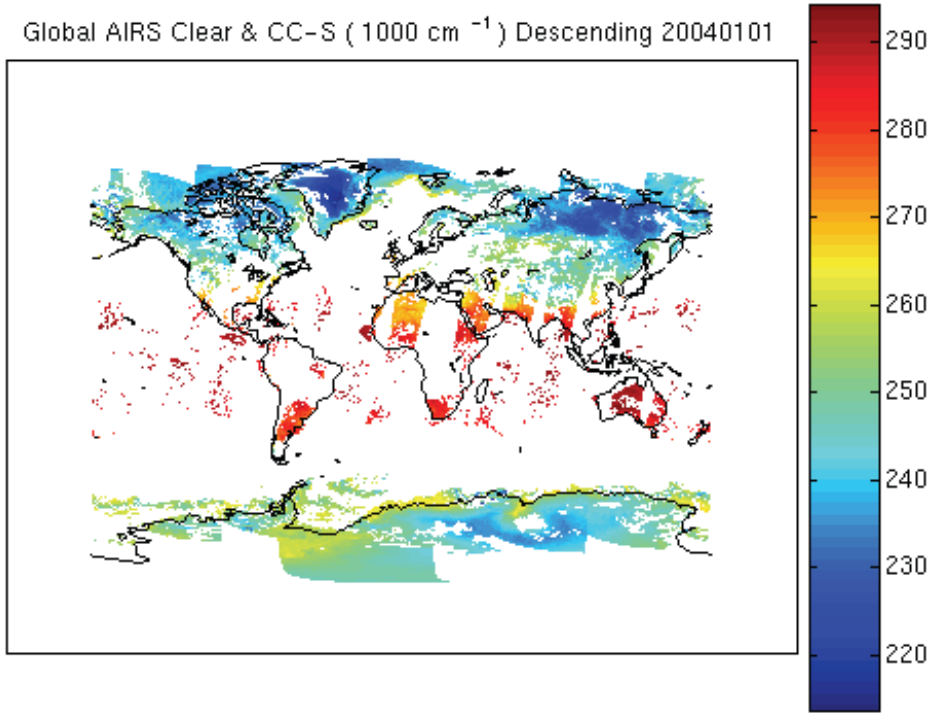
Hurricane Sandy (2012) track forecast RMSE from SDAT



AIRS clear coverage

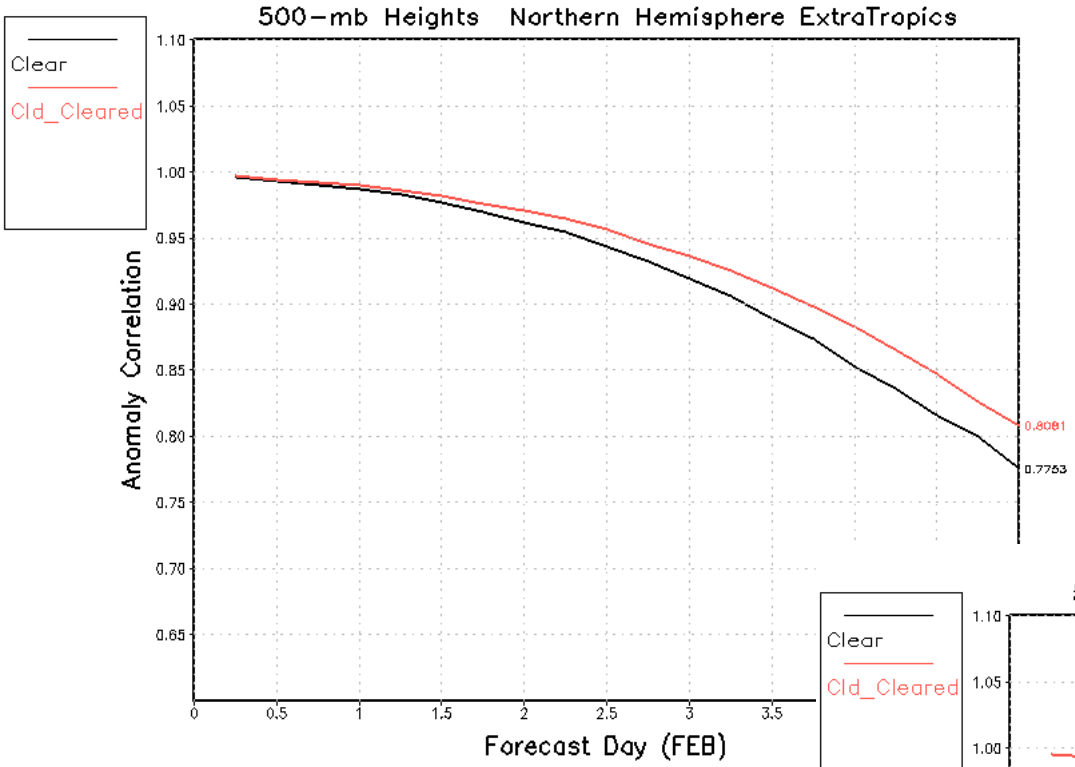


AIRS clear + cloud-clearing coverage

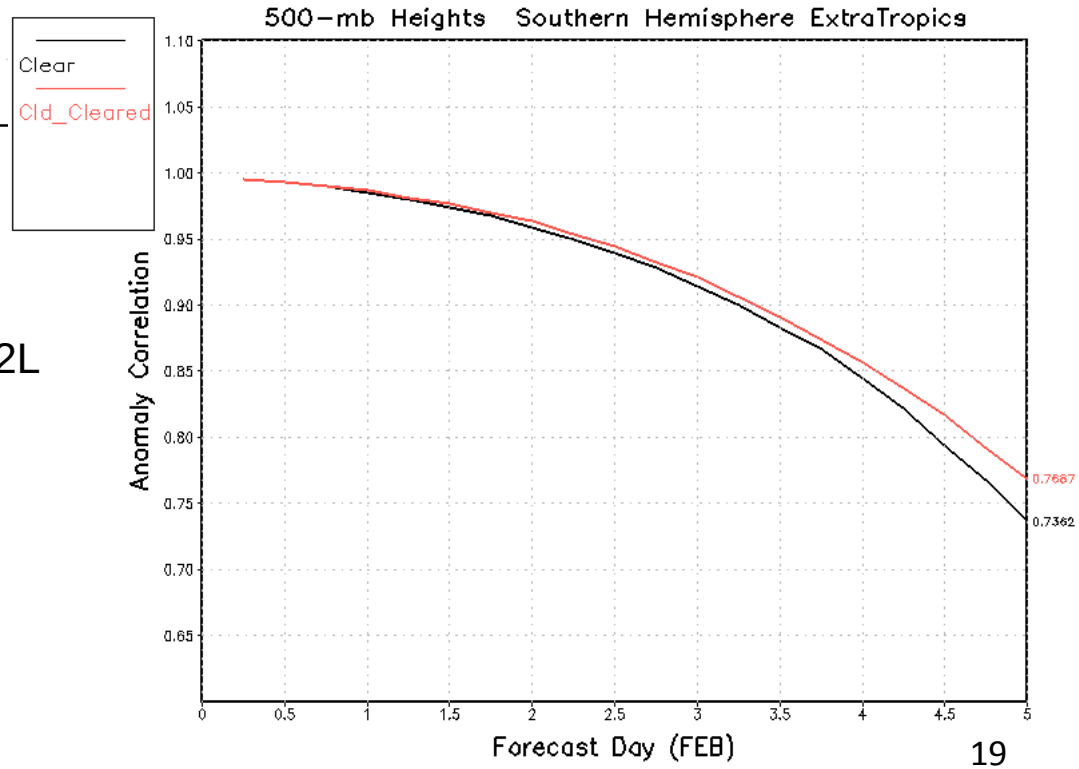


AIRS global clear and cloud clearing brightness temperature (descending) on Jan. 1, 2004.

Zhang et al. (2010)

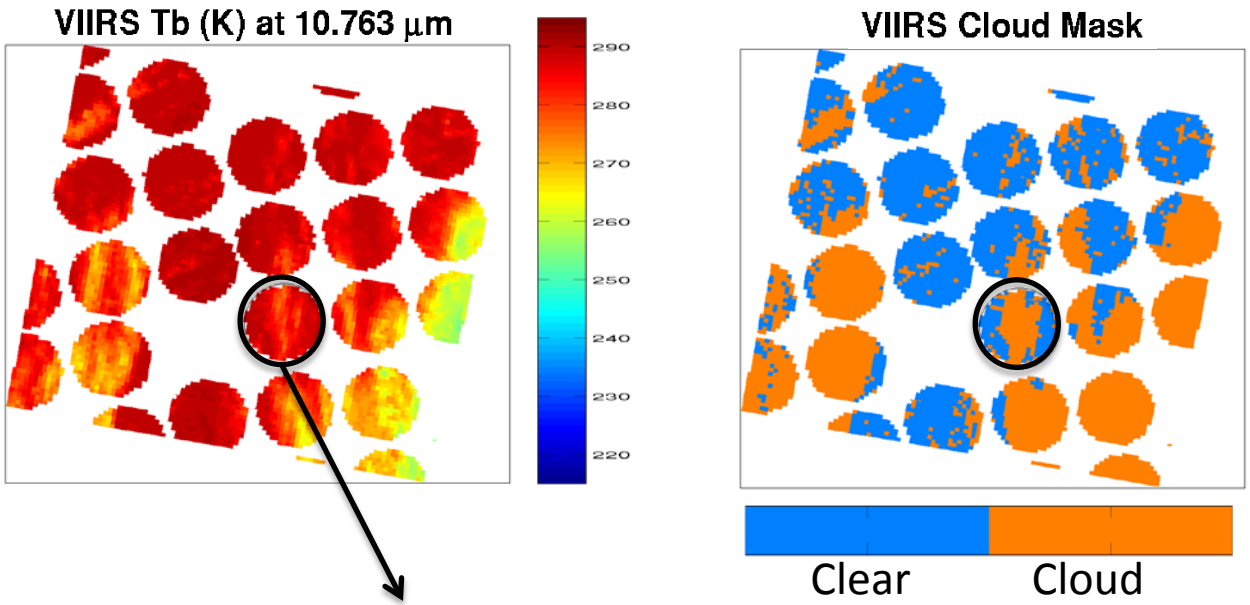


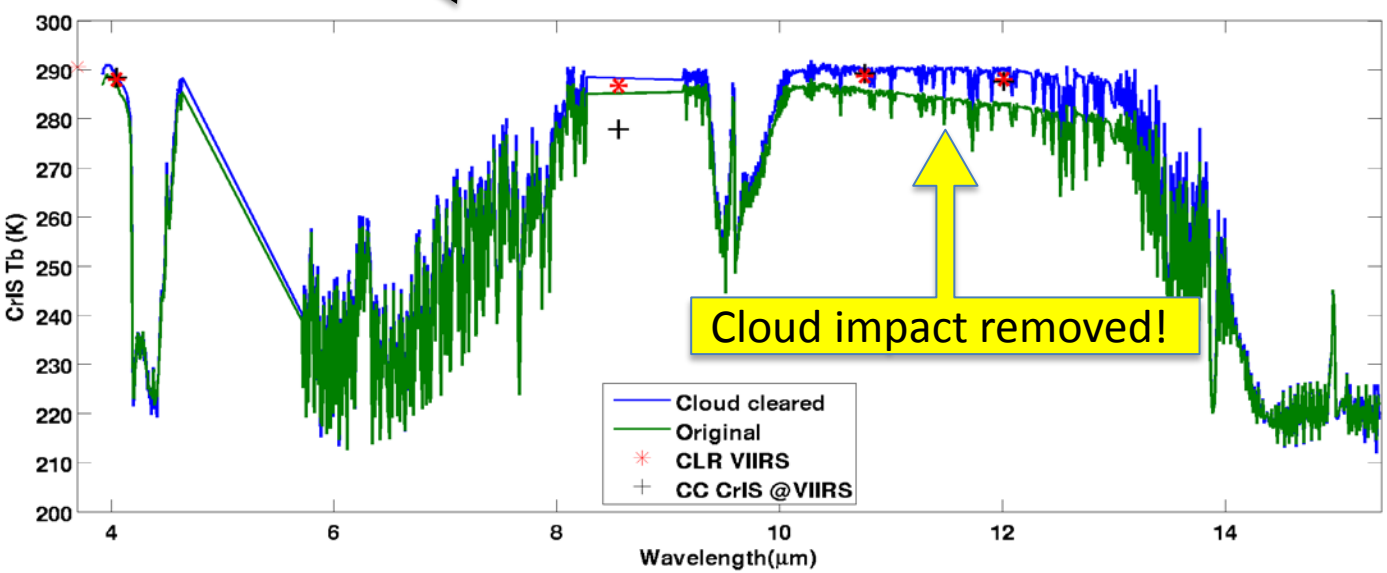
Rienecker et al. (2008): GMAO's Atmospheric Data Assimilation Contributions to the JCSDA and future plans, *JCSDA Seminar*, 16 April 2008.



- GEOS-5 model resolution: 1° x1.25° x72L
- Time frame: Jan 01 to Feb 15 2004
- Other Radiance data:
  - HIRS-2/HIRS3 (clear channels)
  - AMSU-A/EOS-AMSU-A
  - AMSU-B/MHS
  - SSM-I
  - GOES Sounders

CrIS/VIIRS cloud clearing case demonstration





- VIIRS cloud mask identifies partially cloudy FOVs **(black circle)**
- VIIRS radiances help quality control cloud cleared CrIS radiances
- Only three VIIRS bands (4.05, 10.763, and 12.013 um) used (overlapped with CrIS)
- Cloud cleared radiances very close to VIIRS clear sky radiances
- 14 % of partially cloudy FOVs are successfully cloud cleared for Hurricane Joaquin

CLR VIIRS: mean clear sky VIIRS radiances
CC CrIS @VIIRS: cloud cleared CrIS radiances converted to VIIRS spectrum

Noise estimation and QC

Based on $R_\nu^{cc} = \dfrac{R_\nu^1 - R_\nu^2 N^*}{1 - N^*}$

The noise for cloud cleared radiance is

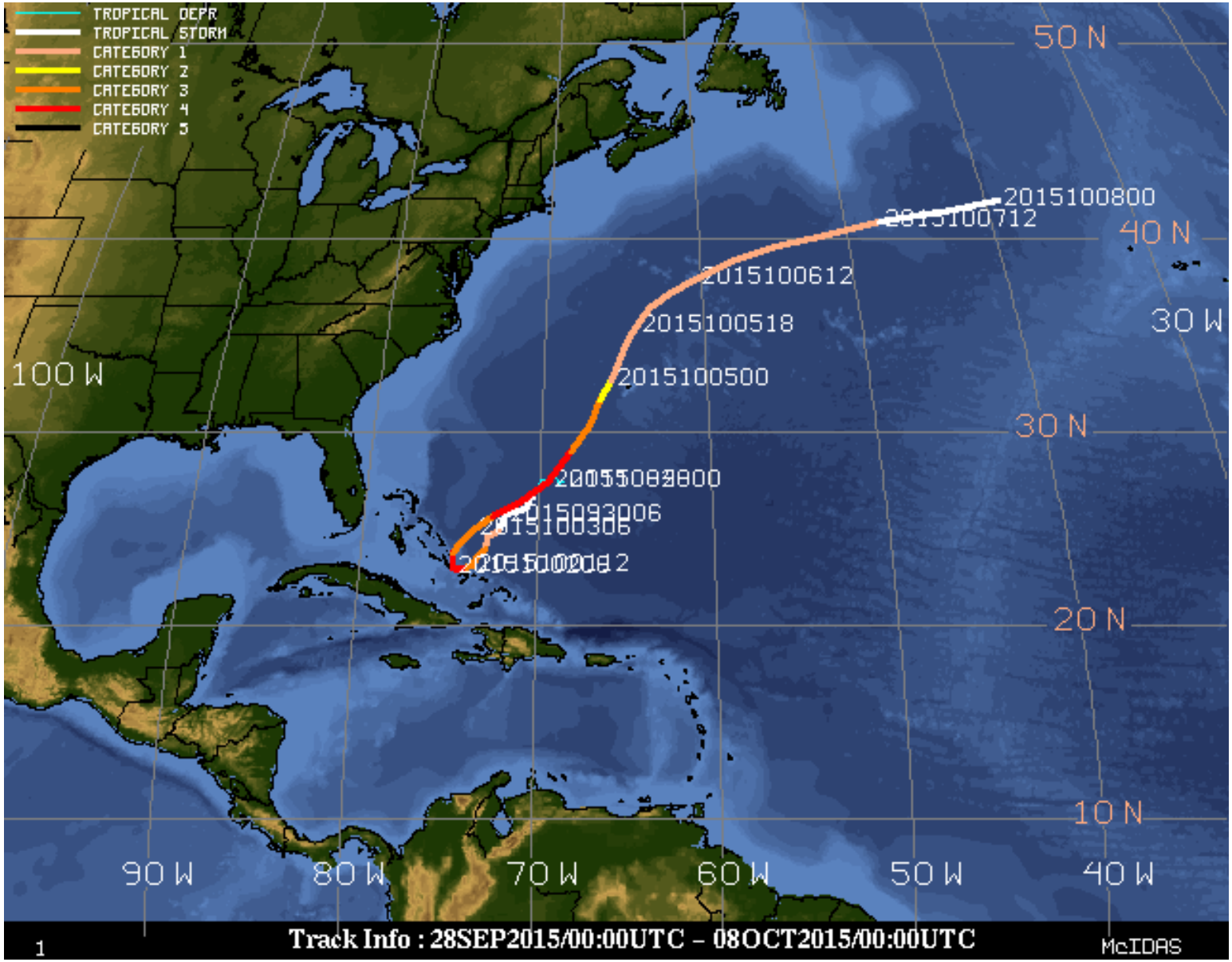
$$\sigma = \delta \sqrt{\frac{1 + N^{*2}}{(1 - N^*)^2}}$$

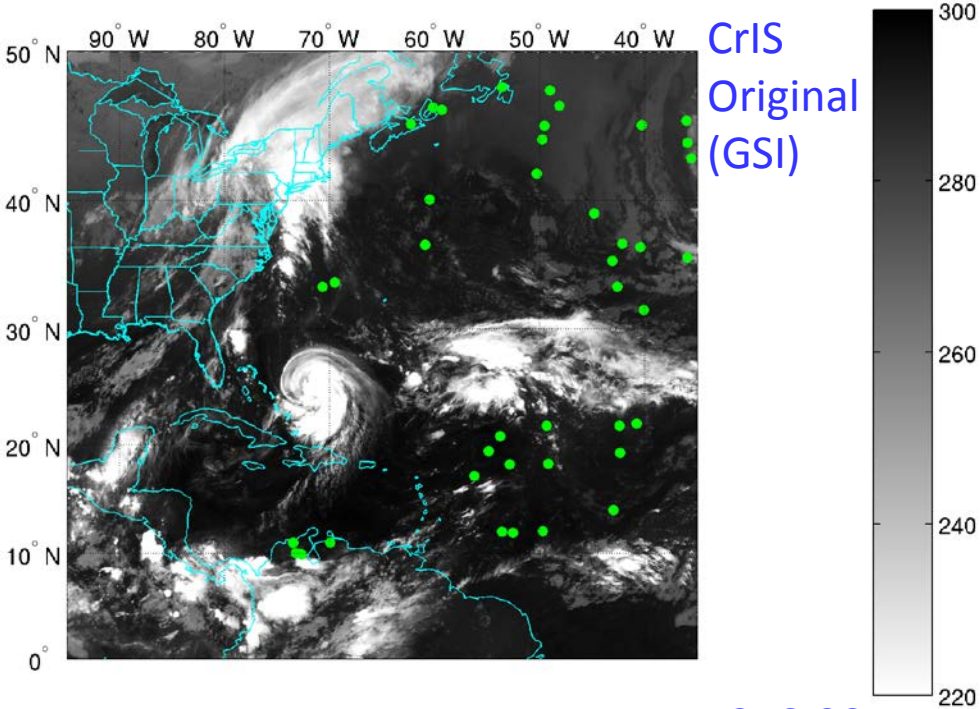
Where σ is the cloud cleared radiance noise, and δ is the original observation noise.

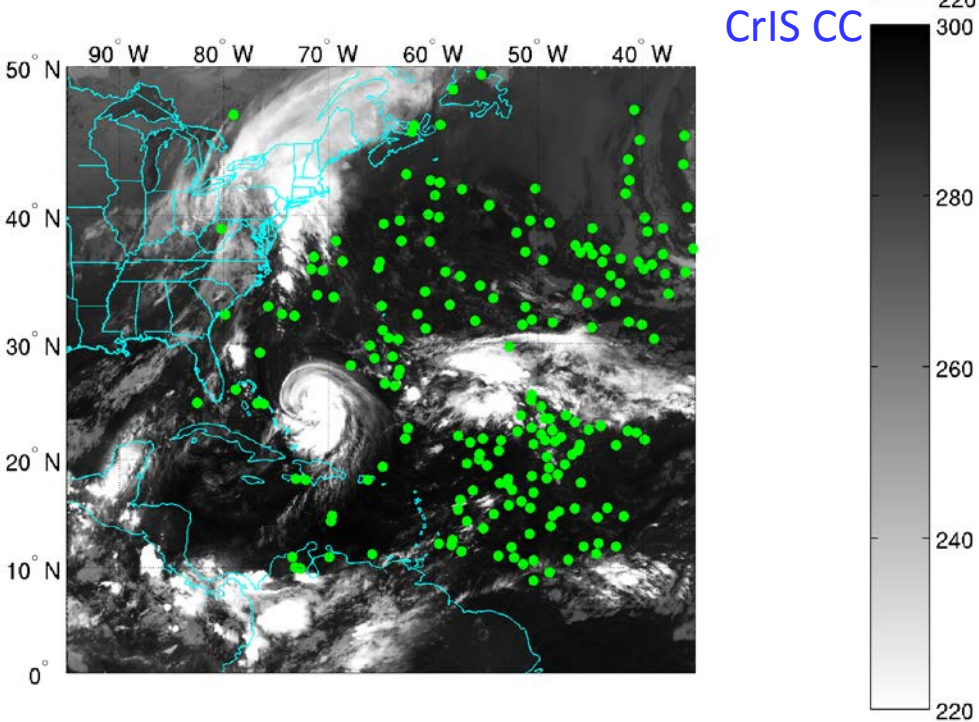
$N^*=0.5$, $\sigma = 2.24\ \delta$ ---- too much noise!

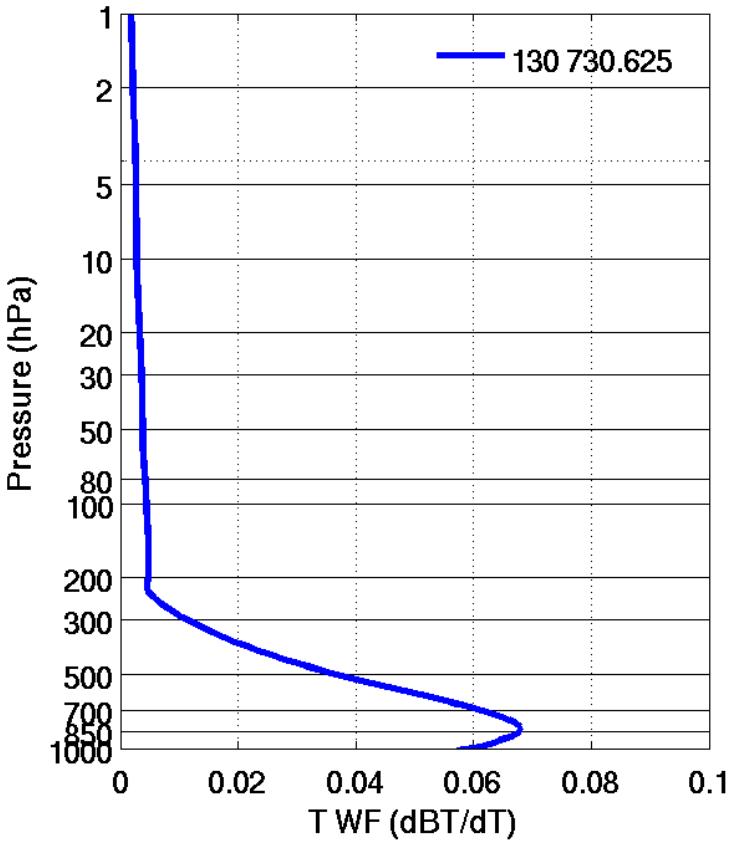
$N^*=0.25$, $\sigma = 1.37\ \delta$ ---- acceptable!

Hurricane Joaquin Best track



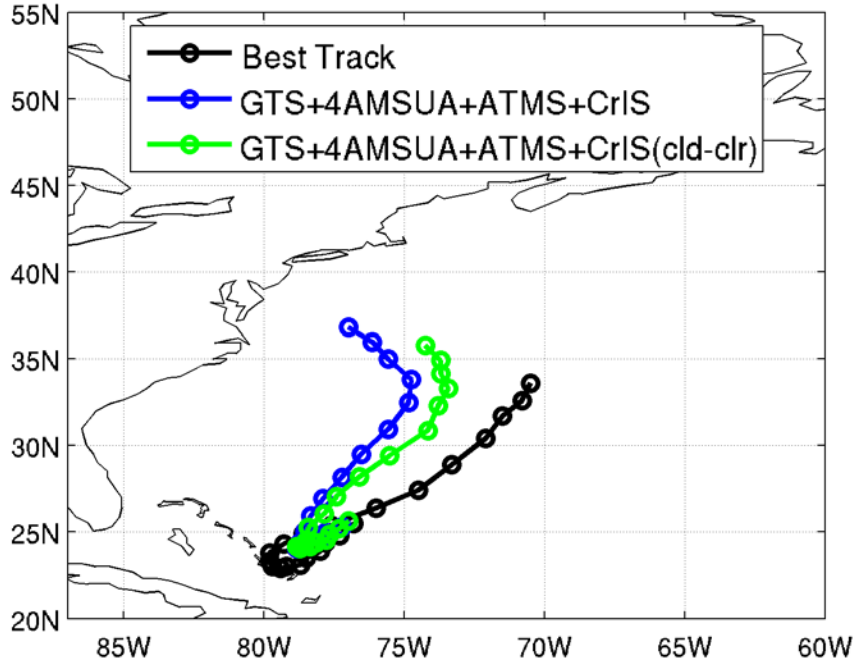




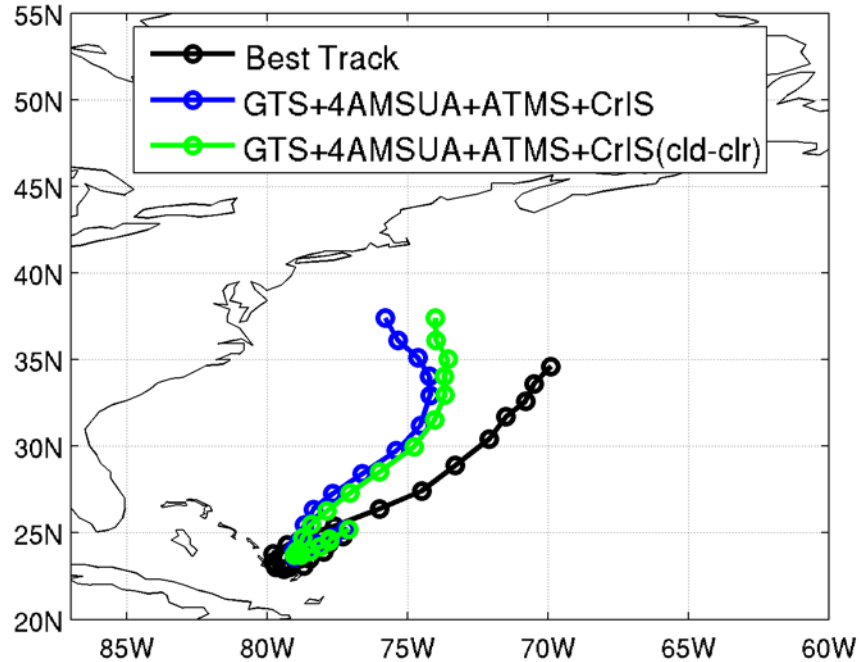


2015-9-30 0600z
Channel 130

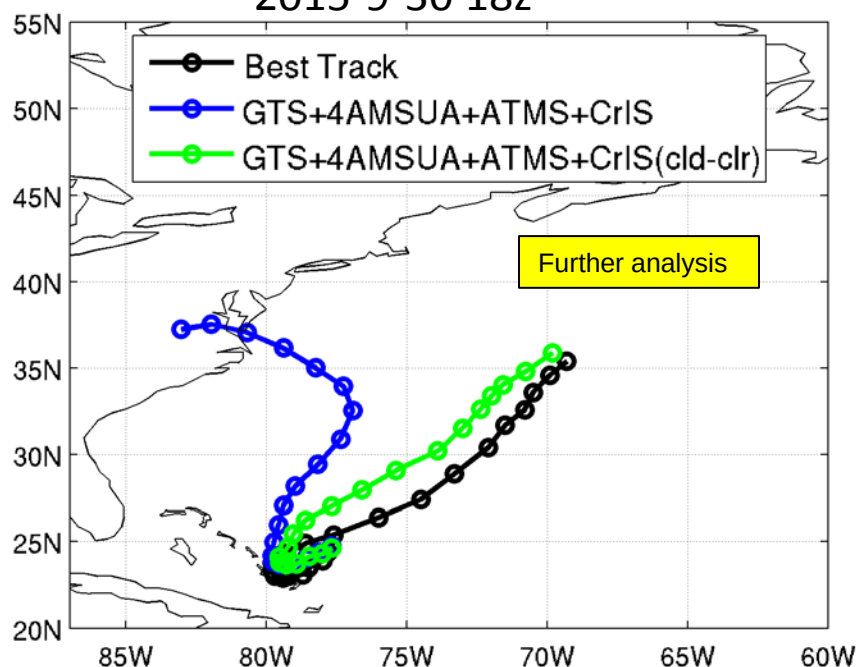
2015-9-30 06z



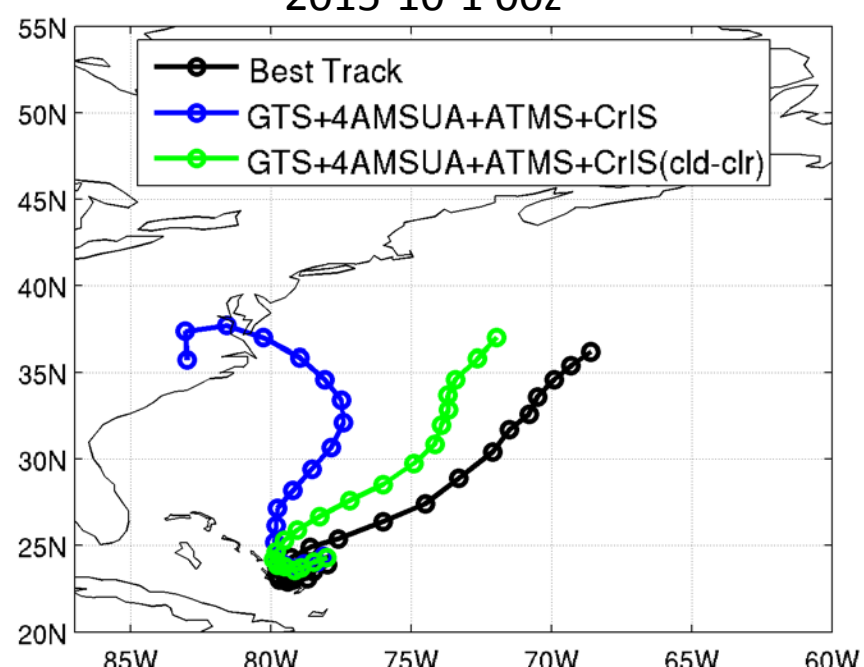
2015-9-30 12z



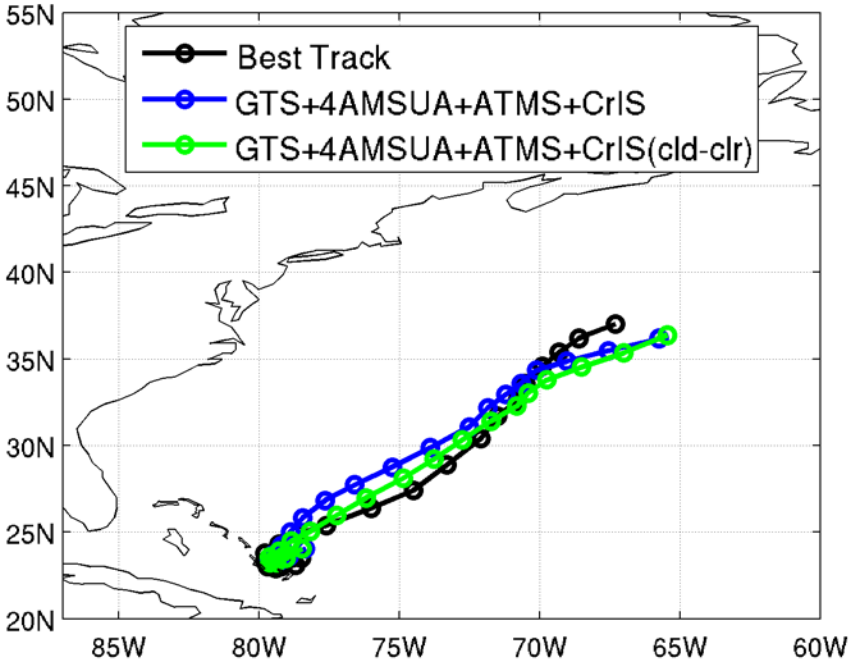
2015-9-30 18z



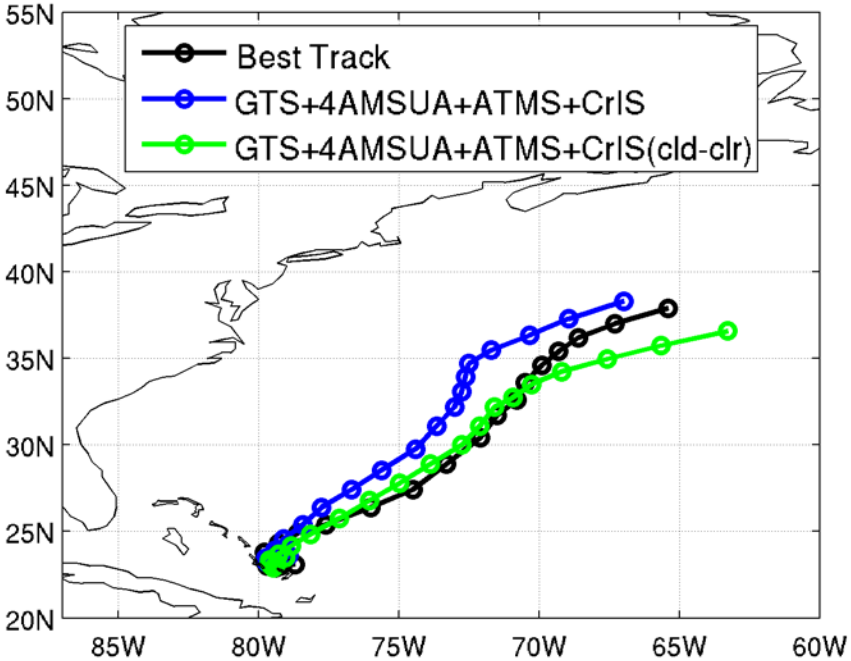
2015-10-1 00z



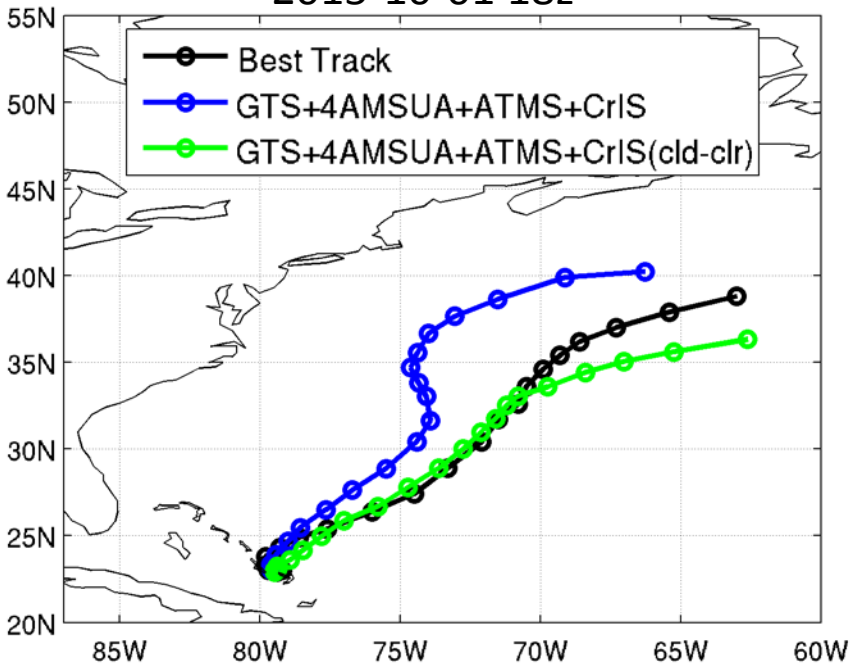
2015-10-01 06z



2015-10-01 12z

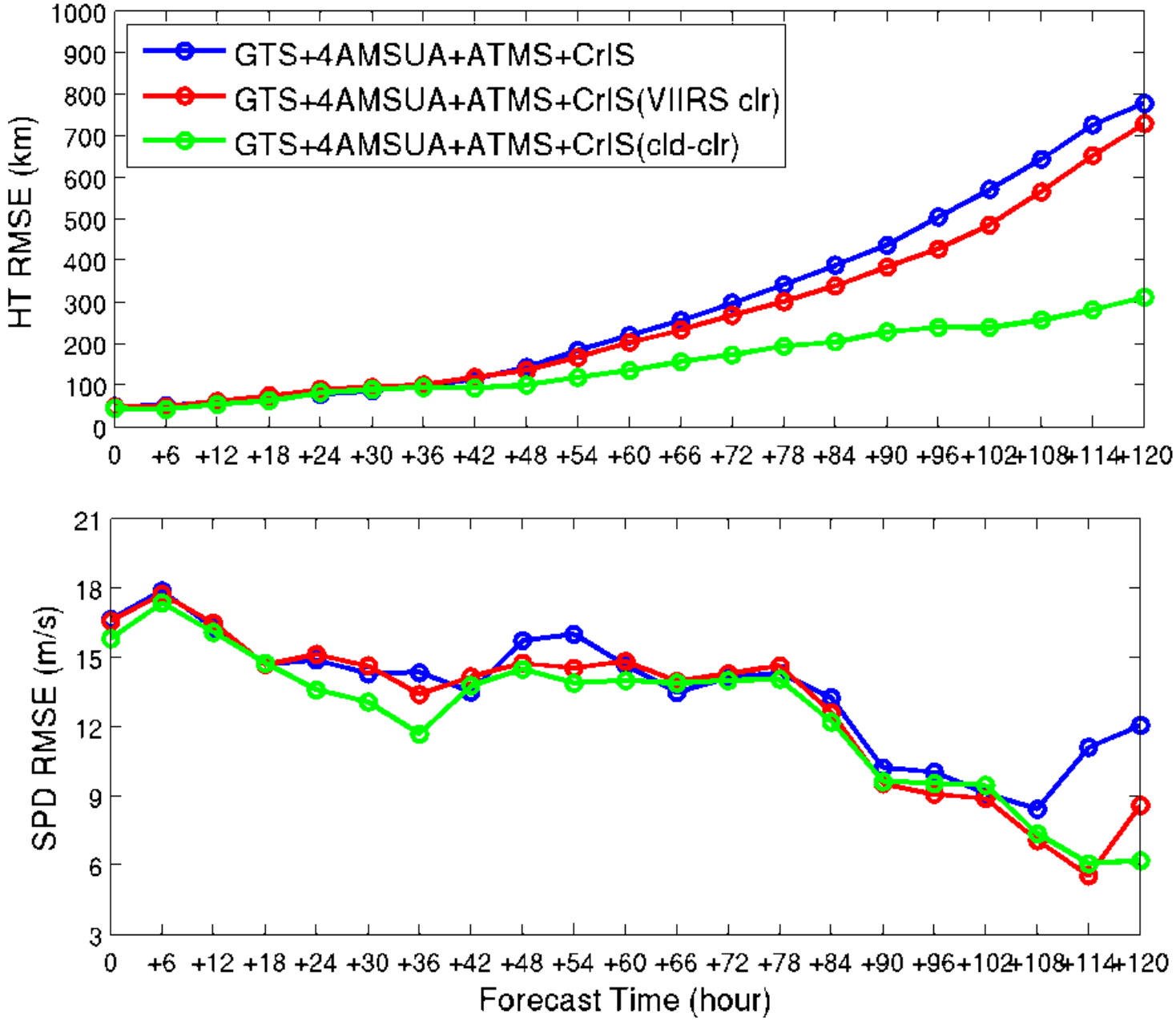


2015-10-01 18z



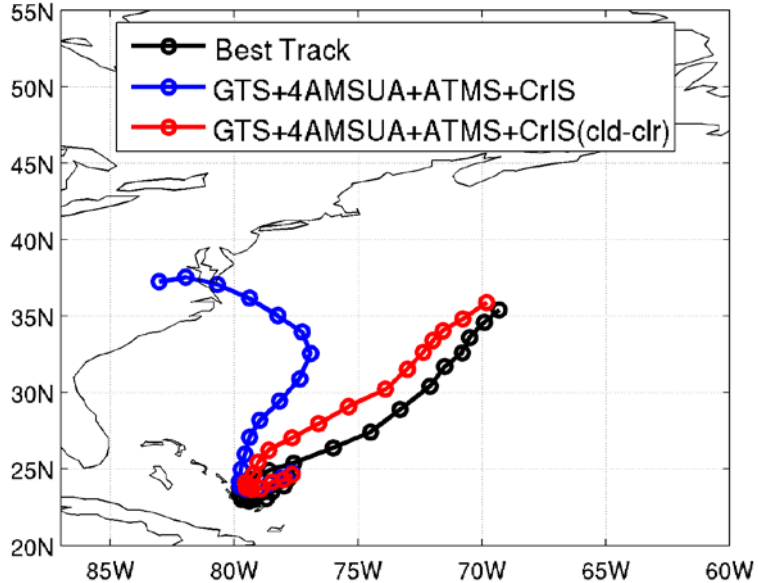
AMSU-A are from noaa-15, 18, 19 and metop-a

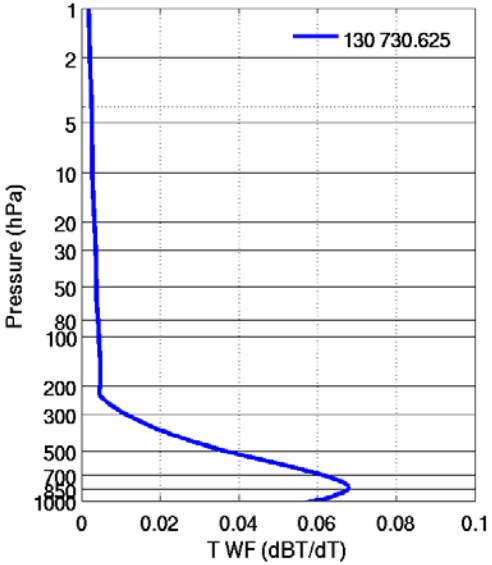
Track and intensity RMSE



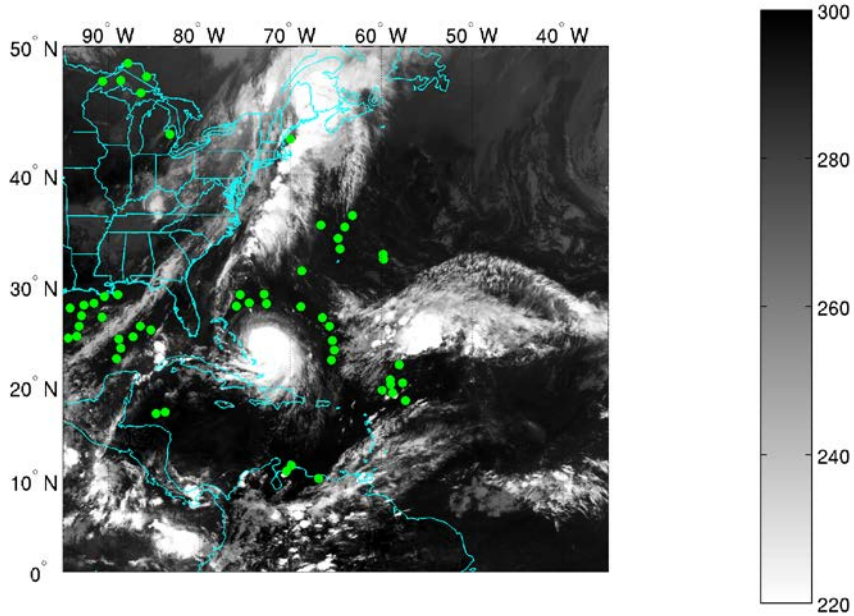
Analyzing 120hr forecast from 09-30 18z

How does cld-clr improve track forecast?

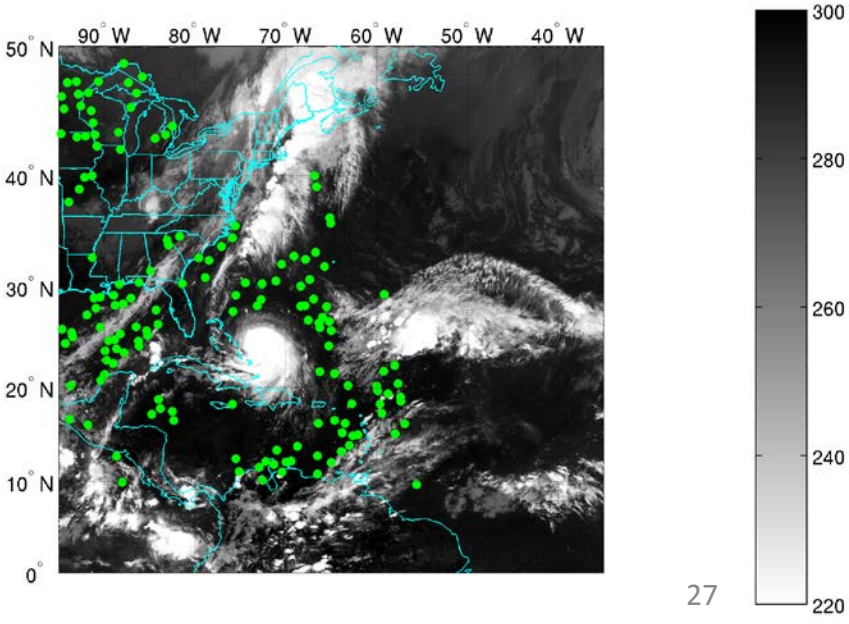




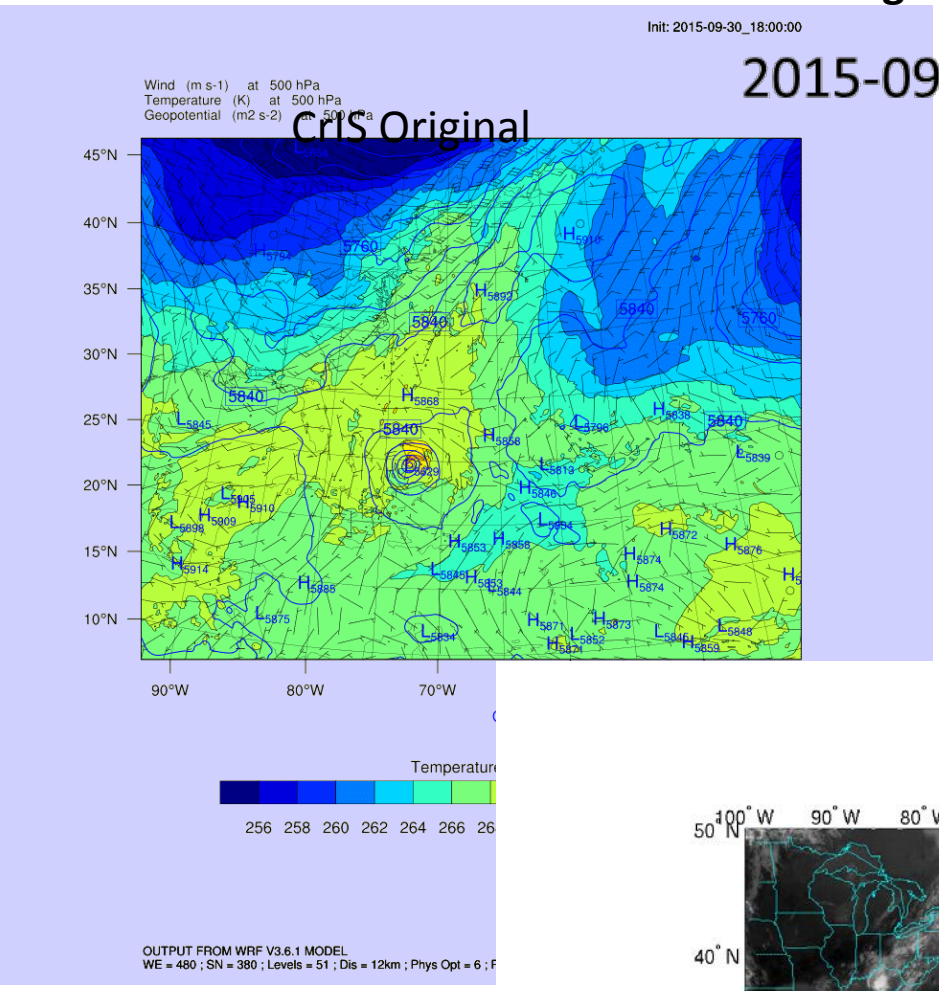
CrIS Original Data assimilated at 09-30 18z of channel 130

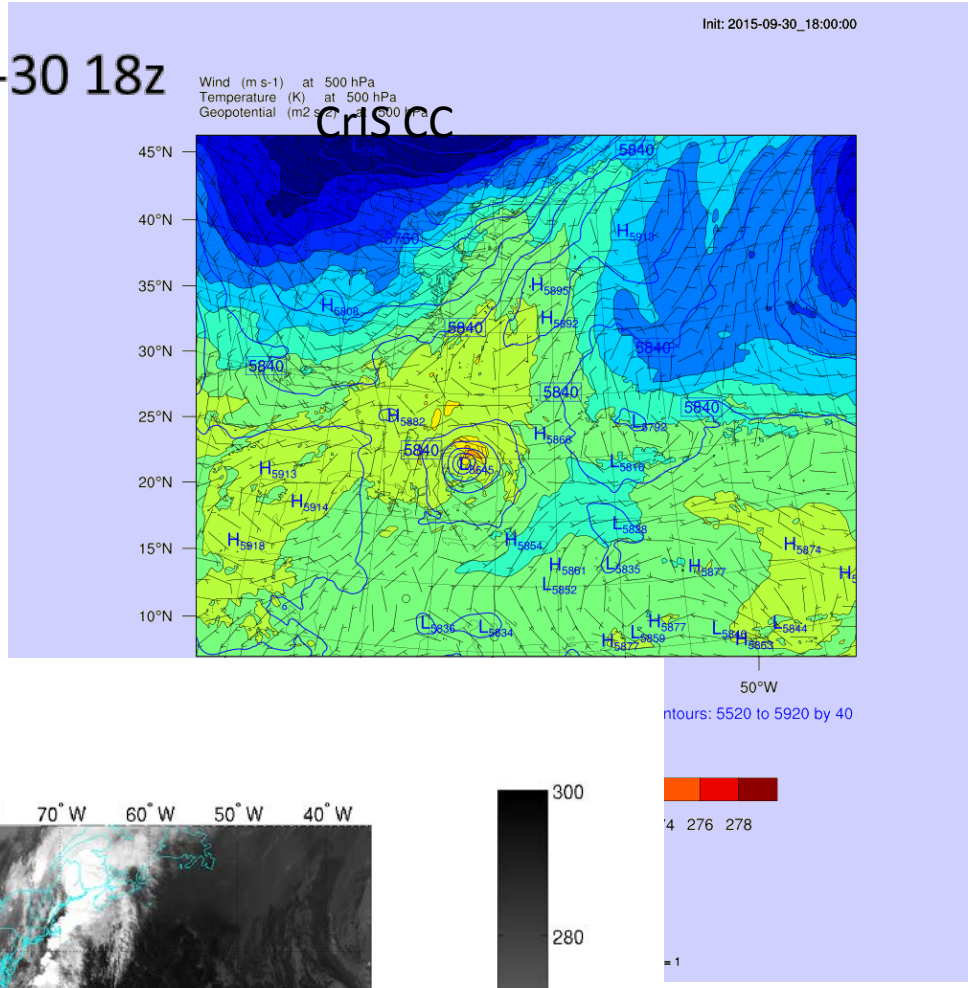


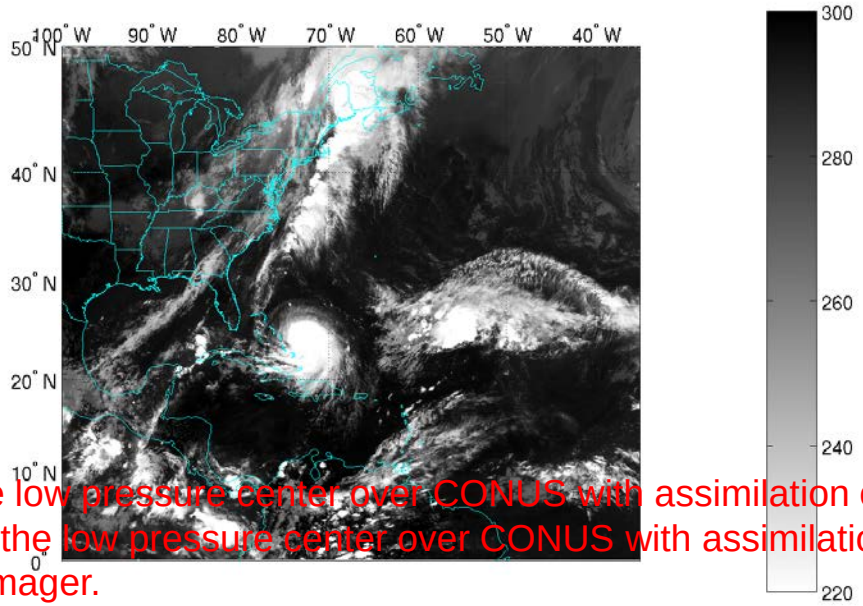
CrIS CC Data assimilated at 09-30 18z of channel 130



120 hr forecasting from 09-30 18z 500hPa





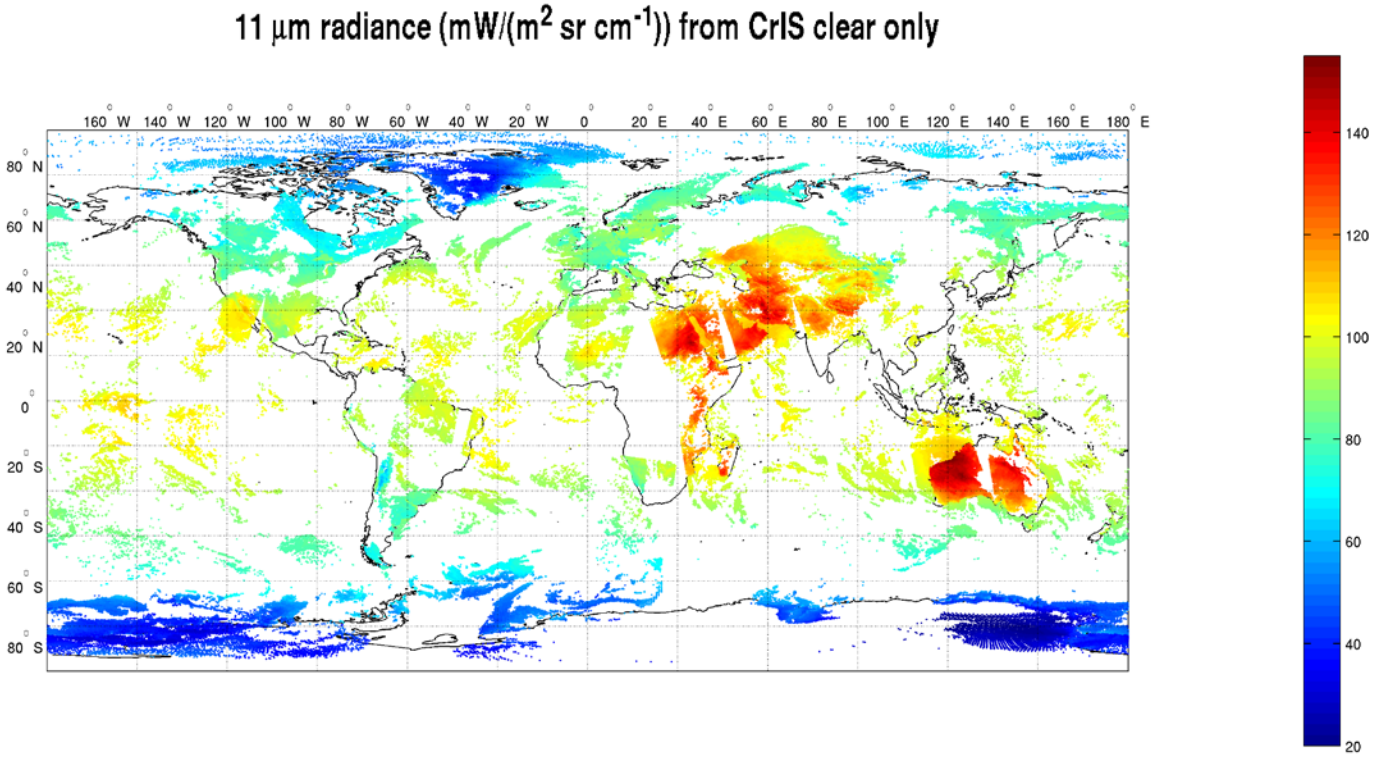


- Hurricane Joaquin is merged with the low pressure center over CONUS with assimilation of CrIS data (left)
- Hurricane Joaquin is separated from the low pressure center over CONUS with assimilation of CrIS CC data (right), which is verified with GOES Imager.

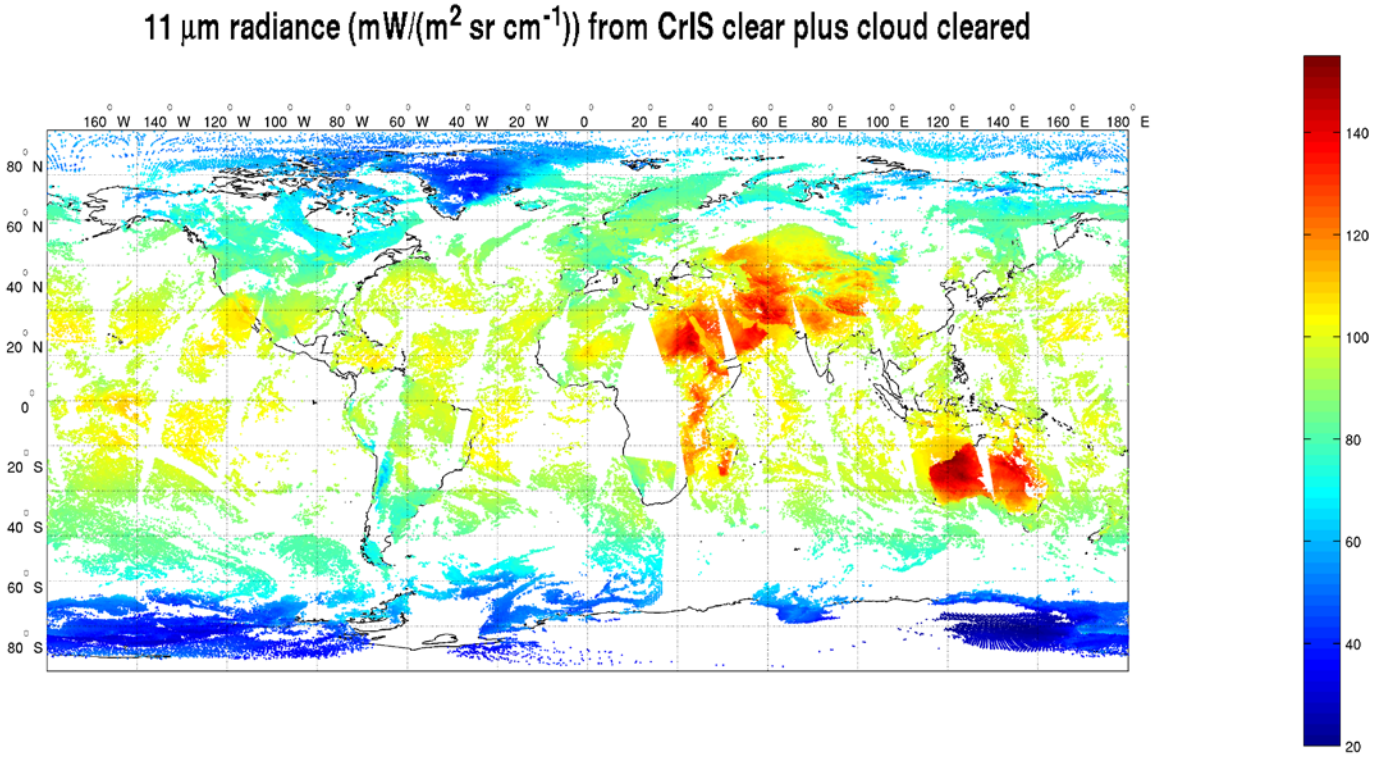
VIIRS-based CrIS CCR data have been provided to EMC for testing

- One day (9/30/2015) of sample data is provided at ftp://ftp.ssec.wisc.edu/ABS/zli/cc_cris/
- A matlab reader is included
- Only cc_flag=3 means successful cloud clearing
- The cloud mask could be used to detect clear/cloud CrIS FOVs
- Data are apodized using Hamming method
- Suggest to inflate observation noise for cloud cleared radiances by 1.4 times
- Contact zhenglong.li@ssec.wisc.edu for support of the data

CrIS clear location coverage using VIIRS for clear detection



CrIS clear + cloud-cleared coverage

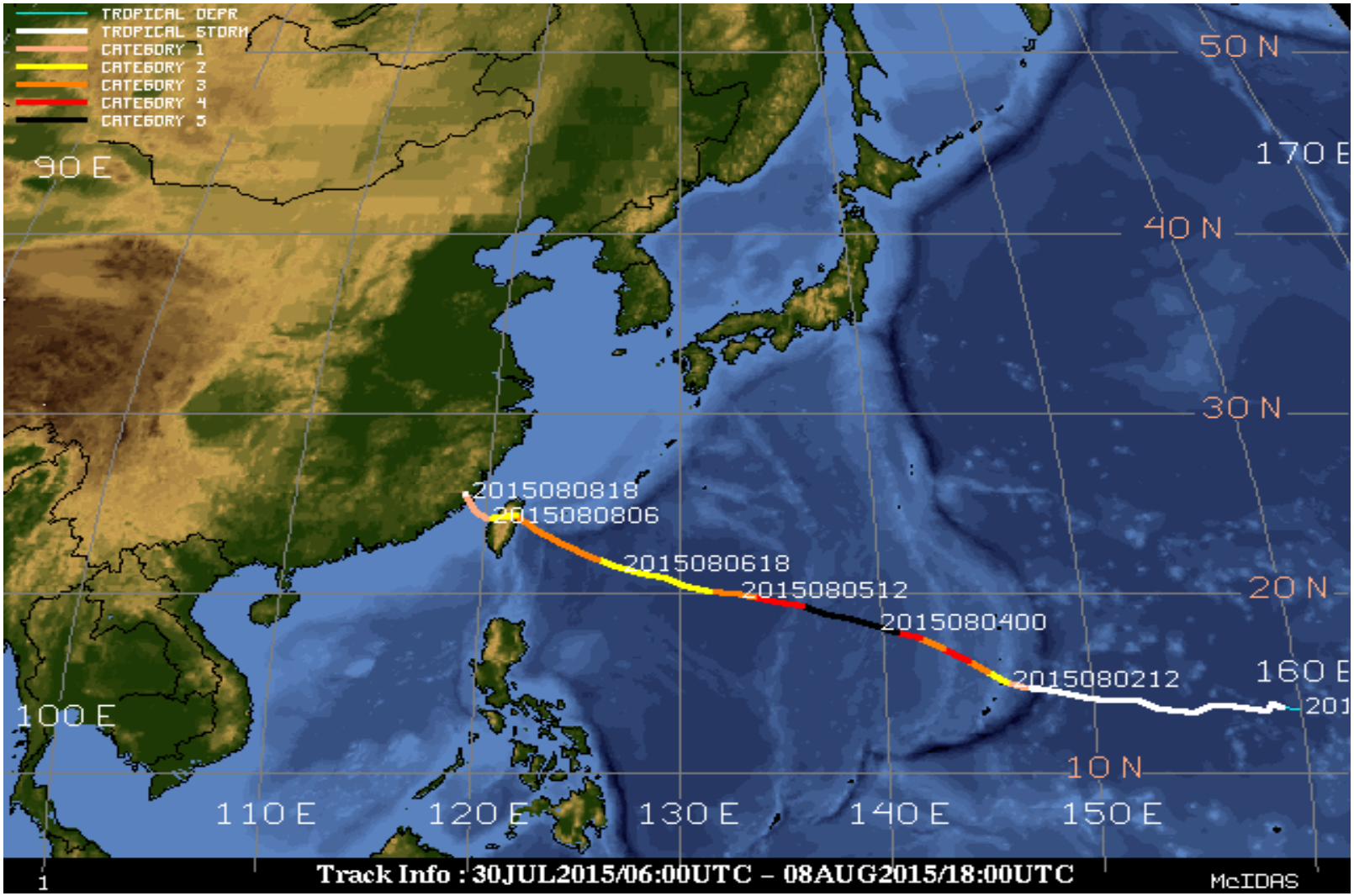


Significantly increase clear observations by 48 % more!

Outlines

- CIMSS real time SDAT (satellite data assimilation for TC forecasts) system as research testbed for improving the utilization of satellite data in regional NWP
- Research progress on IR/MW sounder radiance assimilation with SDAT for tropical cyclone forecasts – JPSS applications
- Research progress on high temporal resolution water vapor information assimilation with SDAT for local storm forecasts – GOES-R applications
  - Layered PW (LPW) assimilation – demonstration with GOES Sounder and AHI
  - High temporal WV information assimilation – 3DVAR versus 4DVAR
- SDAT real time demonstration and applications
  - Performs on 2015 hurricane season
- Future plan

Himawari-8 AHI Data and Assimilation for Typhoon Soudelor (2015)



Univ. Wisconsin-CIMSS

AHI AMV/PW assimilation experiments with CIMSS SDAT as testbed

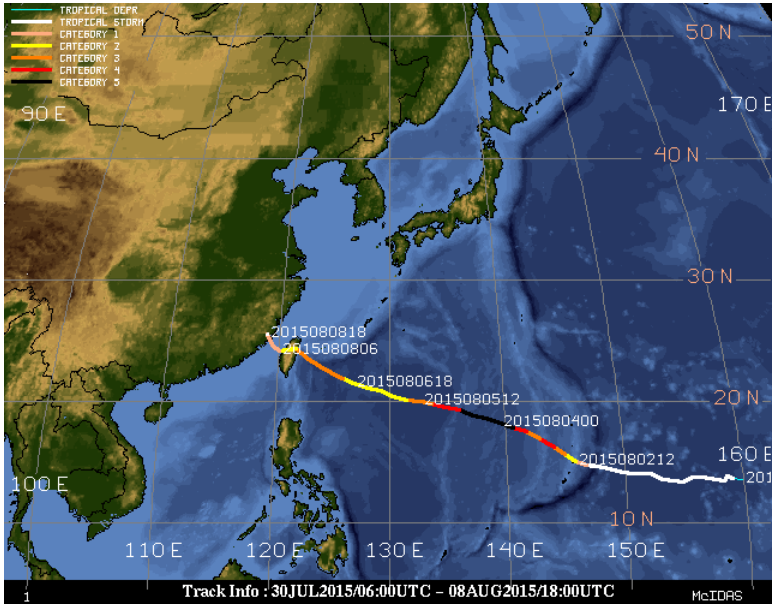
SDAT – Satellite Data Assimilation for Tropical storm
(CIMSS/SSEC/UW-Madison) http://cimss.ssec.wisc.edu/sdat/

WRF-ARW v3.6.1: 12 km horizontal resolution (400*280) , 51 vertical layers from surface to 10 hPa

GSI v3.1: 3-Dvar Data Assimilation Method
- NAM background error covariance matrix
- The PW assimilation modules are implemented in GSI system
- Conventional Data - from GTS
- AMV and PW data - Himawari-8 AHI

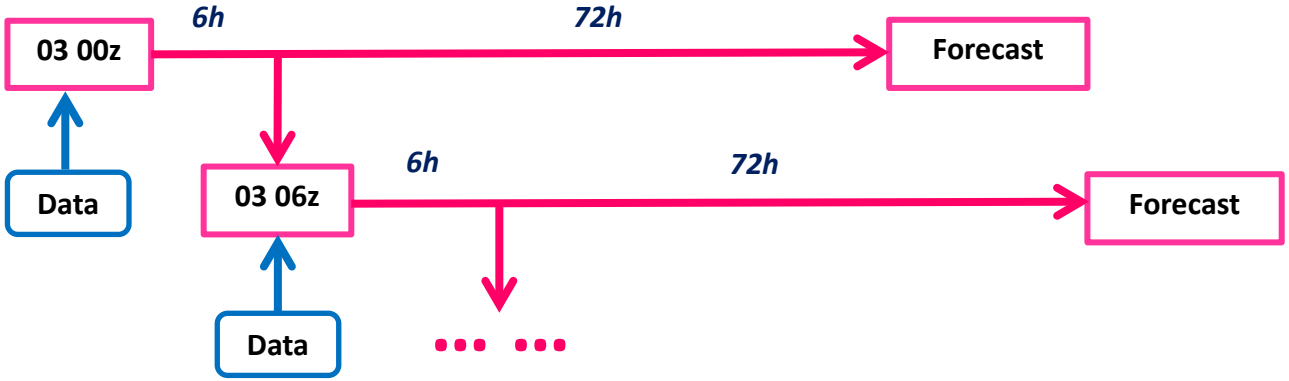
Data
- Ctrl: GTS (conventional observations)
- Exp1: GTS + AMV (IR)
- Exp 2: GTS + PW (Three Layer Precipitable Water: 0.3 – 07, 0.7 – 0.9, 0.9 - SFC)

AHI Data and Assimilation for Typhoon Soudelor (2015)



Experiments

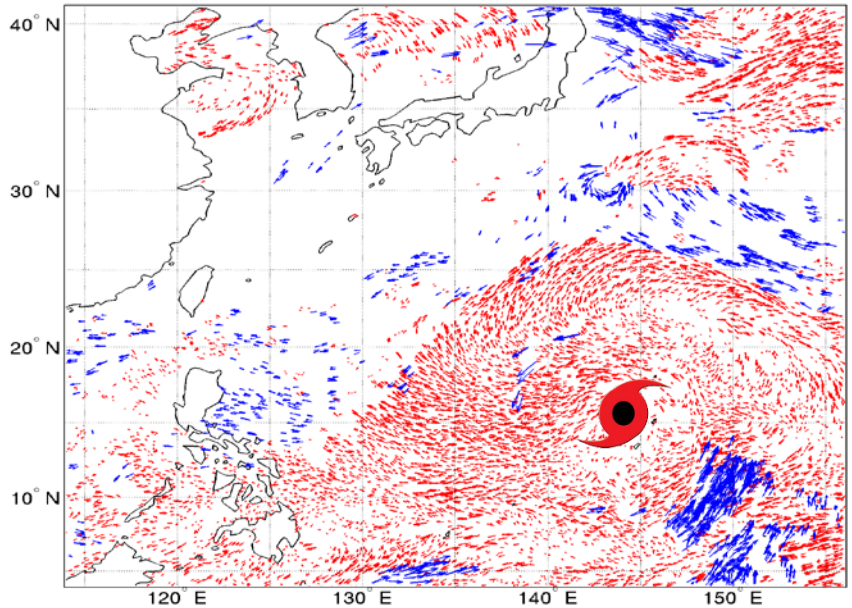
Time window: +/- 30 min



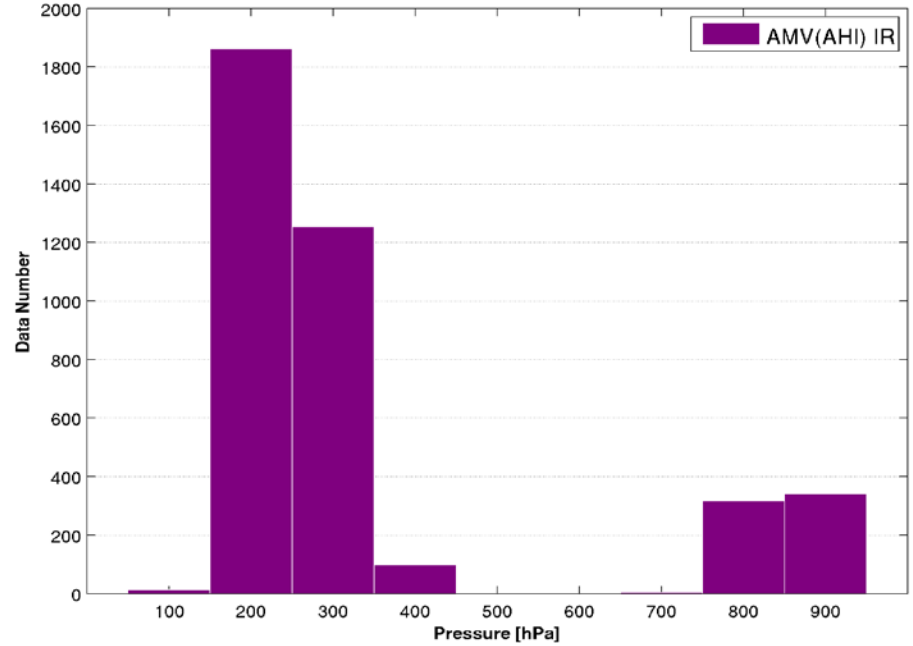
Data are assimilated and forecasts are updated every 6 hours from 00UTC 03 to 00 UTC 05 August 2015

00 UTC 03 August 2015: AHI AMV and PW data assimilated into SDAT

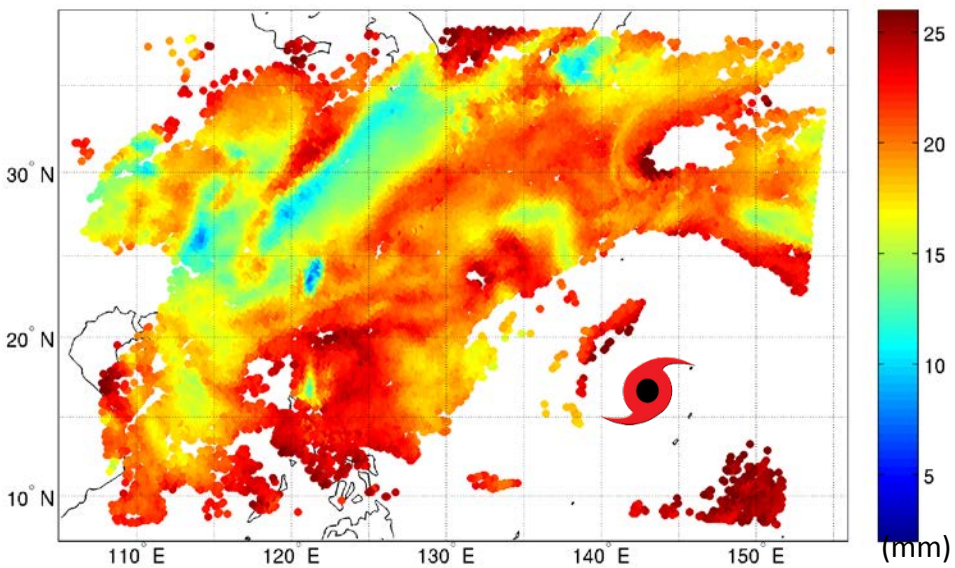
AHI AMV observations (coverage)
100-500mb red, 500-950mb blue



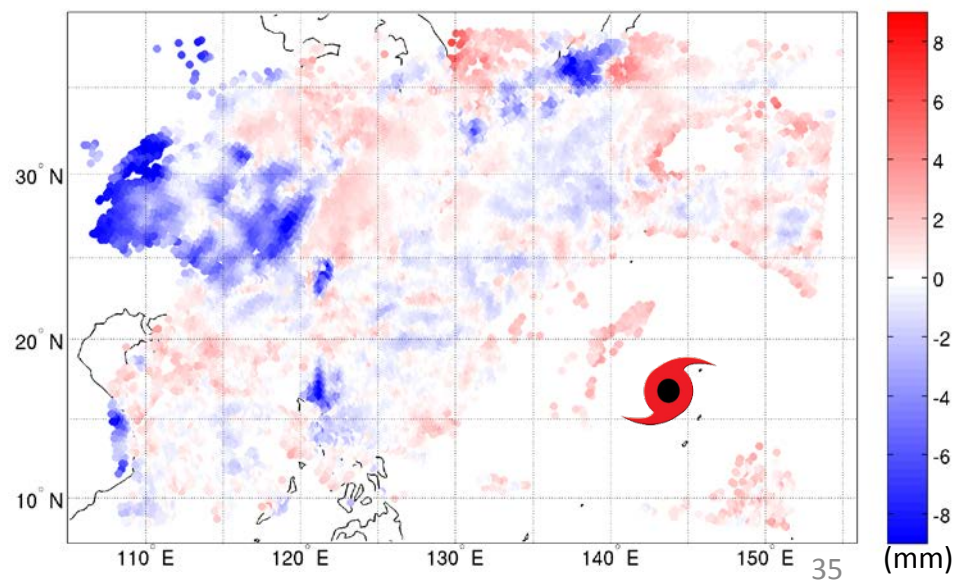
AHI AMV observations by level

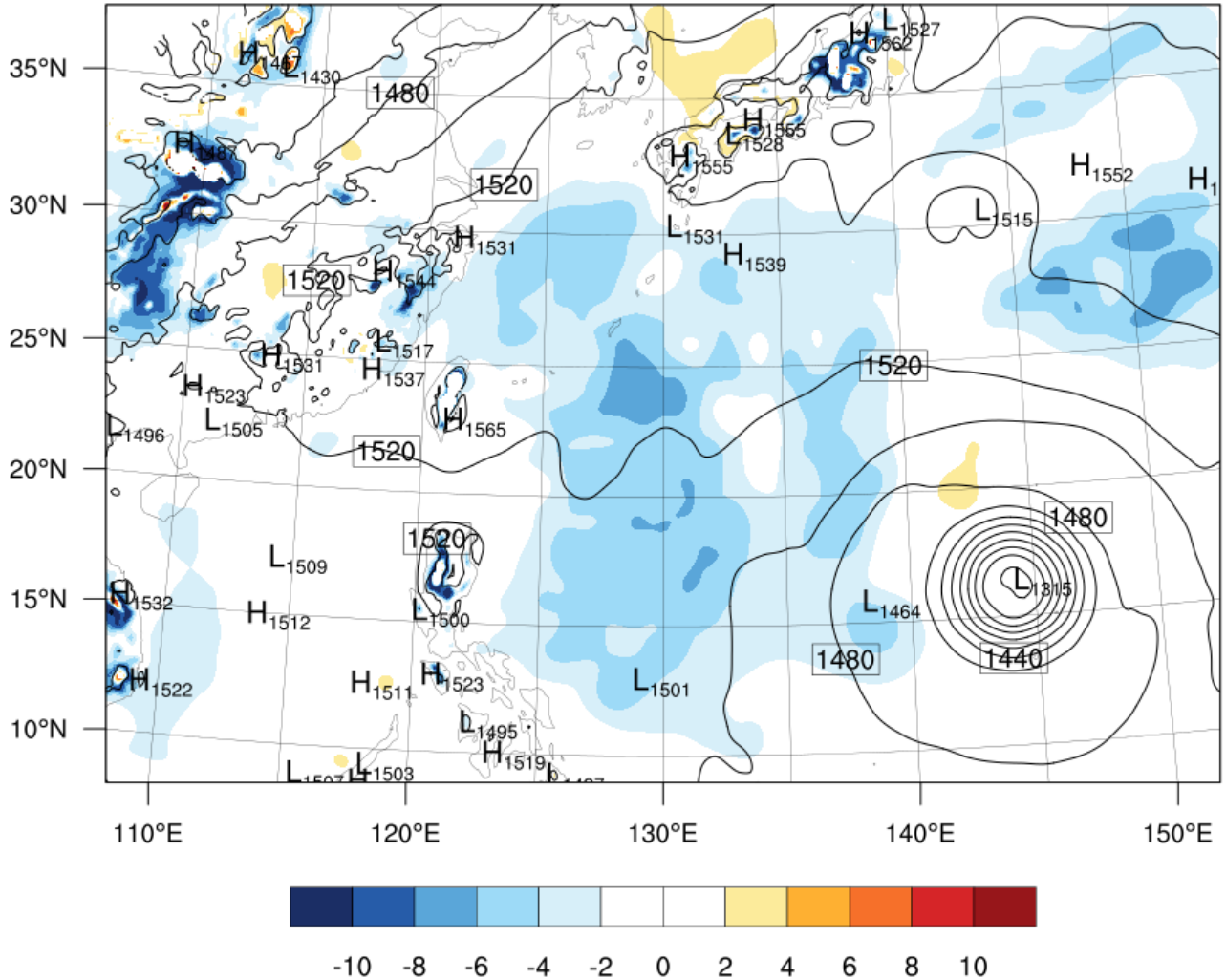


AHI layer PW observations (sigma level 0.7 - 0.9)



O - B





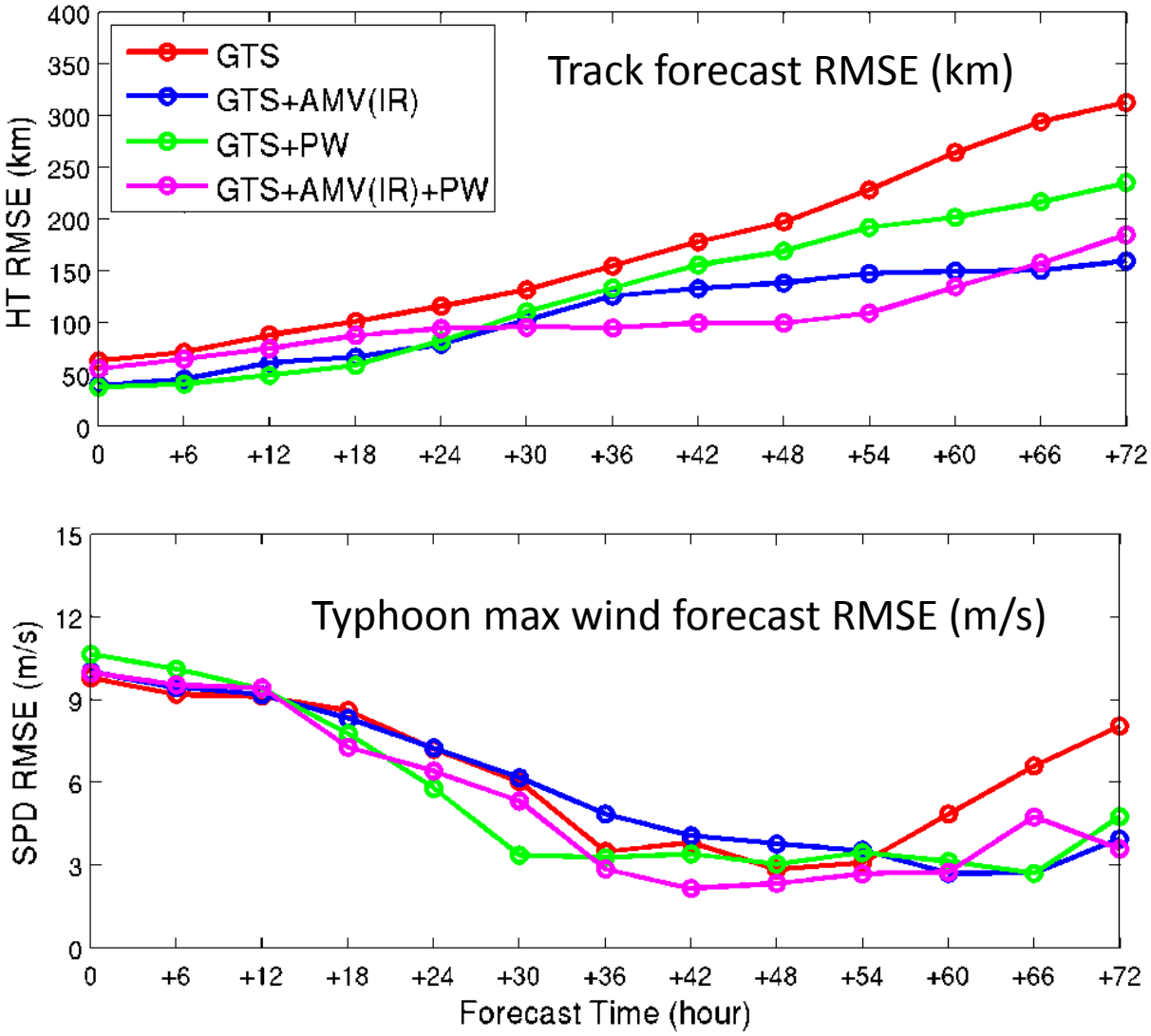
850hPa specific humidity (g/g) analysis difference between assimilating GTS plus three layer PW and assimilating GTS only at 00 UTC 03 August 2015.

Compared with AHI three LPW observations in the environment, the NWP model background is drier in the upper troposphere and wetter in the boundary layer for Typhoon Soudelor case. After assimilation of AHI three LPW observations, 850 hPa analysis is less humidity in the Typhoon environment .

GTS: Conventional data

AMV: AHI AMVs

PW: AHI layer PW from 3 layers (0.3 – 0.7, 0.7 – 0.9, and 0.9 – SFC, in sigma levels)



72-hr NWP forecasts of TY Soudelor (9 cases)

(1) Compared with assimilating conventional data only, adding AMVs or PW (from 3 layers) improves the analysis fields.

(2) Both AMVs and PW improve track forecasts.

(3) PW improves intensity forecasts after 12 hours, AMVs improves intensity forecasts after 54 hours.

(4) Future work will focus on combining AMVs and PW, including LEO sounder data, vortex relocation step, and more frequent assimilation of AMVs /PW.

LPW impact on local storms

WRF-ARW v3.6.1: 4 km horizontal resolution (850*430) , 51 vertical layers from surface to 10 hPa

GSI v3.1: 3-Dvar Data Assimilation Method
- NAM background error covariance matrix
- The LPW assimilation modules are implemented in GSI system

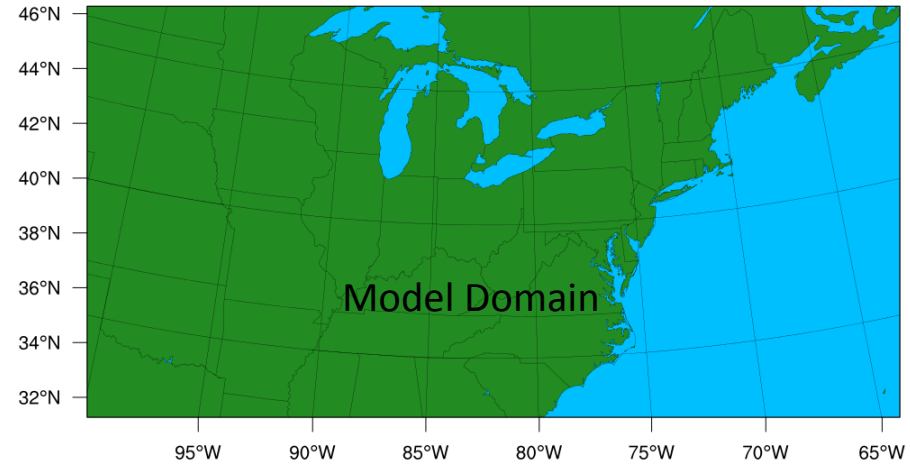
Data (Conventional Data – from GTS; LPW-layered Precipitable Water from GOES-13 and GOES-15 Sounders)
- Ctrl: GTS
- Exp: GTS + H_PW (High PW, sig level 0.3 to 0.7)
- GTS + M_PW (Mid PW, sig level 0.7 to 0.9)
- GTS + L_PW (Low PW, sig level 0.9 to 1)
- GTS + H_PW + M_PW
- GTS + H_PW + L_PW
- GTS + M_PW + L_PW
- GTS + H_PW + M_PW + L_PW

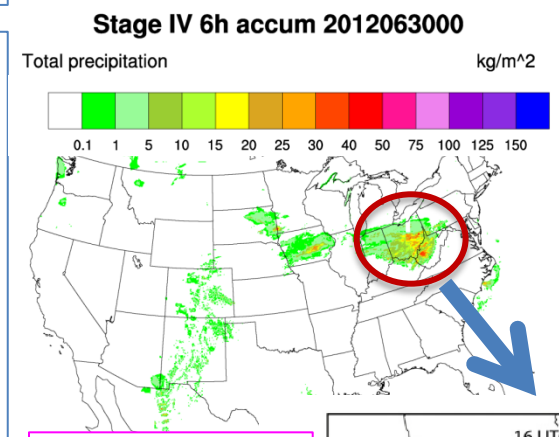
Experiments

Time window: +/- 30 min

29 06z spin up ---- 29 12z assimilation ---- 24 hr forecasts: **GTS**

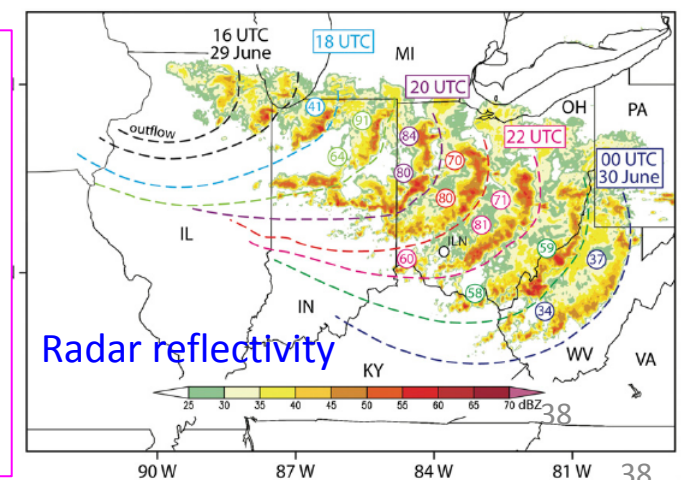
GTS+LPW





The heavy rainfall occurred at June 29 18z to June 30 00 Z, 2012. The following analysis focus on this time period.

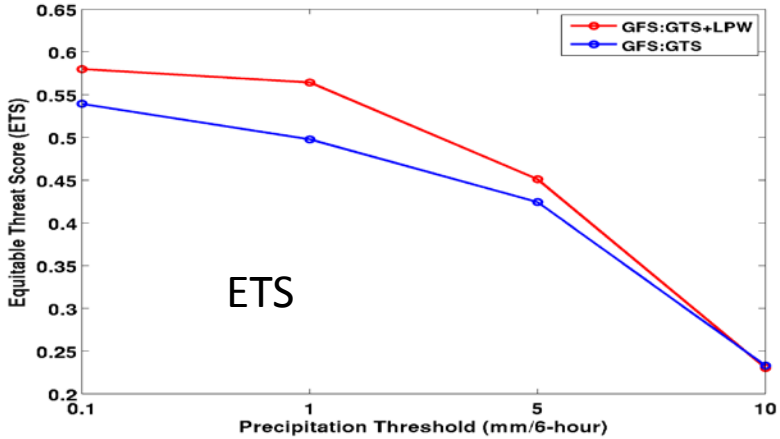
Hourly evolution of composite radar reflectivity (dBZ) at 4km AGL of the derecho producing MCS during the period 1600 UTC 29 Jun–0000 UTC 30 Jun 2012. (Fierro et al., 2014)



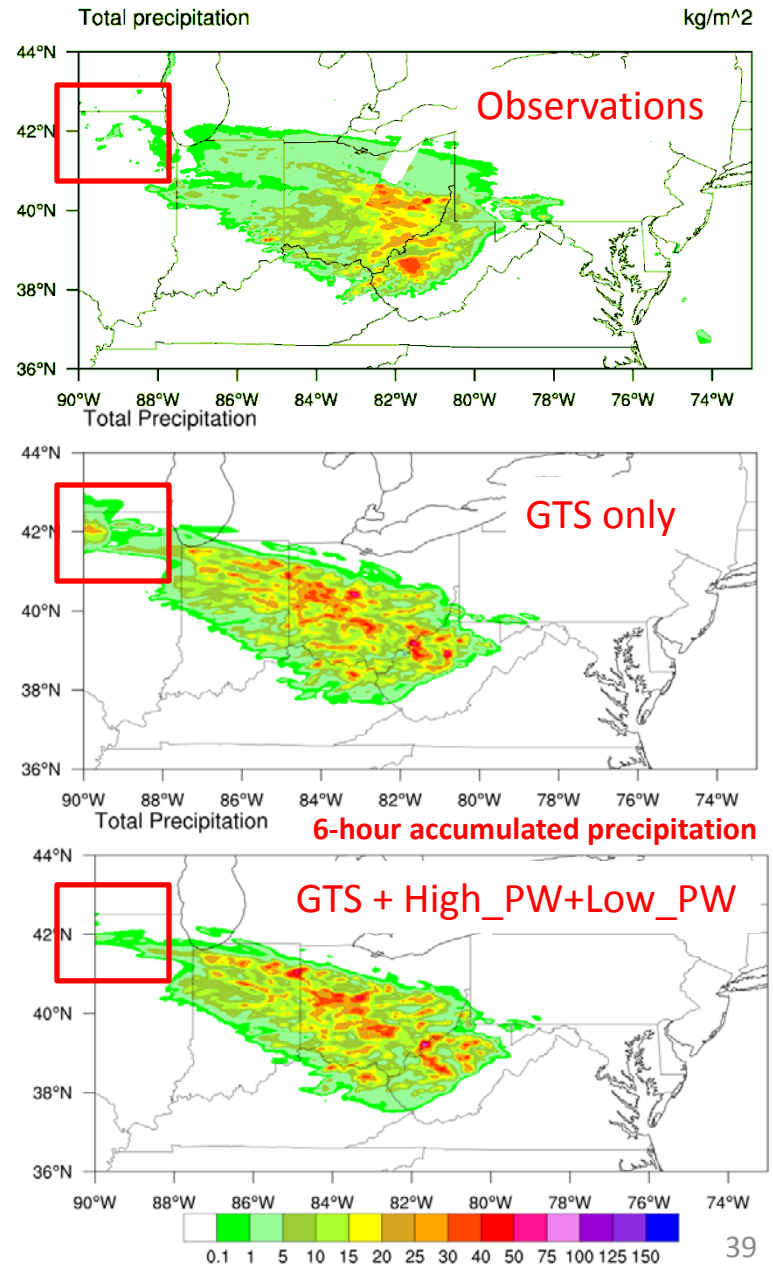
	2012-6-29 18z to 30 00z			
ETS scores	0.1 mm	1 mm	5 mm	10 mm
GTS (conv data)	**0.5393**	**0.4978**	**0.4243**	**0.2330**
GTS+LPW(H)	0.5639	0.5403	0.4447	0.2315
GTS+LPW(M)	0.4881	0.4137	0.3066	0.1770
GTS+LPW(L)	0.5446	0.5093	0.4312	0.2364
GTS+LPW(HM)	0.5578	0.5386	0.4486	0.2412
GTS+LPW(ML)	0.5335	0.4925	0.4274	0.2309
GTS+LPW(HL)	**0.5800**	**0.5644**	**0.4510**	0.2302
GTS+LPW(HML)	0.5434	0.4854	0.4171	**0.2958**

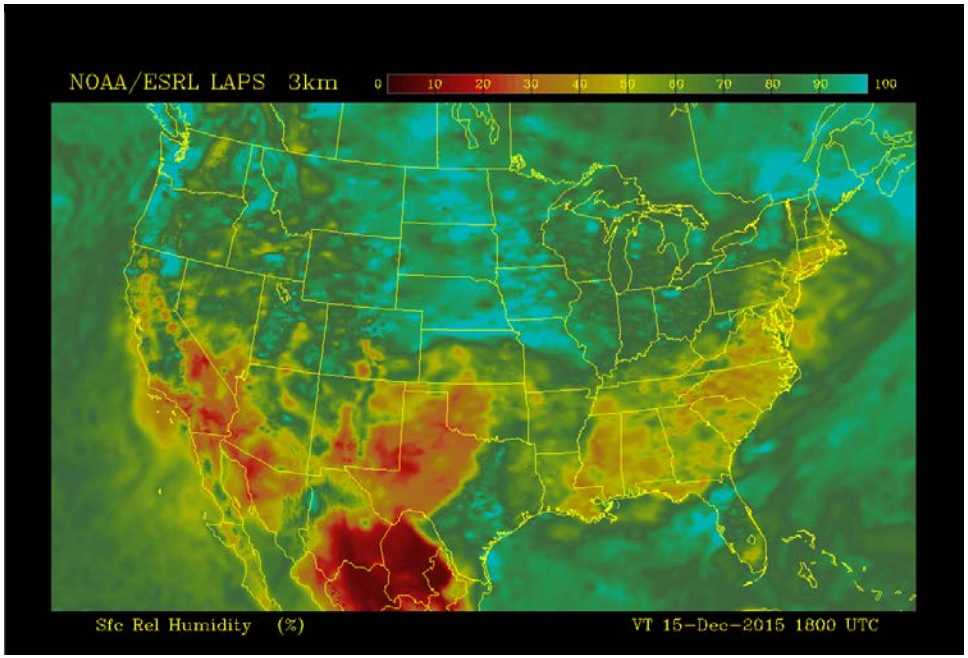
Red: the ETS score is higher than GTS only

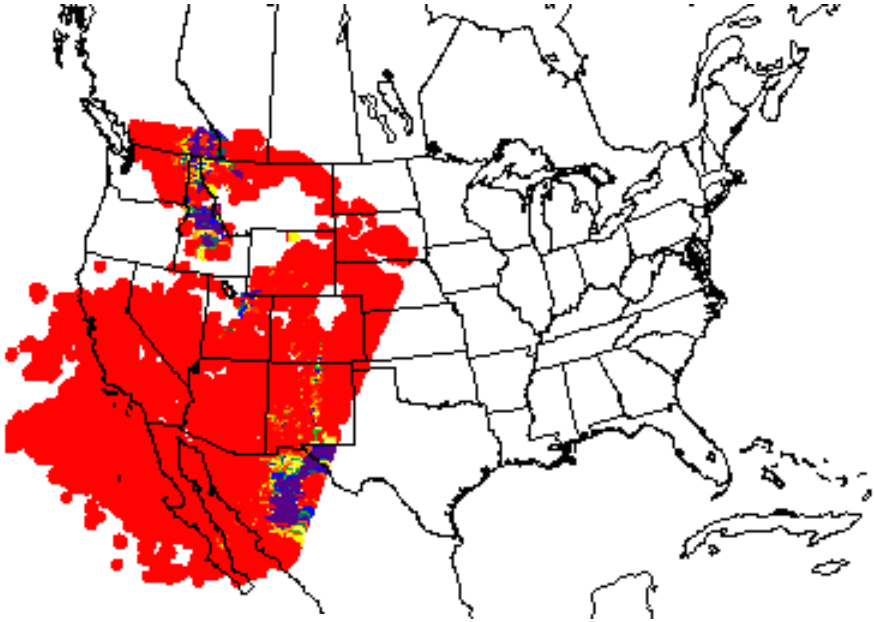
(1) The low-LPW gives the higher ETS in the whole period.
(2) The mid-LPW gives the lowest ETS in the whole period.
(3) The high-LPW and low-LPW together give us the highest ETS scores. For regional NWP storm forecast, high and lower moisture bands are more important from this study.

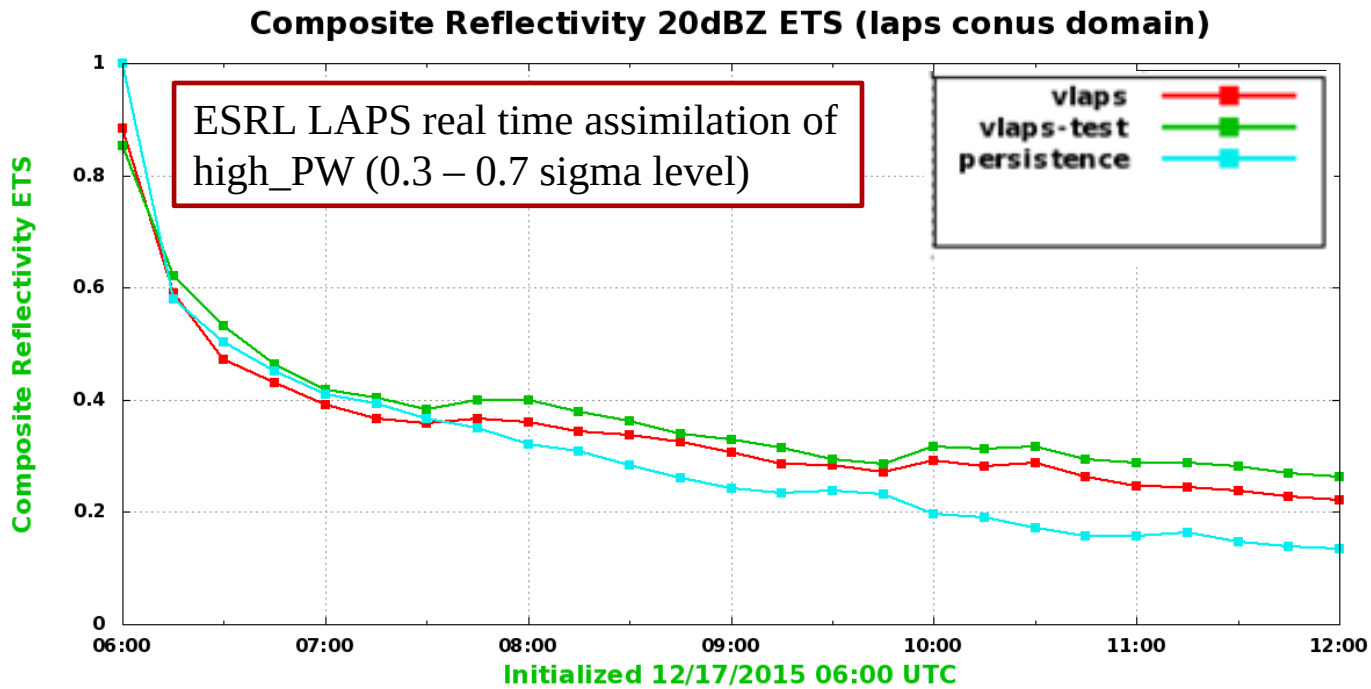


Assimilation of GOES Sounder data correctly removed false precipitation from control run





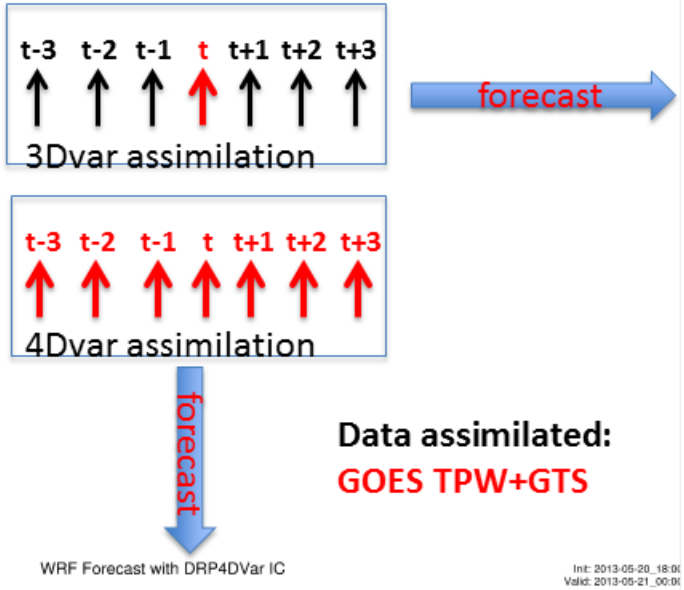


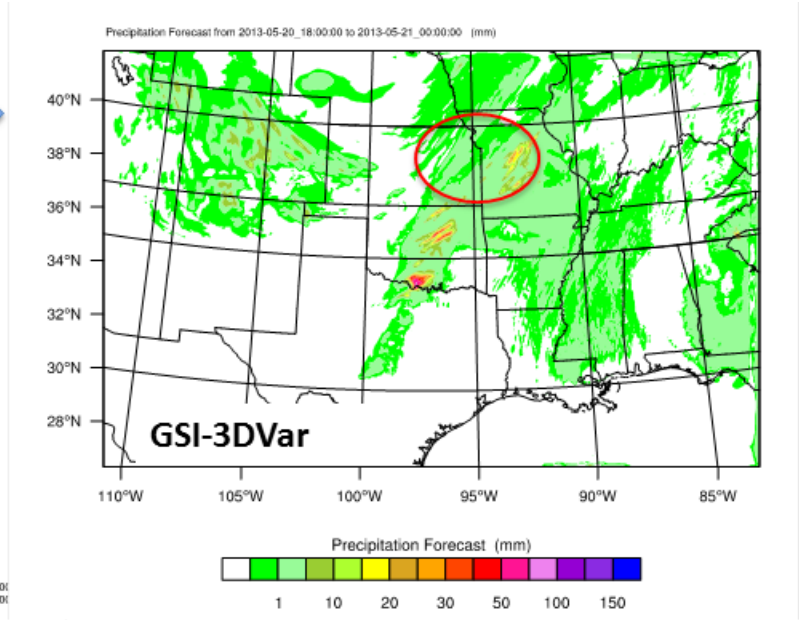


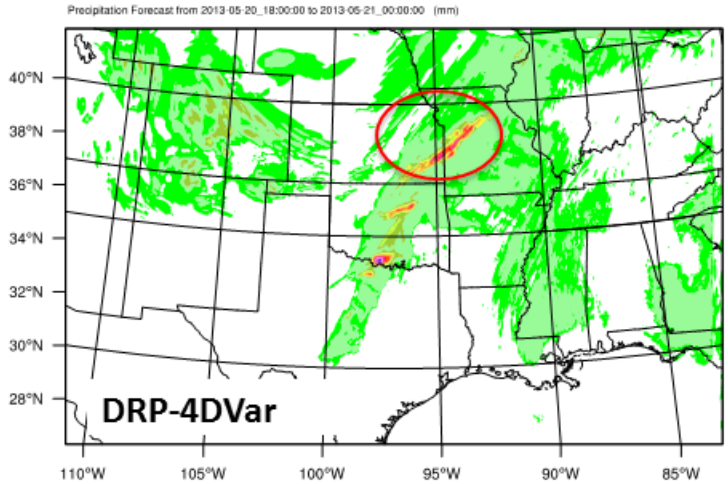
"LPW Data Impact Study Preparing for GOES-R Applications" by Yuanfu Xie et al. (2016)

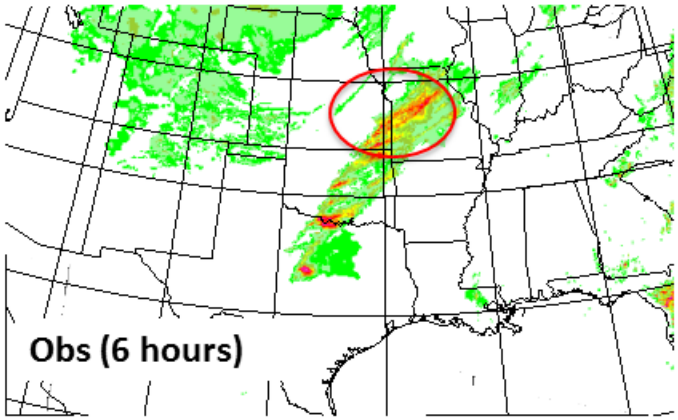
US CONUS domain (upper left), LPW data coverage (upper right), ETS scores from real time LAPS (red) and LAPS test with GOES Sounder LPW assimilated (green) (lower left), bias from the two tests (lower right).

About assimilation of high temporal moisture information from GOES/GOES-R









Wei Cheng (CIMSS)

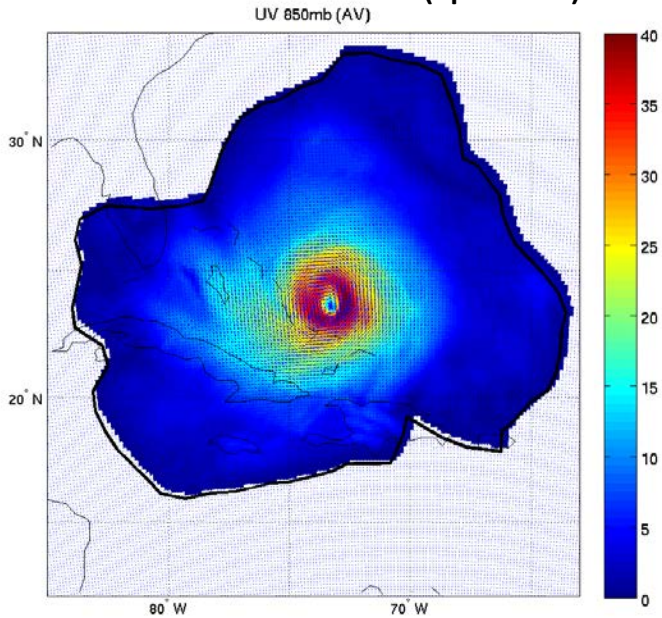
Outlines

- CIMSS real time SDAT (satellite data assimilation for TC forecasts) system as research testbed for improving the utilization of satellite data in regional NWP
- Research progress on IR/MW sounder radiance assimilation with SDAT for tropical cyclone forecasts – JPSS applications
- Research progress on high temporal resolution water vapor information assimilation with SDAT for local storm forecasts – GOES-R applications
- SDAT real time demonstration and applications
  - Performs on 2015 hurricane season (Mark DeMaria, NHC)
- Future plan

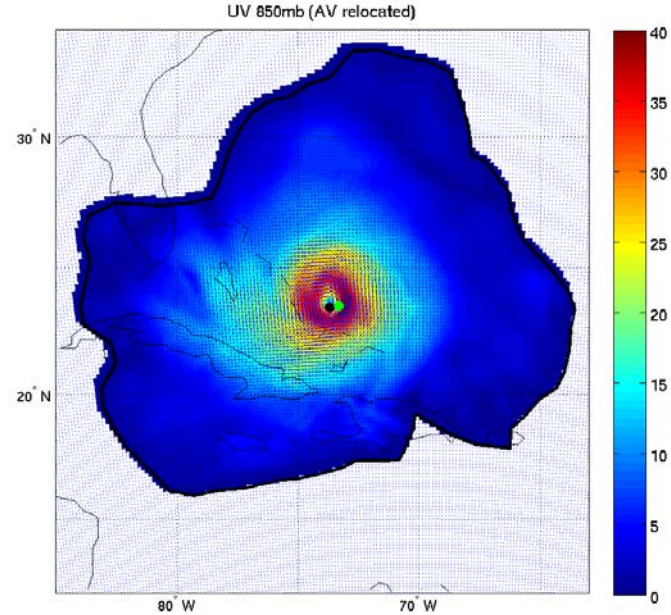
SDAT Hurricane relocation scheme

- Follow Kurihara (1993, 1995) vortex separation method (GFS/HWRF relocation algorithm use a similar way).
- Improve surface pressure isolation.
- Relocate u,v,T,Q,Psurf, gph and other related variables.

Separated uv vortex
at the model level (η=0.85)



Move separated uv vortex
to observed location



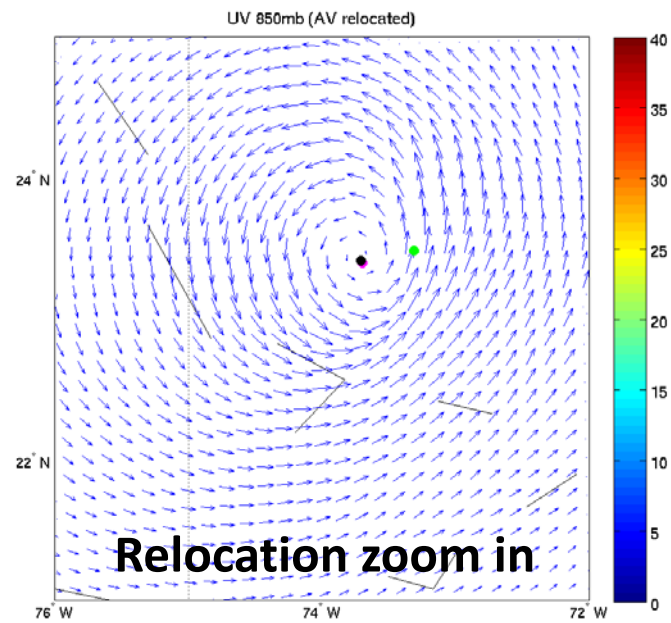
Hurricane Joaquin:
2015.10.01 06 UTC

Vortex Center location:

Observation: (23.40, -73.70) ***(megenta)***

Model before move: (23.49, -73.31) ***(green)***

After move model: (23.42, -73.71) ***(black)***



Relocation zoom in

SDAT Forecasts

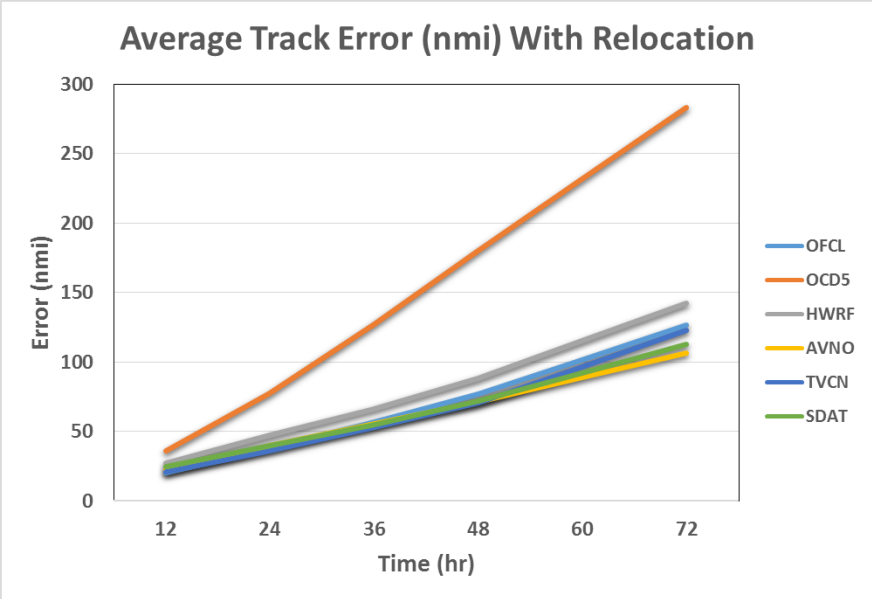
- SDAT forecasts provided by Jun Li and Jinlong Li from 2015 Atlantic season
  - ATCF format
  - 72 hr forecasts of track and intensity
  - 58 forecasts from 4 storms
    - Danny, Erika, Fred and Joaquin
- Versions with and without relocation provided
  - Evaluation focused on relocation version

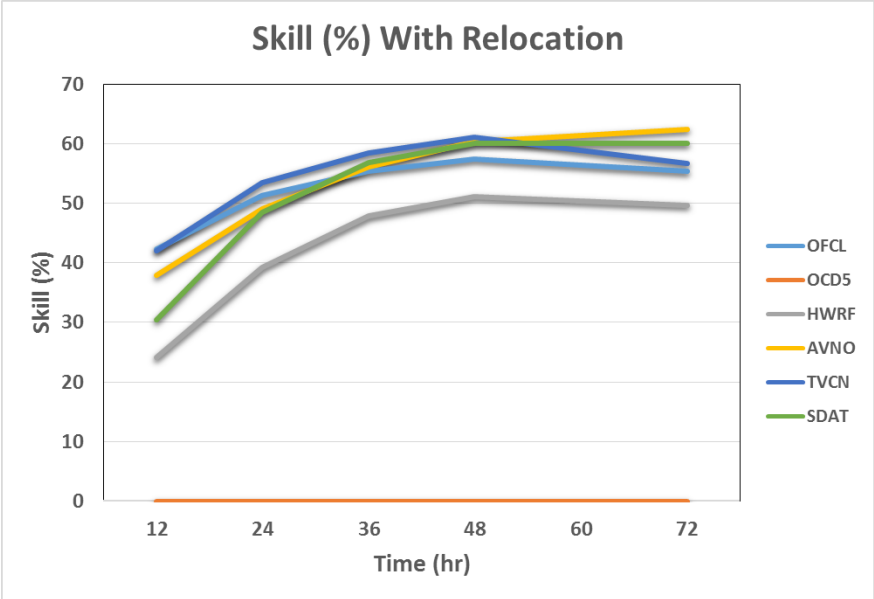
From Dr. DeMaria

Verification Procedure

- Homogeneous comparisons with subset of NHC's operational models
  - Track – HWRF, GFS (called AVNO), TVCN (consensus forecast)
  - Intensity – Interpolated HWRF (HWFI), Interpolated GFDL (GHMI), SHIPS, LGEM, ICON (Consensus forecast)
- Simple statistical model OCD5 used as baseline for skill evaluation
- NHC verification rules applied
  - Cases must be tropical or subtropical to be included
  - Must also have NHC Official Forecast (OFCL)
- Metrics
  - Track – Average Error, Skill relative to OCD5
  - Intensity – Average Error, Bias, Skill relative to OCD5

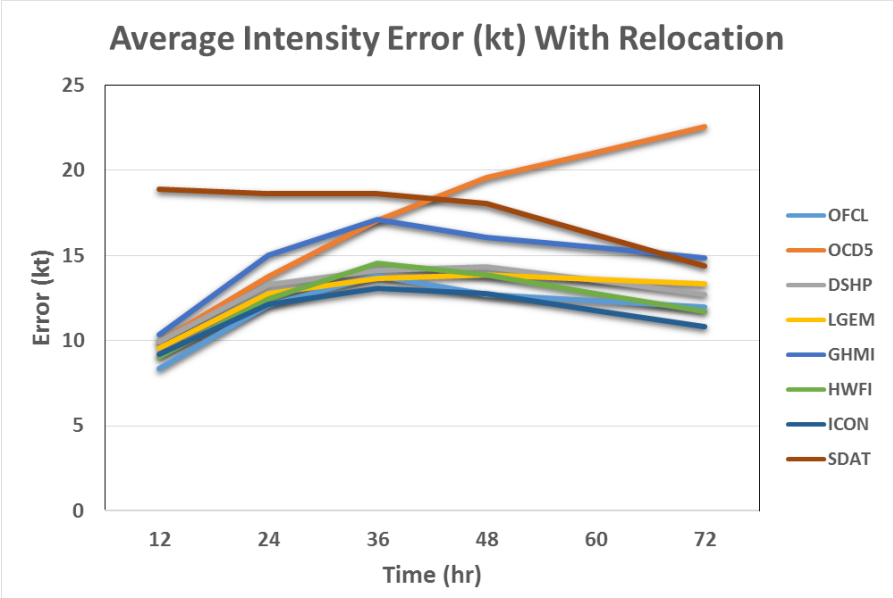
Track Verification

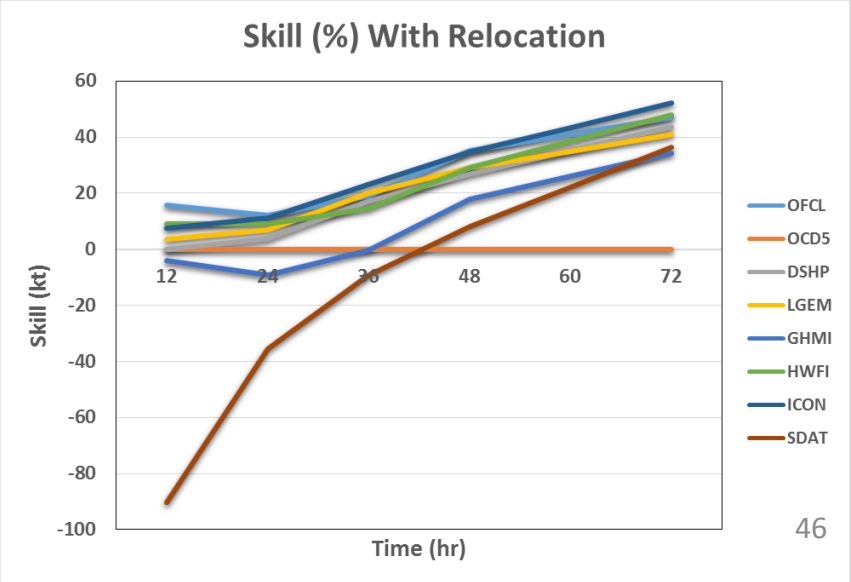




Intensity Verification

From Dr. DeMaria





Results

- SDAT track errors comparable with NHC's best operational models
- SDAT has large track skill compared with OCD5
- SDAT intensity errors much larger than NHC's best operational models
- SDAT very large low intensity bias
- SDAT has little skill at early times, but some skill at 48 and 72 hr

Recommendations

From Dr. DeMaria

- Run to 126 hr if possible
- Address latency using "interpolater"
- See if SDAT adds to consensus track model skill
- Large early intensity errors and large negative bias suggest initialization/spin up problems
- Interpolator method may reduce large initial intensity errors
- Provide forecasts for all TC cases if possible

Future work

Research using SDAT for potential operational transition:

- Assimilate radiances from clear locations + radiances from clear channels (can be used in operational NWP models);
- Continue assimilation of CrIS CCRs (collaborate with Andrew Collard and Chris Barnet);
- Continue assimilation of high temporal resolution GOES-R LPW (potential for RAP and storm scale NWP)
- Study the assimilation of other JPSS/GOES-R products (e.g., clouds)

Improve SDAT for applications

- Implement relocation for 2016 hurricane season;
- Use “Interpolator” for improving intensity forecasts;
- Study if SDAT adds to consensus track model skill;
- Local applications: NWS forecast office in Milwaukee/Sullivan.

Additional information/references

- **SDAT webpage**, http://cimss.ssec.wisc.edu/sdat

- **Related publications**

Han, H., Li J. et al. Microwave sounder cloud detection using a collocated high resolution imager and its impact on radiance assimilation in tropical cyclone forecasts, Monthly Weather Review (revised manuscript submitted)

Li, Jun, P. Wang, H. Han, J. Li, and J. Zheng, 2016: On the assimilation of satellite sounder data in cloudy skies in the numerical weather prediction models, Journal of Meteorological Research. 30, 169-182.

Wang, P., Jun Li, M. Goldberg, T. J. Schmit, et al., 2015: Assimilation of thermodynamic information from advanced IR sounders under partially cloudy skies for regional NWP, Journal of Geophysical Research - Atmosphere, 120, doi:10.1002/ 2014JD022976.

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.