On Assimilation of ATMS and CrIS Data in HWRF

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Outline

- A Brief Description of Data Assimilation
- Improvements Made to HWRF System for Satellite DA
- Positive Impacts of ATMS DA on Hurricane Forecasts
- Mixed Impacts of CrIS DA on Hurricane Forecasts
- Preliminary Results Using 2014 Version of HWRF
- Summary, Current and Future Plan

Assimilation

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}(H(\mathbf{x}) - \mathbf{y}^{obs})^T (\mathbf{O} + \mathbf{F})^{-1}(H(\mathbf{x}) - \mathbf{y}^{obs})$$

$$J(\mathbf{x}_a) = \min_{\mathbf{x}} J(\mathbf{x}) \quad \forall \mathbf{x} \text{ near } \mathbf{x}_b$$

- $\mathbf{x}$ – analysis variable
- $\mathbf{x}_a$ – final analysis
- $\mathbf{x}_b$ – background
- $\mathbf{B}$ – background error covariance
- $\mathbf{y}^{obs}$ – observations
- $\mathbf{O}$ – observation error covariance
- H – observation operator
- $\mathbf{F}$ – forward model error covariance

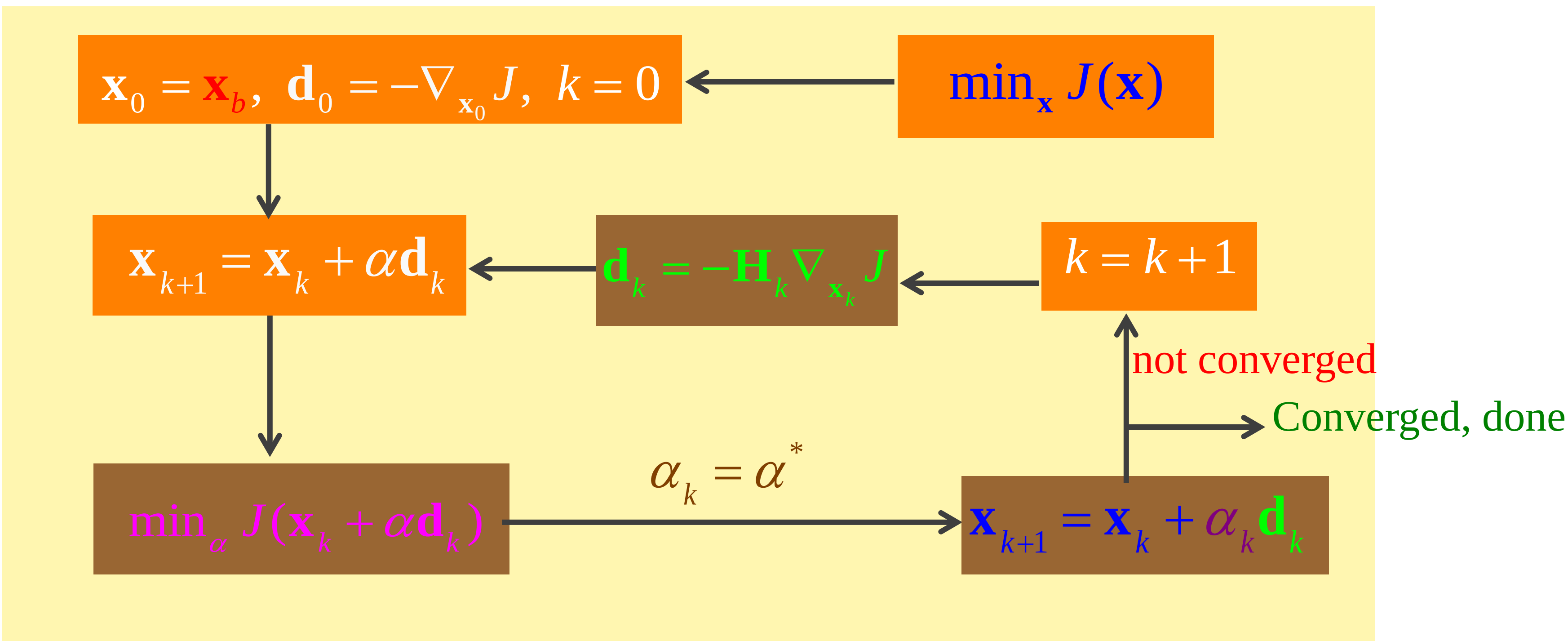
- NCEP GSI 3D-Var Data Assimilation System
- Hurricane Weather Research Forecast (HWRF) System

An Iteration Procedure of Assimilation

Starting from a background field $\mathbf{x}_0 = \mathbf{x}_b$, various minimization algorithms compute a sequence of solution

$$\{\mathbf{x}_k, k = 1, 2, \cdots\}$$

$\mathbf{x}_k$ approaches a local minimizer $\mathbf{x}^*$ of J. $\mathbf{x}^*$ is taken as the DA analysis.



$\mathbf{d}_k$ --- Search direction $\qquad$ α_k --- Step size

Data for Data Assimilation

Three Key Components for Assimilation of Satellite Data:

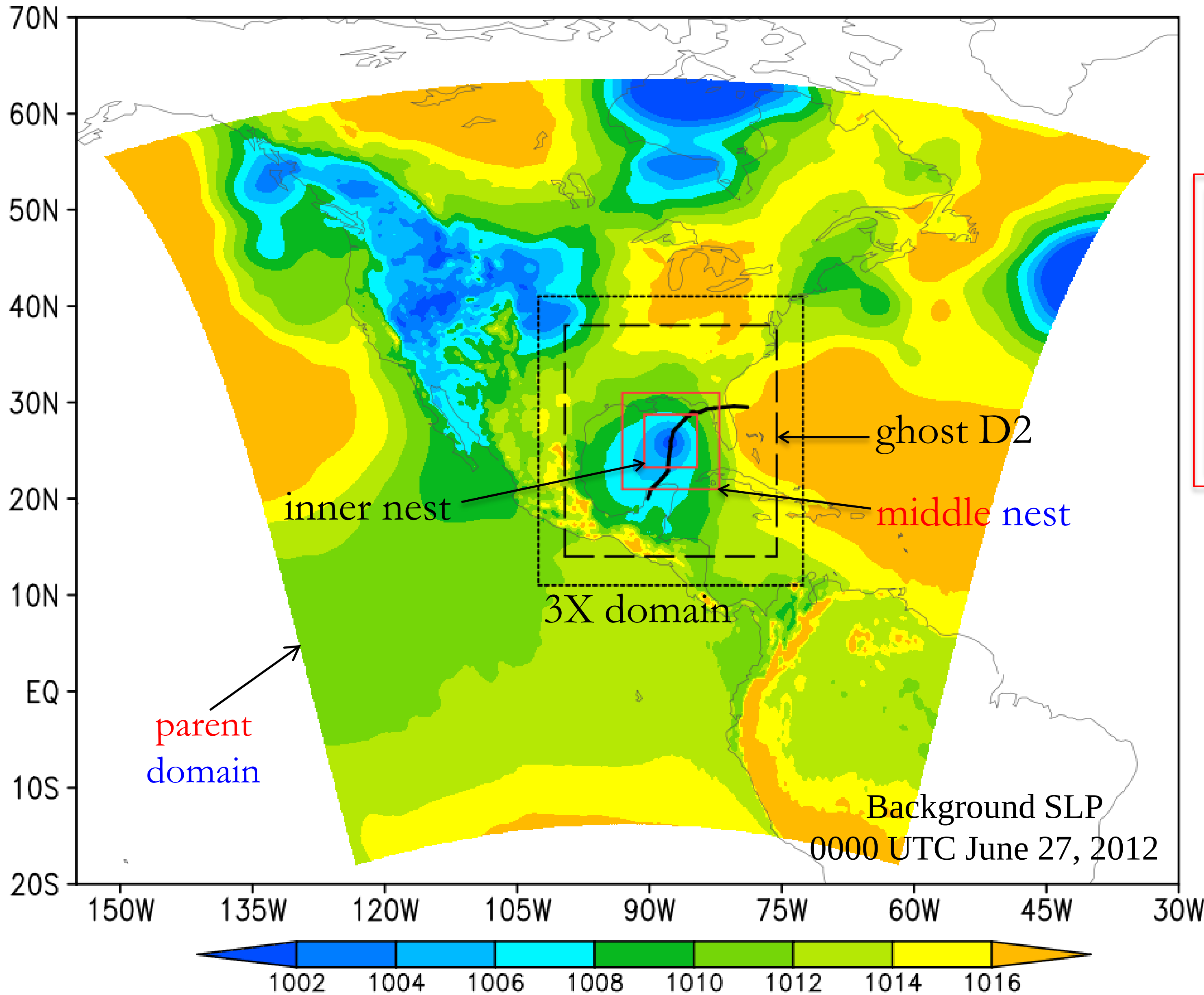
- ✓ **Bias Correction**
- ✓ **Quality Control**
- ✓ **Data Thinning**

- Instrument bias
- Air mass dependent bias
- Erroneous data
- RTM errors
- Spatially correlated data
- Spectrally correlated channels

2. Improvements to HWRF System for Satellite DA

- In 2011 and 2012 version of HWRF system, most of satellite data are not assimilated in HWRF analysis process due to mixed impacts on hurricane track and intensity forecasts
- Model top in 2011-2013 versions of HWRF is too low for assimilation of upper-level channels
- Cold start (background fields are not the HWRF 6-h forecasts
- Analyses show GSI quality controls for satellite water vapor sounding data are problematic (lots of bad data sneak into the analysis process)
- Bias correction schemes for satellite data developed for the global model applications have not been fully vetted for regional model applications

2012 HWRF Domain Sizes for Tropical Storm Debby



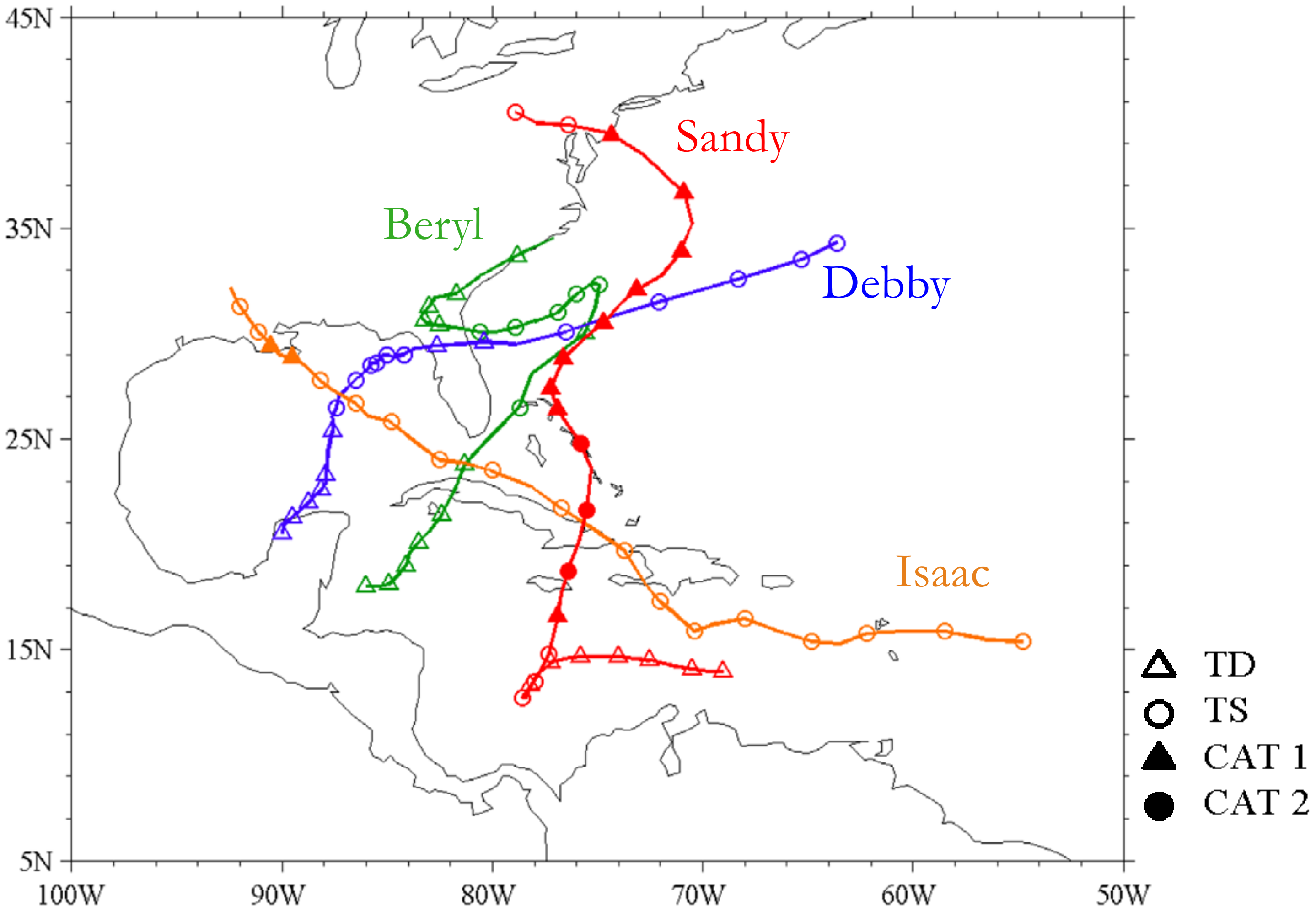
DA

2012 HWRF

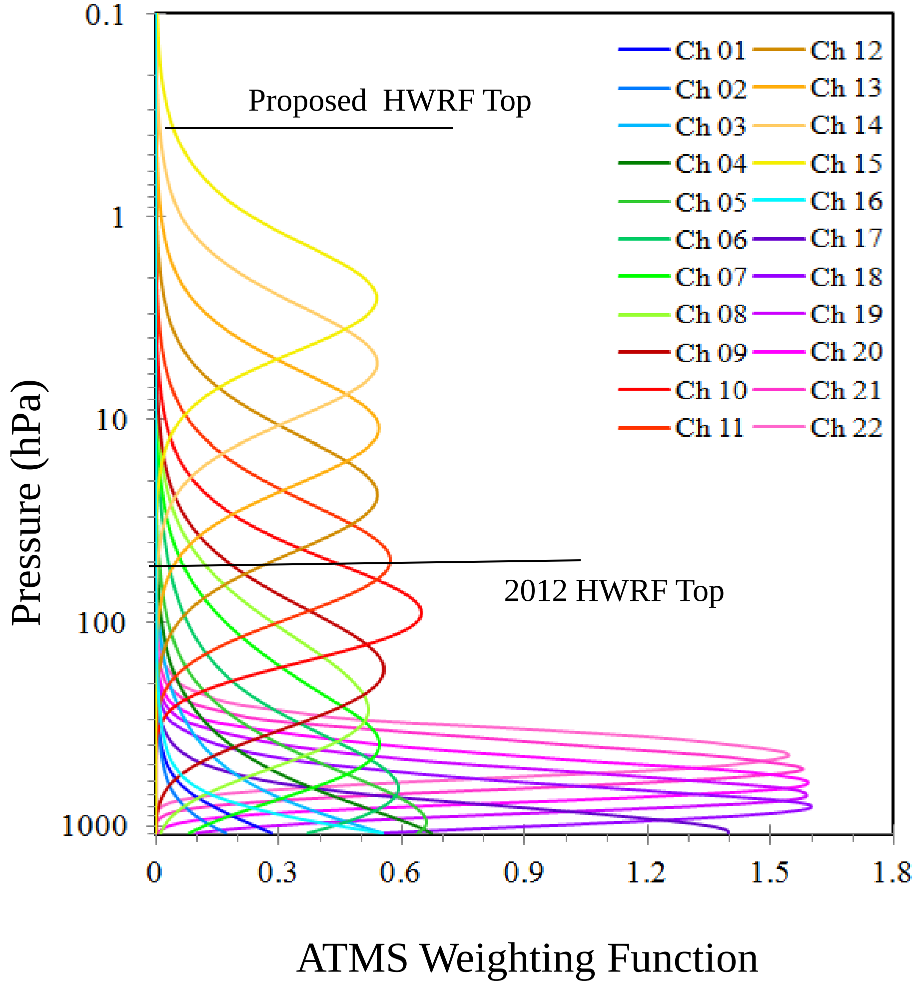
Parent domain
27 km, 750x750

Middle Nest
9 km, 238x150

The Best Tracks of Four 2012 Atlantic Landfall Hurricanes

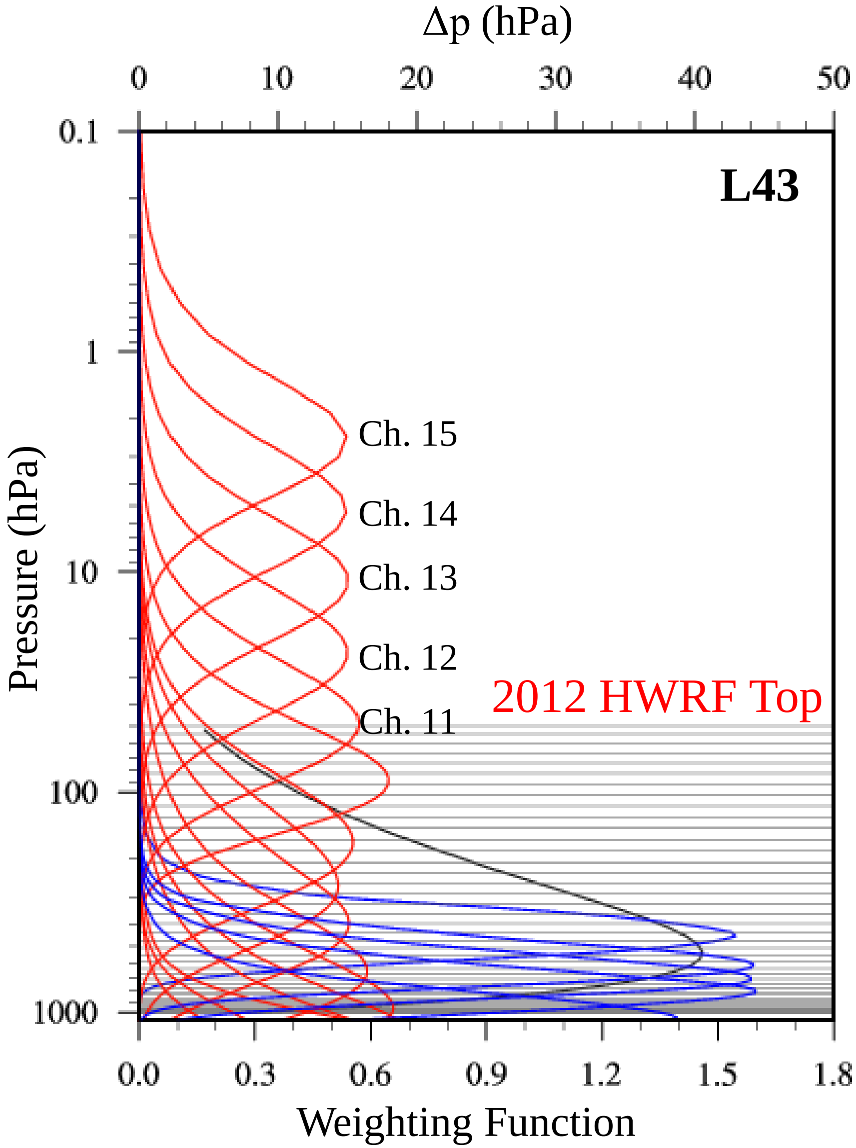


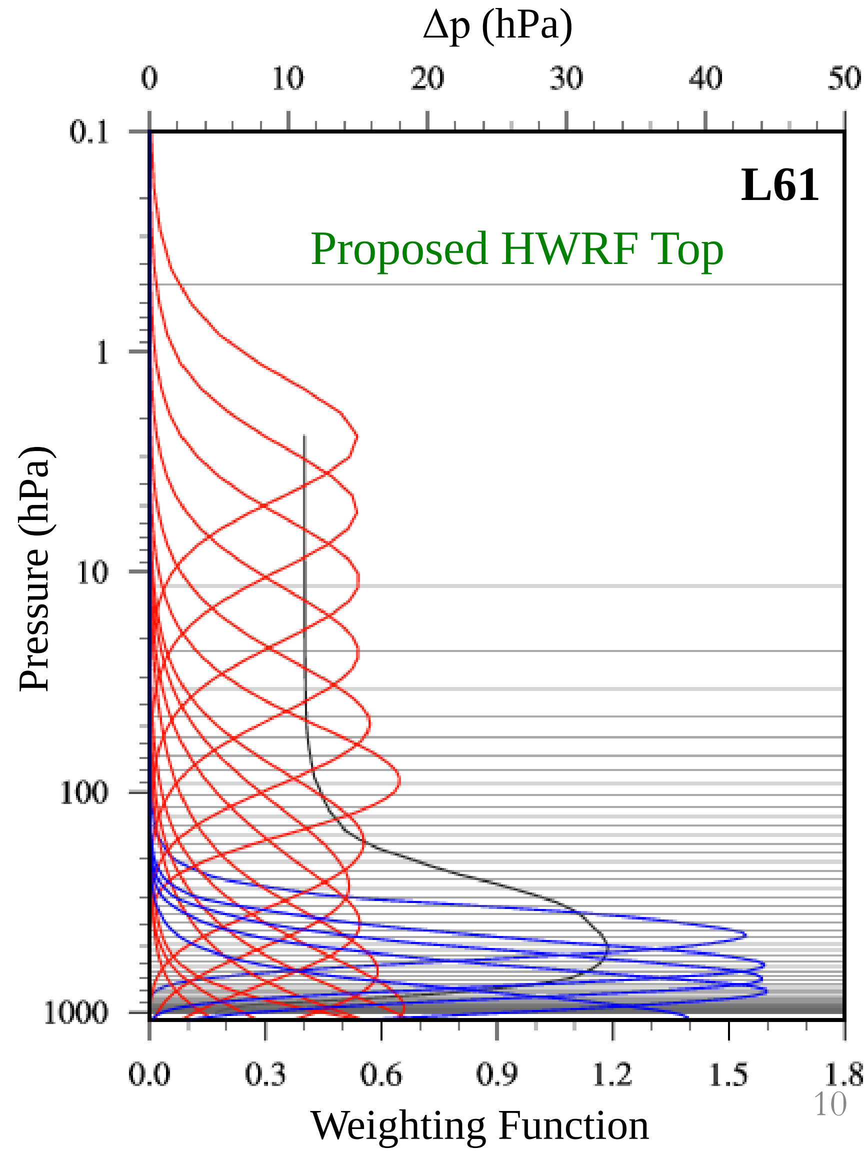
ATMS Weighting Functions

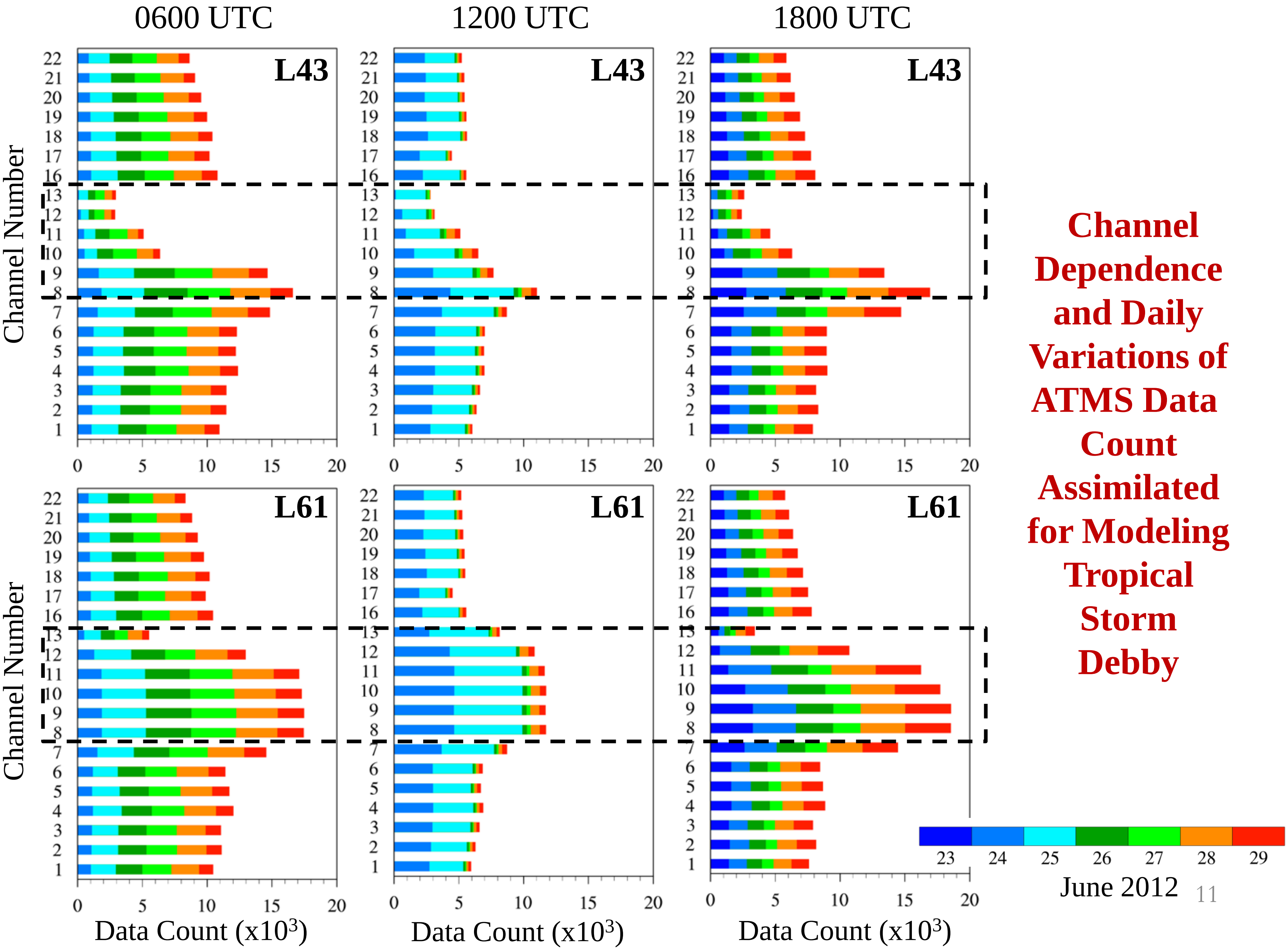


Our approach: Raise the model top to allow for more satellite data be assimilated into hurricane forecast model

Weighting Functions for ATMS Channels

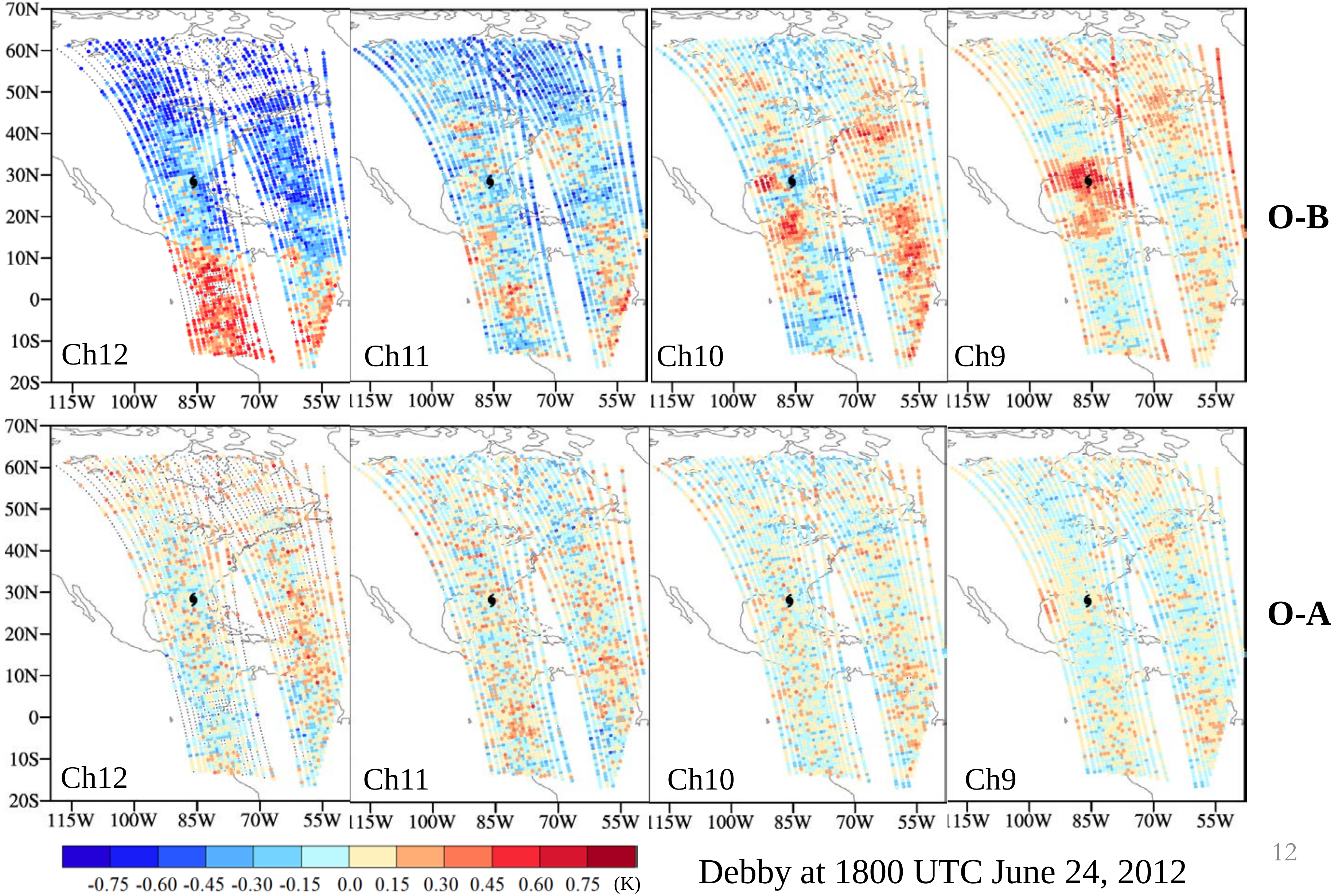






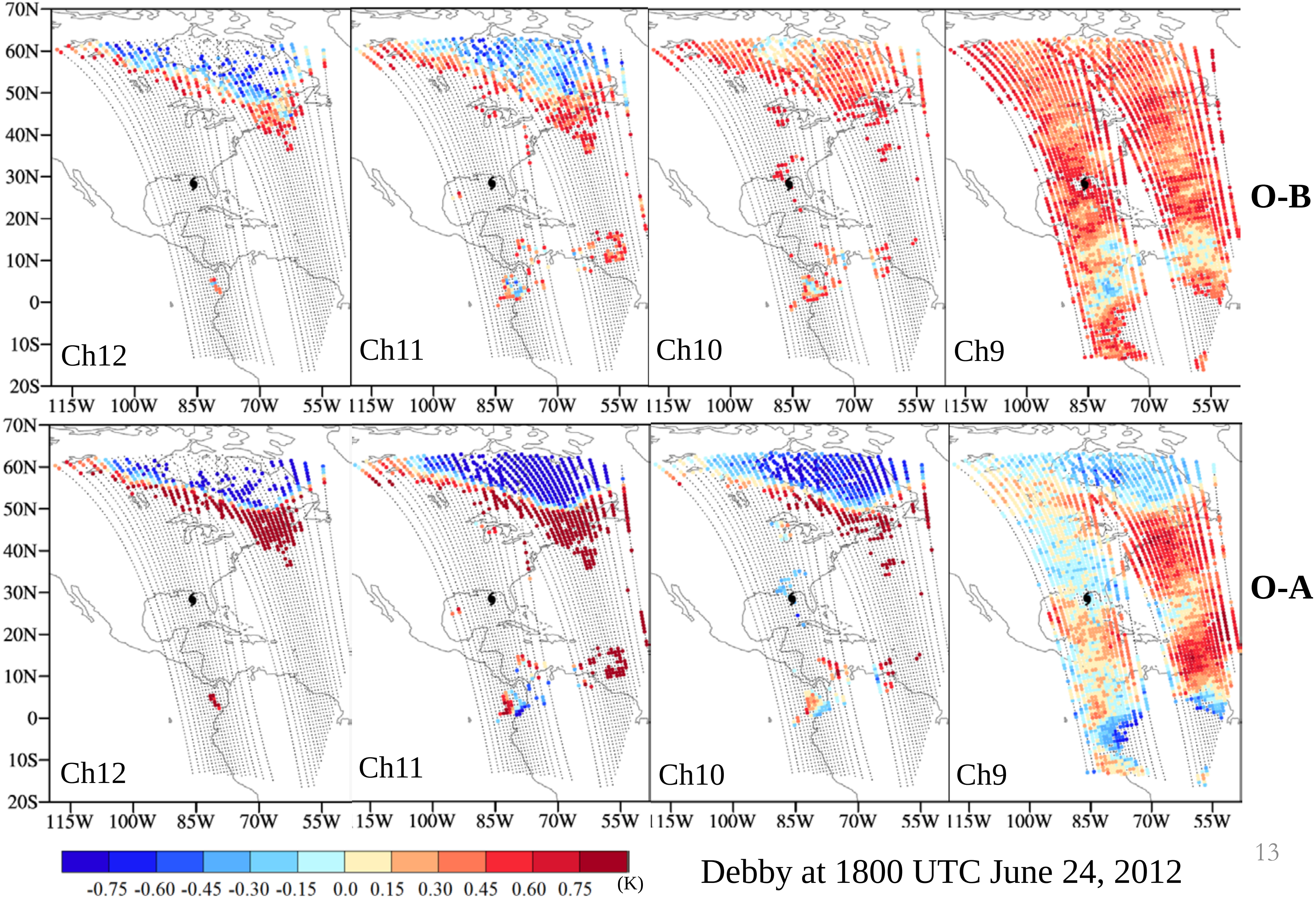
Channel Dependence and Daily Variations of ATMS Data Count Assimilated for Modeling Tropical Storm Debby

Convergence of ATMS Data Assimilation in L61



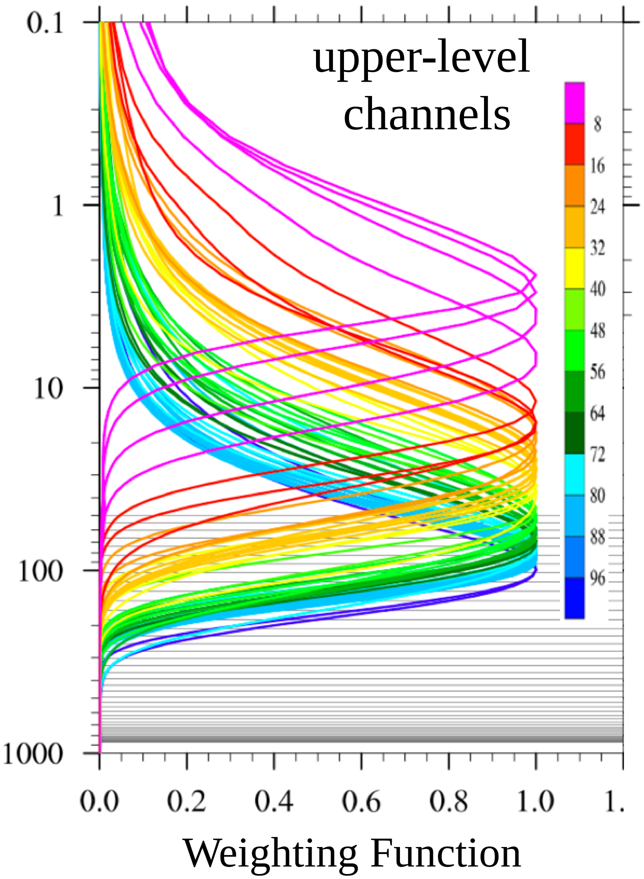
Debby at 1800 UTC June 24, 2012

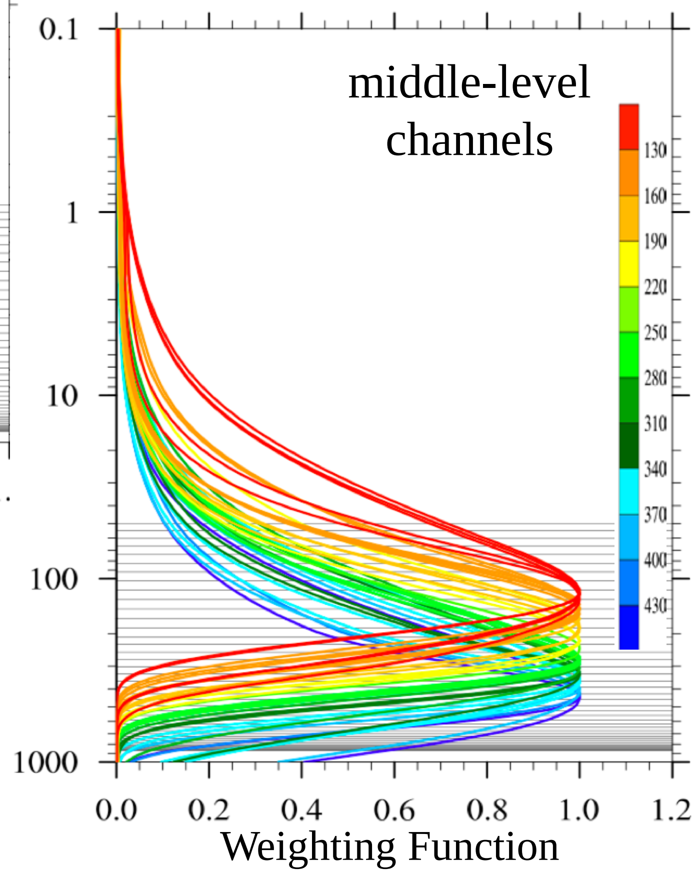
Convergence of ATMS Data Assimilation in L43

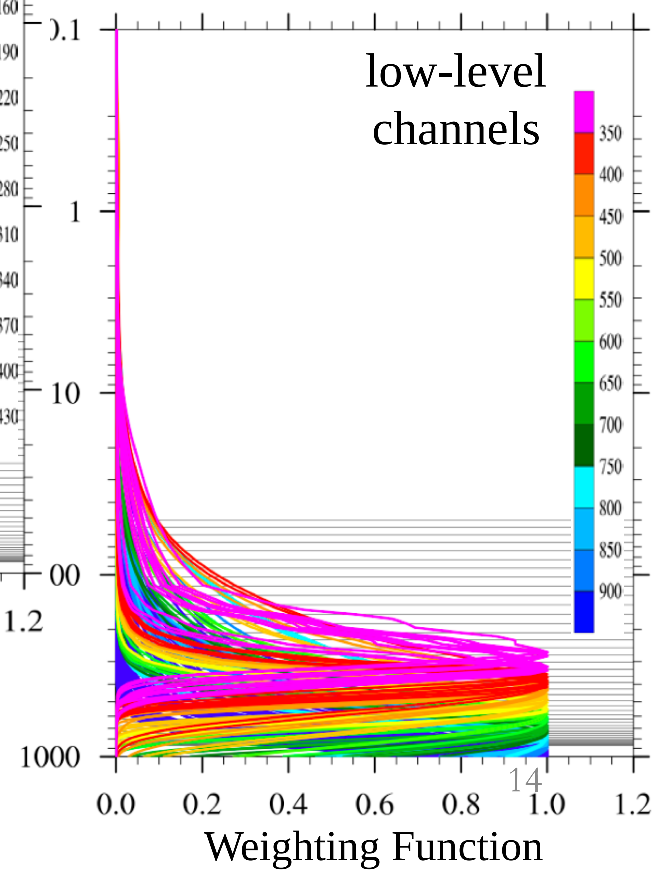


Debby at 1800 UTC June 24, 2012

AIRS Channels (281)

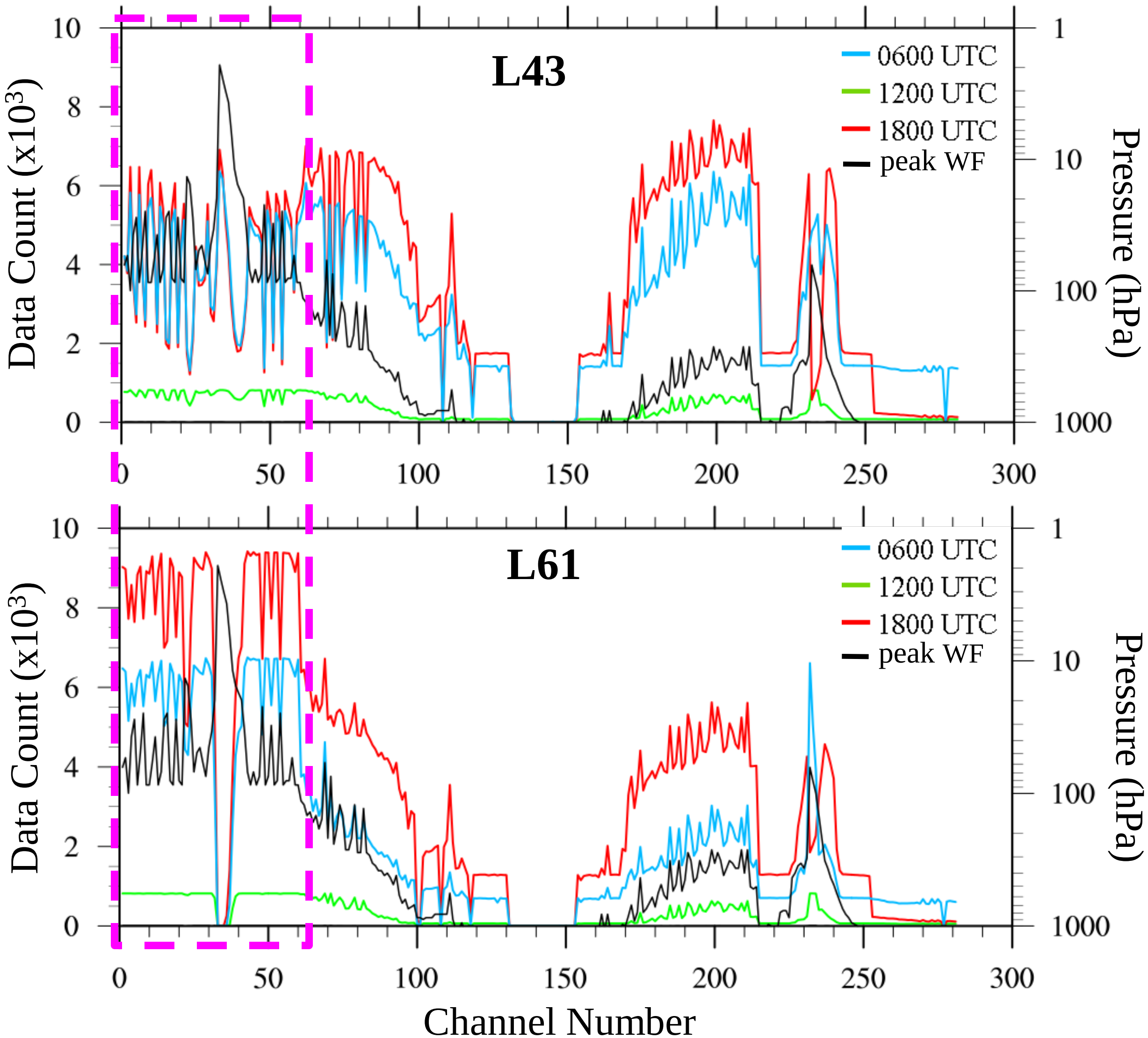






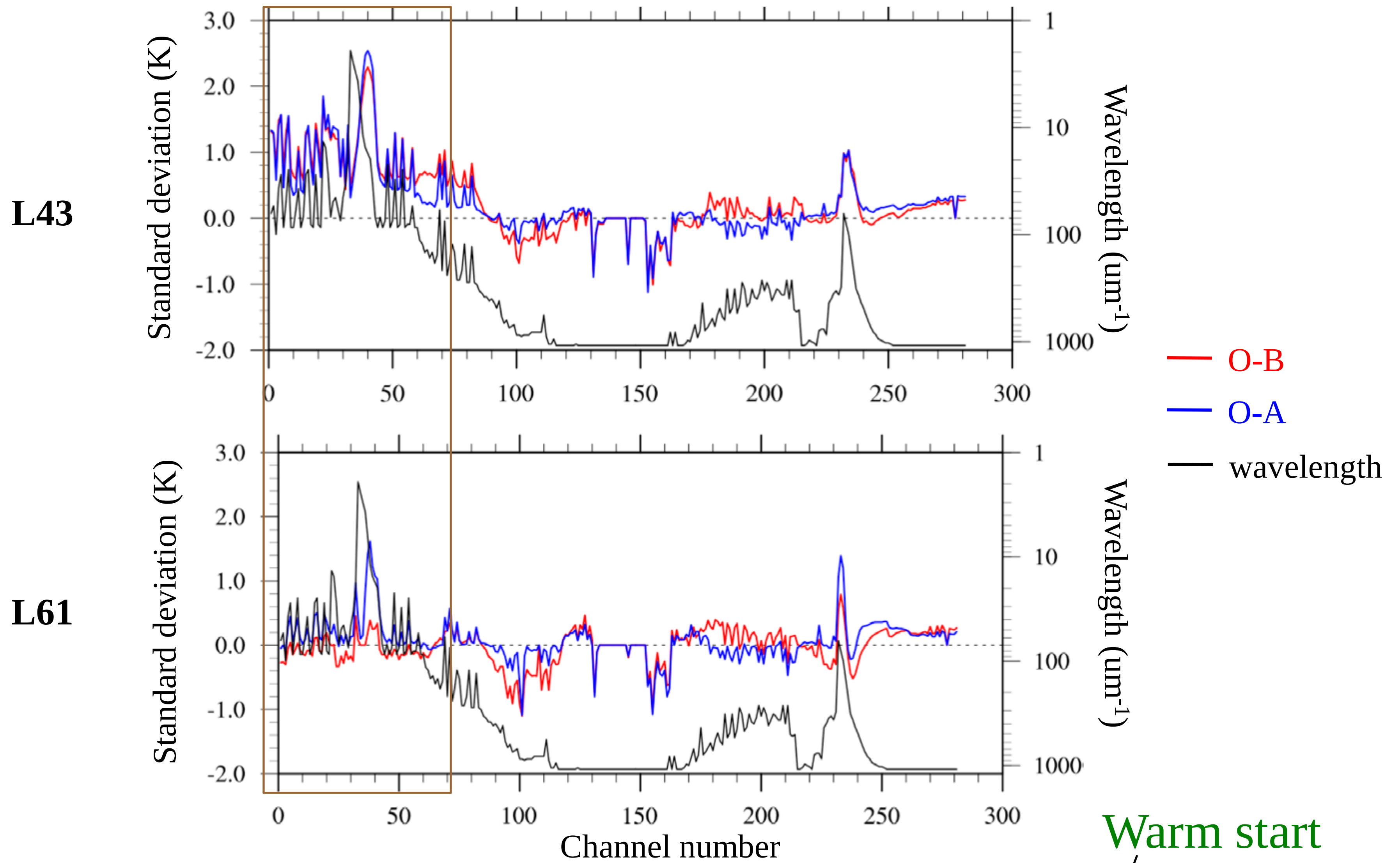
These 281 channels are selected for data assimilation in the GSI/HWRF system. The pressure at which WF reaches a maximum is indicated in color.

AIRS Channel Dependence of Data Count Assimilated During Tropical Storm Debby



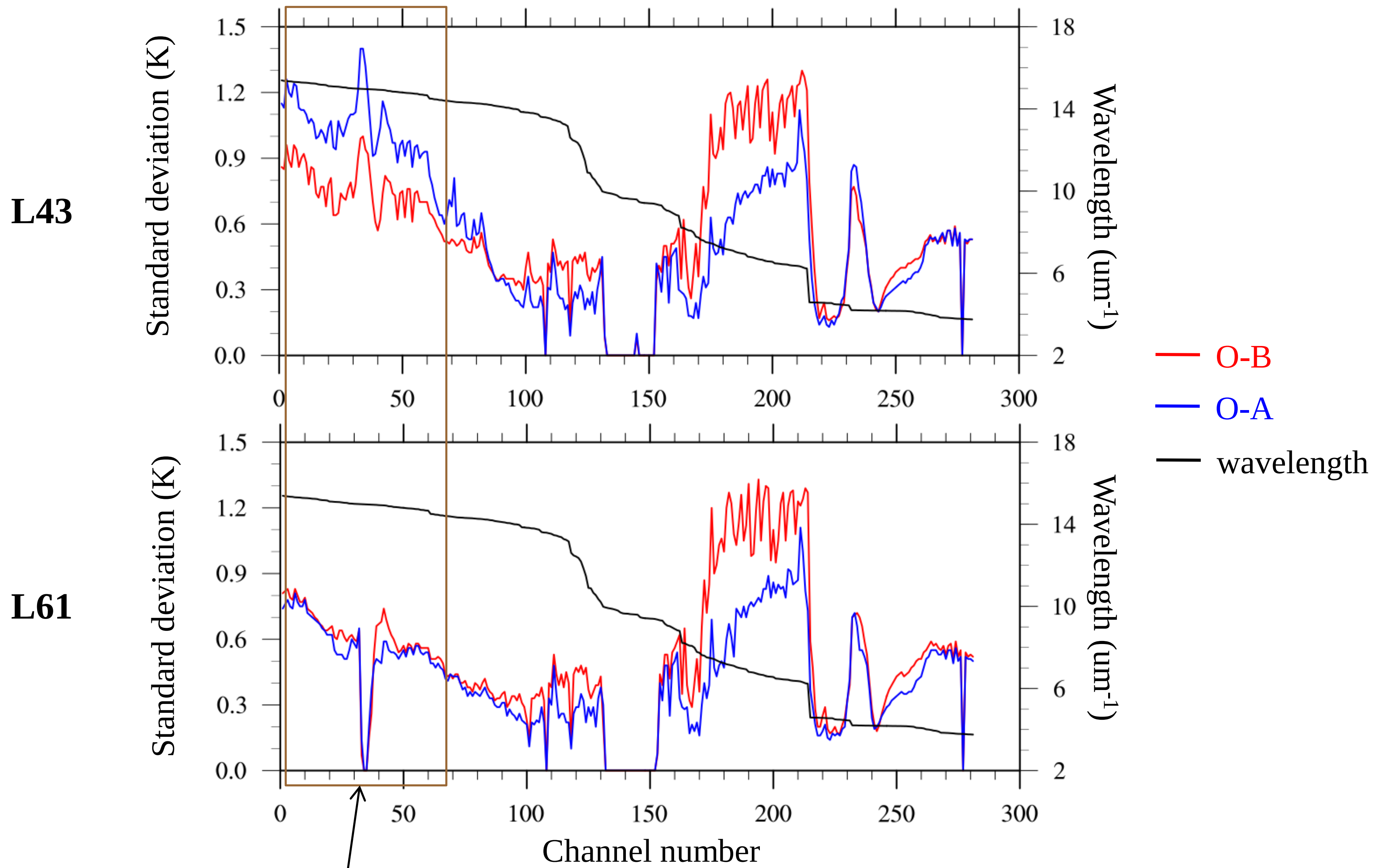
More upper-level channel data are assimilated in L61 with a higher model top (0.5 hPa) than L43 whose model top is located around 50 hPa.

Mean of O-B and O-A from AIRS Data Assimilation



Large positive biases are present in both O-B and O-A fields for many upper-level AIRS channels in L43 but not in L61. L43 background fields are different from L61.

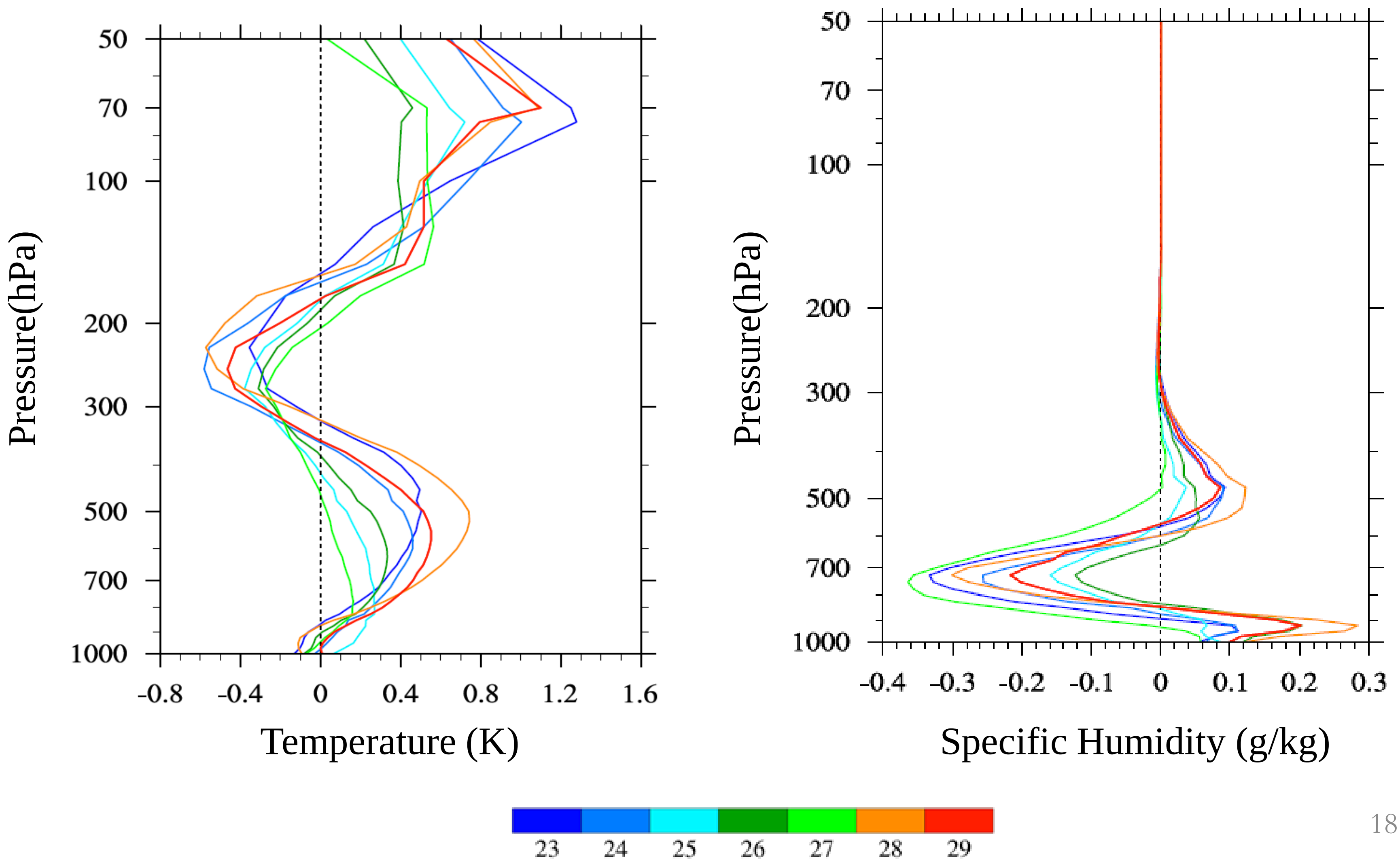
Standard Deviation of O-B and O-A from AIRS DA



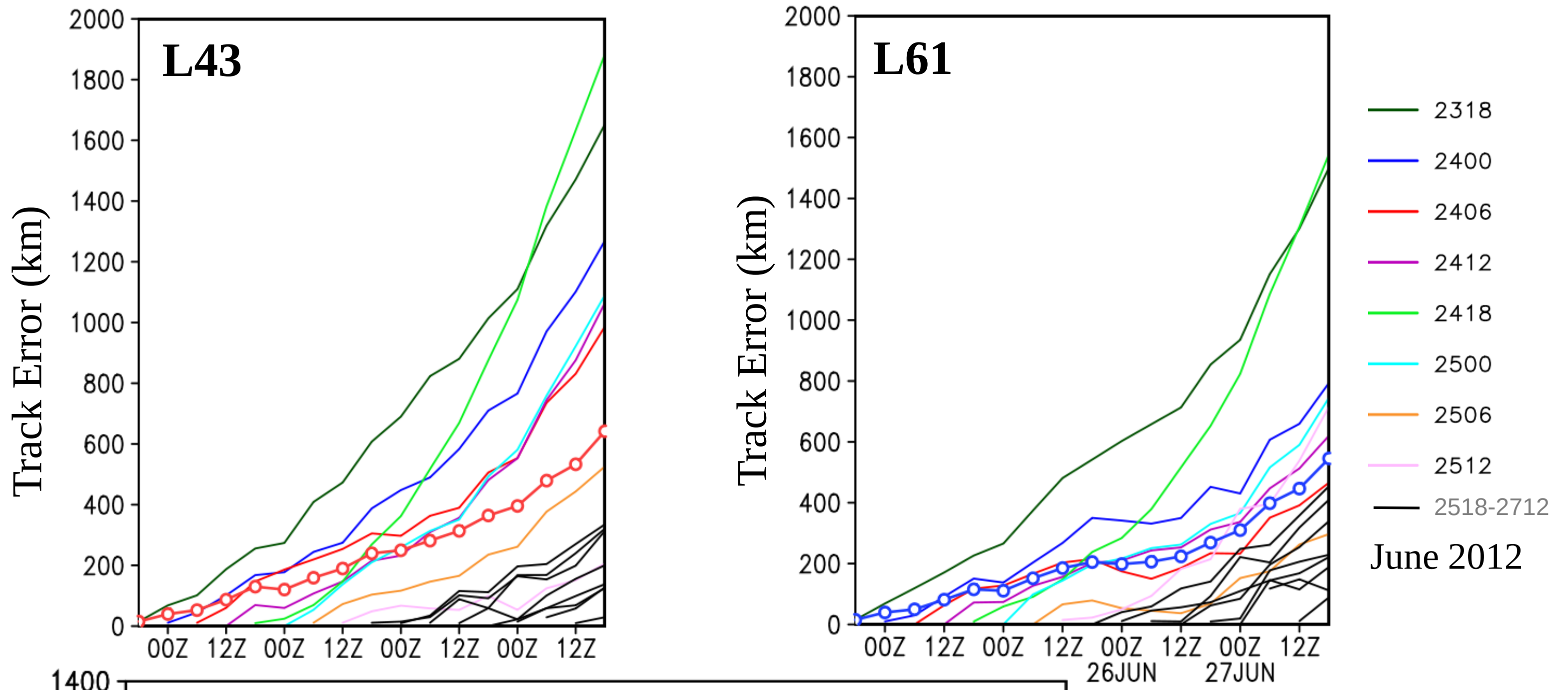
The standard deviation of O-A is greater than that of O-B for upper-level AIRS channels in L43.

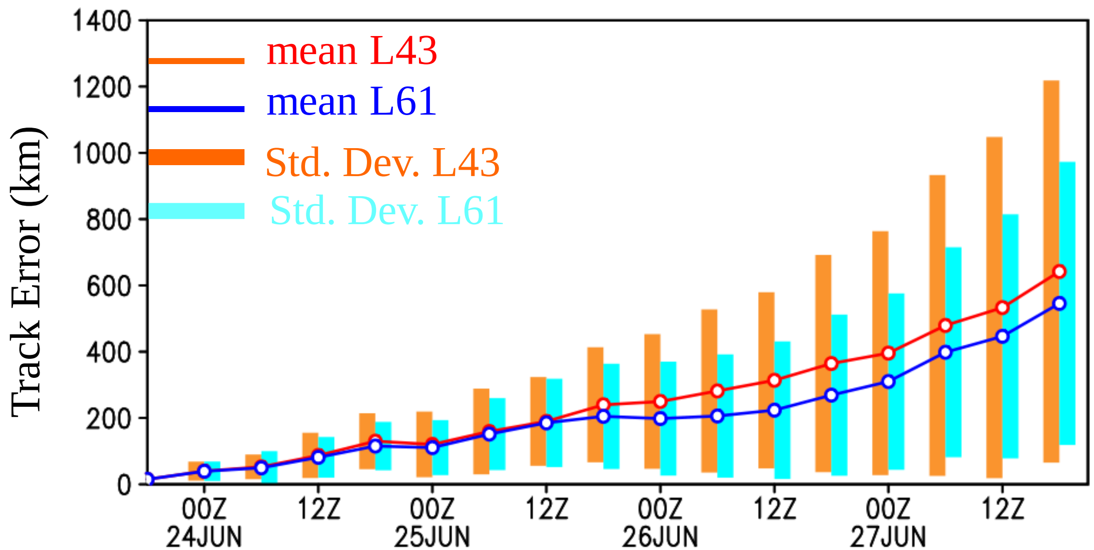
Background Differences between L61 and L43 (L43 – L61)

1800 UTC from June 23 to June 29, 2012 after one-day DA cycle



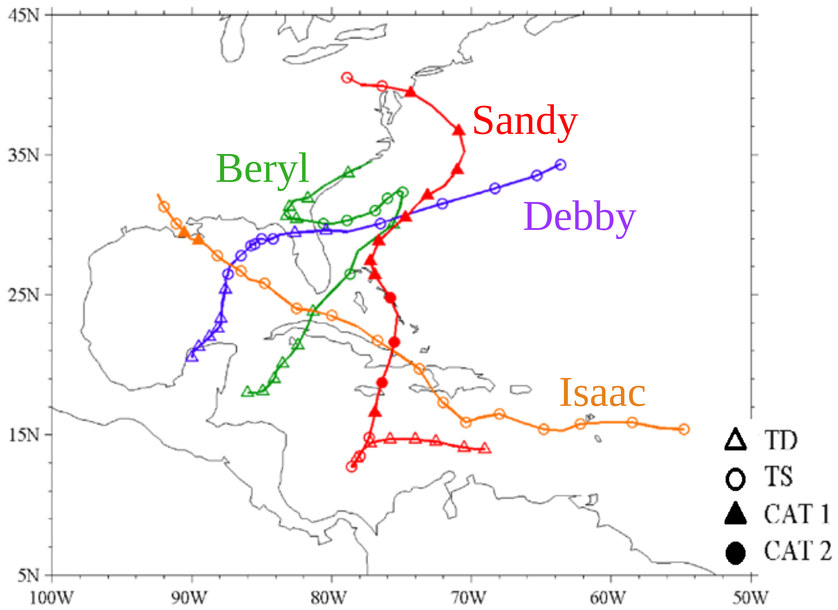
Track Forecasts for Tropical Storm Debby

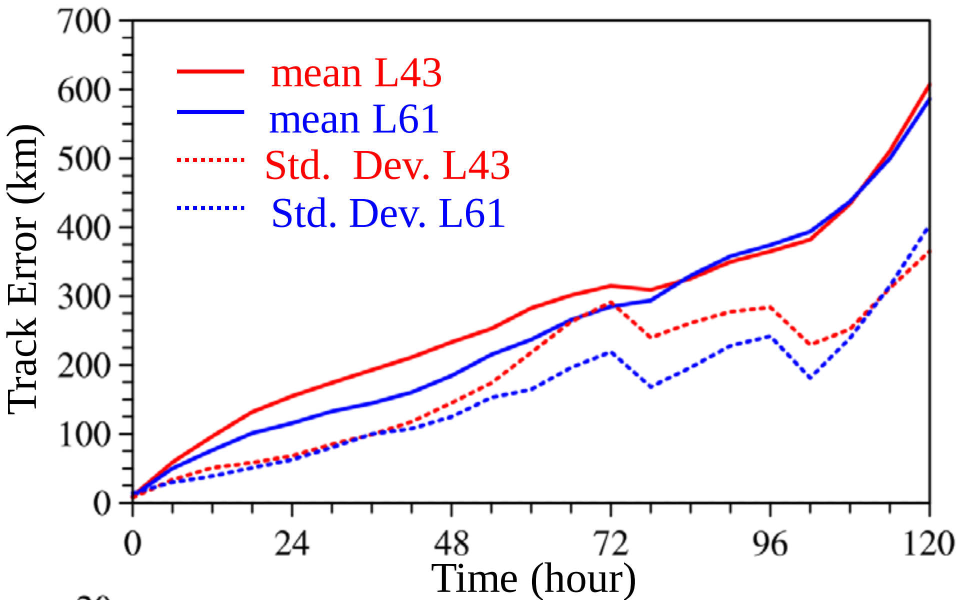


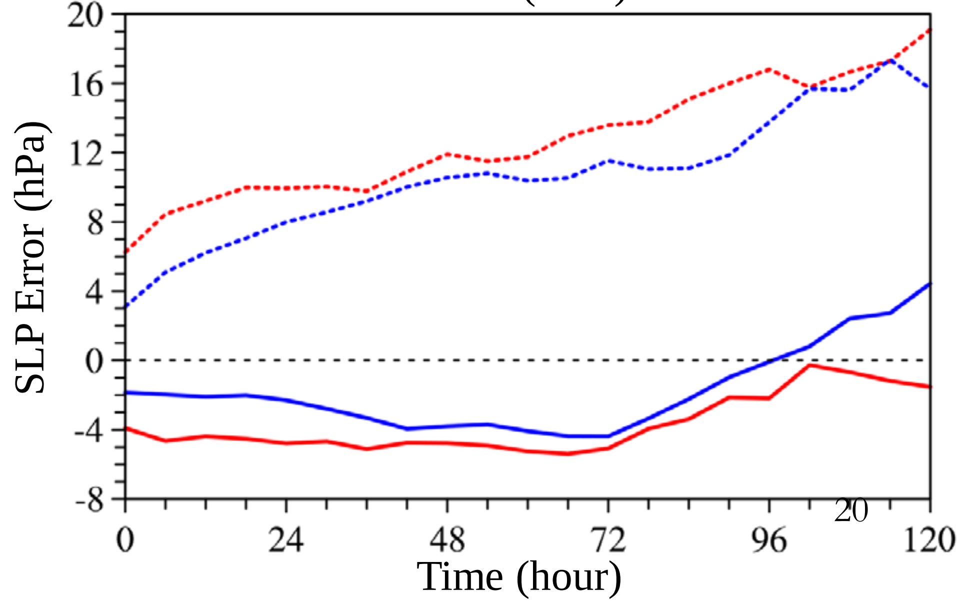


Both the mean and standard deviation of the track forecasts by L61 are smaller than those from L43.

Impacts of Model Top Altitude on Track and Intensity Forecasts for Four 2012 Atlantic Hurricanes







Biases and standard deviations for both track and intensity forecast errors are reduced by raising the model top of the HWRF system.

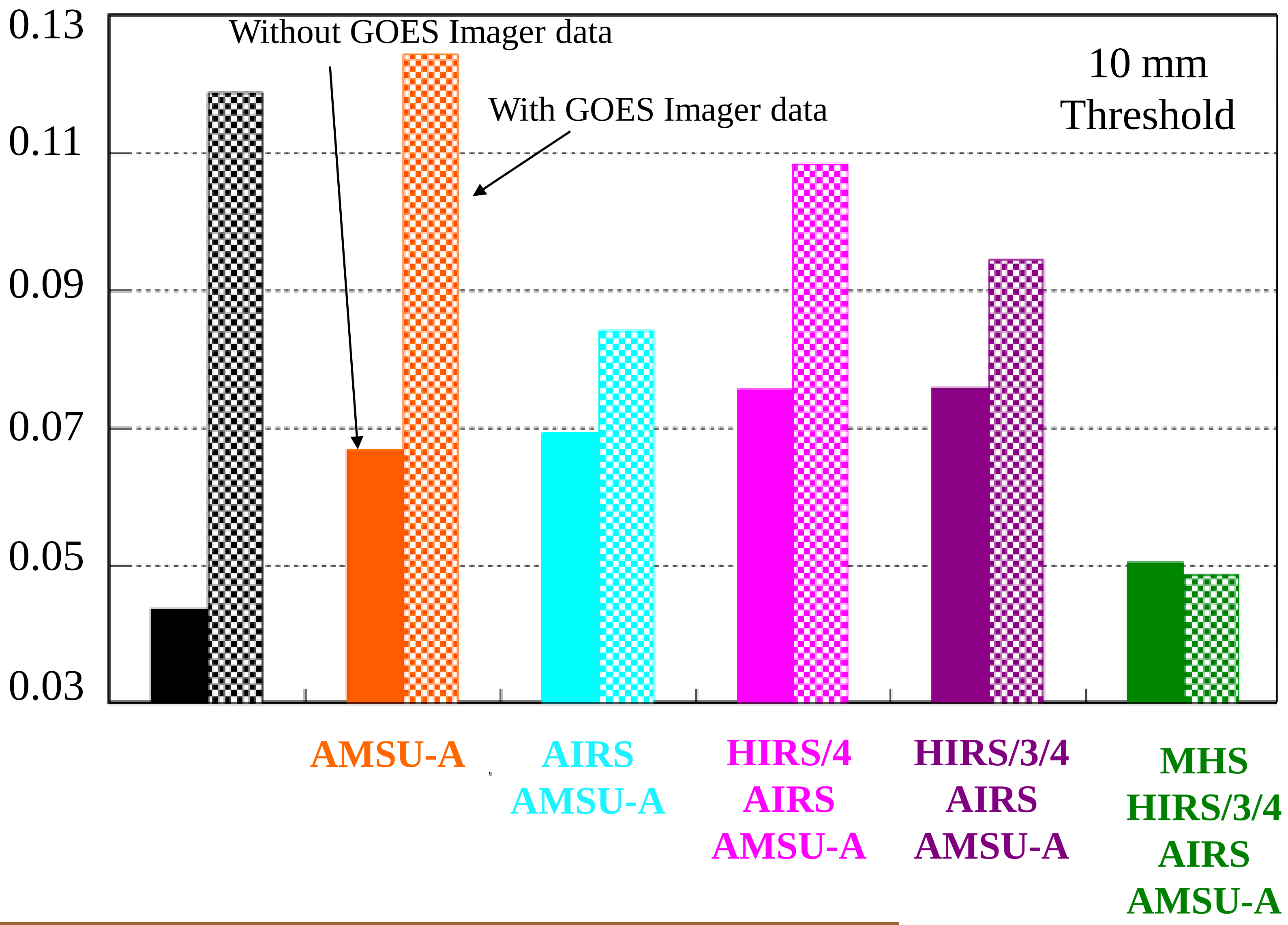
3. Positive Impacts of ATMS DA on Hurricane Forecasts

- Detrimental impacts of MHS DA on QPFs

- ATMS FOVs T and q channels are collocated, which makes the cloud detection much more effective

- Impacts of ATMS data assimilation are consistently positive. ATMS water vapor sounding channels contribute positively to hurricane forecasts due to improved QC

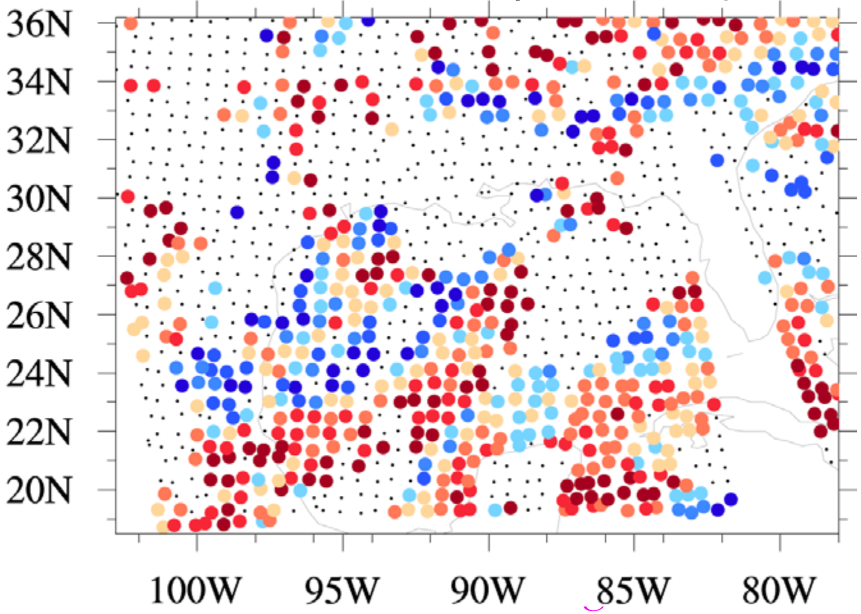
Threat Scores of 24-h Accumulative Rainfall



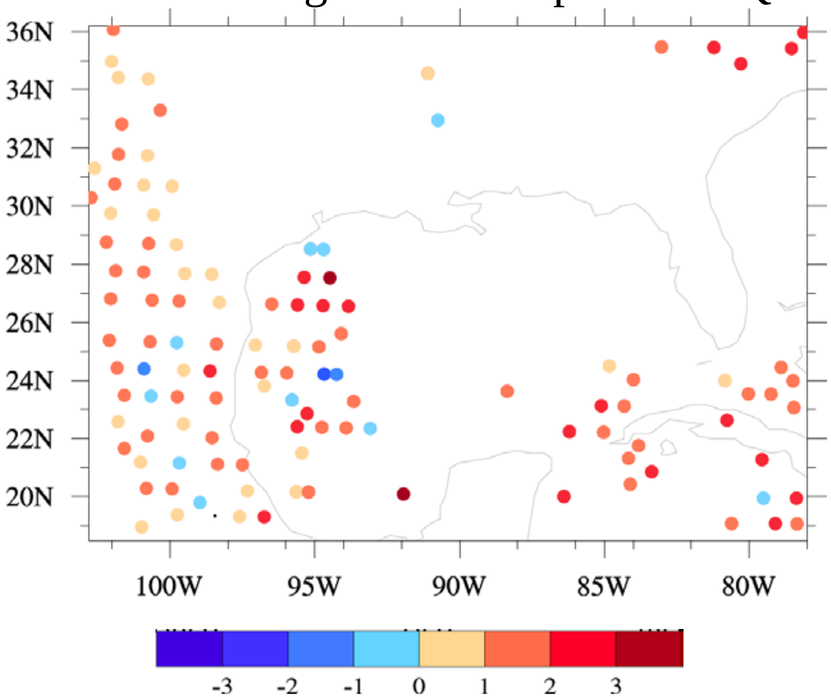
A detrimental impact of MHS DA on QPFs!

O-B Data Distribution of MHS Channel 3 at 1800 UTC 22 May 2008

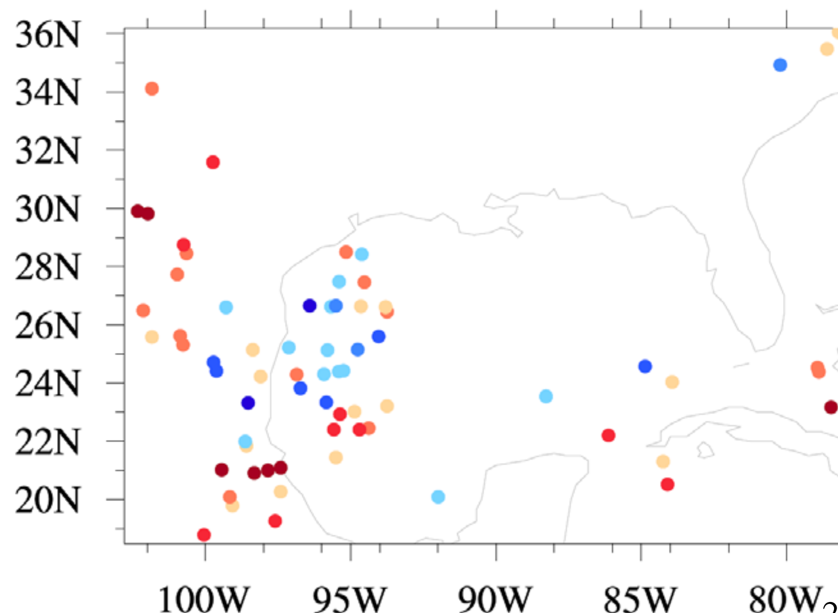
MHS data that pass GSI QC

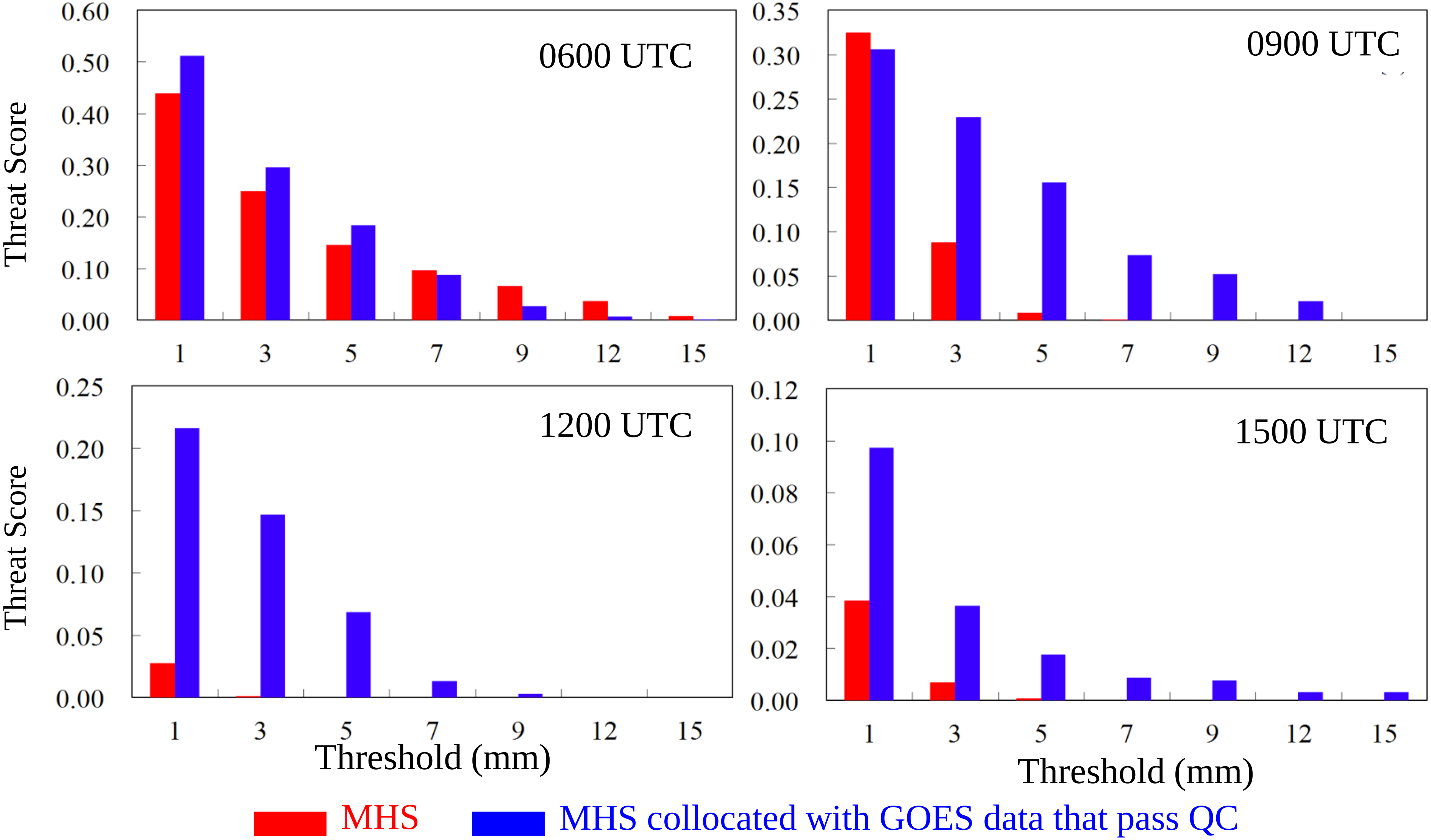


GOES imager data that pass GSI QC



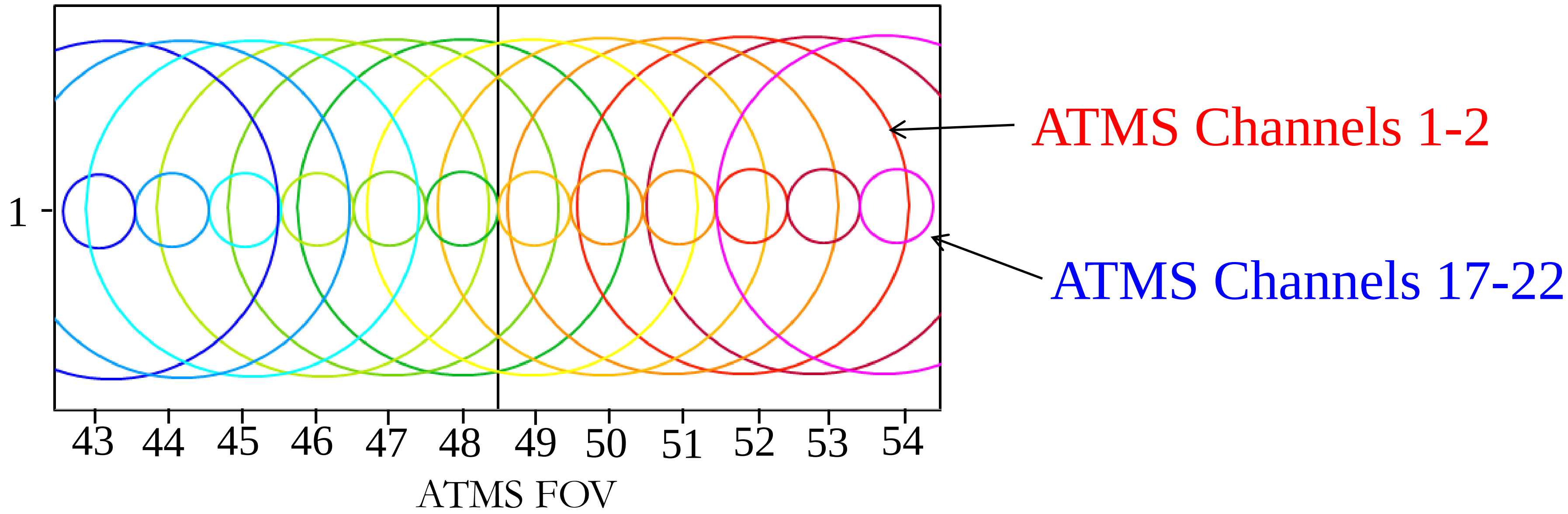
MHS data collocated with GOES imager data that pass GSI QC

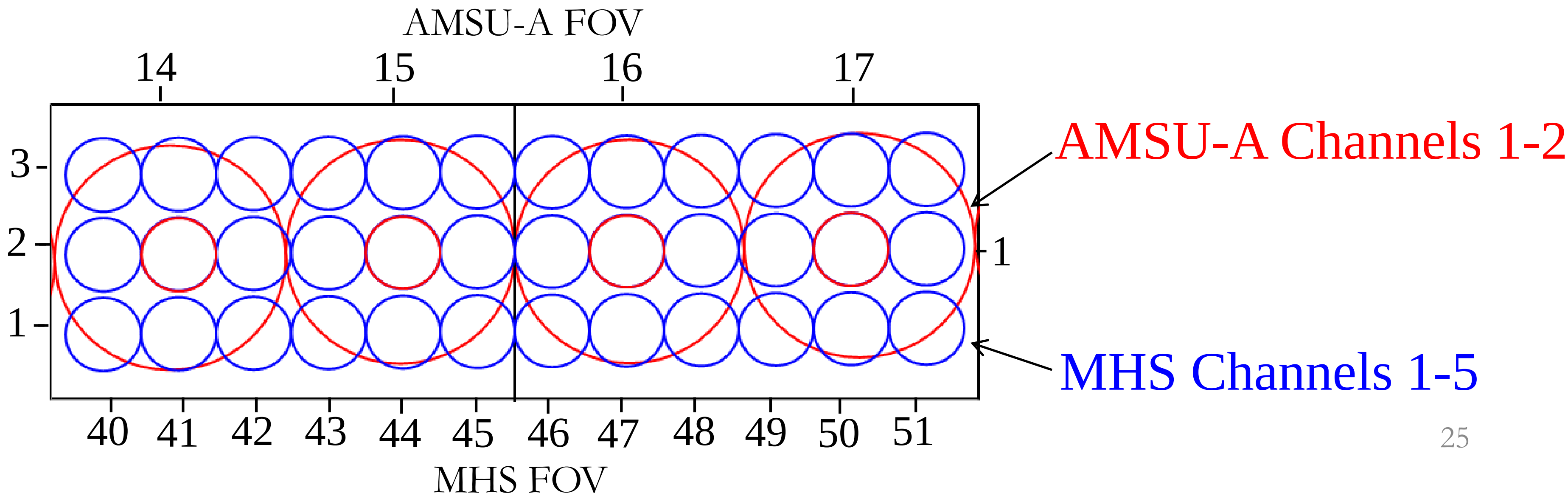




An elimination of MHS data over areas where GOES imager QC detects clouds improved the impact of MHS data assimilation on quantitative precipitation forecasts.

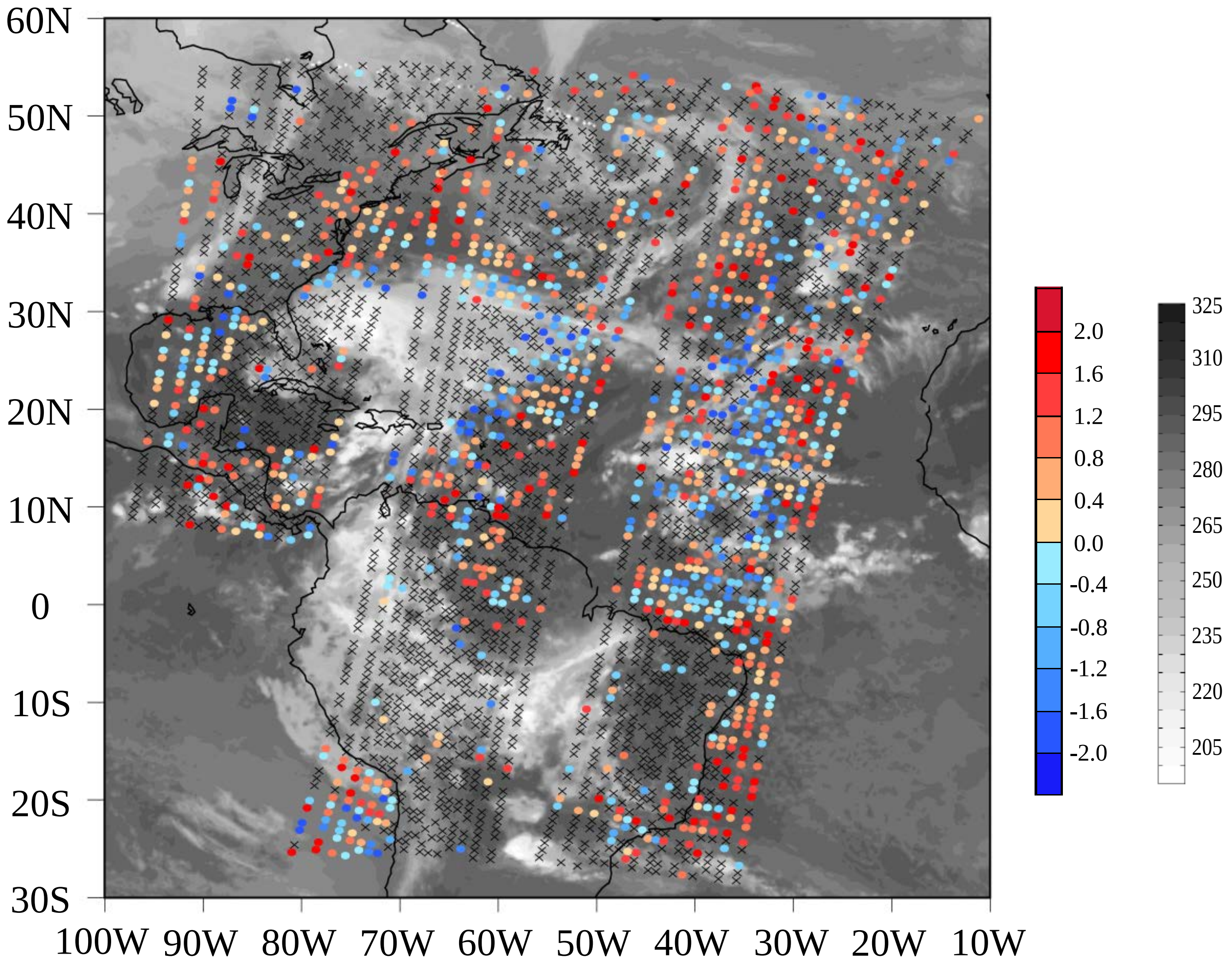
Comparison of FOV Distributions between ATMS and AMSU





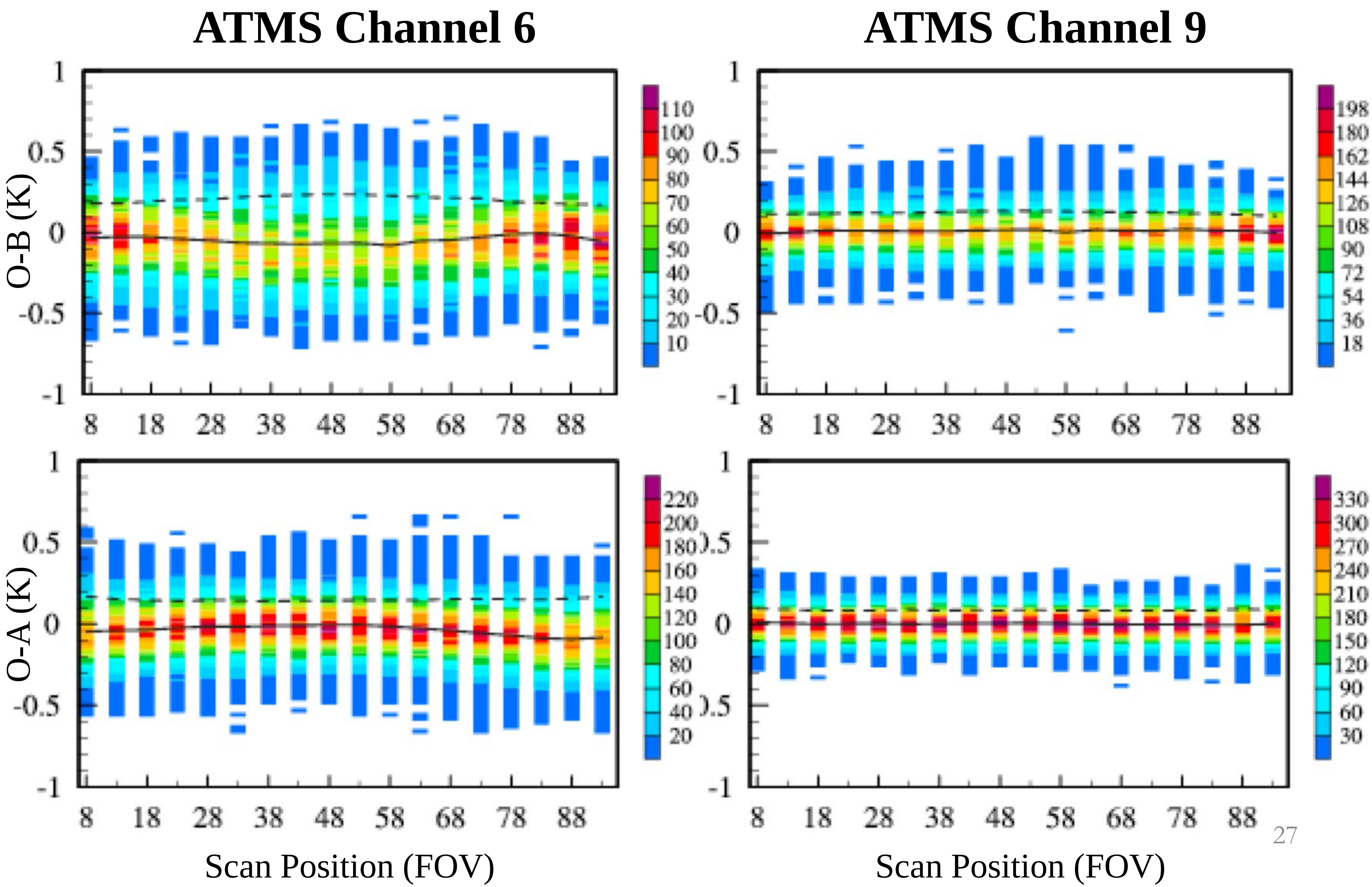
ATMS Quality Control in HWRF/GSI

O-B
ATMS Ch19

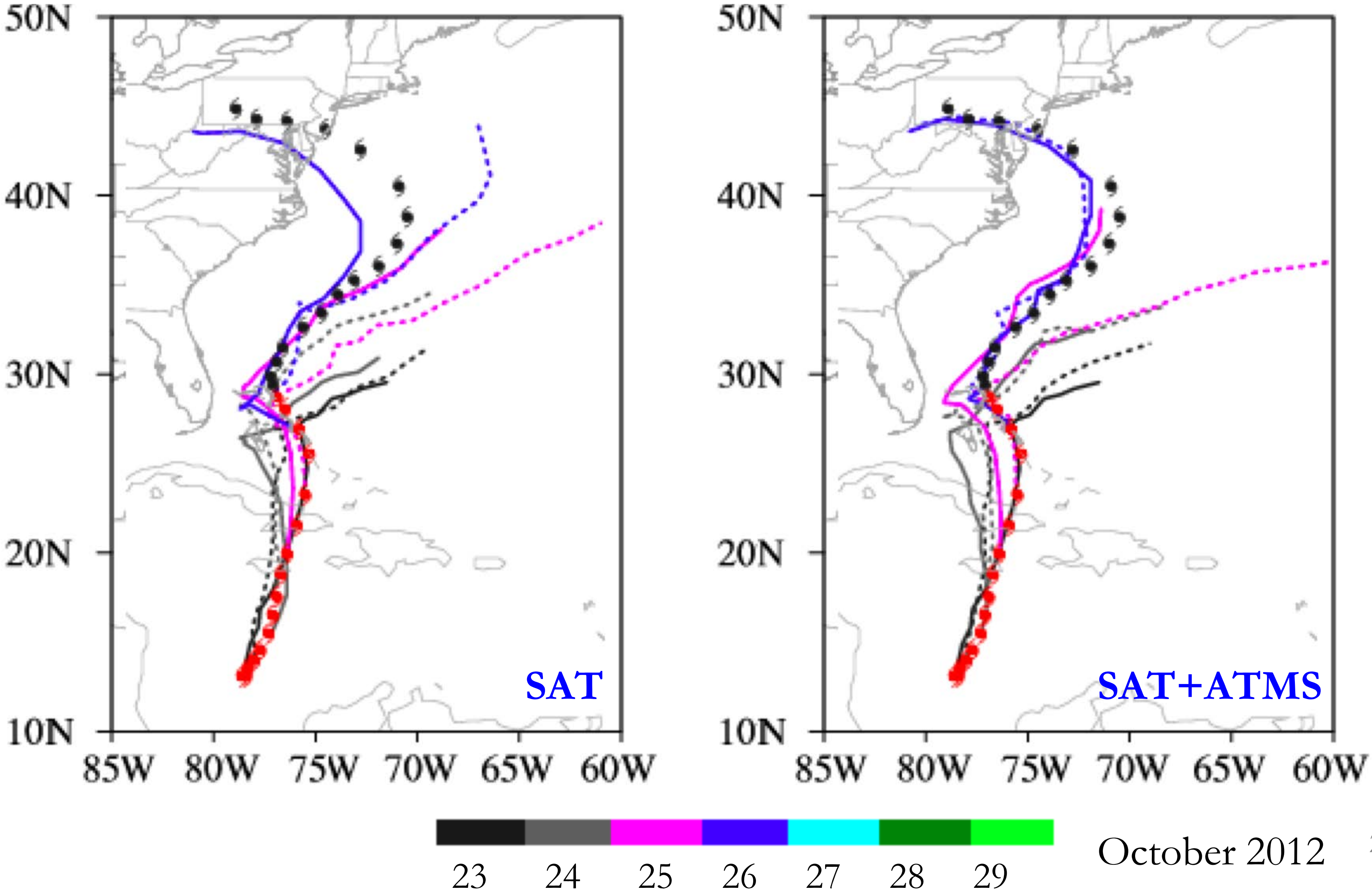


GSI QC performs well for ATMS water vapor sounding channels due to the use of more window channels (1, 2, 16, 17) for cloud detection

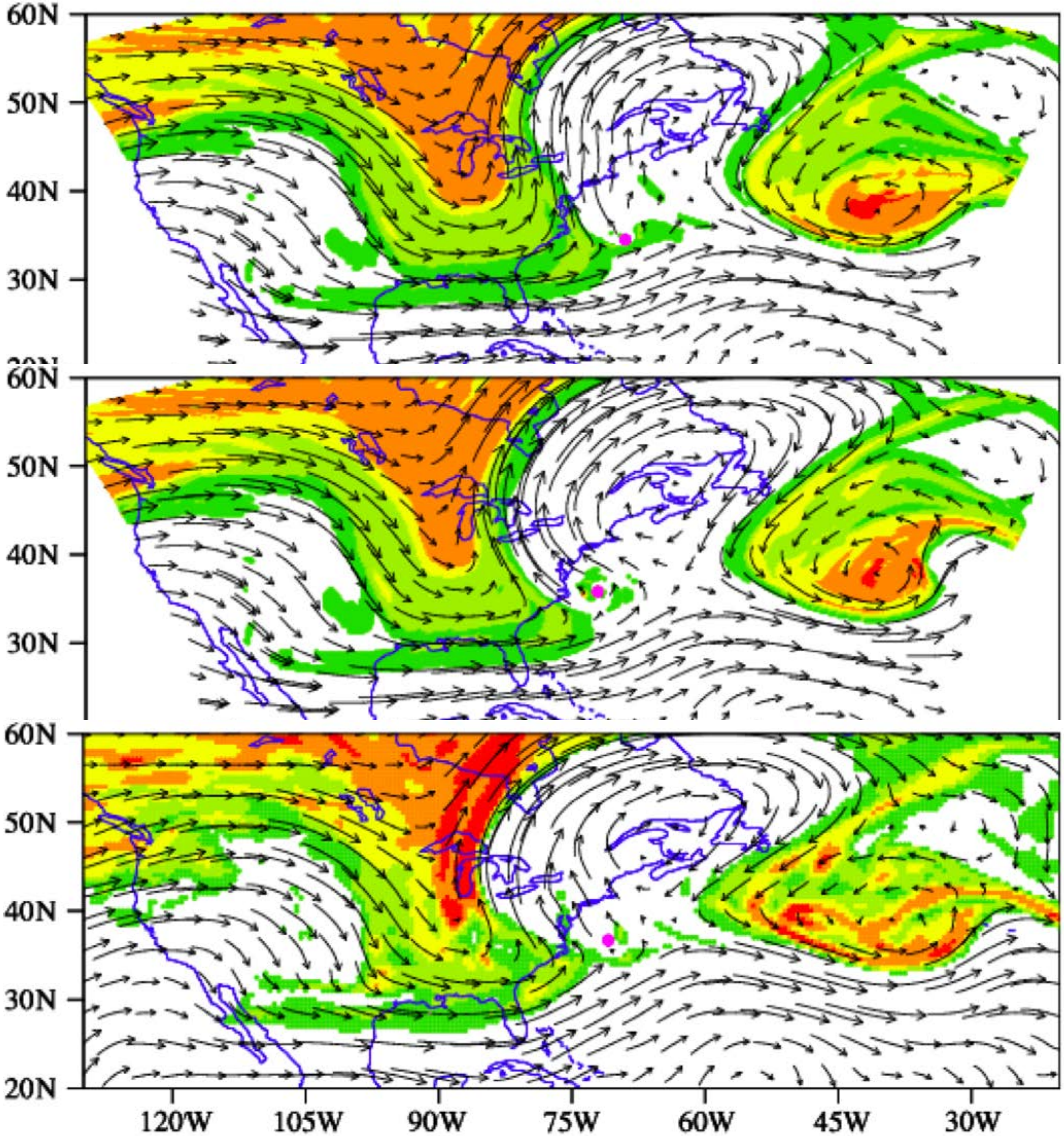
O-B and O-A Data Counts for Hurricane Isaac



Impacts of ATMS Data Assimilation on Track Forecast of Hurricane Sandy



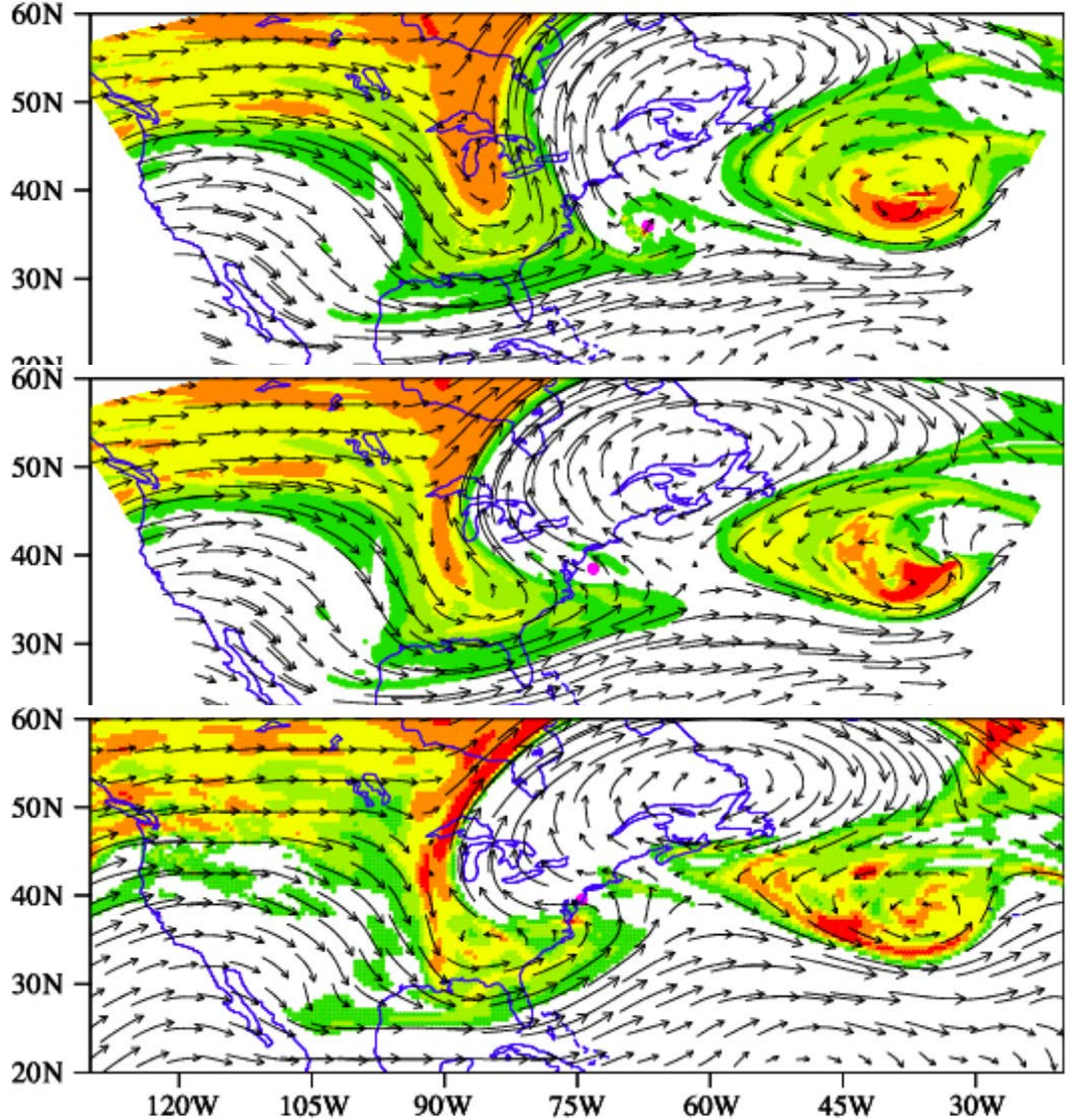
Hurricane Sandy (PV at 200 hPa)



72-h Forecast without ATMS

72-h Forecast with ATMS

NCEP GFS analysis 1200 UTC October 29



Hurricane Sandy (PV at 200 hPa)

84-h Forecast without ATMS

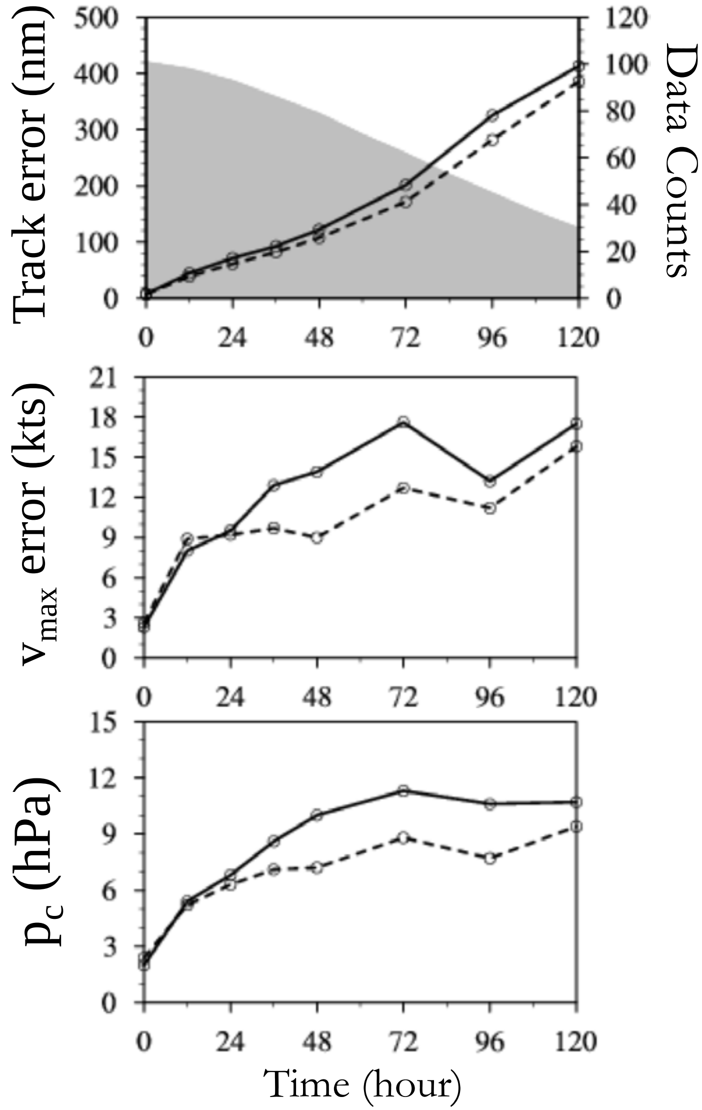
84-h Forecast with ATMS

NCEP GFS analysis

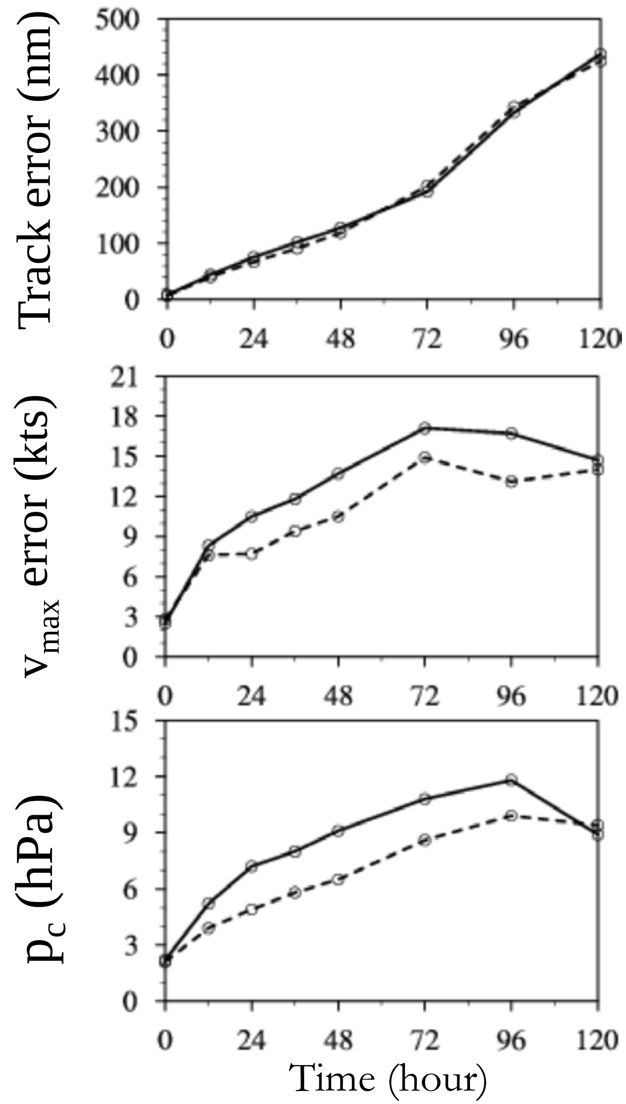
0000UTC October 30

Mean Forecast Errors for Four 2012 Atlantic Hurricanes

Impact of ATMS Data Assimilation



CONV ----- CONV+ATMS



SAT ----- SAT+ATMS

4. Mixed Impacts of CrIS DA on Hurricane Forecasts

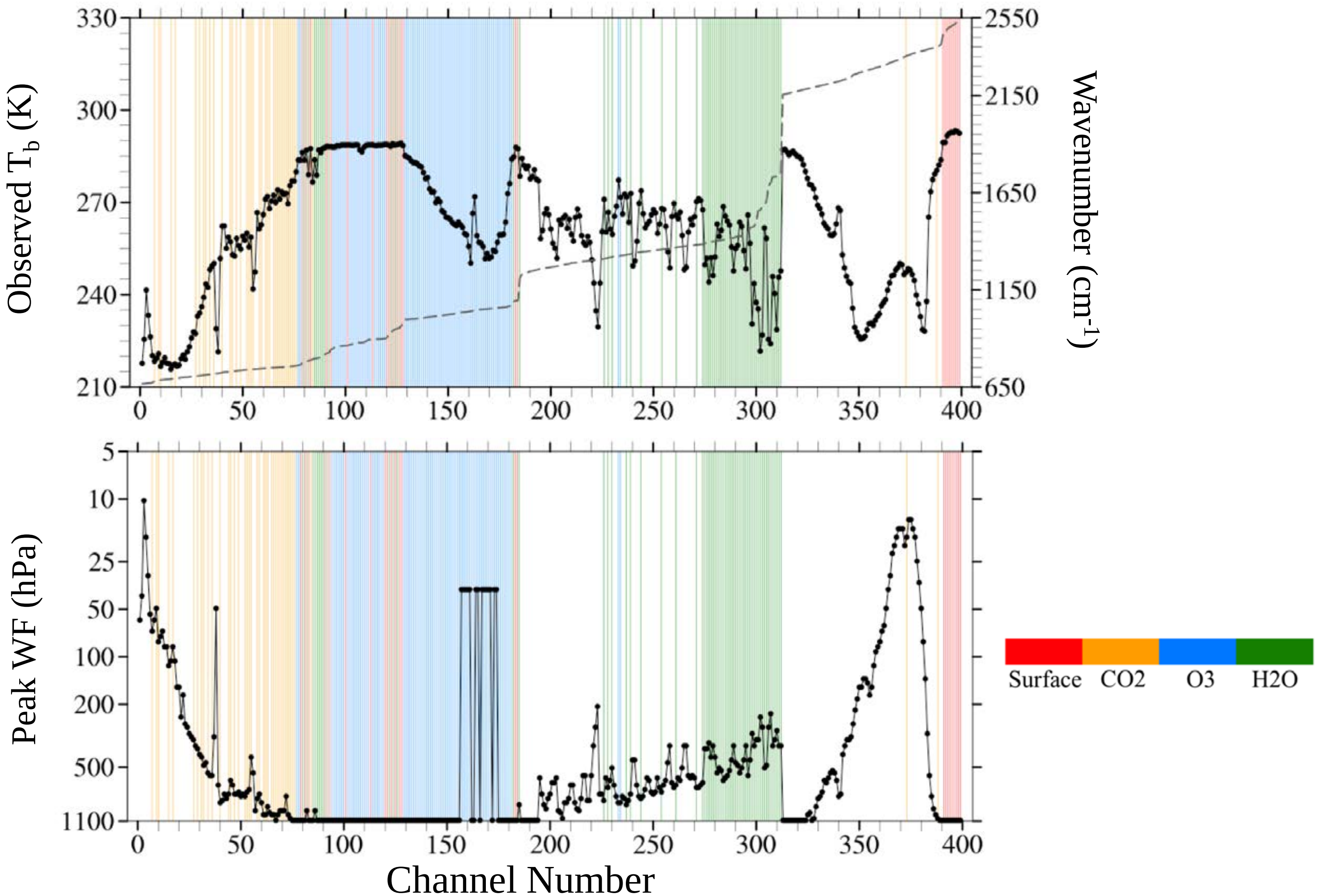
- Examples showing a mixed impact of CrIS DA on TC Forecasts

- Surface-sensitive shortwave channels (3.5-4.6 μm) are cleaner but not assimilated due to the lack of a correction of reflected reflected solar radiance over ocean at daytime

- Nonlocal Thermal Equilibrium emission at 4.3-μm CO_2 band can be as large as several degrees in Kelvin but is not corrected

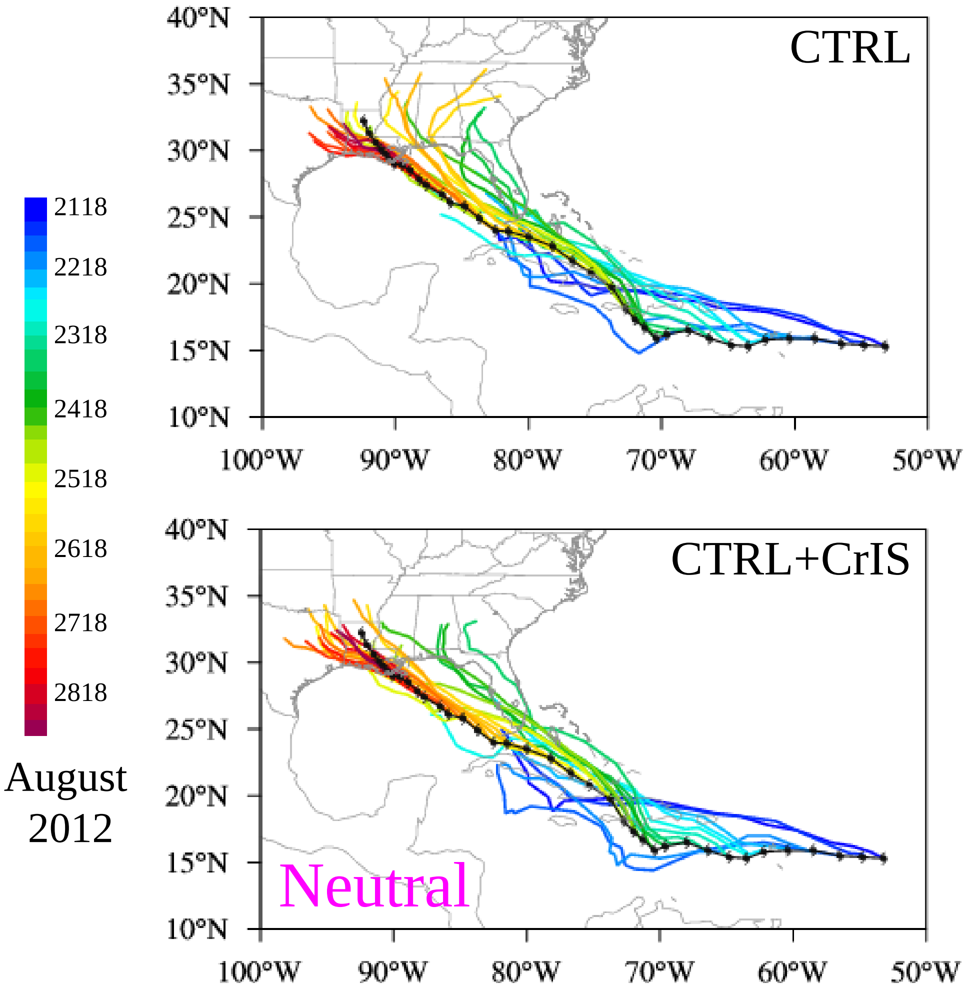
- There exists a significant discrepancy between GSI calculated and VIRRS retrieved cloud top pressures except for ? cloud

399 CrIS Channels Assimilated in HWRF

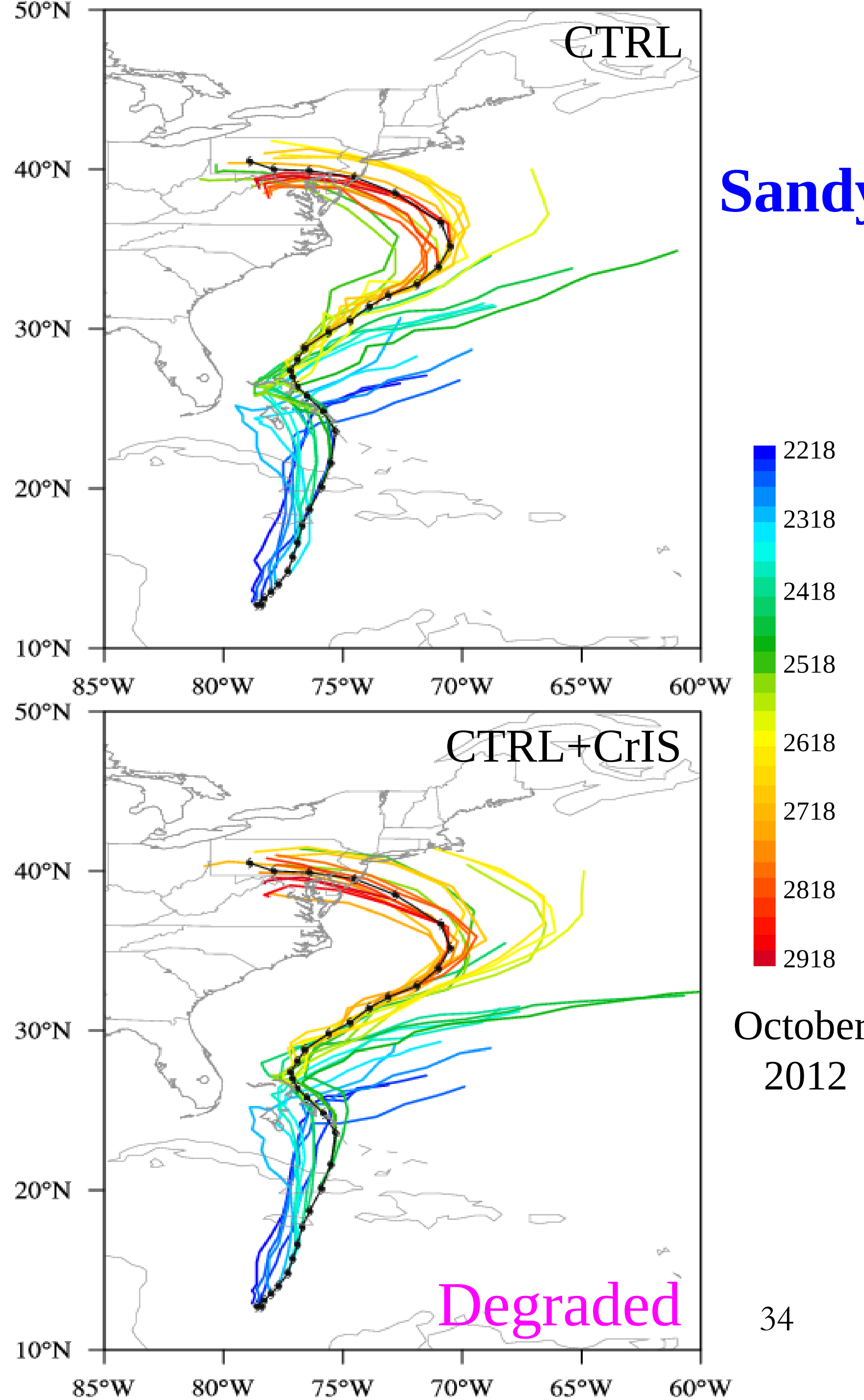


Mixed Impacts of CrIS DA on Track Forecasts

Isaac



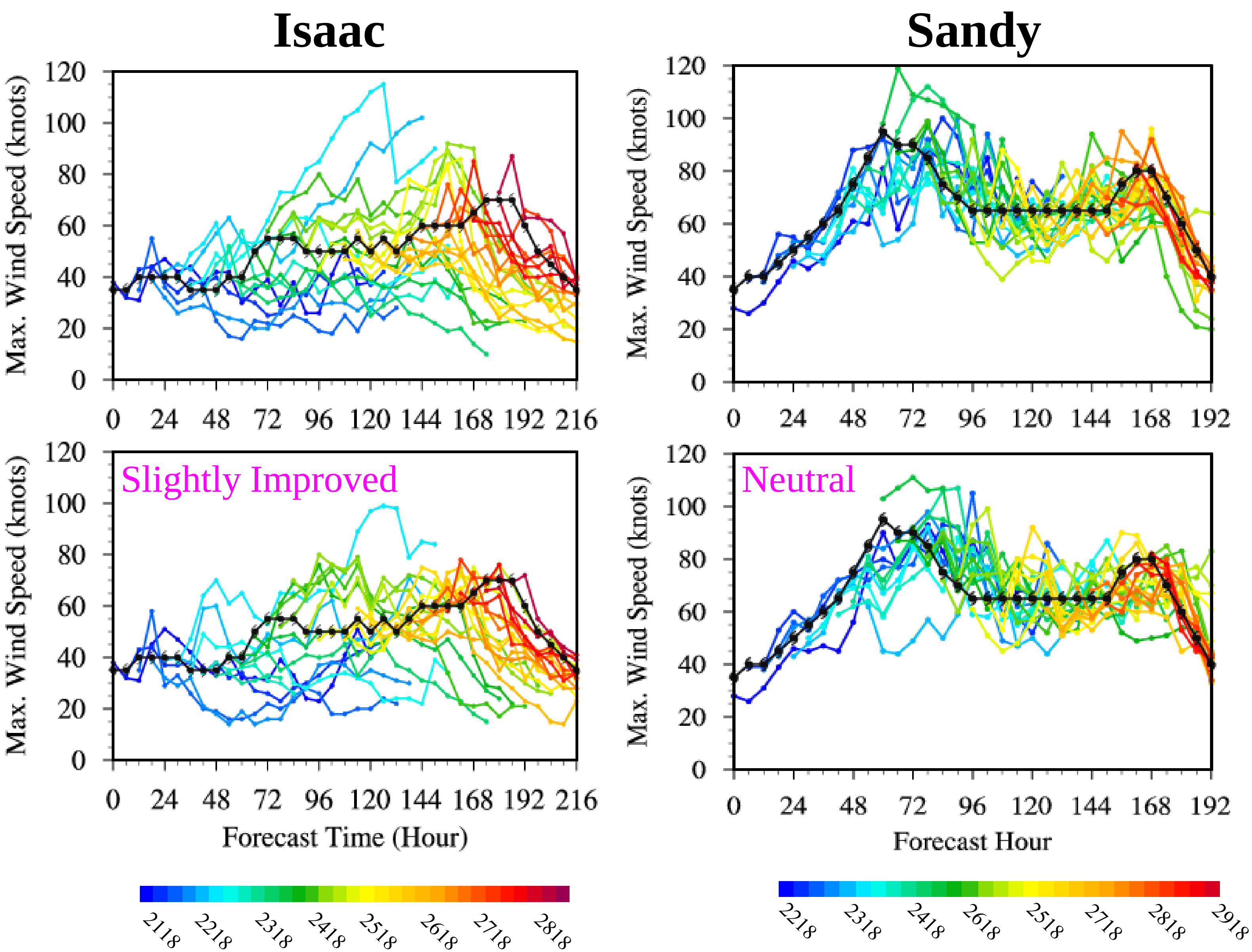
Sandy



Mixed Impacts of CrIS DA on Intensity Forecasts

CTRL

CTRL + CrIS



NLTE and Solar Reflection of Surface Infrared Shortwave Channels

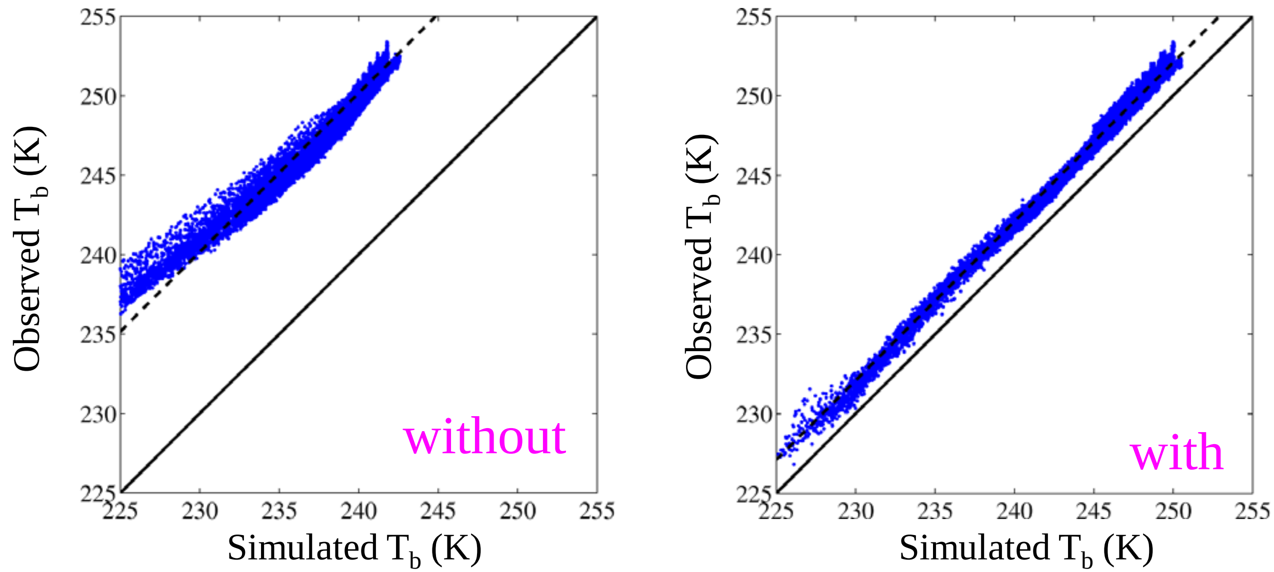
- Nonlocal Thermal Equilibrium (NLTE) emission at 4.3-μm CO_2 band can be as large as several degrees in Kelvin but is not considered in the current HWRF/GSI system
- Surface-sensitive shortwave channels (3.5-4.6 mm) are cleaner but not assimilated due to lack of a correction of reflected solar radiance at daytime in the current HWRF/GSI system

Shortwave infrared sea surface reflection and NLTE effects on CrIS data are assessed using a modified CRTM in which a bidirectional reflectance distribution function (BRDF) for the ocean surface and an NLTE radiance correction scheme developed for the hyperspectral sensors by Chen et al. (2013) are incorporated.

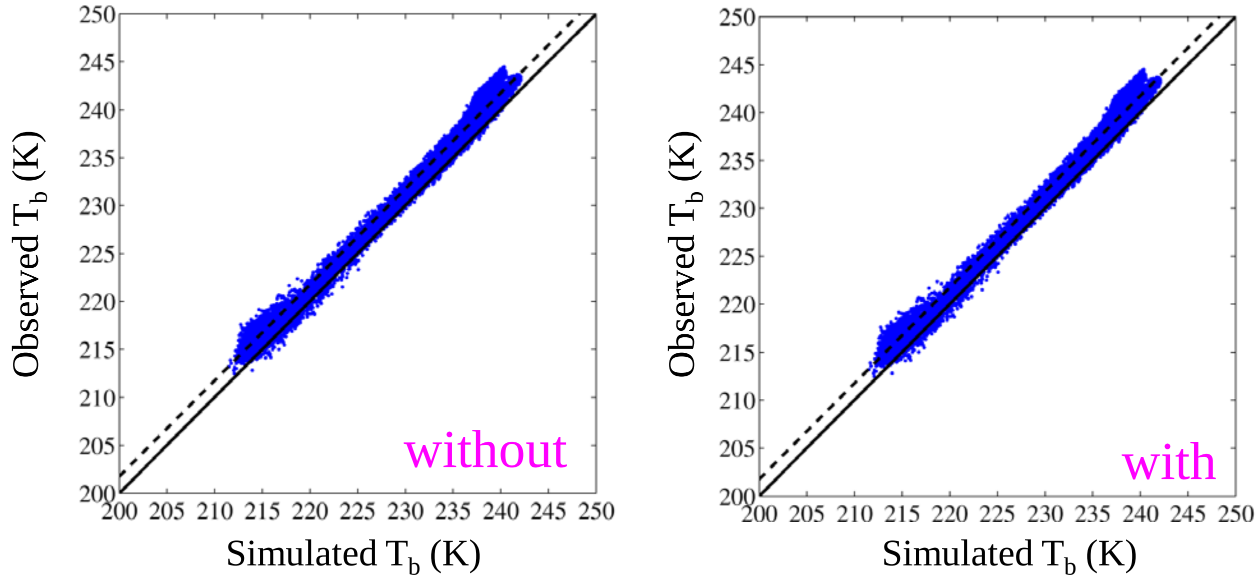
Chen Y., Y. Han, P.-V. Delst, and F. Weng, 2013: Assessment of shortwave infrared sea surface reflection and NLTE effects in CRTM using IASI data. *JTECH*, **30**, 2152-2160.

O-B Scatter Plots with and without NLTE Correction

CrIS Channel 1217 (2330 cm^{-1}, 17 hPa)



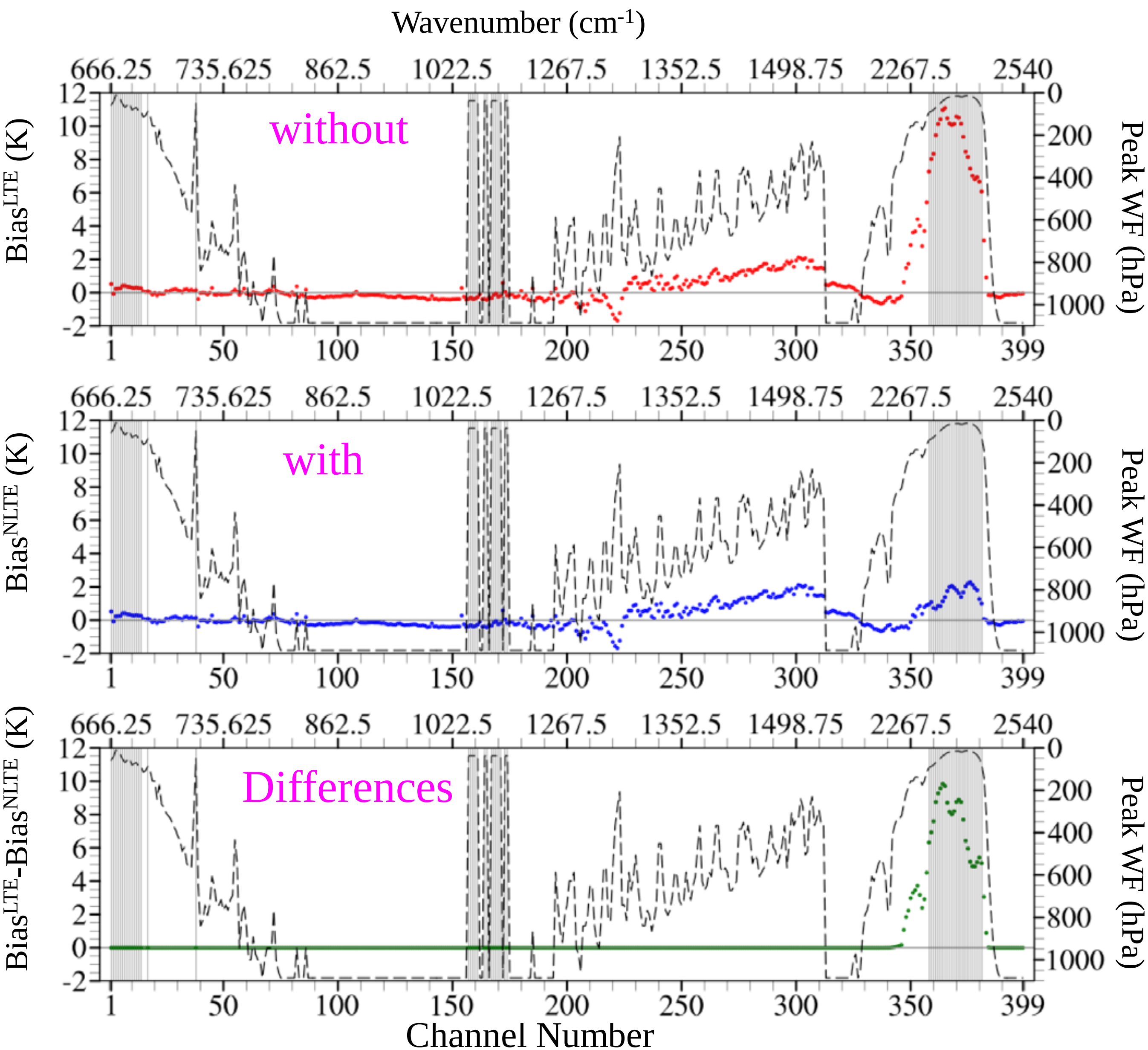
Data over ocean
Ascending node
1800UTC 10/25/12



Same channel
Descending node
0600UTC 10/25/12

O-B Biases with and without NLTE Correction

Ascending node, clear-sky data over ocean at 1800UTC during 22-29 October 12



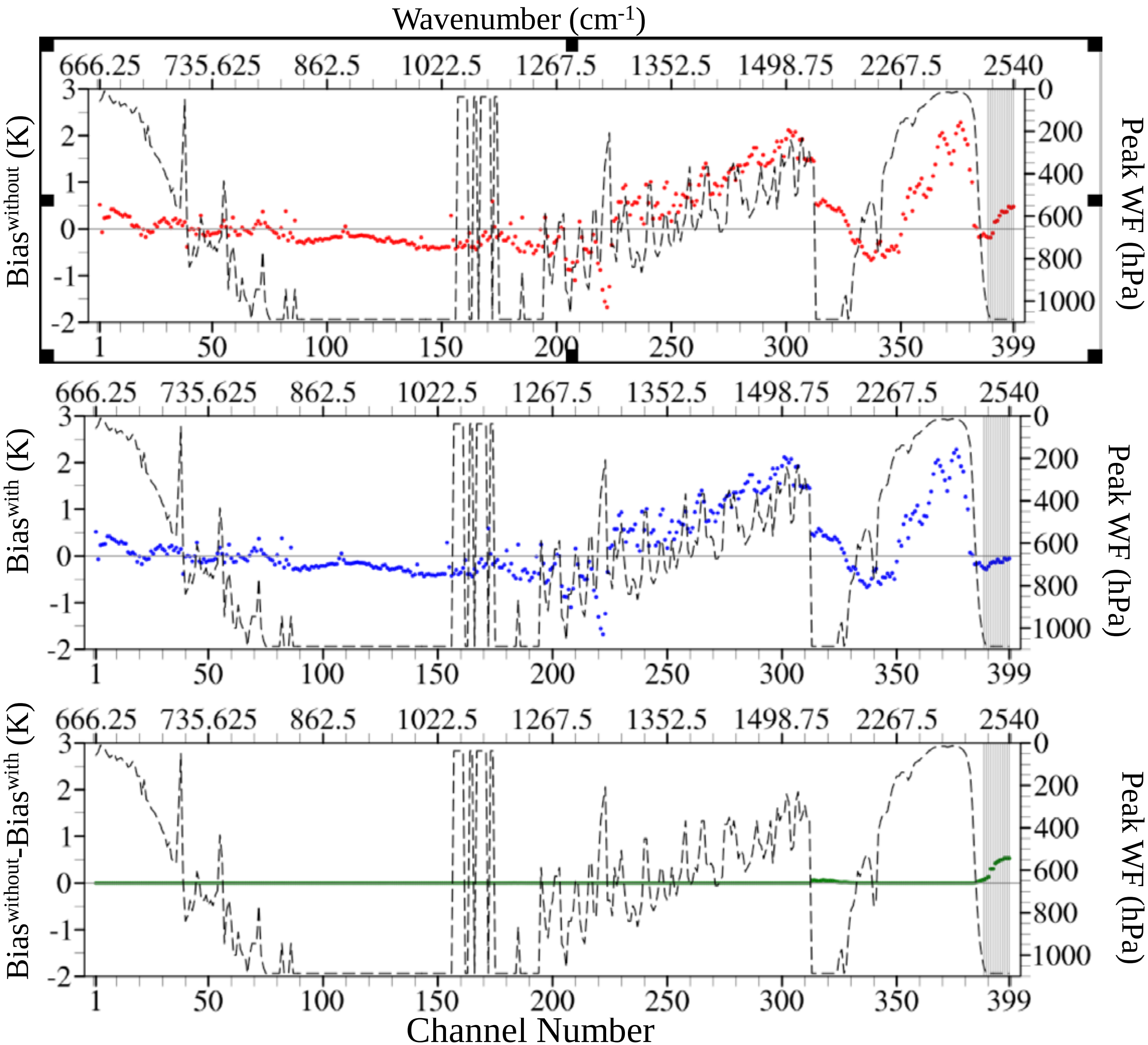
Biases are indicated by colored dots.

Pressure levels at which WF peaks are indicated by the black dashed line.

Channels with WF peaks higher than 100 hPa are indicated by the gray vertical lines.

O-B Biases with and without Solar Correction

Ascending node, clear-sky data over ocean at 1800UTC during 22-29 October 12



Biases are indicated by colored dots.

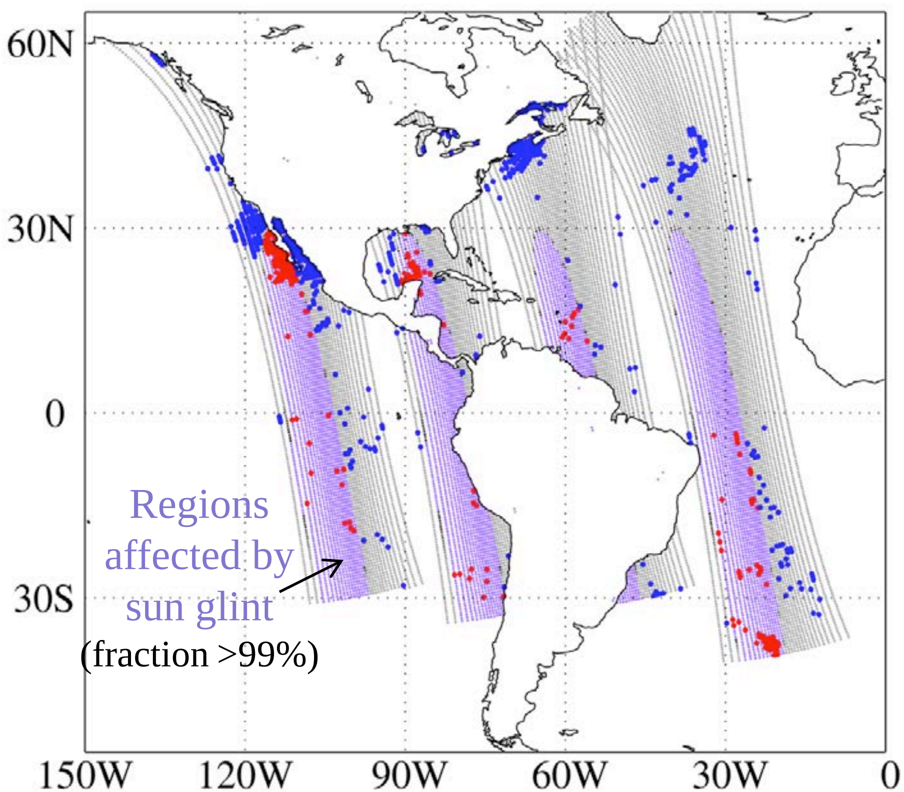
Pressure levels at which WF peaks are indicated by the black dashed line.

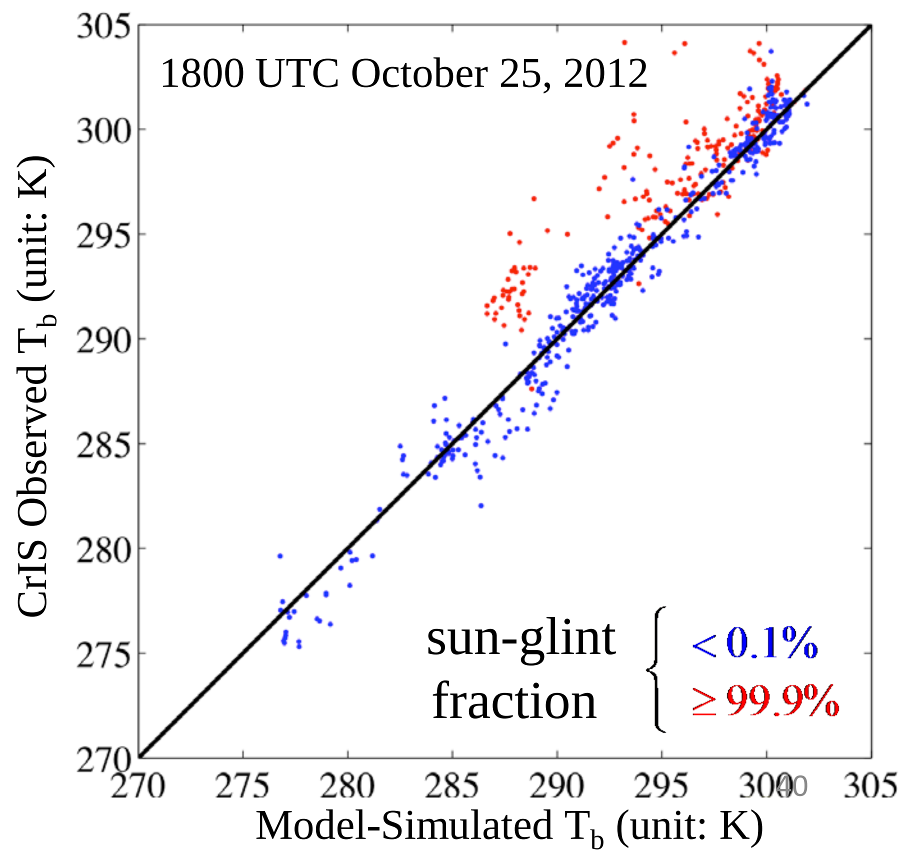
Channels with wavenumbers greater than 2400 µm are indicated by the gray vertical lines.

CrIS Quality Control Related to Sun Glint

Shortwave oceanic data during daytime could be affected by Sun glint. All data with wavenumbers being larger than 2400 cm^{-1} are removed in GSI. But, not all CrIS pixels are affected by sun glint!

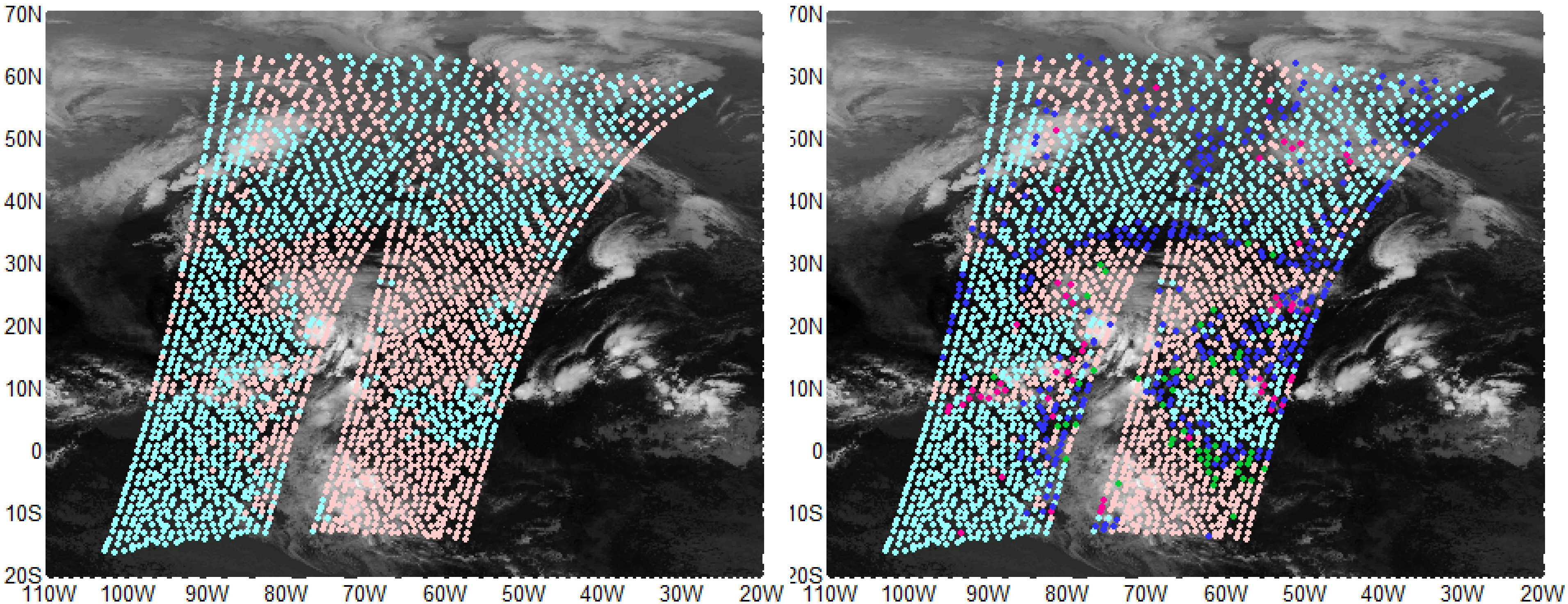
CrIS Channel 1293 (2520.0 cm^{-1}) in Clear-Sky Conditions





QC for CrIS Channel 80 (699cm^{-1}, 265 hPa)

Current GSI QC | Use VIIRS cloud detection

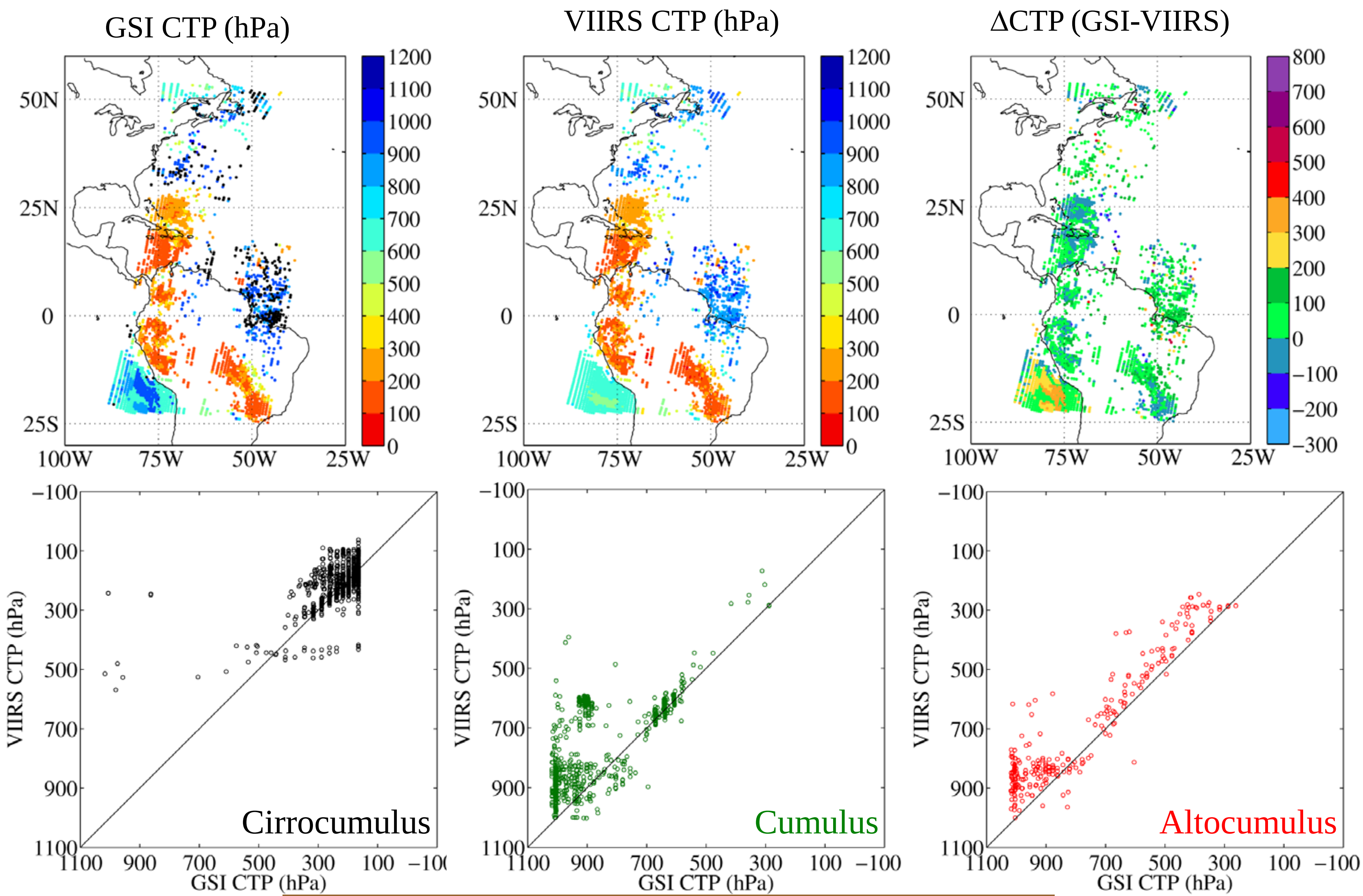


0600 UTC October 26, 2012

- pass all QC
- rejected by original cloud check
- rejected by gross check
- rejected by original cloud check by retained by new cloud check
- pass all QC but rejected by new cloud check
- rejected by old cloud detection, retained by new cloud check but rejected by gross check

VIRRS cloud detection suggests to retain more clear-sky data.

Cloud Top Pressure at 0600 UTC 24 October 2012



GSI cloud top is systematically lower than VIIRS cloud top.

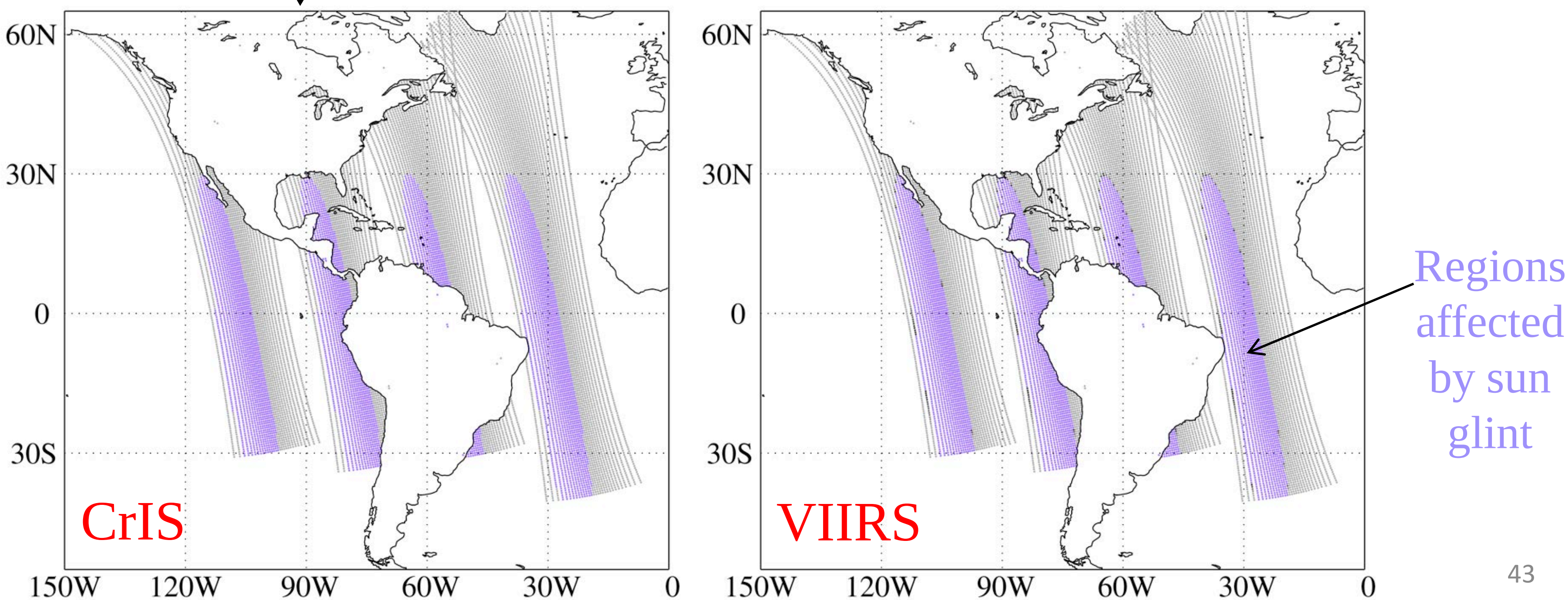
Modified Quality Control Related to Sun Glint

A CrIS pixel is affected by the sun-glint if sun glint angle satisfies

$$0 < \cos^{-1}\left\{\sin\theta_{sat}\sin\theta_{sol}\cos\left[180^{o} - (\phi_{sun} - \phi_{sun})\right] + \cos\theta_{sat}\cos\theta_{sun}\right\} < 36^{0}$$

θ_{sat} – satellite zenith angle θ_{sun} – solar zenith angle

ϕ_{sat} – satellite azimuth angle ϕ_{sun} – solar azimuth angle



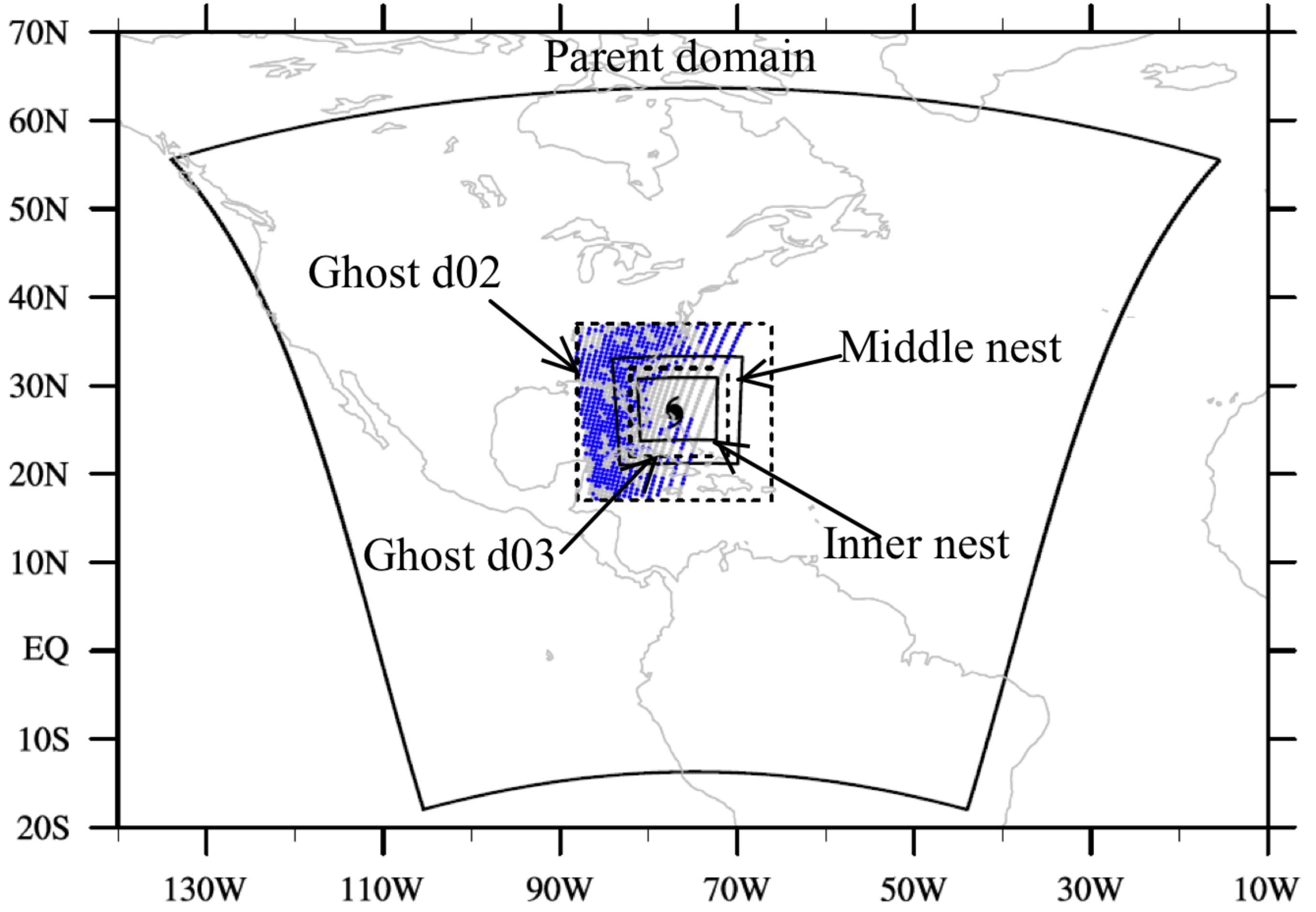
5. Preliminary Results Using 2014 Version of HWRF

- Major Upgrades to 2014 HWRF
  1. Higher model top (2 hPa) and more vertical levels (61)
  2. Satellite DA on middle ghost domain (9 km) and inner ghost nest (3 km)
  3. Improved vortex initialization
  4. DA cycling does not wait until a TC is named

- A Quick Look at 2014 HWRF Results for Hurricane Sandy

- Two Major Concerns
  - To little satellite data are assimilated into HWRF if satellite DA is carried out only within ghost domain (9 km) and inner nest (3 km)
  - Asymmetric components available from satellite retrieval products should be added to vortex initialization

2014 HWRF Domain Setup

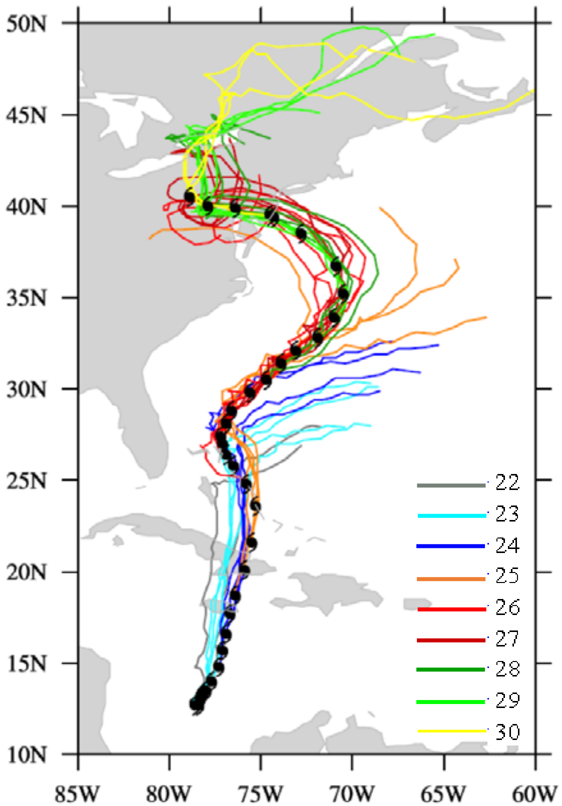


AMSU-A channel 4 data from MetOp-A assimilated in middle ghost domain at 1800 UTC October 26, 2012 are indicated in blue dots.

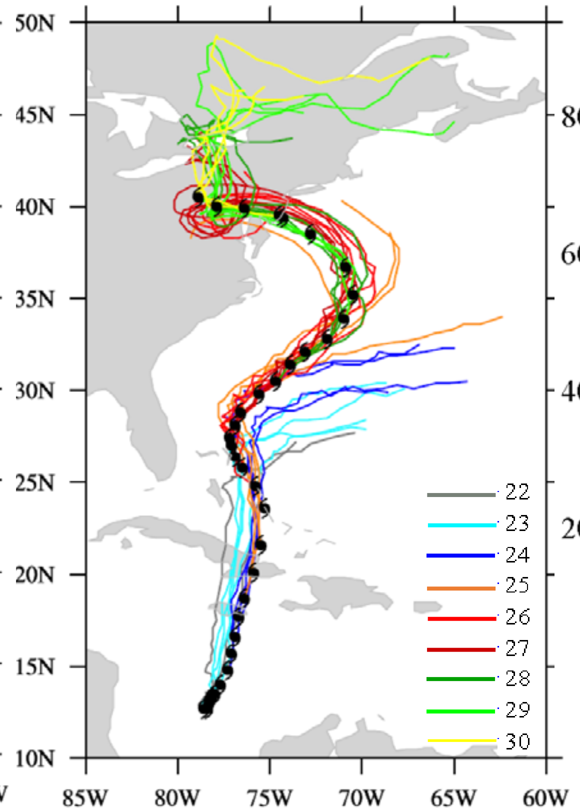
DA is carried out in both Ghost d02 (9 km) and Ghost d03 (3 km).

Sandy Track Forecasts by 2014 HWRF

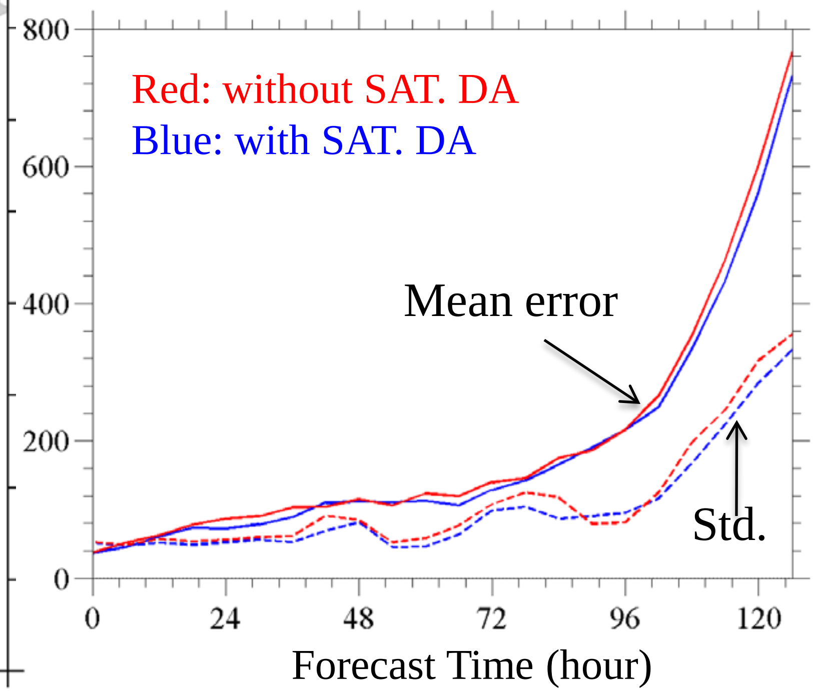
Without SAT. DA



With SAT. DA

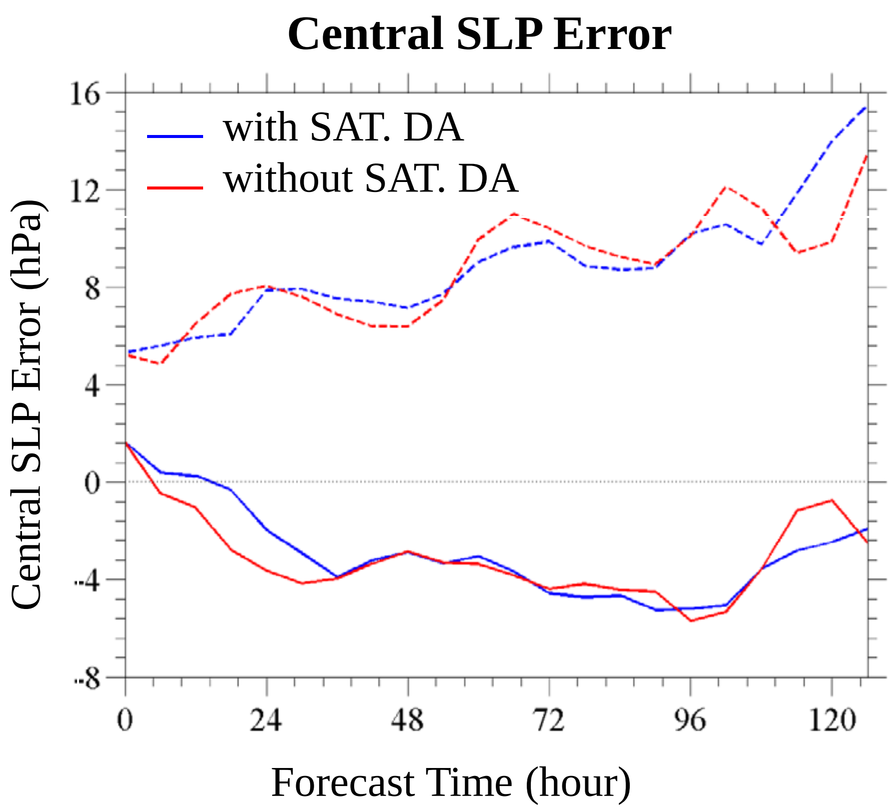


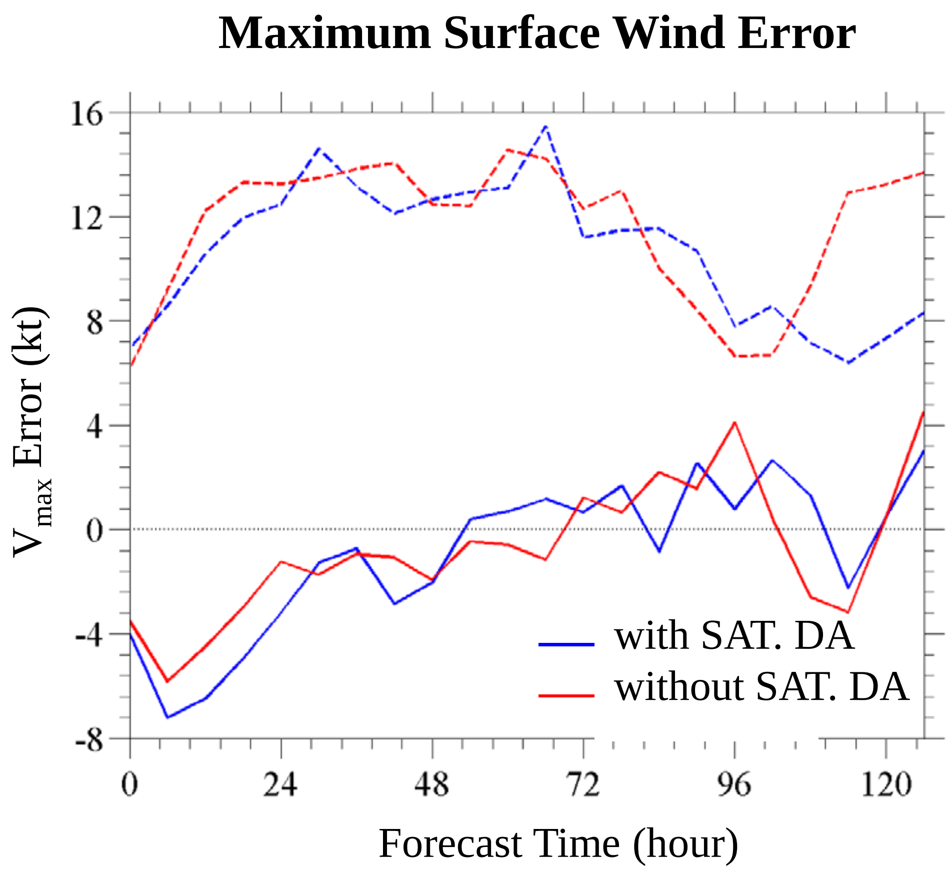
Track Errors (km)



Satellite DA has a marginal positive impact on Sandy's track forecasts.

Sandy Intensity Forecasts with and without Satellite DA Using 2014 HWRF





Satellite DA has a marginal positive impact on Sandy intensity forecasts.

Summary and Conclusions

- The HWRF system was re-configured to have more vertical layers and a higher model top for more effective uses of upper-level satellite sounding data in HWRF, which enabled the HWRF model to generate an improved atmospheric steering flow and thus the movement of tropical cyclones

- A collocated FOV distribution between ATMS temperature and humidity channels makes the cloud detection more effective

- ATMS data assimilation in GSI/HWRF results in a consistent positive impact on the track and intensity forecasts of 2012 landfall hurricanes

- CrIS QC and cloud detection schemes are diagnosed and improved.

- Improvements in the GSI quality control for CrIS channels remain critical and challenging

More details can be found in

Zou, X., F. Weng, Q. Shi, B. Zhang, C. Wu and Z. Qin, 2013: Satellite data assimilation in NWP models. Part III: Impacts of model top on radiance assimilation in HWRF. *J. Atmos. Sci.*, (submitted)

Zou, X., F. Weng, B. Zhang, L. Lin, Z. Qin and V. Tallapragada, 2013: Impact of ATMS radiance data assimilation on hurricane track and intensity forecasts using HWRF. *J. Geophys. Res.*, **118**, 11,558-11,576.

Da C., X. Zou, X., F. Weng, B. Zhang and V. Tallapragada, 2014: Satellite data assimilation in NWP models. Part VI: Impact of CrIS radiance data on hurricane track and intensity forecasts using HWRF. *J. Atmos. Sci.*, (in preparation) .

Zou, X., Z. Qin and F. Weng, 2014: Two separate quality control approaches for MHS data assimilation over land and ocean. *J. Atmos. Sci.* (to be submitted)

Weng, F., X. Zou, X. Wang, S. Yang, and M. D. Goldberg, 2012: Introduction to Suomi NPP ATMS for NWP and tropical cyclone applications. *J. Geophy. Res.*, **117**, D19112, 14pp, doi:10.1029/2012JD018144.