The 95th Annual Meeting, 4-8 January 2015, Phoenix, Arizona

Improved Tropical Storm Forecasts with GOES-13/15 Imager Radiance Assimilation and Asymmetric Vortex Initialization in HWRF

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Outline

- Introduction to GOES Data Characteristics
- Asymmetric Vortex Initialization within HWRF
- Improved Tropical Storm Forecasts with GOES-13/15 Imager Radiance Assimilation and Asymmetric Vortex Initialization in HWRF
- An Objective Regional Cloud Mask Algorithm for GOES Infrared Imager Radiance Assimilation
- Summary and Conclusions

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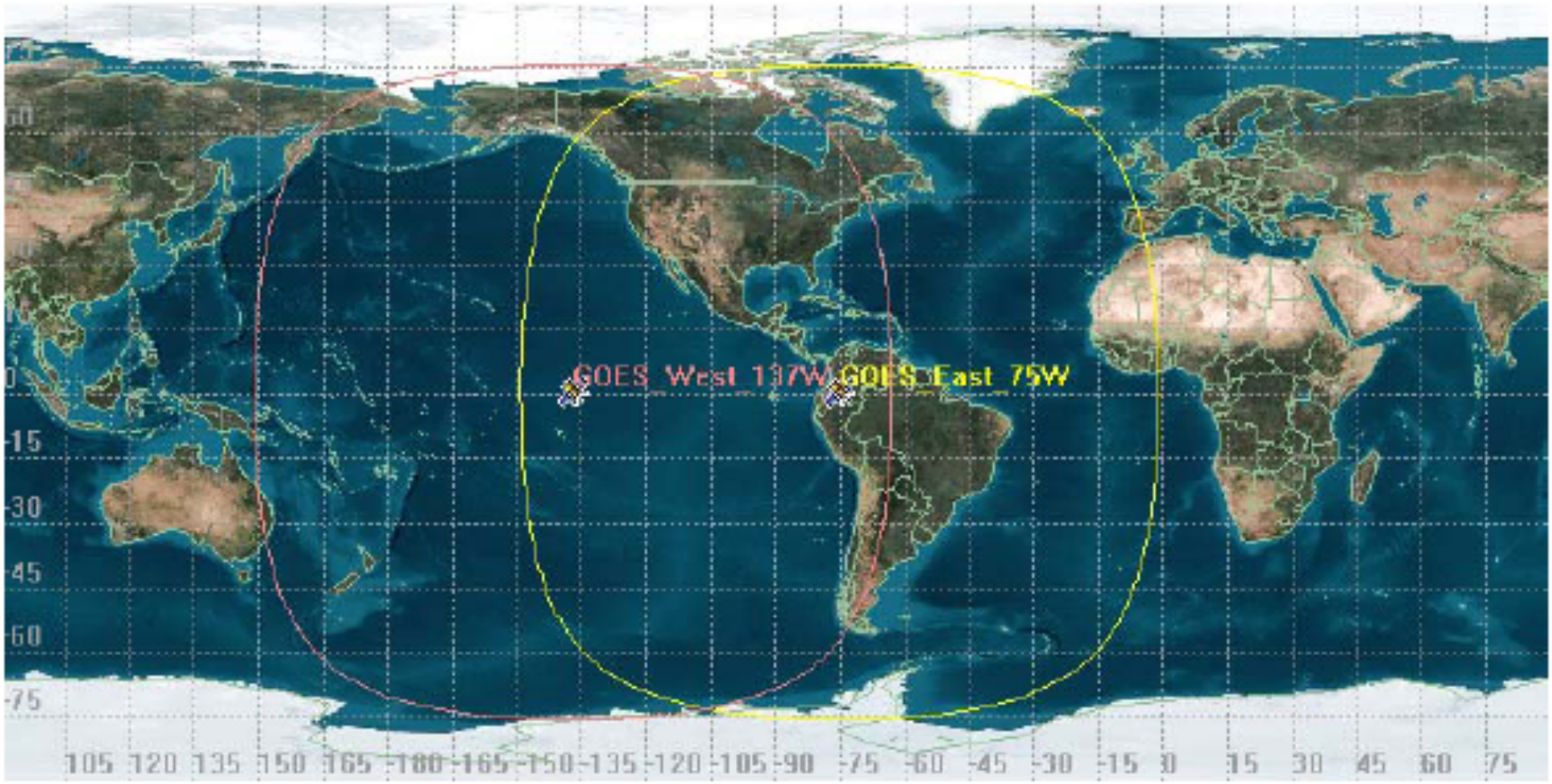
Data Coverage of GOES-15 and GOES-13



Launch Time: GOES-13: May 24, 2006
GOES-15: March 4, 2010

Position: GOES-13: 75°W
GOES-15: 135°W

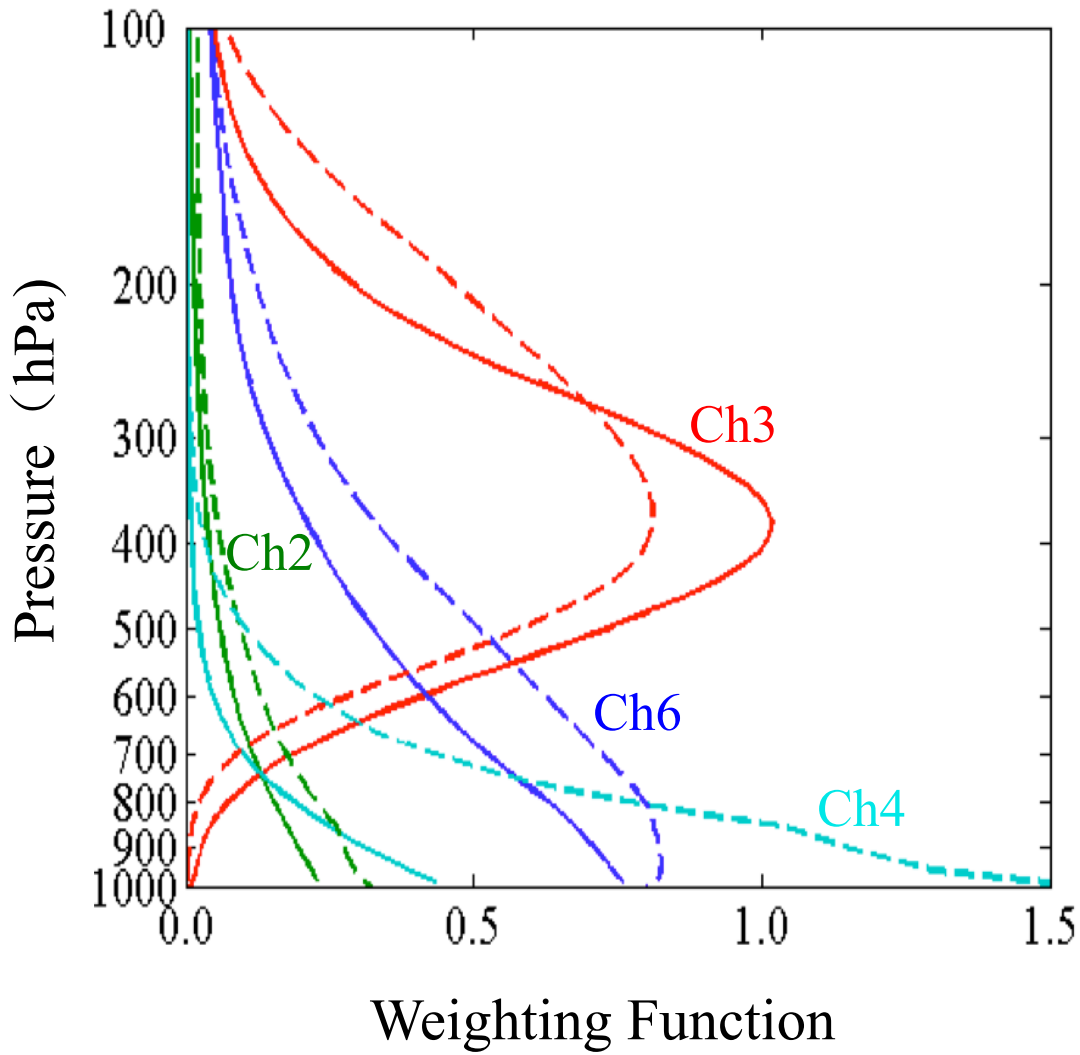
GOES-13/-15 Imager Channel Characteristics

Channel	Frequency (μm)	Band width (μm)	Resolution (km)		Error (K)	
			GOES-13	GOES-15	GOES-13	GOES-15
1	0.65	0.19	1.0	1.0	±5%	±5%
2	3.90	0.34	4.0	4.0	0.051	0.063
3	6.55	1.50	4.0	4.0	0.140	0.170
4	10.7	1.00	4.0	4.0	0.053	0.059
6	13.35	0.70	8.0	4.0	0.061	0.130

Channel Characteristics of GOES-11/-12 Imager

Channel Number	Central Wavelength	Horizontal Resolution	General usage
1	0.65 μm	1 km	Surface and cloud top during daytime
2	3.9 μm	4 km	Low cloud/fog detection
3	6.7 μm 6.5 μm	8 km 4 km	Water vapor at high level
4	10.7 μm	4 km	Surface and cloud top temperature
5	12.0 μm	4 km	Surface and cloud top temperature, water vapor at low level
6	13.3 μm	8 km	Cloud top temperature, effective cloud amount cloud top pressure

Weighting Functions of GOES-13/15 Imager Channels



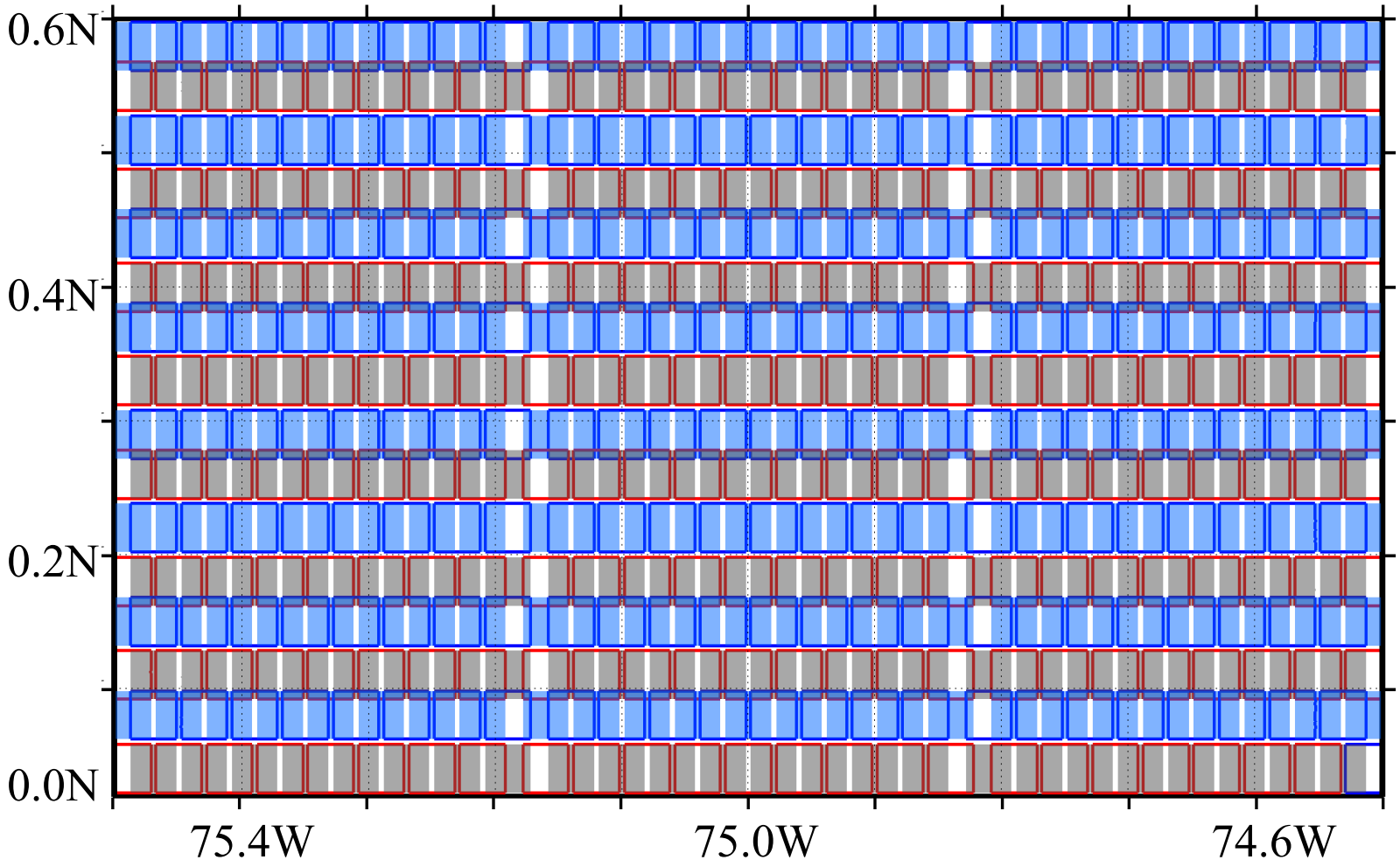
Ch2： Low cloud pattern, fog, fire, snow

Ch3： Middle and ipper-level water vapor and cloud

Ch4： Surface skin and cloud top temperature

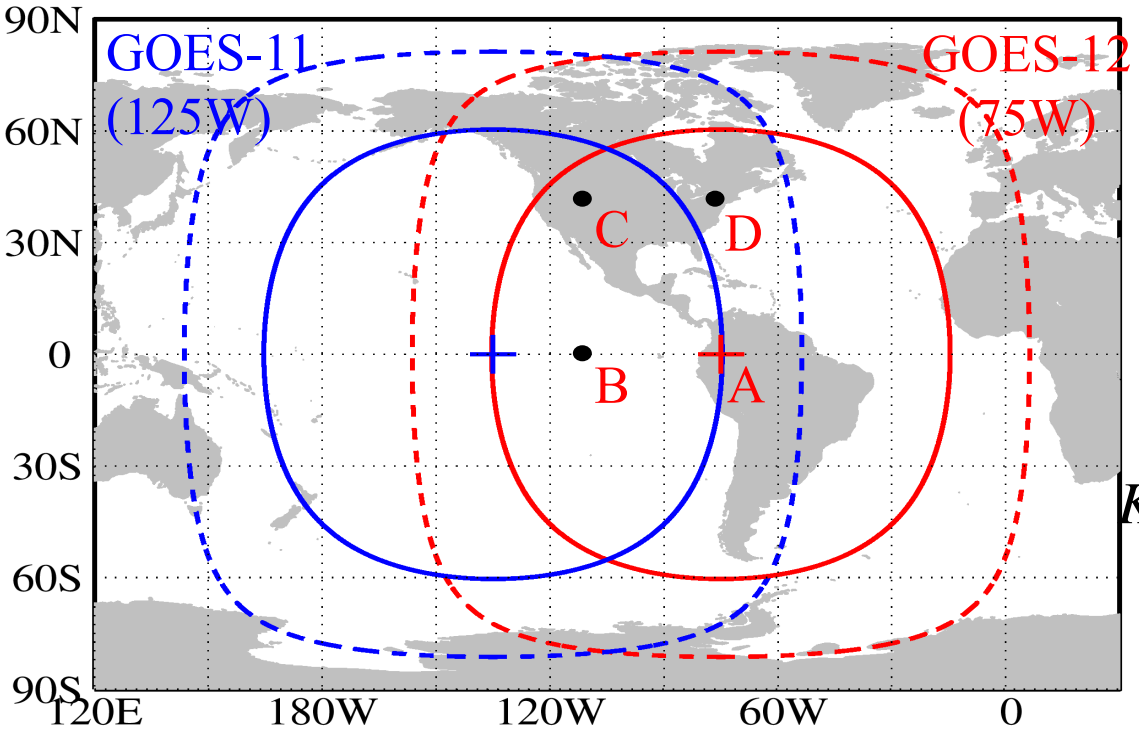
Ch6： Earth emission attenuated by carbon dioxide molecules

GOES Pixel Shapes near Nadir



Da C. and X. Zou, 2014: An introduction to GOES imager data. *Advances in Meteor.l Sci. and Tech.*, **4**, DOI: 10.3969/j.issn.2095-1973.2014.04.008

GOES-11/-12 Imager Spatial Coverage



Pixel Distortion Index

$$K = \frac{a}{h}\frac{\sin^2\alpha + \left(\cos\alpha - \cos\alpha_0\right)^2}{\cos\alpha - \cos\alpha_0}$$

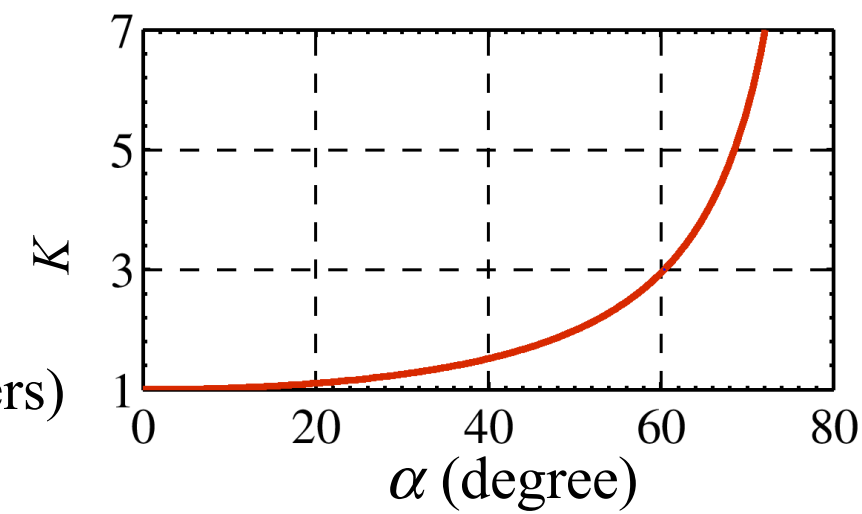
$$\alpha = \left|\lambda - \lambda_{nadir}\right|$$

α --- φ or λ departure from nadir

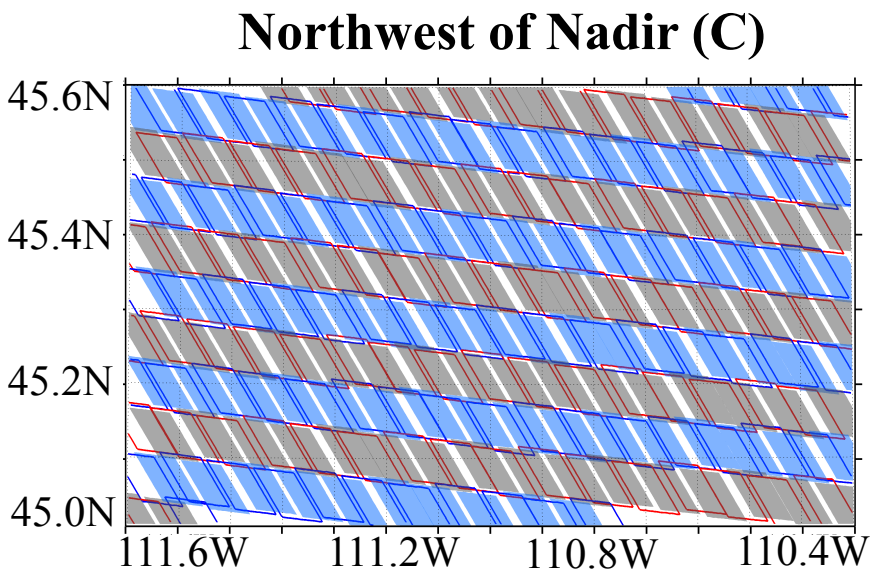
h --- is the satellite altitude

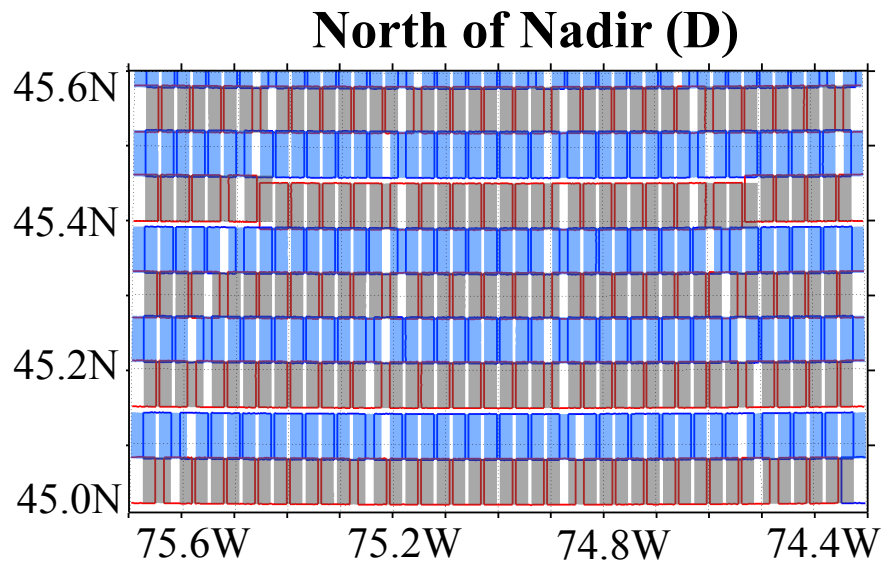
$a = h + Re$ (Earth's radius)

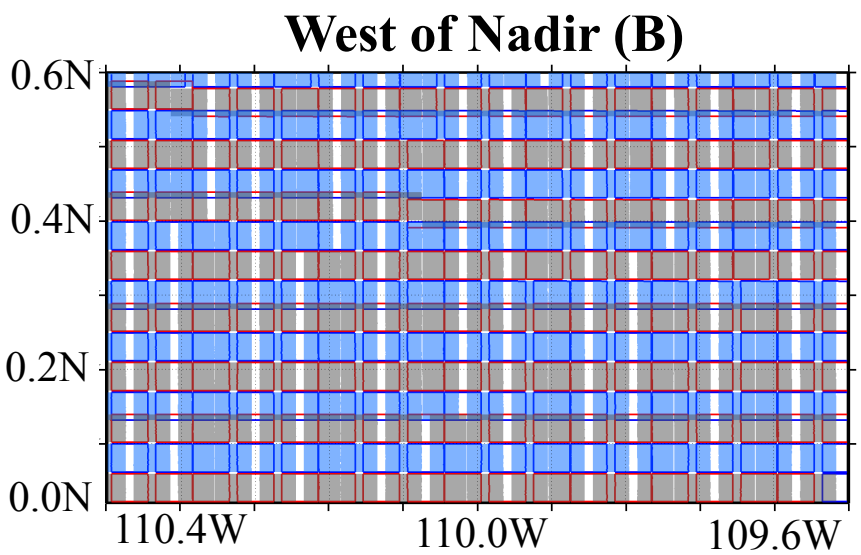
$\alpha_0 = 81.3^o$ (the largest φ or λ GOES covers)

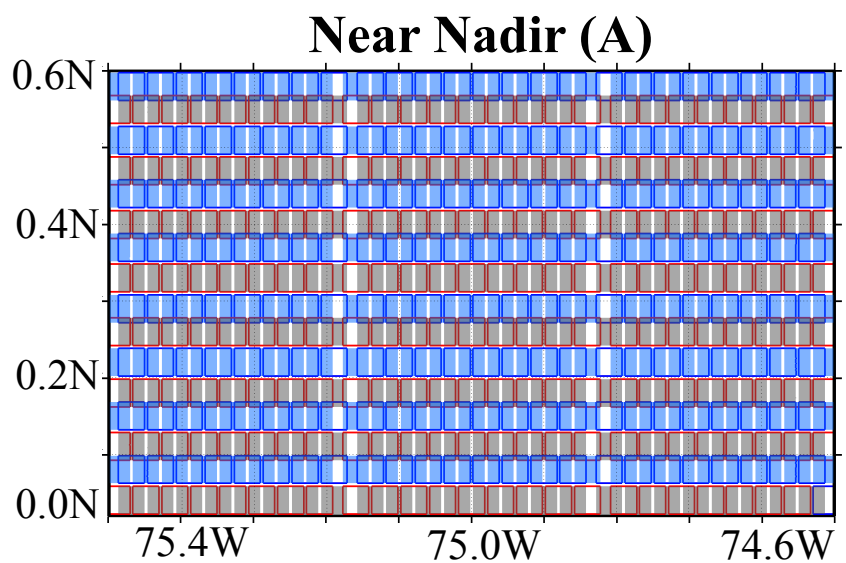


Pixel Shapes at Different Observing Locations









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NOAA 10-Year Program
（2008－2018）

Hurricane Forecast Improvement Program （HFIP）

http://www.hfip.org

HFIP provides the basis for NOAA and other agencies to coordinate hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts. It also engages and aligns the inter-agency and larger scientific community efforts towards addressing the challenges posed to improve hurricane forecasts.

HWRF Vortices

(1) The two-dimensional symmetric tangential wind, radial wind, temperature and mixing ratio were stored in data format for two vortices:

One for deep TCs
One for shallow and medium depth TCs

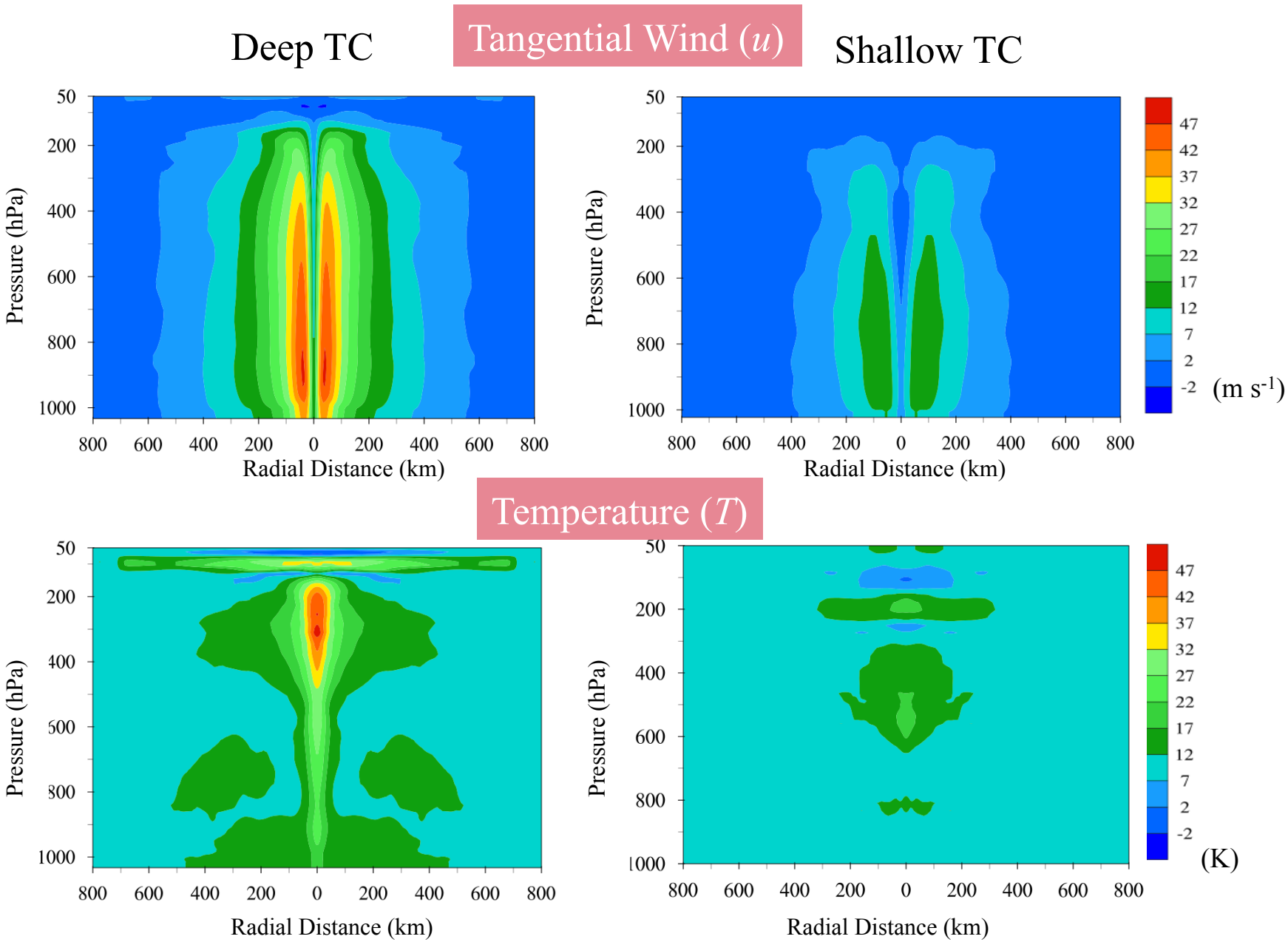
(2) Tangential and radial winds are scaled based on radius of the maximum wind, radius of the outermost closed isobar and the maximum wind speed

(3) Surface pressure is derived from surface tangential wind based on gradient wind balance

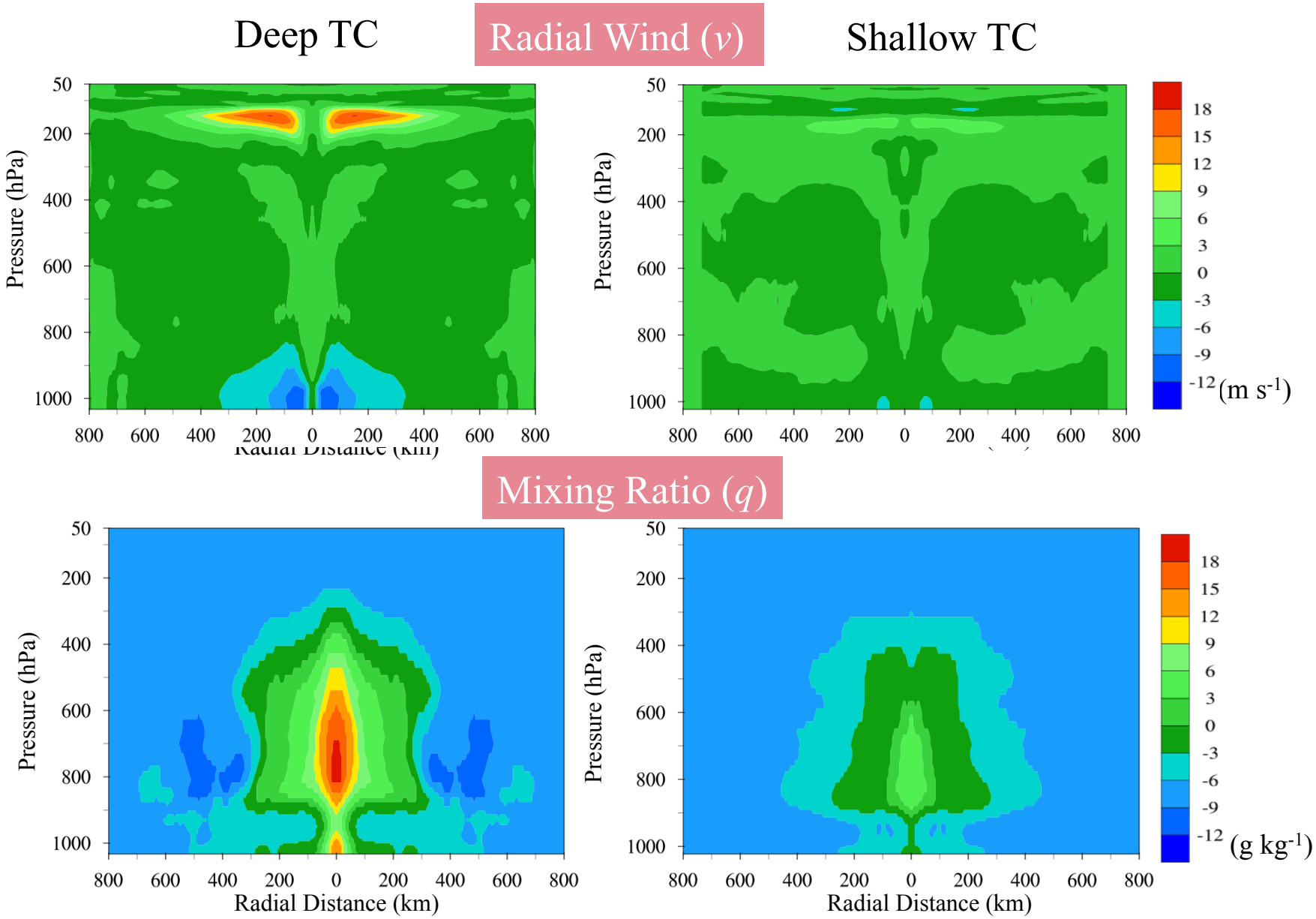
(4) Temperatures at different levels are scaled by an empirical factor

(5) The mixing ratio is modified based on the scaled temperature under the constraint that relative humidity doesn't change.

HWRF Stored Vortices

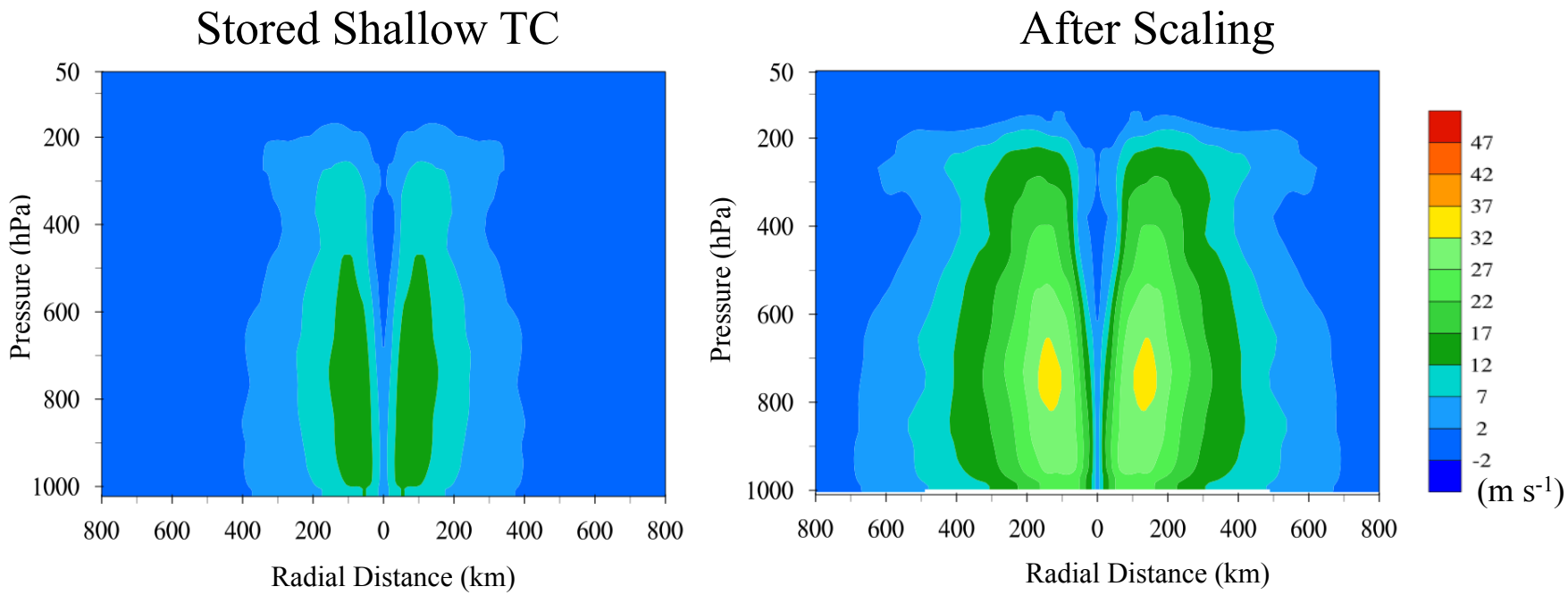


HWRF Stored Vortices



Tangential Winds before and after Scaling

for Hurricane Sandy at 0000 UTC October 24, 2012



Vortex size correction: $r^{corrected-vortex} = \alpha r^{bogus-vortex} + \frac{\beta (r^{bogus-vortex})^2}{2}$

Vortex intensity correction: $\begin{cases} u^{\text{corrected-vortex}} = \gamma u^{bogus-vortex} \\ v^{\text{corrected-vortex}} = \gamma v^{bogus-vortex} \end{cases}$

Vortex Size and Intensity Corrections in HWRF

Vortex size correction:

$$r^{corrected-vortex} = \alpha r^{bogus-vortex} + \frac{\beta (r^{bogus-vortex})^2}{2}$$

$$\begin{cases} R_{\max}^{corrected-vortex} \triangleq R_{\max}^{obs} \\ R_{out}^{corrected-vortex} \triangleq R_{out}^{obs} \end{cases} \Rightarrow \alpha, \beta$$

Vortex intensity correction:

$$\begin{cases} u^{\text{corrected-vortex}} = \gamma u^{bogus-vortex} \\ v^{\text{corrected-vortex}} = \gamma v^{bogus-vortex} \end{cases}$$

$$V_{\max}^{\text{corrected-vortex}} \triangleq V_{\max}^{obs} \Rightarrow \gamma$$

Proposed and Completed Modifications to HWRF Vortex Initialization

1. Raise the model top to 10 hPa (same as NCEP GFS) √

2. Remove the GFS hurricane component at different model levels within the the boundary (e.g., size) of the vortex based on the disturbance field (h_D) at the same level instead of 850 hPa. √

3. Replace the symmetric HWRF vortices with the following two candidates:

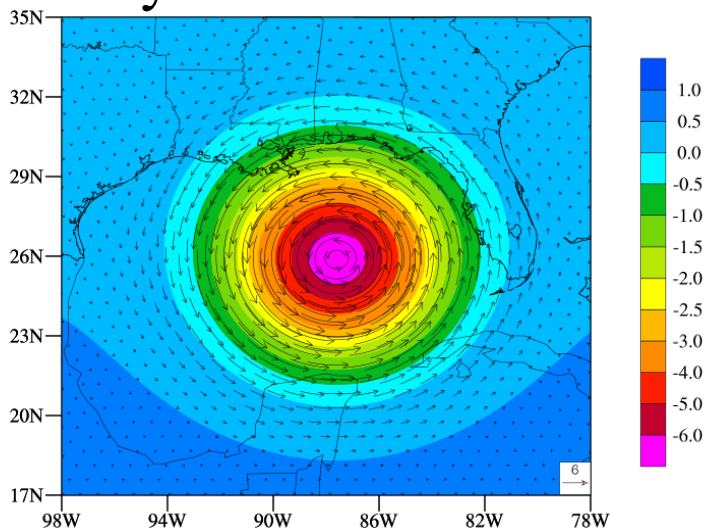
   (a) Dropsonde-derived composite structures
   (b) Axisymmetric model (Rotunno and Emanuel, 1987)

   on going

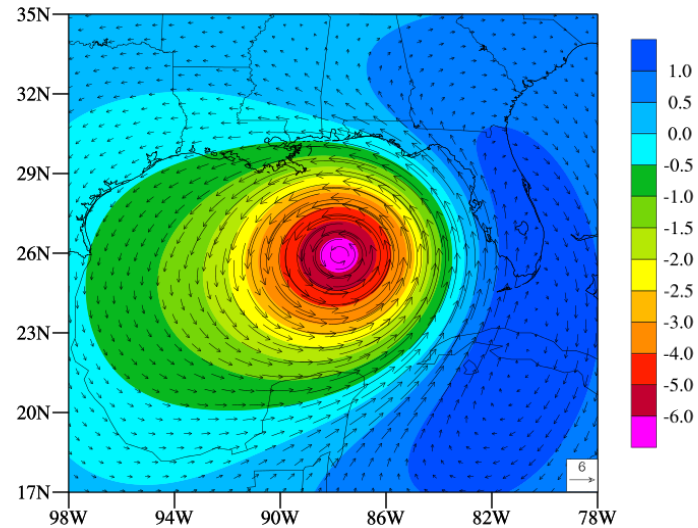
4. Include the asymmetric component using the GFDL method, i.e., integration of a barotropic model. √

Relative Vorticity and Wind Distributions

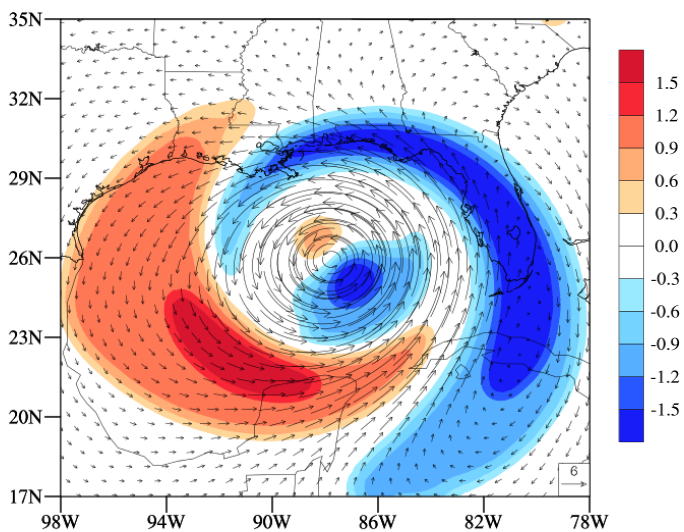
Symmetric Vortex



Asymmetric Vortex



Differences between asymmetric and symmetric vortices



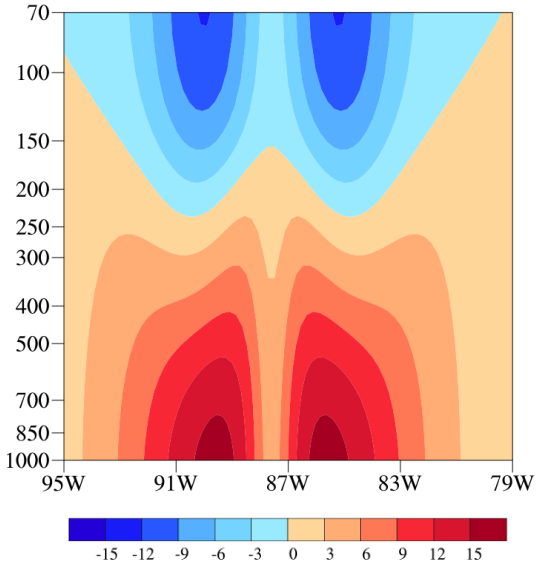
1800 UTC June 23, 2012

Relative vorticity
(shaded, unit: 1/s）

Wind vector
(unit: m/s）

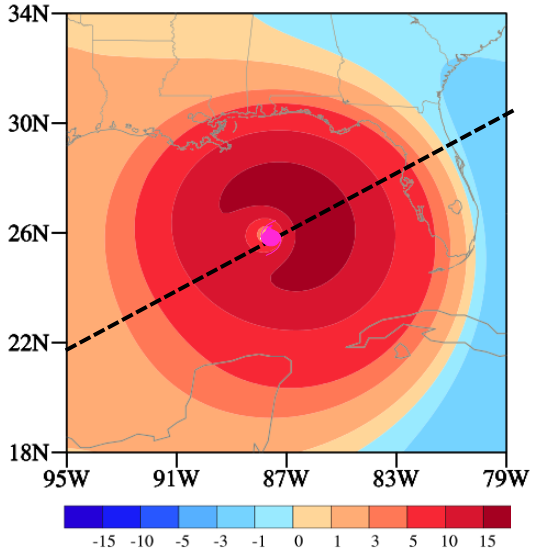
Symmetric Bogus Vortex

Cross-section of tangential wind of symmetric vortex

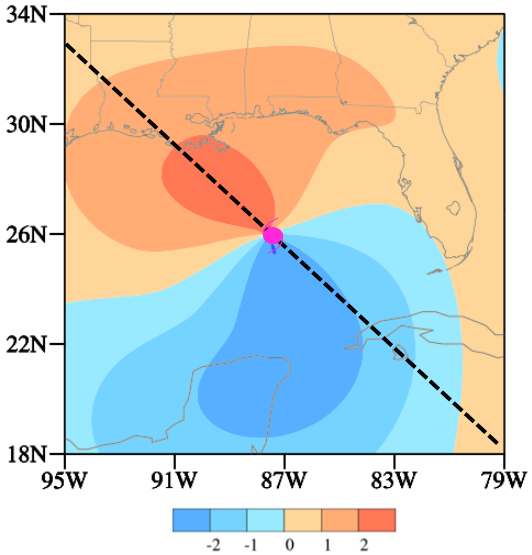


Asymmetric Bogus Vortex

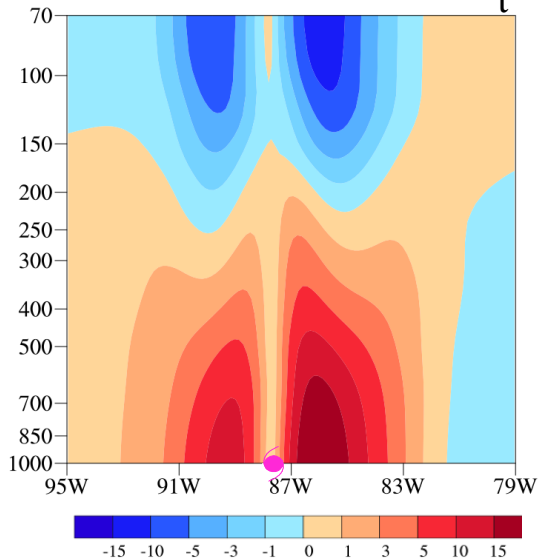
Tangential wind v_t



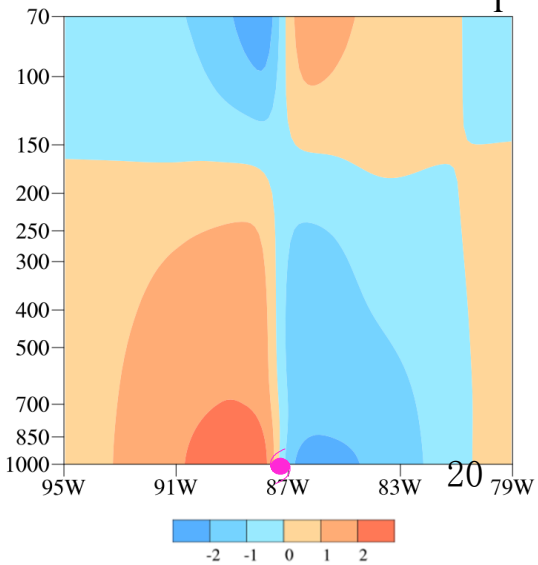
Radial wind v_r



Cross-section of v_t



Cross-section of v_r



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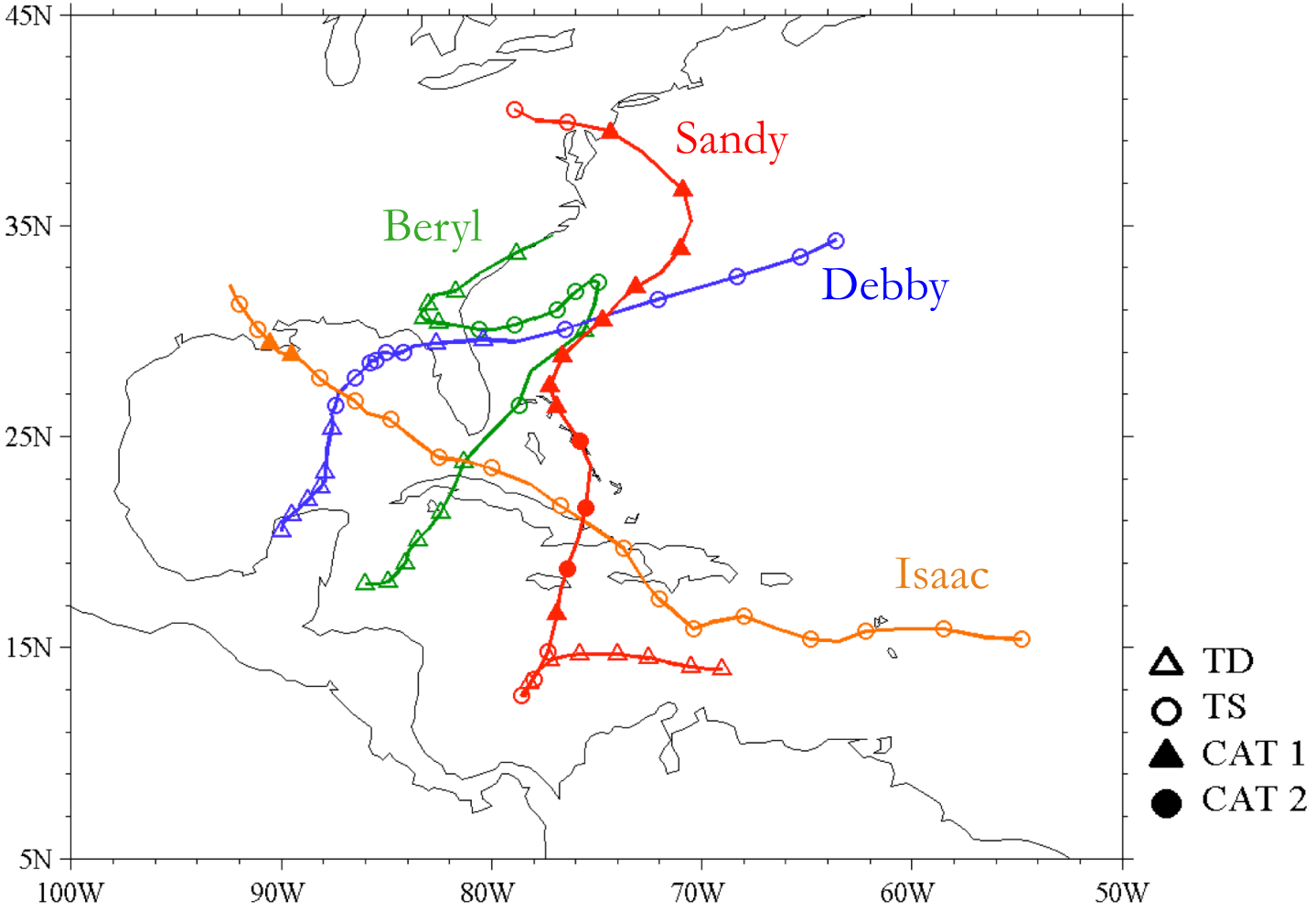
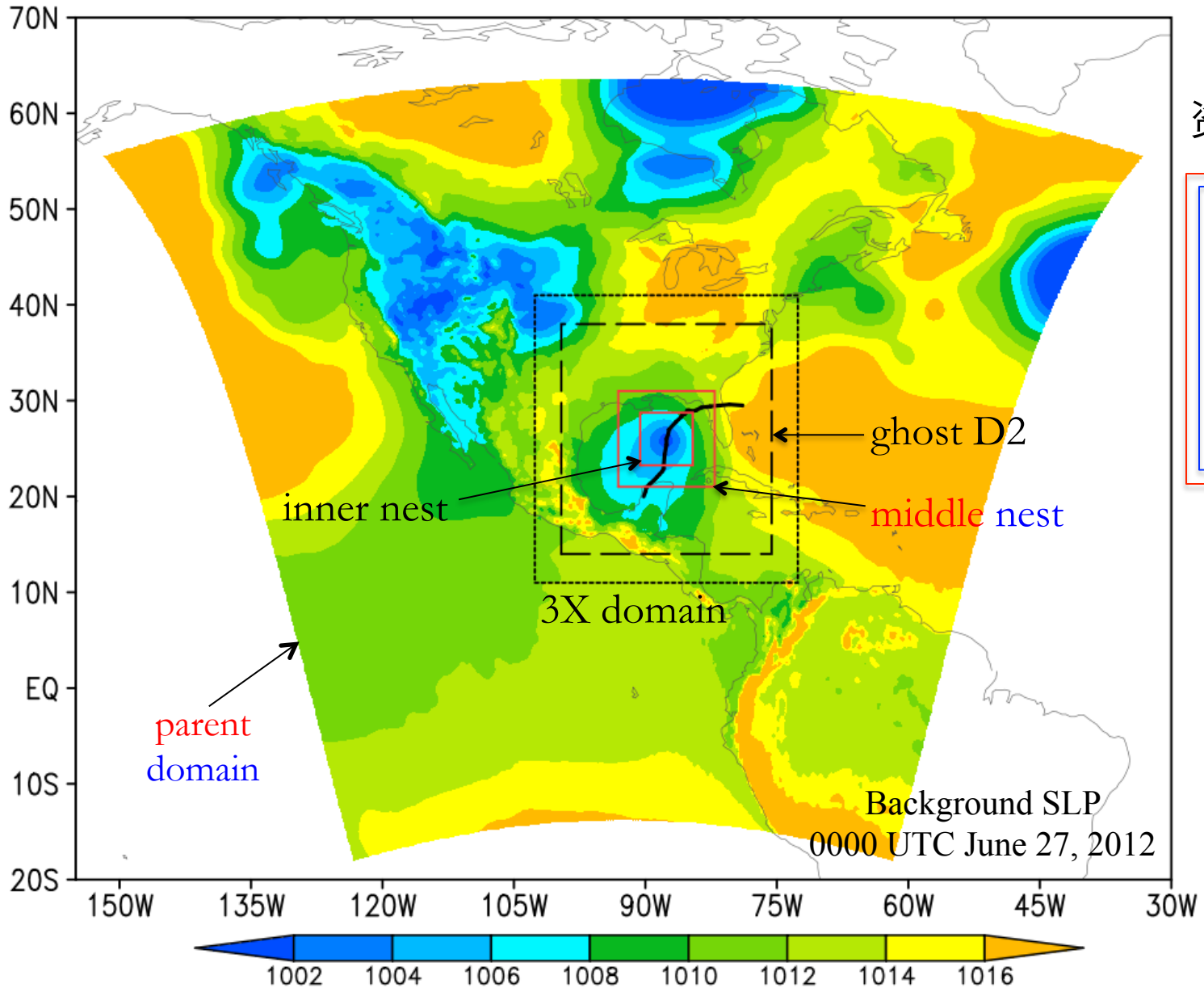
2012 四个登陆台风路径



2012 HWRF 三重套模式区域设置



2012 HWRF
资料同化区域

Parent domain
27 km, 750x750

Middle Nest
9 km, 238x150

HWRF System and Improvements

- 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)

Cost Function

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

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

$\mathbf{x}$ – 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

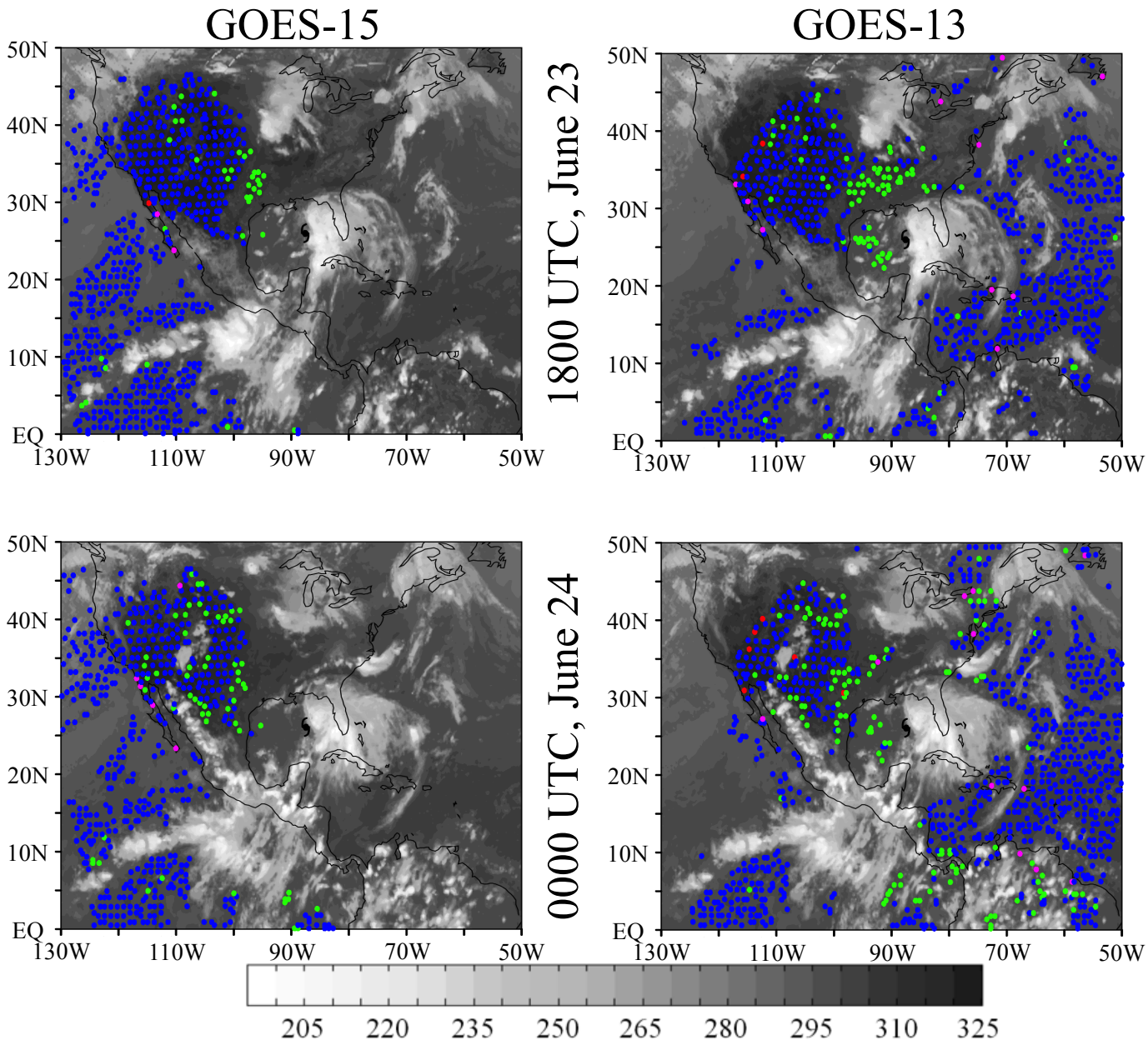
$\mathbf{F}$ – forward model error covariance

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

Three Challenging Areas for Satellite Data Assimilation

1. Bias Correction
   - Instrument bias
   - Air mass dependent bias
2. Quality Control
   - Erroneous data
   - RTM errors
3. Data Thinning
   - Spatially correlated data
   - Spectrally correlated channels

Quality Control for Imager Channel 3

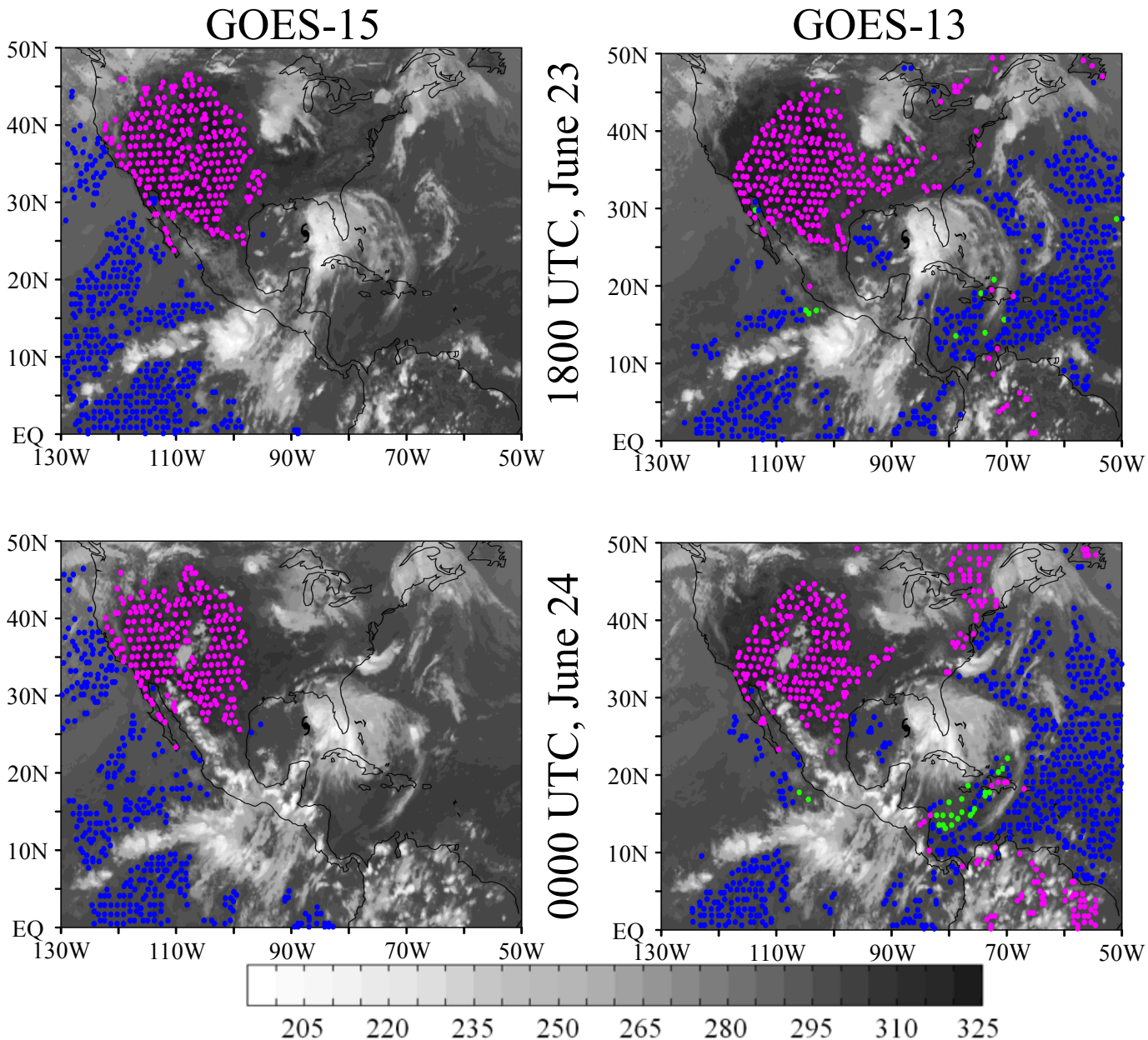


- Pass QC

Removed due to

- Surface type
- Large obs. error
- Large O-B

Quality Control for Imager Channel 5



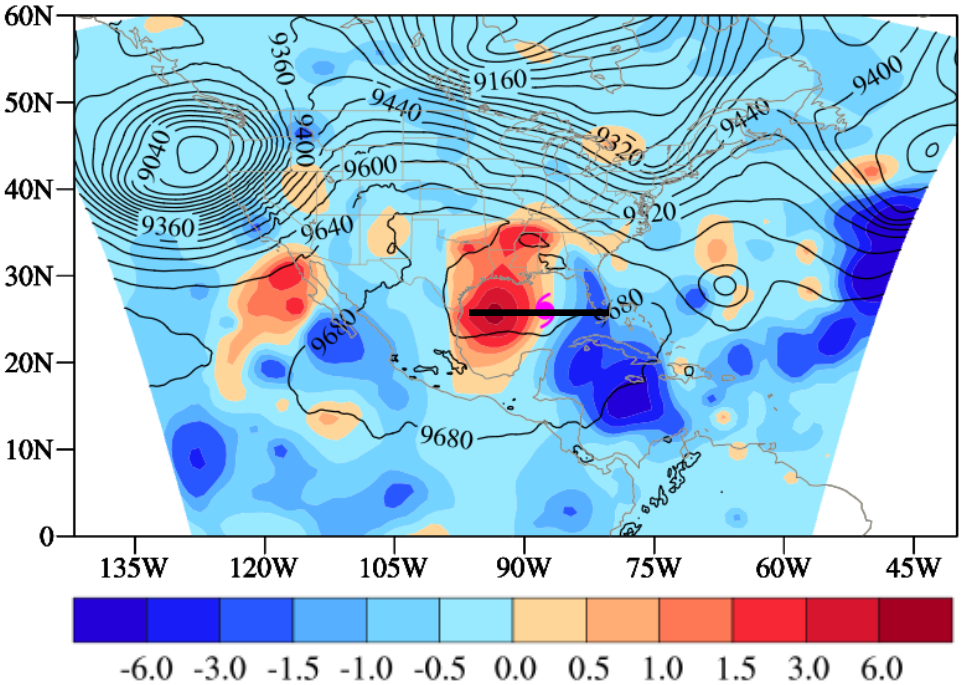
- Pass QC

Removed due to

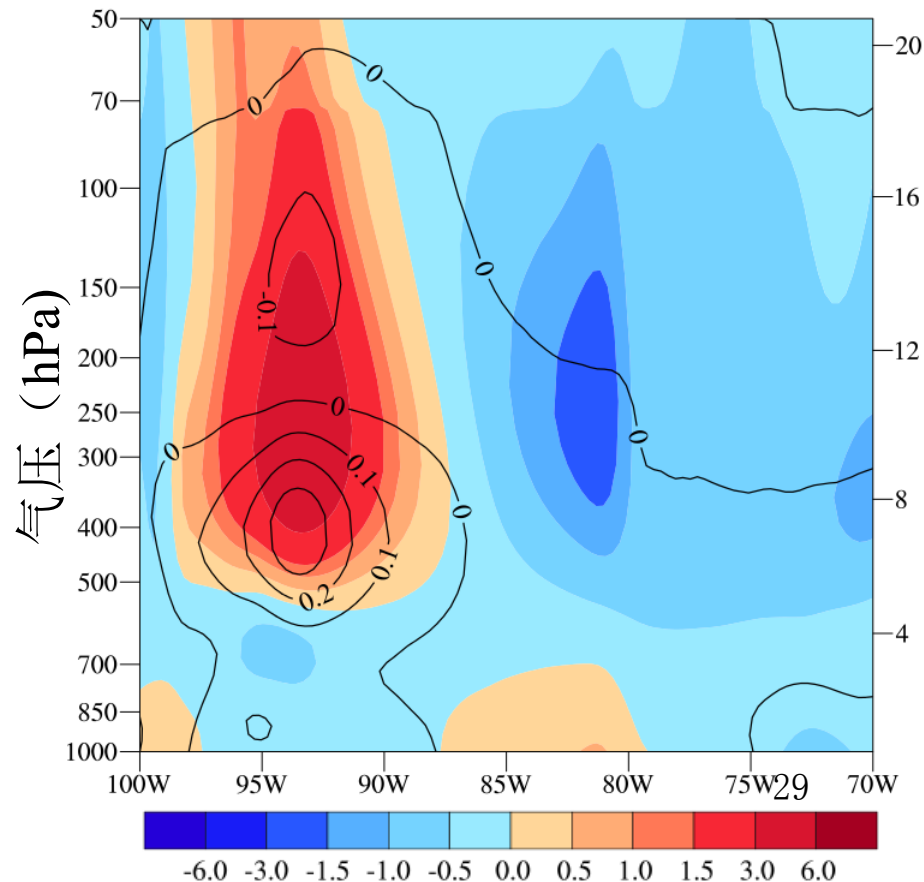
- Surface type
- Large obs. error
- Large O-B

Changes in Geopotetial Analysis Introduced by GOES-13/15 Radiance Assimilation

300 hPa



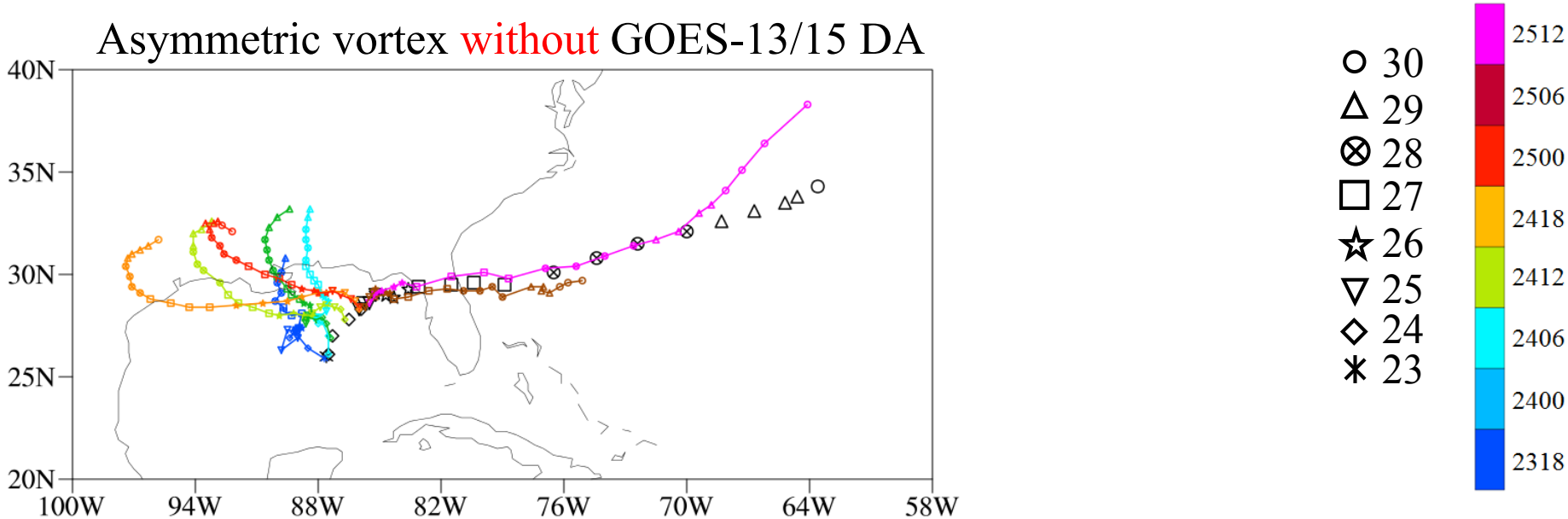
Cross Section



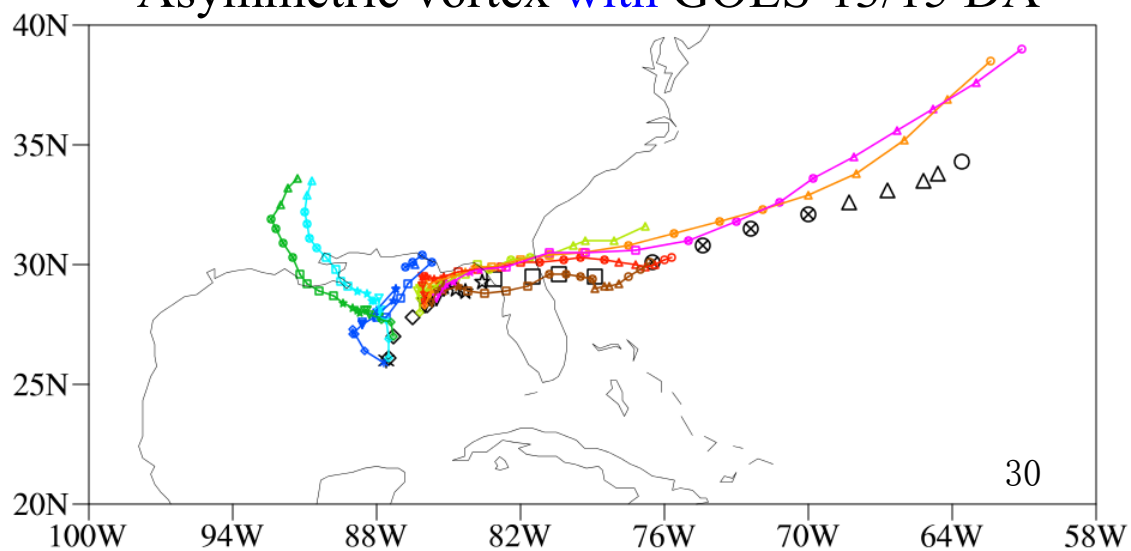
Analysis with GOES DA minus analysis without GOES DA

Track Forecasts of Tropical Storm Debby (2012)

Asymmetric vortex without GOES-13/15 DA

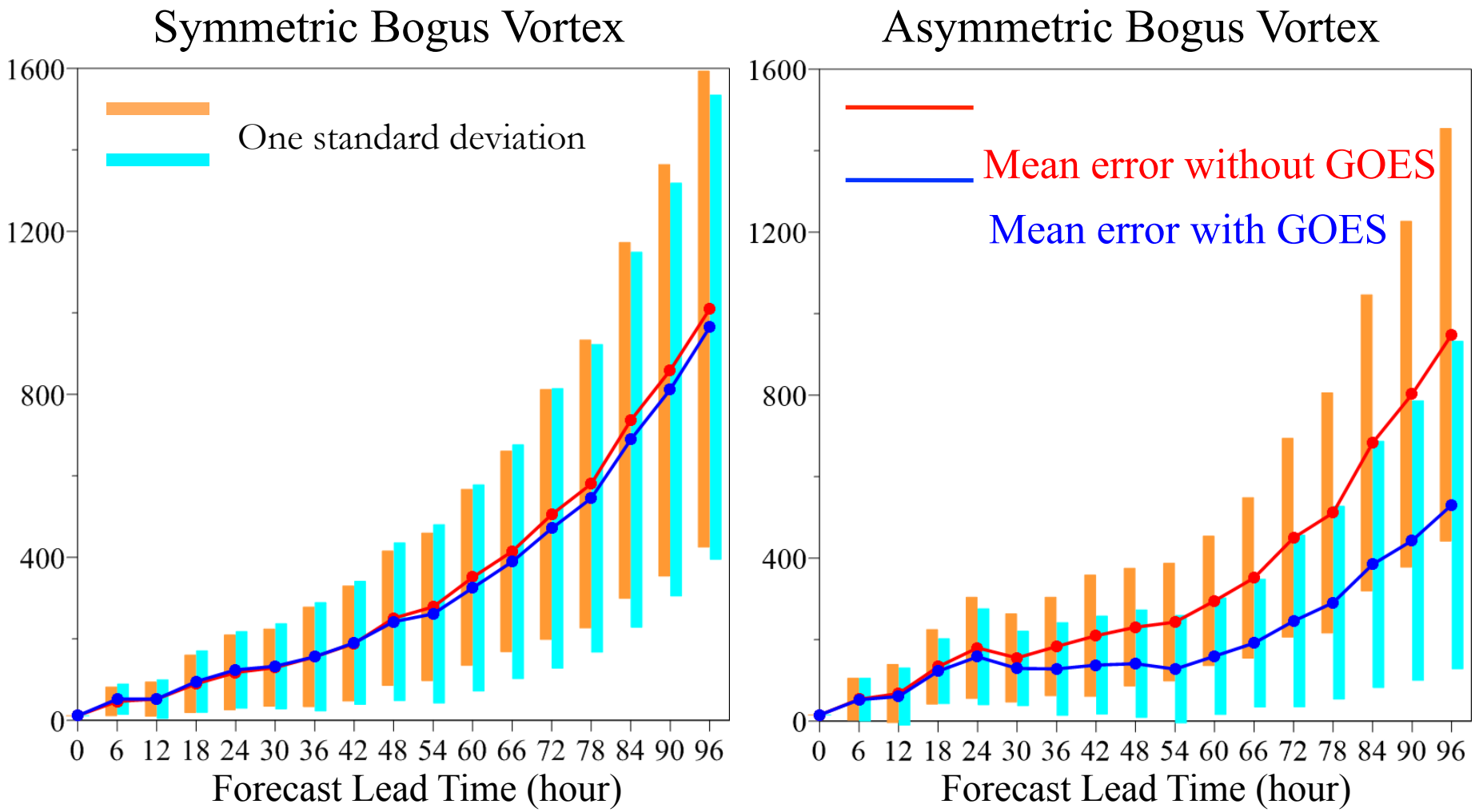


Asymmetric vortex with GOES-13/15 DA



Adding GOES-13/-15 imager radiance observations into the GSI data assimilation allowed the HWRF model to produce a correct eastward track forecast of the tropical storm Debby by almost a day earlier.

Track Errors

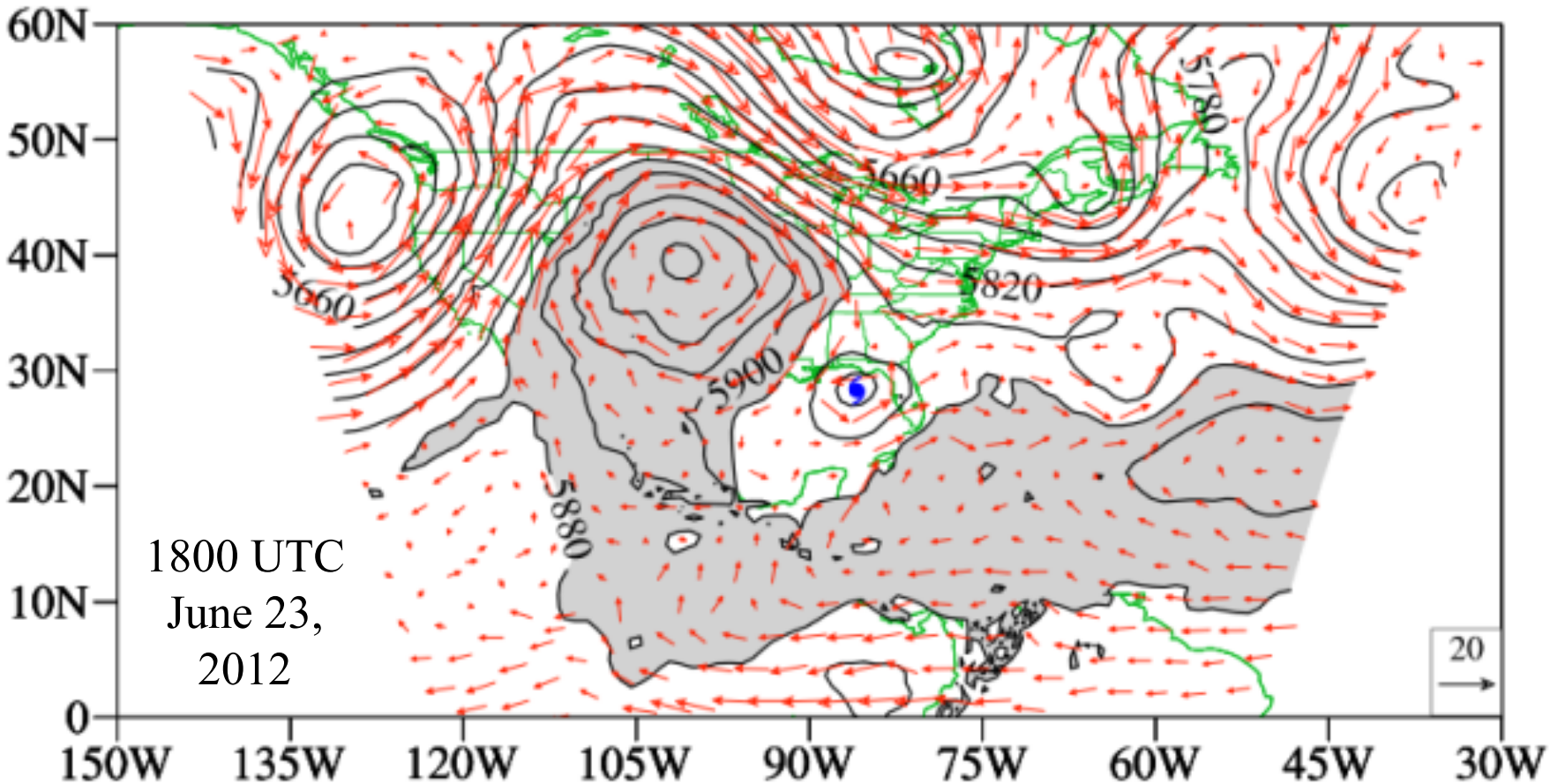


The positive impact of GOES radiance assimilation on track forecasts is much more significant when an asymmetric vortex initialization is incorporated into HWRF.

Under what environments was Debby?

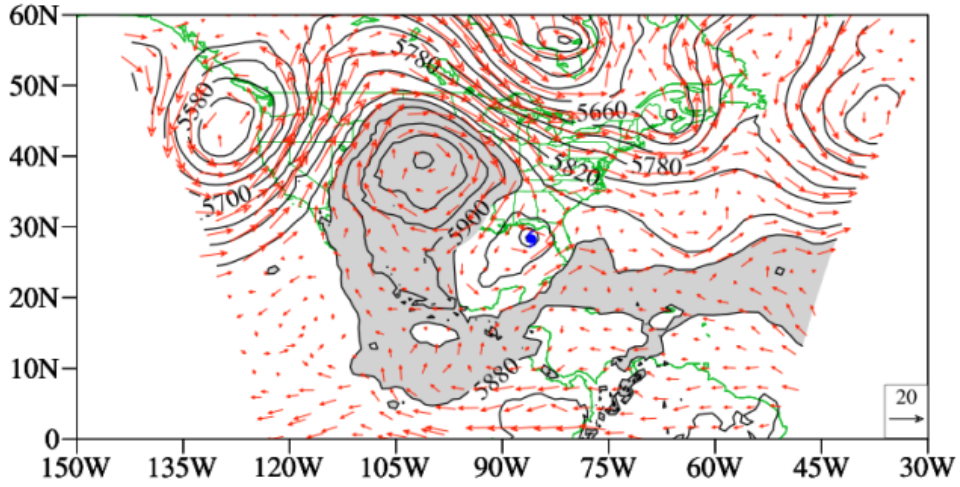
Geopotential and Wind Vector at 500 hPa

Asymmetric Vortex＋GOES Experiment

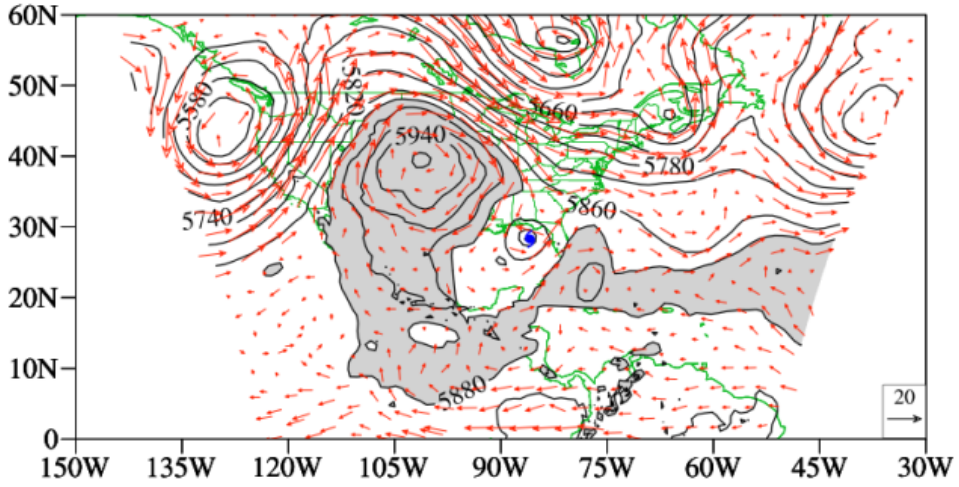


Geopotential and Wind Vector at 500 hPa

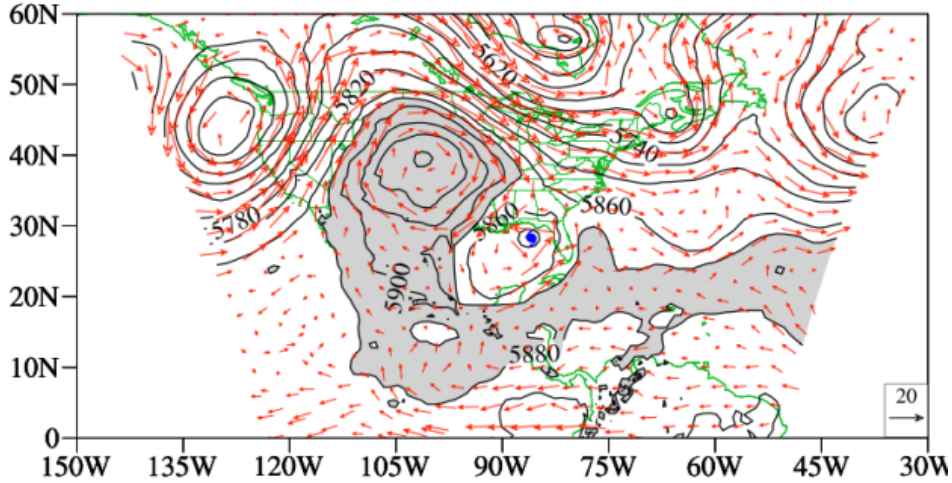
Symmetric Vortex



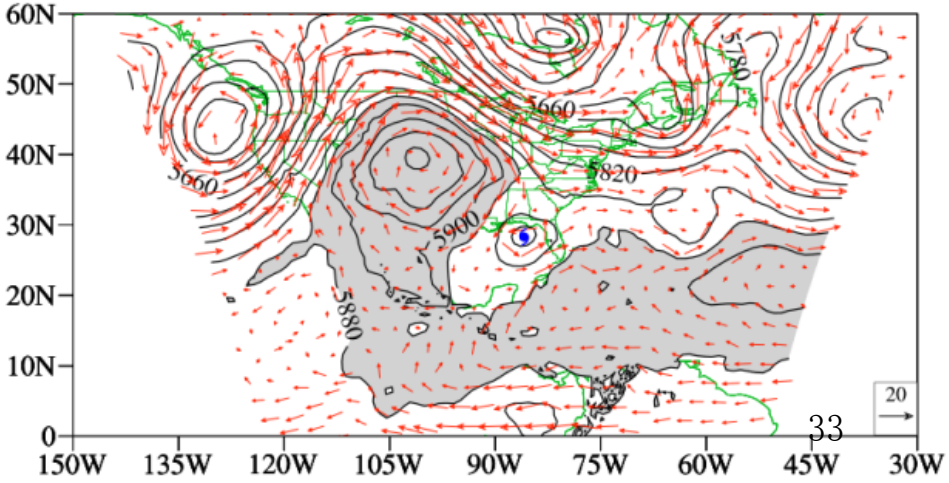
Asymmetric Vortex＋GOES



Asymmetric Vortex



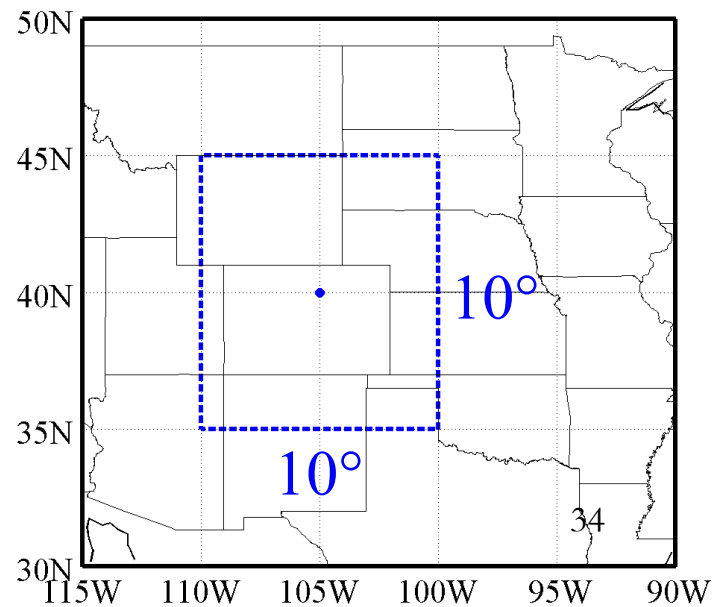
Asymmetric Vortex＋GOES



The Objective Regional Cloud Mask (ORCM) Algorithm for GOES Radiance Assimilation

CM Test	Condition for cloudy pixels
GROSST	$B^{10.7\mu m} - O^{10.7\mu m} > \varepsilon_{GRST}$
TUT	$\sigma_{3\times3}^{10.7\mu m} - \gamma\sigma_{3\times3}^{z} > \varepsilon_{TUT}$
RTCT	$(O_{3\times3}^{10.7\mu m} - \gamma\sigma_{3\times3}^{z})_{\max} - (O_{3\times3}^{10.7\mu m} - \gamma\sigma_{3\times3}^{z}) > \varepsilon_{RTCT}$
CH42T-1	$O^{3.9\mu m} - O^{10.7\mu m} > \varepsilon_{42T}^{1}$
CH42T-2	$O^{10.7\mu m} - O^{3.9\mu m} > \varepsilon_{42T}^{2}$ (nighttime)
CH46T	$(B^{10.7\mu m} - B^{13.3\mu m}) - (O^{10.7\mu m} - O^{13.3\mu m}) > \varepsilon_{46T}$
WtrVprT	$(B^{10.7\mu m} - B^{6.5\mu m}) - (O^{10.7\mu m} - O^{6.5\mu m}) > \varepsilon_{WVT}$

Zou, X. and C. Da, 2014: An objective regional cloud mask algorithm for GOES imager radiances with pixel-dependent thresholds. *J. Geophy. Res.*, **119**, doi:10.1002/2014JD021455.



Threshold Optimization

$$\textit{maximize} \quad f_i^{PCT}(\varepsilon) = \frac{N\left[G^{clr} \cap T_i^{clr}(\varepsilon)\right] + N\left[G^{cld} \cap T_i^{cld}(\varepsilon)\right]}{N\left[T_i\right]}$$

subject to **:**

$$f_i^{CON1}(\varepsilon) = \frac{N\left[G^{clr} \cap T_i^{cld}(\varepsilon)\right]}{N\left[T_i^{cld}(\varepsilon)\right]} \le \alpha_1$$

$$f_i^{CON2}(\varepsilon) = \frac{N\left[G^{clr} \cap T_i^{cld}(\varepsilon)\right]}{N\left[G^{clr}\right]} \le \alpha_2$$

$$\varepsilon \in \left[\varepsilon^{lower}, \varepsilon^{upper}\right]$$

- $f^{PCT}(\varepsilon)$ is PCT based on the result of GROSST.
- $f^{CON1}(\varepsilon)$ describes the percentage of cloudy pixels identified by the ith CM test that were initially flagged as clear-sky pixels by GROSST in the first-guess CM
- $f^{CON2}(\varepsilon)$ represents the percentage of clear-sky pixels in the first-guess CM that are identified as cloudy by the ith CM test

Comparison with MODIS CM Results

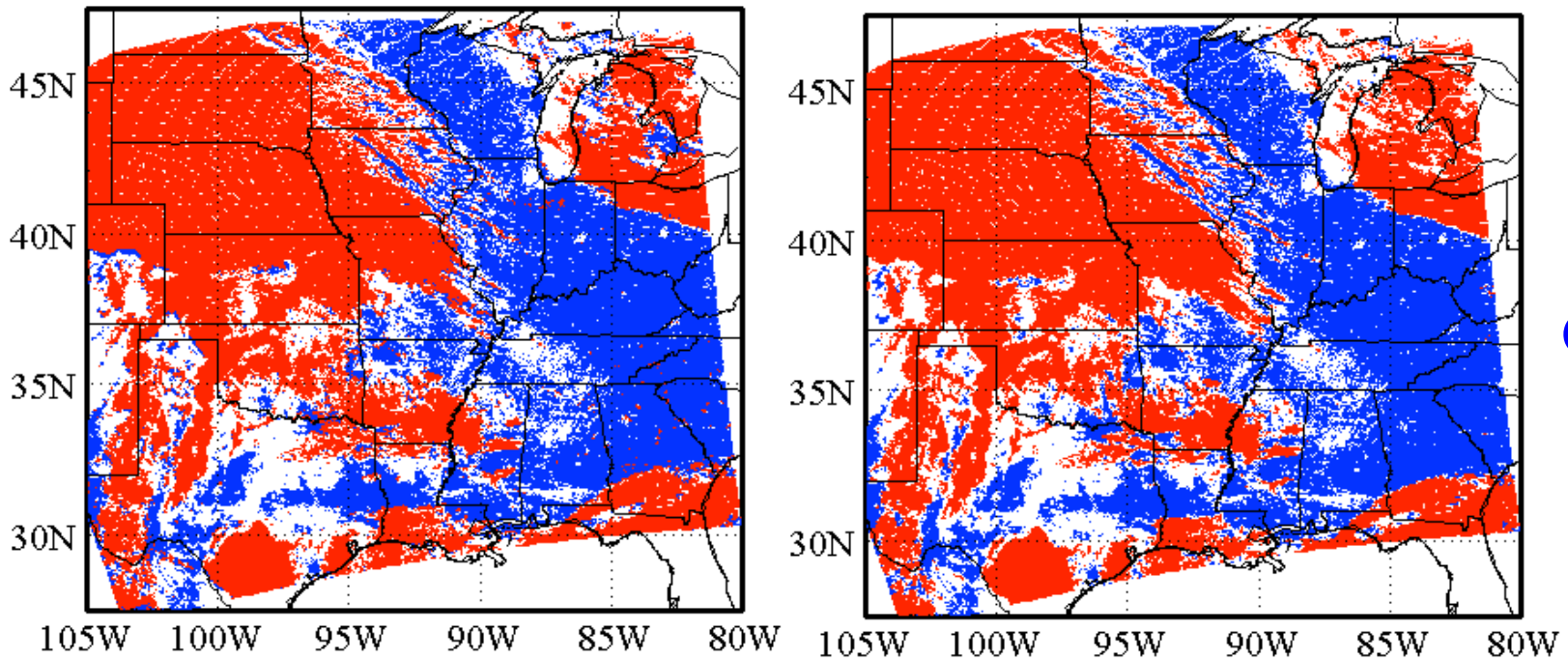
- **Data and Resolution**
  - ✓ Remapped MODIS cloud mask: ≈ 4 km
  - ✓ Remapped GOES pixel is cloud if more than 90% of 1-km high-resolution MODIS pixels are cloudy
  - ✓ Remapped GOES pixel is cloud if more than 90% of 1-km high-resolution MODIS pixels are clear with high-confidence
- **Collocation Criteria**
  - ✓ Spatial separation: ≤ 2 km
  - ✓ Temporal difference: ≤ 15 minutes

MOD35_L2 1-km pixel is mapped to the nearest GOES imager pixel

A Case with Large Cloudy Areas

0740UTC, May 23, 2008

GOES Imager CM **MODIS CM**



Cloudy

Clear-sky

Probability of Correct Typing (PCT) = 95.33%

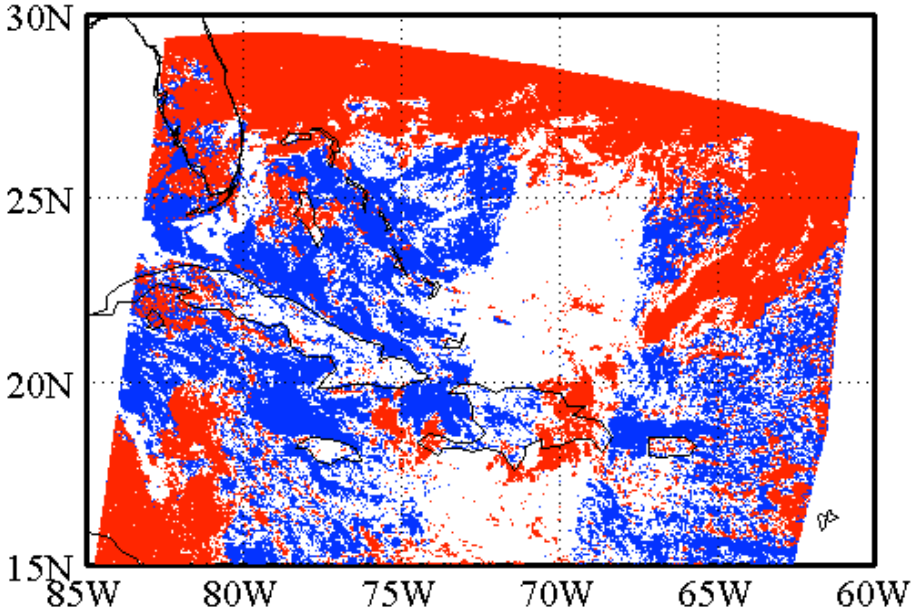
False Alarm (FAR) = 2.03%

Leakage Rate (LR) = 2.64%

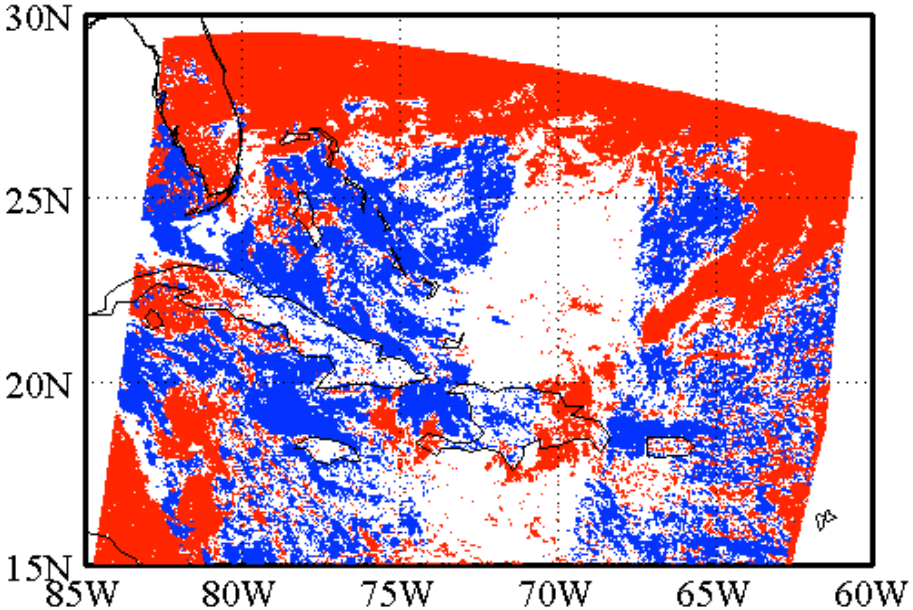
A Case with Isolated Clouds over Ocean

1530UTC, May 23, 200

GOES Imager CM



MODIS CM



Cloudy

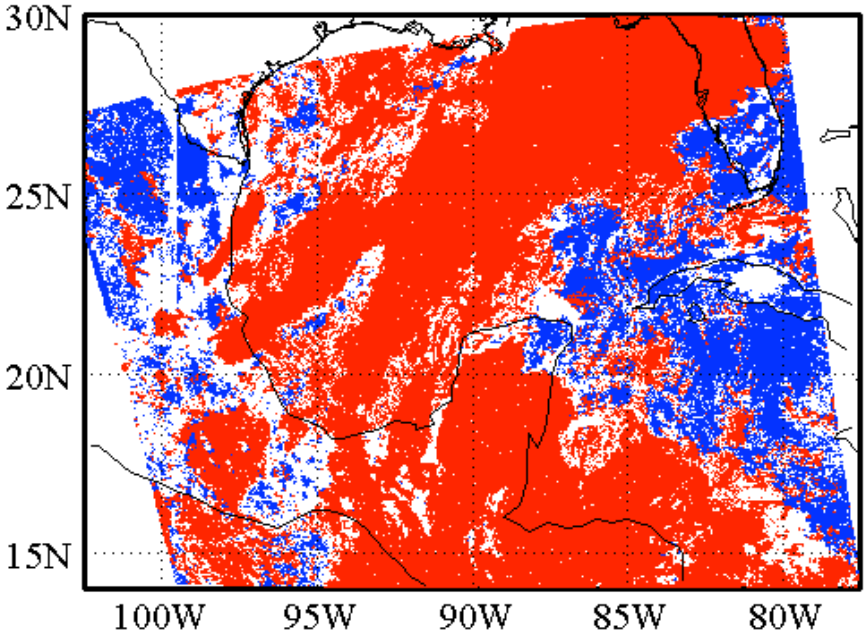
Clear-sky

PCT=92.27% FAR=2.98% LR=4.74%

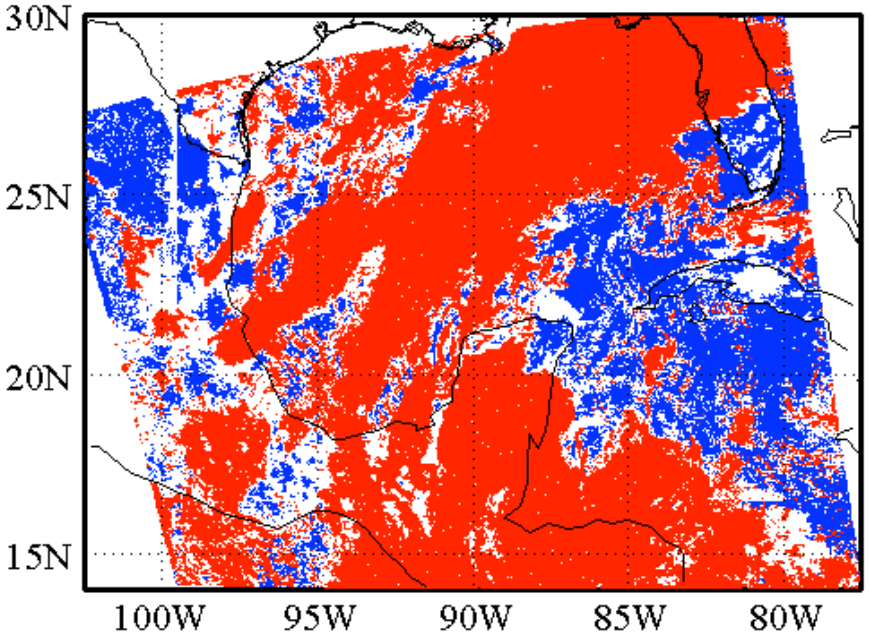
A Case with Congested Clouds and Isolated Clouds

0415UTC, May 22, 2008

GOES Imager CM



MODIS CM



PCT=93.54% FAR=4.17% LR=2.29%

Cloudy

Clear-sky

Summary and Conclusions

- Adding GOES-13/15 radiance assimilation in HWRF system improved track prediction of tropical storm Debby (2012)

- Incorporating an asymmetric bogus vortex allowed GOES-13/15 radiance assimilation to make more positive impacts on track prediction

Future Work

- Improve GOES radiance error estimate and/or QC

- Incorporate a newly developed objective regional cloud mask algorithm (Zou and Da, 2014) into the HWRF system for high resolution GOES radiance assimilation

More details can be found in the following journal papers:

Zou, X., Z. Qin and Y. Zheng, 2015: Improved tropical storm forecasts with GOES-13/15 imager radiance assimilation and asymmetric vortex initialization in HWRF. *Mon. Wea. Rev*., (revised)

Zou, X. and C. Da, 2014: An objective regional cloud mask algorithm for GOES imager radiances with pixel-dependent thresholds. *J. Geophy. Res.*, **119**, doi: 10.1002/2014JD021455.

Da C. and X. Zou, 2014: An introduction to GOES imager data. *Advances in Meteor.l Sci. and Tech.*, **4**, DOI: 10.3969/j.issn.2095-1973.2014.04.008

Qin, Z., X., Zou, and F. Weng, 2013: Evaluating added benefits of assimilating GOES imager radiance data in GSI for coastal QPFs. *Mon. Wea. Rev*., **141**(1), 75-92.

Zou, X., Z. Qin, and F. Weng, 2011: Improved coastal precipitation forecasts with direct assimilation of GOES 11/12 imager radiances, *Mon. Wea. Rev*., **139**, 3711-3729.

Acknowledgement

- Hurricane Forecast Improvement Program (HFIP)

- Geostationary Operational Environmental Satellite R-Series (GOES-R) Program