Radiance Data Assimilation for WRF model: overview and results

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NCAR/MMM

JCSDA connection: CRTM team

Work supported by AFWA, NASA, NSF, KMA

JCSDA Seminar, April 29 2008

Radiance Team

- Zhiquan Liu (Coordination, cloudy radiance)
- Tom Auligné (VarBC, AIRS)
- Hui-Chuan Lin (SSMIS etc.)
- Xin Zhang (software engineering aspects)
- Hui Shao (DATC extended tests)

NOTE: Some works on radiance in part-time.

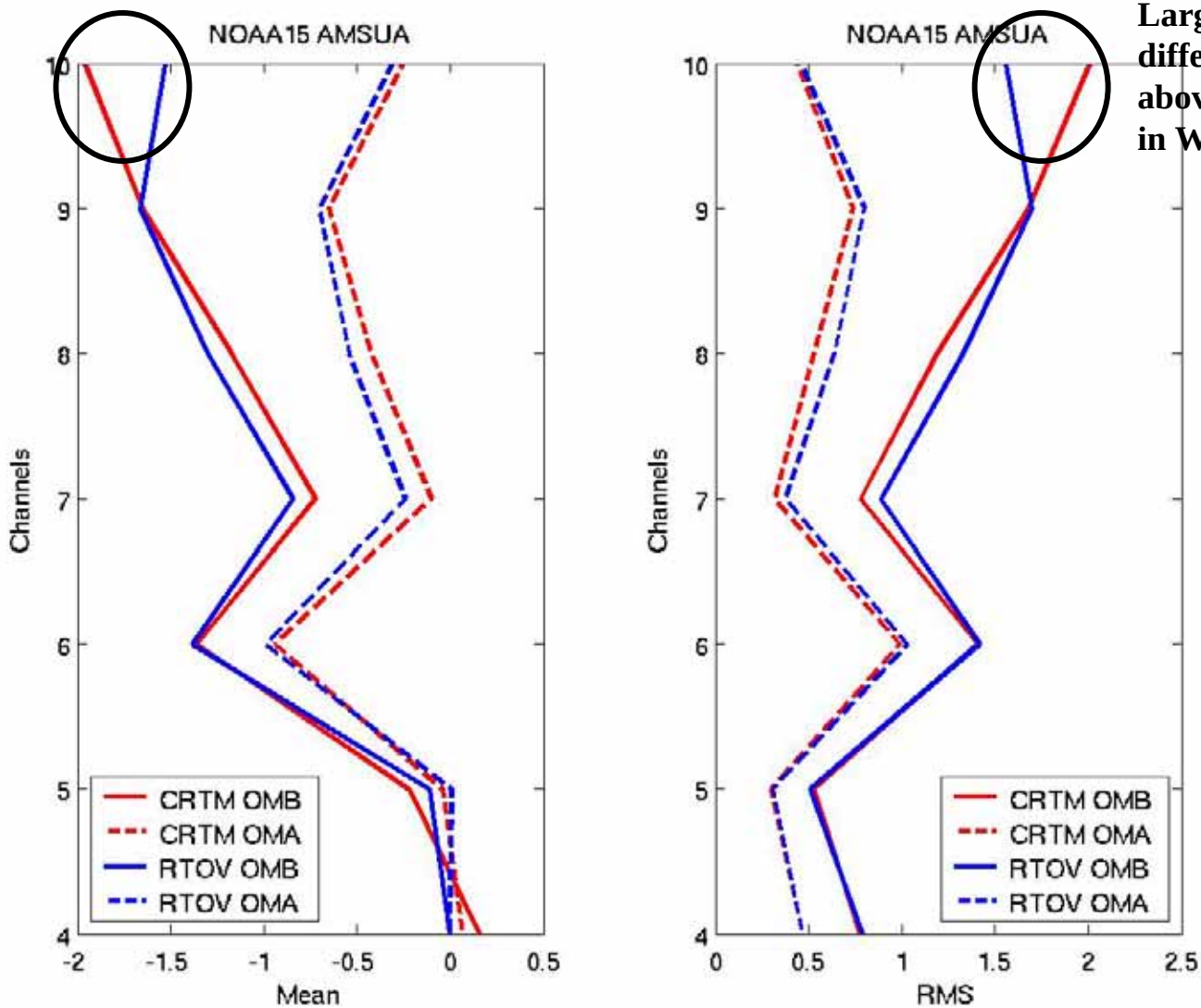
Outline

- Components of radiance assimilation in WRF-Var with demonstrations
- Radiance Assimilation Applications
  - A case study for Hurricane Katrina using RTTOV
  - DATC extended tests using CRTM
- Cloudy radiance assimilation development using CRTM
- 4DVAR+Radiance

Components of radiance assimilation

- Data Ingestion
  - NCEP radiance BUFR data
    - AMSU-A/B, MHS, HIRS, AIRS
  - SSMIS from AFWA/NRL, UPP produced
- Radiative Transfer Model
  - Both CRTM and RTTOV
- Bias Correction
  - Scan bias and air-mass bias (Harris and Kelly, 2001)
  - Variational Bias Correction (Derber and Wu, 1998)
- Quality Control
- Thinning and Load balancing
- Observation error tuning (Desroziers & Ivanov, 2001)
- Monitoring tool
- Work for 3DVAR/FGAT/4DVAR

CRTM_Beta vs. RTTOV8_5



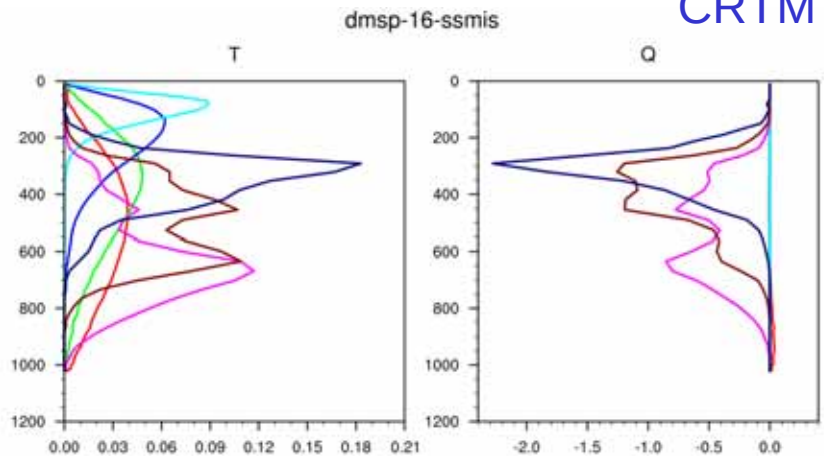
Large difference due to different treatment above the model top in WRF-Var

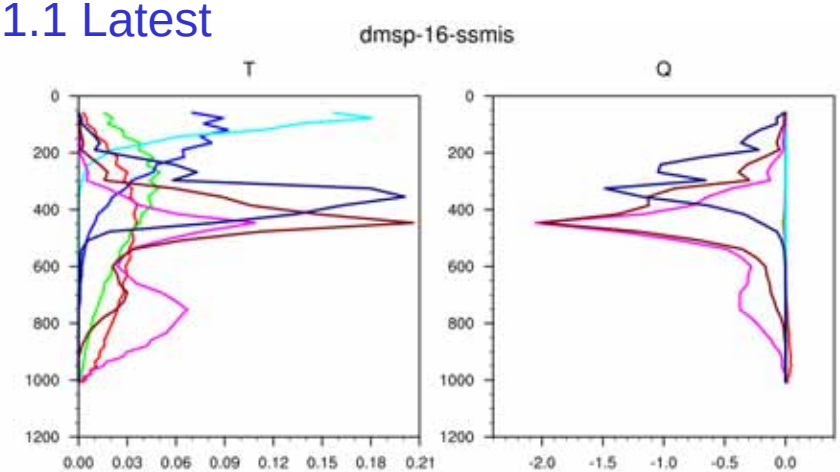
Forward calculation is similar using CRTM and RTTOV

CRTM Jacobian for SSMIS AMSU-like channels

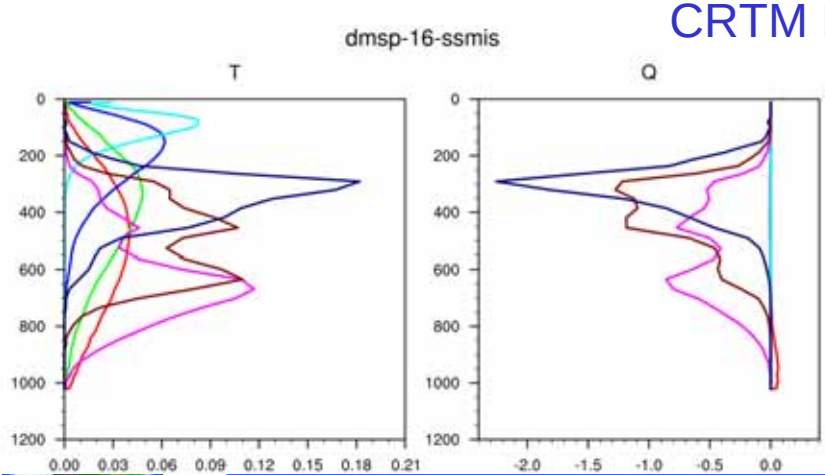
Atlantic domain Ptop=10hPa East Asia domain Ptop=50hPa

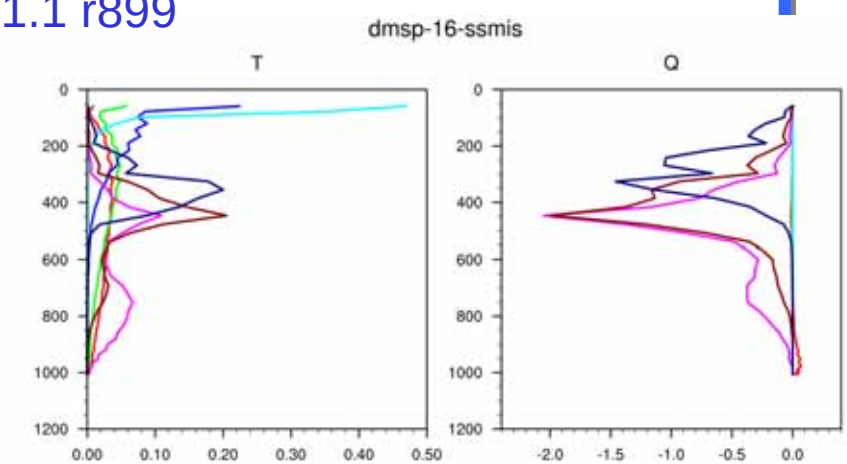
CRTM REL-1.1 Latest





CRTM REL-1.1 r899





Recent speed up of CRTM

Pre-release version (provided by Mark Liu) vs. the latest CRTM release

Overall Timing Summary (from WRF-Var tracing feature)

Routine Name	Calls	Elapsed Time (seconds)				CPU Time (seconds)				Speed up
	per PE	Average per PE	%	Minimum	Maximum	Total	%	Minimum	Maximum	64 PE
da_crtm_direct	103.0	0.51	0.2	0.3 on 5	0.8 on 8	16.53	16.6	0.1 on 56	0.4 on 7	32.63
da_crtm_direct	103.0	0.23	0.1	0.1 on 58	0.5 on 15	7.84	8.7	0.0 on 34	0.2 on 15	33.77

Forward model 2.2 times faster

da_crtm_tl	2162.0	15.06	7.3	7.4 on 57	25.9 on 8	474.11	477.2	3.5 on 26	12.5 on 8	31.48
da_crtm_tl	2162.0	8.76	4.6	4.3 on 26	16.7 on 15	277.02	306.0	2.1 on 26	8.4 on 15	31.61

Tangent Linear model 1.7 times faster

da_crtm_ad	2265.0	13.39	6.5	8.2 on 26	22.8 on 8	413.68	416.3	3.7 on 26	10.9 on 8	30.90
da_crtm_ad	2265.0	8.01	4.2	4.7 on 26	13.5 on 15	252.30	278.7	2.3 on 57	6.7 on 15	31.49

Adjoint model 1.67 times faster

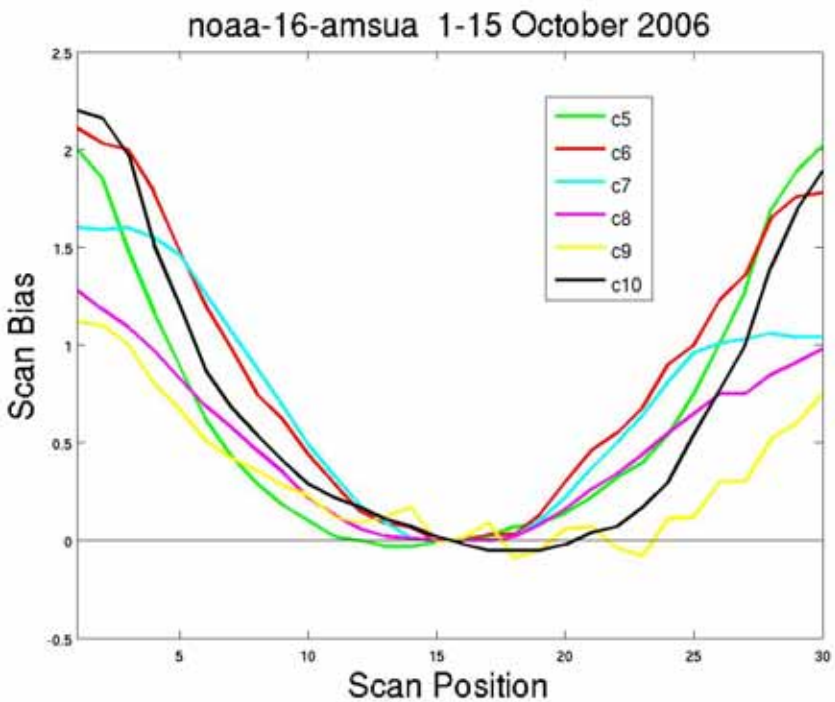
Air-Mass dependent Bias Correction

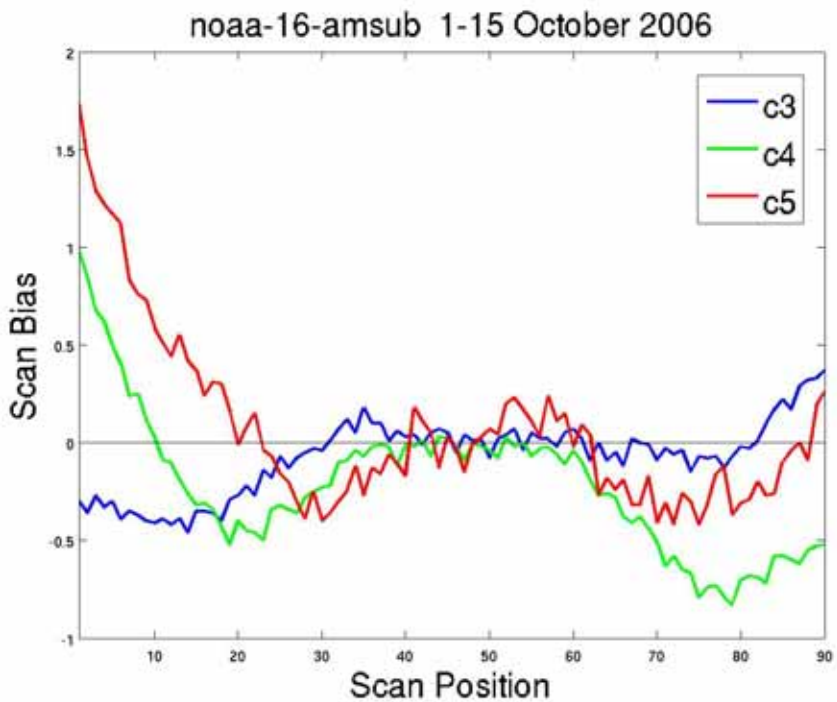
- Harris & Kelly (2001) scheme
  - Bias coefficient calculated offline and fixed
  - Separate total bias into scan bias and air-mass dependent bias
  - Air-mass bias is predicted by some ‘predictors’
    - 1000-300mb thickness
    - 200-50mb thickness
    - surface skin temperature
    - Total column precipitable water

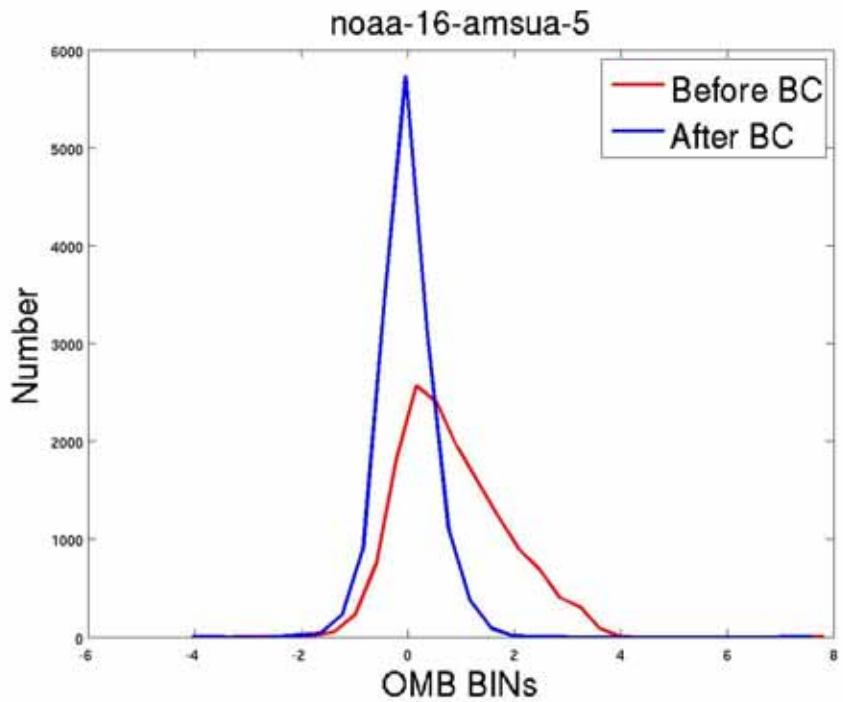
Scan Bias

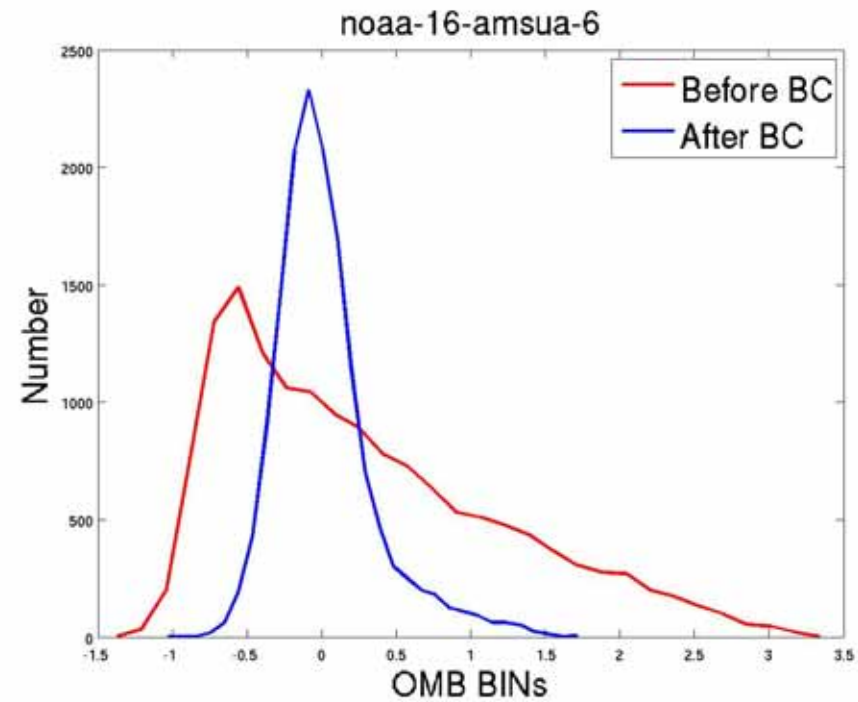
- Scan Bias = d(limb) - d(nadir)
  - d(.) is departure (omb or oma)
  - This is relative bias between limb and nadir

Scan bias statistics for SWA domain with 15 days data






noaa-16-amsua-5
Before BC
After BC
Number
OMB BINs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Before BC
After BC
Number
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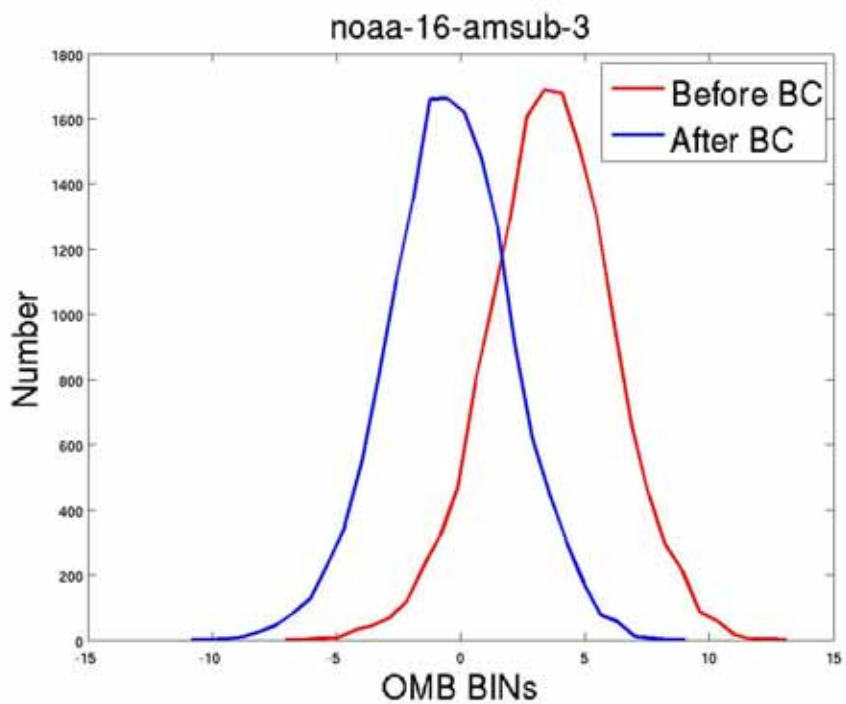
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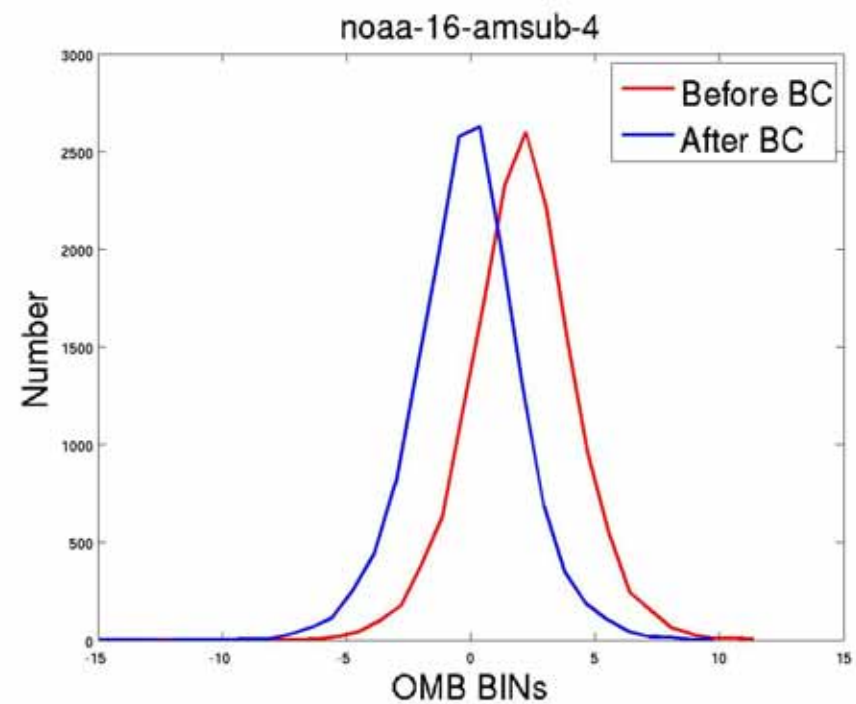
Before BC
After BC
Number
OMB BINs


noaa-16-amsub-4
Before BC
After BC
Number
OMB BINs

Variational bias correction: VarBC

For each instrument/channel, the **biais** is described from (a few) **parameters** (associated with air-mass and scan predictors).

These parameters can be estimated within the variational assimilation, jointly with the atmospheric model state (Derber and Wu 1998) (Dee 2005)

- Inclusion of the bias parameters in the control vector : $x^T \rightarrow [x, \beta]^T$
- Modification of the observation operator to include the bias : $H(x) \rightarrow H(x,\beta)$

J_b: background term for x — J_o: observation term

$$\mathbf{J}(\mathbf{x}) = (\mathbf{x_b} - \mathbf{x})^{\mathbf{T}} \mathbf{B}_{\mathbf{x}}^{-1} (\mathbf{x_b} - \mathbf{x}) + [\mathbf{y} - b - H(\mathbf{x})]^{\mathbf{T}} \mathbf{R}^{-1} [\mathbf{y} - b - H(\mathbf{x})]$$

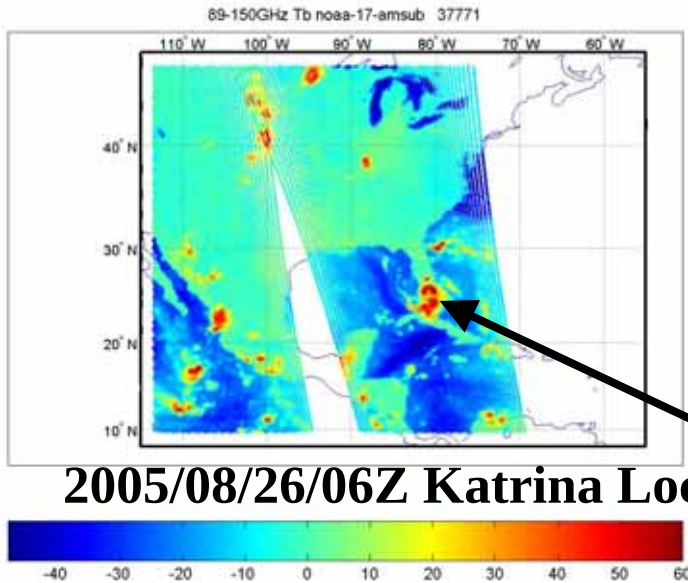
J_b: background term for x — J_o: corrected observation term

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x_b} - \mathbf{x})^{\mathbf{T}} \mathbf{B}_{\mathbf{x}}^{-1} (\mathbf{x_b} - \mathbf{x}) + [\mathbf{y} - \mathbf{b}(\beta) - H(\mathbf{x})]^{\mathbf{T}} \mathbf{R}^{-1} [\mathbf{y} - \mathbf{b}(\beta) - H(\mathbf{x})]$$
$$+ (\beta_{\mathbf{b}} - \beta)^{\mathbf{T}} \mathbf{B}_{\beta}^{-1} (\beta_{\mathbf{b}} - \beta)$$

J_β: background term for β

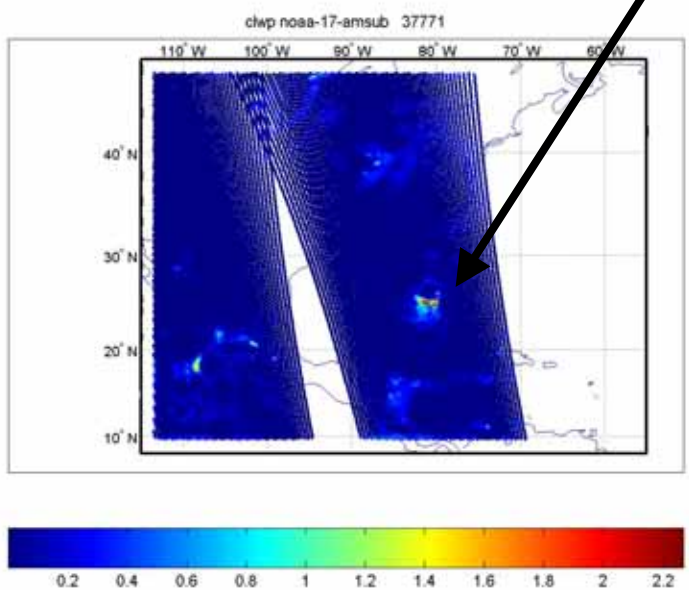
QC: AMSU Precipitation Detection

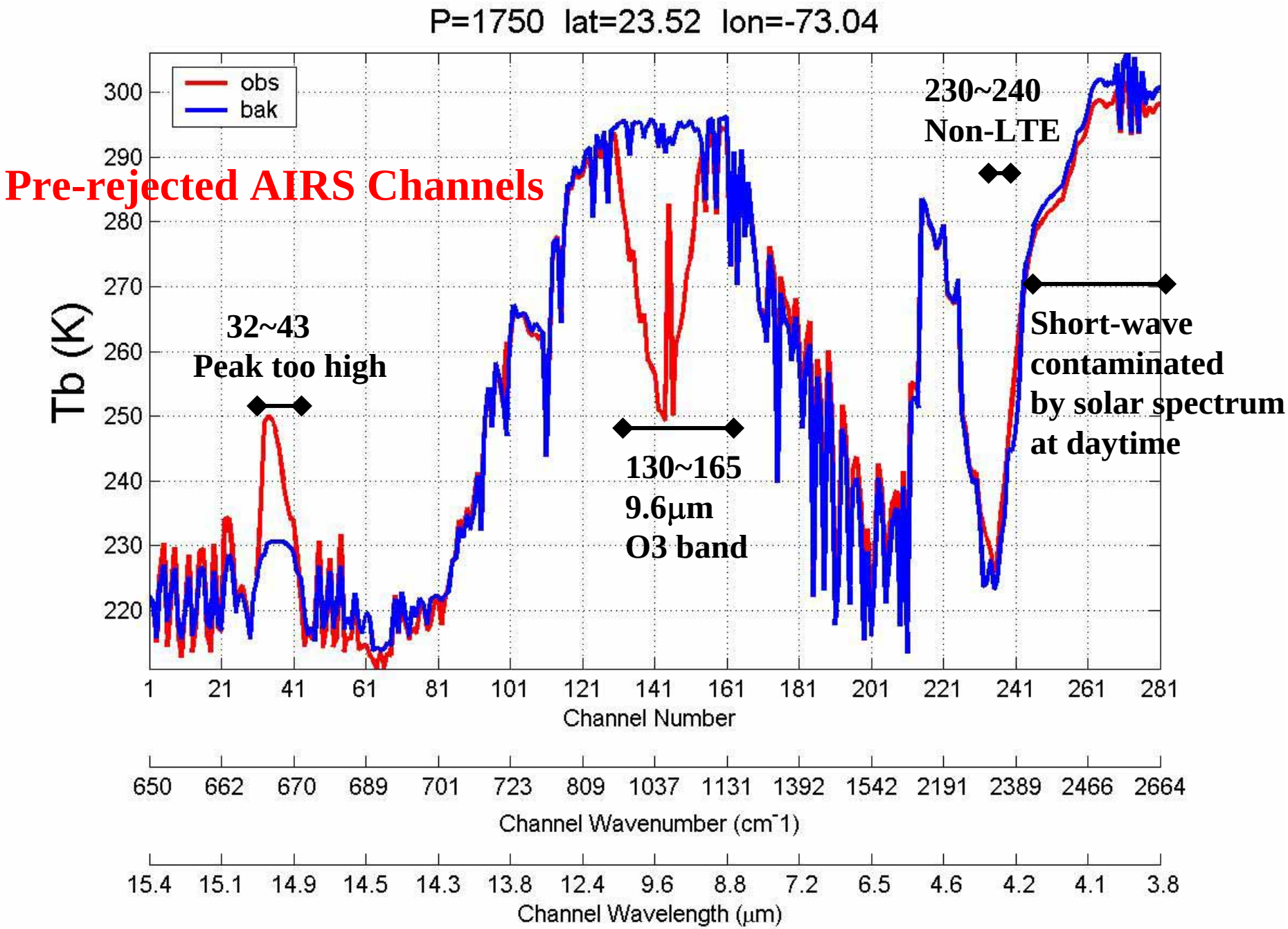
AMSU-B Scatter Index (89GHz-150GHz) Tb Rejected if >=3K



2005/08/26/06Z Katrina Location

Cloud Liquid Water Path(mm) From Guess Rejected If >=0.2mm

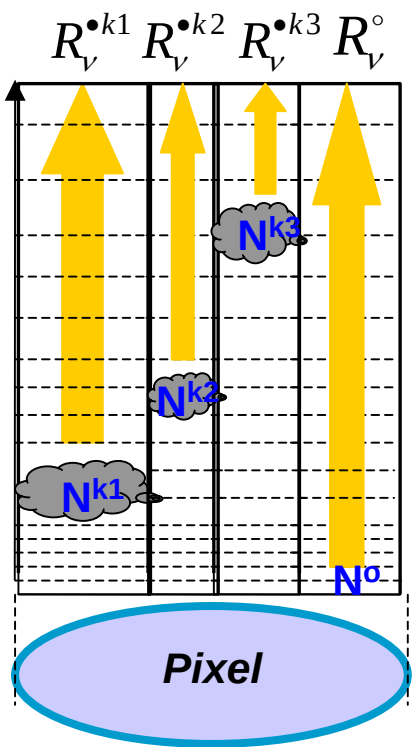



P=1750 lat=23.52 lon=-73.04
obs
bak
Pre-rejected AIRS Channels
32~43
Peak too high
130~165
9.6μm
O3 band
230~240
Non-LTE
Short-wave
contaminated
by solar spectrum
at daytime
Tb (K)
300
290
280
270
260
250
240
230
220
1 21 41 61 81 101 121 141 161 181 201 221 241 261 281
Channel Number
650 662 670 689 701 723 809 1037 1131 1392 1542 2191 2389 2466 2664
Channel Wavenumber (cm-1)
15.4 15.1 14.9 14.5 14.3 13.8 12.4 9.6 8.8 7.2 6.5 4.6 4.2 4.1 3.8
Channel Wavelength (μm)

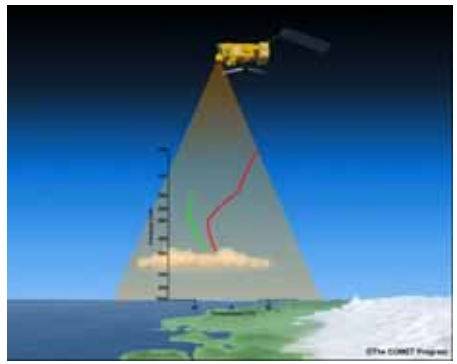
AIRS cloud detection (courtesy T. Auligne)

Cloud detection strategy:

from « hole hunting » (identifying clear pixels)
to identifying clear channels (insensitive to the cloud).



Multivariate Minimum Residual (MMR) scheme



R_ν° Radiance calculated in clear sky

$R_\nu^{\bullet k}$ Radiance calculated for a thin opaque cloud at level k

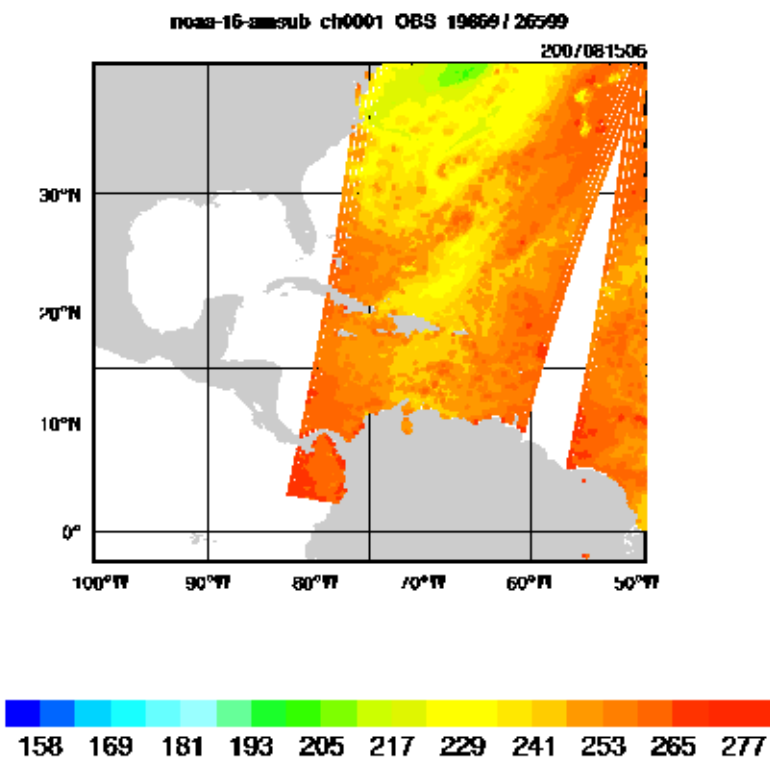
$$R_\nu^{Cld} = \sum_{k=1}^{n} N^k R_\nu^{\bullet k} + N^{\circ} R_\nu^{\circ} \quad \text{with} \quad \begin{cases} 0 \le N^k \le 1, \forall k \in [0,n] \\ N^{\circ} + \sum_{k=1}^{n} N^k = 1 \end{cases}$$

For each pixel, the *n* cloud fractions $\mathbf{N^k}$ are adjusted **variationally** to fit the observed spectrum:

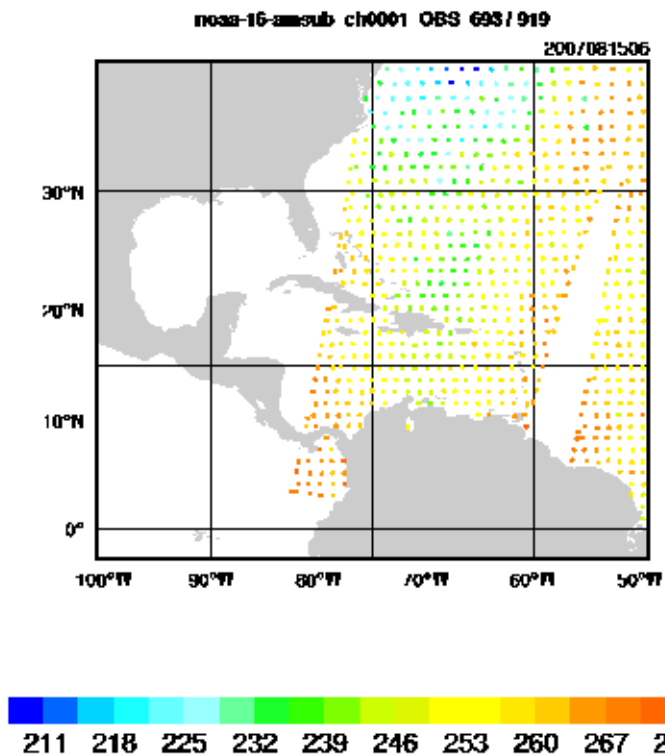
$$J(N) = \frac{1}{2} \sum_{\nu} \left(\frac{R_\nu^{Cld} - R_\nu^{Obs}}{R_\nu^{\circ}} \right)^2$$

Thinning Demonstration

No Thinning



120km Thinning Mesh



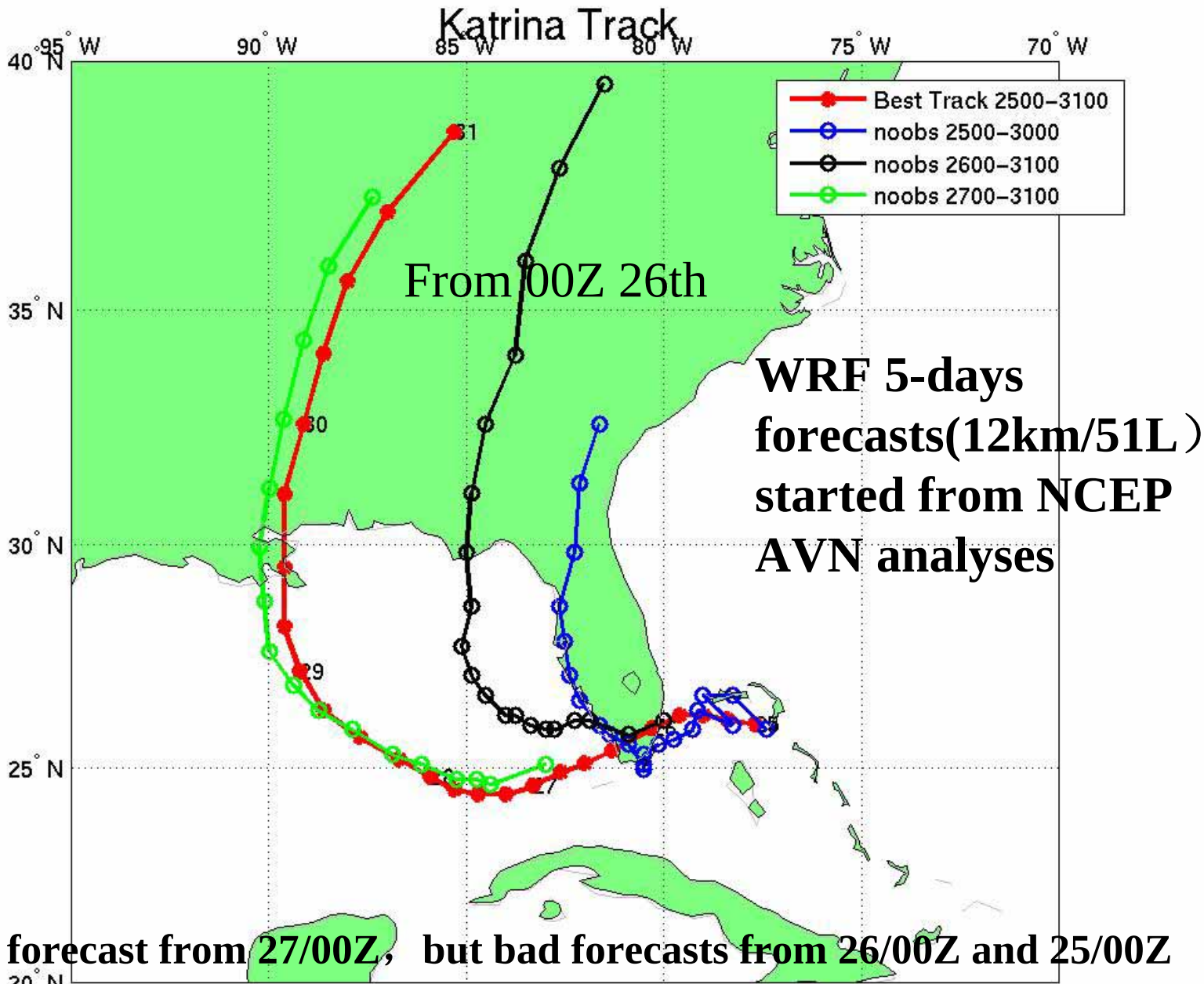
Pick one pixel closest to the center of the box

Application to Katrina Case with WRF-ARW

Use RTTOV

Assimilate only AMSU-A
Channels 1~4 over sea
Channels 5~10 both over sea and land
Pixels over precipitating area rejected

12km51L, model top 10mb (limited by NCEP GFS product)



WRF 5-days forecasts(12km/51L）started from NCEP AVN analyses

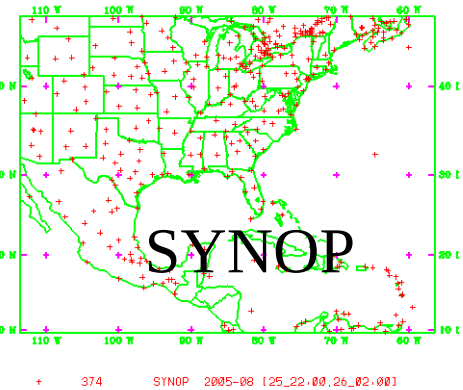
Good forecast from 27/00Z， but bad forecasts from 26/00Z and 25/00Z try to improve the forecast from 26/00Z by AMSU-A assimilation.

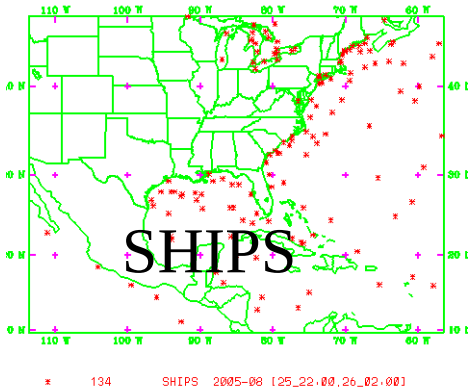
4 Assimilation Experiments at 00Z 26th

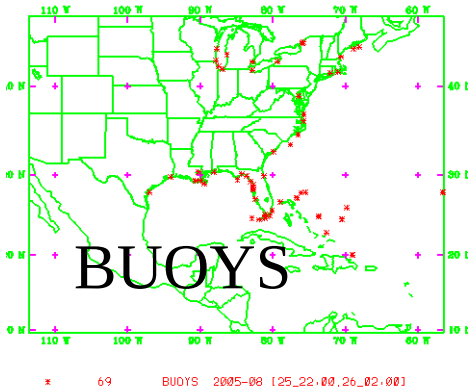
Background is a WRF 6h forecast from 18Z 25th

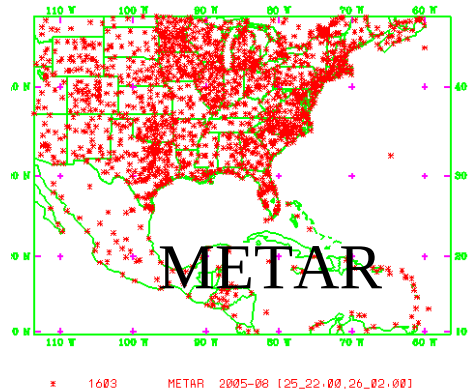
- GTS
  - only use conventional data
- AMSUA
  - only use AMSUA radiance
- GTS+AMSUA
  - conventional plus AMSUA radiance
- AMSUA+SLP
  - AMSUA radiance plus one single SLP located at center of Hurricane

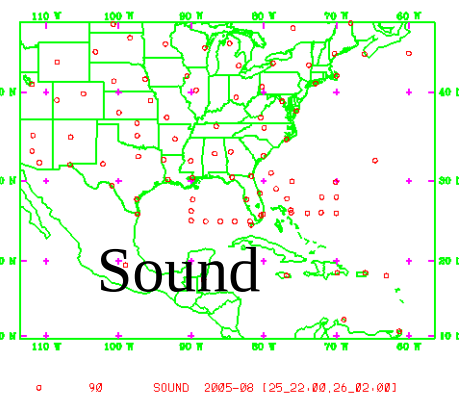
Followed by a 5-day forecast

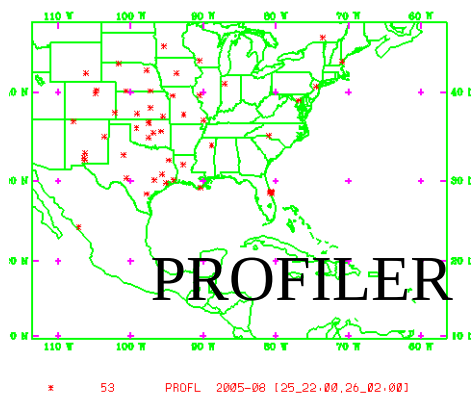


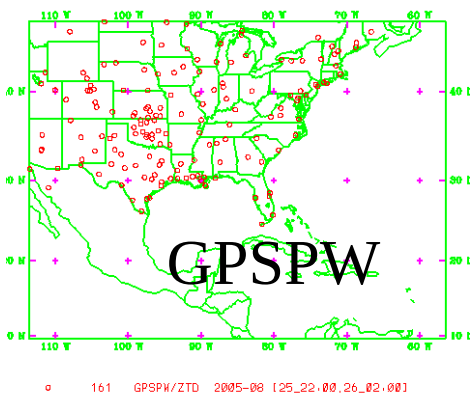


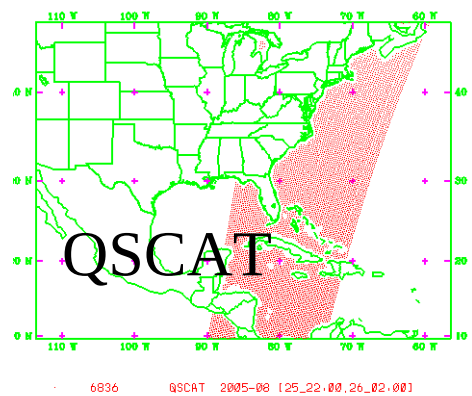


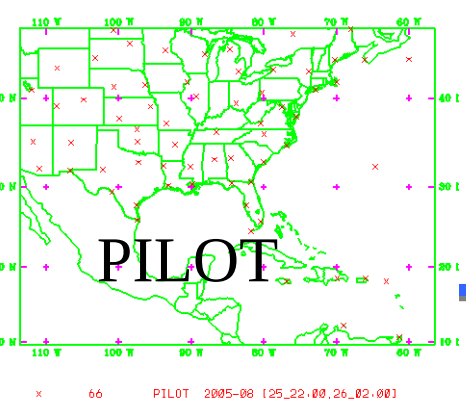


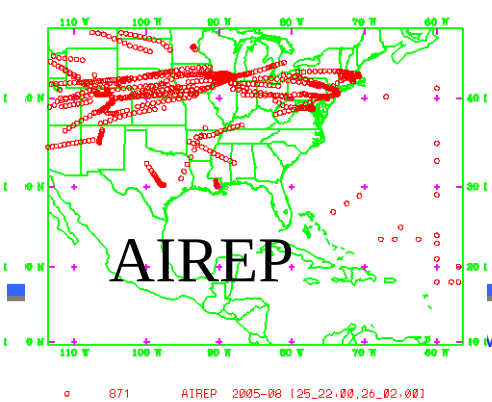






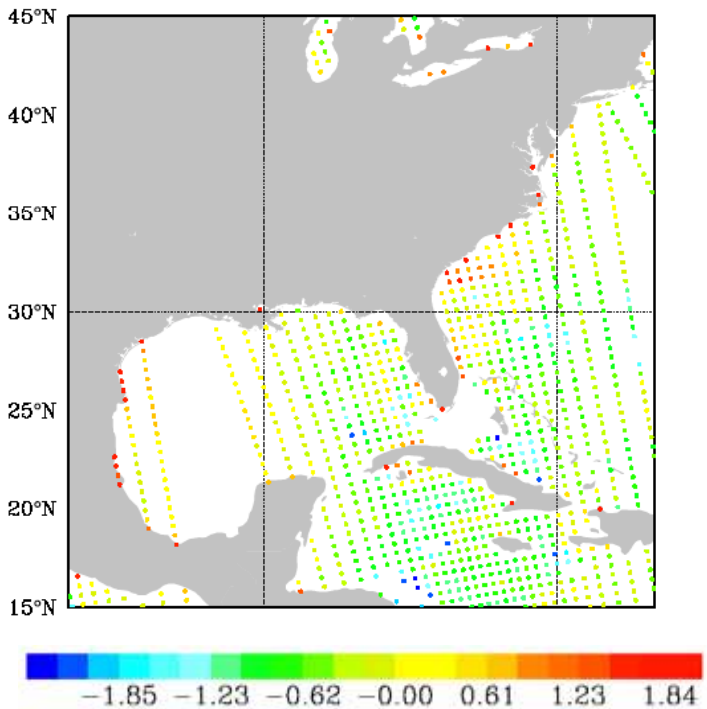




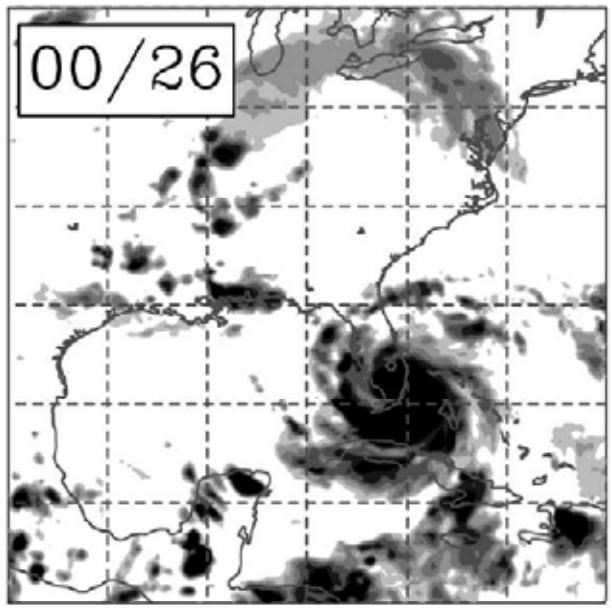


Conventional data coverage at 00Z 26th August

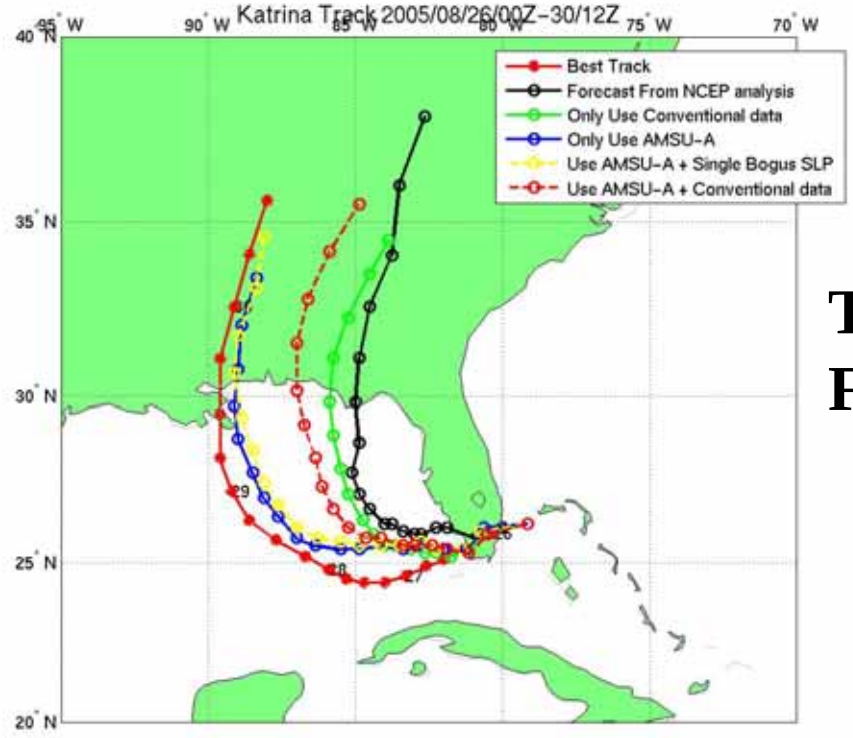
Satellite Observations



OMB of NOAA-15 AMSU-A channel 4 after Quality Control



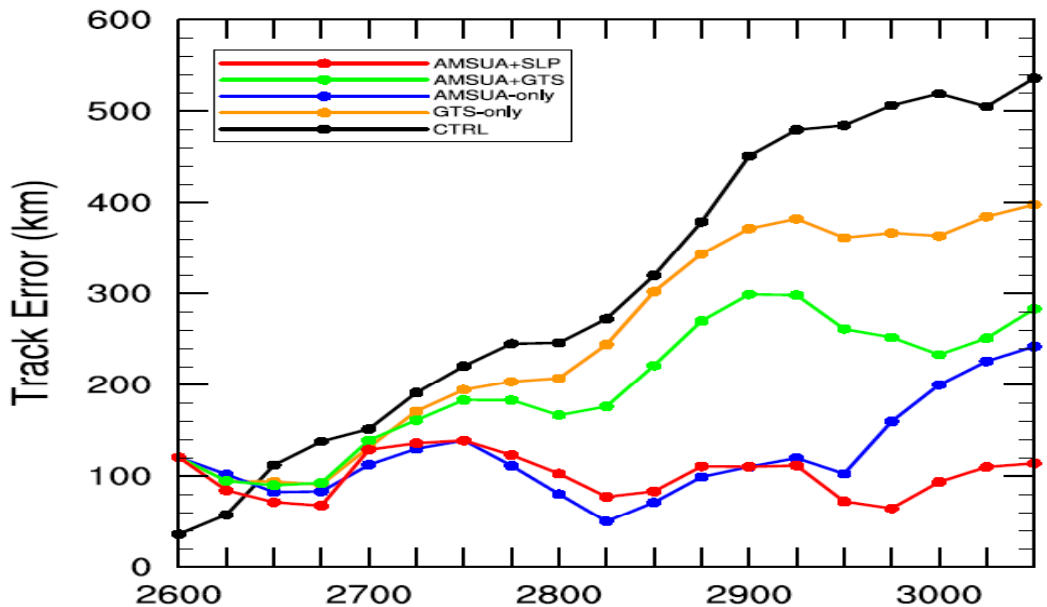
GOES IR image

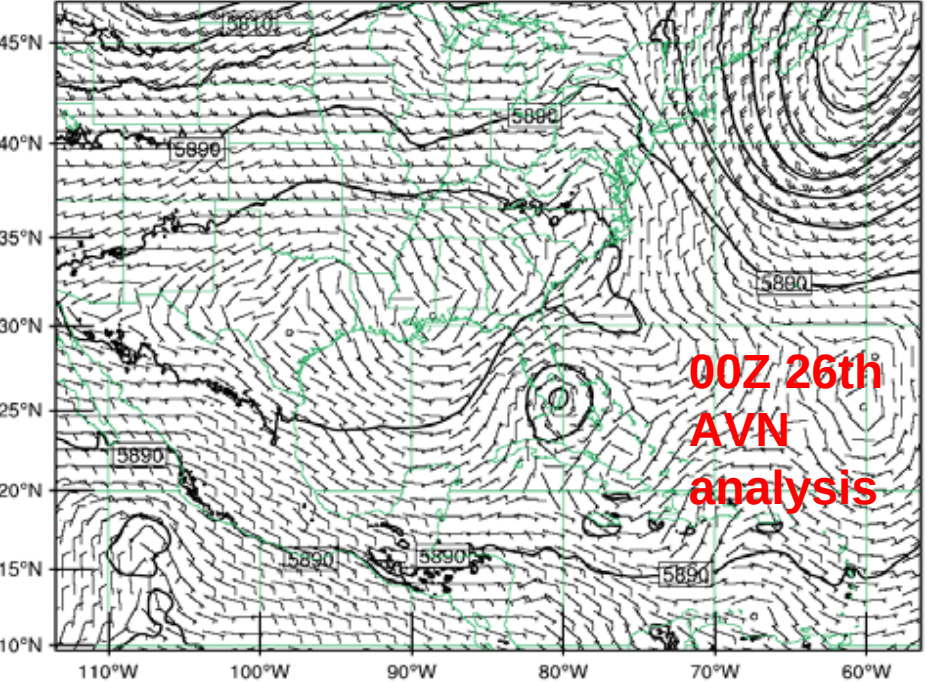


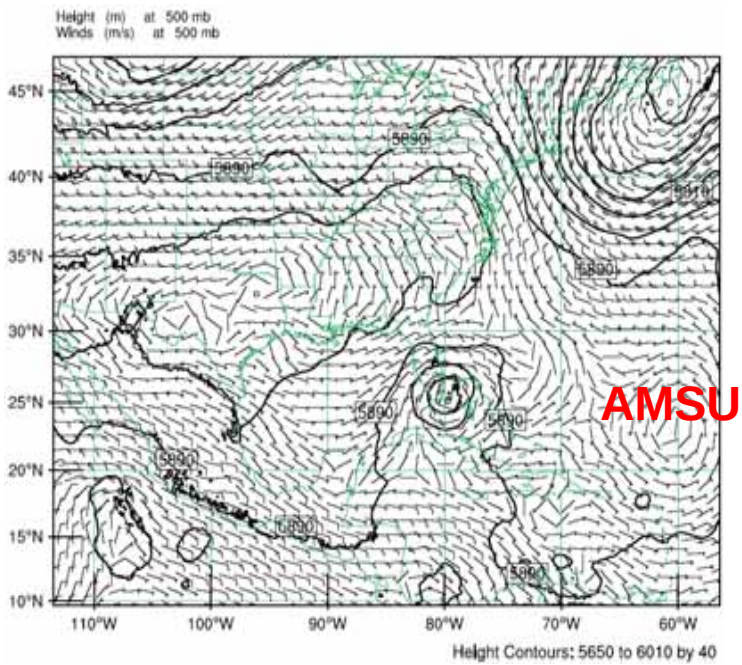
Track improvement mainly From AMSU-A assimilation

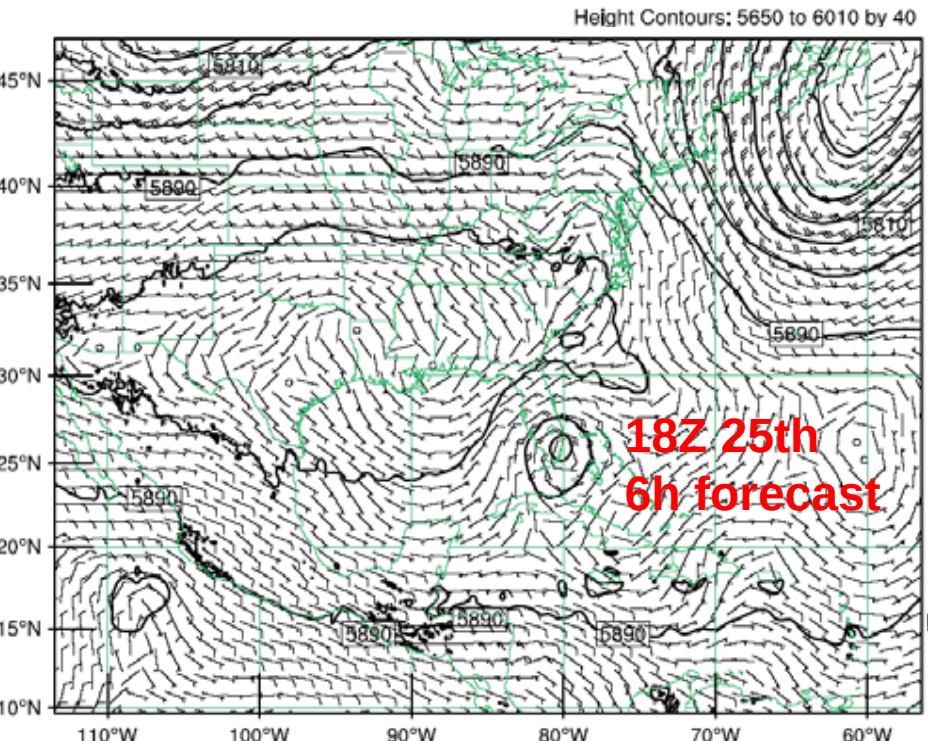
Track Error

Track

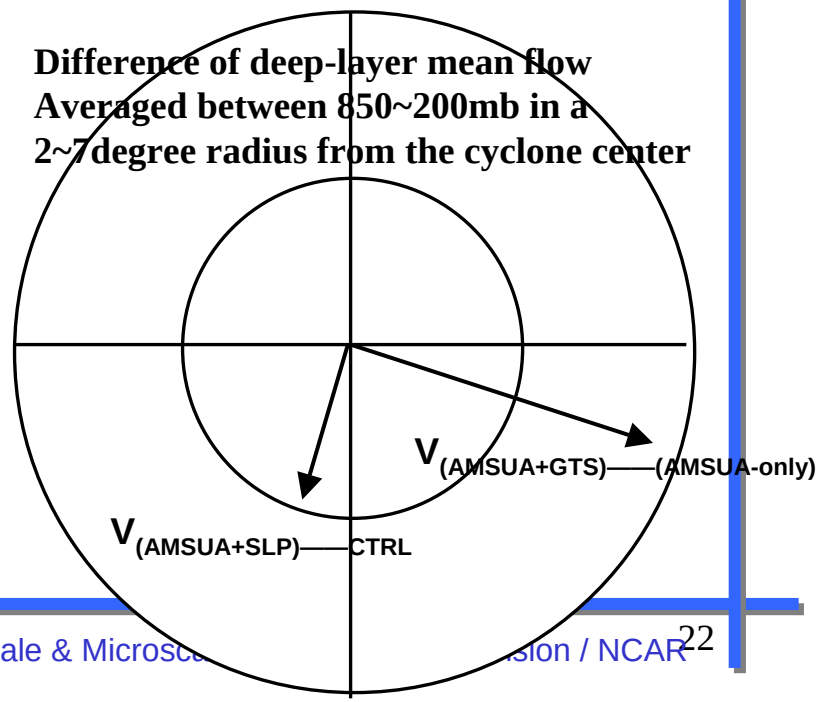


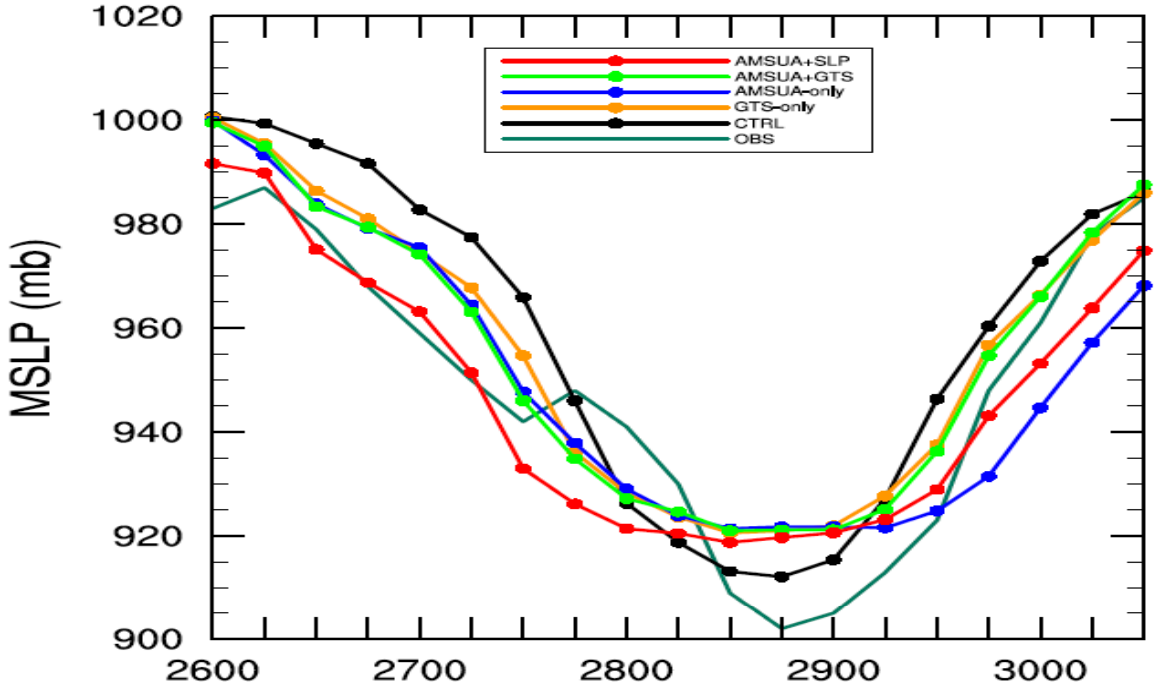


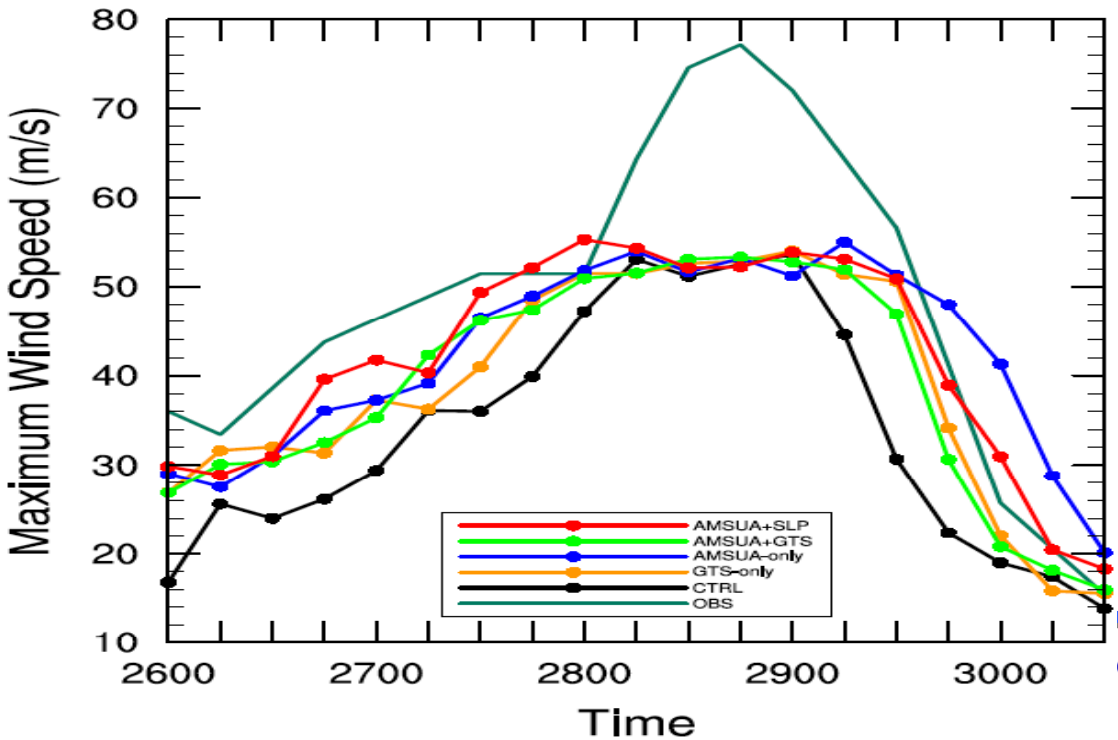




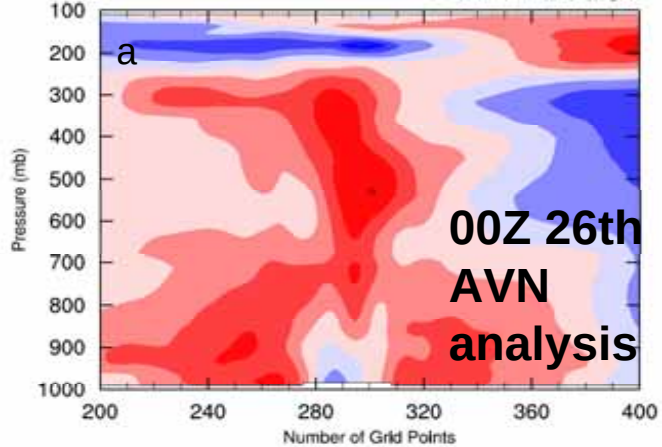
Difference of deep-layer mean flow Averaged between 850~200mb in a 2~7degree radius from the cyclone center



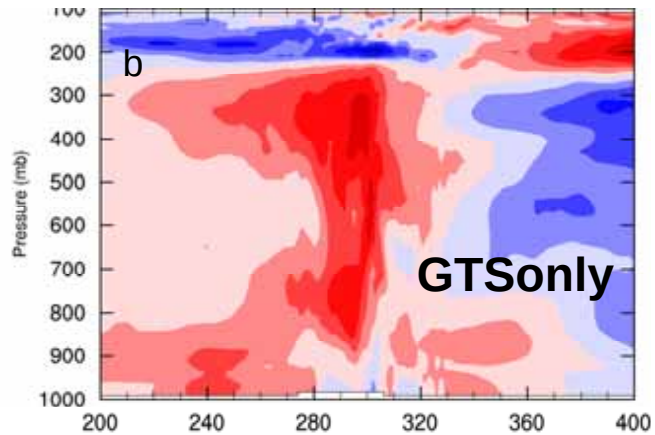


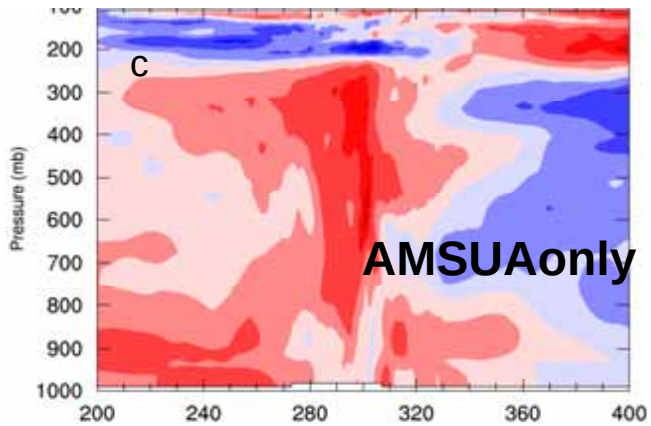


Best one is AMSU-A+SLP

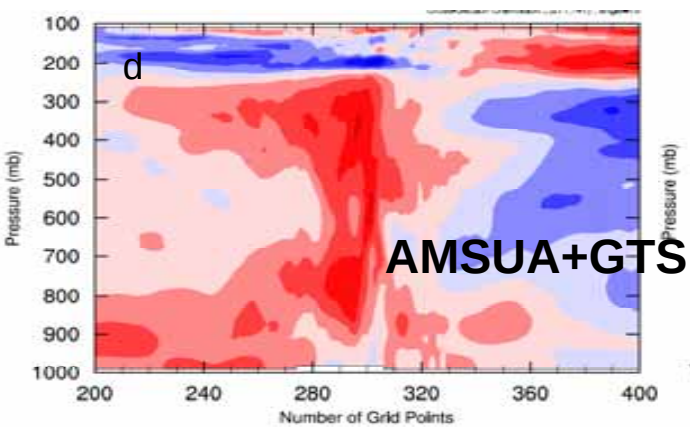


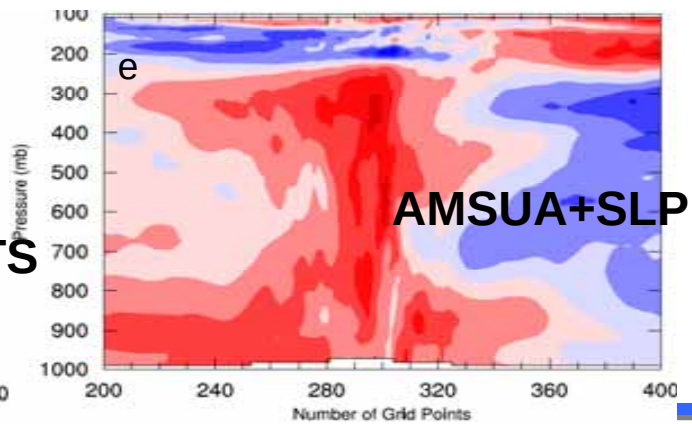
vertical cross section of the temperature deviation through the TC center. The center is near 290

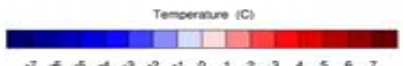


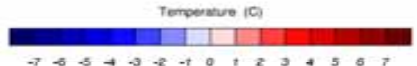


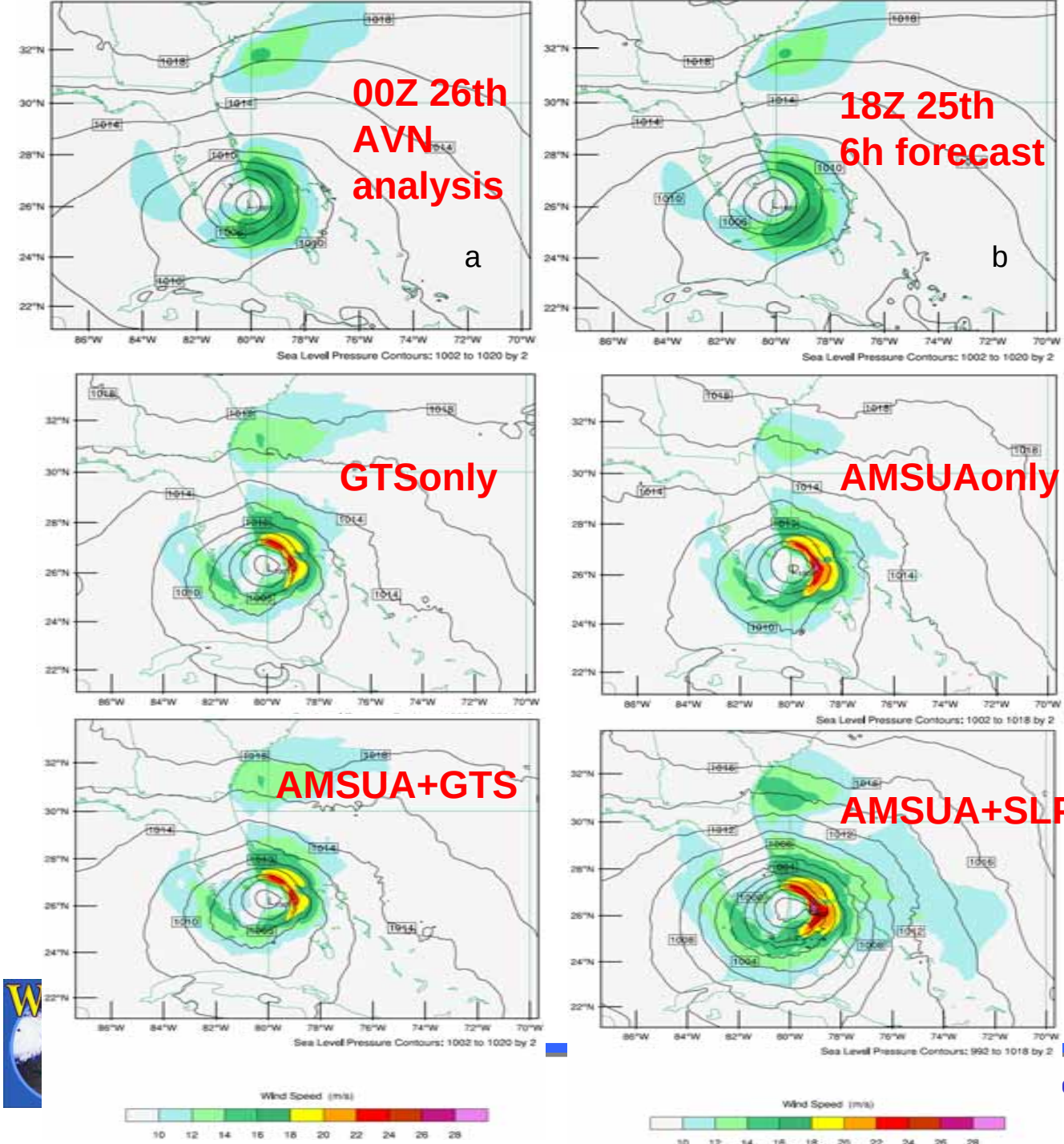
Warm core is Strengthened after assimilation, it is Important for TC Intensification.









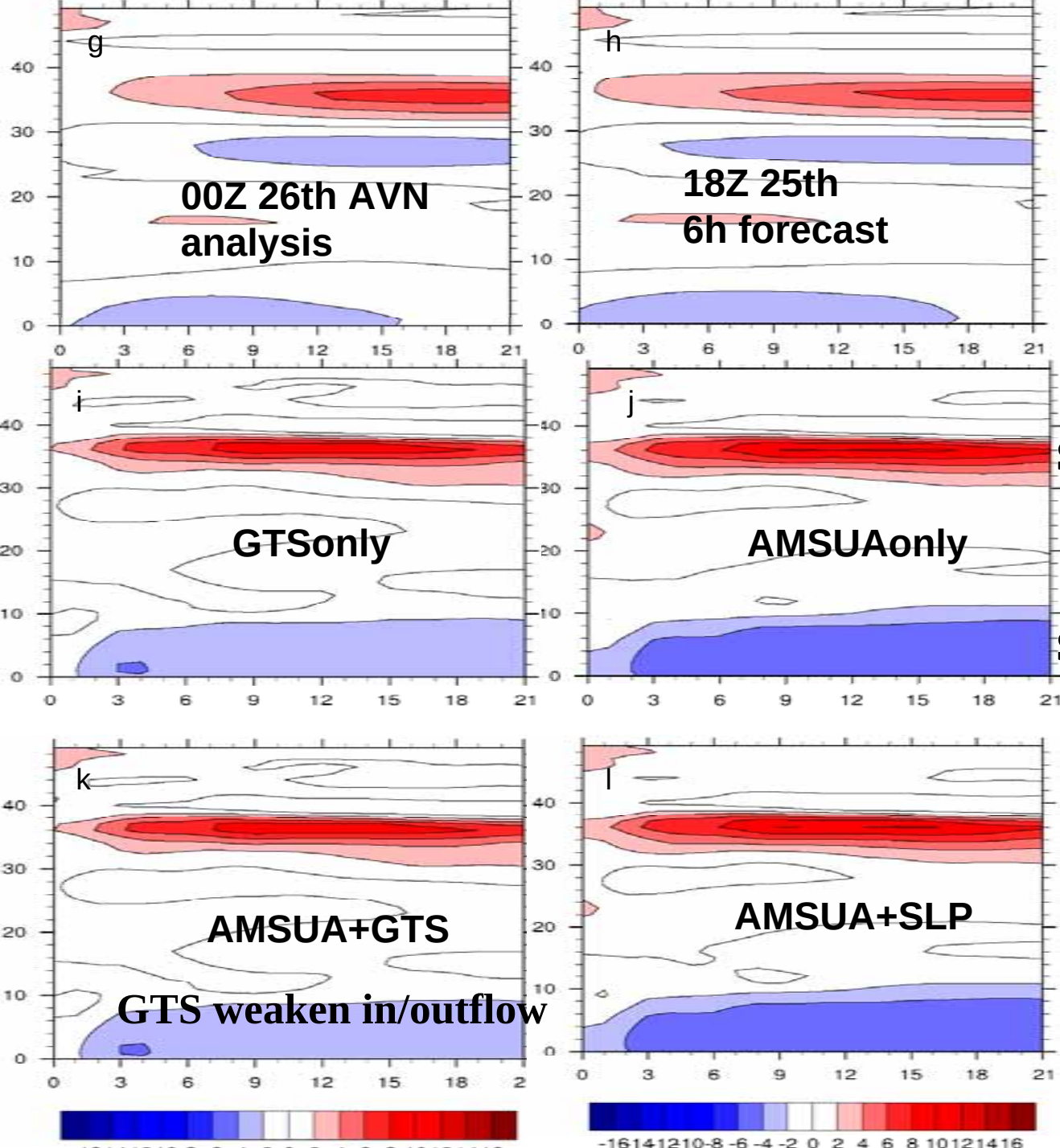


Best track:
983 hPa, 35 m/s

MWS 16~18m/s

AMSU-A affect wind analysis through background error covariance constraint

MWS increased to 24~26m/s with WRF-Var



vertical cross section of axisymmetric mean radial winds

Strengthen outflow

Strengthen inflow

Advantage for TC intensification

GTS weaken in/outflow

Remarks from Katrina case

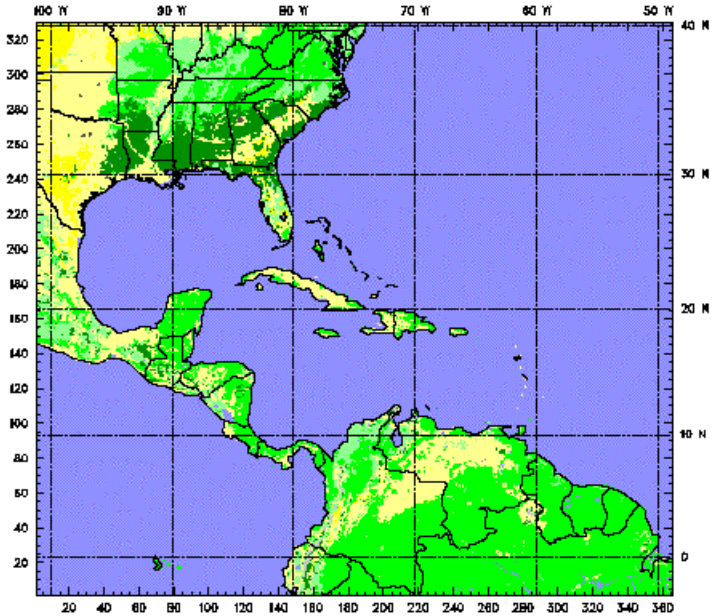
- AMSU-A assimilation improves TC track forecast by improving initial environment wind field through background error covariance constraint.
- AMSU-A assimilation improves intensity analysis and forecast by both improving initial T and wind field structure of TC votex.
- A SLP obs are very useful for intensity analysis and forecast

DATC extended tests

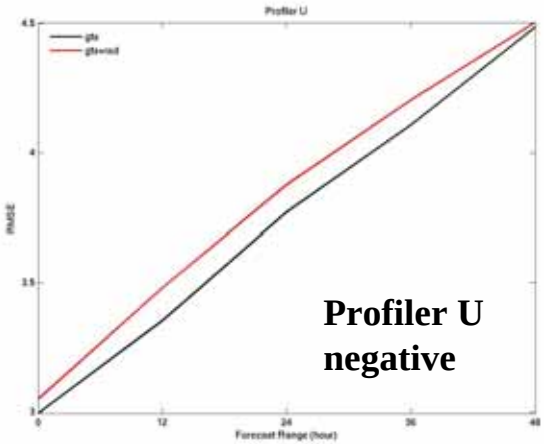
- DATC: Data Assimilation Testbed Center
  - Parallel with DTC (Developmental Testbed Center), focus on tests for model part
- Testbeds for radiance impact
  - East Asia
  - Atlantic
  - Antarctic

DATC: Atlantic Testbed

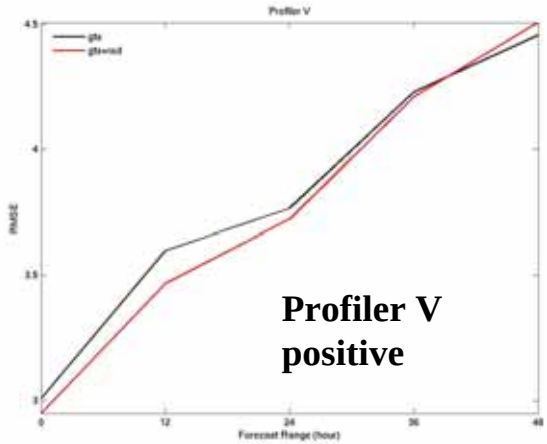
- **361*325*57L, 15km**
- **model top: 10mb**
- **Full cycling exp. for 6 days**
  - **15 ~ 20 August 2007**
- **GTS: assimilate NCAR conventional obs**
  - **Select similar data type used by AFWA**
- **GTS+AMSU+MHS (use NCEP BUFR rad.)**
  - **NOAA-15/16/18, AMSU-A, ch. 5~10**
  - **NOAA-15/16/17, AMSU-B, ch. 3~5**
  - **NOAA-18, MHS (similar to AMSU-B)**
  - **Radiance used only over water**
  - **thinned to 120km**
  - **+-2h time window**
  - **Bias Correction (H&K, 2001)**
- **48h forecast twice each day**
  - **00Z, 12Z**
- **Might not optimal to use all sensors/satellites at the first try, but I want to test the robustne ss of the system with all Microwave sensors which can be assimilated in WRF-Var now.**



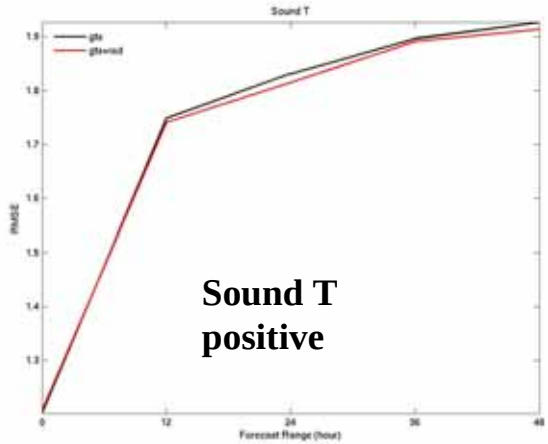
Land Use Category



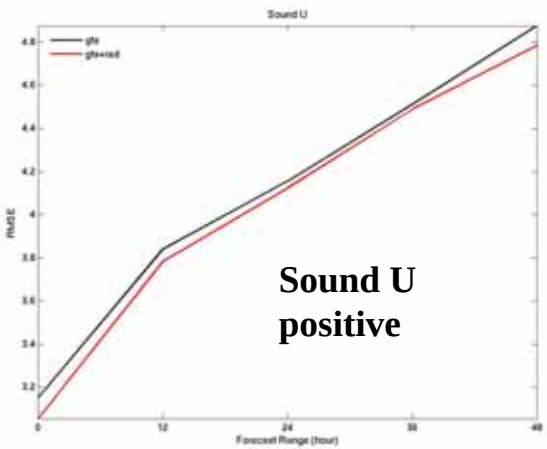
Profiler U negative



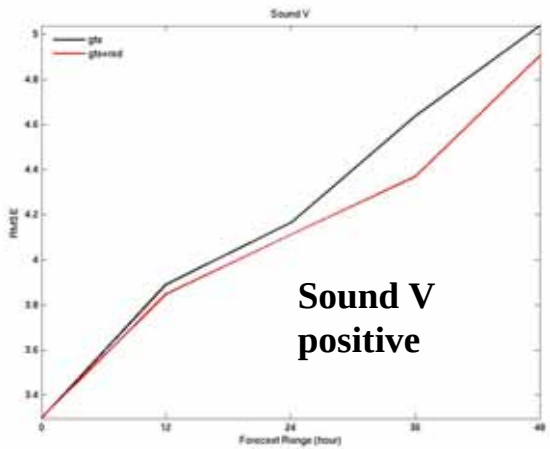
Profiler V positive



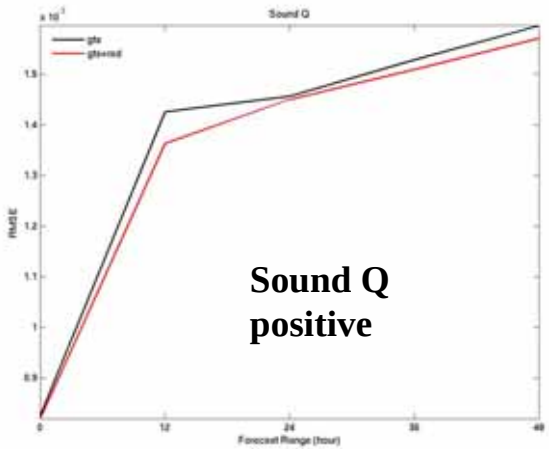
Sound T positive



Sound U positive

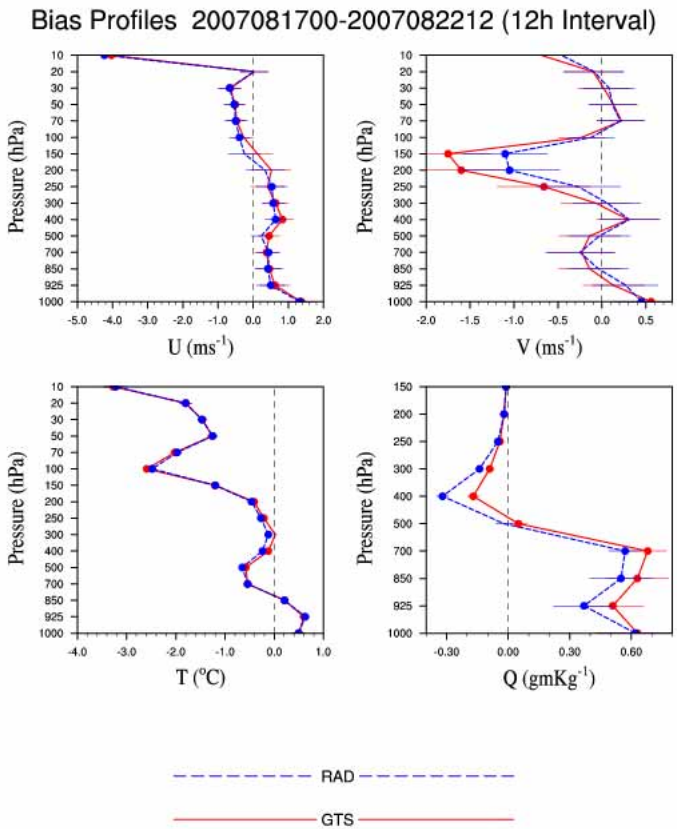


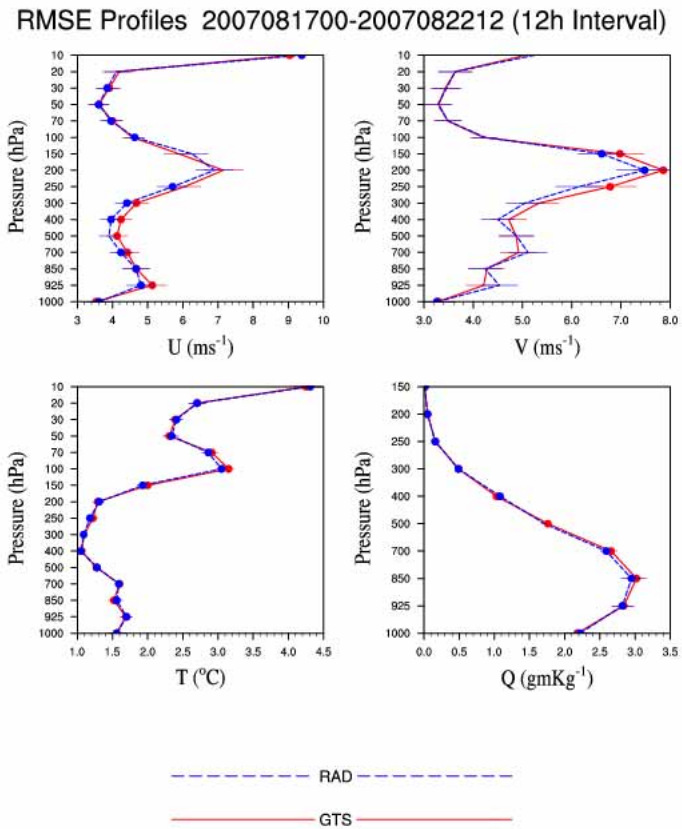
Sound V positive



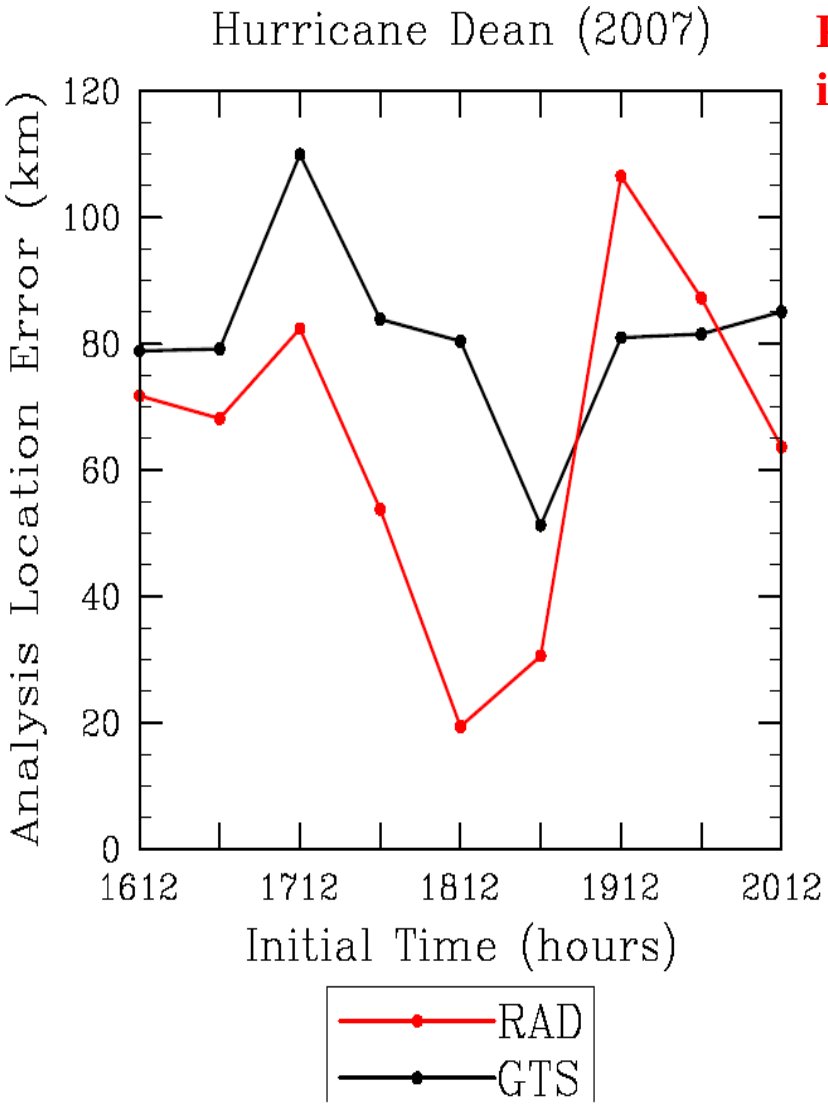
Sound Q positive

48h forecast error vs. sound

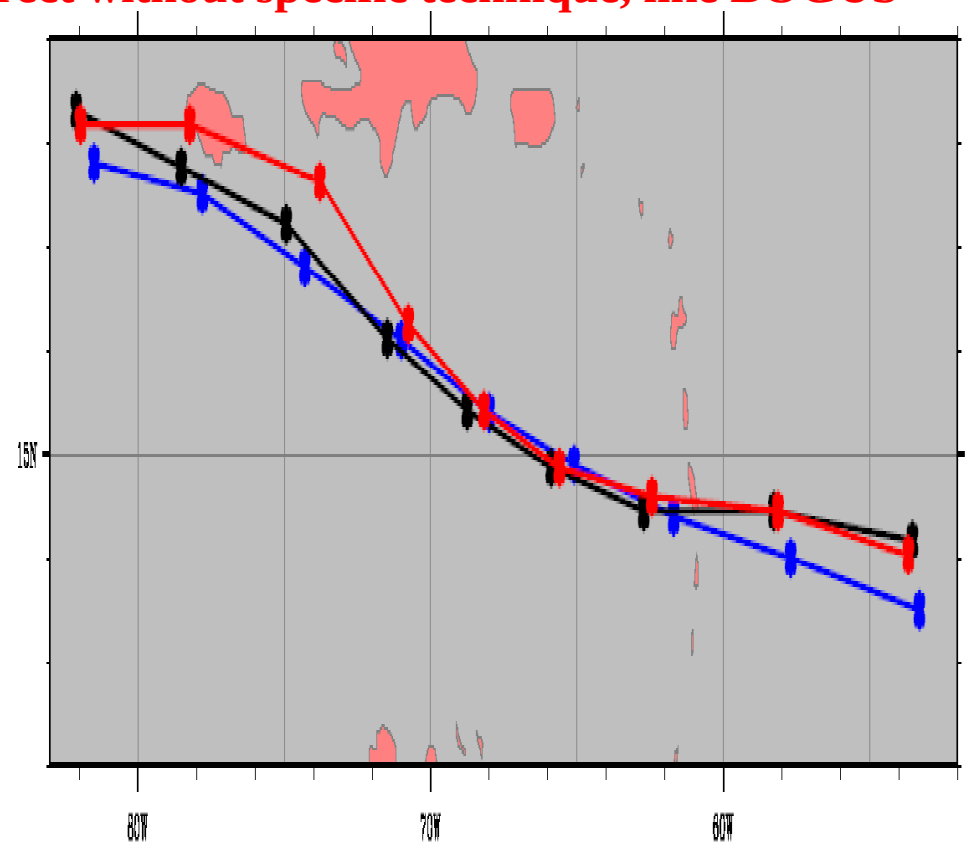


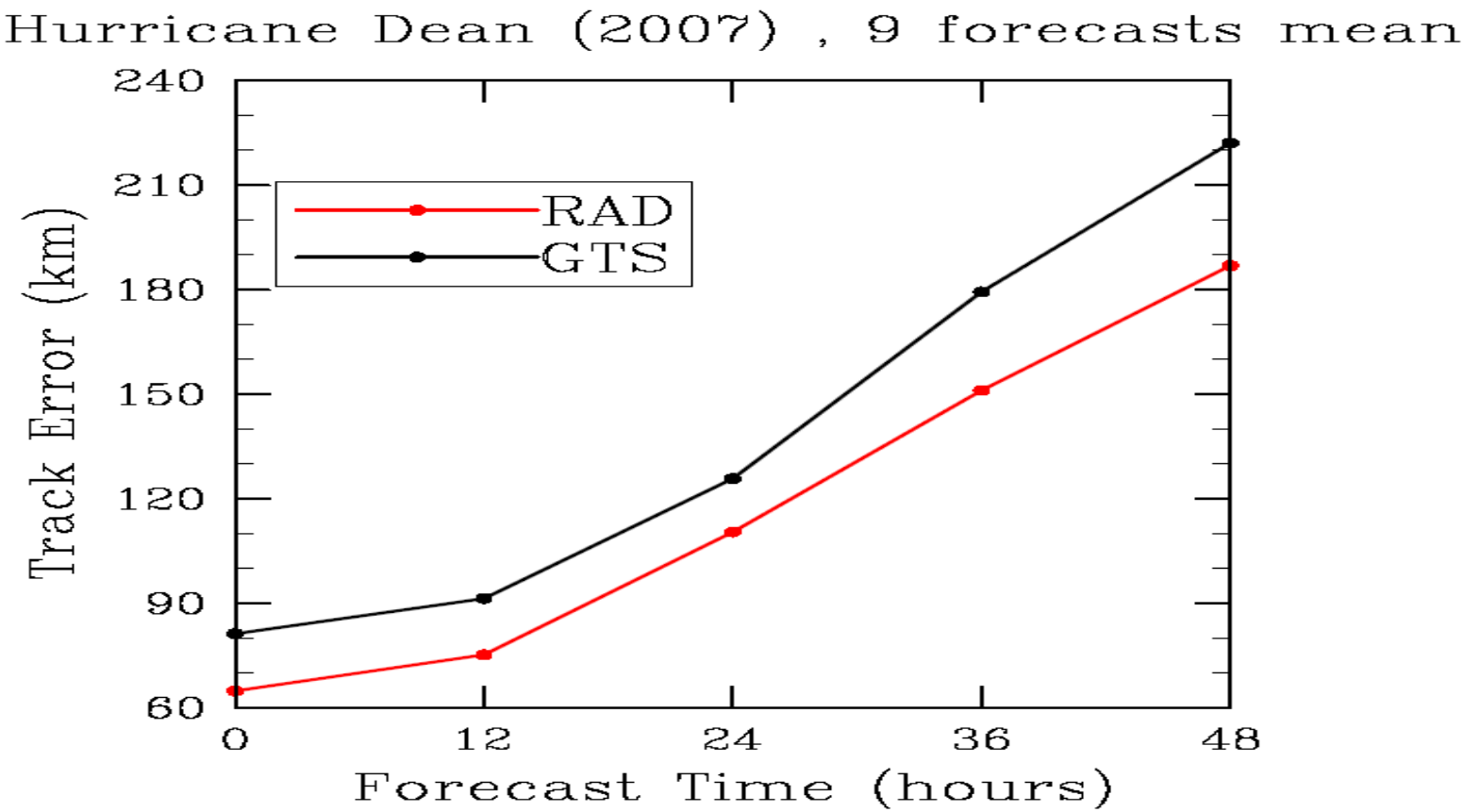


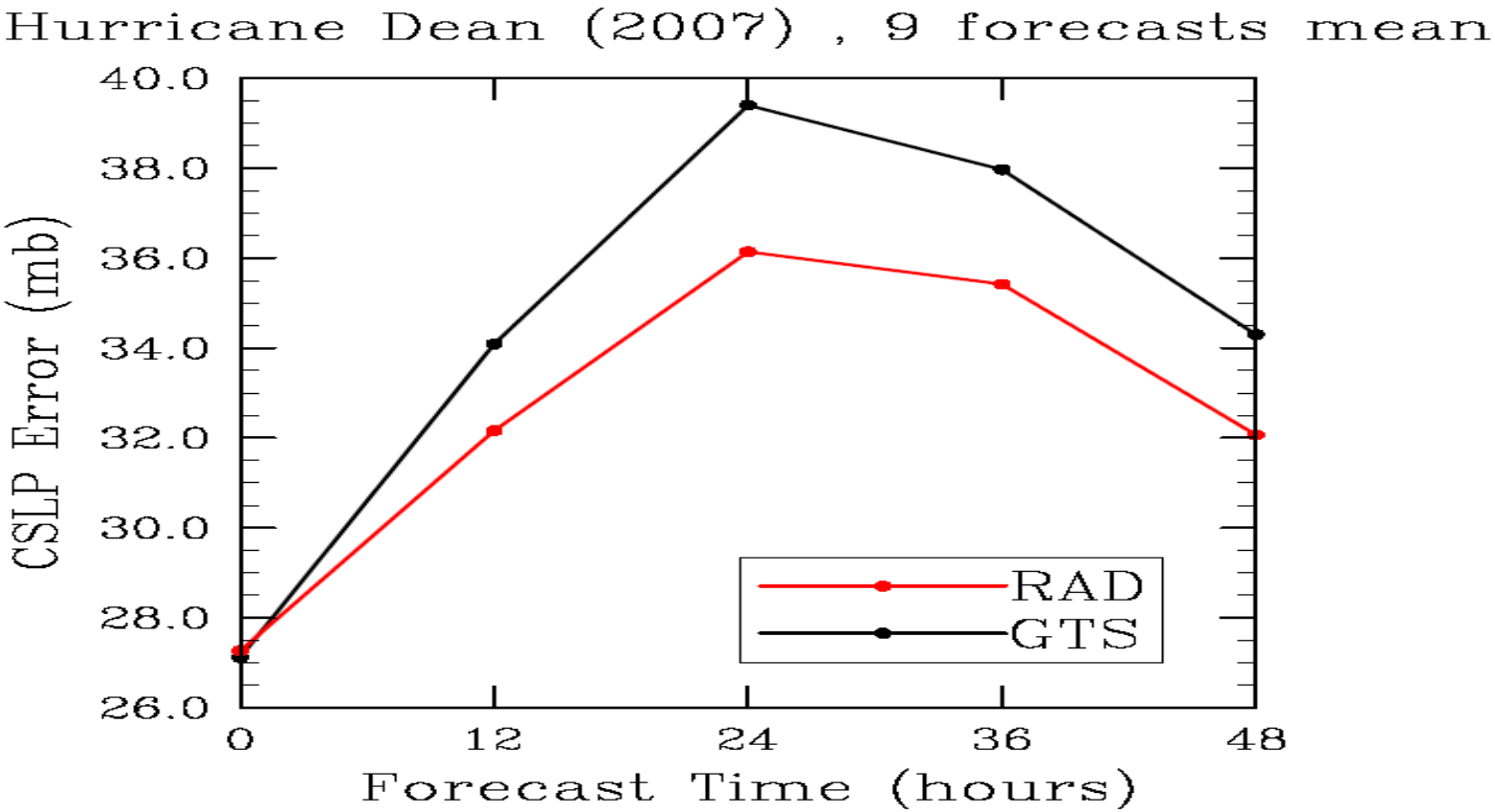
Hurricane Dean
Analysis location and error



Full cycling can not ensure that analysis location is correct without specific technique, like BOGUS

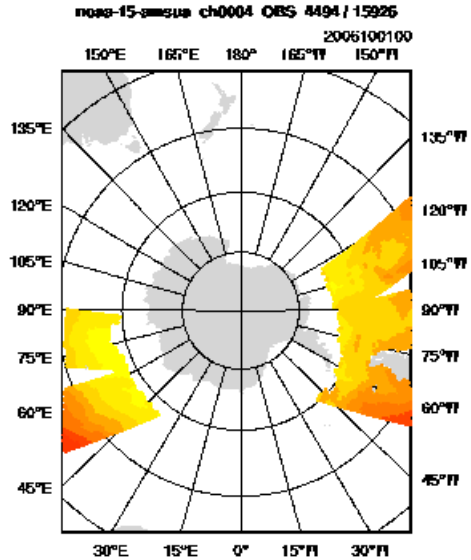


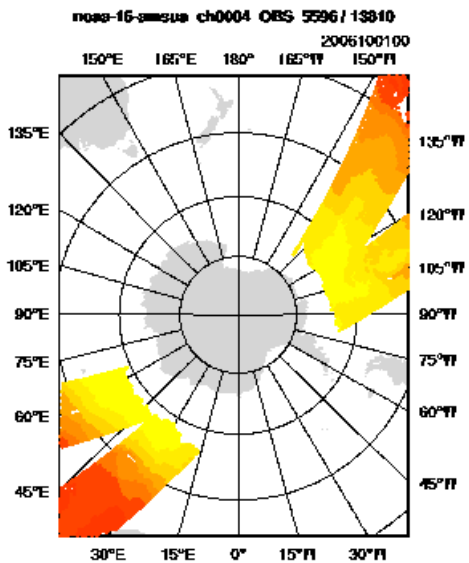

Hurricane Dean (2007) , 9 forecasts mean
Track Error (km)
240
210
180
150
120
90
60
0
12
24
36
48
Forecast Time (hours)
RAD
GTS

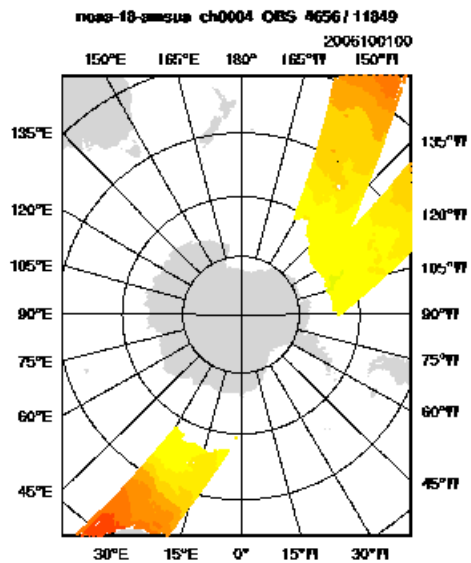

Hurricane Dean (2007) , 9 forecasts mean
CSLP Error (mb)
40.0
38.0
36.0
34.0
32.0
30.0
28.0
26.0
0
12
24
36
48
Forecast Time (hours)
RAD
GTS

DATC: Antarctic Testbed

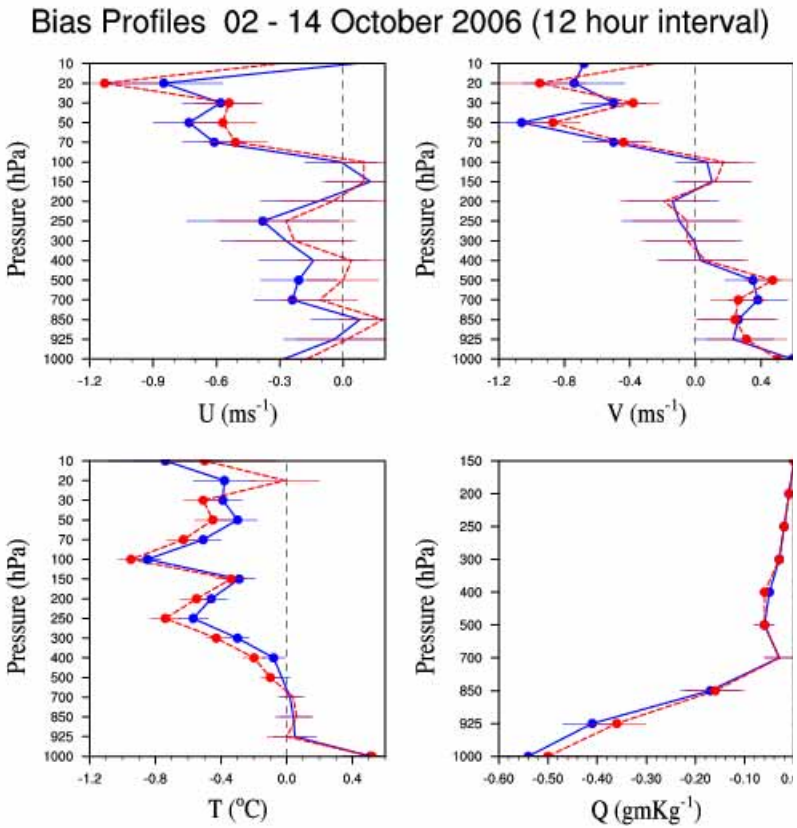
- **57L, 60km**
- **model top: 10mb**
- **Full cycling exp. for 14 days**
  - **1 ~ 14 October 2006**
- **GTS: assimilate NCAR conventional obs**
- **GTS+AMSU-A (NCEP BUFR rad.)**
  - **NOAA-15/16/18, AMSU-A, ch. 4~9**
  - **Radiance used only over water**
  - **+-2h time window**
  - **Bias Correction (H&K, 2001)**
- **72h forecast twice each day**
  - **00Z, 12Z**

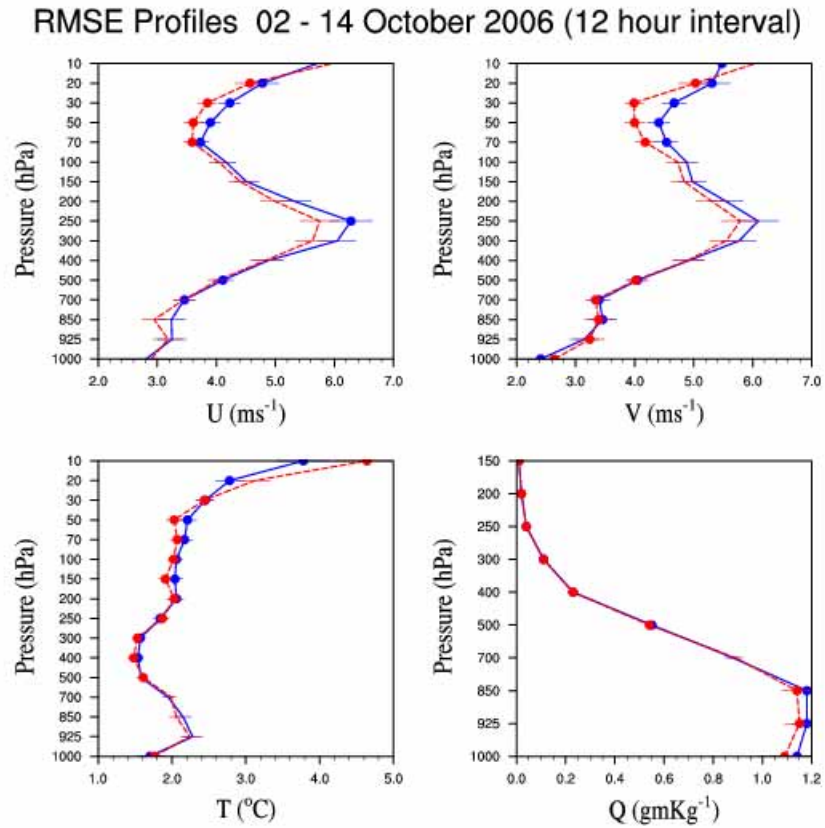






36h forecast vs. Sound





GTS+AMSUA

GTS

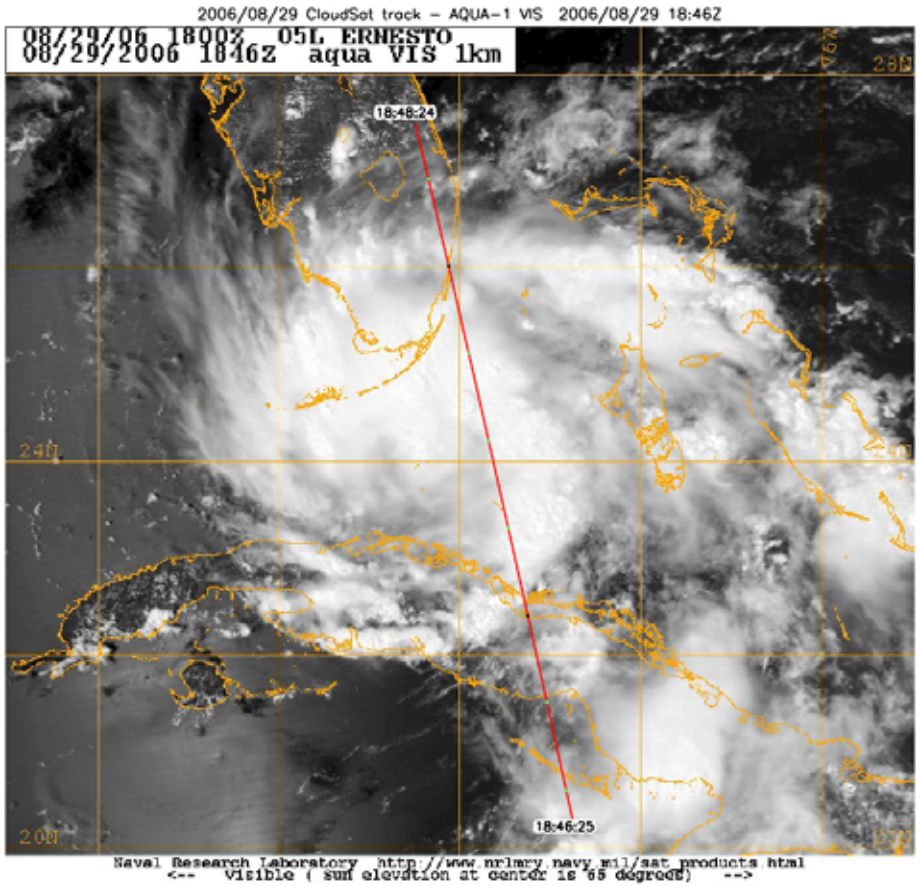
GTS+AMSUA

GTS

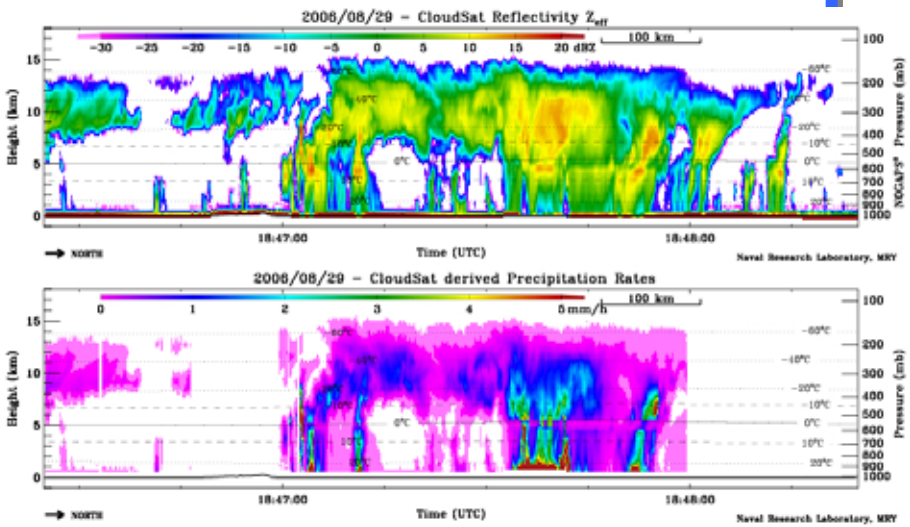
Cloudy radiance Assimilation

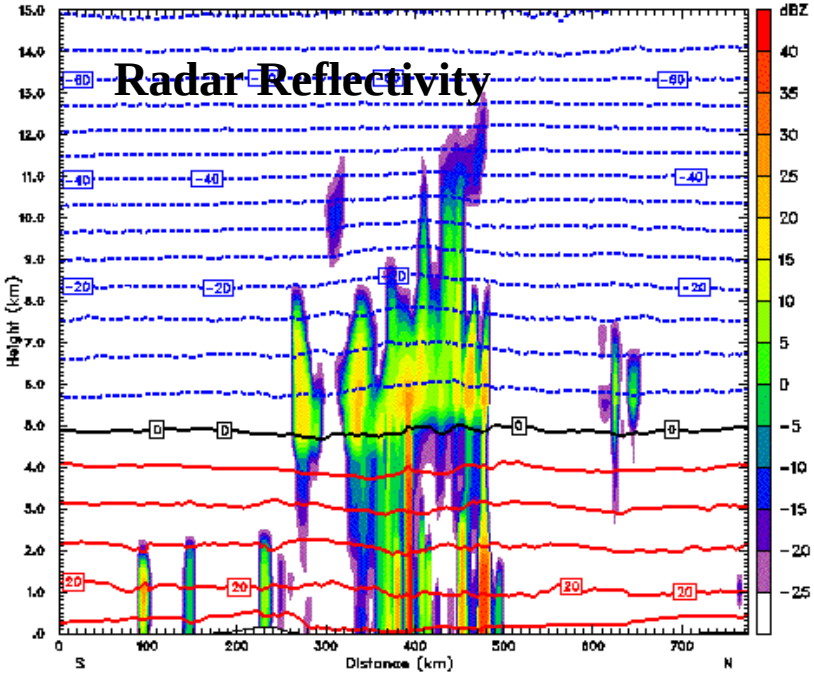
- CRTM cloudy radiance Forward/TL/AD calculation interface implemented
  - Input: hydrometeors profiles and particle radius
- Particle size is diagnosed from cloud water content (Bauer, 2001)
- No hydrometeor control variables available in WRF-3DVAR, instead Total Water (Qt) as control variable, and a warm-rain process' TL/AD is used to partition Qt into cloud water and rain (Xiao et al., 2007) in 3DVAR
  - Warm-rain process limits the application
- Initial test with WSM3 microphysics scheme for hydrometeors forecast with a 4km resolution
  - Include cloud water/ice, rain/snow, no mixture phase

Tropical Storm Ernesto (2006/08/29)



CloudSat path: 18:46:25 - 18:48:24

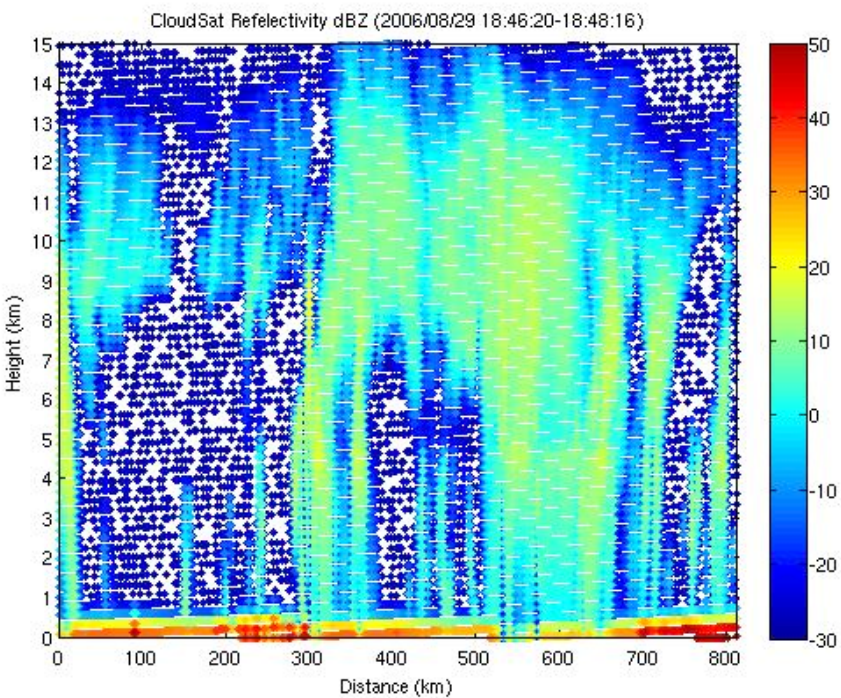




WRF 4km Forecast at 19h

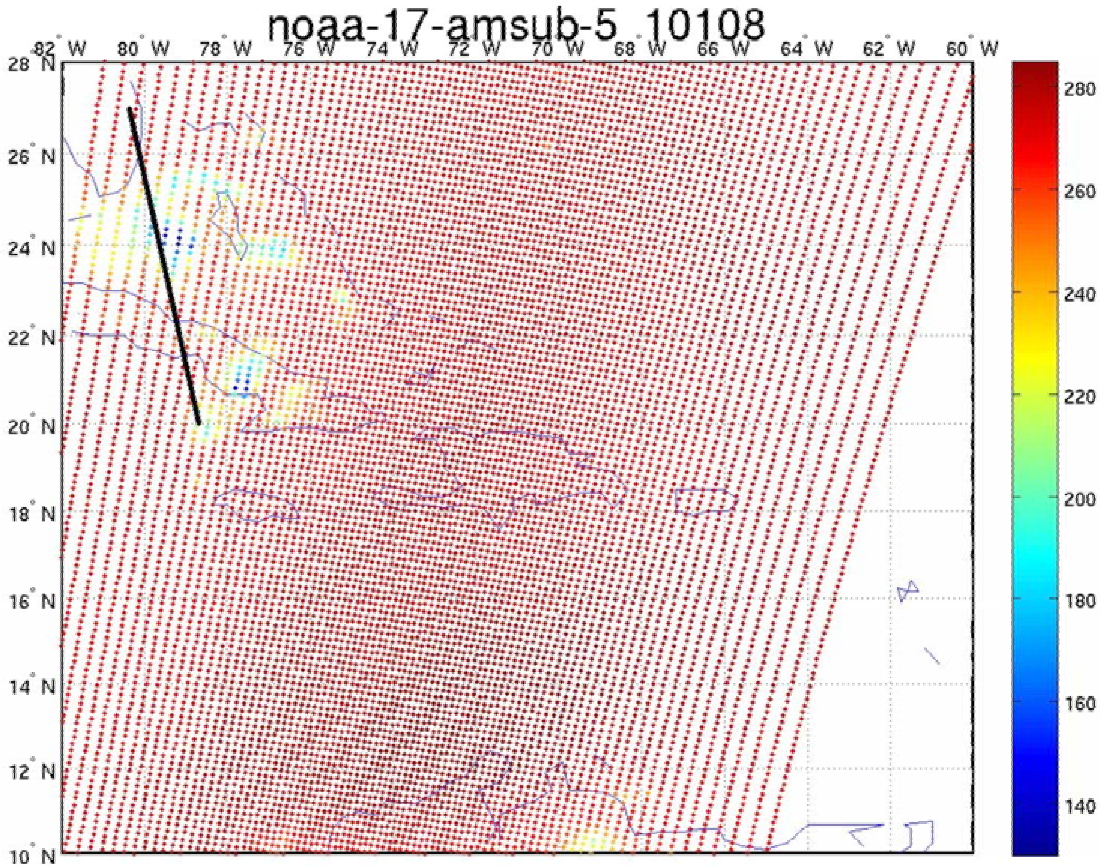
WRF forecast performance For hydrometeor parameters:

Location of precipitation mismatched With cloudsat observation



CloudSat Reflectivity

AMSU-B cloudy radiance calculation case



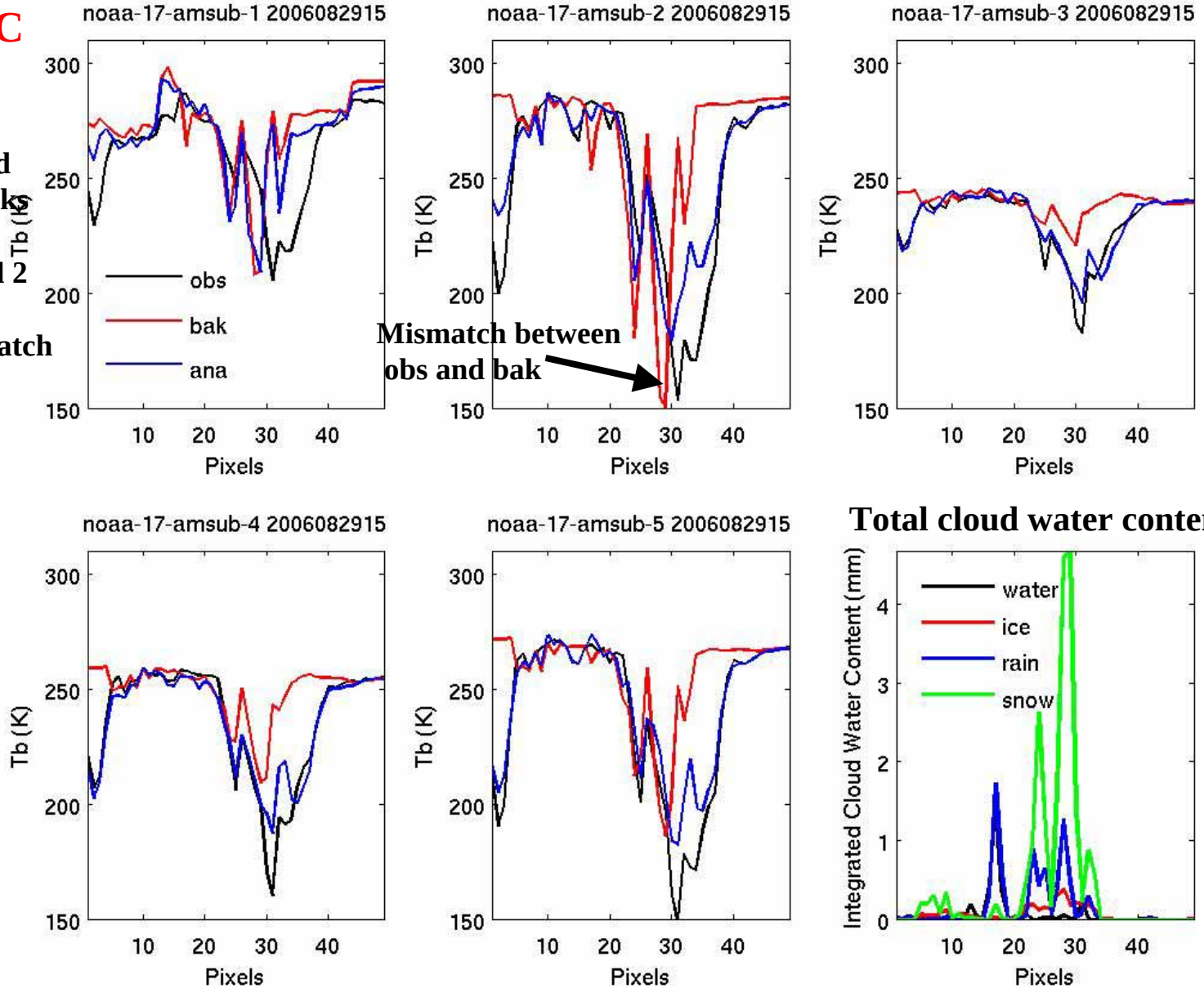
OBS time around 2006-08-29-15:23

Select pixels near CloudSat Path

NOAA-17-AMSUB Tb along CloudSat path

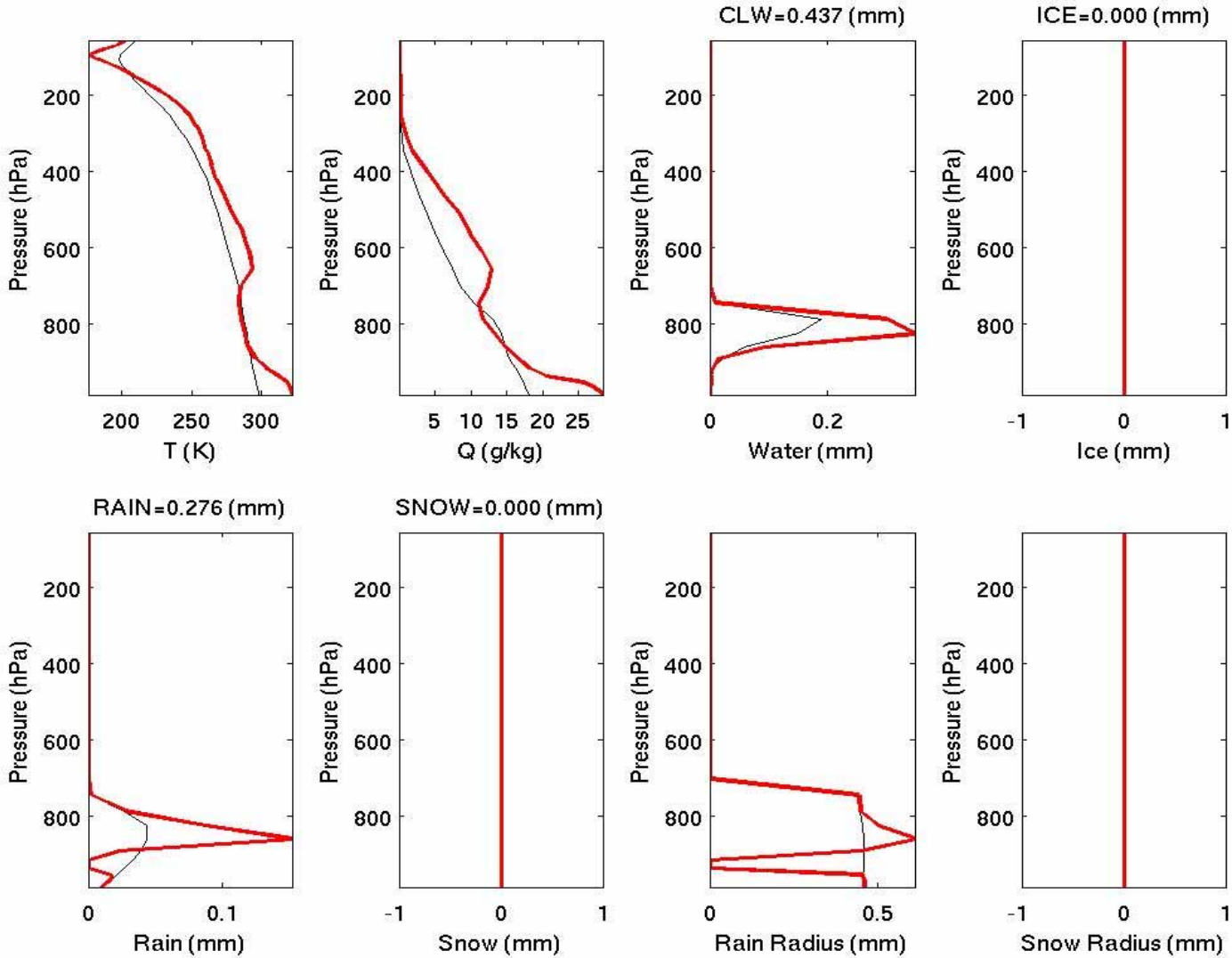
NO ANY QC

CRTM forward Calculation looks quite good for Channels 1 and 2 Regardless of Location mismatch

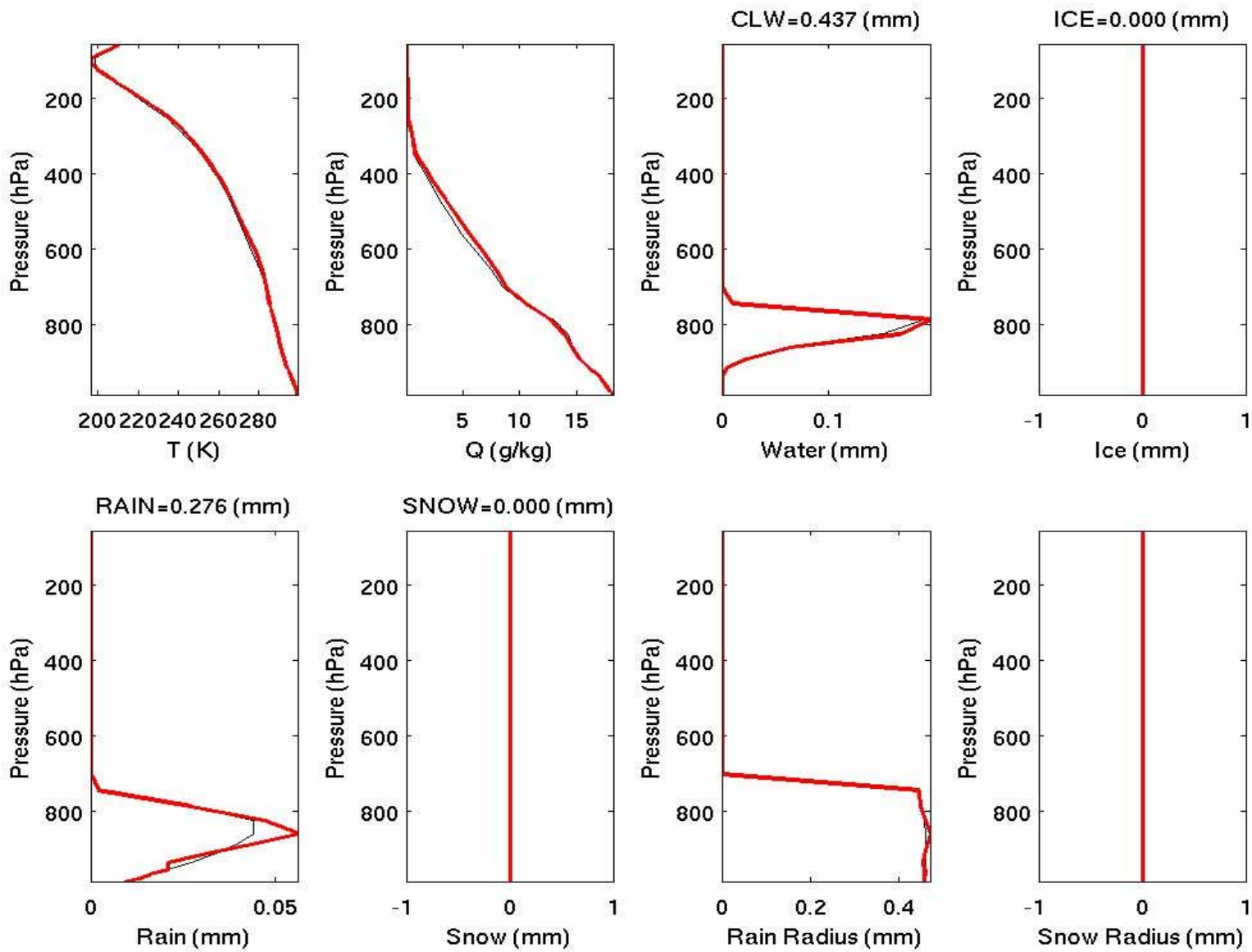


Profile 16, red line: analysis (no any QC)

Large analysis increment for T, Q, CLW, Rain



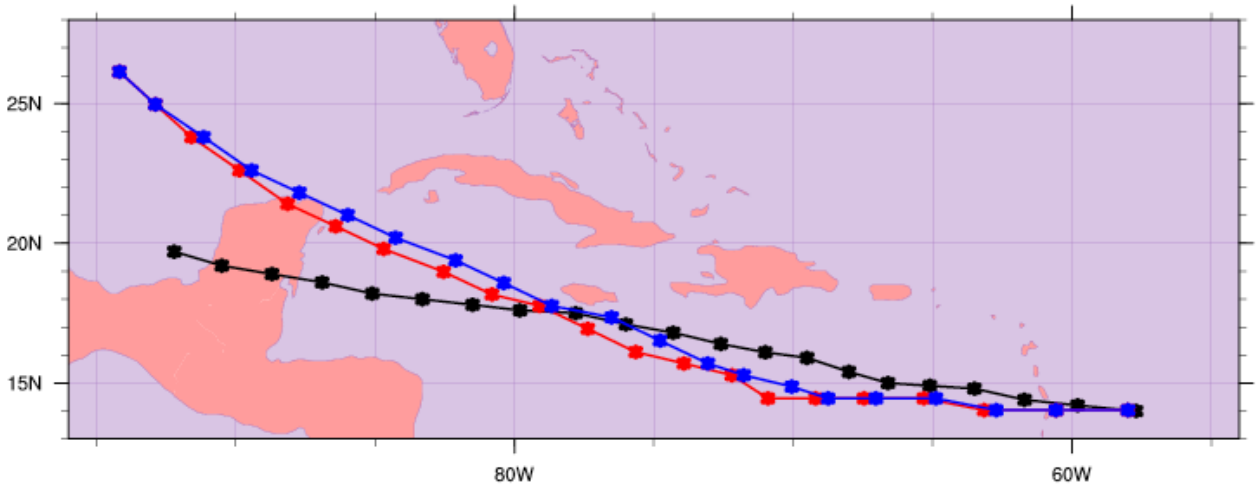
Profile 16, red line: analysis (with simple QC)

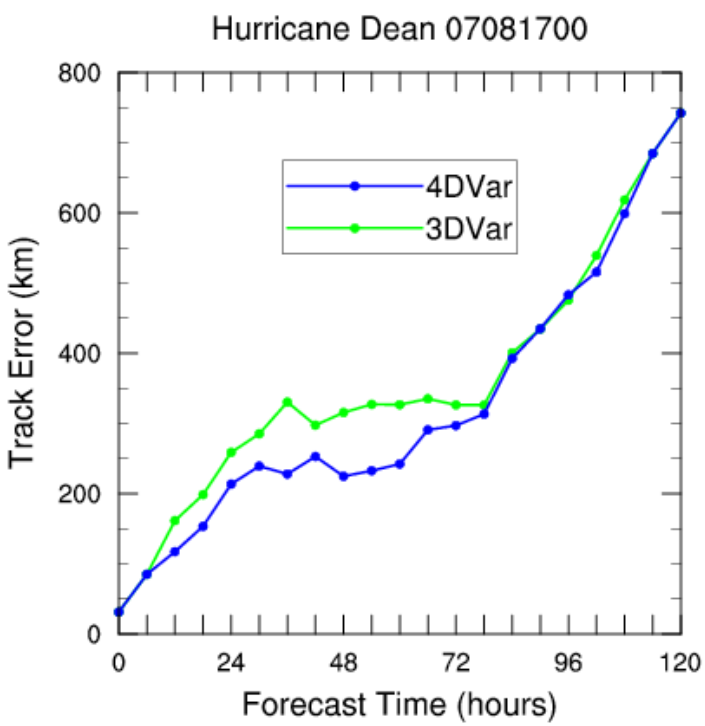


Next steps for cloudy radiance assimilation

- 1DVAR as a preprocessor with QC and BC
  - Also useful as a research tool
- Cloudy radiance assimilation with 4DVAR
  - Require more complex physical process as well as its TL/AD
- Limit T, Q increment
- Background and observation error statistics over cloud conditions
- Other possibilities for cloud control variables
  - e.g., Full hydrometeor control variables
- Validation with A-Train data

4DVAR vs. 3DVAR





45km resolution
(4DVAR is still very slow)

model top = 10mb

Only assimilate radiance data (AMSU/MHS), 6h time window

Future plans

- Add more instruments
  - IASI, GOES platforms
- Tune the system for various testbeds
- Further developments for cloudy radiance assimilation and 4DVAR+radiance
- Explore ensemble-based radiance assimilation