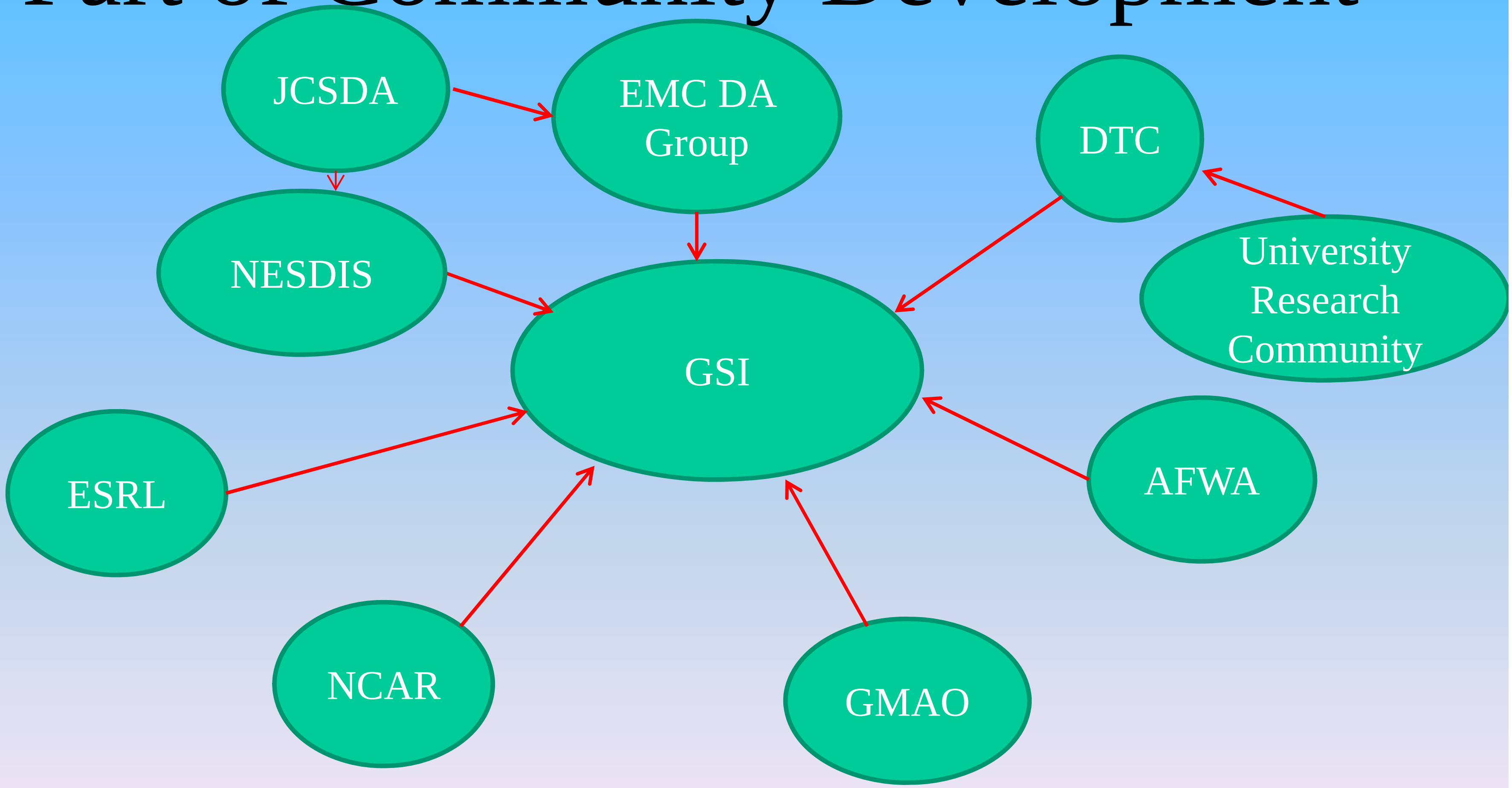
Progress and Plans for the Environmental Modeling Center's (EMC) Gridpoint Statistical Interpolation (GSI) Development

Andrew Collard, Daryl Keist, David Parrish, Ed Safford, Emily Liu, Manuel Pondeca, Miodrag Rancic, Lidia Cucurull, Haixia Liu, Xu Li, XiuJuan Su, Shun Liu, Wan-Shu Wu, Paul van Delst, Yanqiu Zhu, Mingjing Tong, David Groff, Ho-Chun Huang, Mike Lueken, George Gayno, Min-Jeong Kim, Runhua Yang, Yoichiro Ota, Jim Purser, Russ Treadon, and John Derber

Outline

- Community Development
- Ongoing EMC Development
  - Assimilation techniques
  - Use of Observations
  - Maintenance, Collaboration and General Improvements
- Future EMC Directions

Part of Community Development



Community development

- Major change for EMC DA Team to move into community development
- Tool for community development has been subversion and trac
- Requires change in how we do work with significant increase in communication among developers
  - Also requires changes in partners way of doing work – often more difficult
  - However EMC cannot count on community for critical changes since we have operational responsibility
- GSI oversight board
  - Improve communication among groups
  - Ensure coding standards are followed
- Substantial percentage of the EMC DA Team's time is used in supporting community.
- Most of the GSI updates come from EMC.

Assimilation techniques

- Hybrid
  - Implementation of Hybrid/3dvar-EnKF for Global – David Parrish, Russ Treadon, Mike Lueken, Daryl Kleist, Jeff Whittaker (ESRL)
  - Hybrid for NAM – Wan-shu Wu
  - Hybrid for HWRF – Mingjing Tong
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  - Add 4d capability to hybrid – Daryl Kleist
  - LETKF in Hybrid – Yoichiro Ota
- 4d-Var – Misha Rancic
- Constraint
  - Add surface friction, mixing, precip and cloud physics to strong constraint – Min-Jeong Kim, Misha Rancic, Daryl Kleist
  - Regional Strong Constraint – David Parrish
- GSI Aerosol assimilation – Ho-Chun Huang
- Inclusion of NSST capability – Xu Li
- Cloudy Radiance Assimilation – Min-Jeong Kim, Emily Liu, Yanqiu Zhu, Will McCarty (GMAO)

Implementation of Hybrid/3dvar-EnKF

David Parrish, Russ Treadon, Mike Lueken, Daryl Kleist, Jeff Whittaker (ESRL), Yoichiro Ota (JMA)

- Current background error covariance (applied operationally) in VAR
  - Isotropic recursive filters
  - Poor handle on cross-variable covariance
  - Minimal flow-dependence added
    - Implicit flow-dependence through linearization in normal mode constraint (Kleist et al. 2009)
    - Flow-dependent variances (only for wind, temperature, and pressure) based on background tendencies
  - Tuned NMC-based estimate (lagged forecast pairs)
- Other changes part of hybrid package

EnKF/3DVar hybrid

$$J_{\mathrm{Var}}(\mathbf{x}') = \frac{1}{2}(\mathbf{x}')^{\mathrm{T}}\mathbf{B}_{\mathrm{Var}}^{-1}(\mathbf{x}') + \frac{1}{2}(\mathbf{y}_{\mathrm{o}}' - \mathbf{H}\mathbf{x}')^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y}_{\mathrm{o}}' - \mathbf{H}\mathbf{x}') + J_{\mathrm{c}}$$

J : Penalty (Fit to background + Fit to observations + Constraints)

x' : Analysis increment ($x_a - x_b$) ; where x_b is a background

$\mathbf{B}_{\mathbf{Var}}$: Background error covariance

H : Observations (forward) operator

R : Observation error covariance (Instrument + representativeness)

$\mathbf{y}_o$' : Observation innovations

J_c : Constraints (physical quantities, balance/noise, etc.)

B is typically static and estimated a-priori/offline

Hybrid Variational-Ensemble

- Incorporate ensemble perturbations directly into variational cost function through extended control variable
  - Lorenc (2003), Buehner (2005), Wang et. al. (2007), etc.

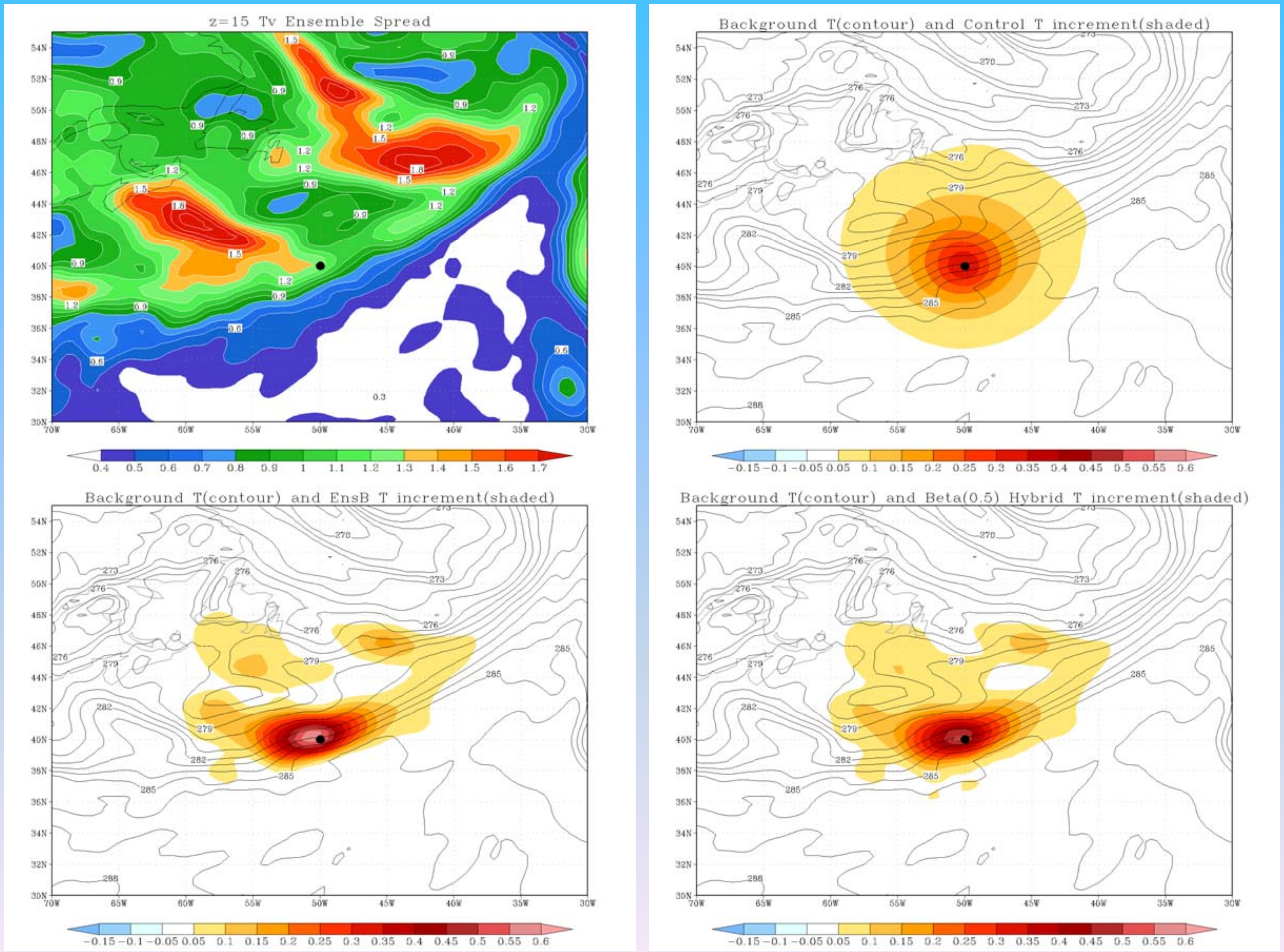
$$J\left(\mathbf{x}_{\mathrm{f}}^{'},\alpha\right)=\beta_{\mathrm{f}}\frac{1}{2}\left(\mathbf{x}_{\mathrm{f}}^{'}\right)^{\mathrm{T}}\mathbf{B}^{-1}\left(\mathbf{x}_{\mathrm{f}}^{'}\right)+\beta_{\mathrm{e}}\frac{1}{2}(\alpha)^{\mathrm{T}}\mathbf{L}^{-1}(\alpha)+\frac{1}{2}\left(\mathbf{y}_{\mathrm{o}}^{'}-\mathbf{H}\mathbf{x}_{\mathrm{t}}^{'}\right)^{\mathrm{T}}\mathbf{R}^{-1}\left(\mathbf{y}_{\mathrm{o}}^{'}-\mathbf{H}\mathbf{x}_{\mathrm{t}}^{'}\right)$$

$$\mathbf{x}_{\mathrm{t}}^{'}=\mathbf{x}_{\mathrm{f}}^{'}+\sum_{k=1}^{K}\left(\alpha_k\circ\mathbf{x}_k^{\mathrm{e}}\right)$$

$$\frac{1}{\beta_{\mathrm{f}}}+\frac{1}{\beta_{\mathrm{e}}}=1$$

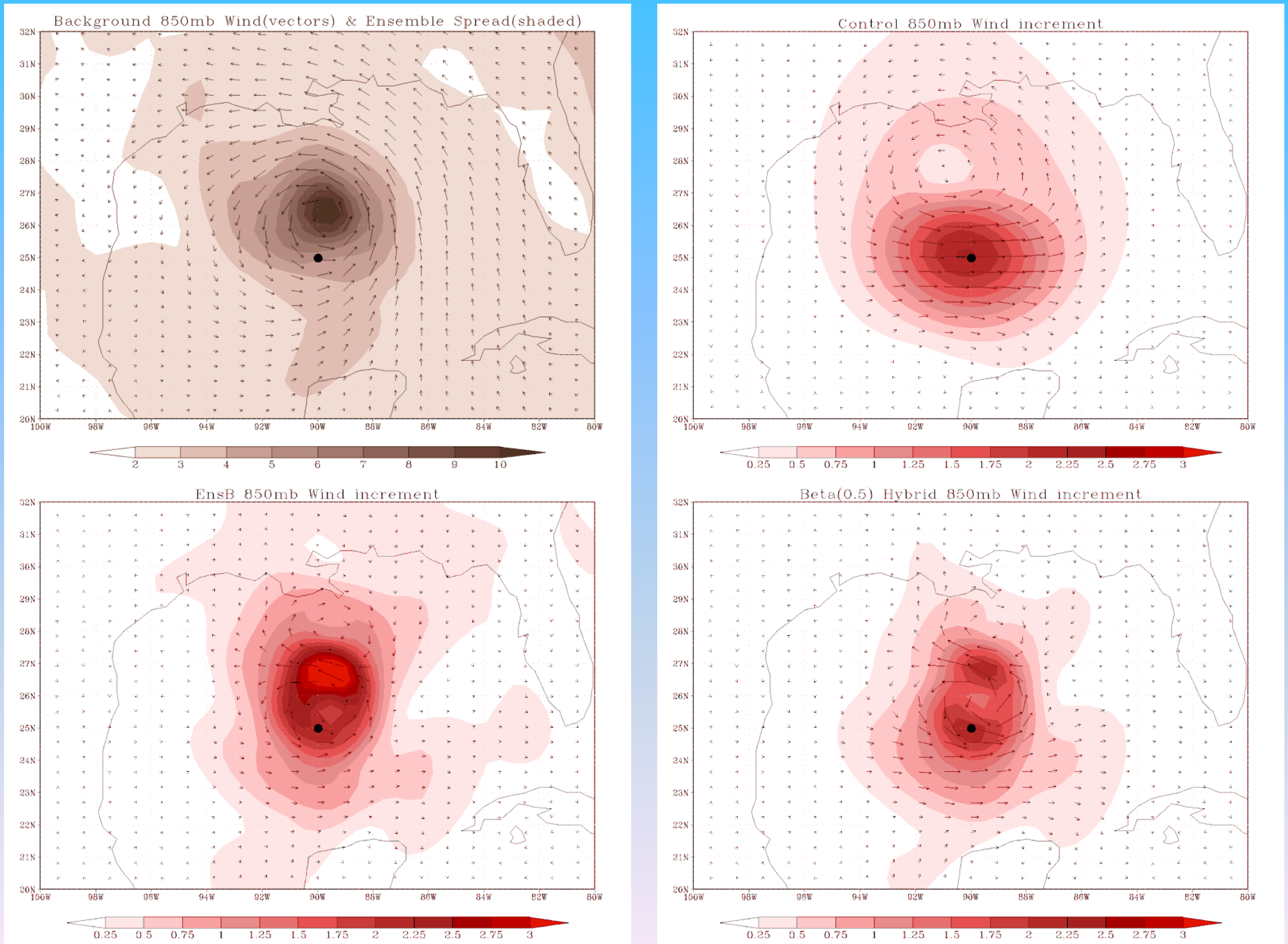
β_{f} & β_{e}: weighting coefficients for fixed and ensemble covariance respectively
$\mathbf{x}_{\mathrm{t}}$: (total increment) sum of increment from fixed/static **B** ($\mathbf{x}_{\mathrm{f}}$) and ensemble **B**
α_k: extended control variable; $\mathbf{x}_k^{\mathrm{e}}$:ensemble perturbation
L: correlation matrix [localization on ensemble perturbations]

Single Observation



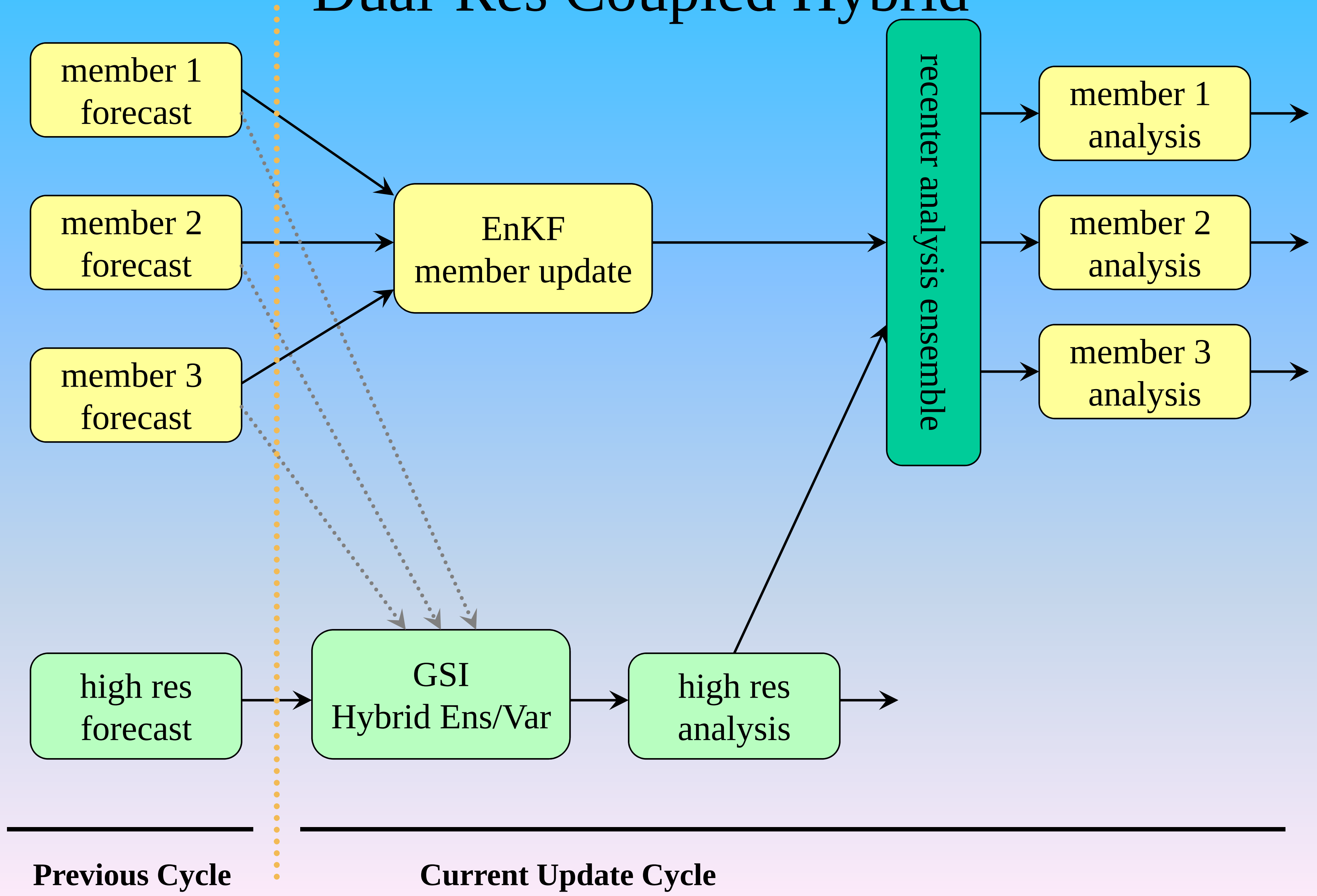
Single 850mb Tv observation (1K O-F, 1K error)

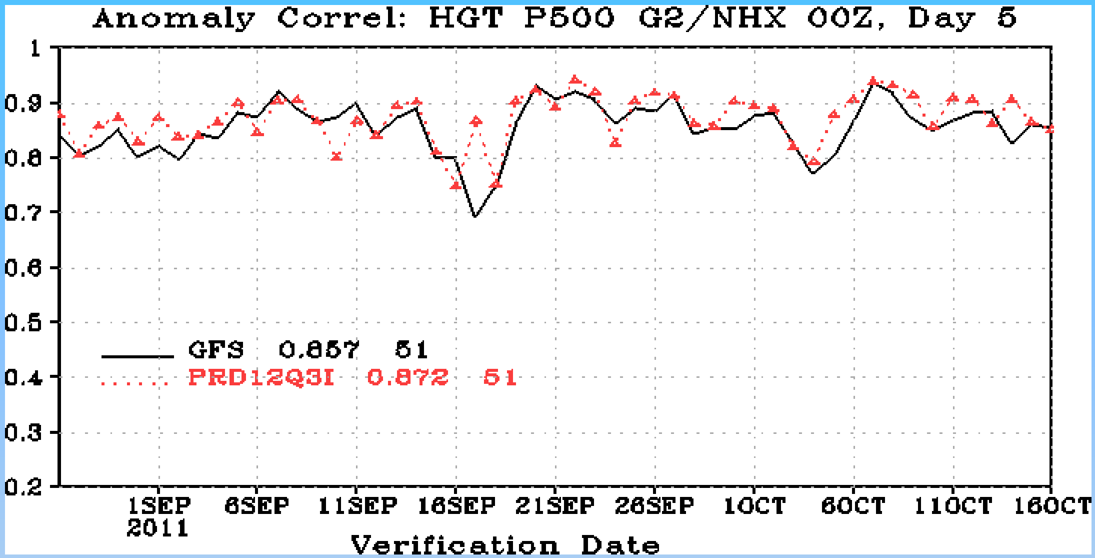
Single Observation

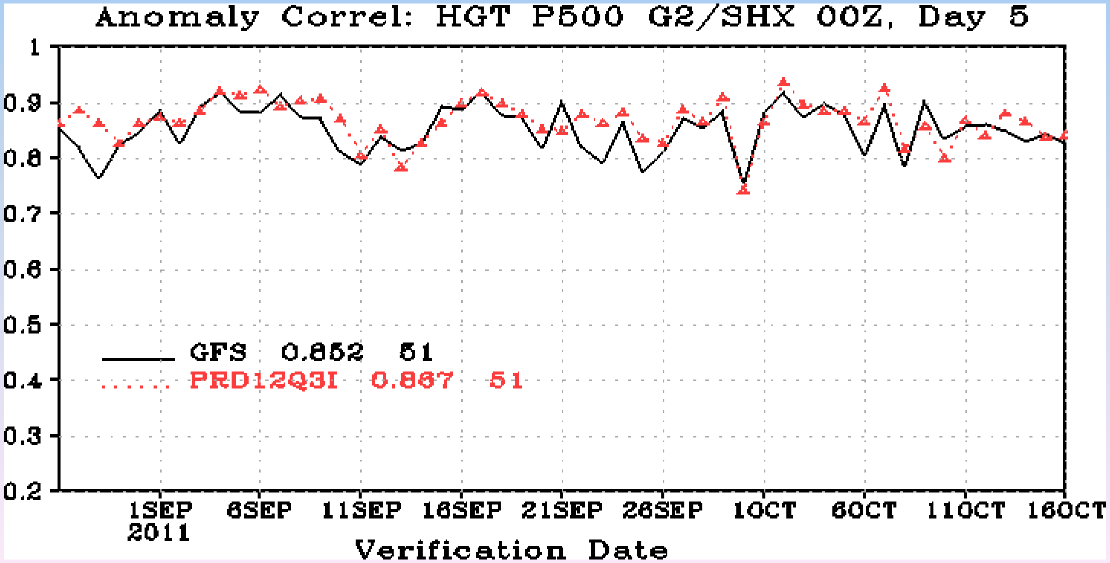


Single 850mb zonal wind observation (3 m/s O-F, 1m/s error) in Hurricane Ike circulation

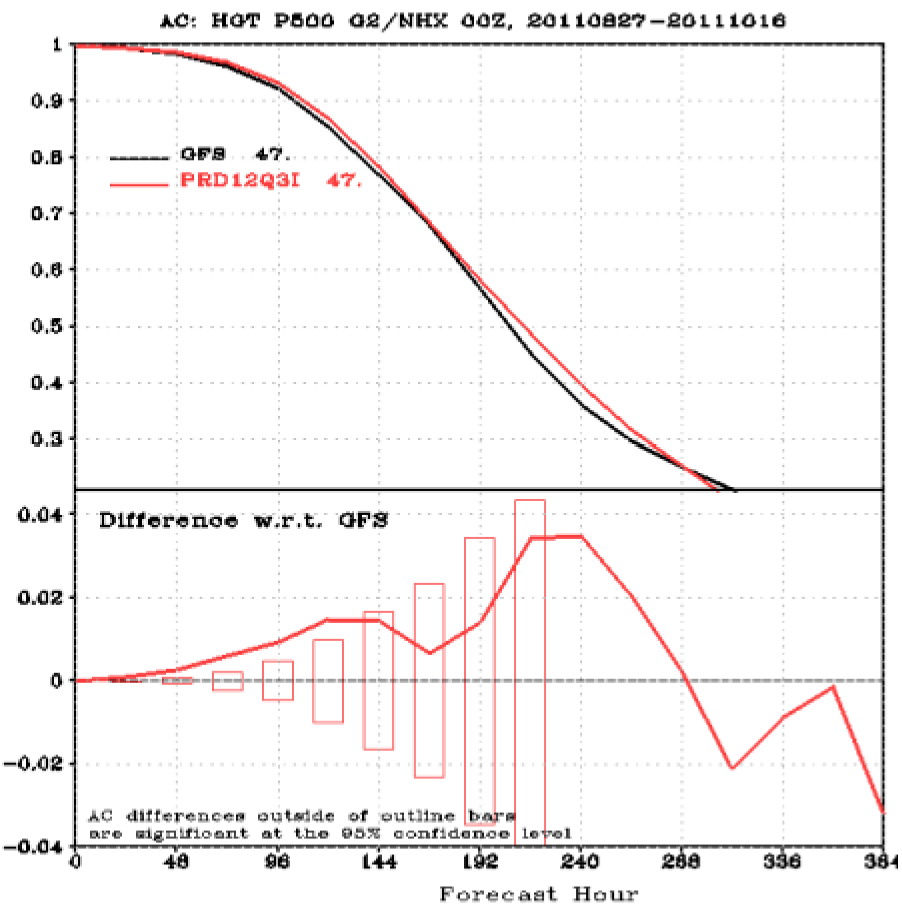
Dual-Res Coupled Hybrid

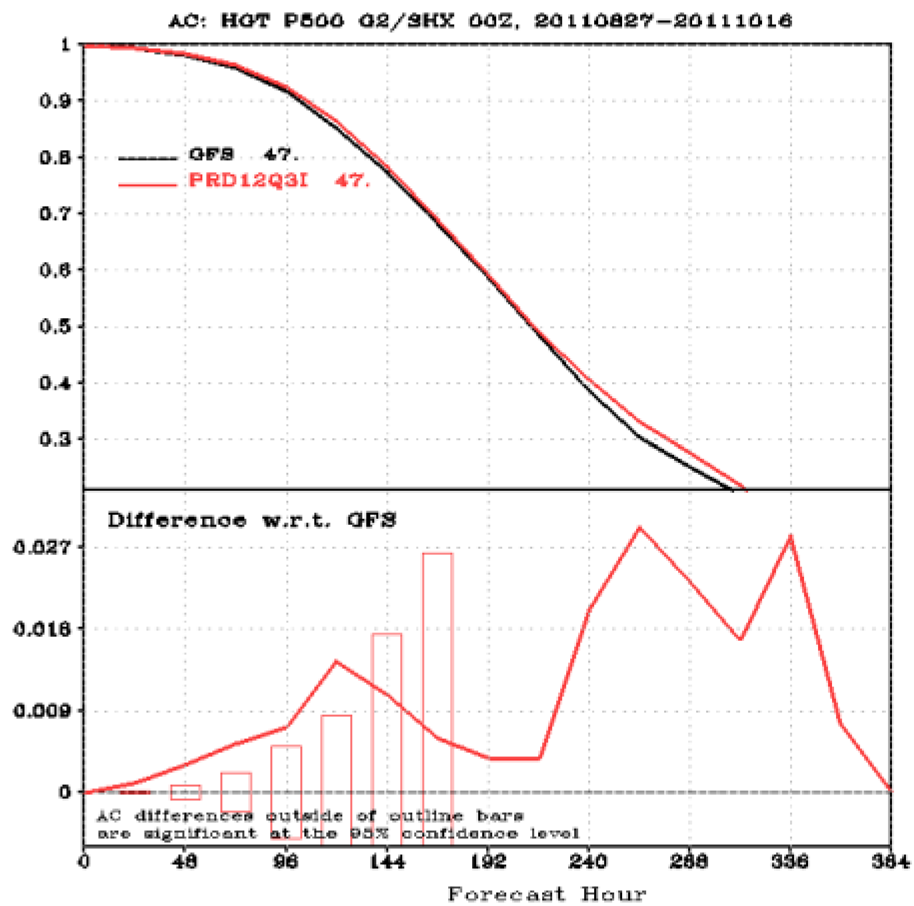



Anomaly Correl: HGT P500 G2/NHX 00Z, Day 5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
GFS 0.857 51
PRD12Q3I 0.872 51
1SEP 2011
6SEP
11SEP
16SEP
21SEP
26SEP
1OCT
6OCT
11OCT
16OCT
Verification Date

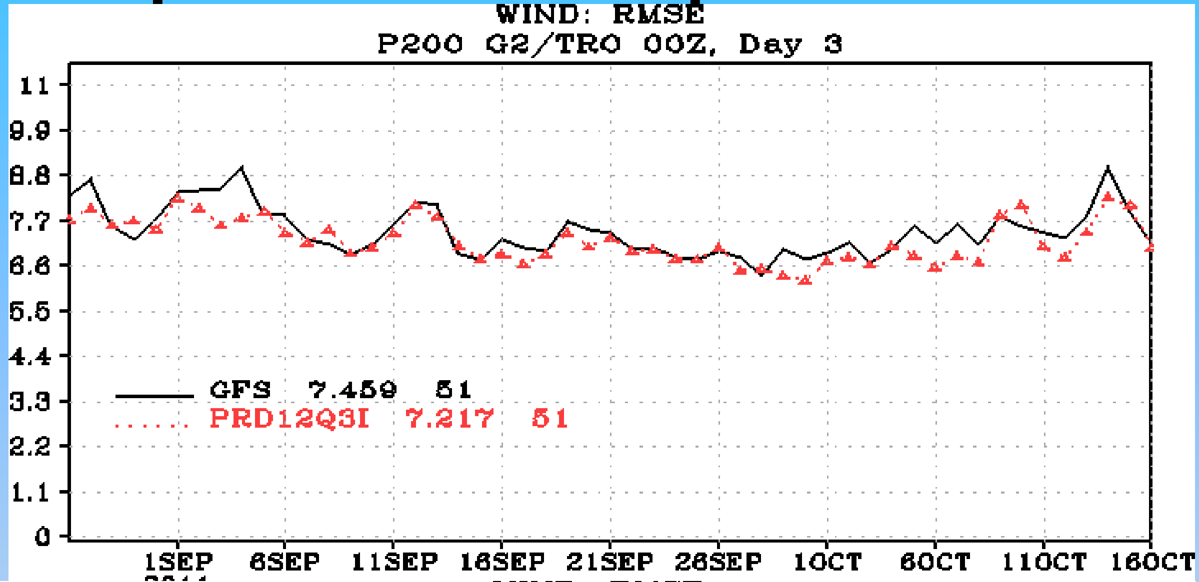

Anomaly Correl: HGT P500 G2/SHX 00Z, Day 5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
GFS 0.852 51
PRD12Q3I 0.867 51
1SEP 2011
6SEP
11SEP
16SEP
21SEP
26SEP
1OCT
6OCT
11OCT
16OCT
Verification Date

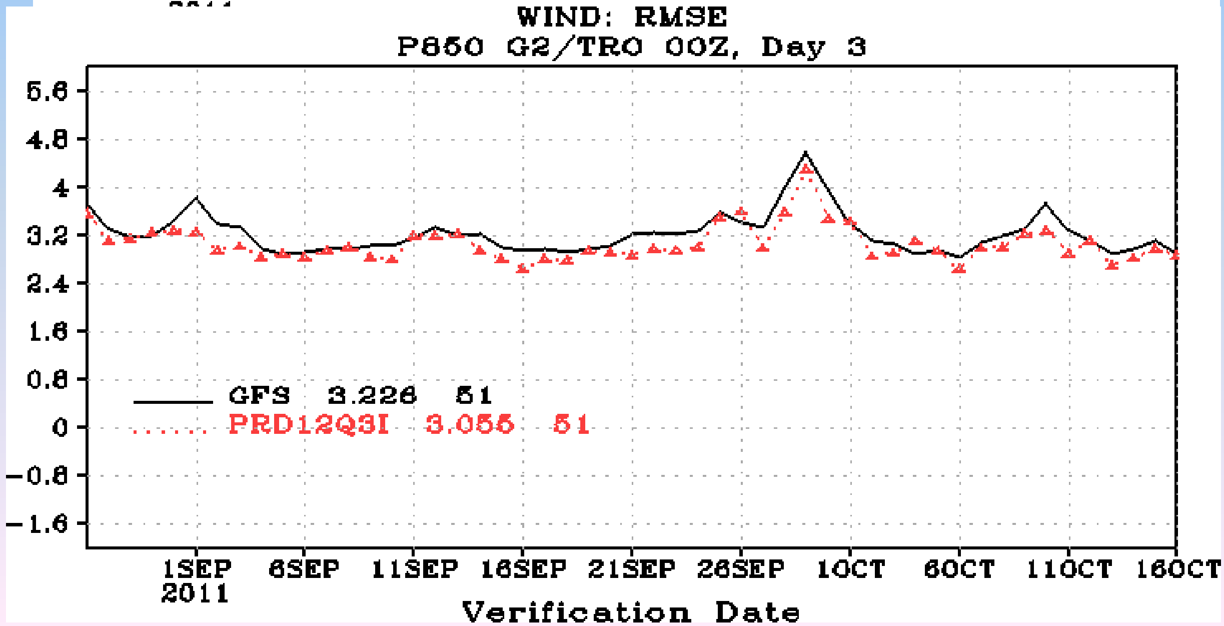
Retrospective Die-off curves

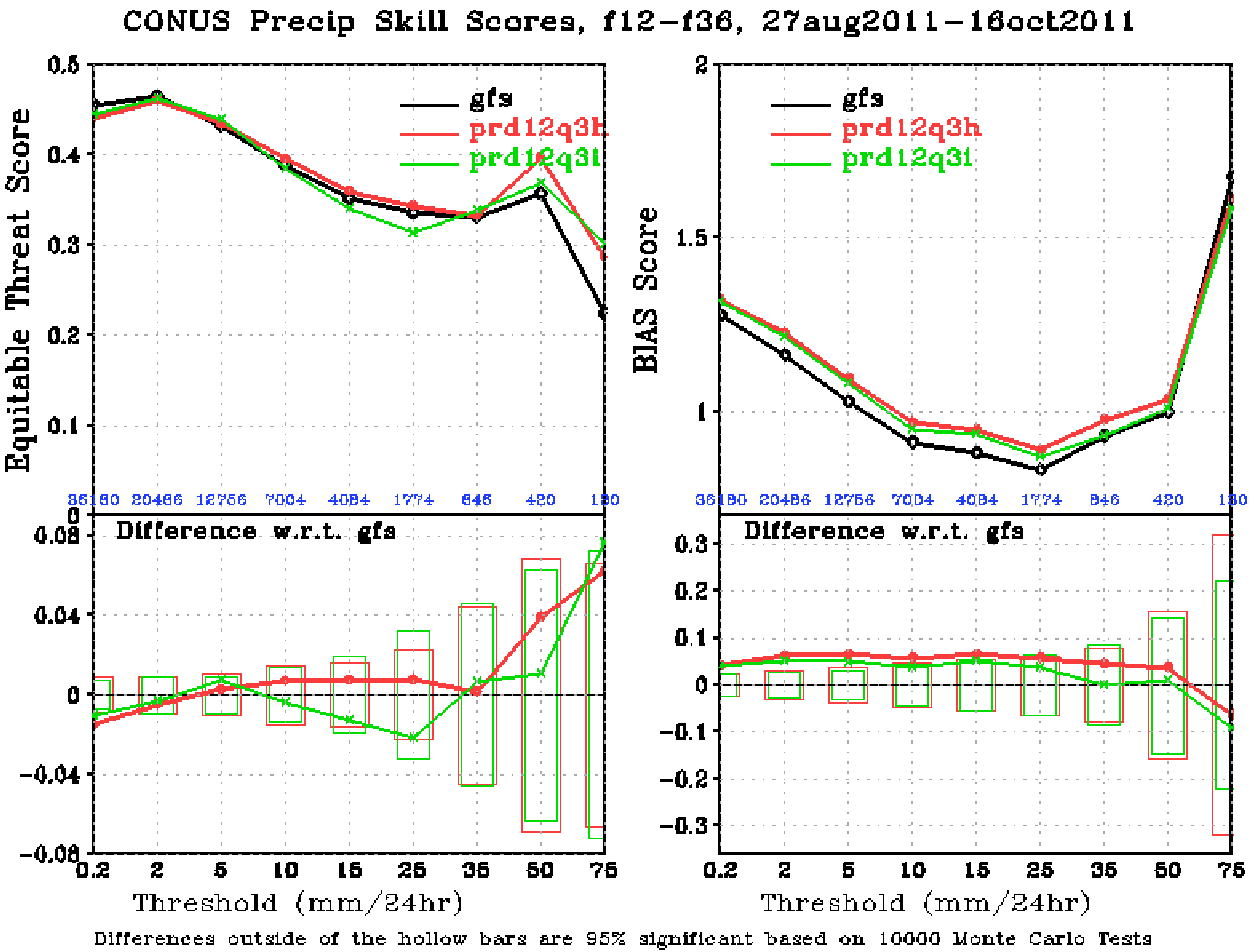




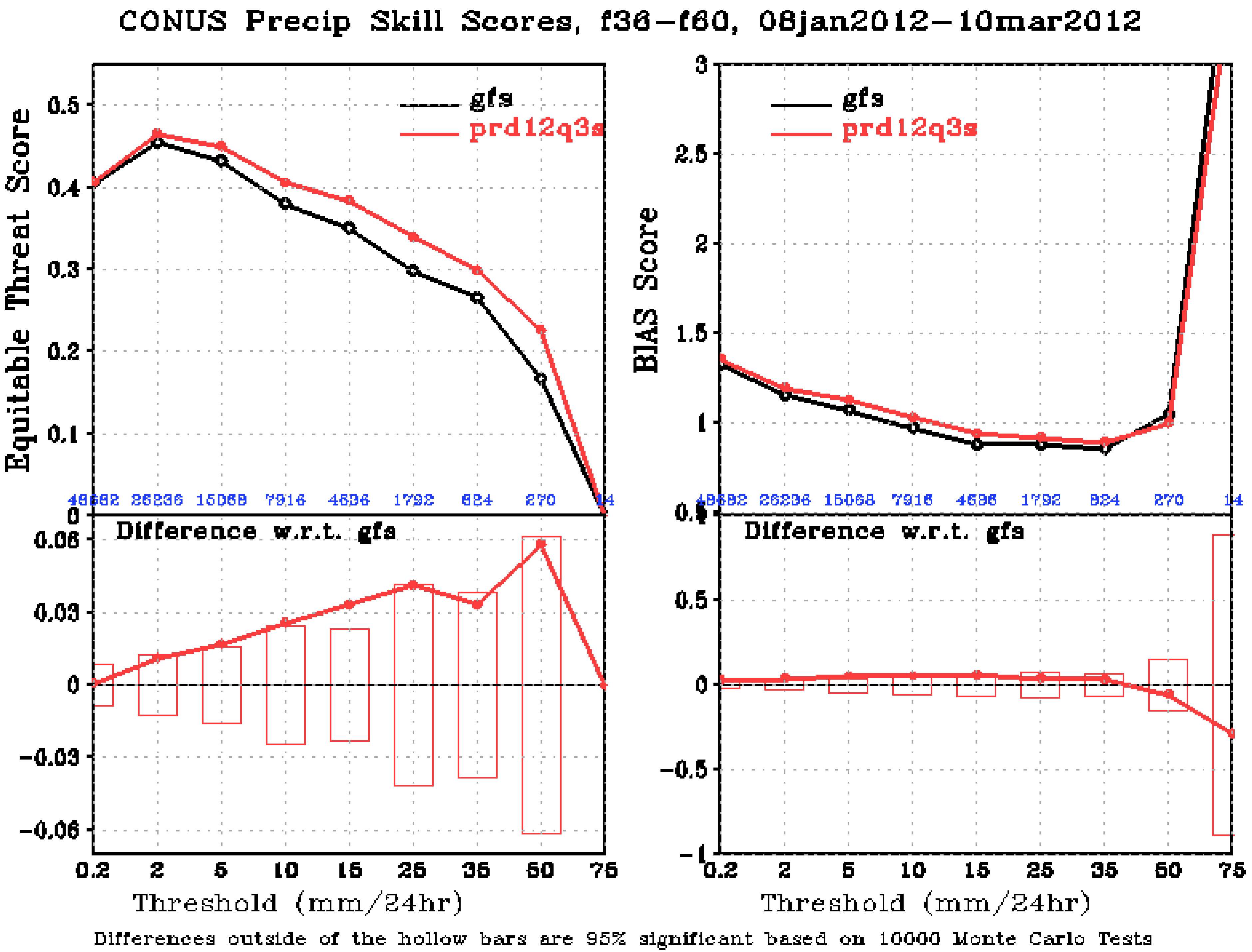
Retrospective Tropical Winds



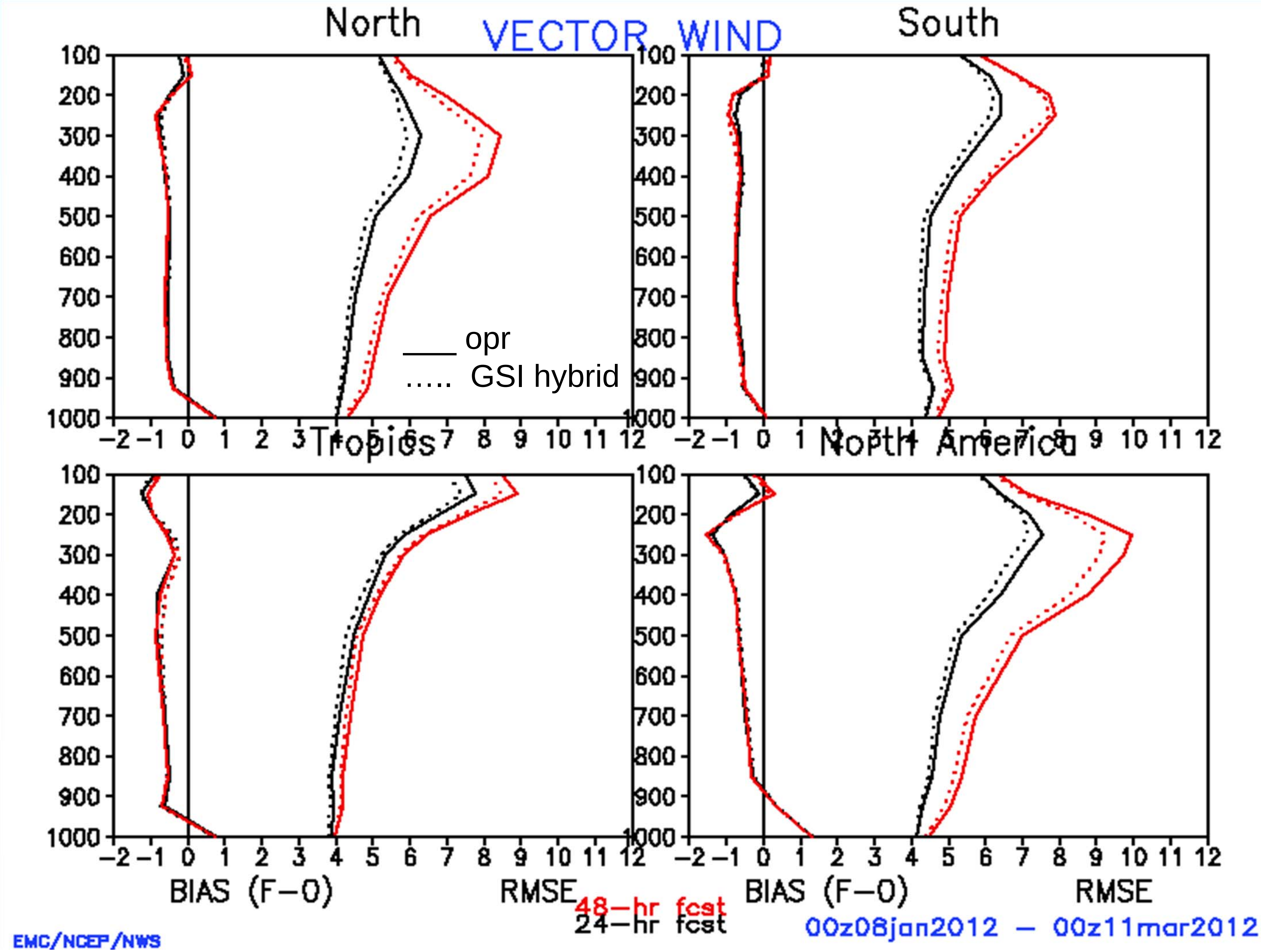


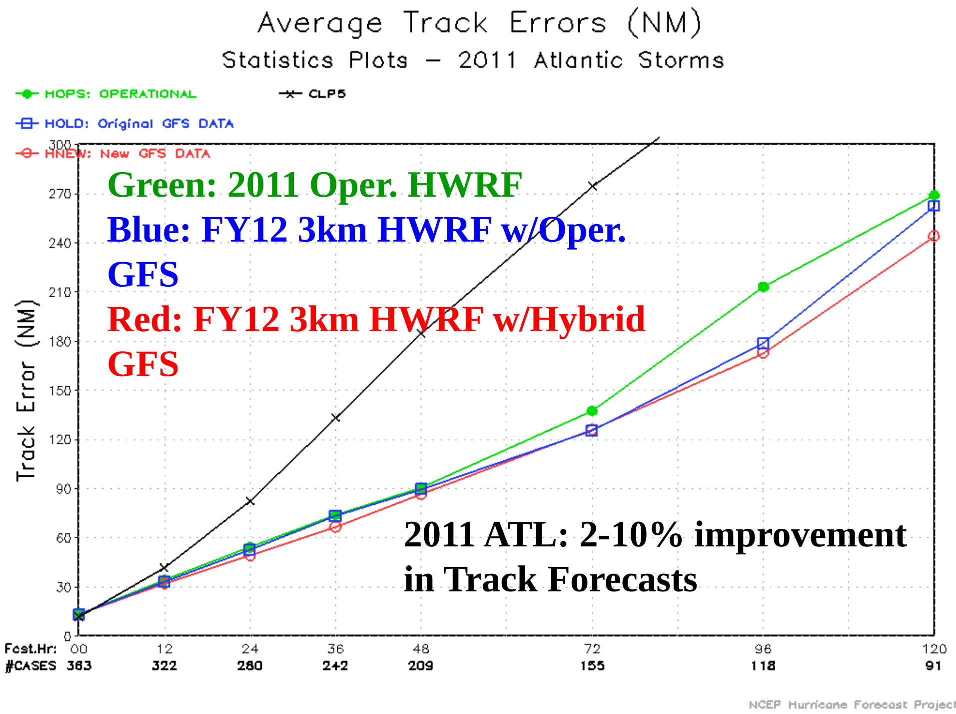


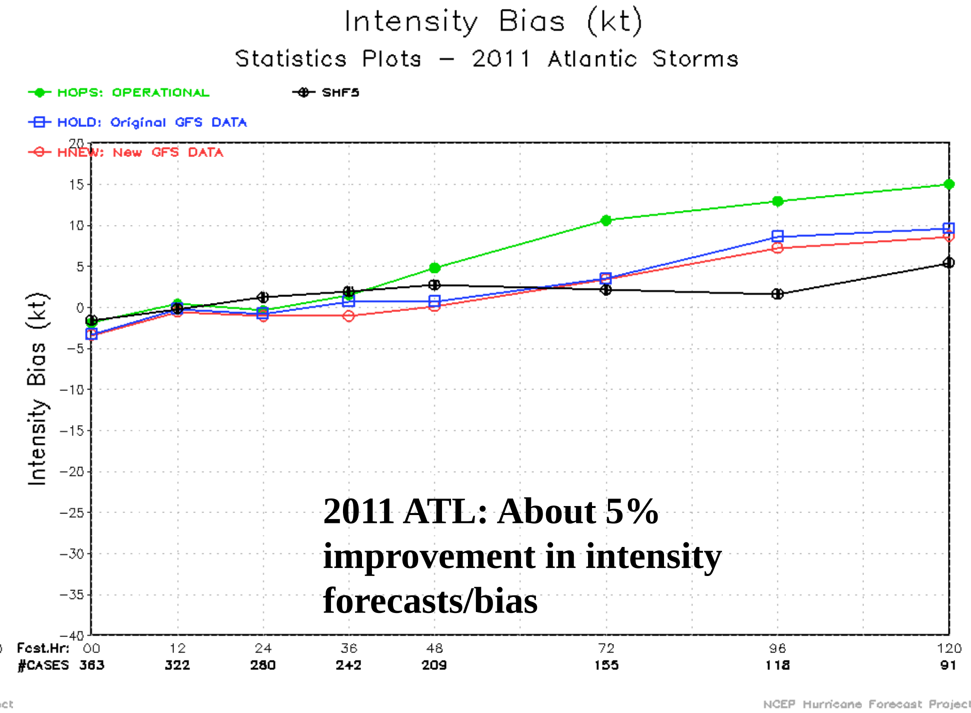
CONUS Precip Skill Scores, f12-f36, 27aug2011-16oct2011
Equitable Threat Score
BIAS Score
gfs
prd12q3h
prd12q3i
36180 20486 12756 7004 4094 1774 846 420 130
Difference w.r.t. gfs
0.2 2 5 10 15 25 35 50 75
Threshold (mm/24hr)
Differences outside of the hollow bars are 95% significant based on 10000 Monte Carlo Tests

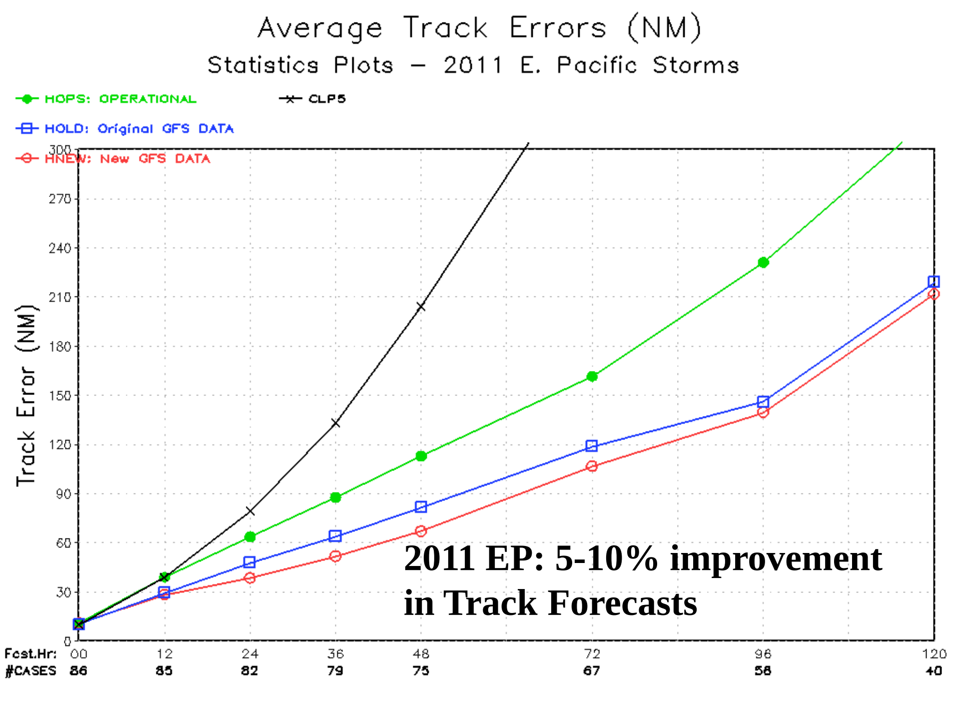


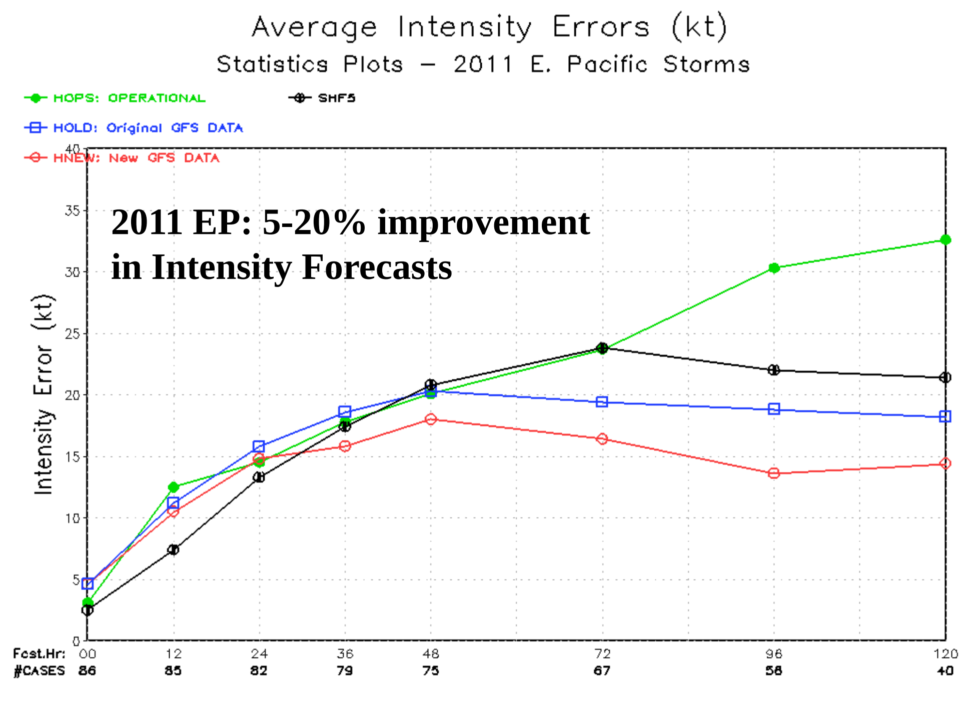
CONUS Precip Skill Scores, f36–f60, 08jan2012–10mar2012
Equitable Threat Score
gfs
prd12q3s
BIAS Score
Difference w.r.t. gfs
Threshold (mm/24hr)
0.2 2 5 10 15 25 35 50 75
48692 26236 15068 7916 4696 1792 824 270 14
Differences outside of the hollow bars are 95% significant based on 10000 Monte Carlo Tests


VECTOR WIND
North
South
Tropics
North America
___ opr
….. GSI hybrid
100
200
300
400
500
600
700
800
900
1000
−2 −1 0 1 2 3 4 5 6 7 8 9 10 11 12
BIAS (F−O)
RMSE
48−hr fcst
24−hr fcst
00z08jan2012 − 00z11mar2012
EMC/NCEP/NWS


Average Track Errors (NM)
Statistics Plots – 2011 Atlantic Storms
HOPS: OPERATIONAL
CLP5
HOLD: Original GFS DATA
HNEW: New GFS DATA
Green: 2011 Oper. HWRF
Blue: FY12 3km HWRF w/Oper. GFS
Red: FY12 3km HWRF w/Hybrid GFS
2011 ATL: 2-10% improvement in Track Forecasts
Track Error (NM)
Fcst.Hr: 00 12 24 36 48 72 96 120
#CASES 363 322 280 242 209 155 118 91
NCEP Hurricane Forecast Project


Intensity Bias (kt)
Statistics Plots – 2011 Atlantic Storms
HOPS: OPERATIONAL
SHF5
HOLD: Original GFS DATA
HNEW: New GFS DATA
2011 ATL: About 5% improvement in intensity forecasts/bias
Intensity Bias (kt)
Fcst.Hr: 00 12 24 36 48 72 96 120
#CASES 363 322 280 242 209 155 118 91
NCEP Hurricane Forecast Project


Average Track Errors (NM)
Statistics Plots – 2011 E. Pacific Storms
HOPS: OPERATIONAL
CLP5
HOLD: Original GFS DATA
HNEW: New GFS DATA
2011 EP: 5-10% improvement in Track Forecasts
Track Error (NM)
Fcst.Hr: 00 12 24 36 48 72 96 120
#CASES 86 85 82 79 75 67 56 40
NCEP Hurricane Forecast Project


Average Intensity Errors (kt)
Statistics Plots – 2011 E. Pacific Storms
HOPS: OPERATIONAL
SHF5
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2011 EP: 5-20% improvement in Intensity Forecasts
Intensity Error (kt)
Fcst.Hr: 00 12 24 36 48 72 96 120
#CASES 86 85 82 79 75 67 56 40
NCEP Hurricane Forecast Project

HVEDAS Extensions and Improvements

- Expand hybrid to 4D
  - Hybrid within 'traditional 4DVAR' (with adjoint)
  - Pure ensemble 4DVAR (non-adjoint)

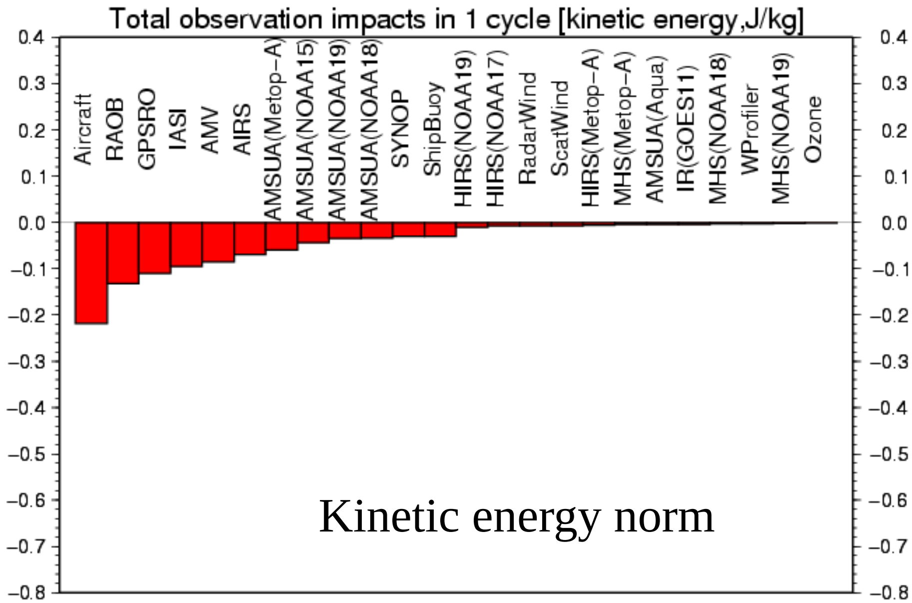
- EnKF improvements
  - Explore alternatives such as LETKF
  - Adaptive localization and inflation

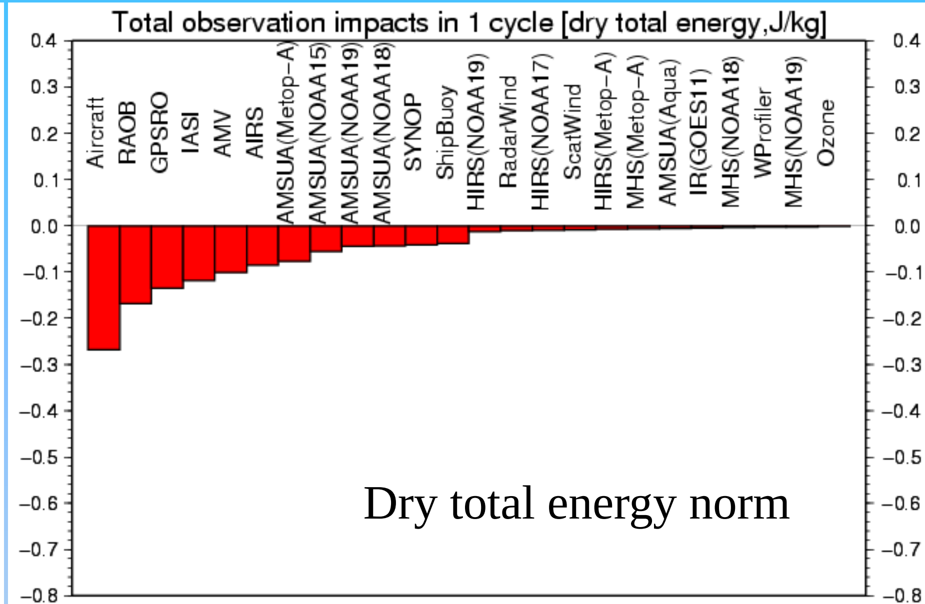
- Non-GFS applications in development
  - NAM /Mesoscale Modeling
  - Hurricanes/HWRF
  - Storm-scale initialization
  - Rapid Refresh
  - Other global models (NASA GEOS-5, NOAA FIM)

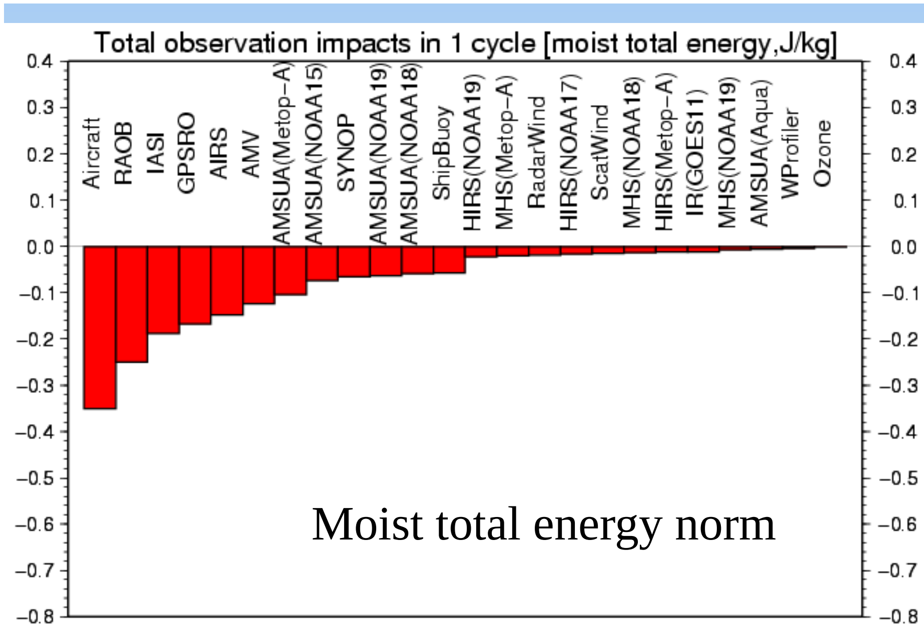
- NCEP strives to have single DA system to develop, maintain, and run operationally (global, mesoscale, severe weather, hurricanes, etc.)
  - ***GSI (including hybrid development) is community code***
  - EnKF used for GFS-based hybrid being expanded for use with other applications (not yet supported by DTC)

- Observation impacts and sensitivity, Yoichiro Ota

Observation impacts with various norms







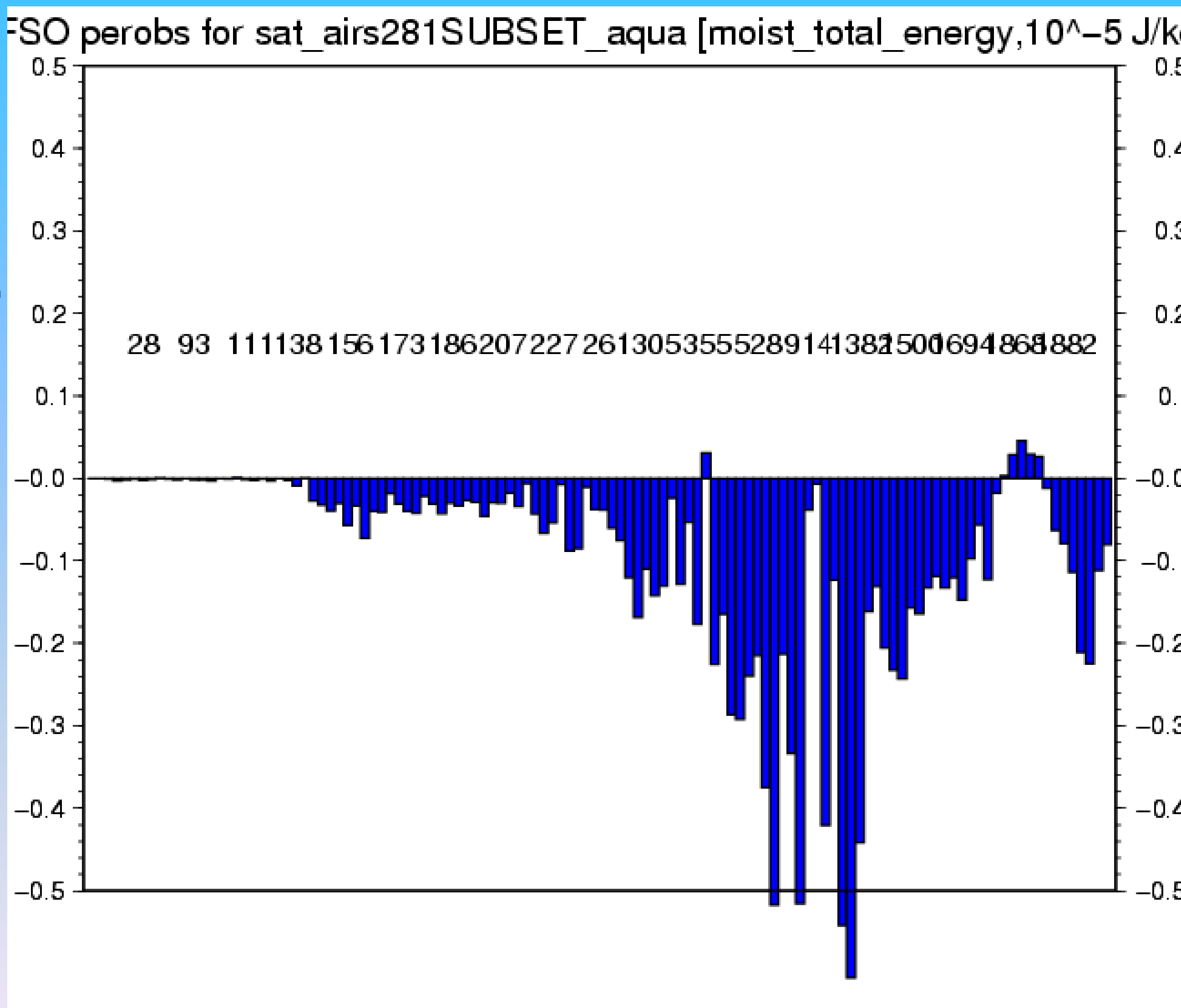
Average total observation impacts of various observation types.
From 12UTC October 21 2010 to 06UTC October 28 2010 (28 cases).
Evaluation FT is 24 hours. Impacts are estimated with the serial EnSRF and simple horizontal advection of localization function.

Serial EnSRF

Impact per 1 obs: AIRS moist total energy

Serial EnSRF
at the same
analysis time

292219



Assimilation techniques

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Cloudy Radiance Assimilation

Min-Jeong Kim, Emily Liu, Yanqiu Zhu, Will McCarty (GMAO)

- Large numbers of radiances contain cloud (and precipitation) signal.
- If cloudy radiances can be properly used, potential for significant improvement in forecasts of temperature, wind, moisture and cloud fields.
- Initially addressing simpler problem with microwave and non-precipitating clouds
- Planned for initial operational implementation in the next next global GSI upgrade (Spring – Fall 2013)

Necessary modifications for cloudy radiances

- Simulate cloudy radiances (CRTM)
- Define control variable(s) for clouds
- Define background error for control variable(s) – hybrid?
- Define quality control (currently only doing nonscattering clouds)
- Define observation errors
- Develop forward model for cloud physics
  - Tangent Linear
  - Adjoint (for gradient)

GSI w/o cloudy radiances

User input & initializations

Read in & distribute Observations, guess fields background error (T ,q, sfc P, u, v ozone)

Additional initializations

Outer loop

a) Calculate simulated obs and sensitivities at obs locations (radiances and jacobians with CRTM)

b) Applying bias corrections

c) Screening observation with QC processes

d) Set up right hand side of analysis equation

e) Call inner loop

- i. Compute gradient information
- ii. Apply background error
- iii. Compute search direction
- iv. Compute step size
- v. Update inner loop analysis increment

f) Update outer loop analysis increment

Write analysis & related output

Revised procedure with cloudy radiances

User input & initializations

Read in & distribute Observations, guess fields background error (T ,q, sfc P, u, v ozone, clouds)

Additional initializations

Outer loop **(add analysis control variable)**

a) **Calculate simulated obs and sensitivities at obs locations (radiances and jacobians with CRTM)** **(clear and cloudy radiances)**

b) **Applying bias corrections** **(revised for cloudy radiances)**

c) **Screening observation with QC processes** **(removing radiances we cannot simulate)**

d) **Set up right hand side of analysis equation** **(including cloud forcing)**

e) **Call inner loop**

  i. Compute gradient information (through linearization and adjoint of physics)

  ii. Apply background error (including cloud control variable)

  iii. Compute search direction

  iv. Compute step size (including cloudy radiances)

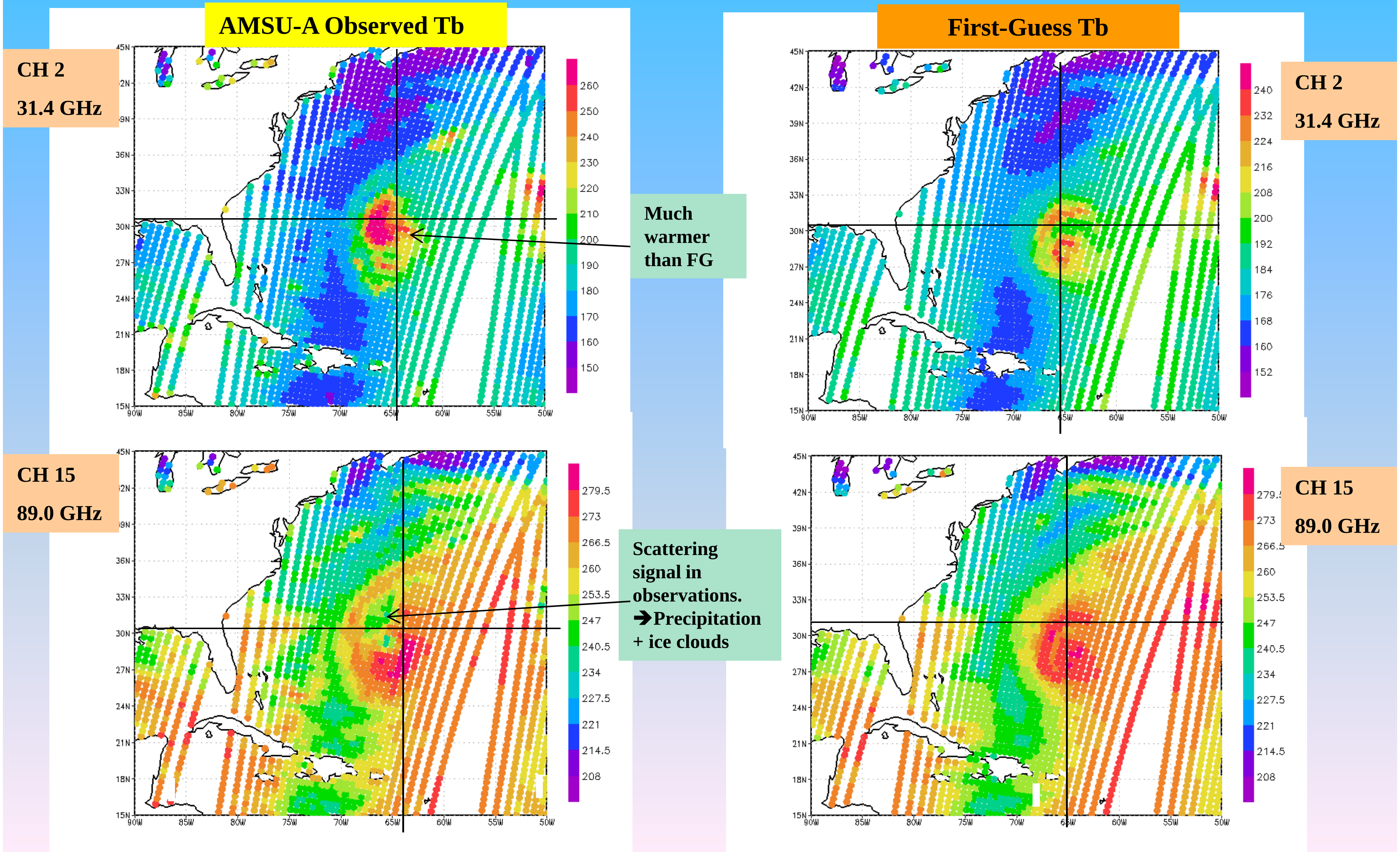
  v. Update inner loop analysis increment (through linearization of physics)

f) **Update Outer Loop analysis increment** (through physics update clouds)

Write analysis & related output

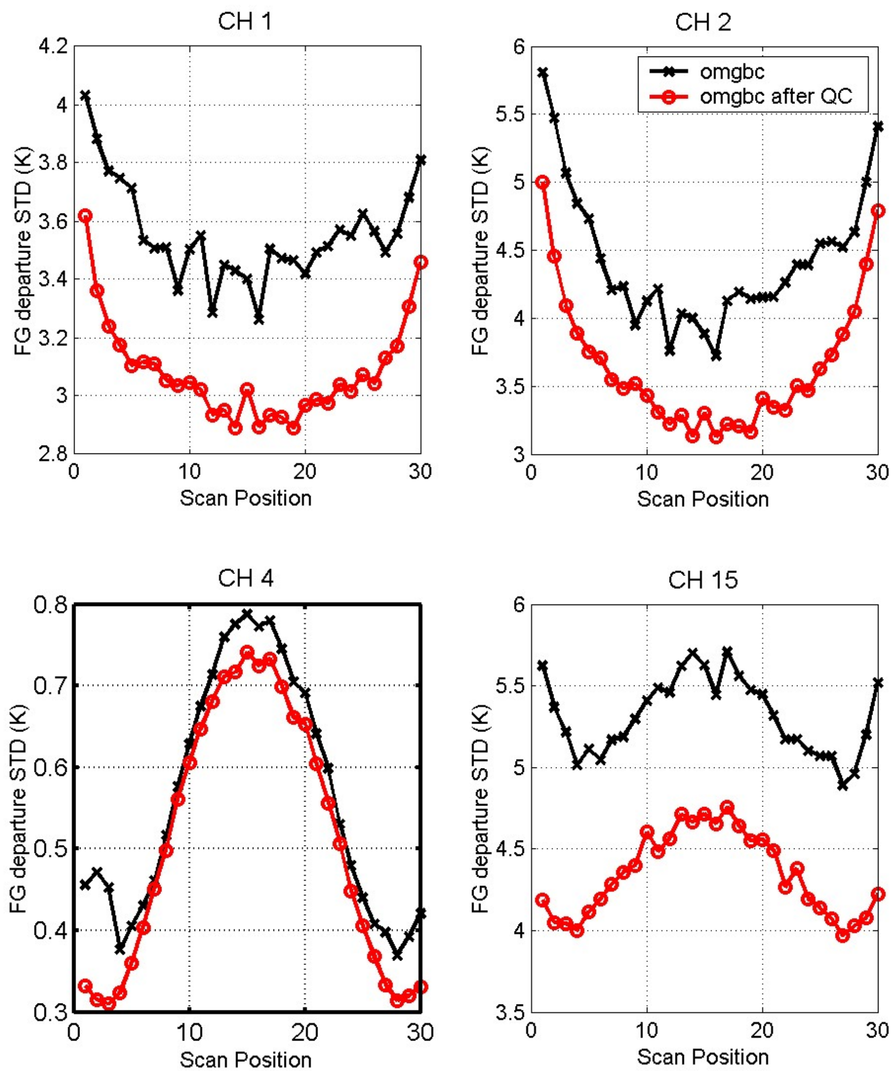
Observation operator

Community Radiative Transfer Model (CRTM)



Observation Error (scan angle dependence)

Standard Deviation (STD) of First-guess Departure (NOAA-18 AMSU-A)



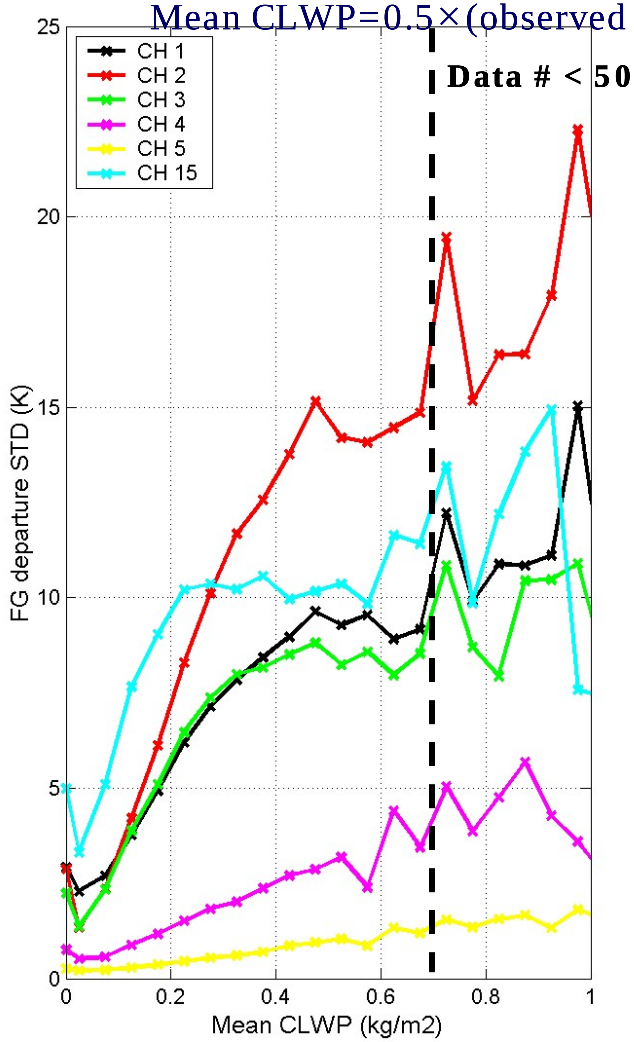
omgbc: O-F after bias correction
omgbc after QC: O-F after bias correction and QC passed

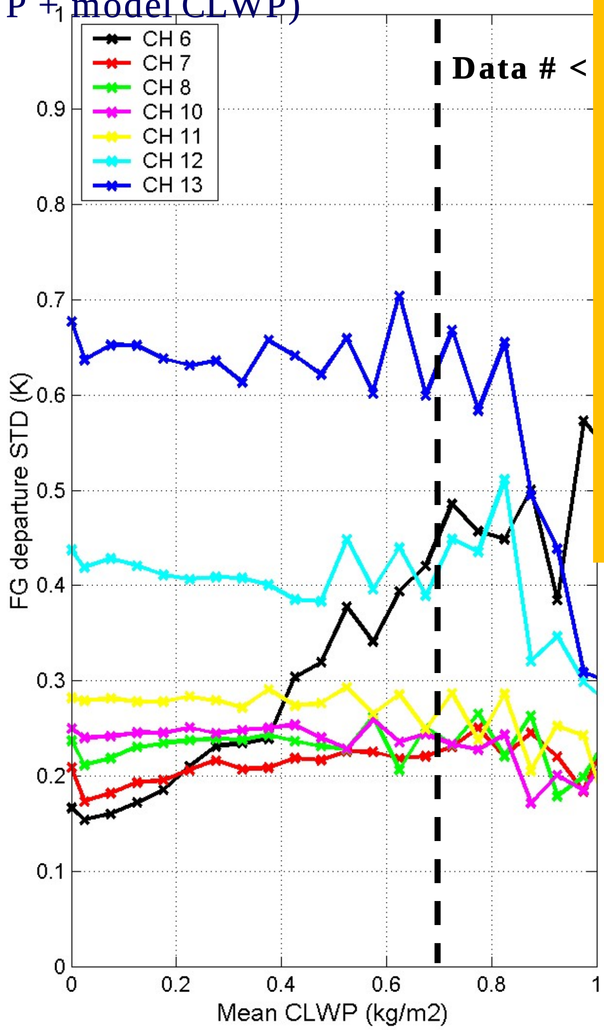
- Standard deviation depends on scan angle.
- Ch1,2,15 and Ch 3 and 4 behave differently.

Observation Error

Function of Mean Cloud Liquid Water Path (CLWP)

Mean CLWP=0.5×(observed CLWP + model CLWP)





- FG departure divided by std ratio as a function of scan position were used to get STD in these plots.
- Once observation error are defined as function of CLWP, the error value will be rescaled by multiplying with std ratio depending on scan position.

Quality Control (QC)

1. Screening cloud affected AMSU-A data
   Criteria:(1) scattering index (using ch1, 2, and 15 + ch6 Tb departure)
   (2) retrieved clwp + ch4 Tb departure

➔ New: Screening retrieved averaged CLWP > 0.5kg/m^2 over the ocean

2. Topography effect: for observations at Zsfc > 2km, observation errors get increased.

3. Transmittance at the top of the model less than 1 : inflating observation error

4. Too much sensitivity to sfc temperature/sfc emissivity: inflating observation error

5. New gross check for all-sky(clear and cloudy) radiance data

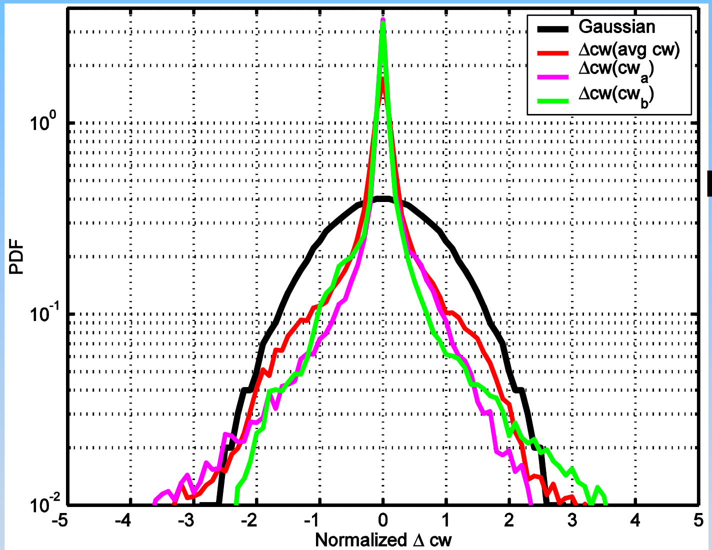
$$\frac{|\Delta Tb_{ich}|}{\sigma_{ich}} > 3$$

σ_{ich} : New observation error (i.e. function of averaged CLWP)

Moisture Control Variable

What differentiates GSI analysis results when different configurations for moisture control variables are used?

Cloud water error statistics show "non-Gaussian" distribution.



Approach I

- Single control variable: **total moisture, $q_{tot}(=q+q_c)$**
- **UK Met Office** has been using q_{tot} as a single moisture control variable

Approach 2

- Keep **two separate control variables** for water vapor and clouds
- However, **develop a different form of cloud water related control variable** of which error distribution is more Gaussian than q_c
- **ECMWF**'s current efforts are toward this approach.
- This will be tested for comparisons with Approach 1.

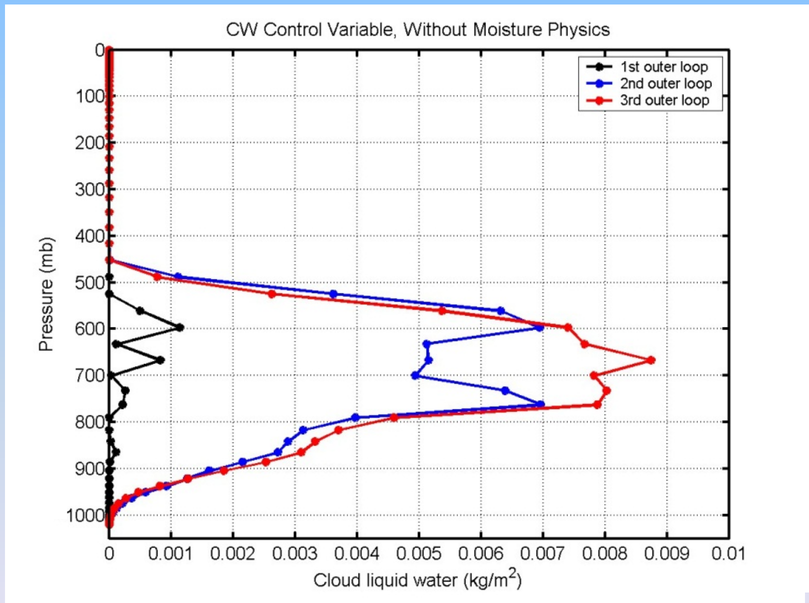
Moisture Control Variable

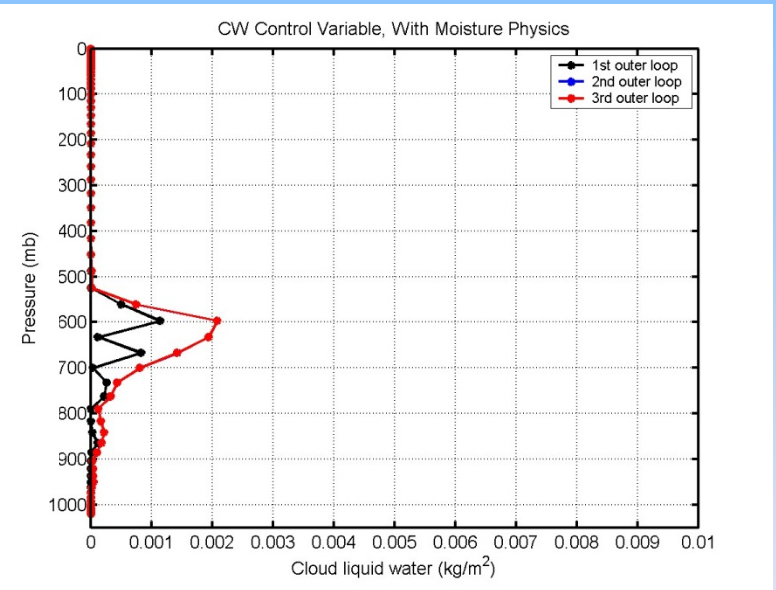
What differentiates GSI analysis results when different configurations for moisture control variables are used?

	Moisture input for observation operator (CRTM)	**Moisture Control variable**
Operational (Control)	q	q
Approach 1 (Exp1)	q, ql, qi	q, cw(=ql+qi)
Approach 2 (Exp2)	q, ql, qi, rain, snow	q_{TOT}
Approach 3 (Exp3) **(In progress by Emily Liu)**	q, ql, qi	Normalized Total Relative Humidity (RH Total=ql+qi+cw)
Approach 4 (Exp4) **(In progress by Min-Jeong)**	q, ql, qi	Different forms of cw (e.g. cw/qs, cw/N where N is cloud coverage and qs is saturated mixing ratio)

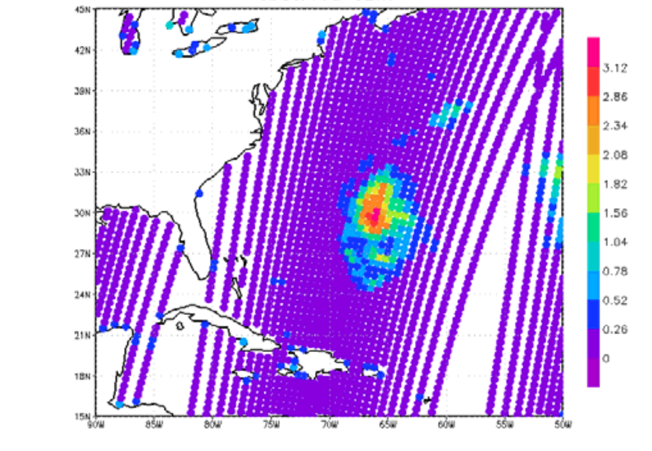
Single Obs Test Results

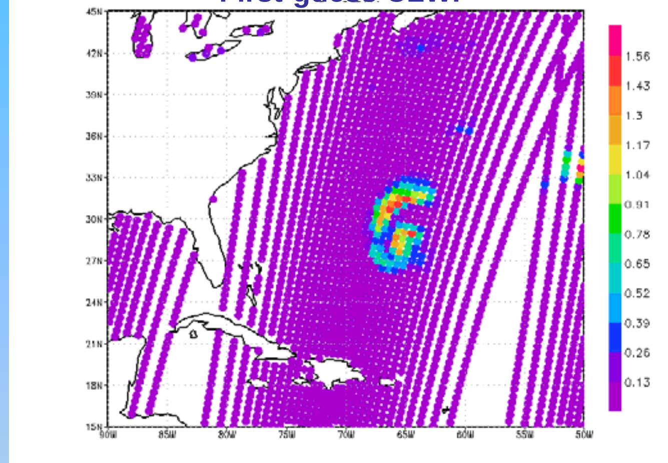
Cloud liquid water profiles

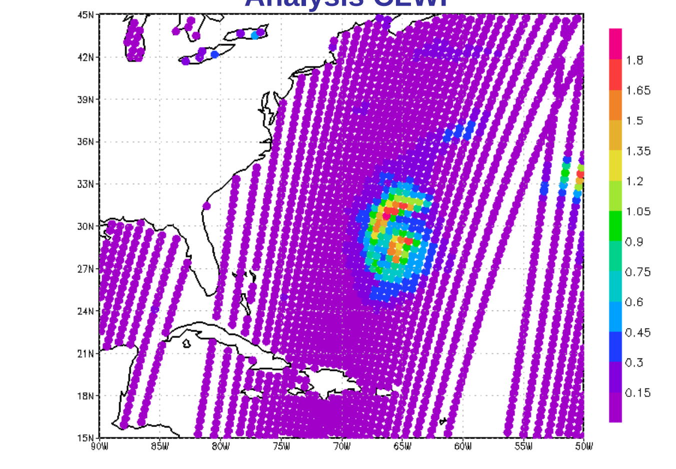


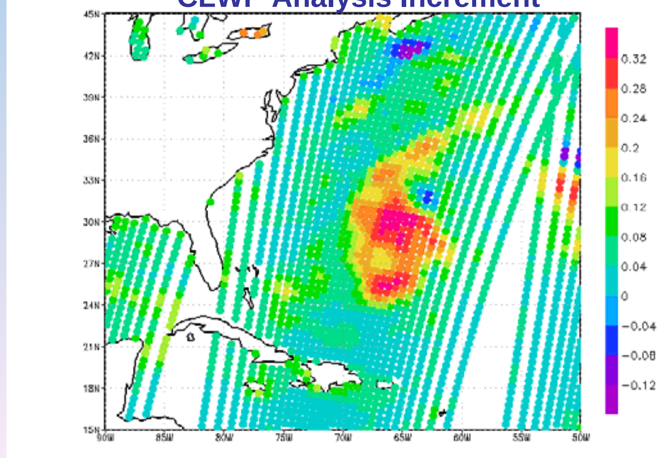


Cloud analysis increment


Retrieved CLWP (observations)


First-guess CLWP


Analysis CLWP


CLWP Analysis Increment

- **Clouds have been actively assimilated.**
- **Cloud analysis fields got improved and closer to the observations (retrieved clouds).**

Summary Cloud Assimilation

- There has been great progress in assimilating AMSU-A cloudy radiance data in NCEP Global Data Assimilation System (GDAS).
- New observation errors and quality control methods, which are applicable for clear and cloudy sky conditions, have been developed.
- Testing/comparing different options for moisture control variables are in progress.
- Preliminary results from case studies show that cloud fields are now being actively assimilated and cloud analysis fields get much closer to the retrieved values.
- Need to use hybrid background error for “cloud balance”. Dual Res???
- Will be used in simplest situations (microwave – non-precipitating) first in operations. (Planned for next Global GSI upgrade)

Use of observations

New data and improved use of current observations

- Radar Data
  - Creation and use of new VAD (after QC) winds – Shun Liu
  - Ground based Doppler radar data – Shun Liu
  - Aircraft based Doppler radar data – Mingjing Tong
- Conventional Data
  - Mesoscale surface observations – Manuel Pondeca, Steve Levine, XiuJuan Su
  - Use of visibility and wind speed in RTMA – Yanqiu Zhu
  - Improve use of significant levels in RAOB profiles – Wan-shu Wu
- Satellite Data
  - Use of ATMS and CrIS data - Andrew Collard (ATMS impact experiments run by JCSDA)
  - Use of consistent physical retrievals for CLW QC – Andrew Collard
  - Use of AURA MLS ozone profiles – Haixia Liu
  - Bias correction enhancements for GSI – Yanqui Zhu, David Parrish
  - Satellite wind usage upgrade (EUMETSAT and hourly winds) –XiuJuan Su
  - SSMI/S data – Andrew Collard, Emily Liu, Banghua Yan (NESDIS) and Ellen Liang (NESDIS)
  - GOES-R/SEVERI radiances – Haixia Liu
  - Enhanced assimilation of GPS-RO data – Lidia Cucurull, R.J. Purser

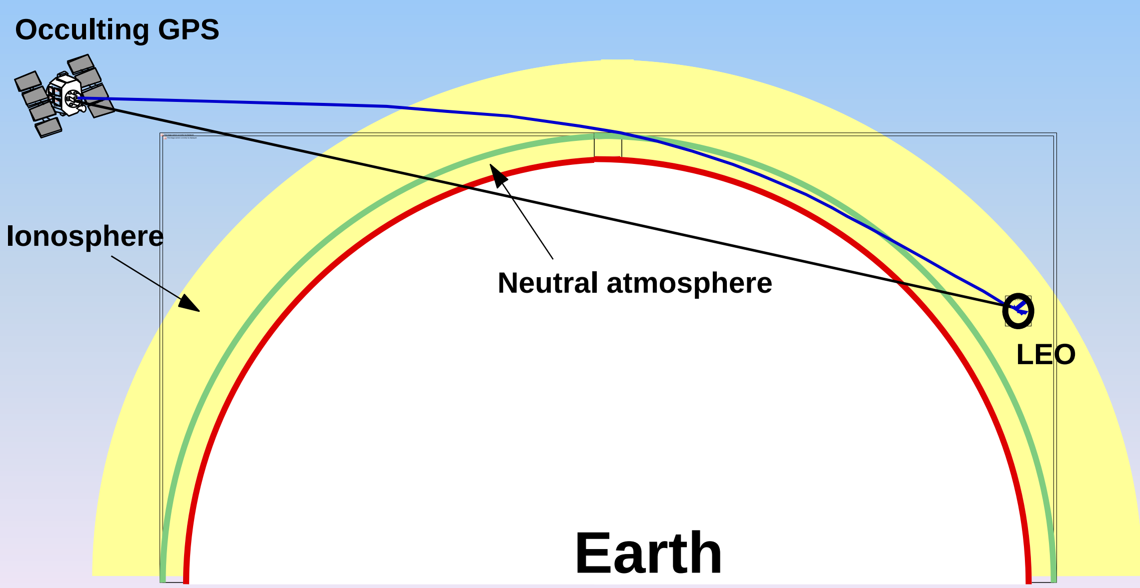
Enhanced assimilation of GPS-RO data

Lidia Cucurull, R.J. Purser

- To be implemented along with Hybrid is the use of Bending angle rather than Refractivity
- New and improved forward model to reduce eliminate singularities
- Data used up to 50km from 30km for refractivities
- Improved quality control (little data rejected)
- Cucurull, L., J.C. Derber, and R.J. Purser, A bending angle forward operator for GPS Radio Occultation measurements, submitted to JGR.

Radio Occultation concept

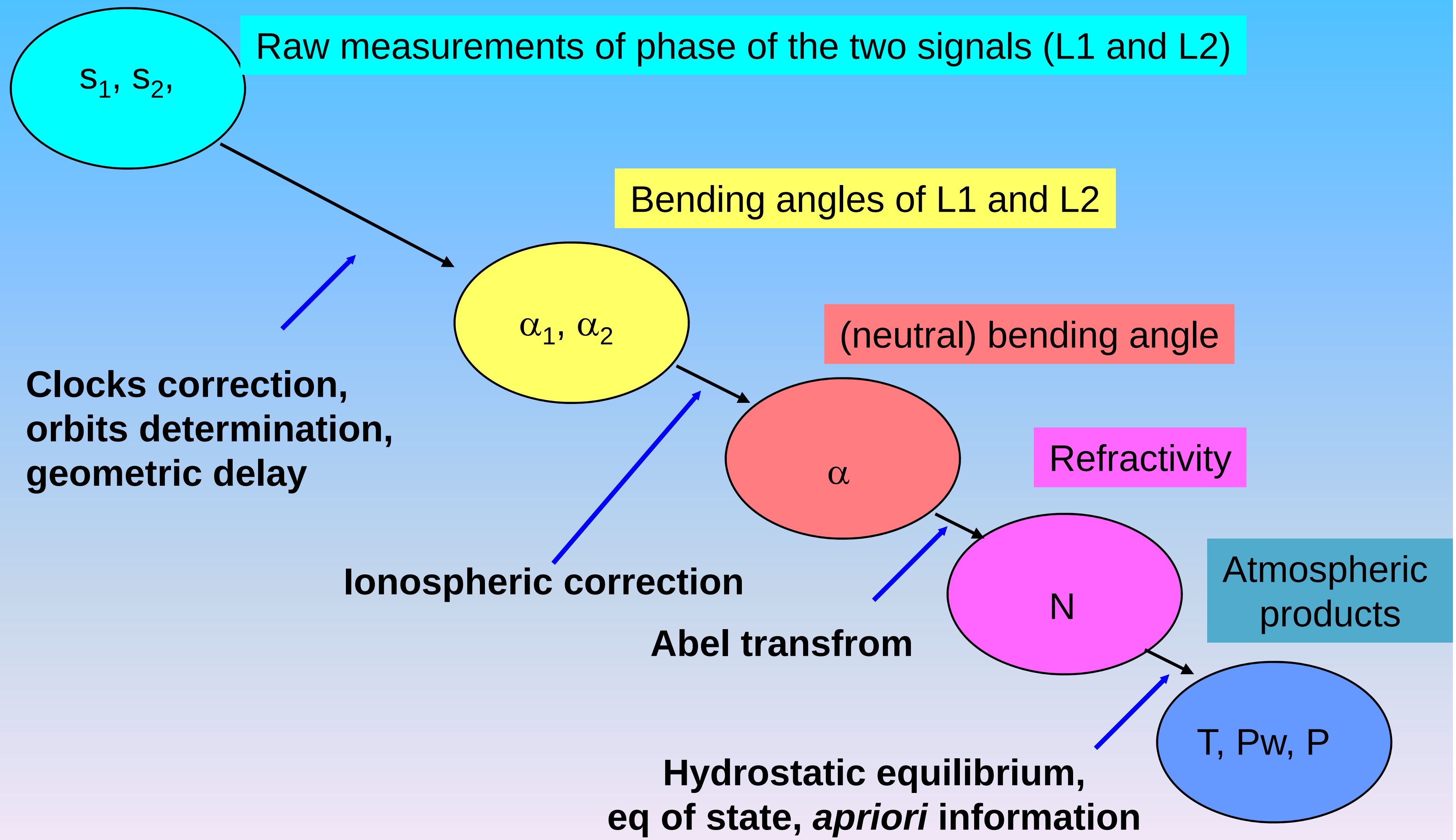
- An occultation occurs when a GPS (GNSS) satellite rises or sets across the limb wrt to a LEO satellite.
- A ray passing through the atmosphere is refracted due to the vertical gradient of refractivity (density).
- During an occultation (~ 3min) the ray path slices through the atmosphere



Raw measurement: change of the delay (phase) of the signal path between the GPS and LEO during the occultation. (It includes the effect of the atmosphere).

GPS transmits at two different frequencies: ~1.6 GHz (L1) and ~1.3 GHz (L2).

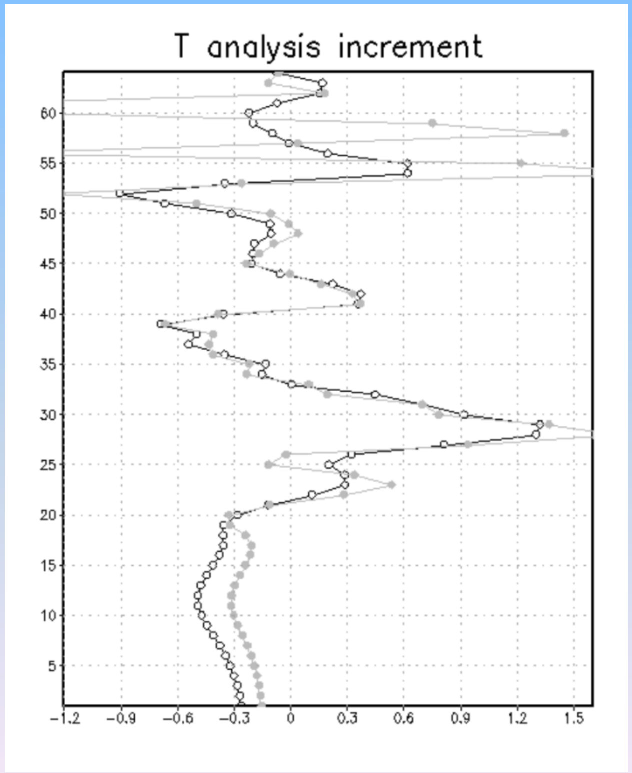
What do we “want” to assimilate?

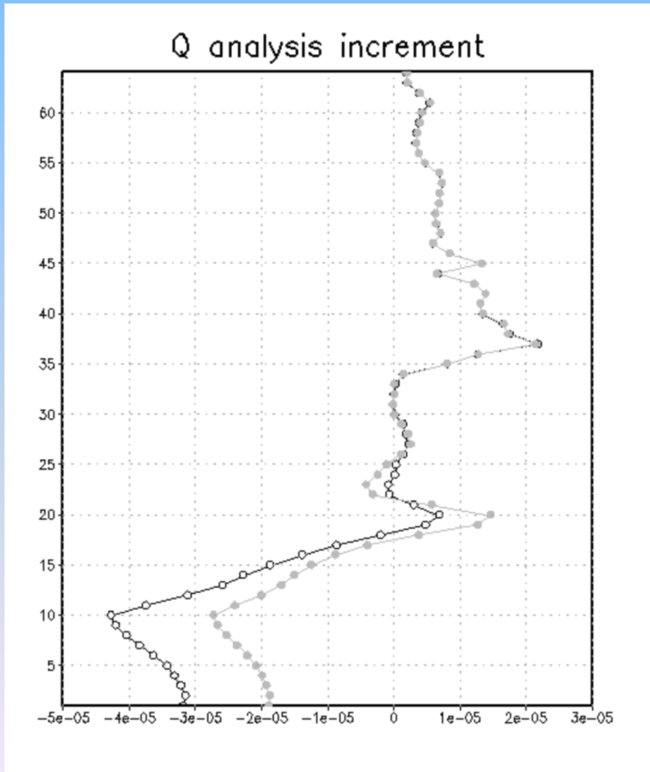


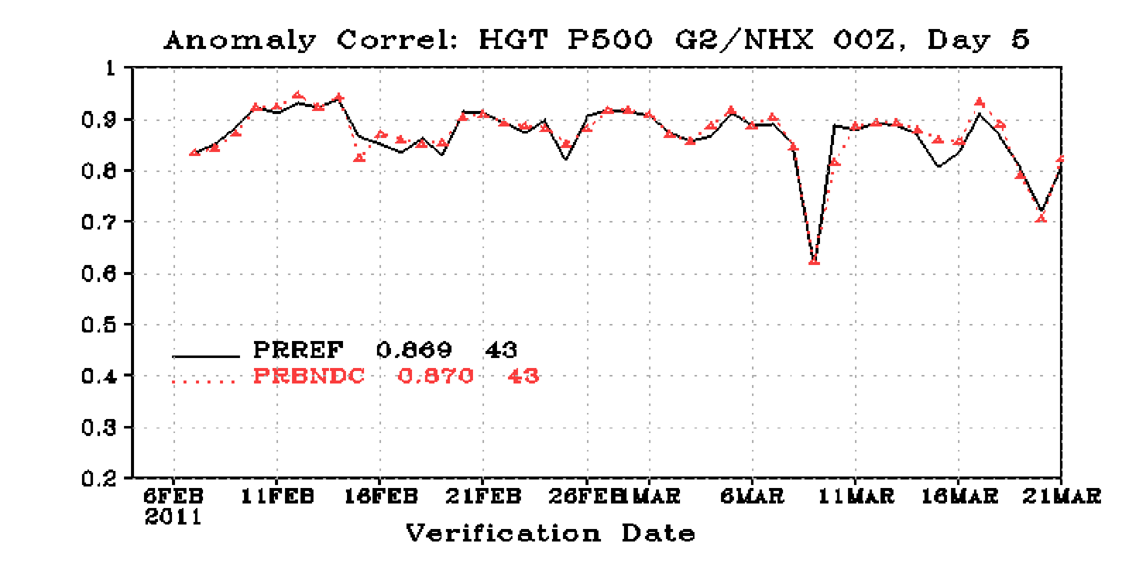
GPS RO Refractivity vs. Bending angle experiment design

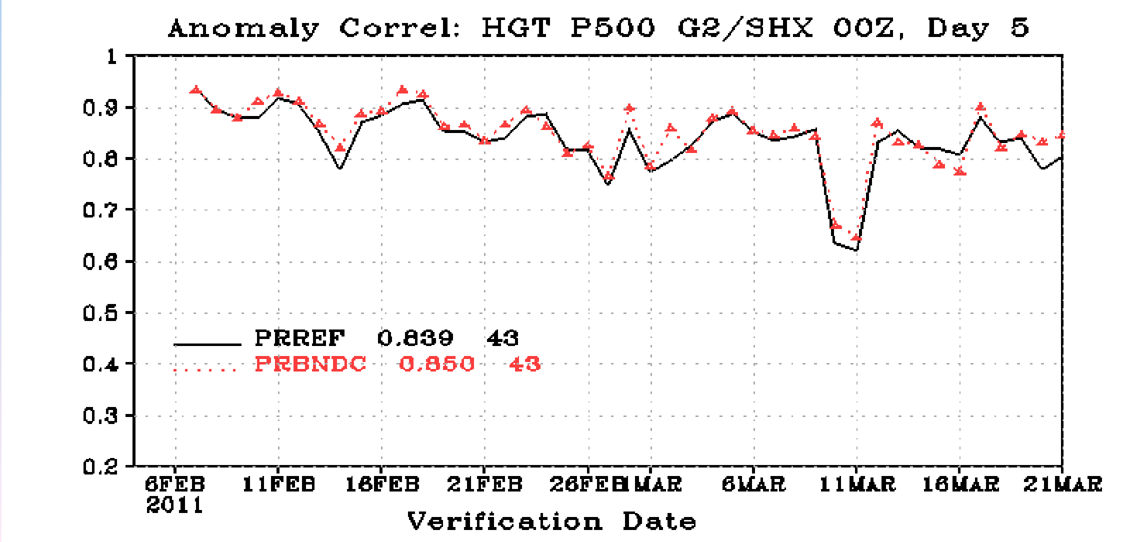
- Uses COSMIC 1-6, SAC-C, TerraSAR-X, METOP/GRAS, GRACE-A, C/NOFS
- Period 1 February to 22 March 2011
- Non-Hybrid GSI
- T382L64

Impact of using bending angle rather than refractivity






Anomaly Correl: HGT P500 G2/NHX 00Z, Day 5
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
PRREF 0.869 43
PRBNDC 0.870 43
6FEB 2011
11FEB
16FEB
21FEB
26FEB
1MAR
6MAR
11MAR
16MAR
21MAR
Verification Date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0.8
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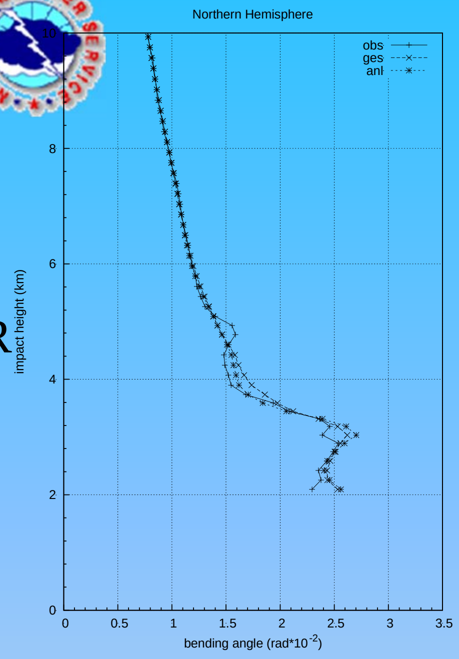
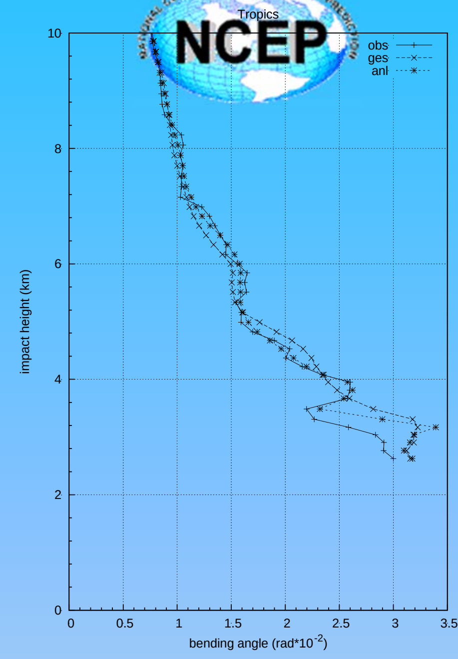
0.6
0.5
0.4
0.3
0.2
PRREF 0.839 43
PRBNDC 0.850 43
6FEB 2011
11FEB
16FEB
21FEB
26FEB
1MAR
6MAR
11MAR
16MAR
21MAR
Verification Date

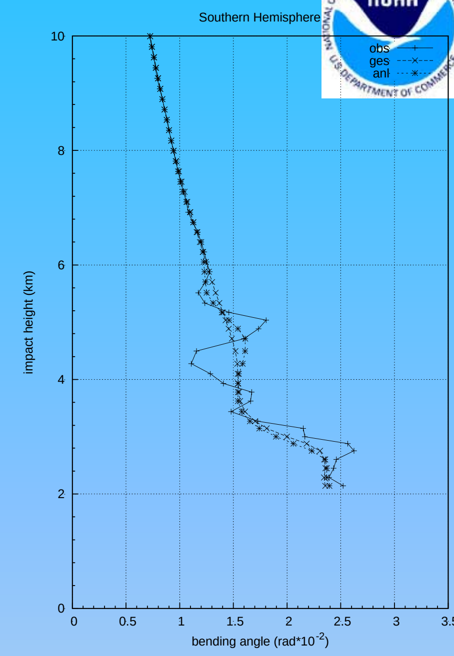
Current work

- Use of GPS RO data in Super-refraction layers
- Usually found in tropics at the top of the boundary layer. Large change in refractive index.
- Use of Refractivity data in this case results in negative bias and impacts all data below
- Cannot currently measure Bending Angles > .03 - .04 rad because of instrument SNR – but may be able to used data below the Super-refraction layer

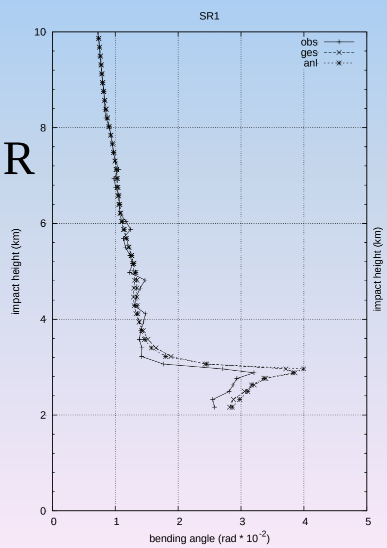
Non-SR

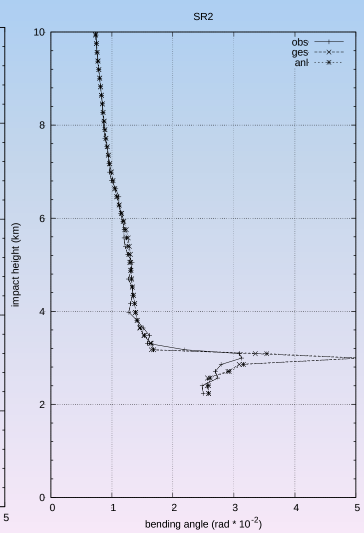

Northern Hemisphere
obs
ges
anl
impact height (km)
bending angle (rad*10^{-2})

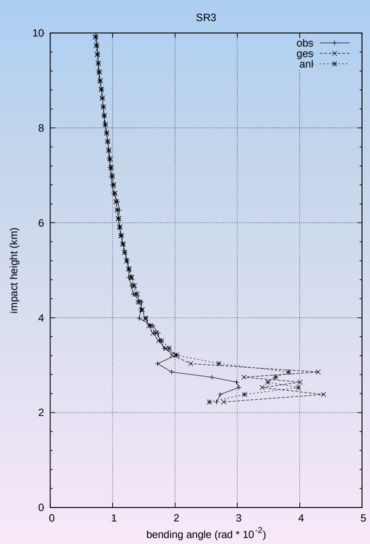

Tropics
obs
ges
anl
impact height (km)
bending angle (rad*10^{-2})

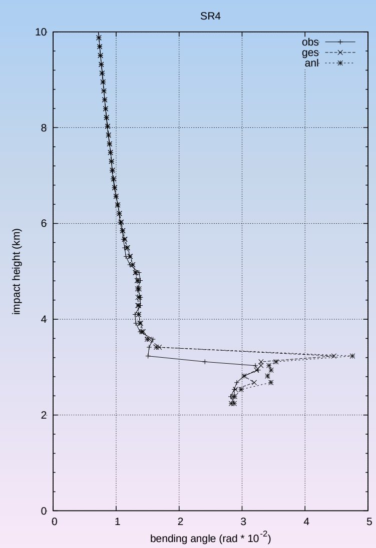

Southern Hemisphere
obs
ges
anl
impact height (km)
bending angle (rad*10^{-2})

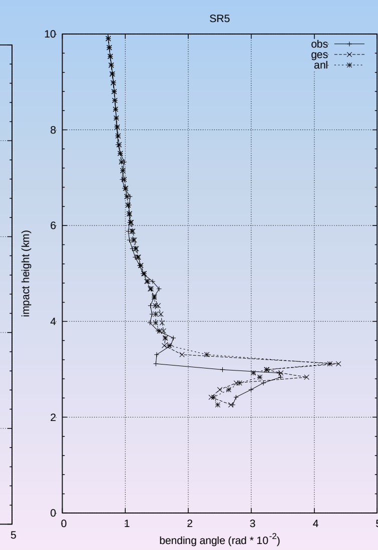
SR

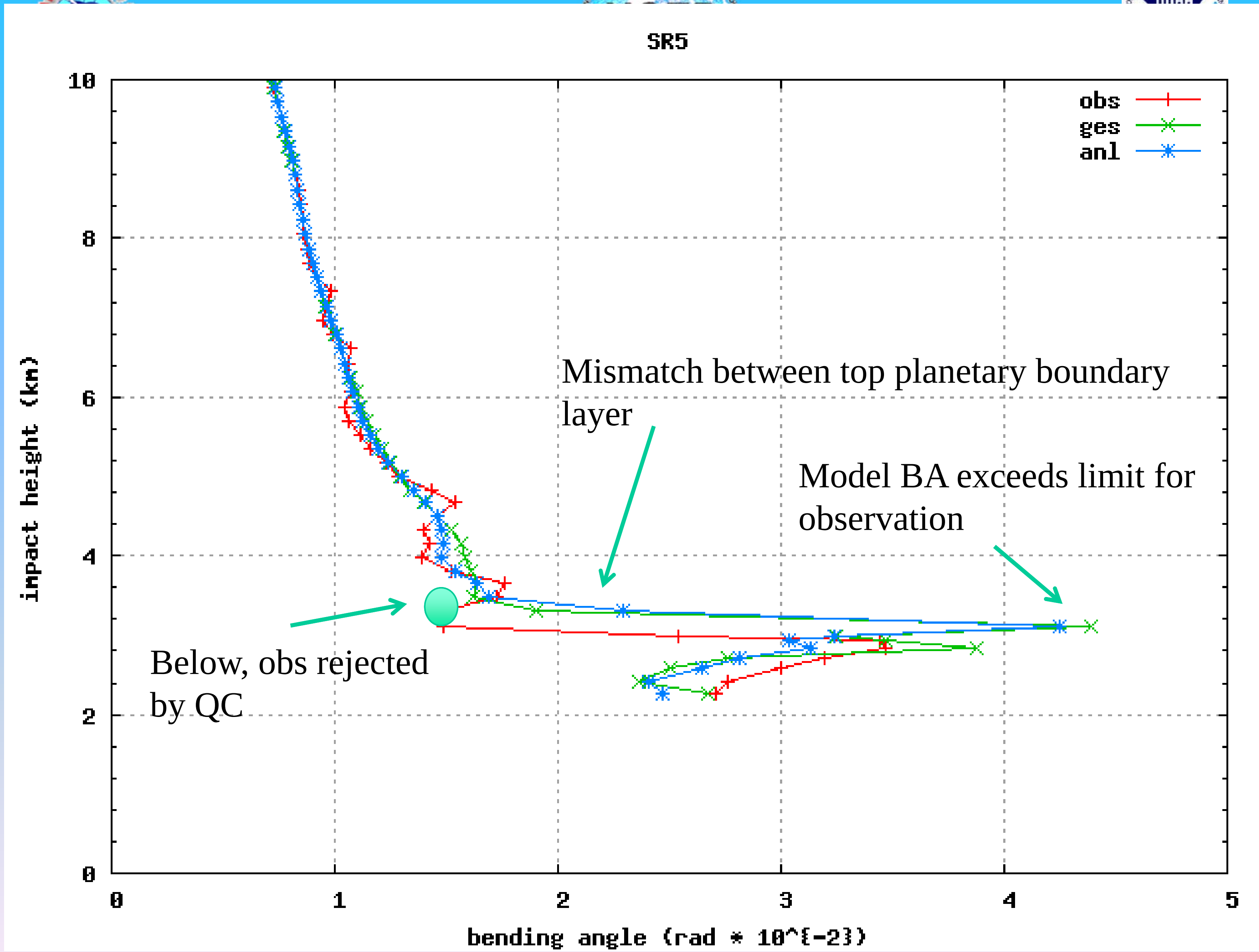

SR1
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})


SR2
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})


SR3
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})


SR4
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})


SR5
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})


SR5
obs
ges
anl
impact height (km)
bending angle (rad * 10^{-2})
0
1
2
3
4
5
0
2
4
6
8
10
Mismatch between top planetary boundary layer
Model BA exceeds limit for observation
Below, obs rejected by QC

Maintenance, Collaboration and General improvements

- Improvement of RTMA application – Manuel Pondeca
- Improvement of NAM analysis – Wan-shu Wu
- Improvement of HWRF analysis – Mingjing Tong
- Add global NMMB capability – David Parrish
- Update to revised versions of global cloud and precip physics – Min-Jeong Kim
- Radiance maintenance and enhancement
  - CRTM improvement– Paul VanDelst, David Groff, Quanhua Liu(NESDIS), Yong Chen(NESDIS)
  - Add climatological CO_2, CO, NO_2, CH_4 - Runhua Yang
  - Radiance monitoring upgrade – Ed Safford
  - FOV updates for new satellite instruments – George Gayno, ?? (NESDIS)
- General Maintenance and improvements
  - Maintenance of EMC GSI trunk - Mike Lueken
  - Code Structure improvement – Mike Lueken, Ricardo Todling (GMAO)
  - Improve Structure of diagnostic files and unify data monitoring – Andrew Collard, Ed Safford
  - Code transfer to different machines – Daryl Kleist, Russ Treadon, Others
  - Code optimization – All
  - Pre-operational testing and parallels (Russ Treadon, George Gayno and all)

Major Future Activities

- Cloud Assimilation
- Hybrid enhanced (4d+) and extended to other models
- New observations – NPP, JPSS, GOES-R, METOP-B, etc.
- Aerosol and trace gas assimilation
- Improved use of currently used data
- Transition between machines/supporting operations
- Improved optimization/code structure
- Collaborative research