Convective-Scale Satellite Data Assimilation

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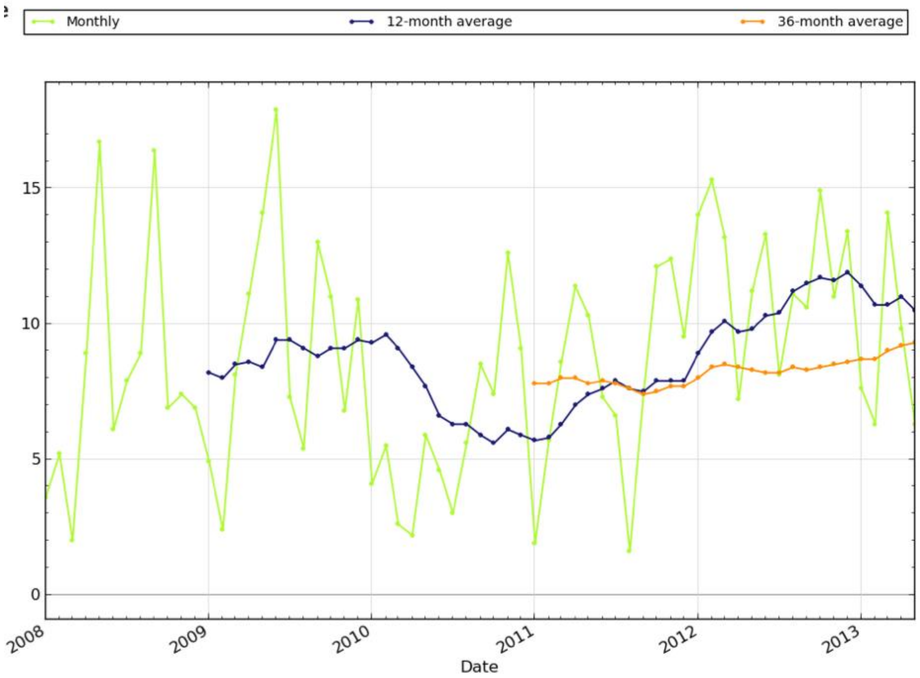
Convective Scale NWP: Why Bother? (© Barker)

Percentage benefit wrt UK Index
(forecast skill for surface weather)



Local and severe weather

- Moist processes
- Clouds, fog
- Visibility
- Precipitation
- Orographic effects

10% represents > 5-10 years lead over global model

Source: Dale Barker (Met Office)

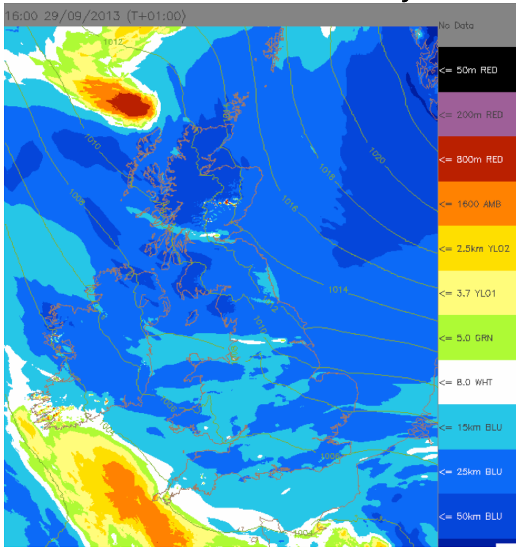
Convective Scale DA: Spatial and Temporal Needs

Smaller spatial and temporal scales
- Rapid Update Cycling (hourly or sub-hourly)
- More timely use of satellite data (short cut-off)
- Quick turnaround (4DVar penalized)
- Uncertainties and predictability (probabilistic forecasts)

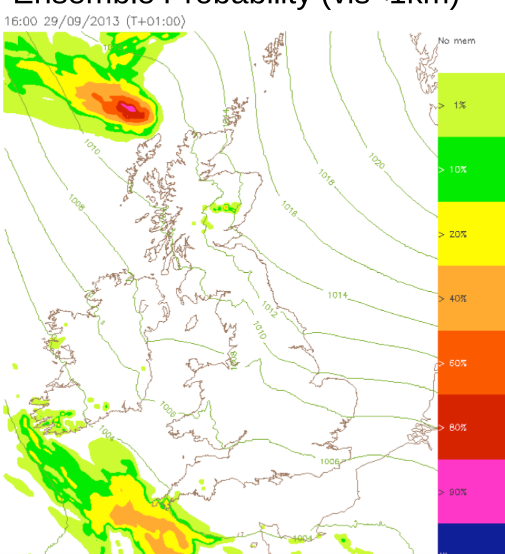
Thinning and/or super-obbing
- Ability to observe small structures
- Correlated errors (measure, processing, representativeness)
- “Big Data” paradigm

Cycling requirements
- Wait for valuable observations
- Wait for model spin-up to settle
- Hurry to get skillful forecast

Ensemble Mean Visibility

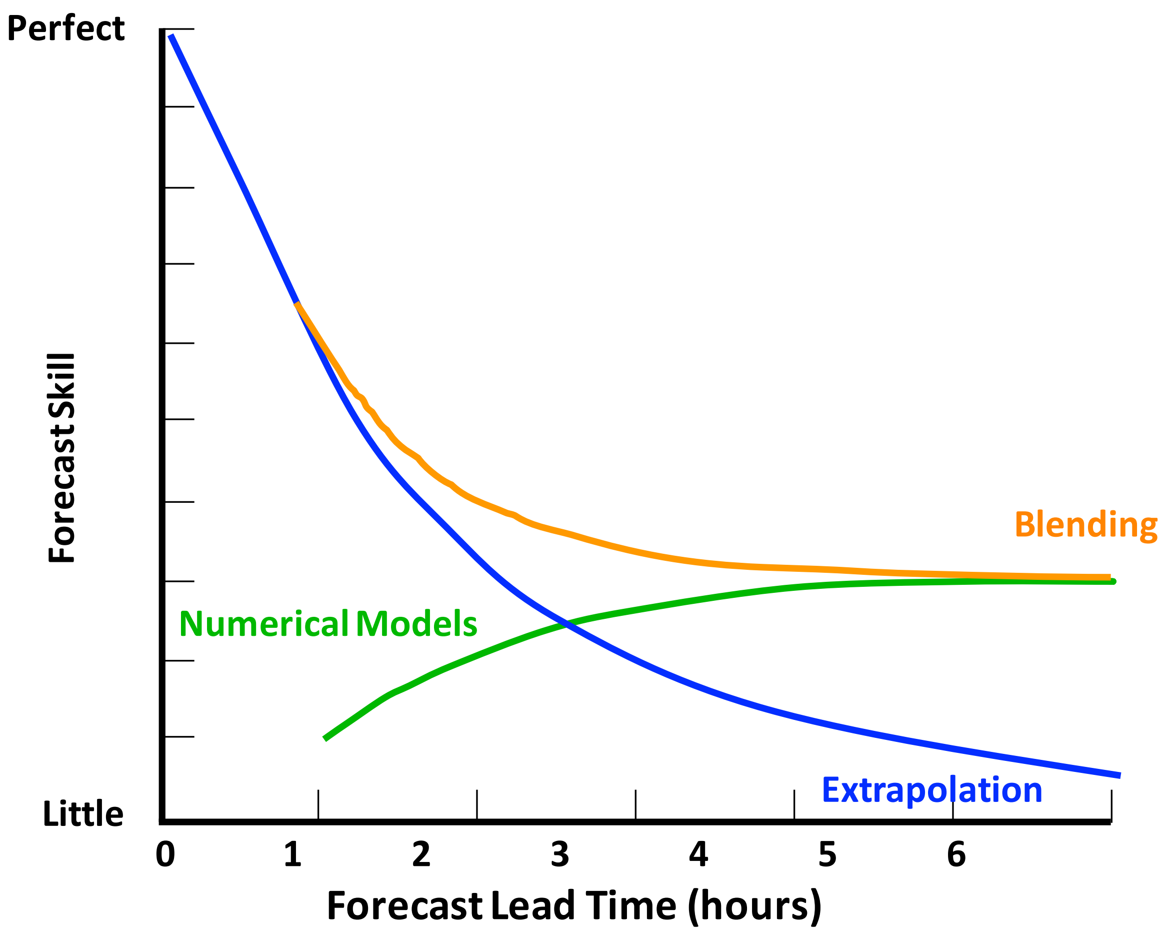


Ensemble Probability (vis<1km)



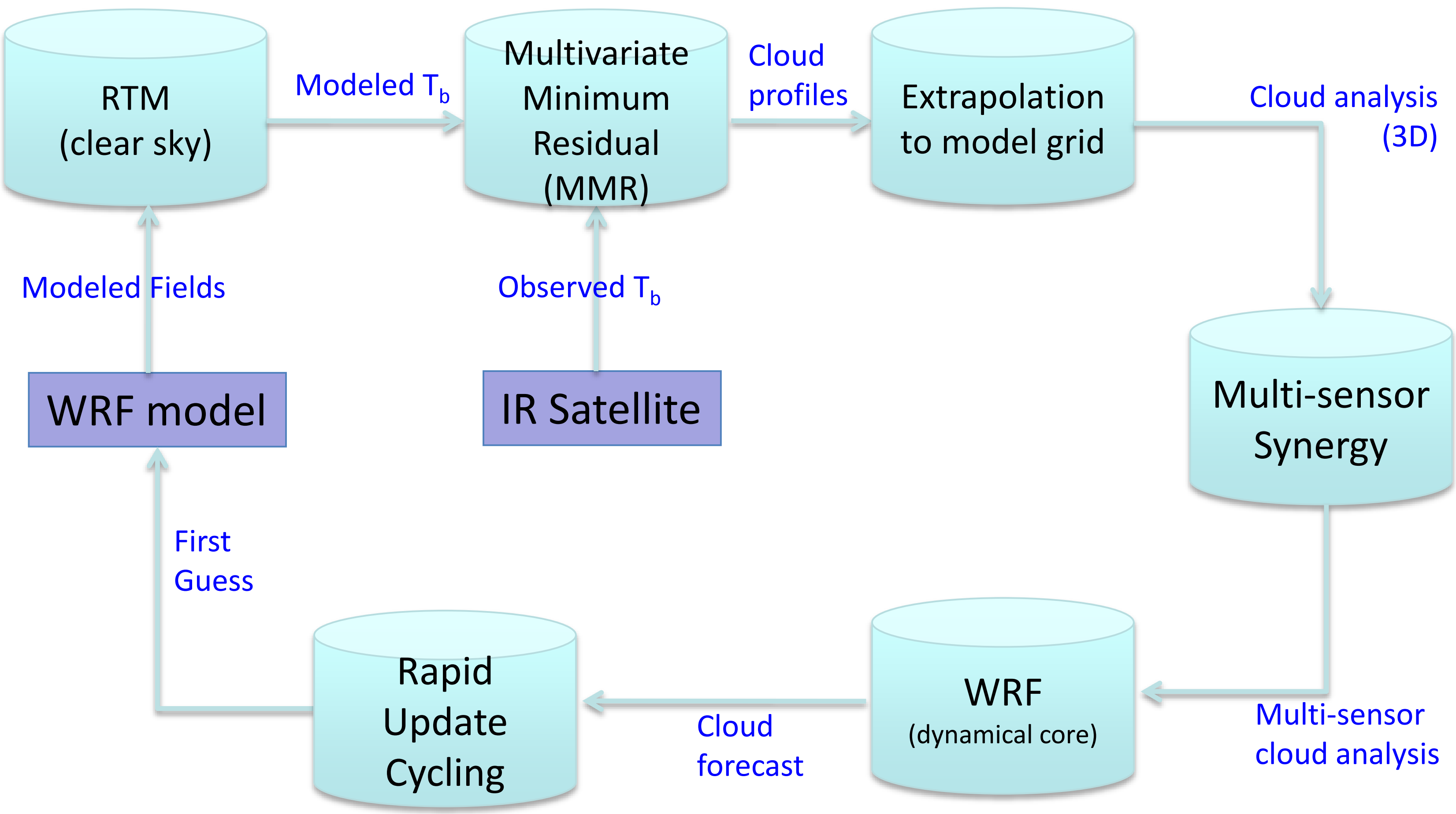
Source: Dale Barker (Met Office)

Convective Scale Initialization: Two Approaches

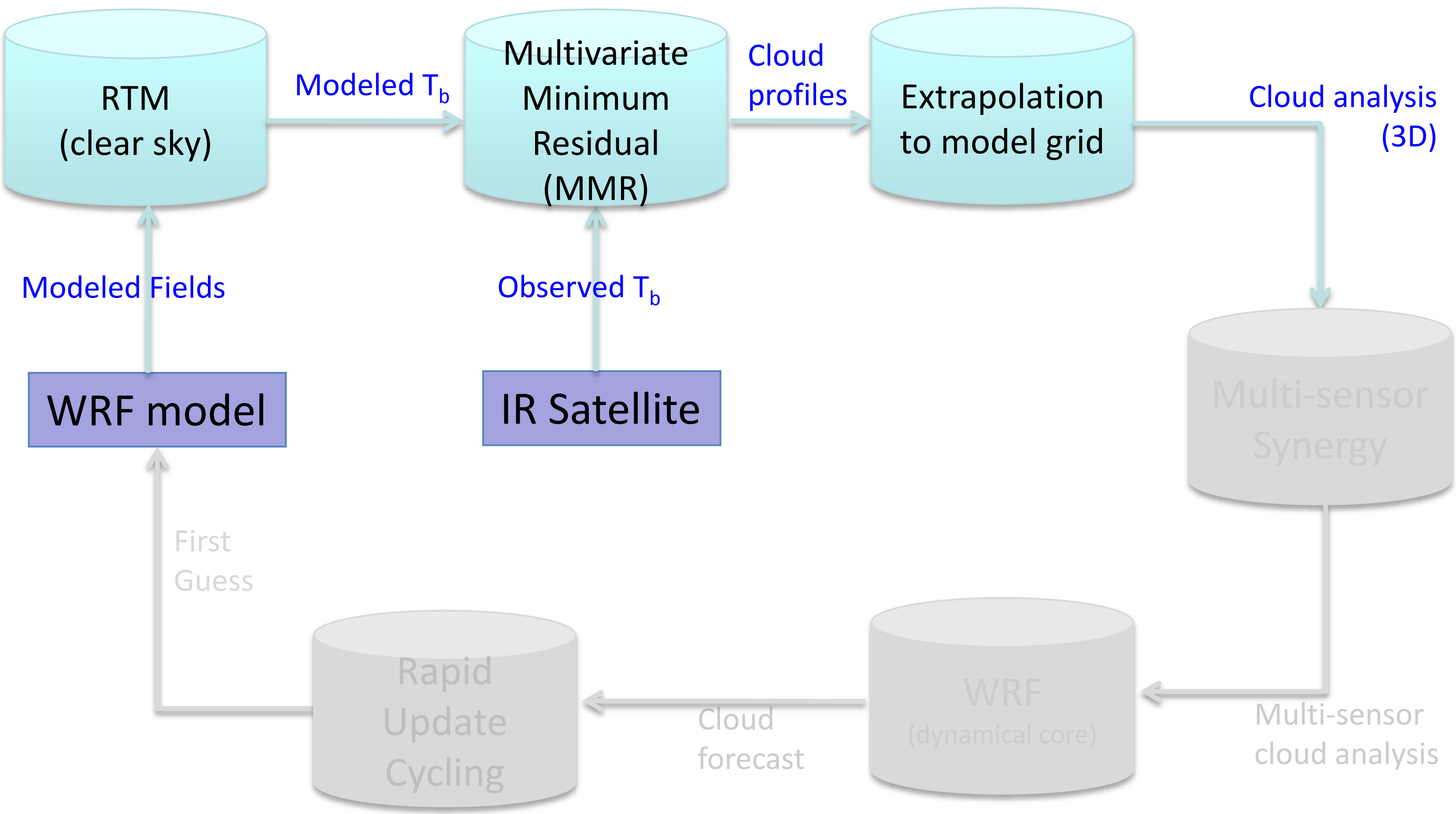


Source: Sai Ravela (MIT)

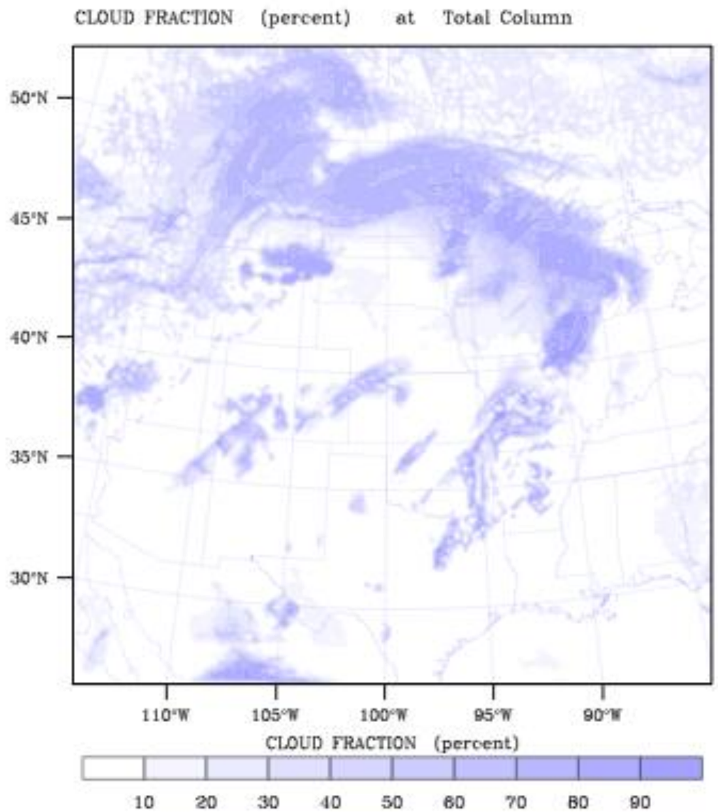
MADCast: Multi-sensor Advection Diffusion nowCast

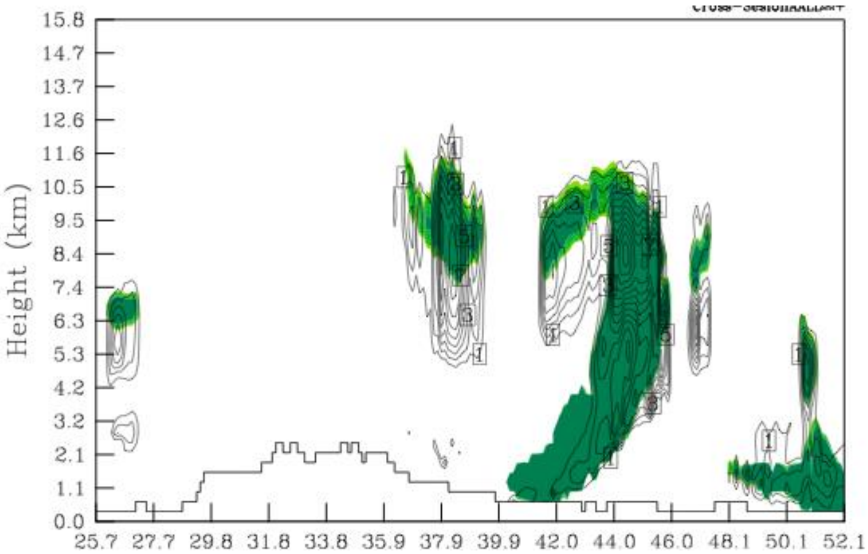


MADCast: Multi-sensor Advection Diffusion nowCast

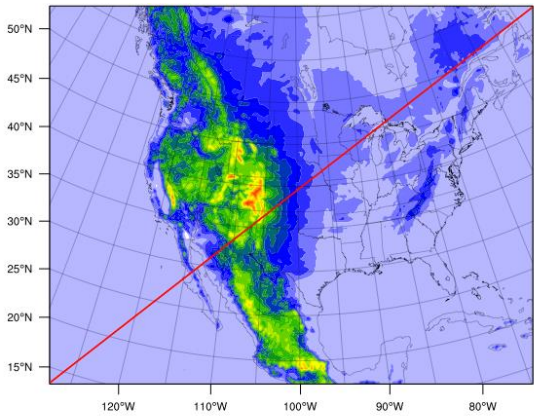


MADCast: Simulated Observation Experiment

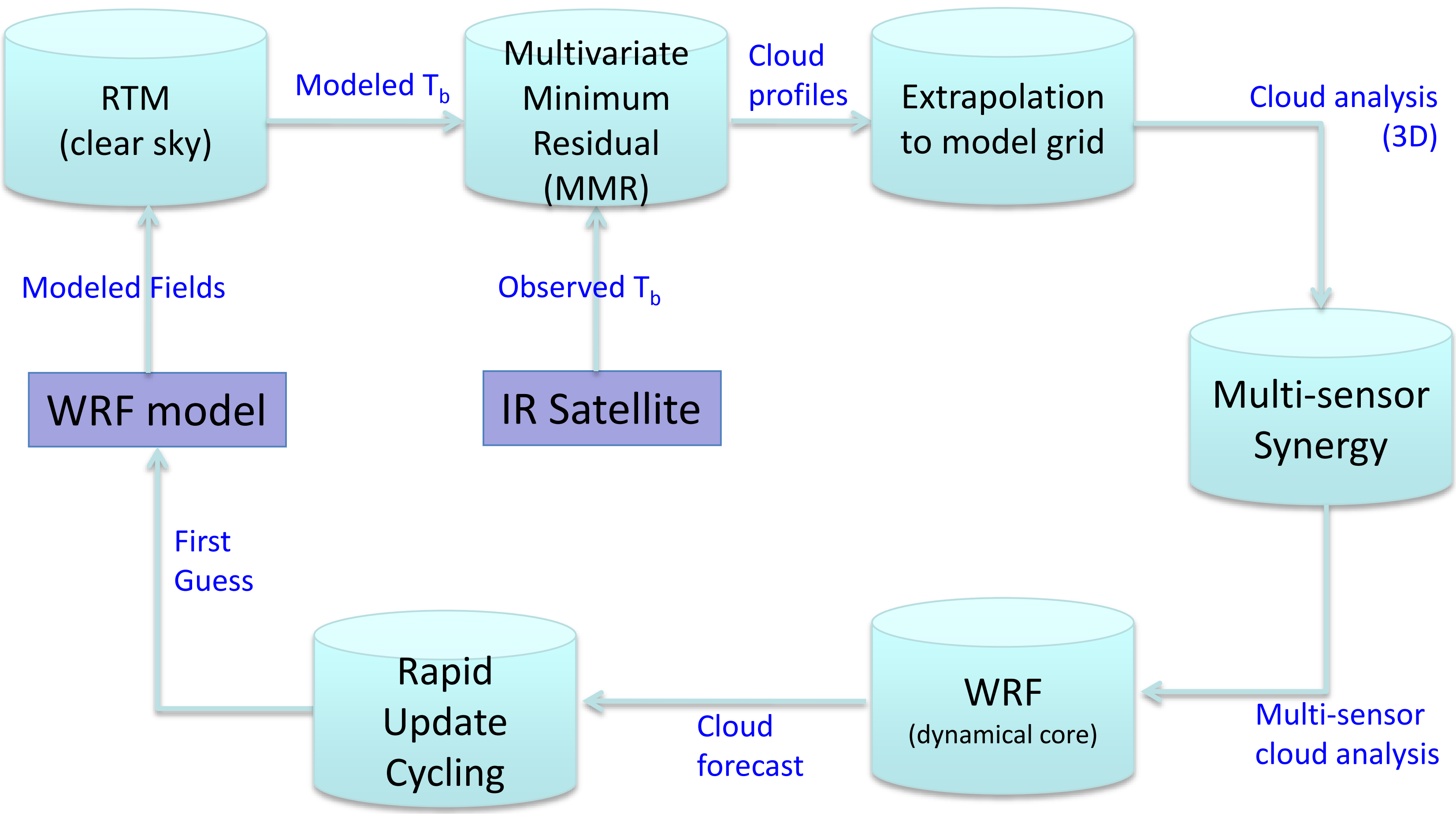




Vertical Cross Section

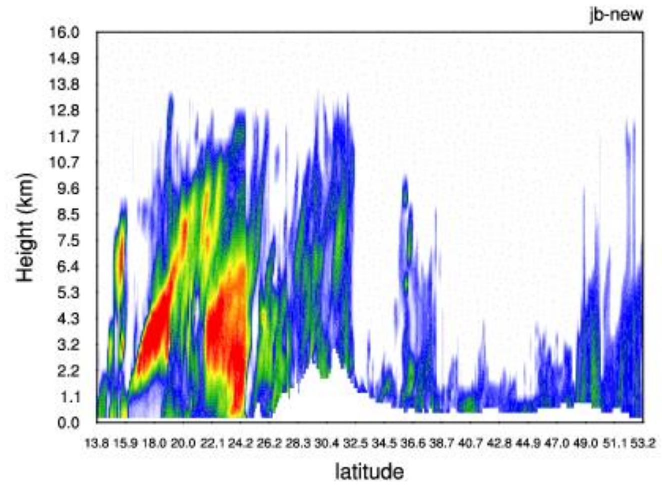


MADCast: Multi-sensor Advection Diffusion nowCast

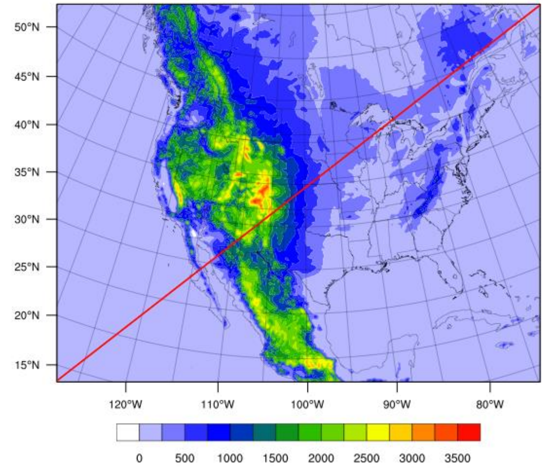


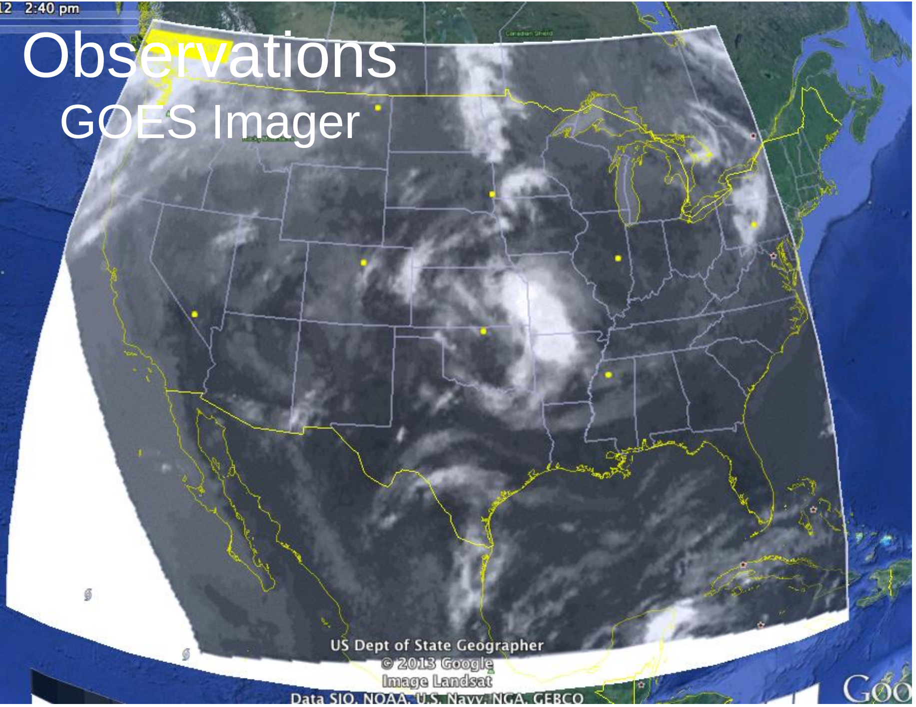
MADCast: Real Observation Experiment

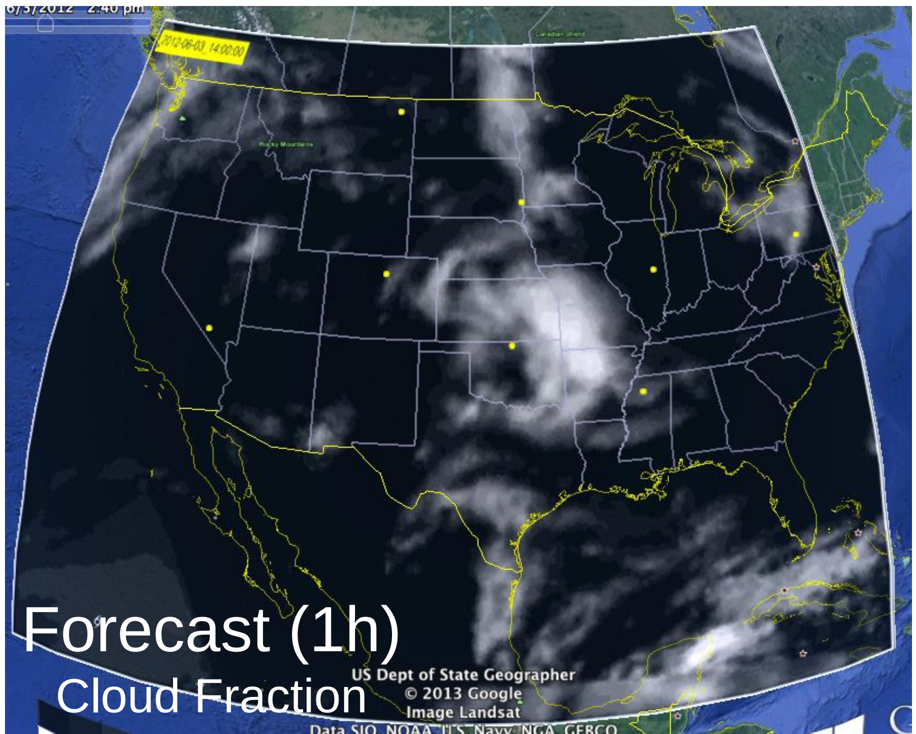
Multi-sensor **synergistic** analysis of cloud fraction (GOES, AIRS, IASI, CrIS, MODIS)

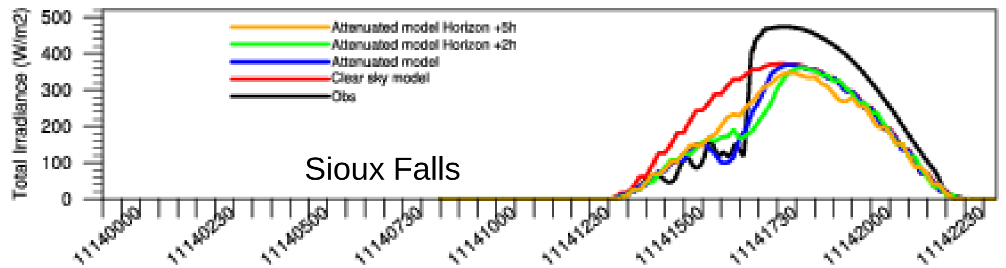


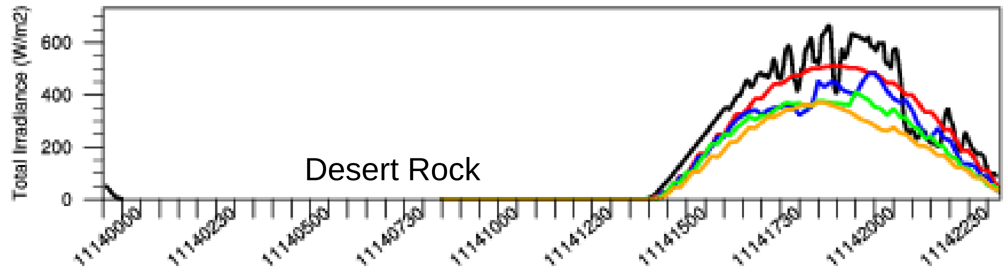
Vertical Cross Section

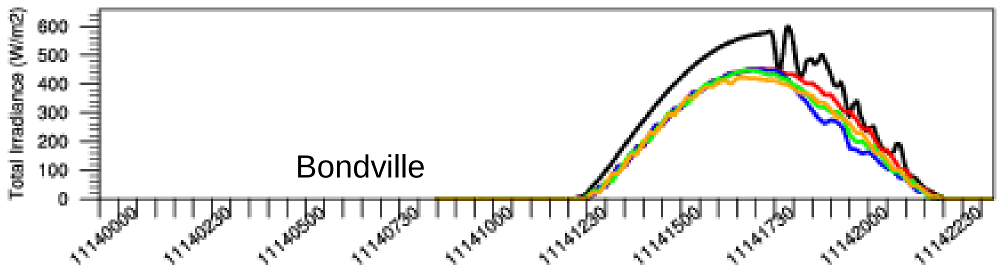


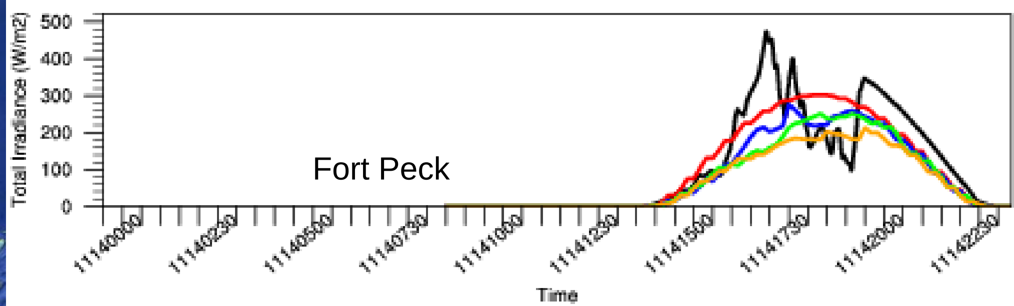

Observations
GOES Imager
US Dept of State Geographer
© 2013 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO


Forecast (1h)
Cloud Fraction
US Dept of State Geographer
© 2013 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

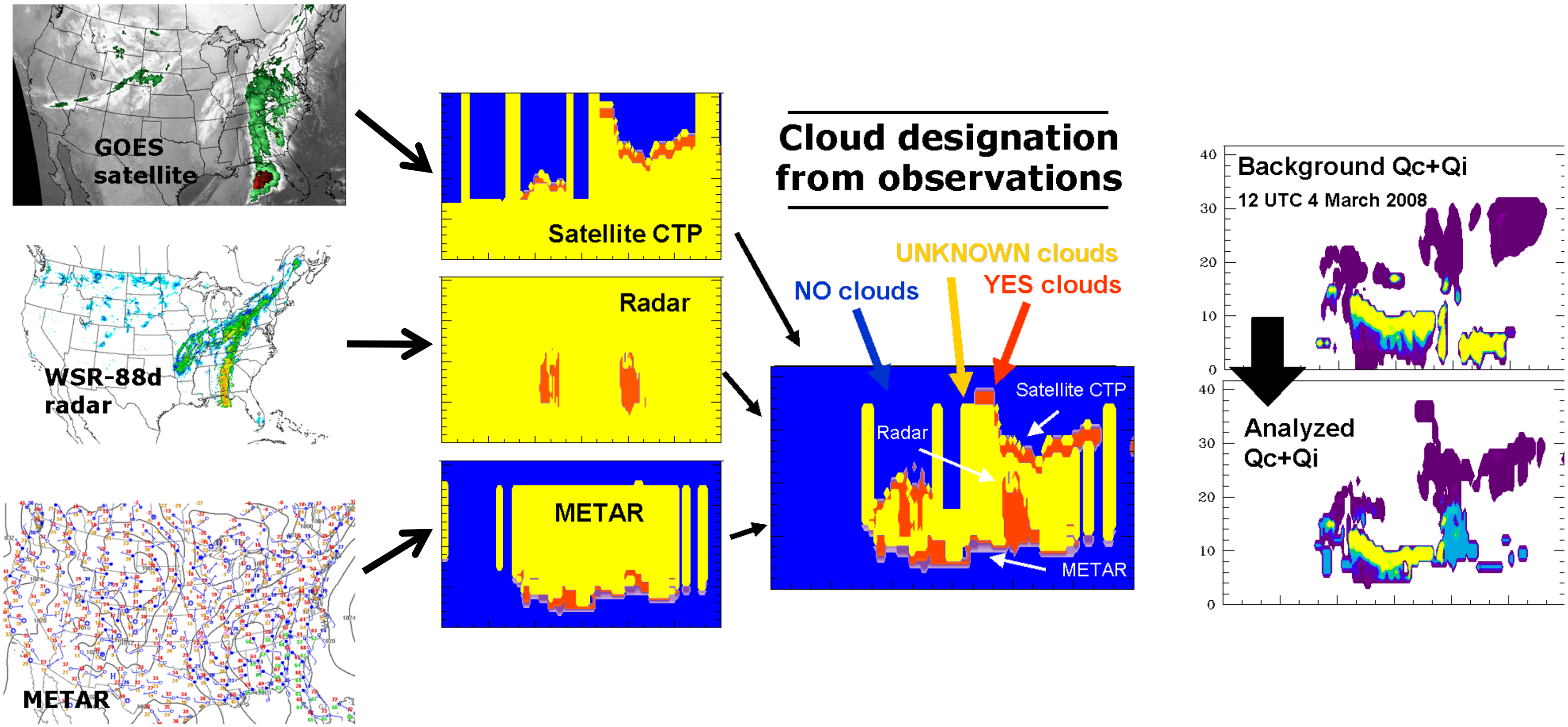

Attenuated model Horizon +5h
Attenuated model Horizon +2h
Attenuated model
Clear sky model
Obs
Sioux Falls
Total Irradiance (W/m2)
0
100
200
300
400
500
11140000
11140230
11140500
11140730
11141000
11141230
11141500
11141730
11142000
11142230


Desert Rock
Total Irradiance (W/m2)
0
200
400
600


Bondville
Total Irradiance (W/m2)
0
100
200
300
400
500
600


Fort Peck
Total Irradiance (W/m2)
0
100
200
300
400
500
Time

Rapid Refresh: Cloud Analysis Schematic



observation

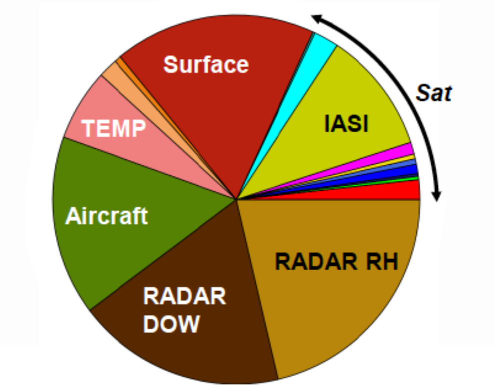
- Uses METAR, satellite, radar, lightning data
- Updates RR 1h-fcst RR hydrometeor, water vapor fields
- Generates latent heating from radar and lightning data

Source: Ming Hu (NOAA)

Convective Scale DA: Satellite Observations

- **Real Observations**
  - **IASI:** Guidard et al. (QJRMS 2011). *AROME*.
  - **TRMM Microwave Imager (TMI):**
    Aonashi and Eito (JMSJapan, 2011). Displaced MLEF. *JMANHM*.
  - **MSG SEVIRI:** Stengel et al. (QJRMS 2010). 4DVar *HIRLAM*. Schomburg and Schraff (QJRMS 2013). LETKF *COSMO* (retrieved cloud top).
    Barker (WSDA 2014). AMSU-B/MHS. *3DVar UKV*

- **OSSEs**
  - **GOES-R:** Otkin (JGR 2010),
    Jones et al. (MWR, 2014). EnKF *DART*.
  - **MTG IRS:** Guedj (EUMETSAT). Correlated obs error.
  - **GPM:** Chambon et al. (QJRMS 2013). *MLEF*.
  - **GLM:** Stefanescu et al. 1DVar+3DVar assimilation of total lightning. *WRFDA*.



Active obs in AROME for one rainy day

Source: T. Montmerle (Météo-France)

All-Sky Radiances: Challenges

Method

State augmentation to include model cloud microphysics variables in the analysis (q_c, q_i, …)

Goals

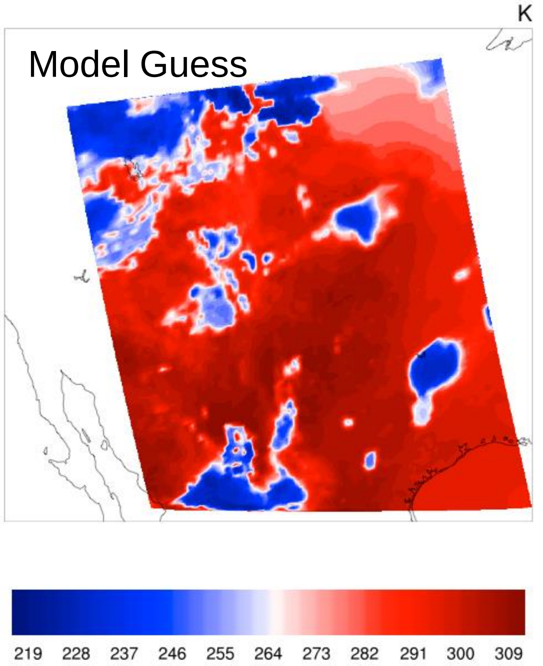
- Fit observations at initial time
- Sustain cloud increments in forecast

All-sky radiances

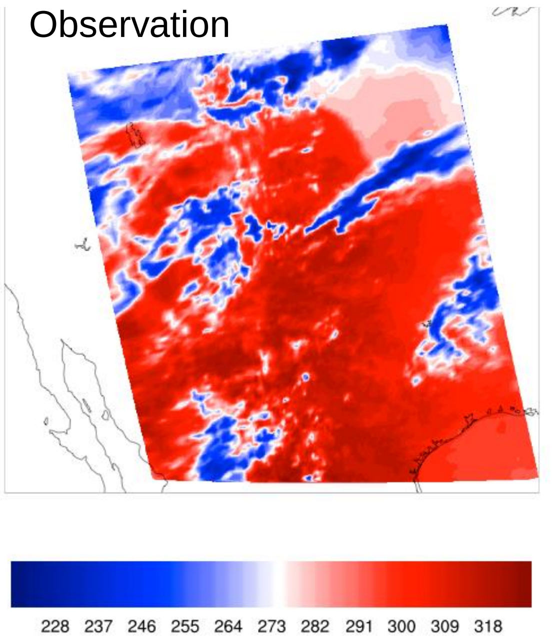
- Assimilate cloud-and-precip-affected radiances
- Accuracy and efficiency of radiative transfer
- Non-linear observation operators
- Jacobian calculation: modified base state

Satellite radiances sensitive to land surface

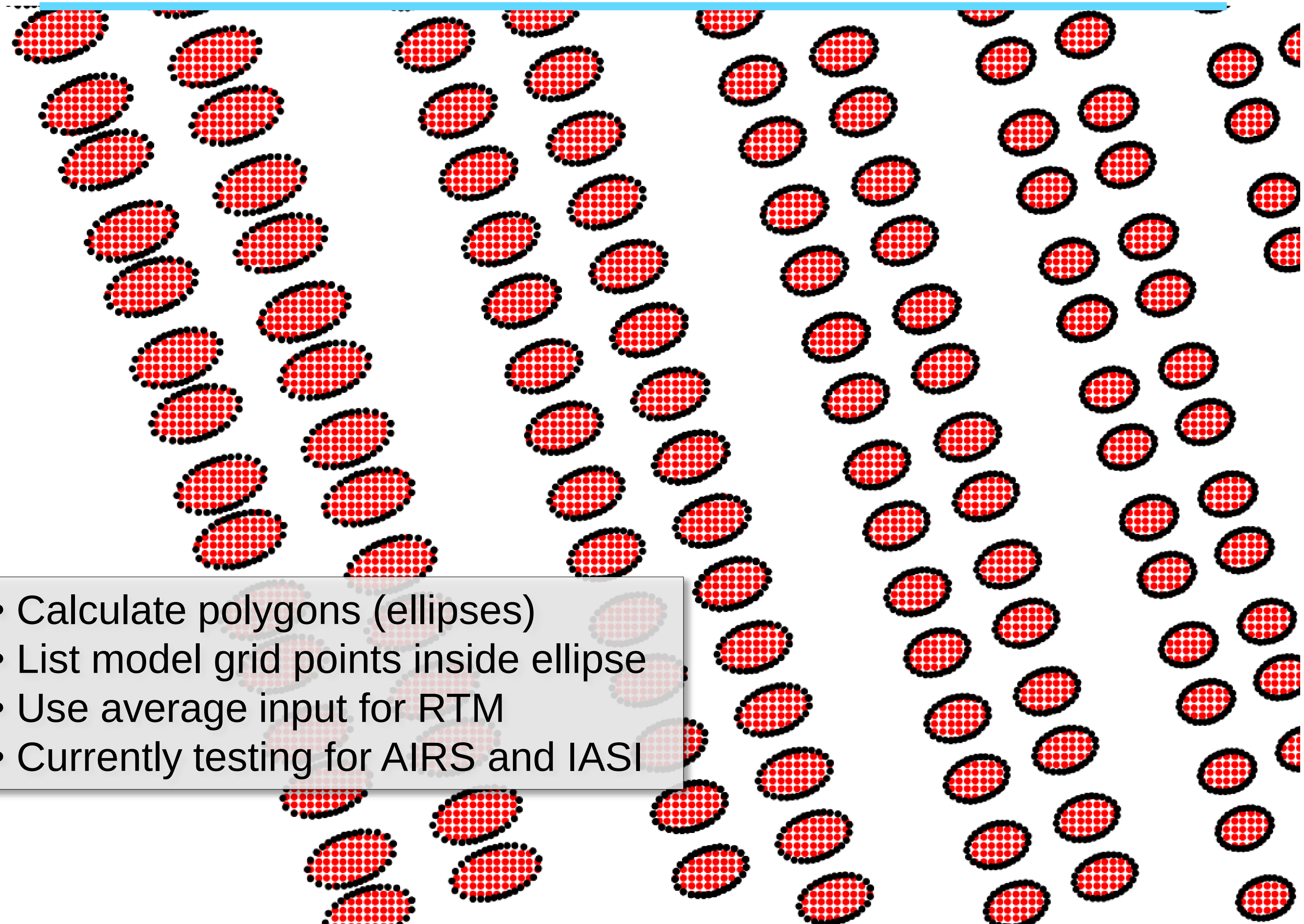
- Forecast needed near populated areas
- Improved modeling of T_{skin} and emissivity over land, snow, sea-ice
- T_{skin} introduced as a sink variable



AIRS Channel #787

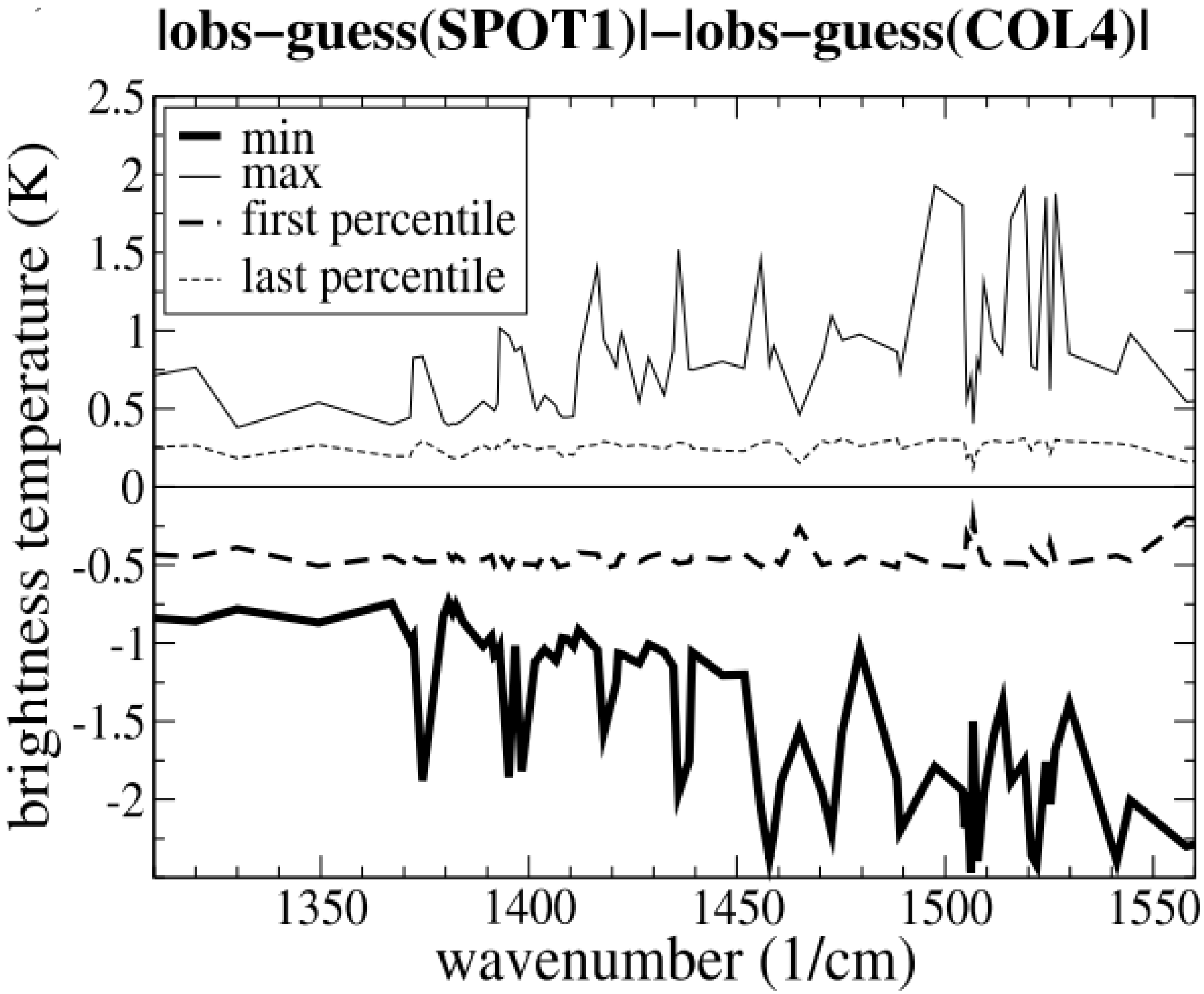


Satellite Field of View (FoV): Interpolation



- Calculate polygons (ellipses)
- List model grid points inside ellipse
- Use average input for RTM
- Currently testing for AIRS and IASI

Satellite Field of View (FoV): Interpolation



Duffourg et al. (2010)

All-sky Radiances: Observation Error Covariances

Huber Norm: estimated via Iterated Reweighted Least Square (IRLS)
= reweighting of observations according to OmF at each outer-loop

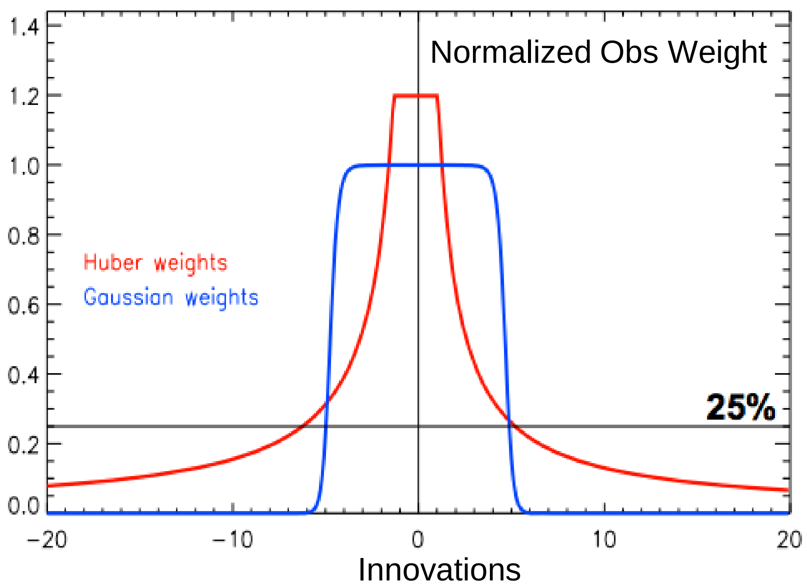
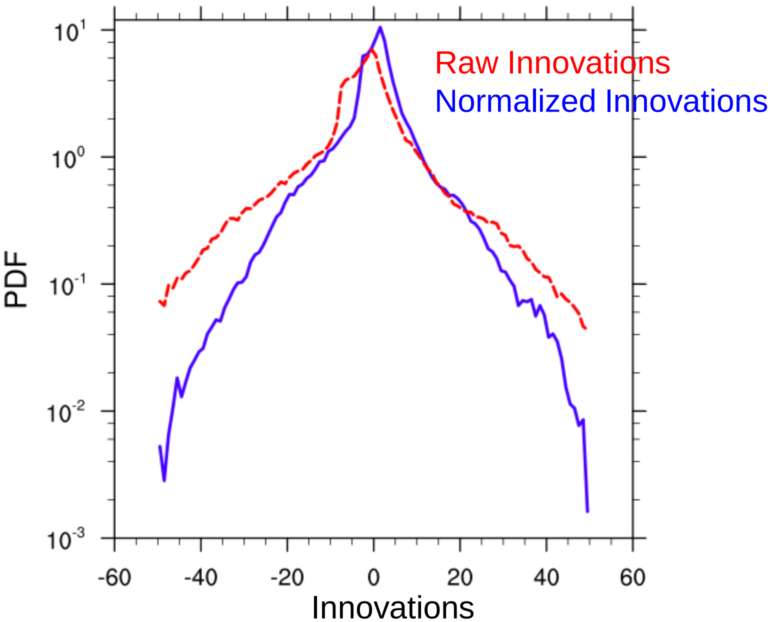
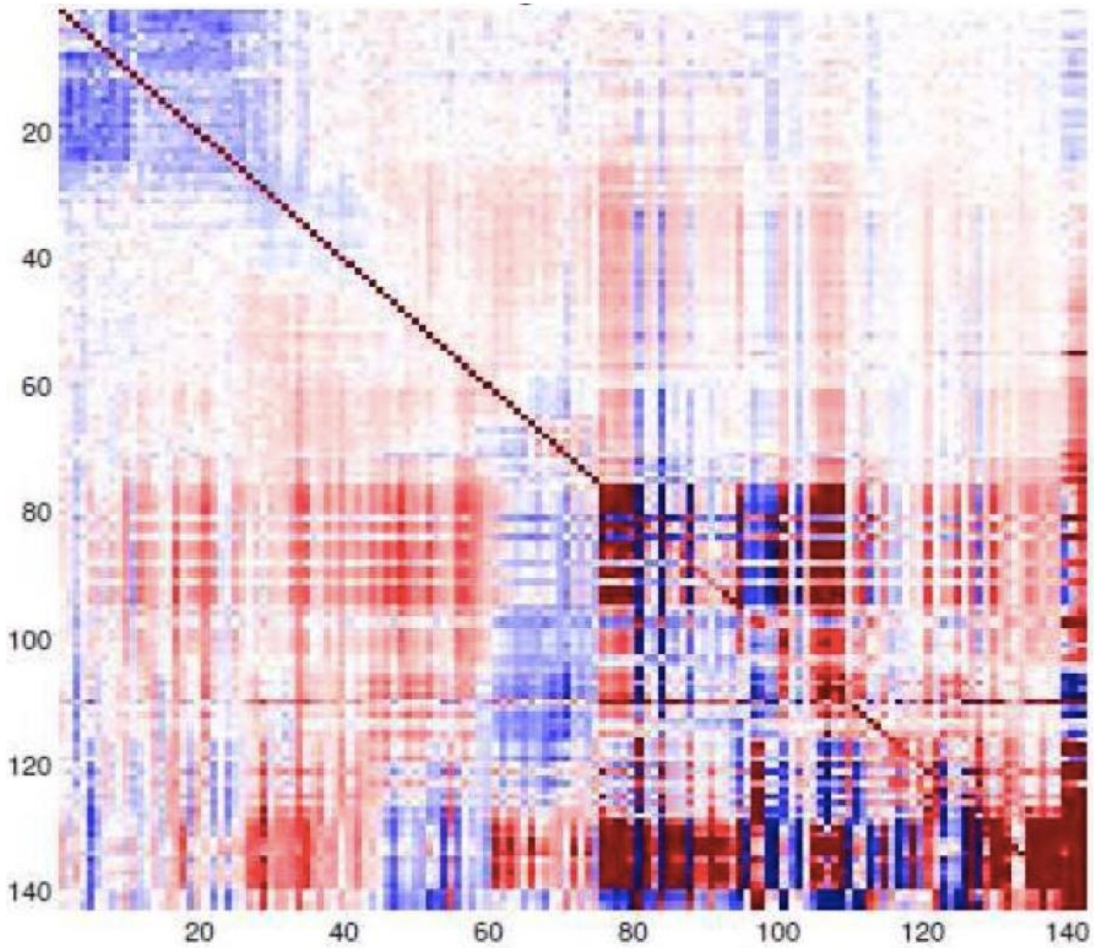


Figure from Fisher (2008)



All-sky Radiances: Observation Error Covariances

AIRS Diagnostic R Matrix

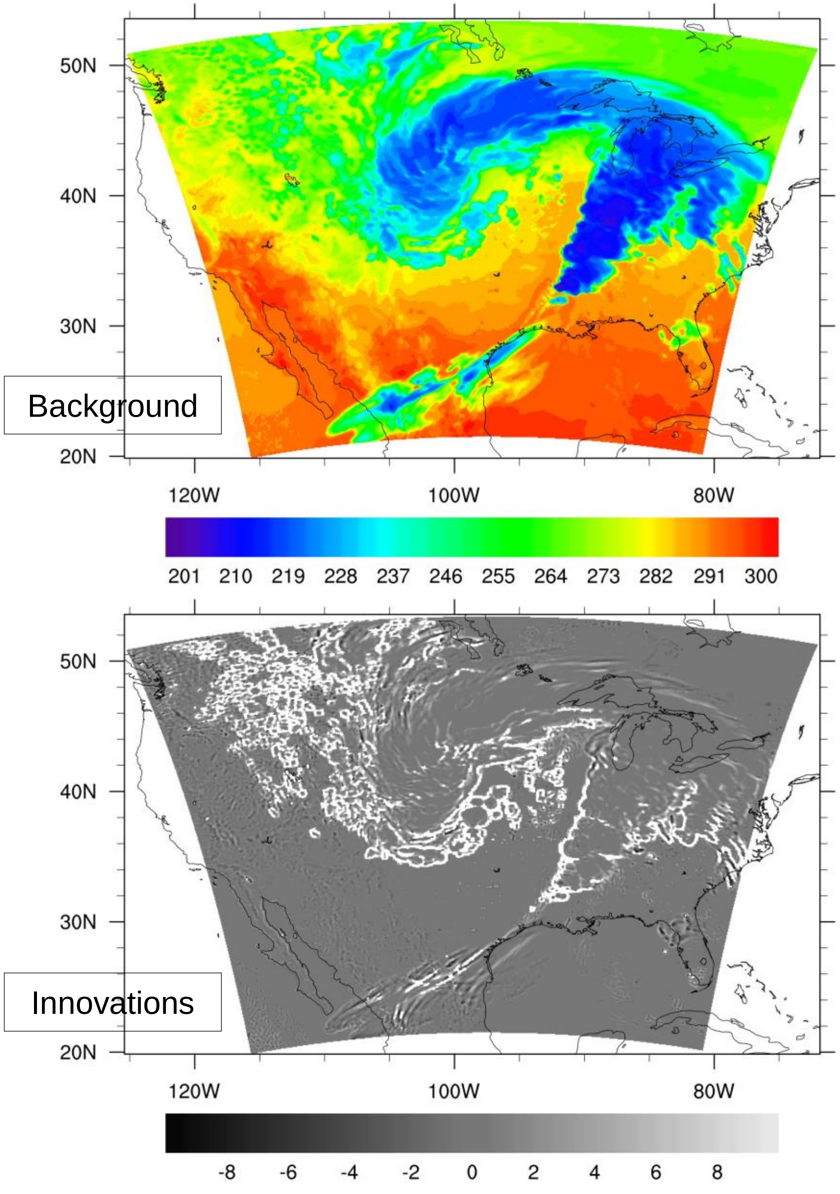


Correlated errors
(esp. for moisture channels)

At least partly due to
representativeness error
(Waller et al. 2014)

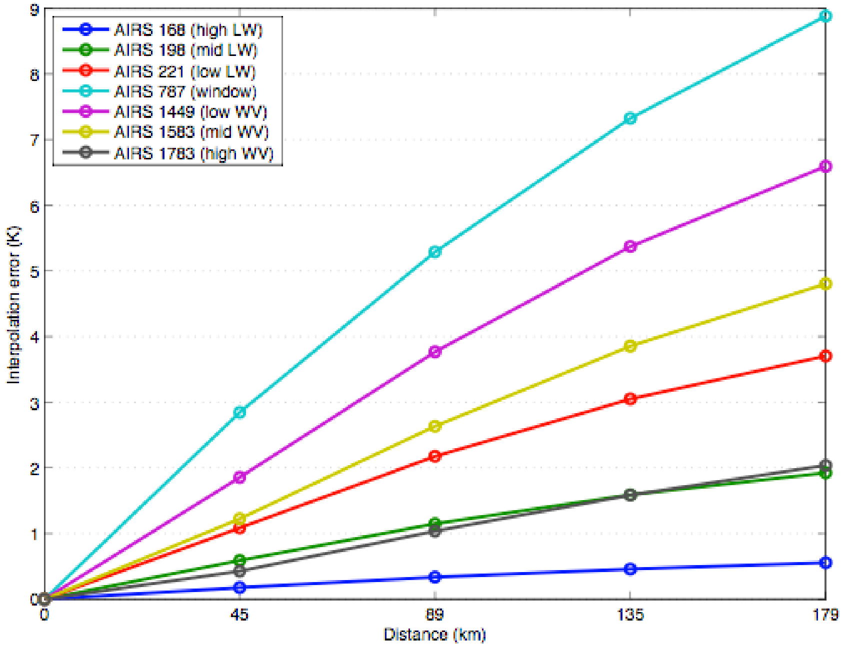
Source: Weston (2011)

Representativeness Error

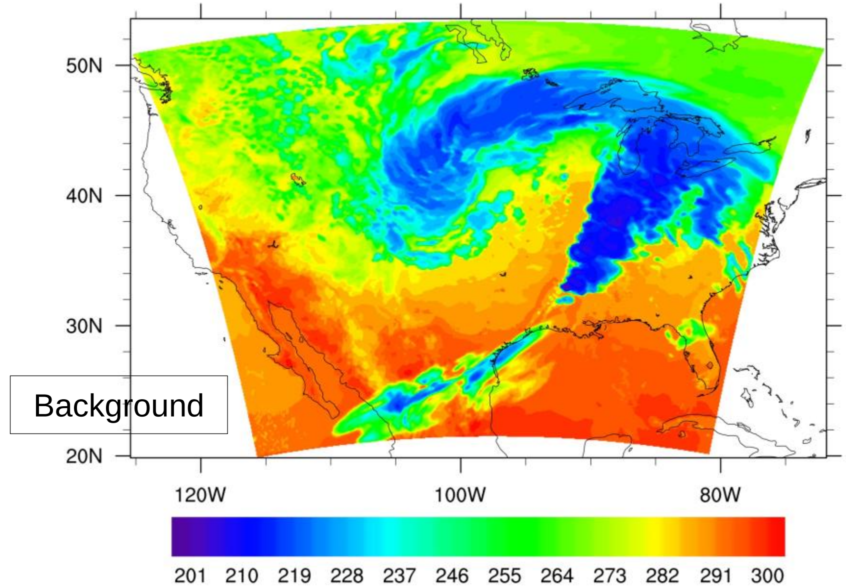


<u>Simulated mismatch in resolution:</u>
(Daley 1993, Liu and Rabier 2002, Waller et al. 2014)

- Perfect observations (high resolution)
- Perfect Background (lower resolution)

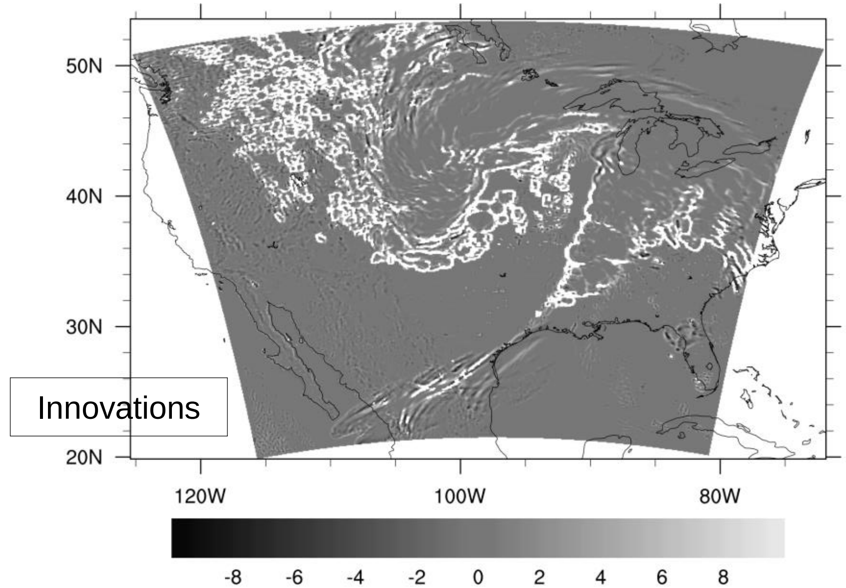


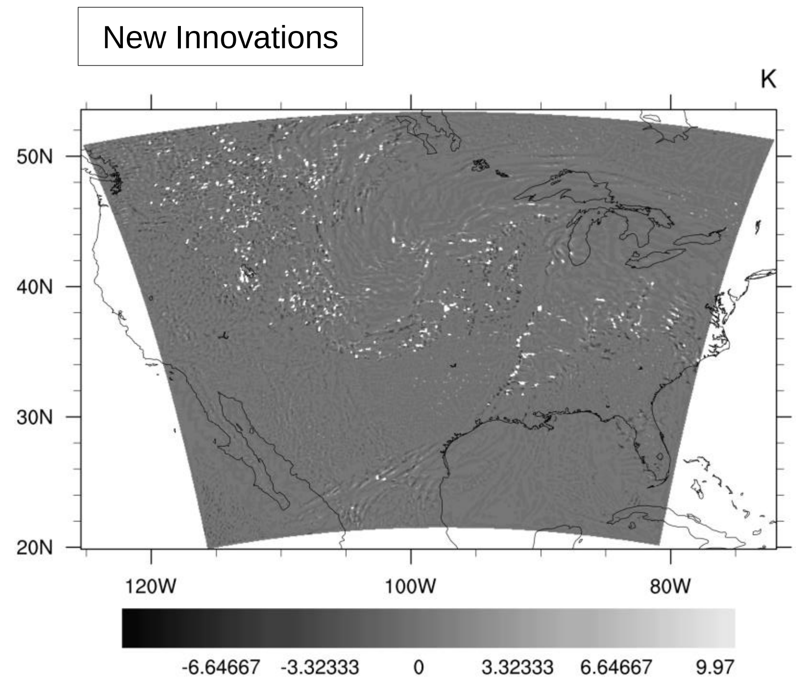
Representativeness Error



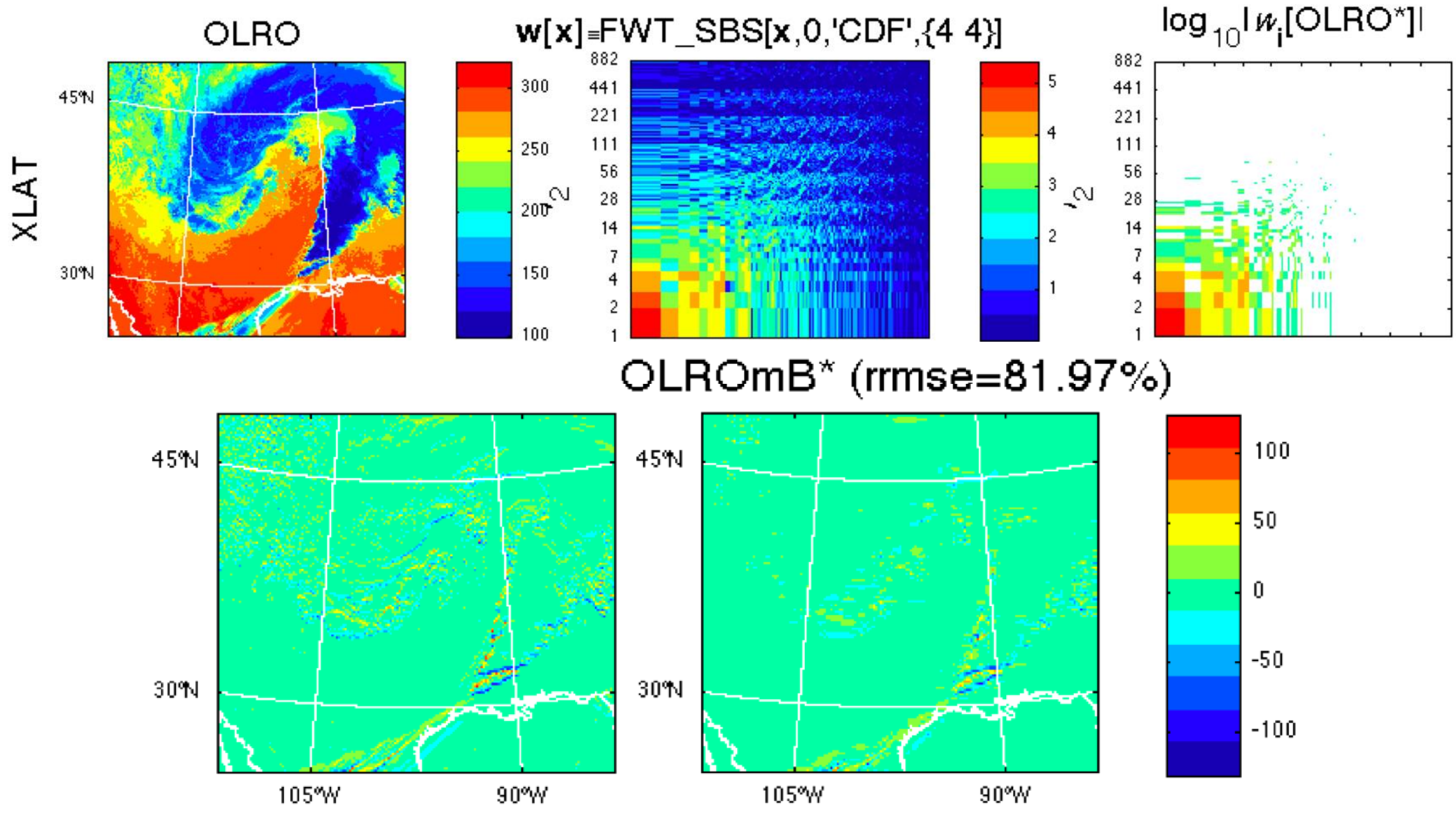
Modified interpolation scheme:

1. Automatic detection of sharp gradients
2. New “proximity” for interpolation

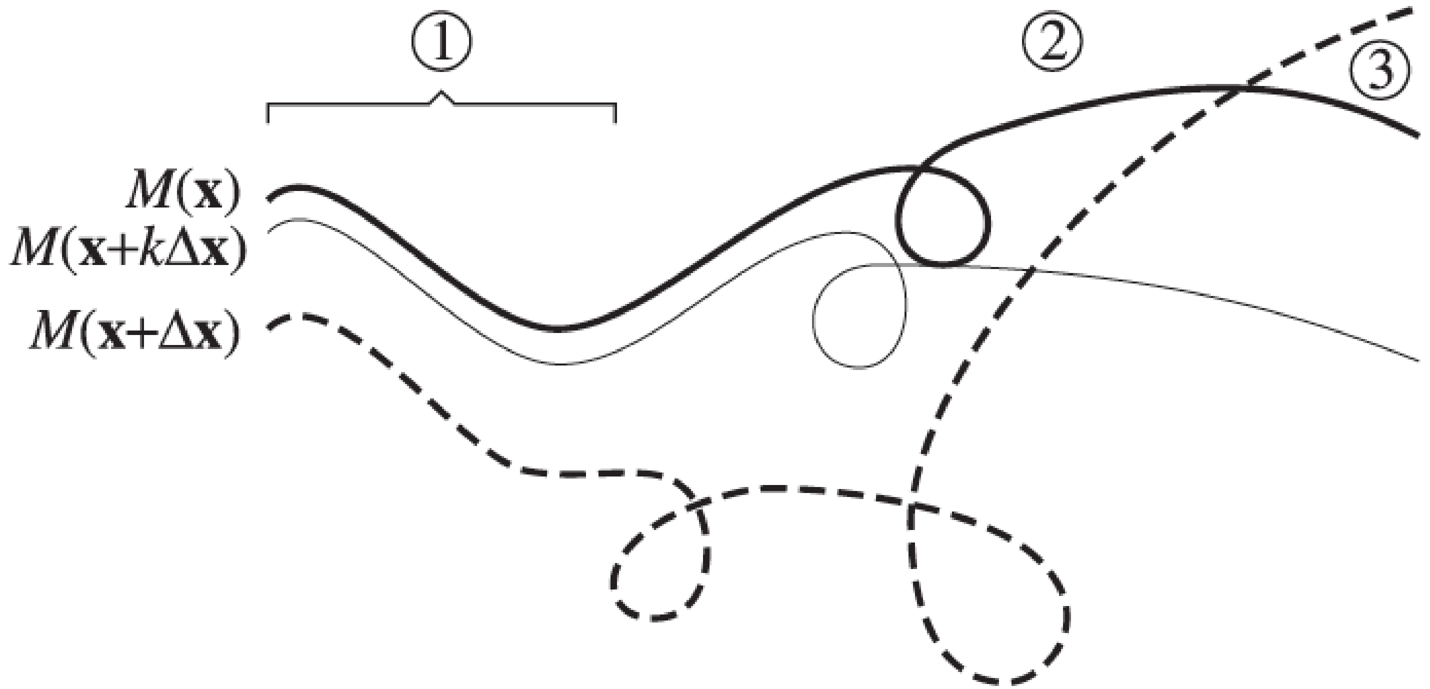




Representativeness Error: Wavelet Scale Matching



Obs. Operator: Tangent-Linear Approximation



① Linear regime: $M(\mathbf{x}+\Delta\mathbf{x}) \approx M(\mathbf{x}) + \Delta\mathbf{x}\ (\partial M/\partial\mathbf{x})$

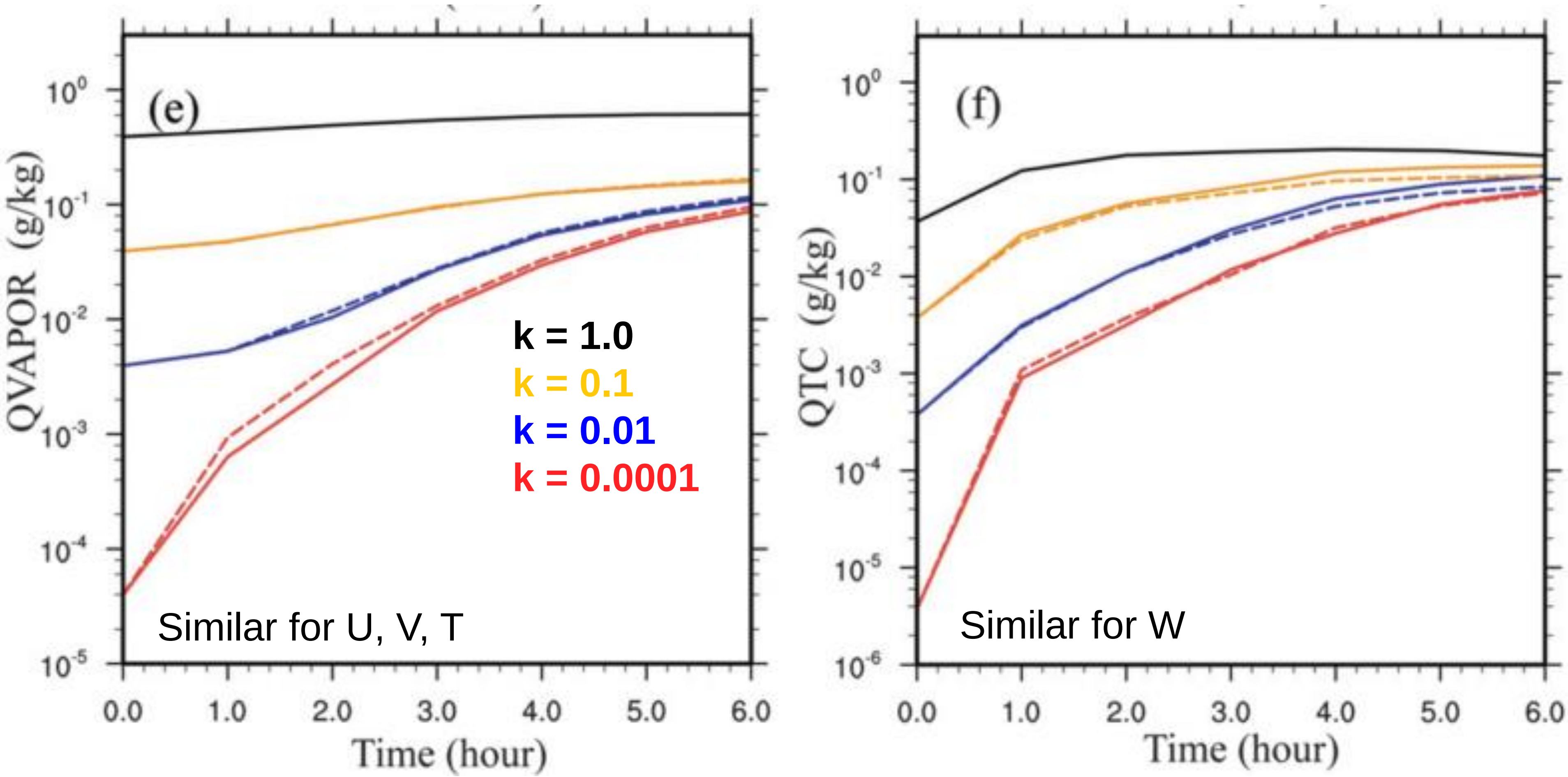
$$\rightarrow M(\mathbf{x}+k\Delta\mathbf{x}) - M(\mathbf{x}) \approx k\,[M(\mathbf{x}+\Delta\mathbf{x}) - M(\mathbf{x})]$$

② Nonlin. regime: $M(\mathbf{x}+k\Delta\mathbf{x}) - M(\mathbf{x}) \neq k\,[M(\mathbf{x}+\Delta\mathbf{x}) - M(\mathbf{x})]$

③ Contradictory region: Adjusting $\mathbf{x}$ towards $\mathbf{x}+k\Delta\mathbf{x}$ at the initial time worsens the fit with the data from $M(\mathbf{x}+\Delta\mathbf{x})$

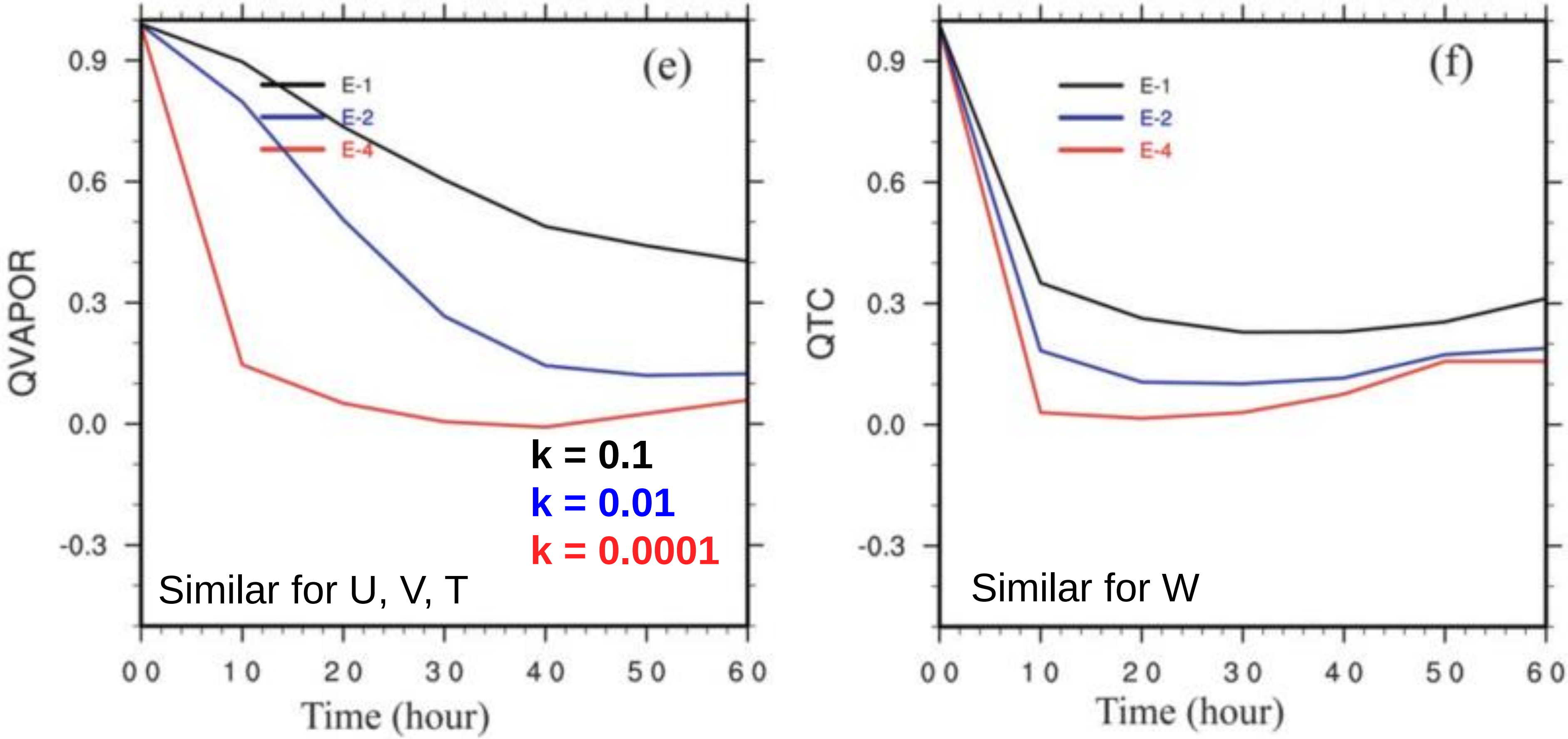
Source: Fabry and Sun (2010)

Obs. Operator: Tangent-Linear Approximation



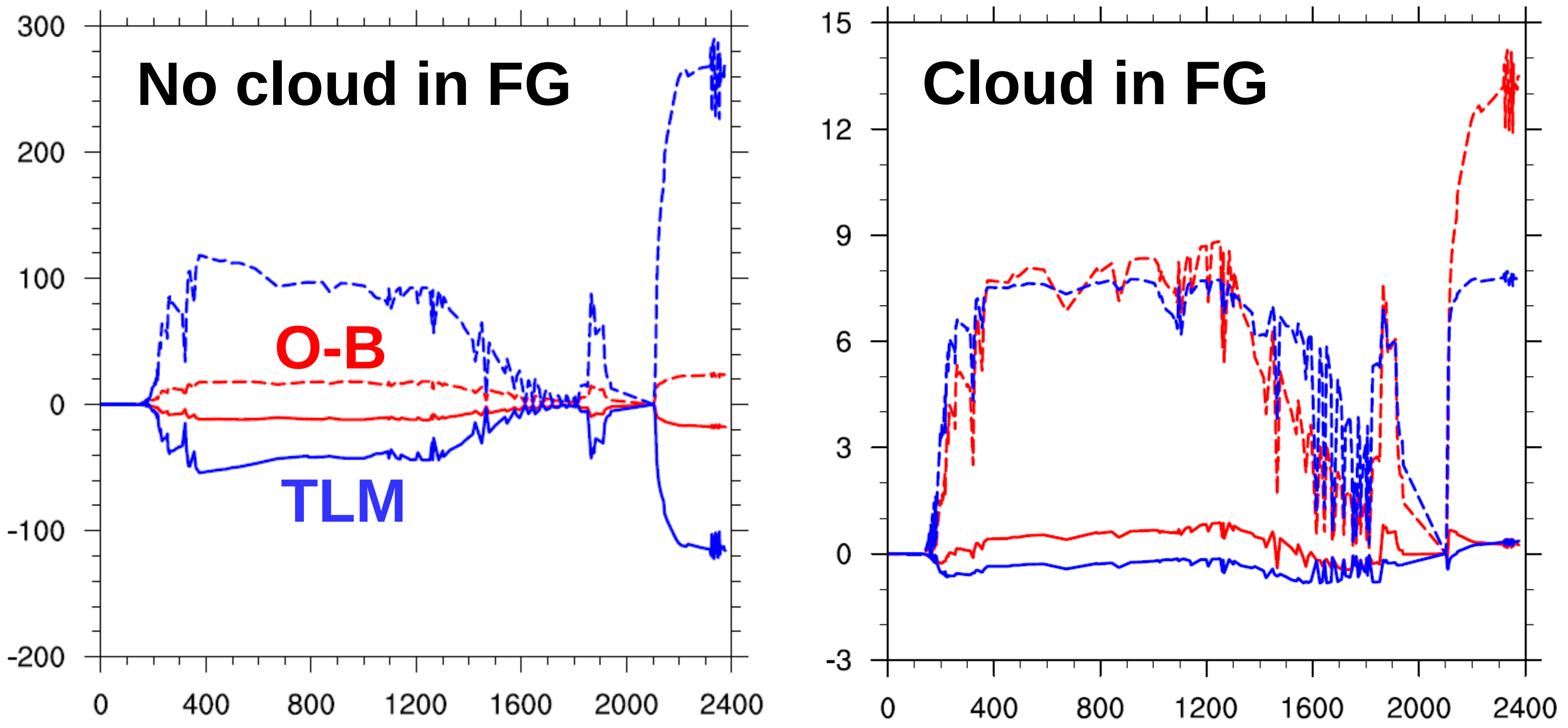
Source: Wang et al. (2012)

Obs. Operator: Tangent-Linear Approximation



Source: Wang et al. (2012)

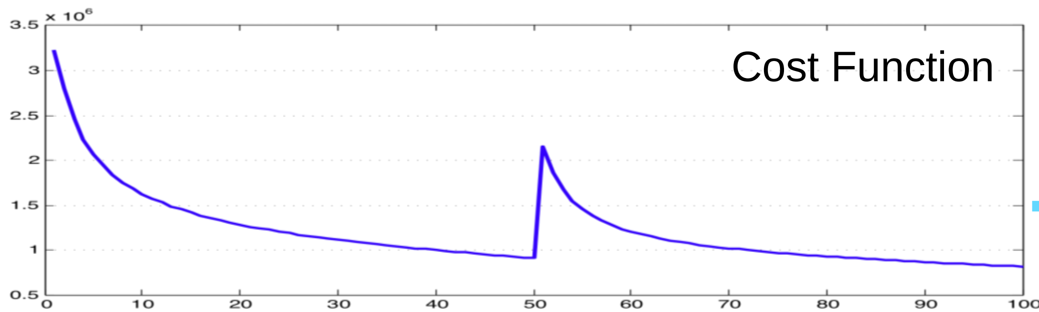
Obs. Operator: Tangent-Linear Approximation

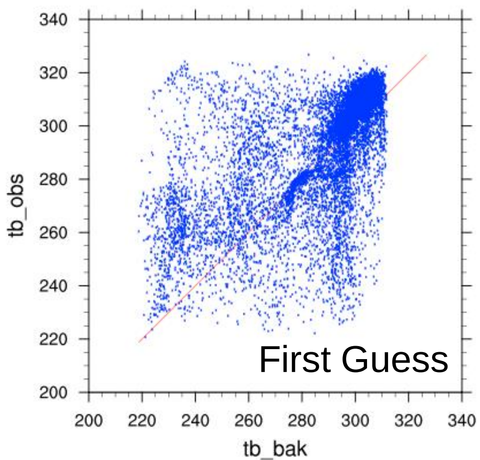


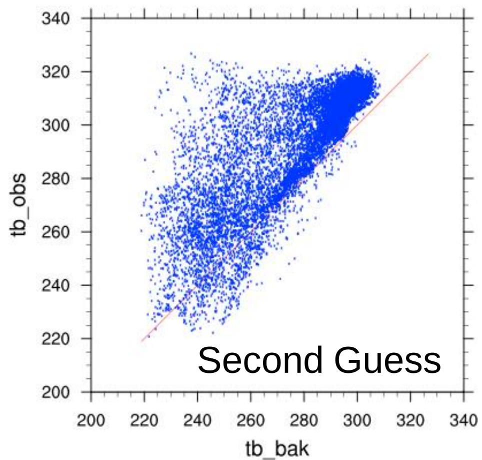
Non-linear Perturbation: $H(x_t) – H(x_b)$

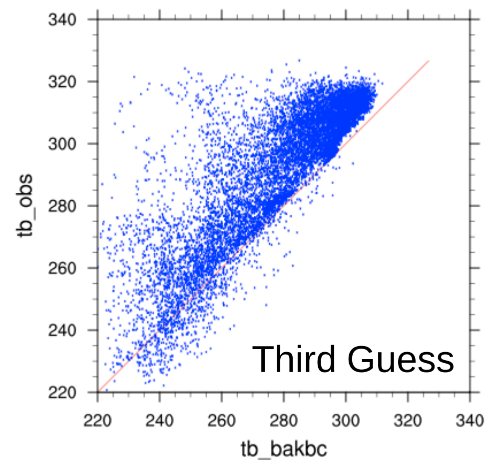
Tangent-linear Perturbation: $\hat{H}(x_t\text{-}x_b)$

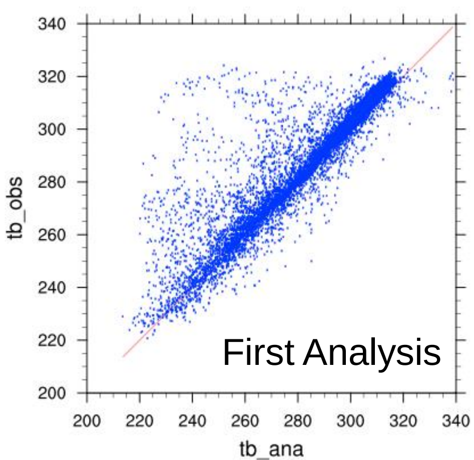
Middle Loop

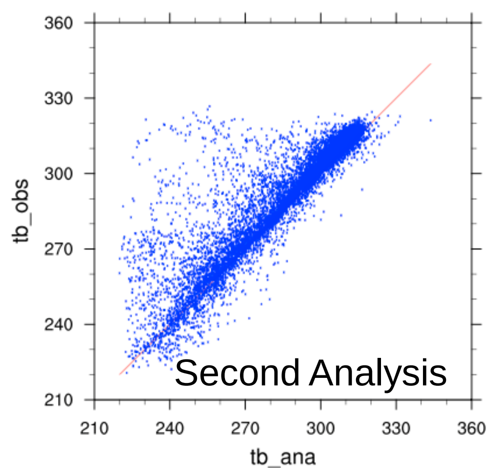


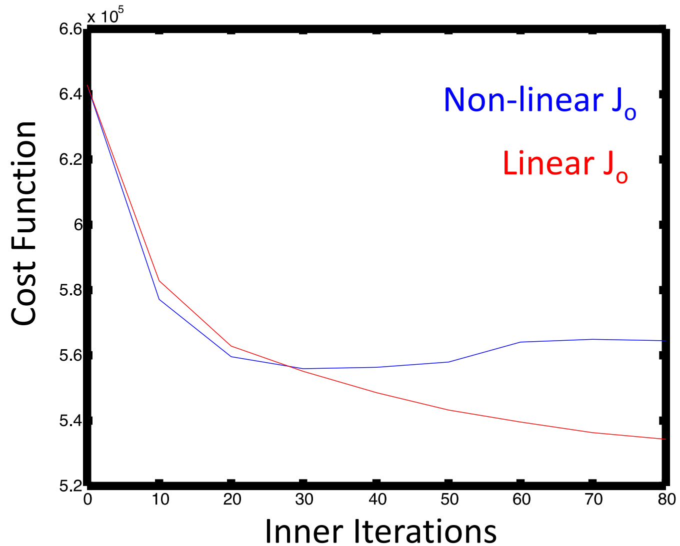






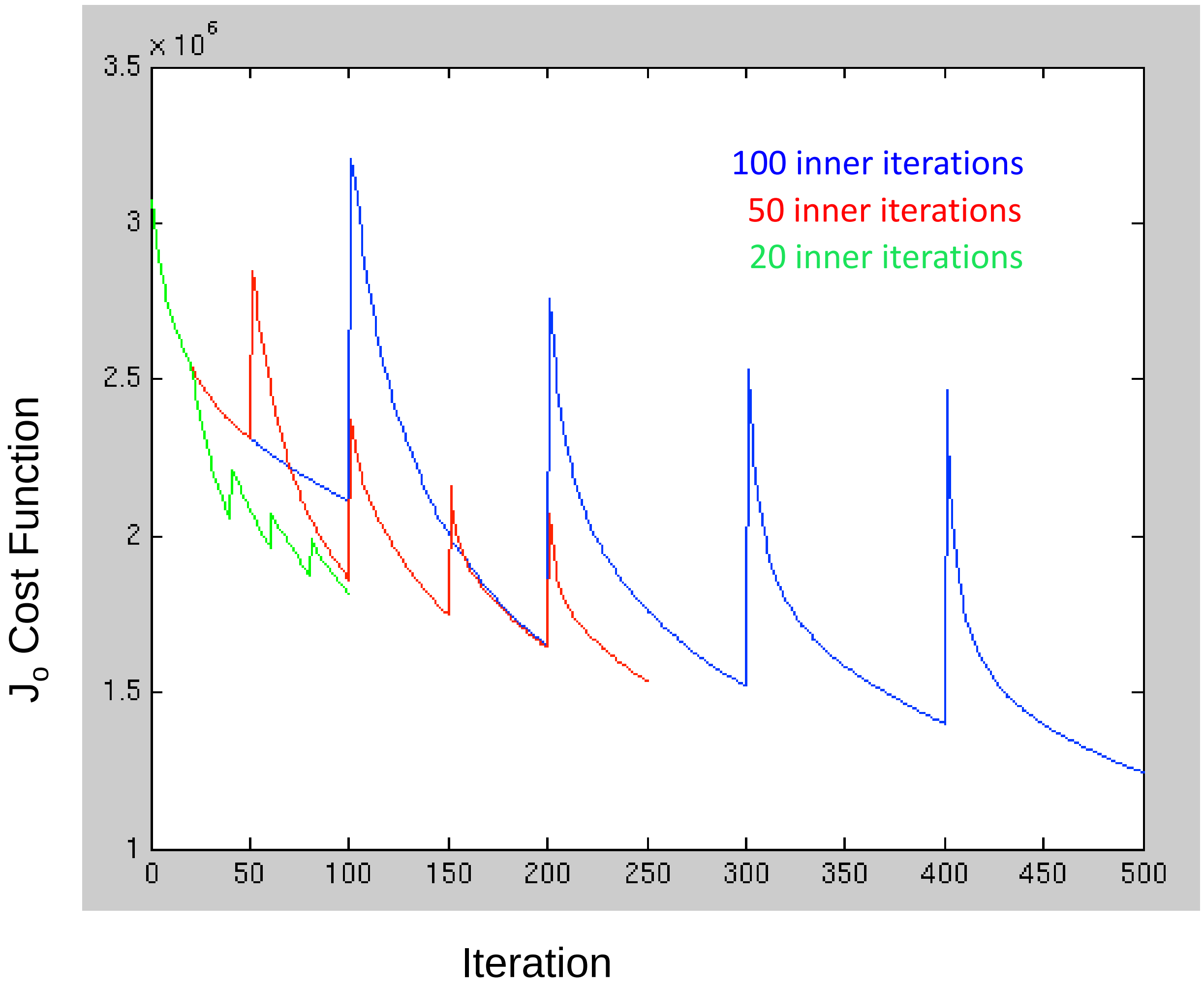


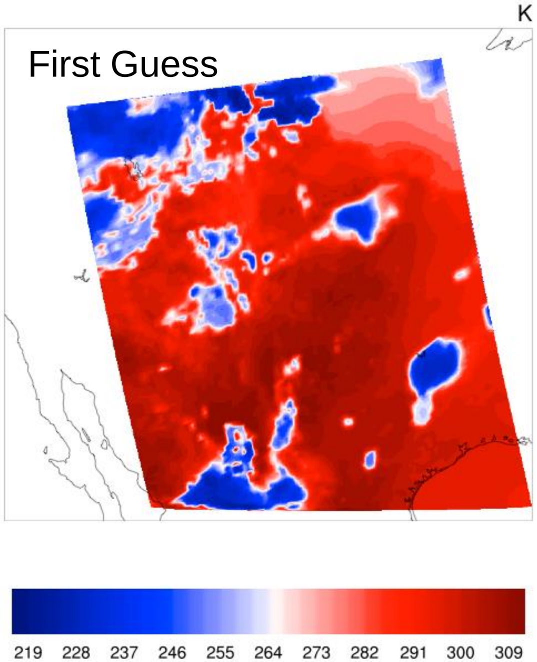


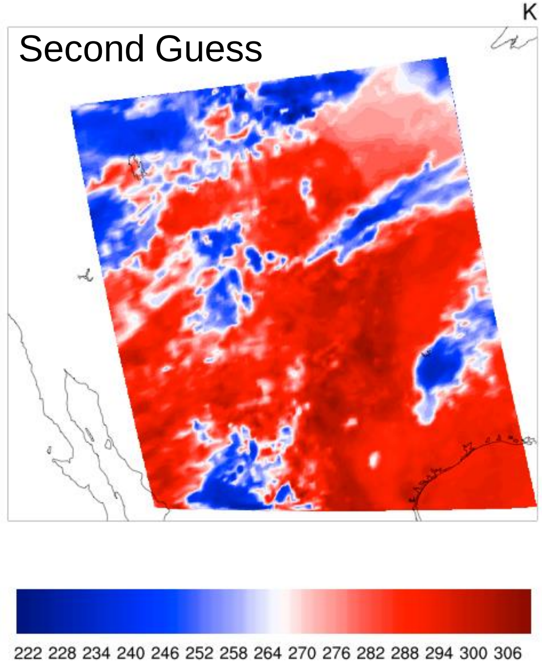


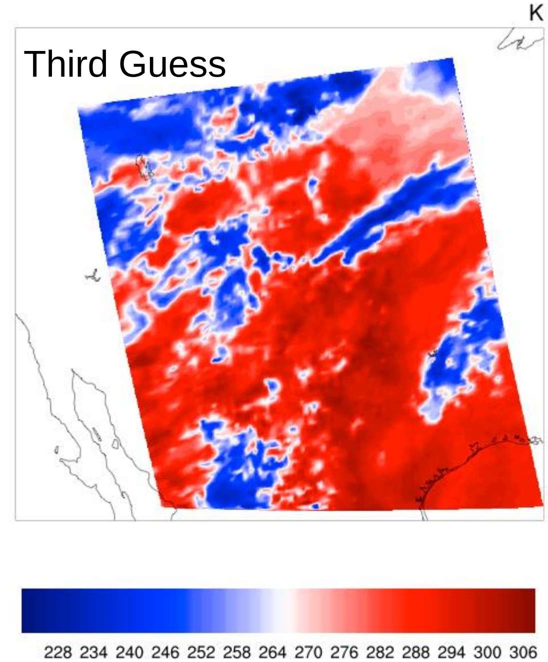
AIRS Window Channel #787

Middle Loop: Fit to Observations

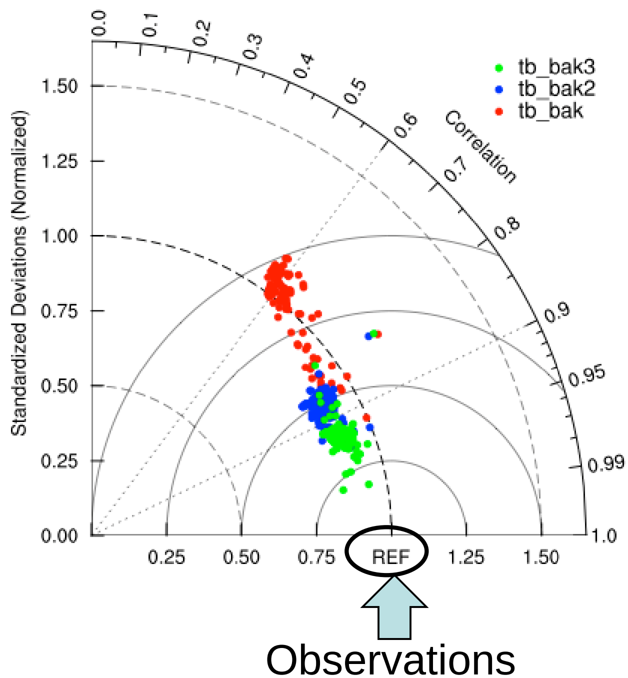


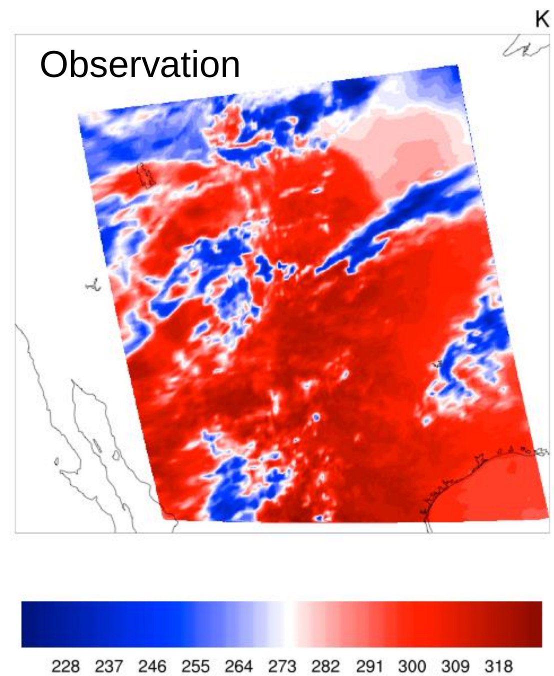






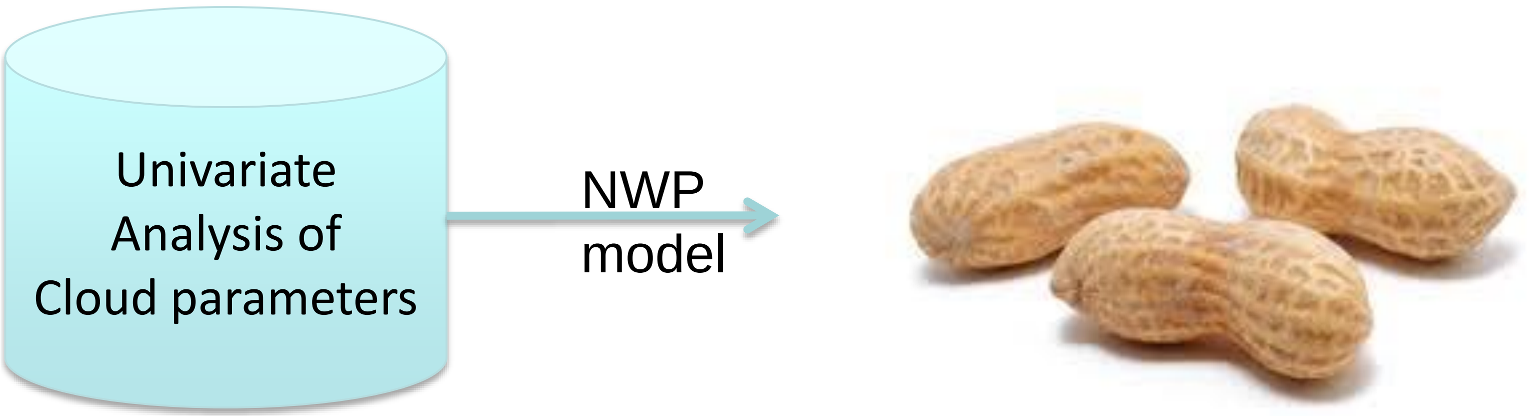
Update of q_{cloud}, q_{ice} in WRF





AIRS Window Channel #787

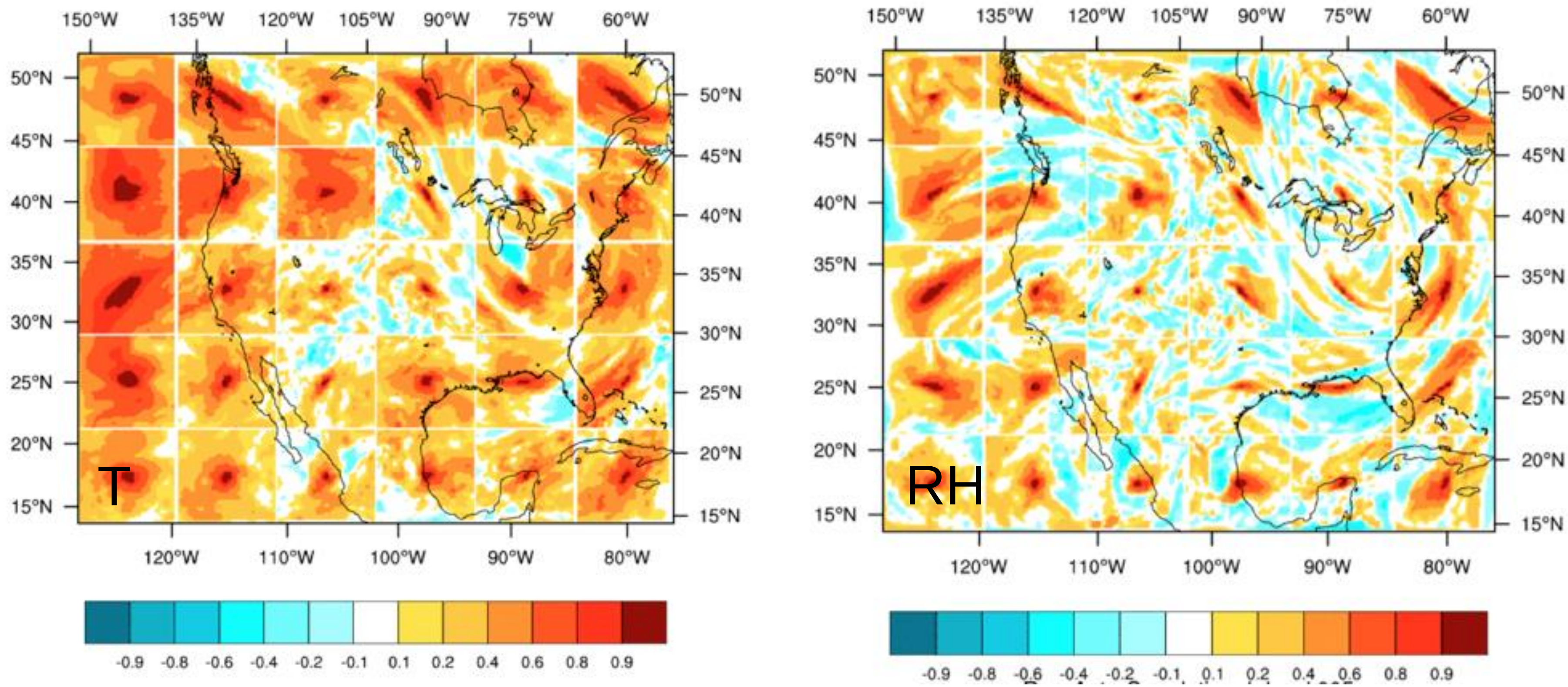
Cloud Analysis: Impact on Forecast



Background Error Covariances are required to update observed and unobserved model variables in a ***balanced*** way

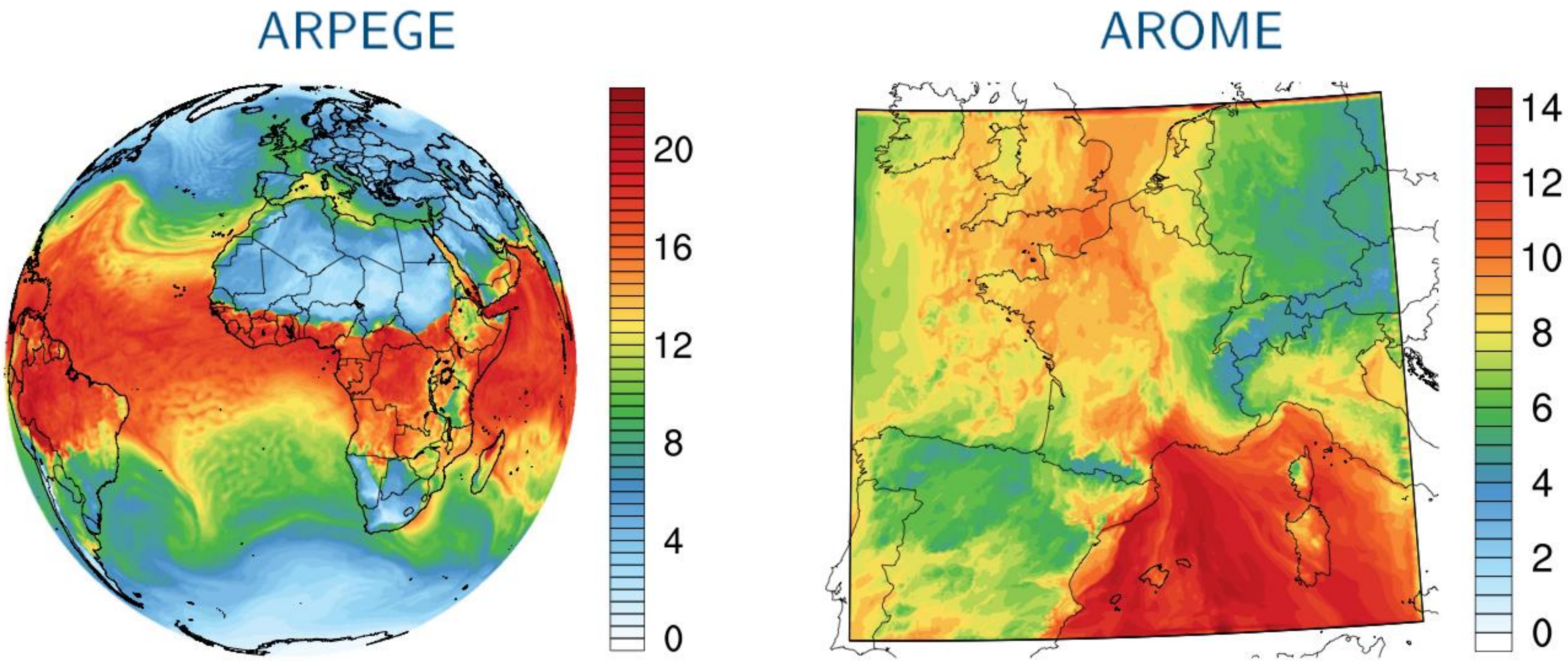
BE Covariances: Raw Ensemble Auto-Correlations

Horizontal autocorrelations (mid-troposphere)



- Heterogeneous
- Anistropic
- Flow dependent
- Wide range of spatio-temporal scales

BE Covariances: Impact of Model Resolution

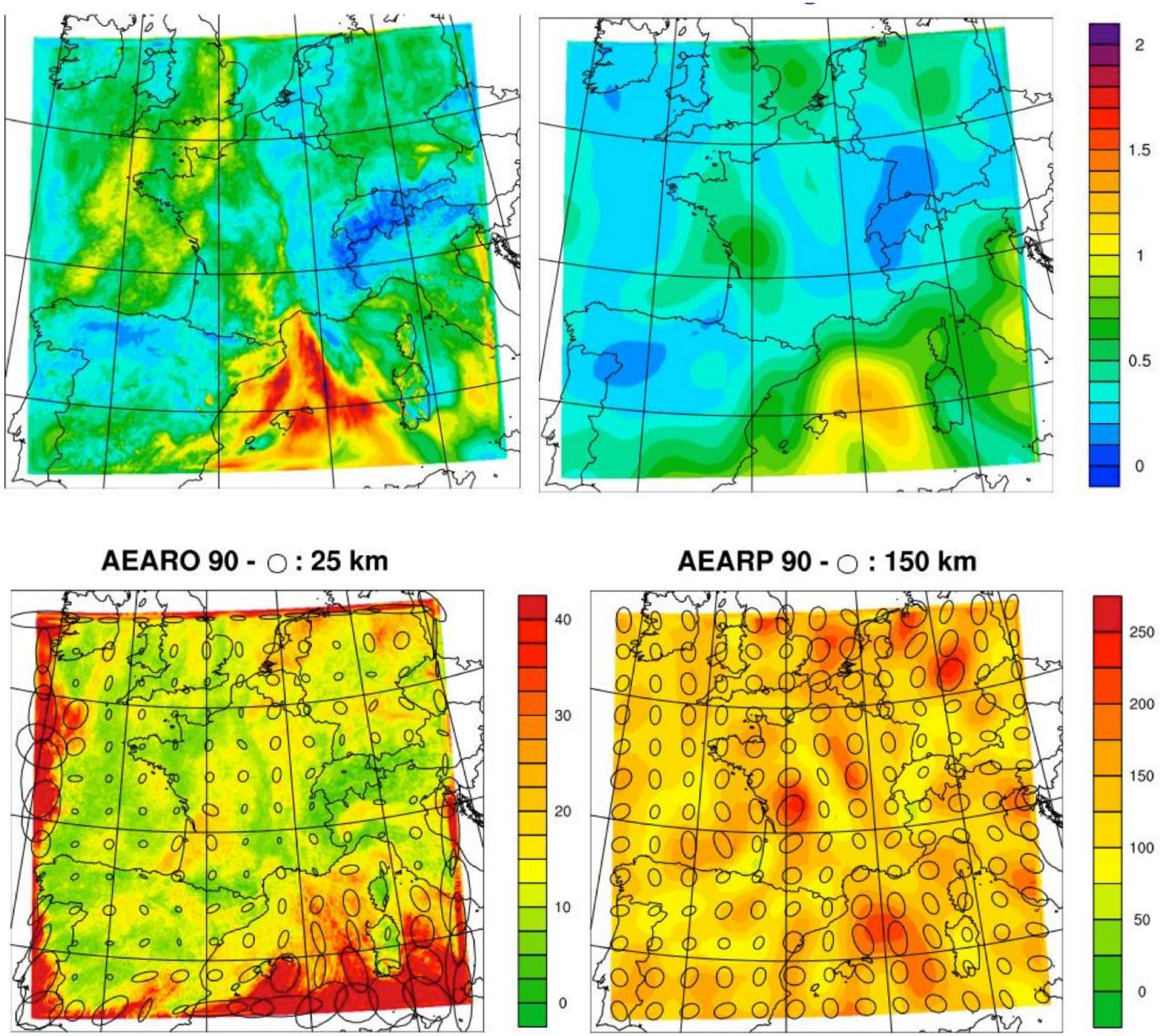


3 h forecasts of specific humidity ($g.kg^{-1}$) in low layer

Source: Benjamin Ménétrier

q at 945hPa

BE Covariances: Impact of Model Resolution

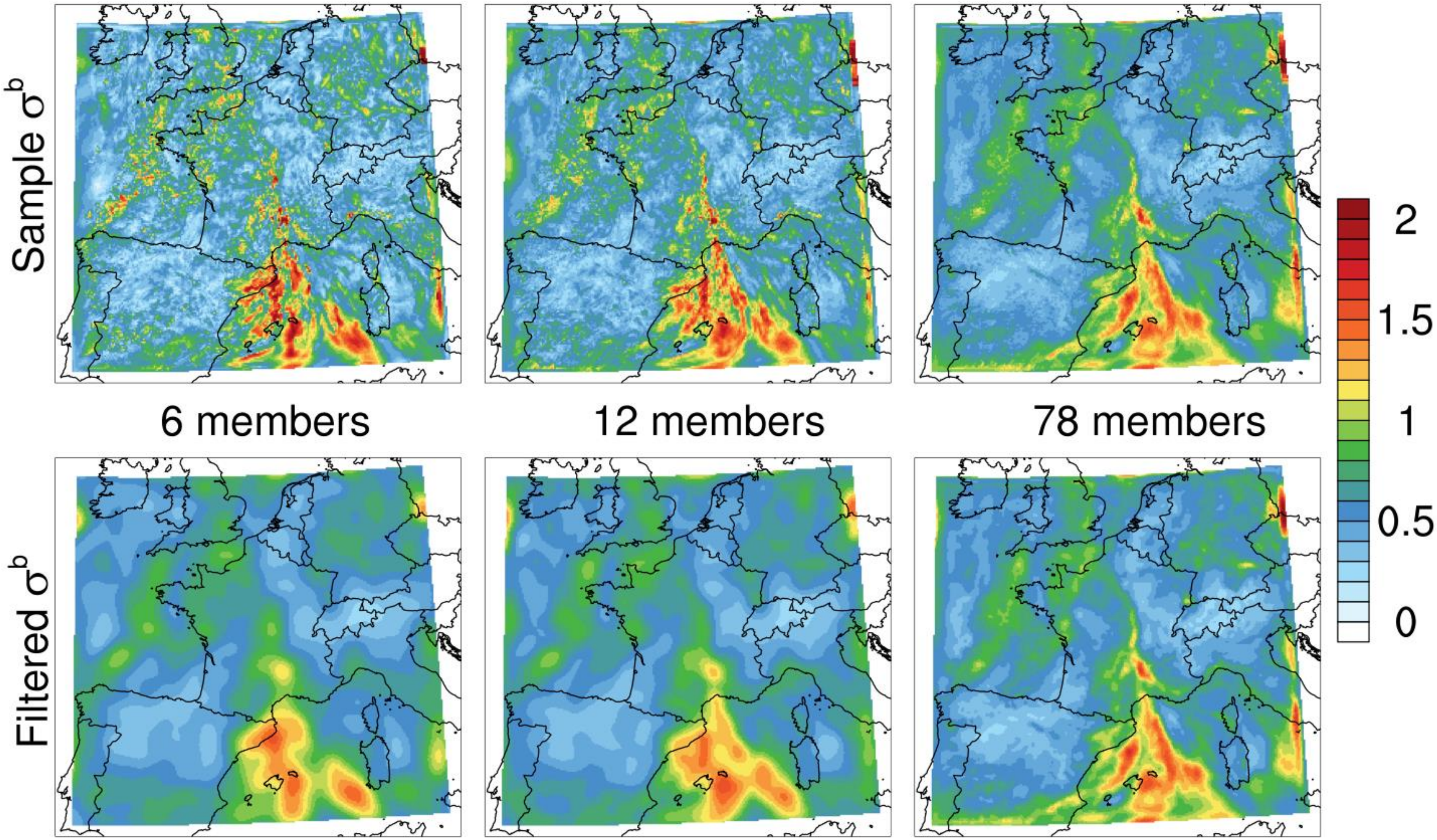


Variance

Length-scale
and
LCH tensor

Ménétrier et al. (2011)

BE Covariances: Variance Filtering

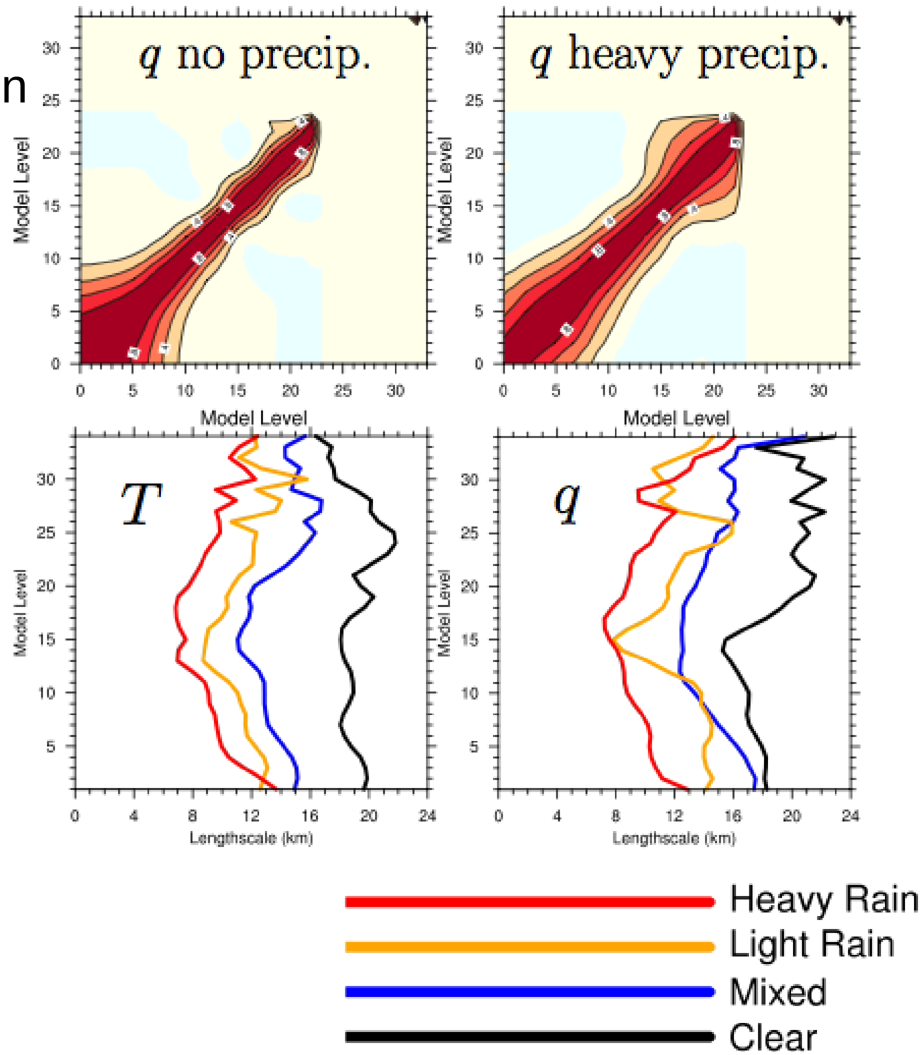


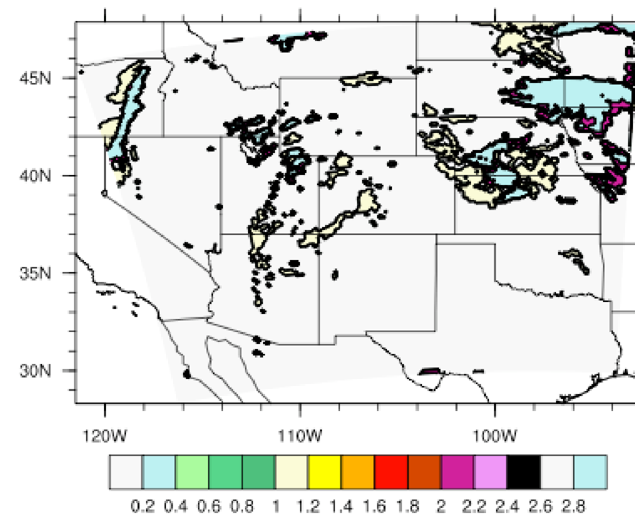
Ménétrier et al. (2014)

Background Error Covariances: Masked Statistics

Vertical auto-correlation

Horizontal lengthscale

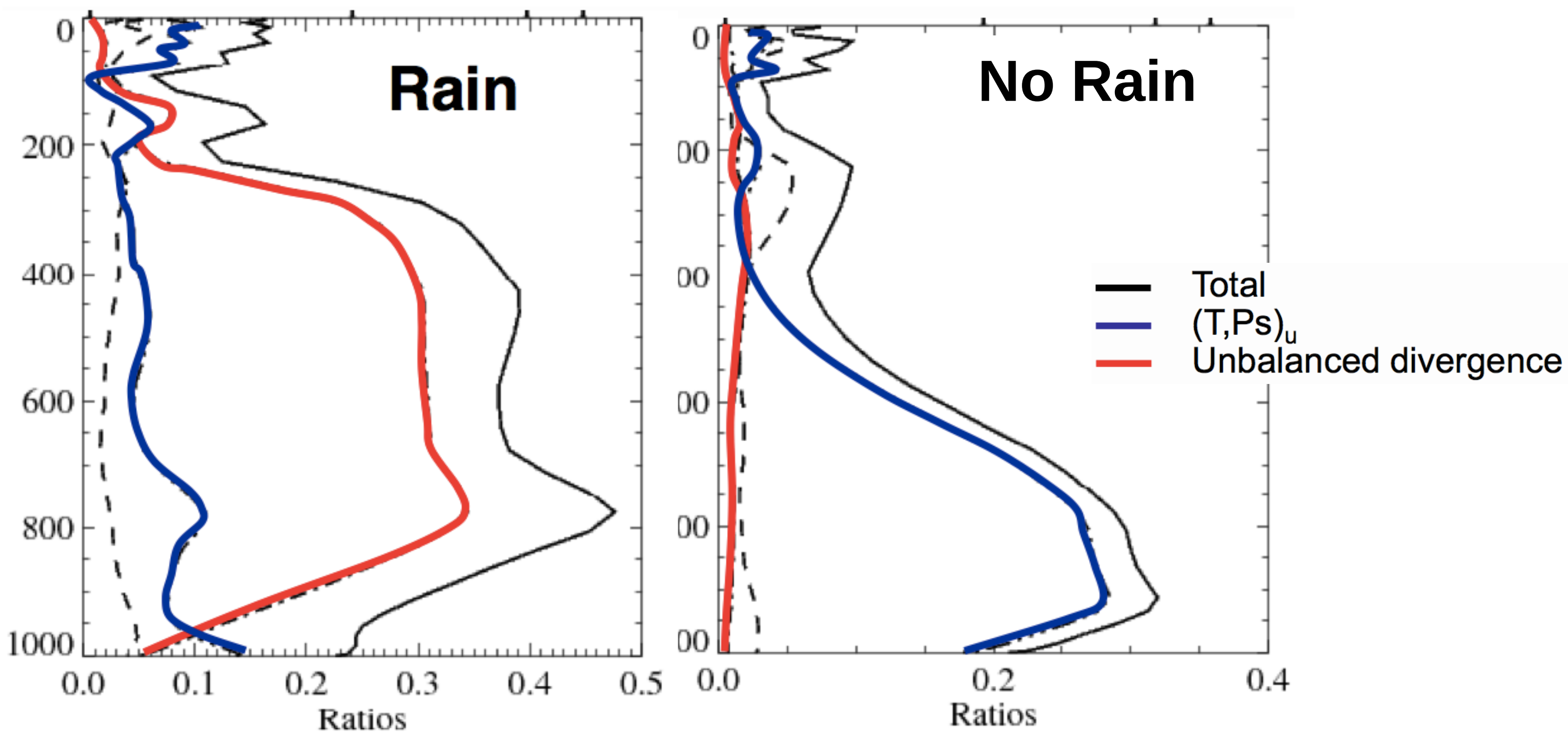




Michel et al. (2011)

Background Error Covariances: Masked Statistics

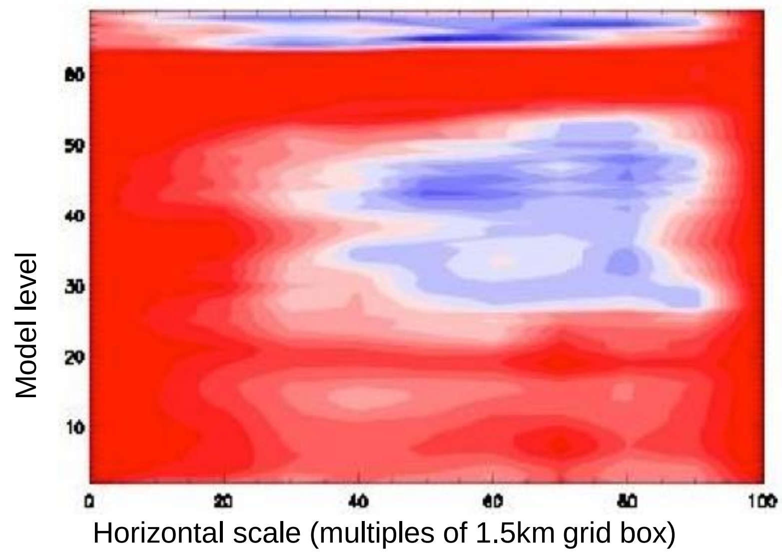
Fraction of explained variance for q



Montmerle and Berre (2010), Ménétrier and Montmerle (2011), Brousseau et al. (2012)

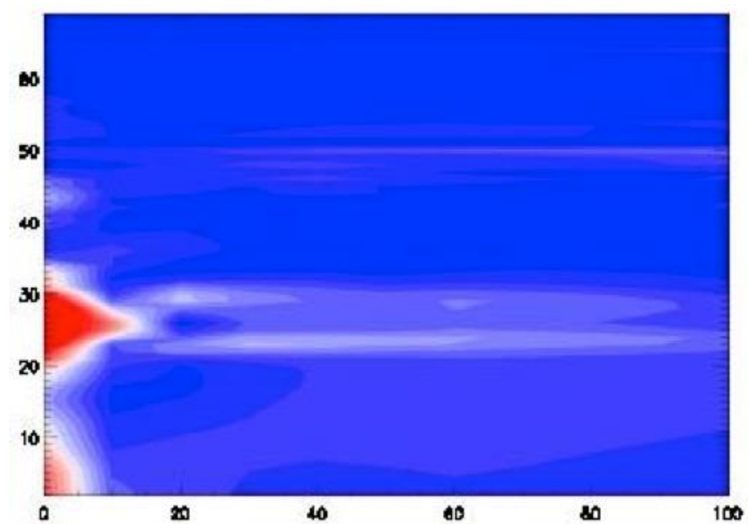
BE Covariances: Balance

Geostrophic balance



Balanced
Unbalanced

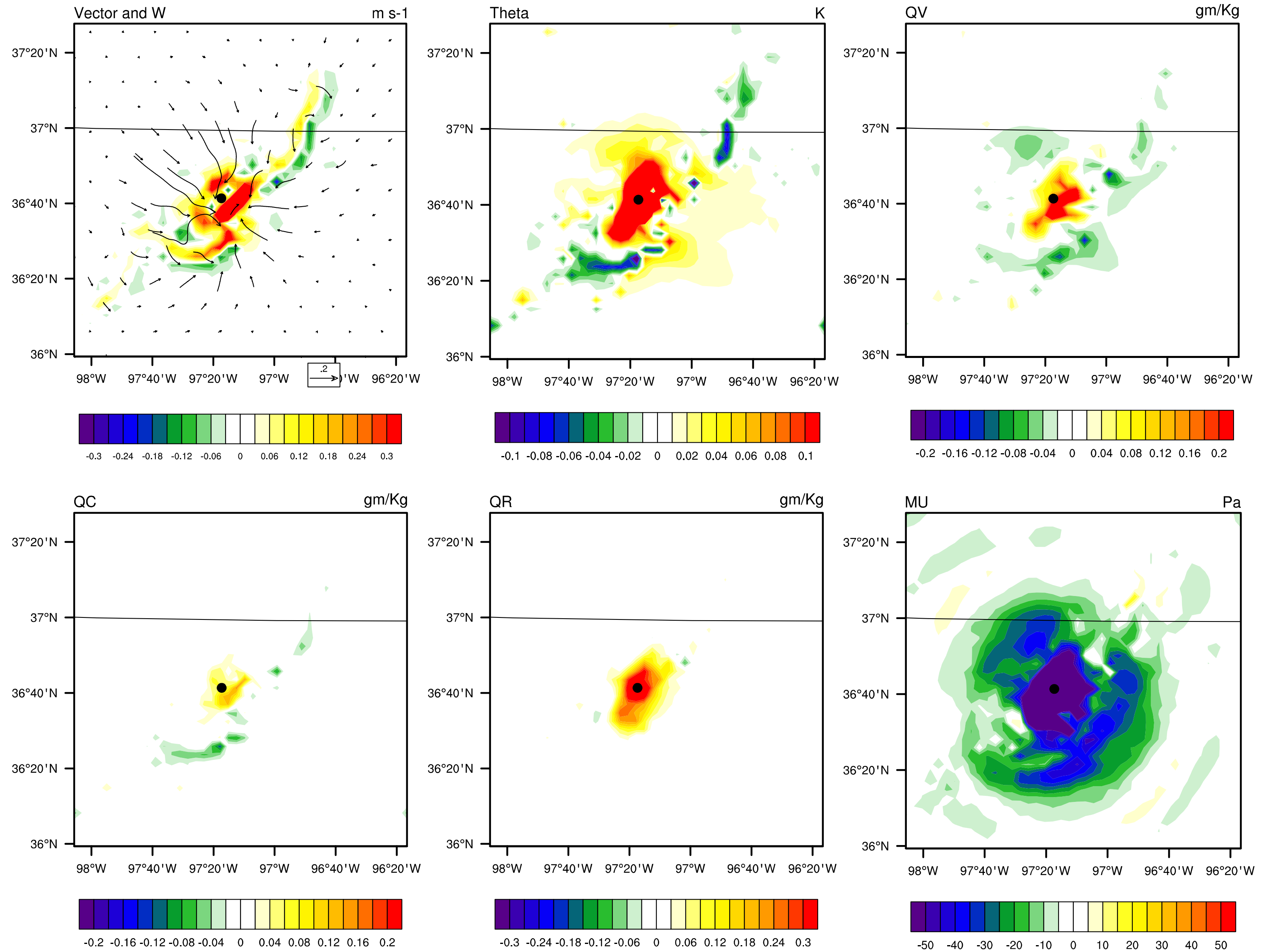
Hydrostatic balance



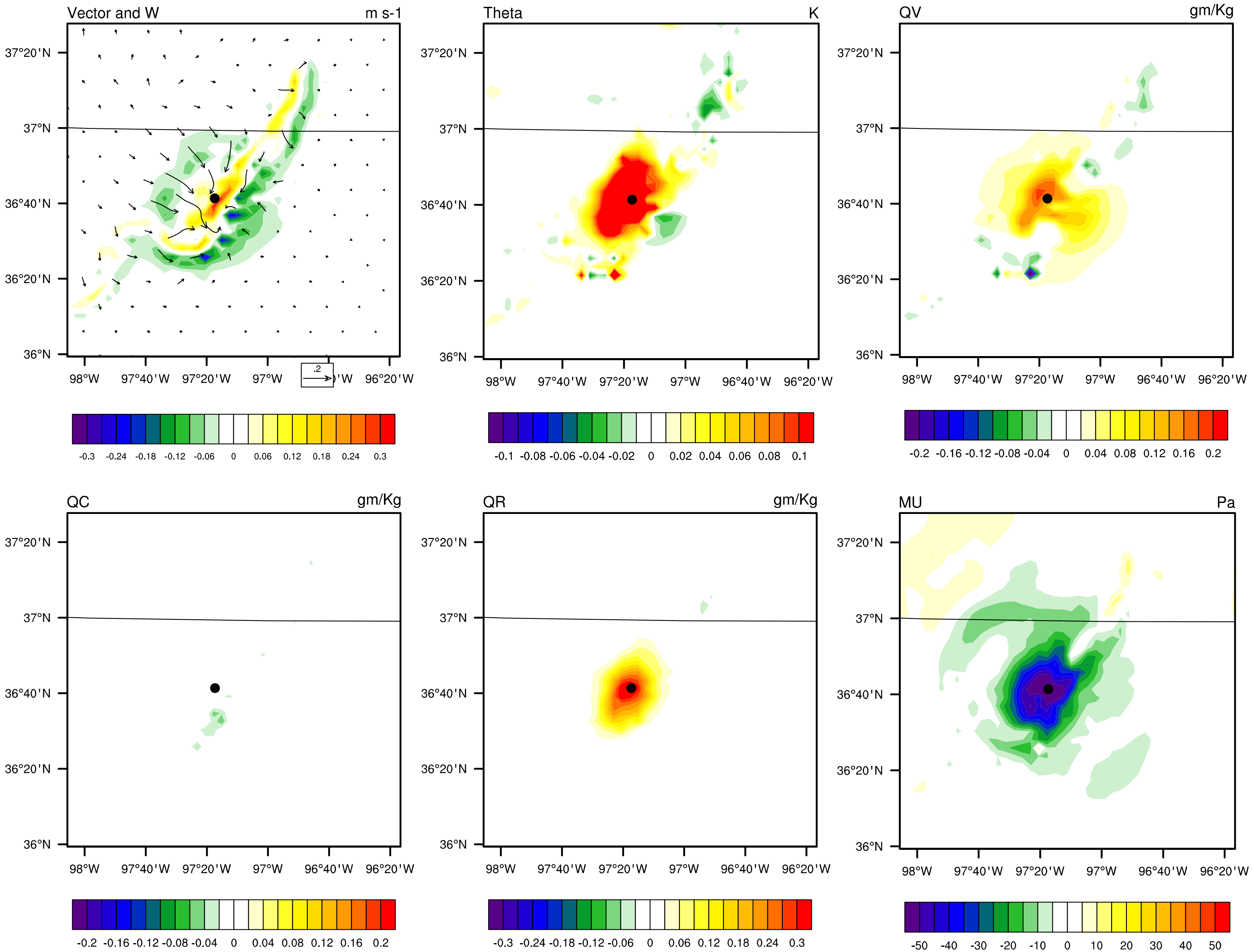
- **Complex, non-linear, flow-dependent relationship b/w model variables**
- **Traditional balance not applicable at high-resolution**

Source: Ross Bannister (NCEO, Reading)
Also Betra-Carvalho et al. (QJRMS, 2012)

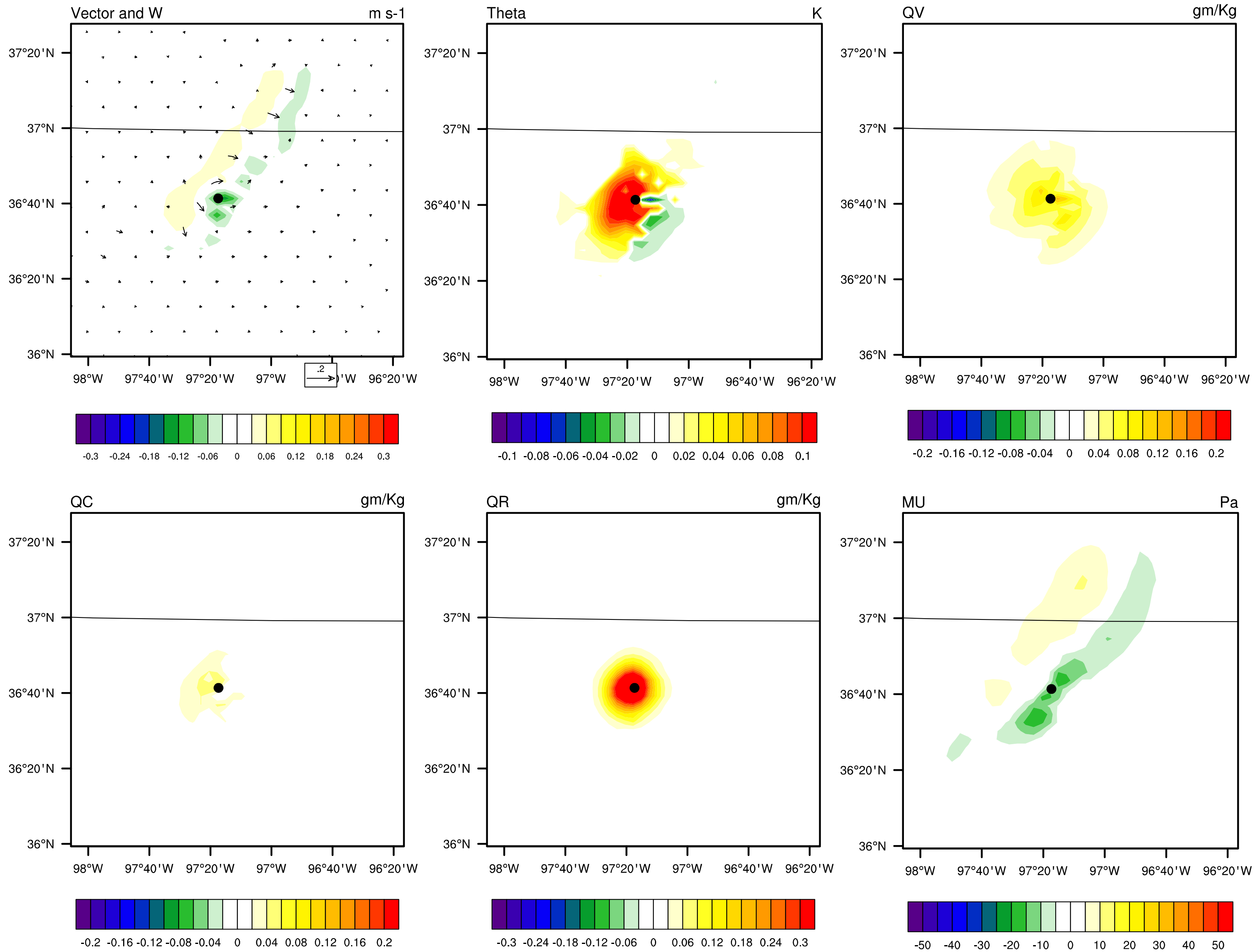
Mini-4DVar (10min)



Mini-4DVar (5min)



Mini-4DVar (1min)



Hybrid Ensemble/Variational Data Assimilation

$$J = \frac{1}{2}\mathbf{v}^T\mathbf{v} + \frac{1}{2}\left(\mathbf{y}^o - H\left(\mathbf{x}^b\right) + \mathbf{HUv}\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^o - H\left(\mathbf{x}^b\right) + \mathbf{HUv}\right)$$

$$\mathbf{B} = \mathbf{U}\mathbf{U}^T \qquad\qquad \delta\mathbf{x} = \mathbf{U}\mathbf{v}$$

Ensemble Covariance included in 3D/ 4DVar via ***state augmentation***

(Lorenc 2003, Buehner 2005, Wang et al. 2008, Fairbairn et al., 2012)

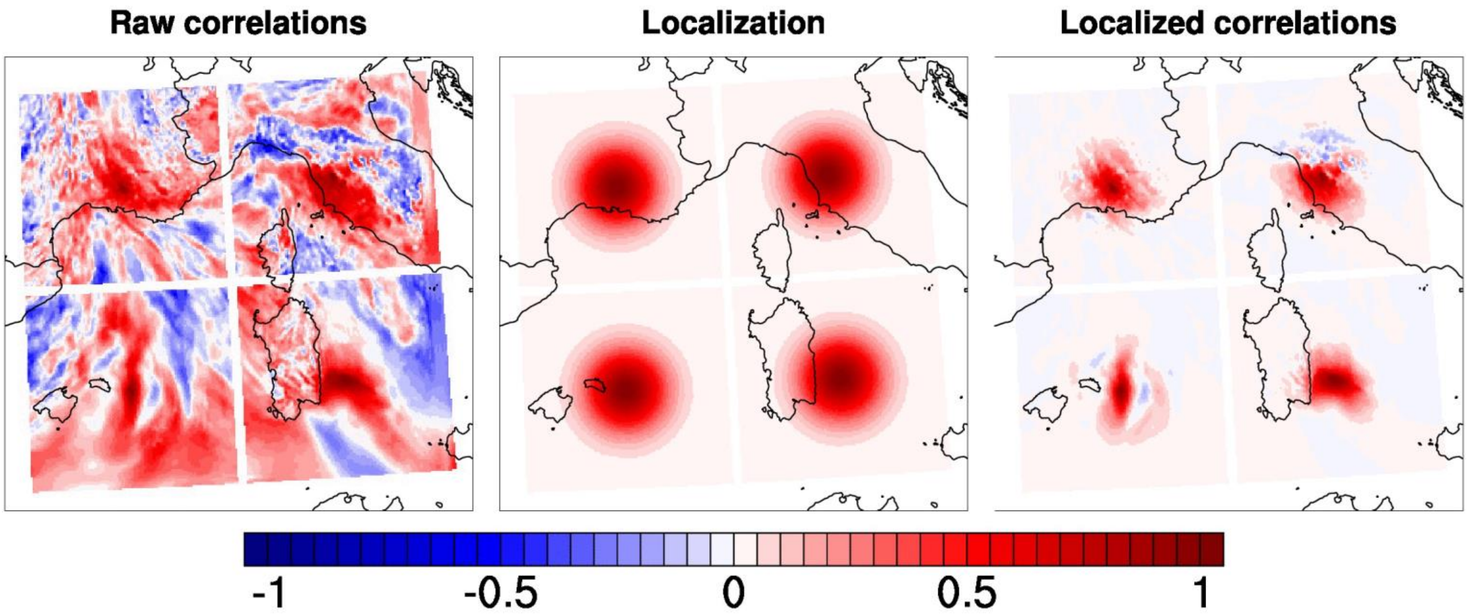
$$\mathbf{v} = \begin{pmatrix} \mathbf{v}^c \\ \mathbf{v}_1^e \\ \vdots \\ \mathbf{v}_m^e \\ \vdots \end{pmatrix}$$

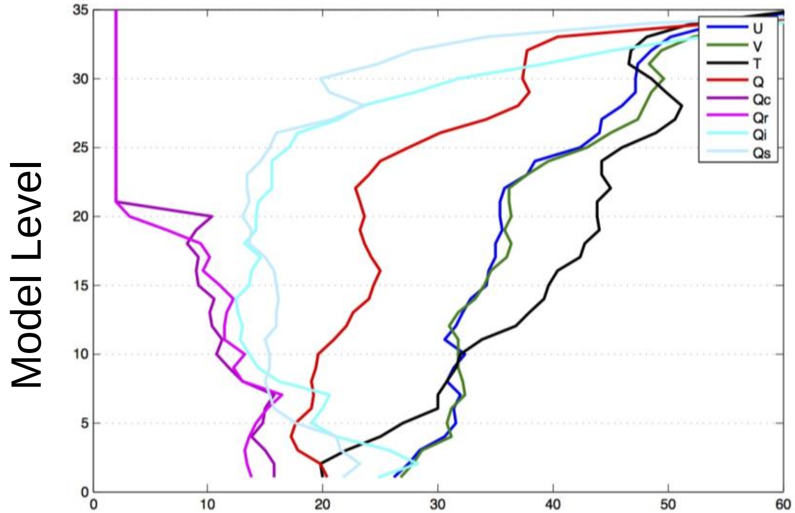
$$\delta\mathbf{x} = \beta_c \mathbf{U}^c\mathbf{v}^c + \beta_e \sum_{m=1}^{M} \delta\mathbf{x}_m^f \circ \left(\mathbf{U}^e\mathbf{v}_m^e\right)$$

Stationary multivariate covariance model including clouds

Localized [+ filtered] ensemble covariance

Background Error Covariances: Masked Statistics

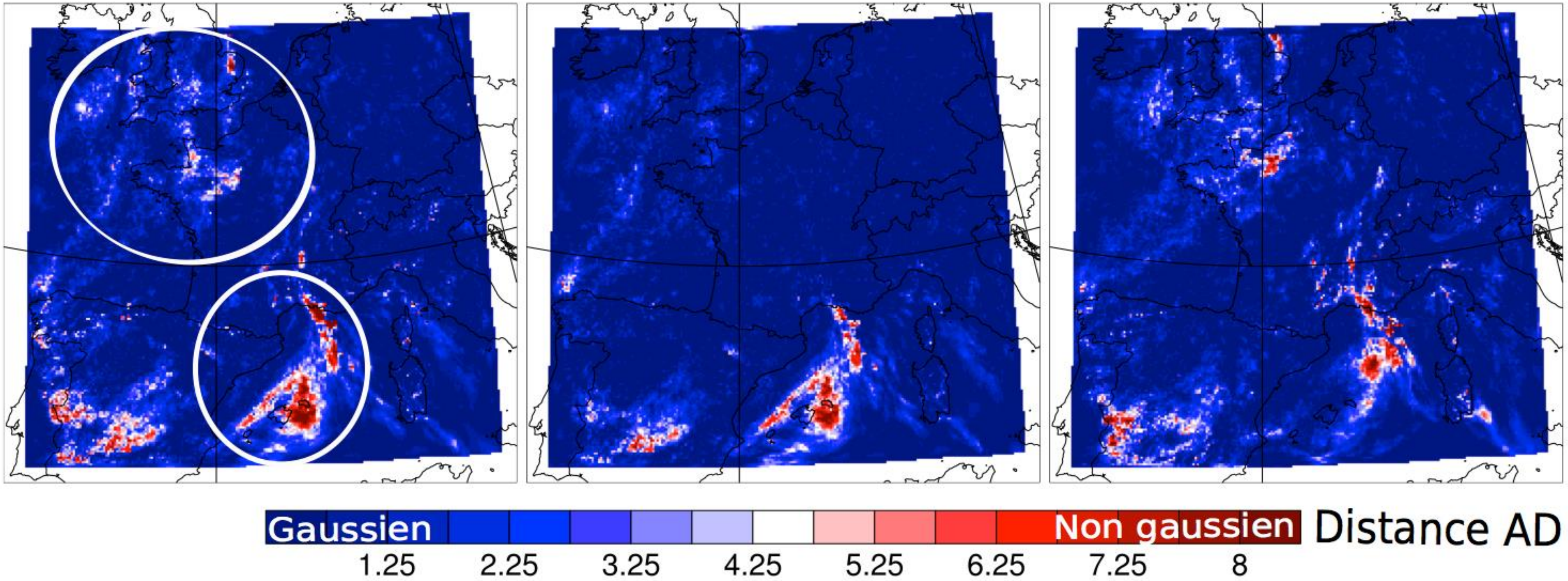




Source: Benjamin Ménétrier

Background Errors: Non-Gaussianity

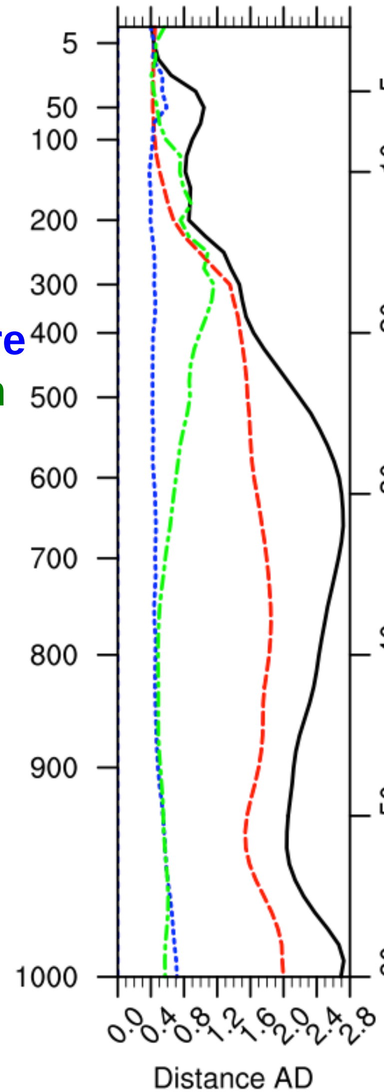
Anderson-Darling distance to a Gaussian PDF

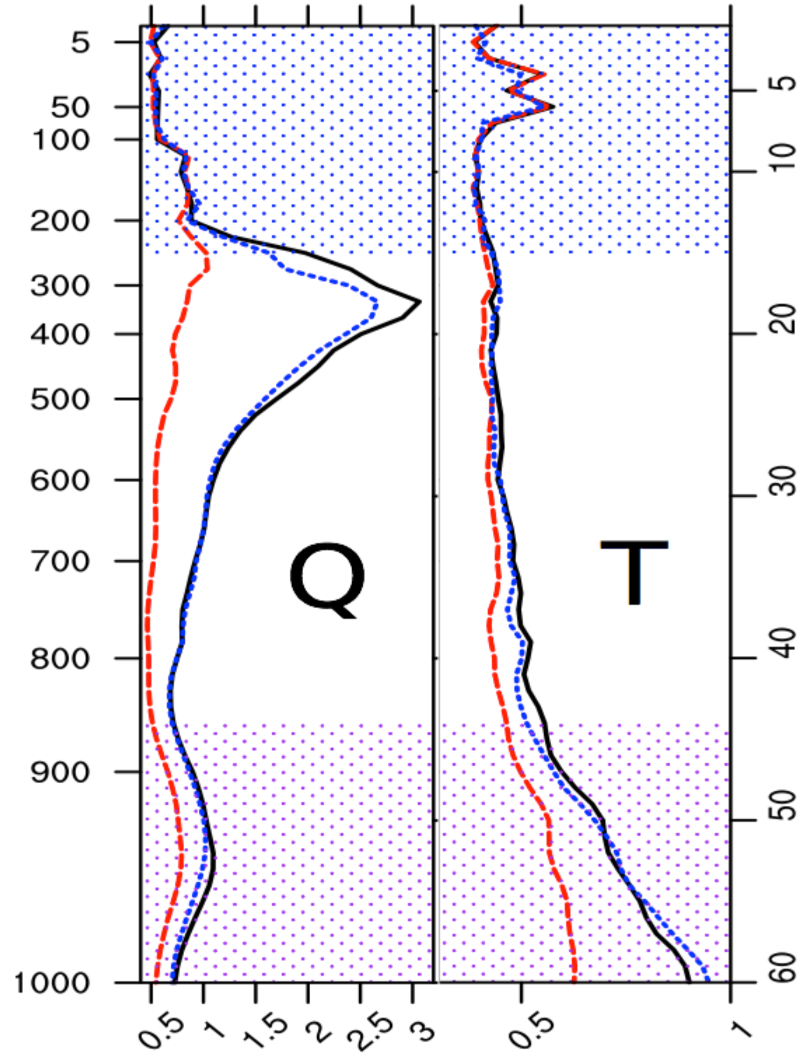


Source: Raphael Lagrand (Météo-France)

Background Errors: Non-Gaussianity

Temperature
Specif Hum
Divergence
Vorticity





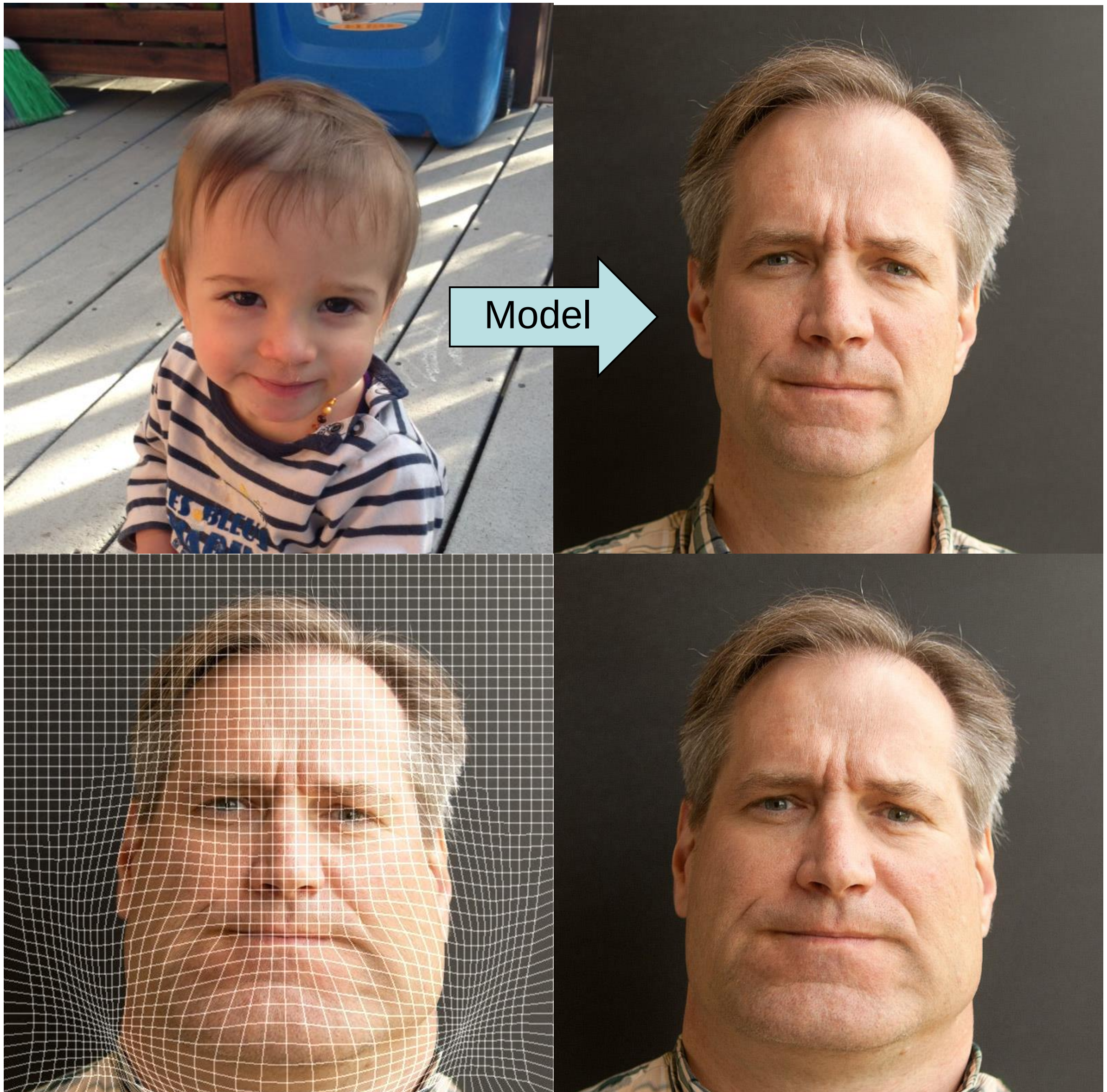
3h fcst
6h fcst
Analysis

Source: Raphael Lagrand (Météo-France)

Displacement Analysis: Grid Warping

Current State

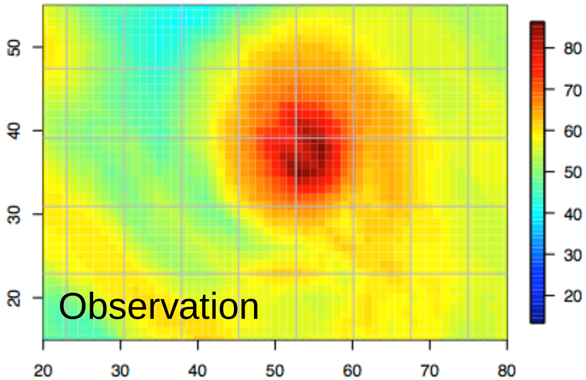
Forecast

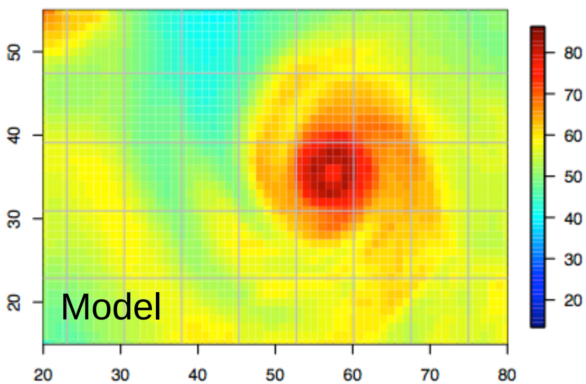


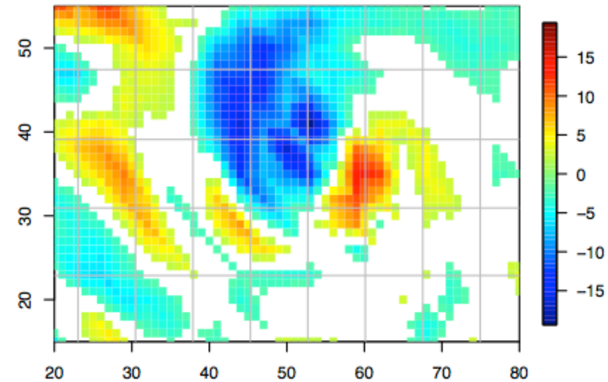
Grid Warping

Observation

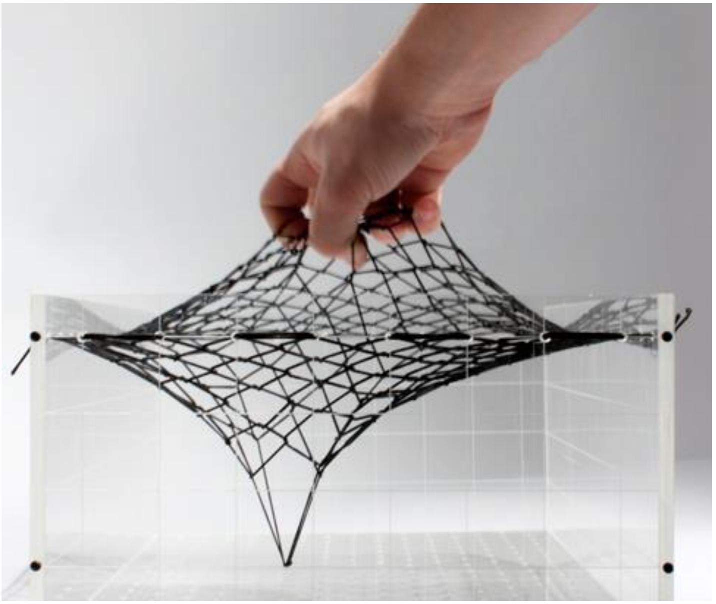
Displacement analysis in WRF (dWRF)





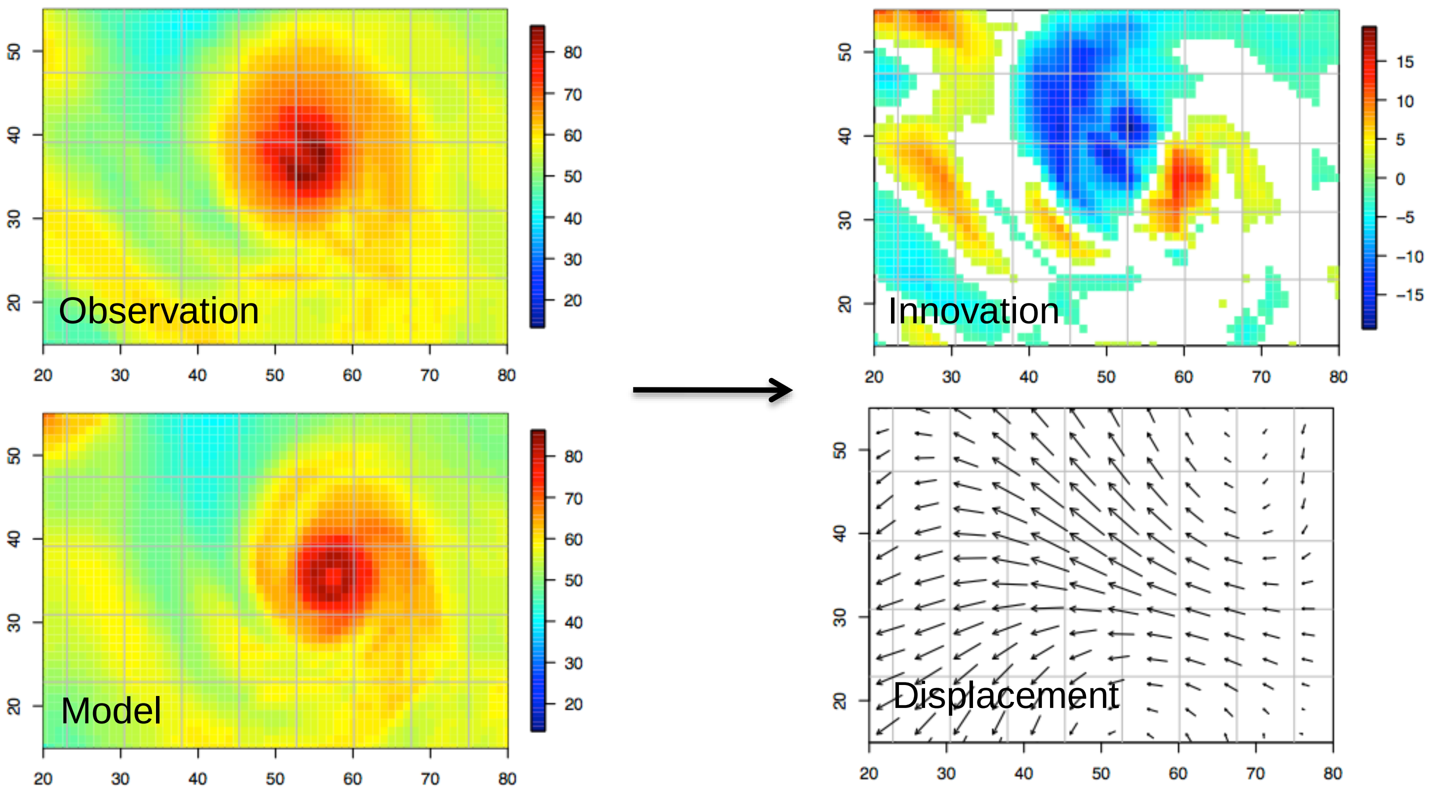


Innovation



- Hurricane Katrina OSSE
- Synthetic observations (TPW)

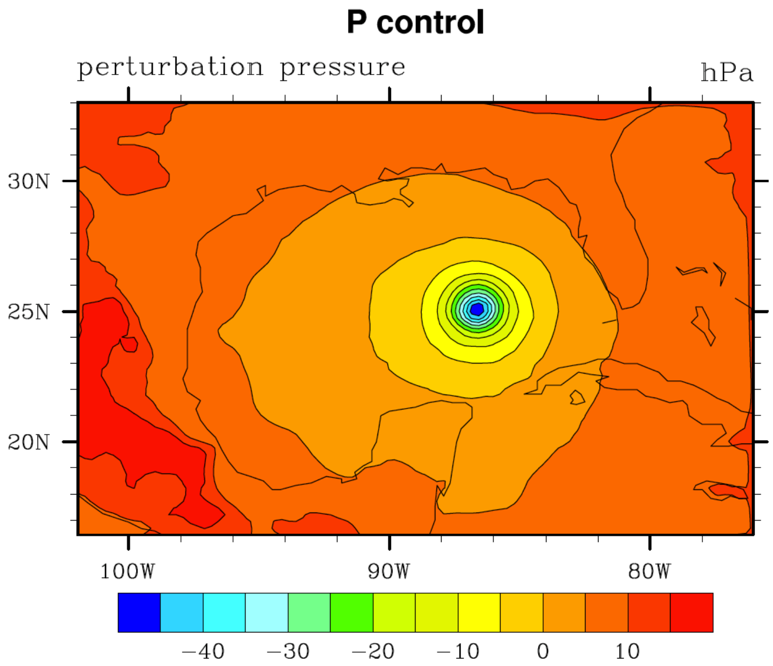
Displacement analysis in WRF (dWRF)



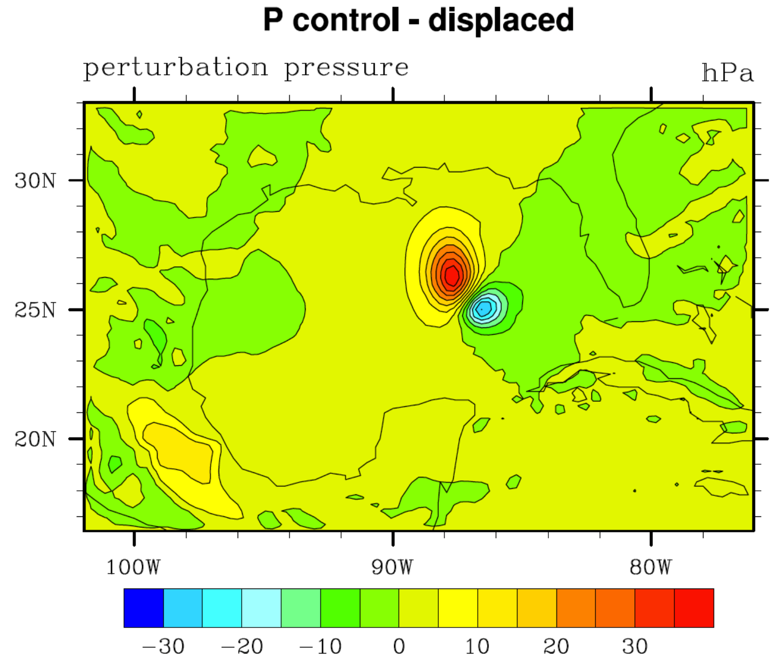
Assimilation system can operate in two modes:

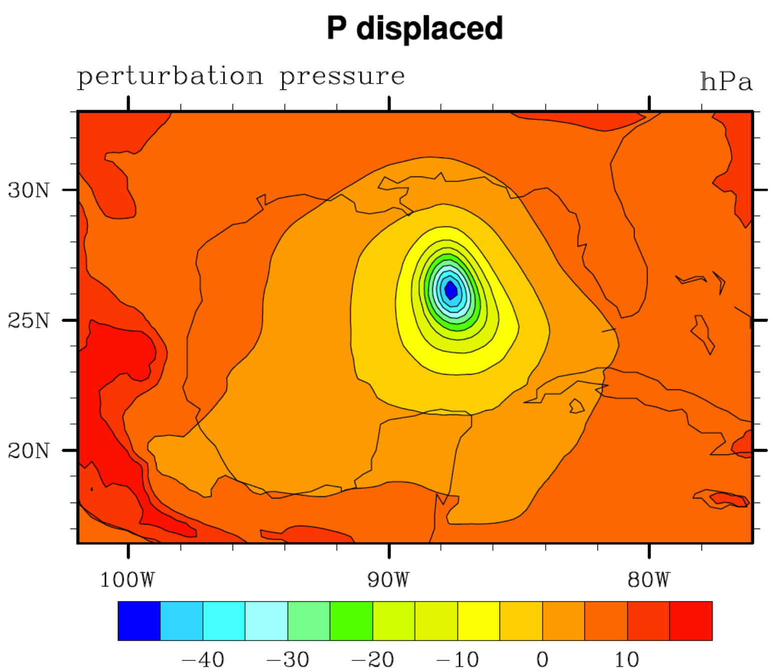
- Standard (*i.e.* additive increments)
- Displacement

Nehrkorn et al. (MWR 2013, 2014)

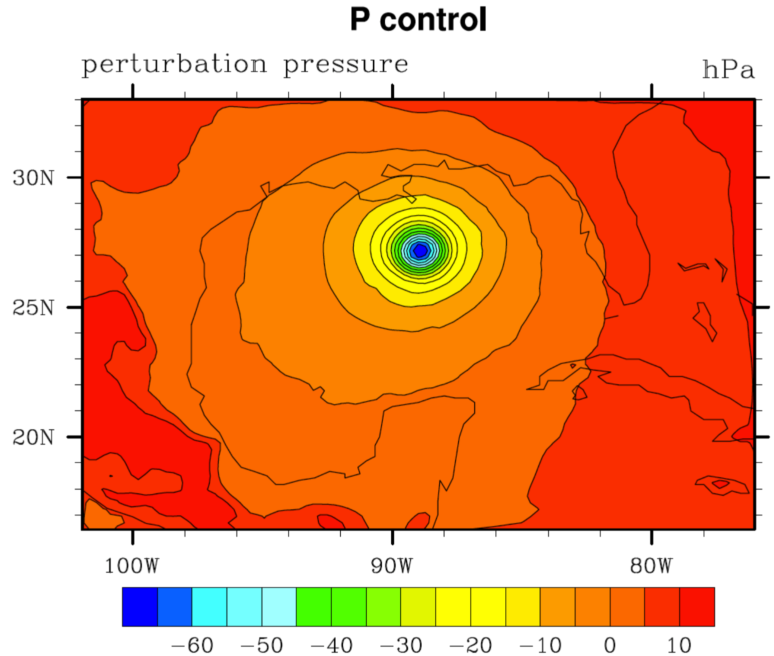


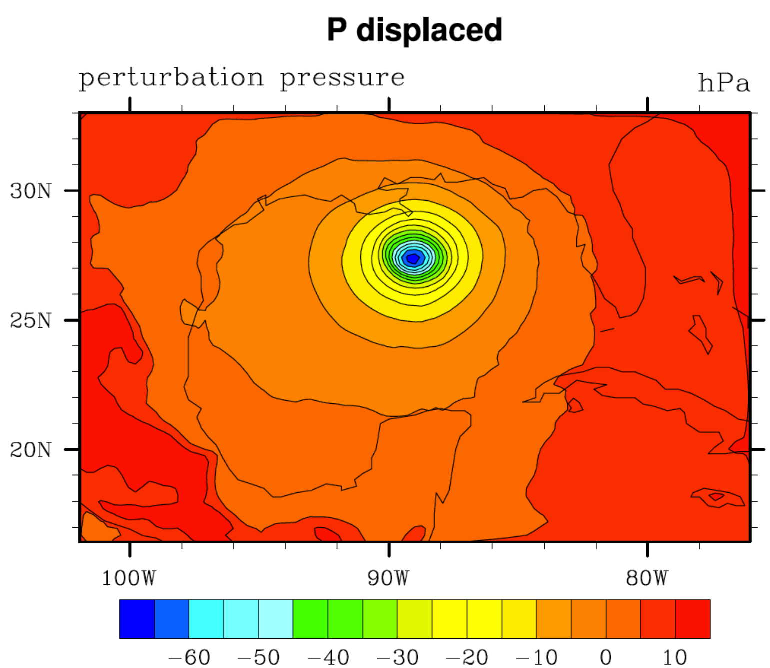
Initial time:
08-28-05 06:00:00z



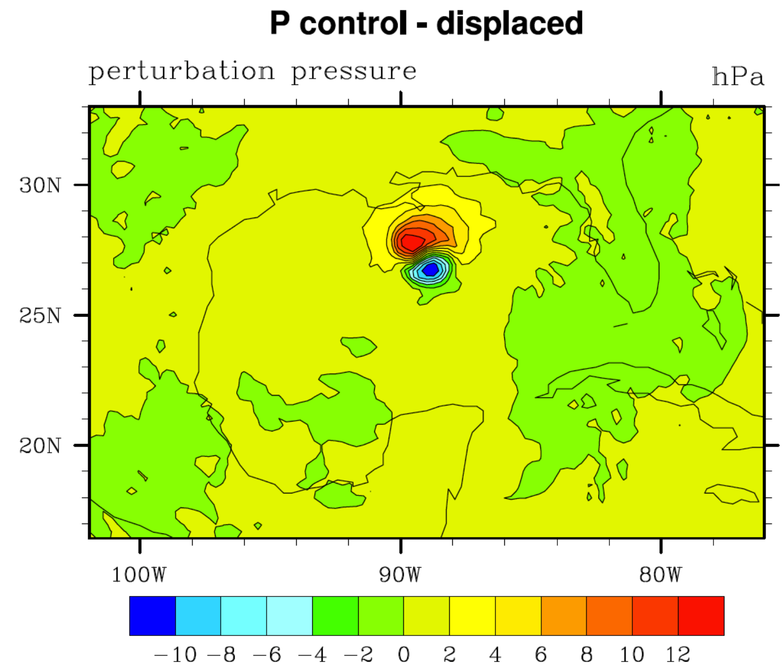


Vortex displaced
forward along track



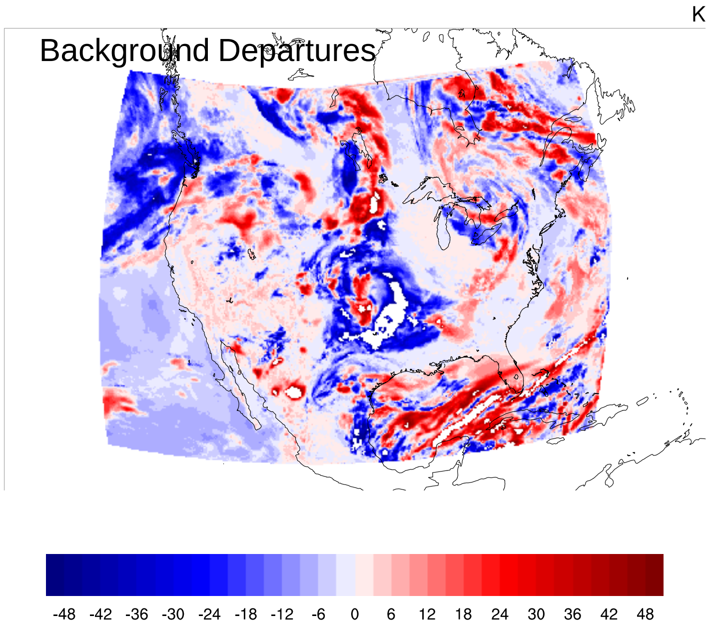


18 Hour forecast time: 08-29-05 00:00:00z

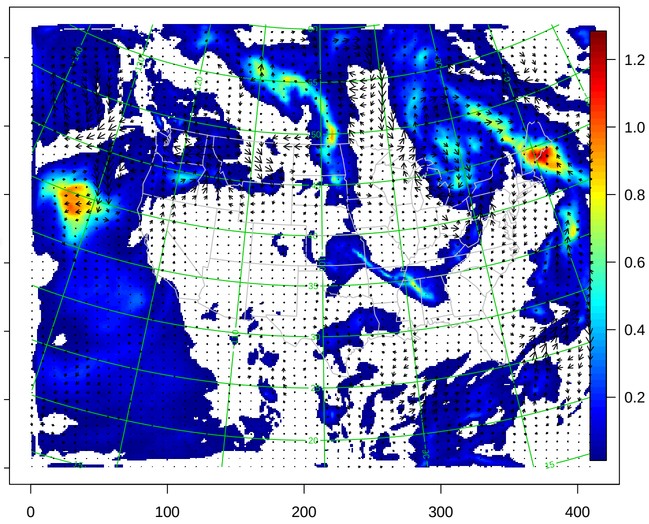


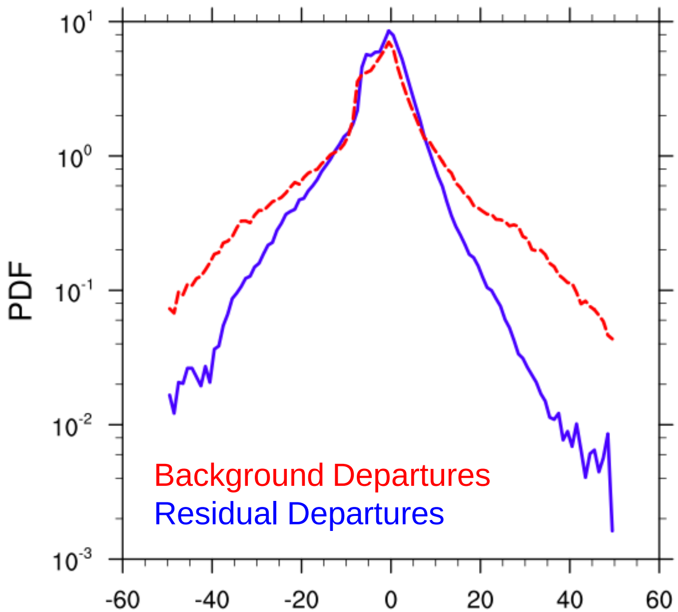
18 hours later vortex maintains forward position

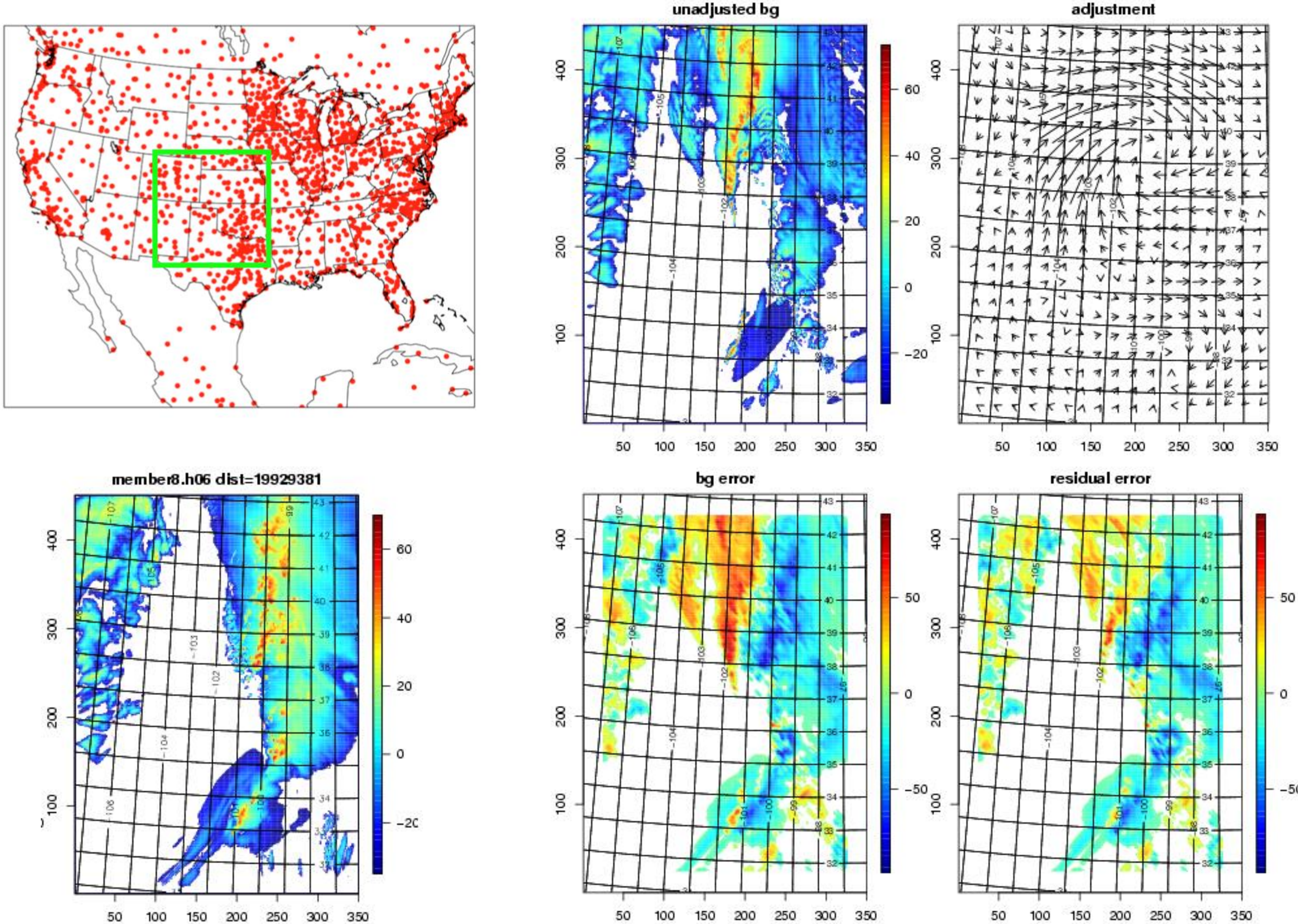
dWRF DA: GOES All-Sky Radiances



dWRF



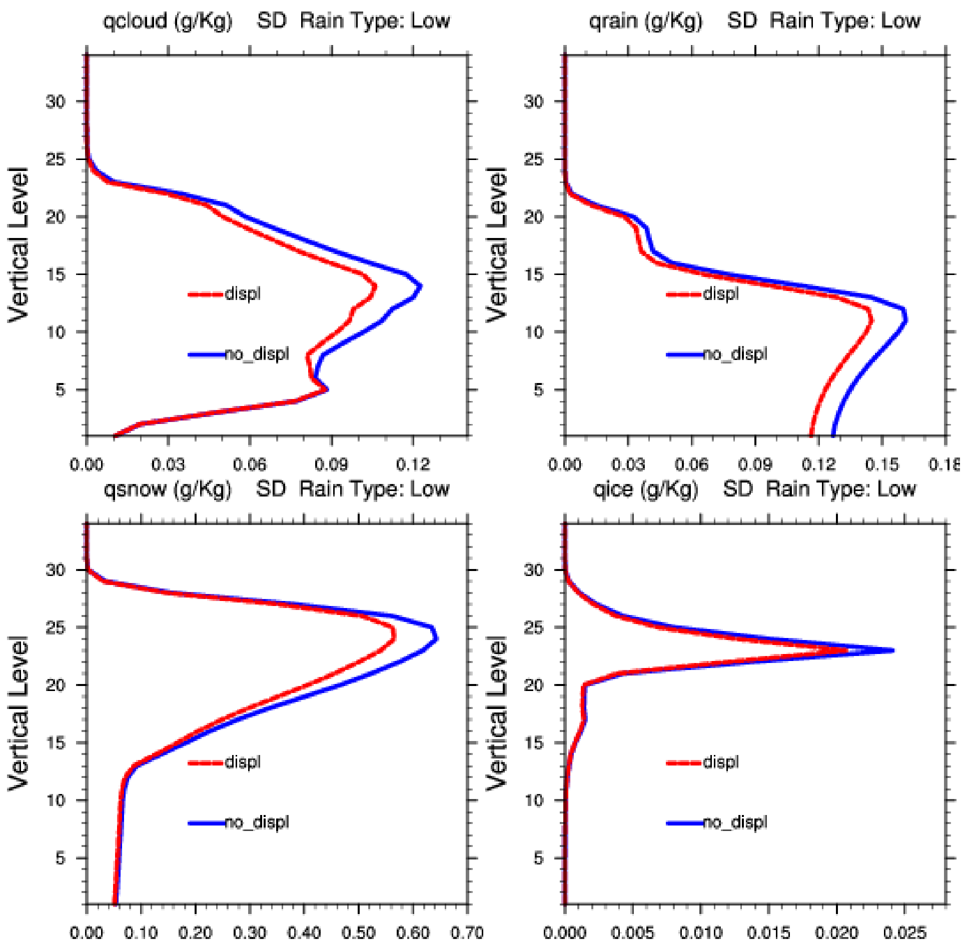




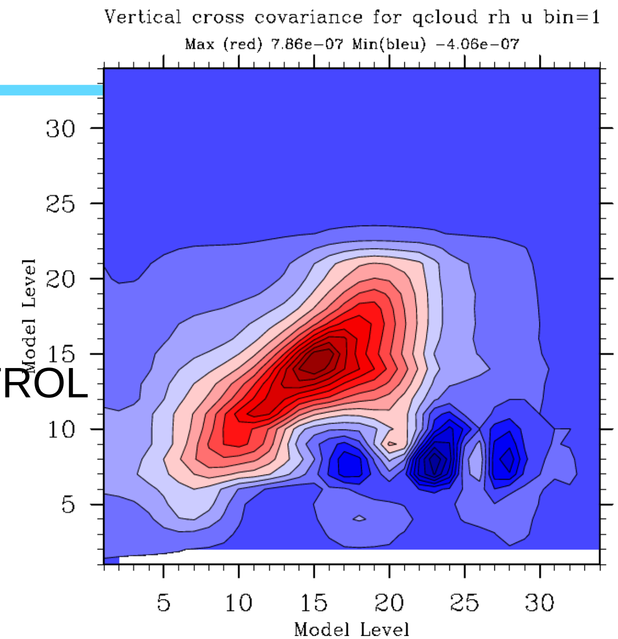
unadjusted bg
adjustment
member8.h06 dist=19929381
bg error
residual error

Displacement: BE Covariances

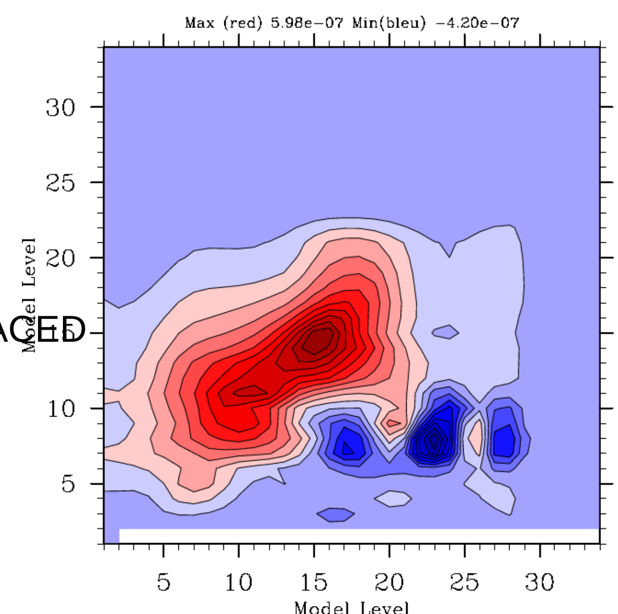
RH-q_c



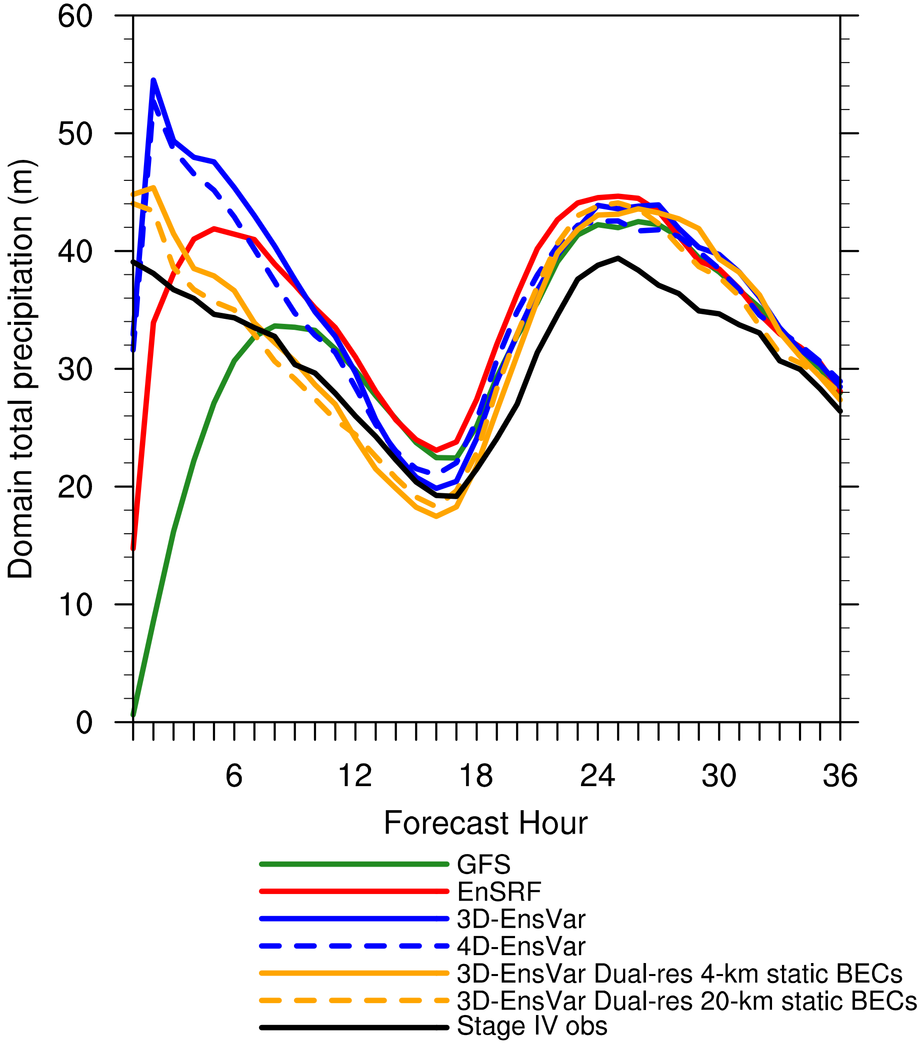
CONTROL



DISPLACED



Convective Scale: Model Spin-up



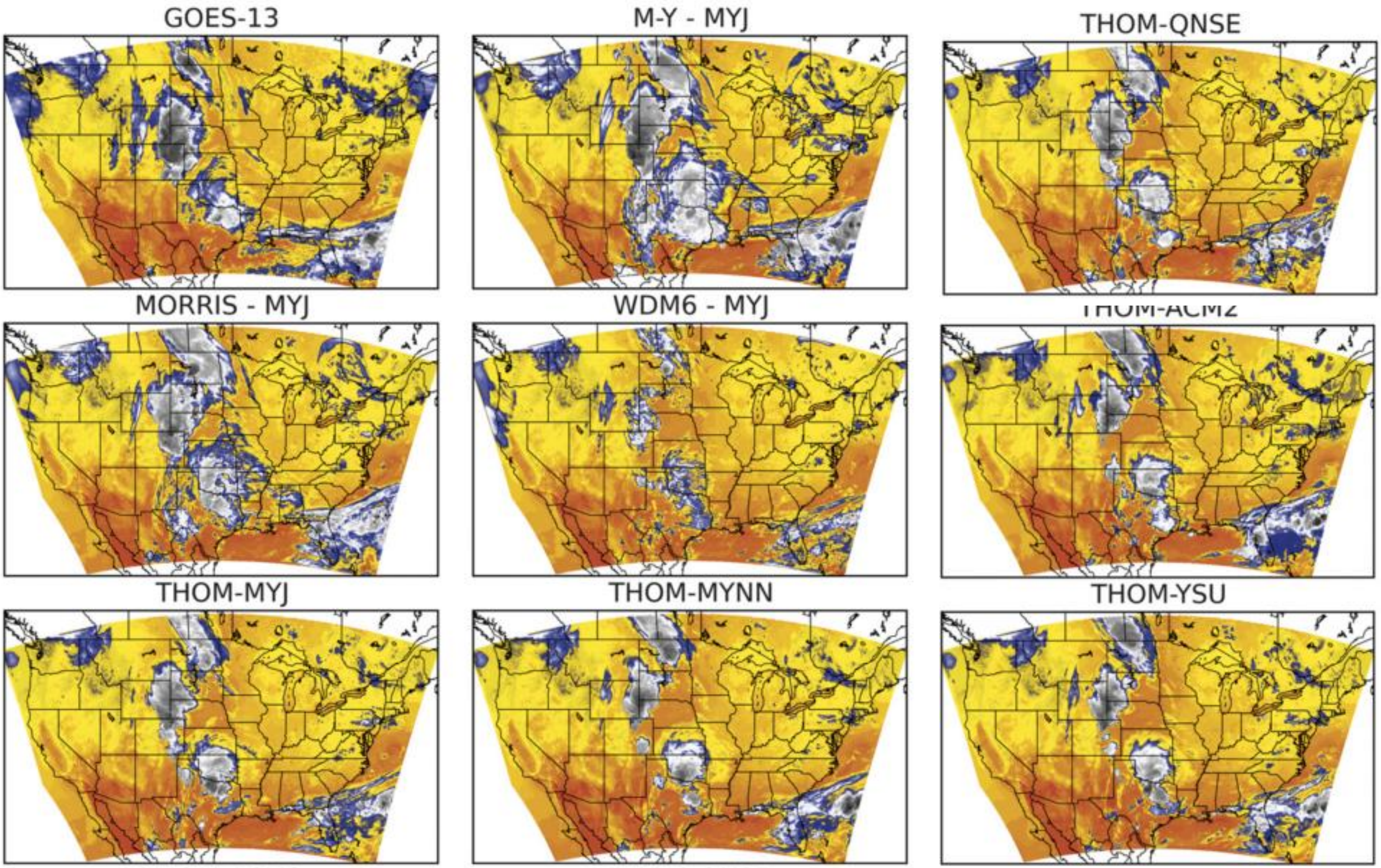
Initialization: Unbalanced analysis

- DFI, Incremental DFI, Diabatic DFI
- IAU, 4DIAU
- 4DVar, 4DEnVar
- Resolution gap b/w DA and model

Source: Craig Schwartz

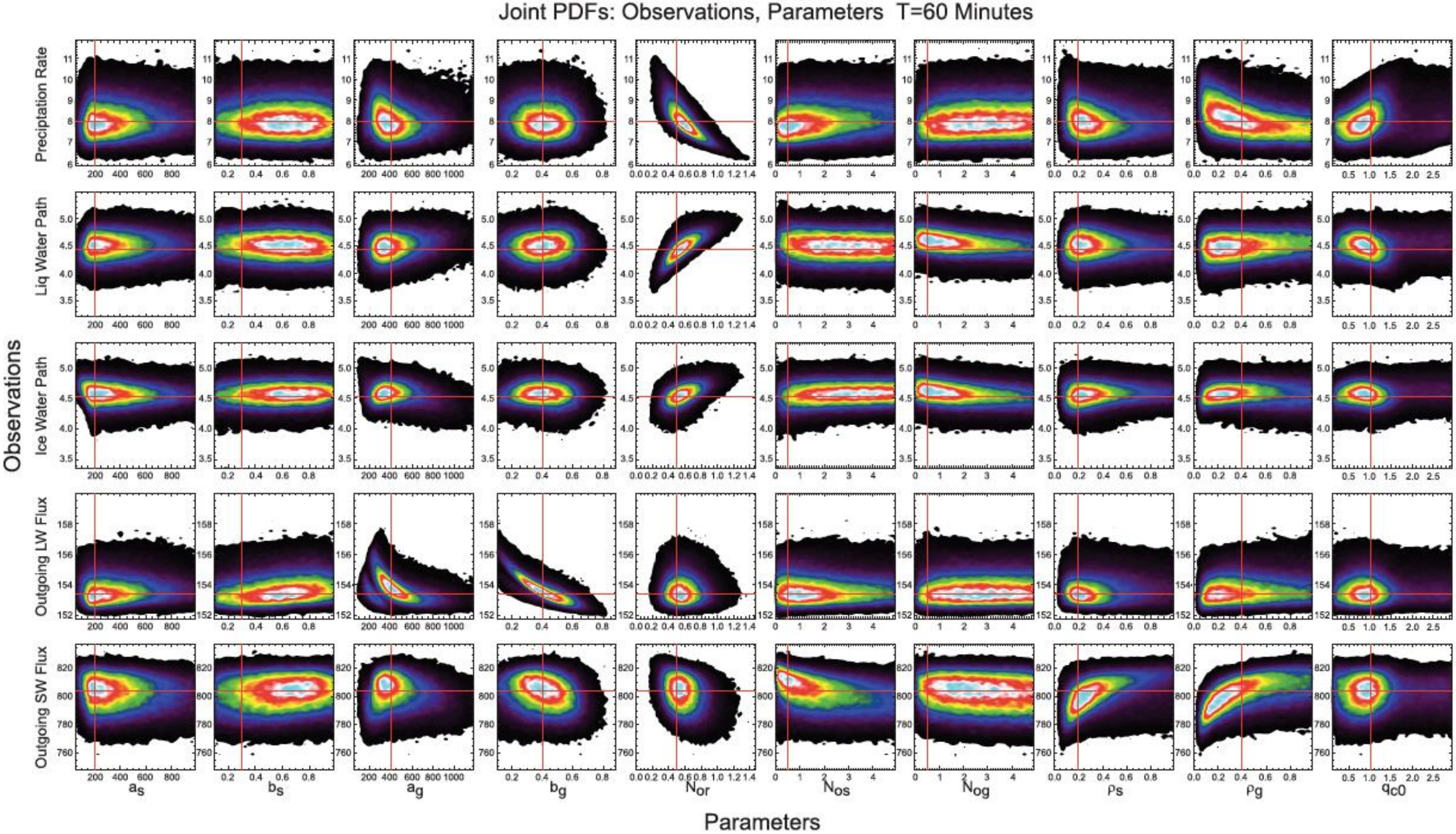
Convective Scale: Model Error

GOES-13 10.7μm



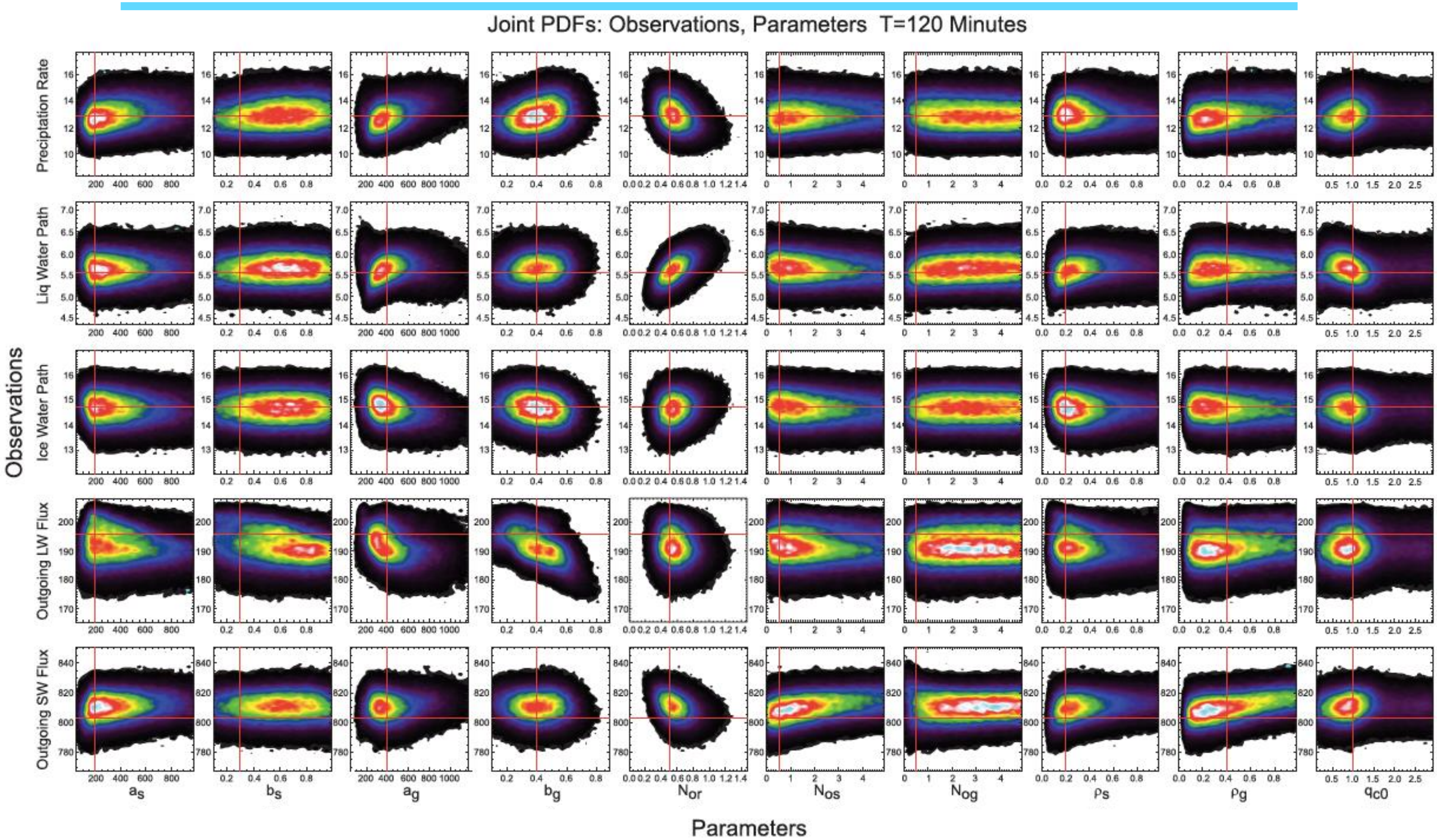
Cintineo et al. (2014)

Convective Scale: Model Error



Posselt and Vukicevic. (2010)

Convective Scale: Model Error



Posselt and Vukicevic. (2010)

Conclusions

Advances

- Include cloud parameters in analysis state
- Multiple re-linearizations of observation operator
- Improved flow-dependent multivariate BE covariances
- Increasingly relying on information from (filtered) ensembles
- Displacement analysis for coherent features

Question

- At convective scale, will current DA methods be defeated by non-linearities (before we reach retirement age)???

Perspectives

Coupled Assimilation

- Land surface (temperature and soil moisture)
- Ocean (SST, mixing)
- Hydrology (run-off)
- Aerosols (visibility)
- Composition (air quality, photolysis)

Model error

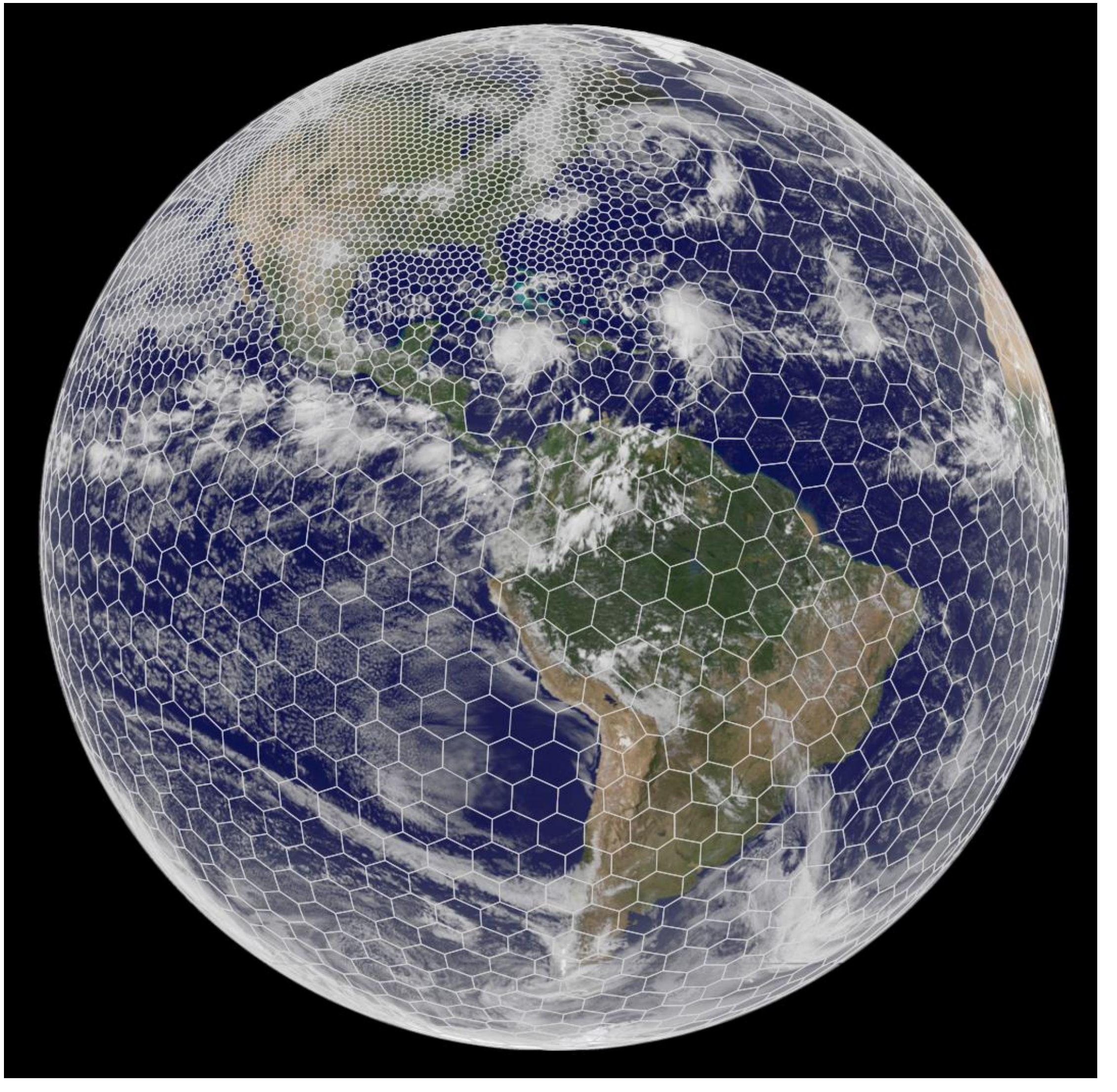
- Accurately represent model error
  (weak constraint, stochastic model processes, …)

Interaction with larger scales

- Multi-scale covariances → **DA across scales**

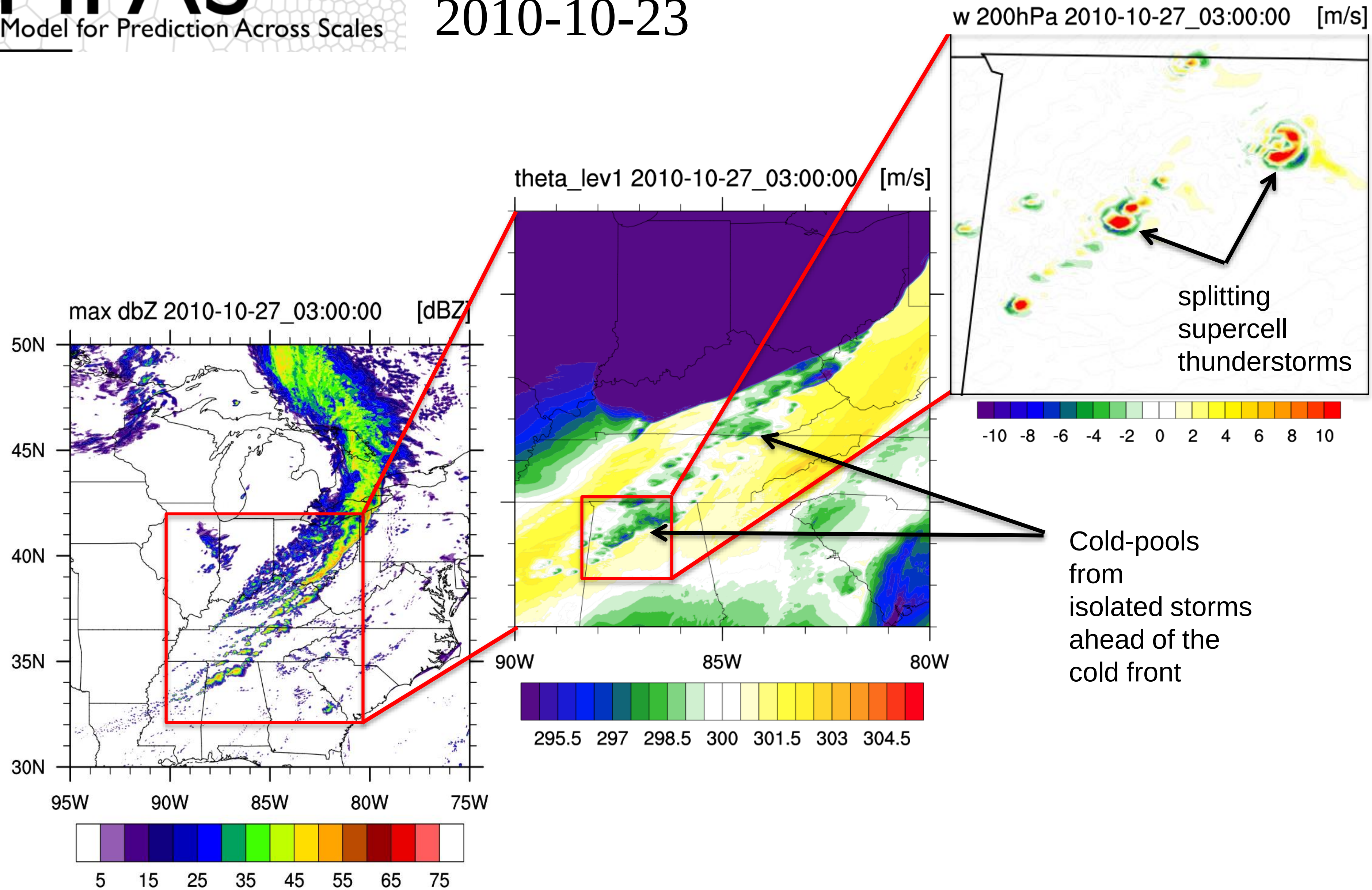
(Jk Constraint, Lateral Boundary Conditions) http://mpas-dev.github.io

- New Global model
- Nonhydrostatic
- Voronoi meshes
- Variable resolution
- WRF, CAM, GFS physics
- Scalable code
- MPAS-A (NCAR)
- MPAS-O and MPAS-LI (LANL)



Source: Bill Skamarock

3 km global MPAS-A simulation 2010-10-23



Source: Bill Skamarock

The End