Assimilating satellite microwave radiance measurements over the Antarctic

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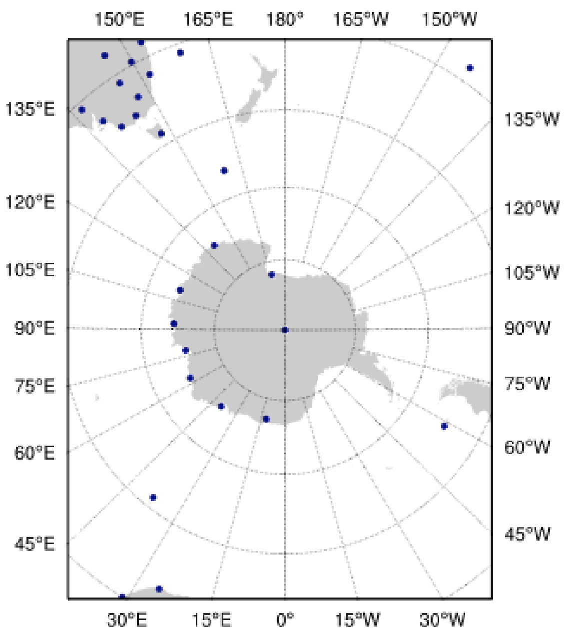
Why Antarctica?

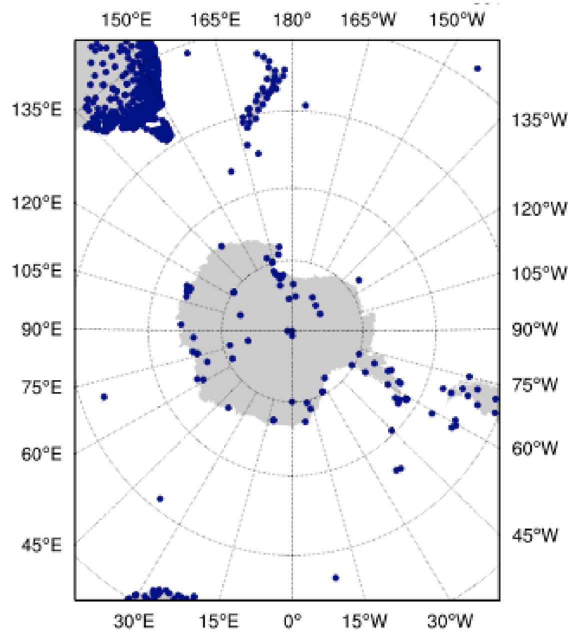
We were inspired by “Happy Feet”

Why Antarctica?

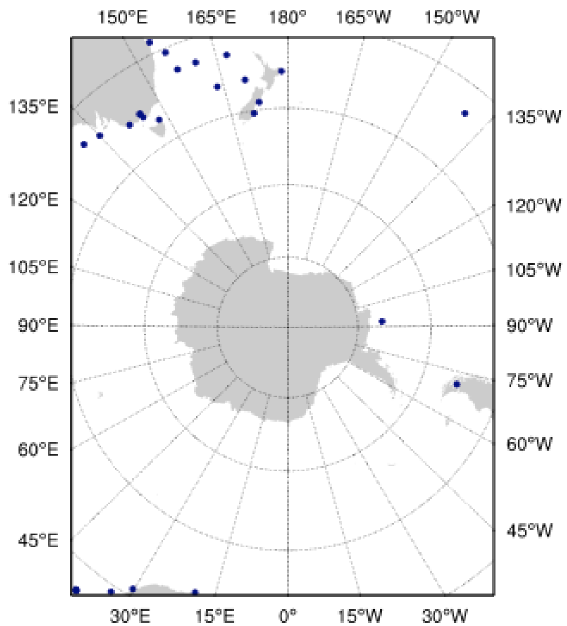
•Interesting data assimilation problem since there are few *in situ* observations, especially over the sea



Soundings



Synop



Ships

Available observations at 0000 UTC 02 Oct 2007

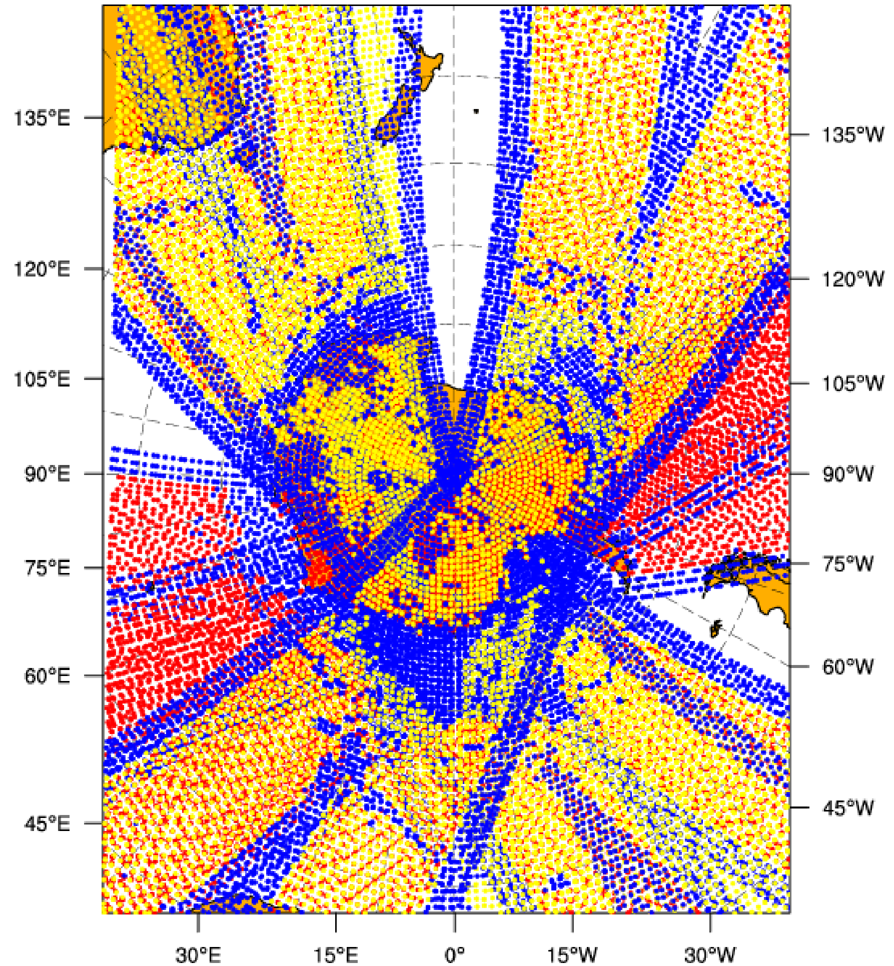
•Remotely-sensed observations are important for successful data assimilation

Microwave Radiances

- Does assimilating microwave radiances lead to better forecasts over the Antarctic?

AMSU: Advanced Microwave Sounding Unit

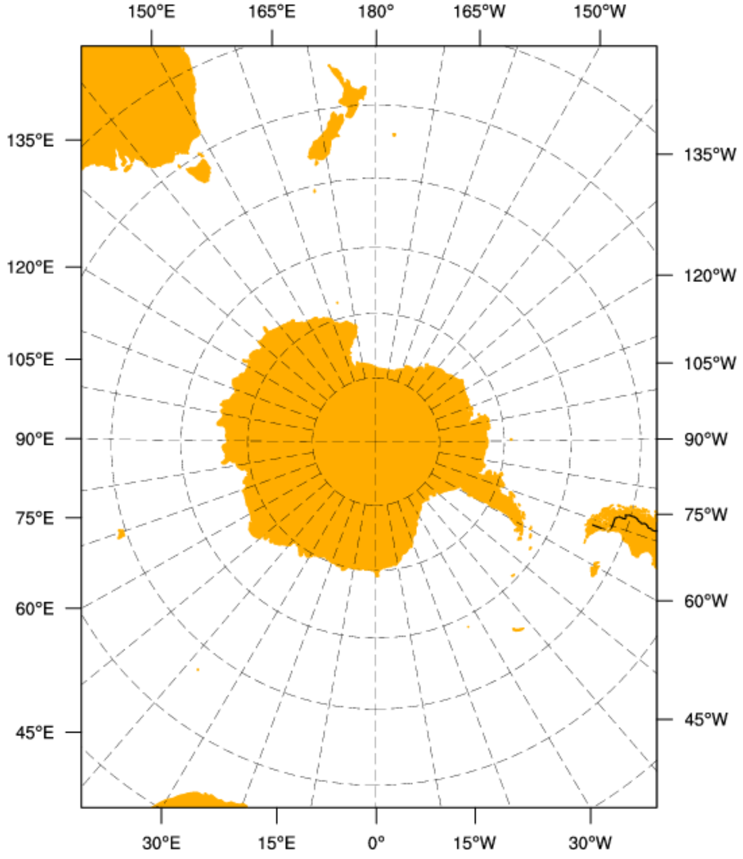
MHS: Microwave Humidity Sensor



Available AMSU-A, AMSU-B, and MHS radiance observations at 0000 UTC 02 Oct 2007

Configuration Parameters

- WRFDA 3DVAR analyses at 00 and 12 UTC over October 2007
- Analyses initialized 72-hr WRF-ARW forecasts
- 6-hr WRF forecasts (initialized by the GFS) used as backgrounds
  - <u>No “cycling” of background fields</u>
  - Lateral boundary conditions from the GFS
  - 45-km horizontal grid spacing
  - 44 vertical levels; 10 hPa model top



Experimental Design

•**<u>Three experiments</u>**

1) Assimilated conventional observations only

2) Assimilated conventional observations and AMSU-A, AMSU-B, and MHS radiances using initial *bias correction coefficients* that were "spun-up" for 3 months (July-September) before the assimilation

3) Same as #2, but with "cold-start" bias correction coefficients

What are these bias correction coefficients?

Radiance Bias Correction (BC)

- Satellite measurements are prone to error
- Biases of satellite observations are measured with respect to the data assimilation system itself
- Biases arise for several reasons:
    - Satellite instrument errors
    - Scanning position/angles
    - Atmospheric thermodynamic profile
    - The model background field

Predictor-based BC

- Specify a set of predictors to perform BC
  - Values of the predictors are known
  - Either based on the model state (e.g., thickness between two pressure levels) or properties of the observing system (e.g., scanning angle)
- Each predictor has a corresponding coefficient (β_i) that determines its weight
  - We do NOT necessarily know the weights
- Want to find the *optimal* weights (coefficients)

How to Find Optimal BC Coefficients?

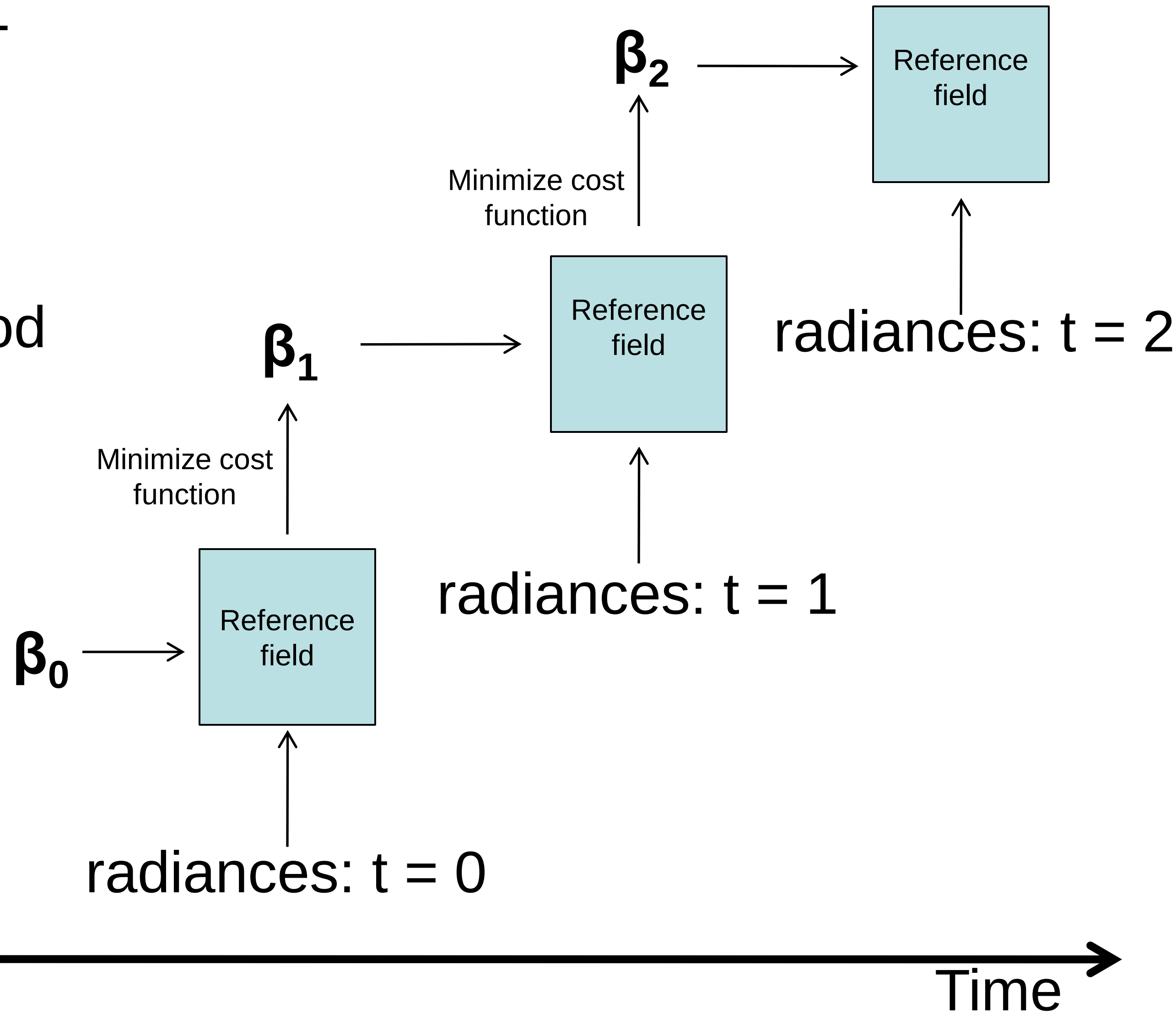
•Could do it during the analysis within the 3DVAR framework, fully considering all observations, the background field, and previous BC coefficients: "variational bias correction"

•Do it *independently* of the full analysis, just considering the radiance observations: "offline monitoring"

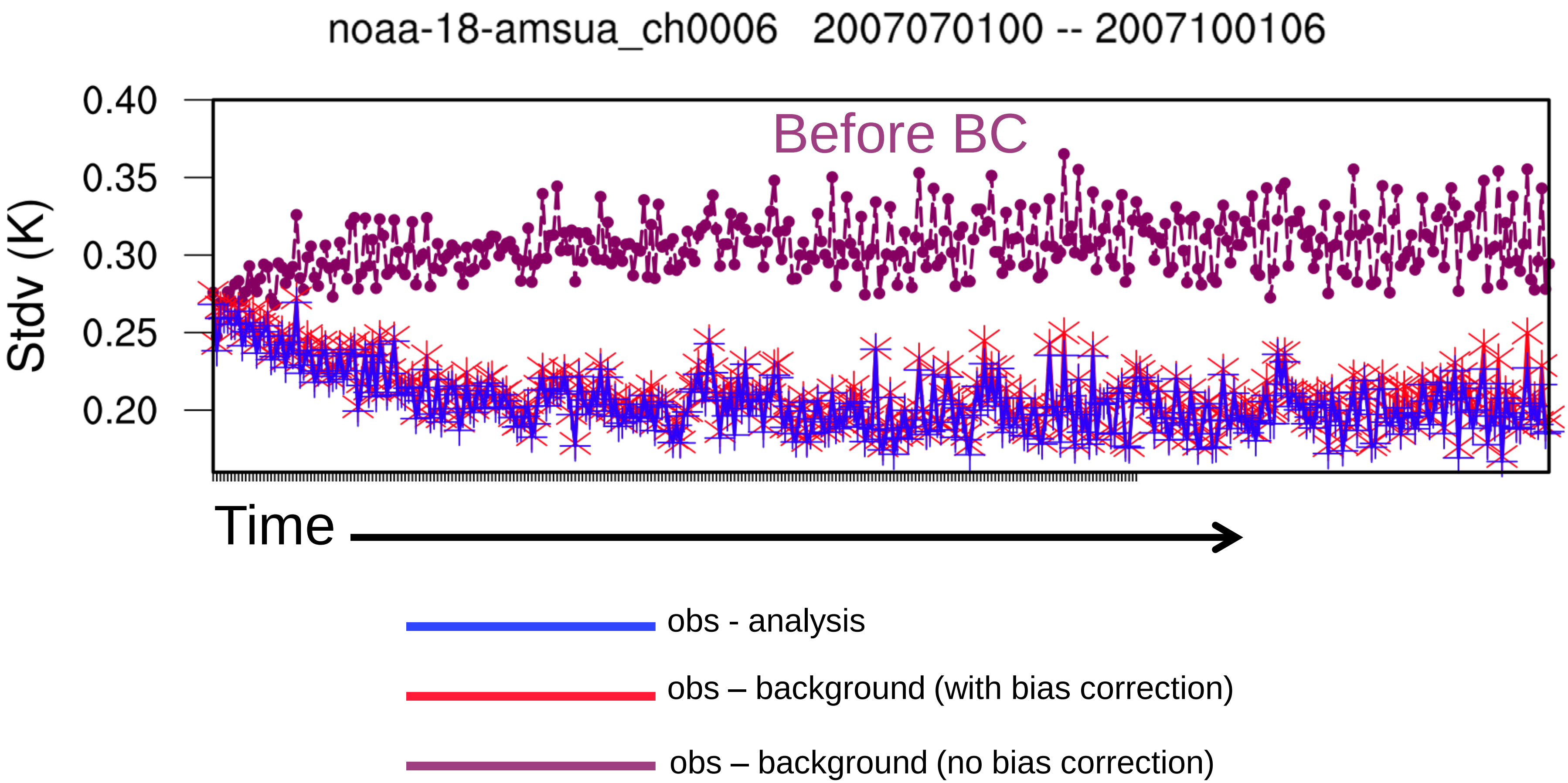
1) Assimilated conventional observations only
2) Assimilated conventional observations and AMSU-A, AMSU-B, and MHS radiances using initial *bias correction coefficients* that were "spun-up" for 3 months (July-September) before the assimilation
3) Same as #2, but with "cold-start" bias correction coefficients

Offline Monitoring Procedure

- Only “cycle” the coefficients (**β**), NOT the background field
- Assumption: The reference field is good
- Minimize cost function with **β** as sole dependent variable



Offline Monitoring Statistics

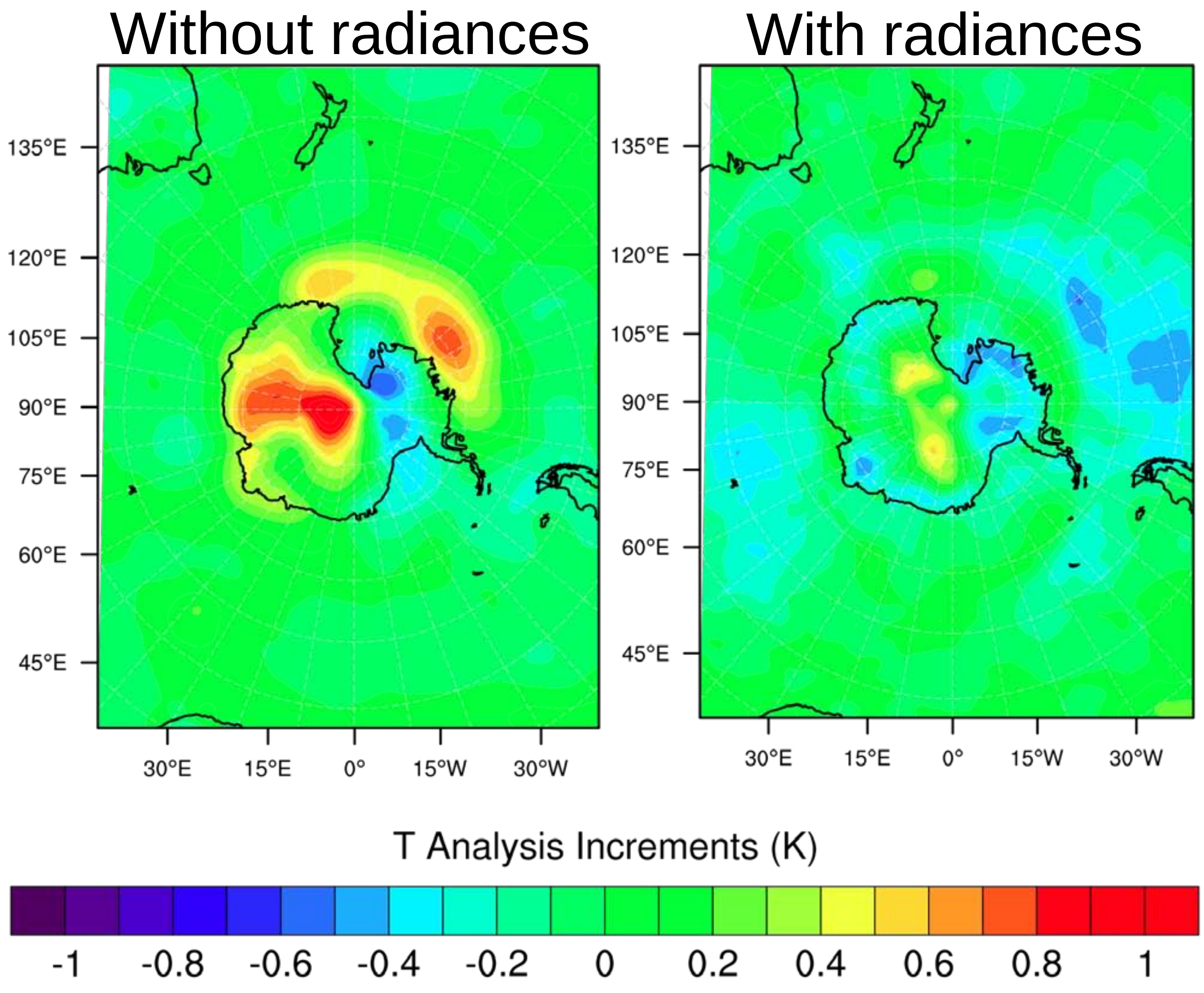


Diagnostic Approach

- Often difficult to discern visual differences between experiments
- Few observations available for verification, especially over water
- Used ERA-Interim reanalyses as “truth” and basis for verification
- Focused on statistics aggregated over all analyses/forecasts
    - Root mean square error (RMSE)

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(f_i - o_i)^2}$$

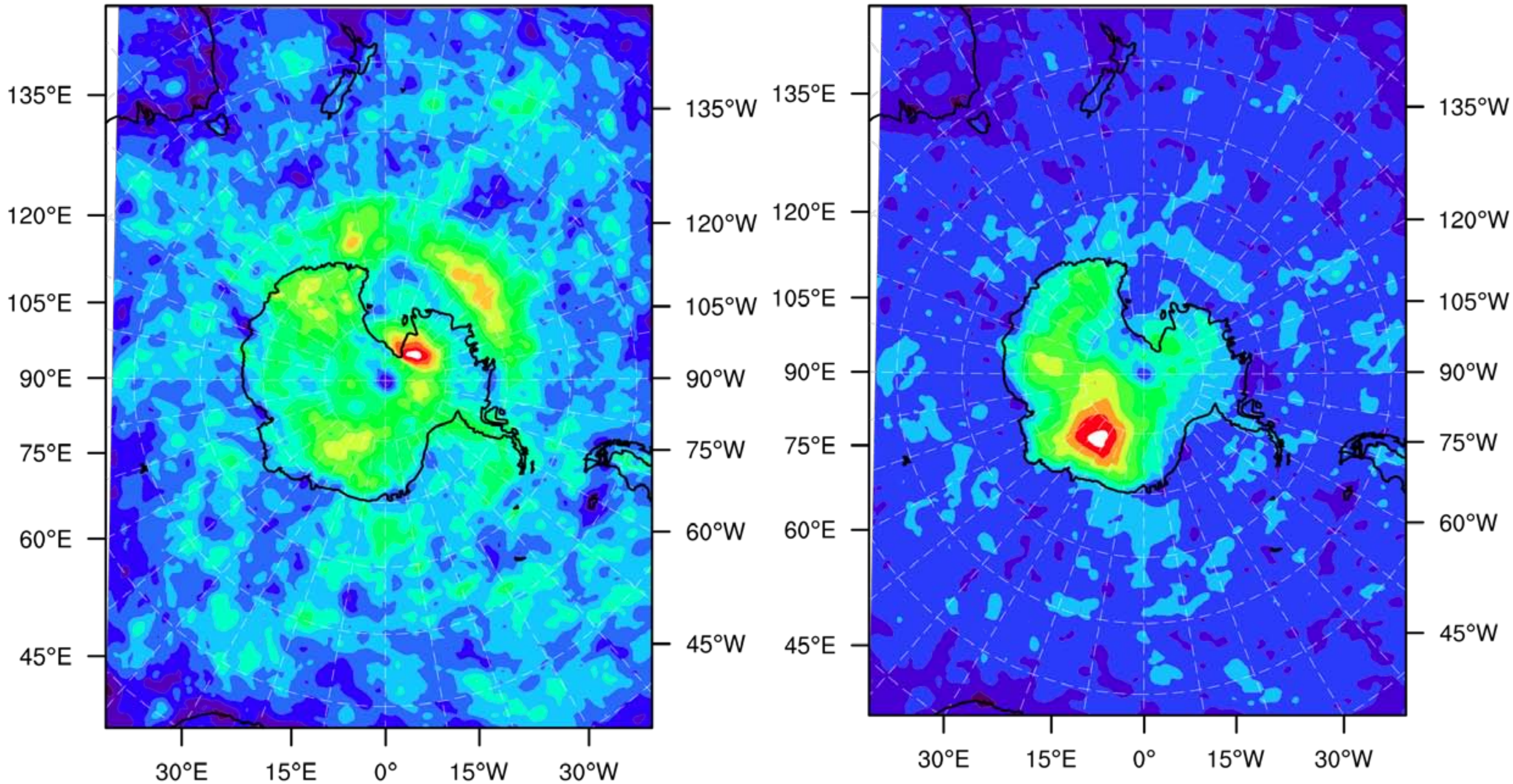
Mean 500 hPa temperature analysis increments



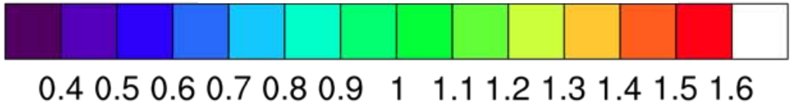
Mean 500 hPa Temperature RMSE

- RMSE at the analysis time

Without radiances | With radiances

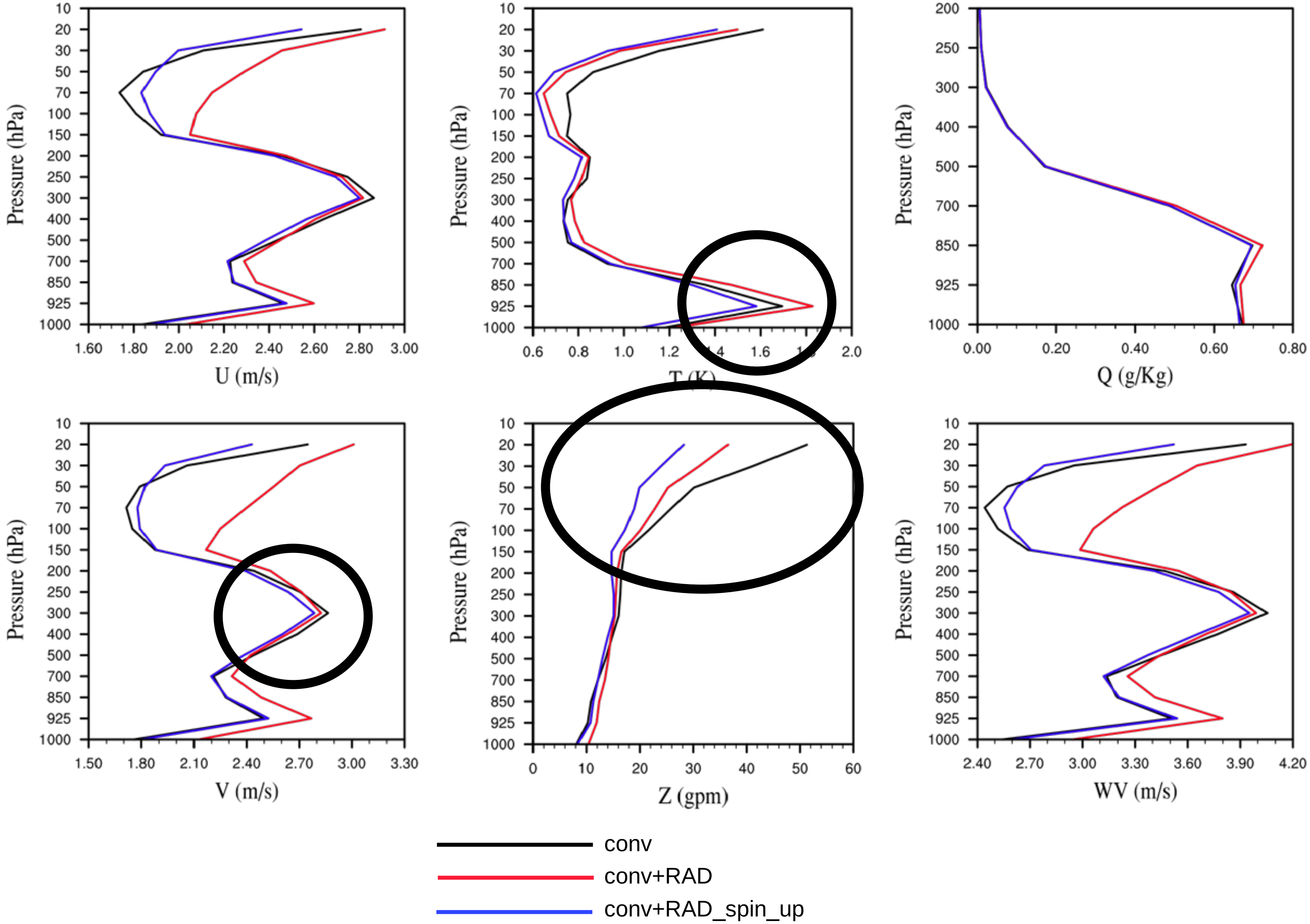


RMSE (K)



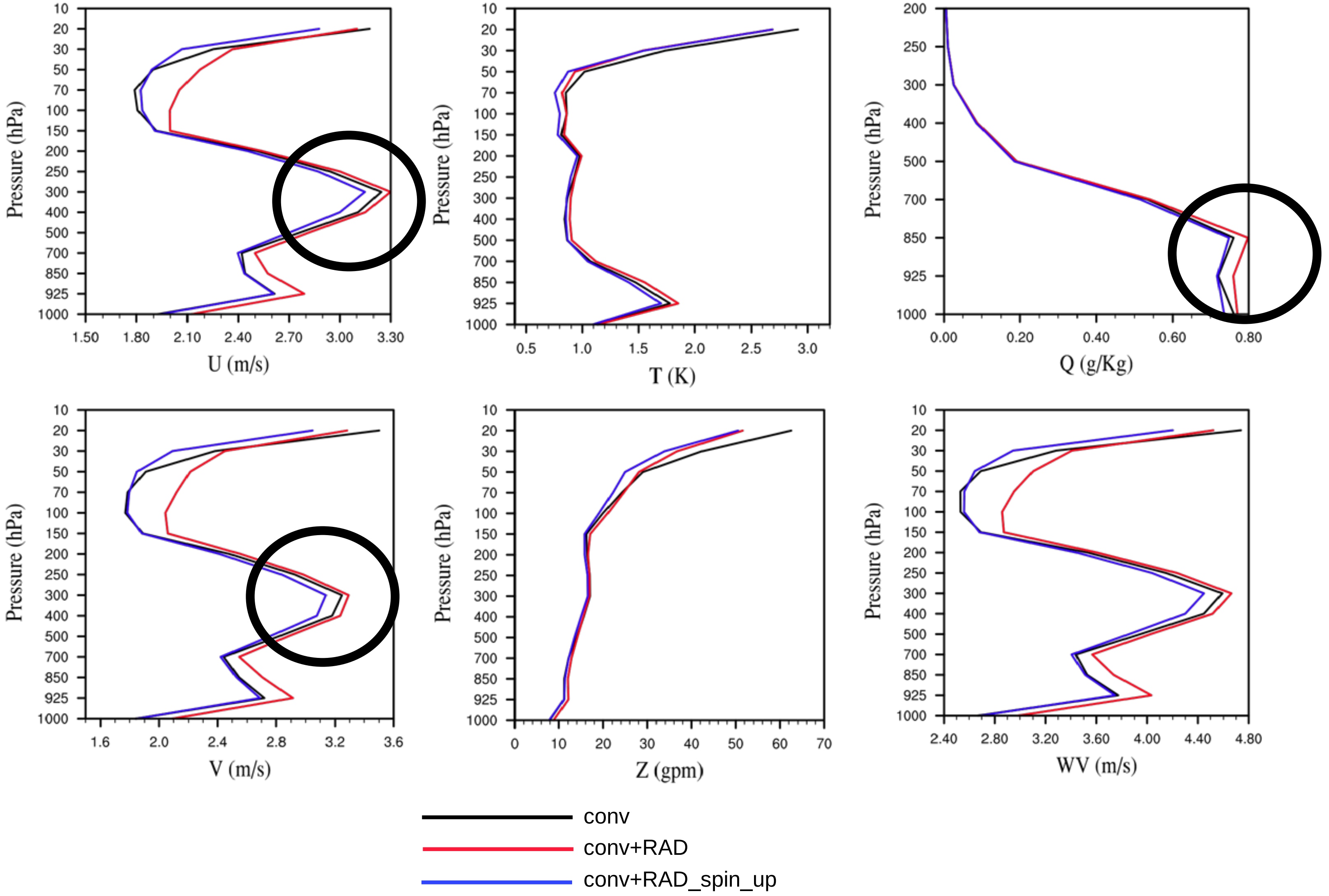
Aggregate RMSE

- RMSE at the analysis time



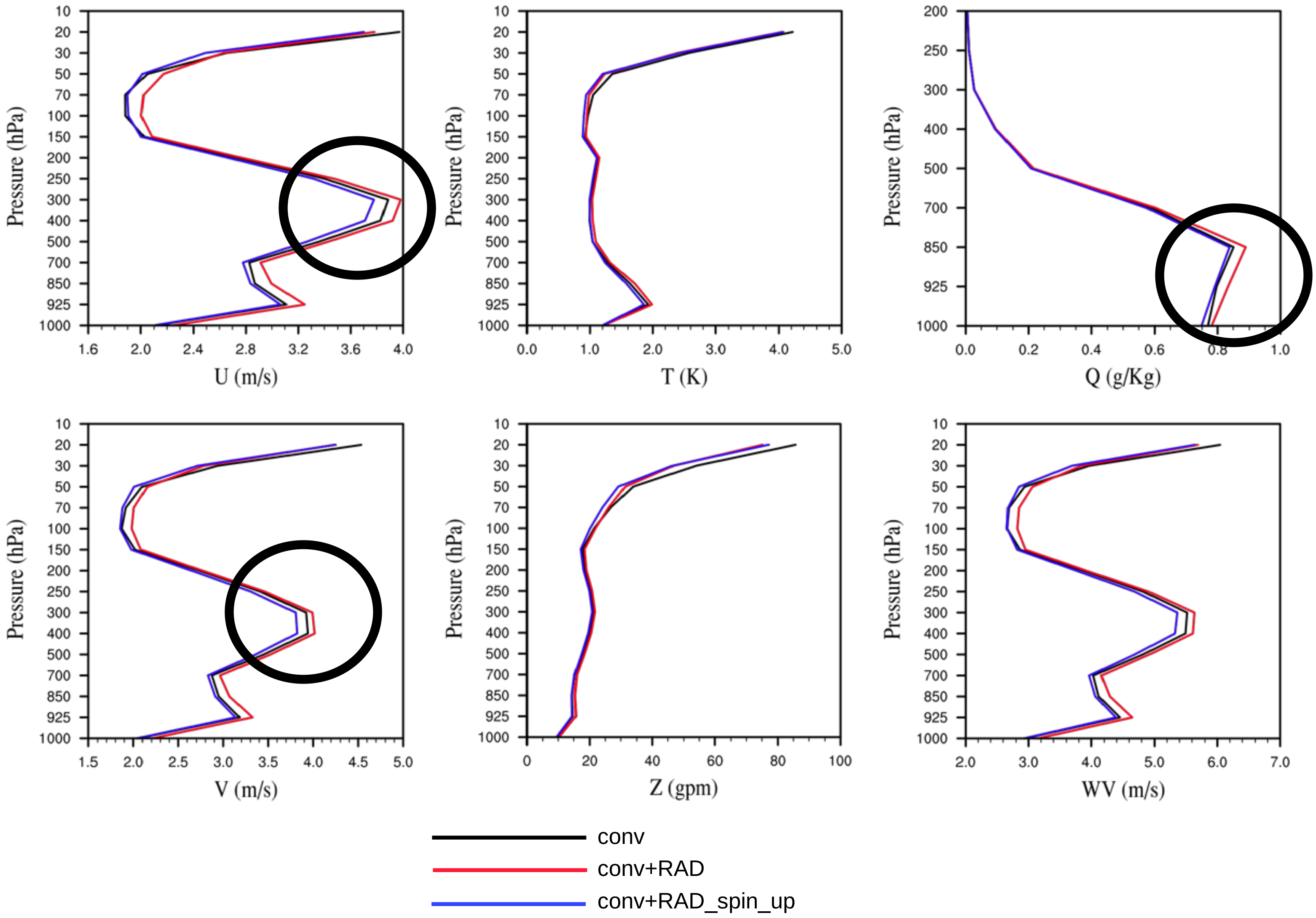
Aggregate RMSE

- RMSE for 12-hr forecasts



Aggregate RMSE

- RMSE for 24-hr forecasts



Conclusions

•Addition of radiances led to better analyses and short-term forecasts over the Antarctic when initial bias correction coefficients were spun-up

•Without initially spun-up coefficients, analyses and short-term forecasts were degraded

Properly bias correct radiances, or else…

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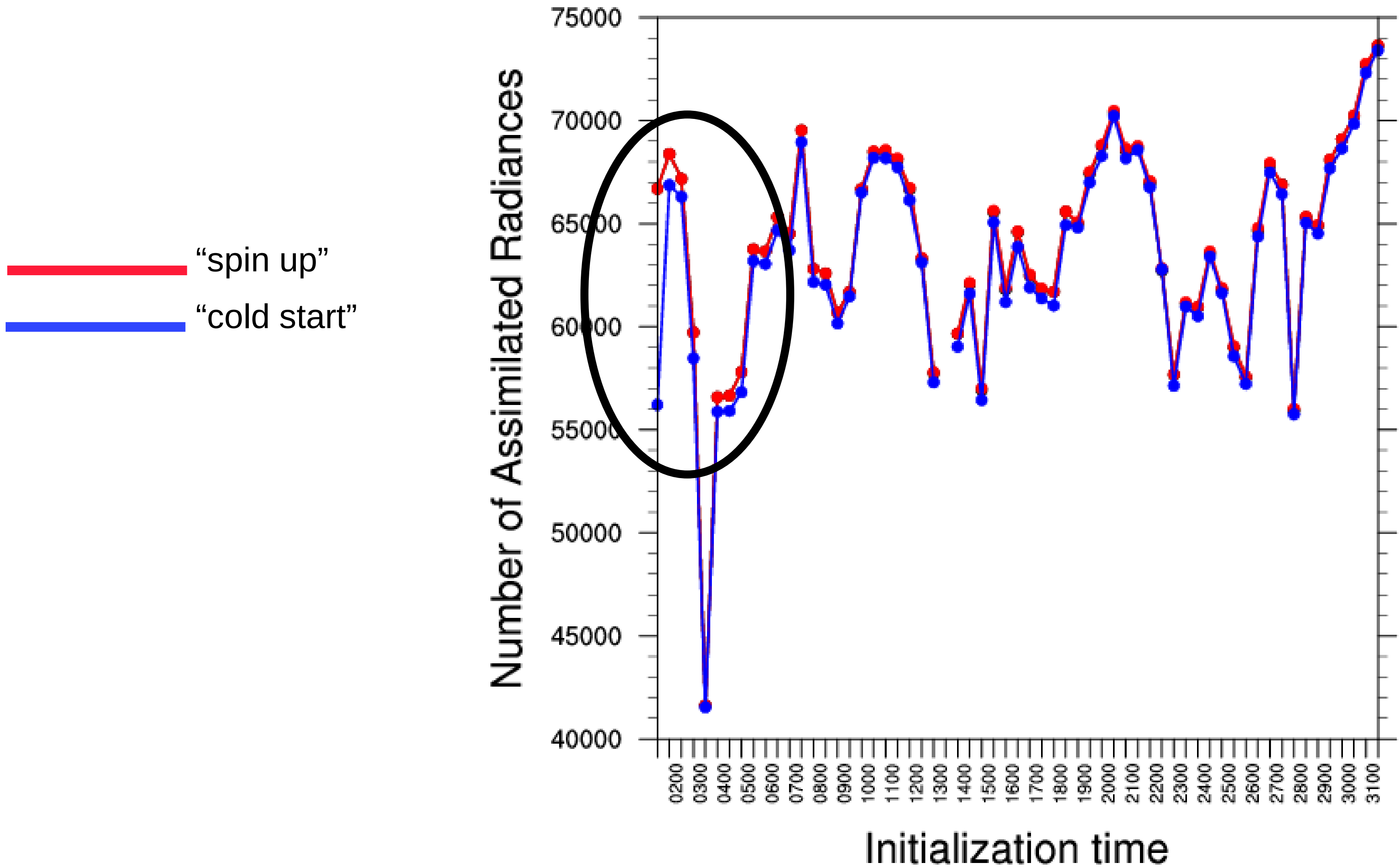
Number of Assimilated Radiances



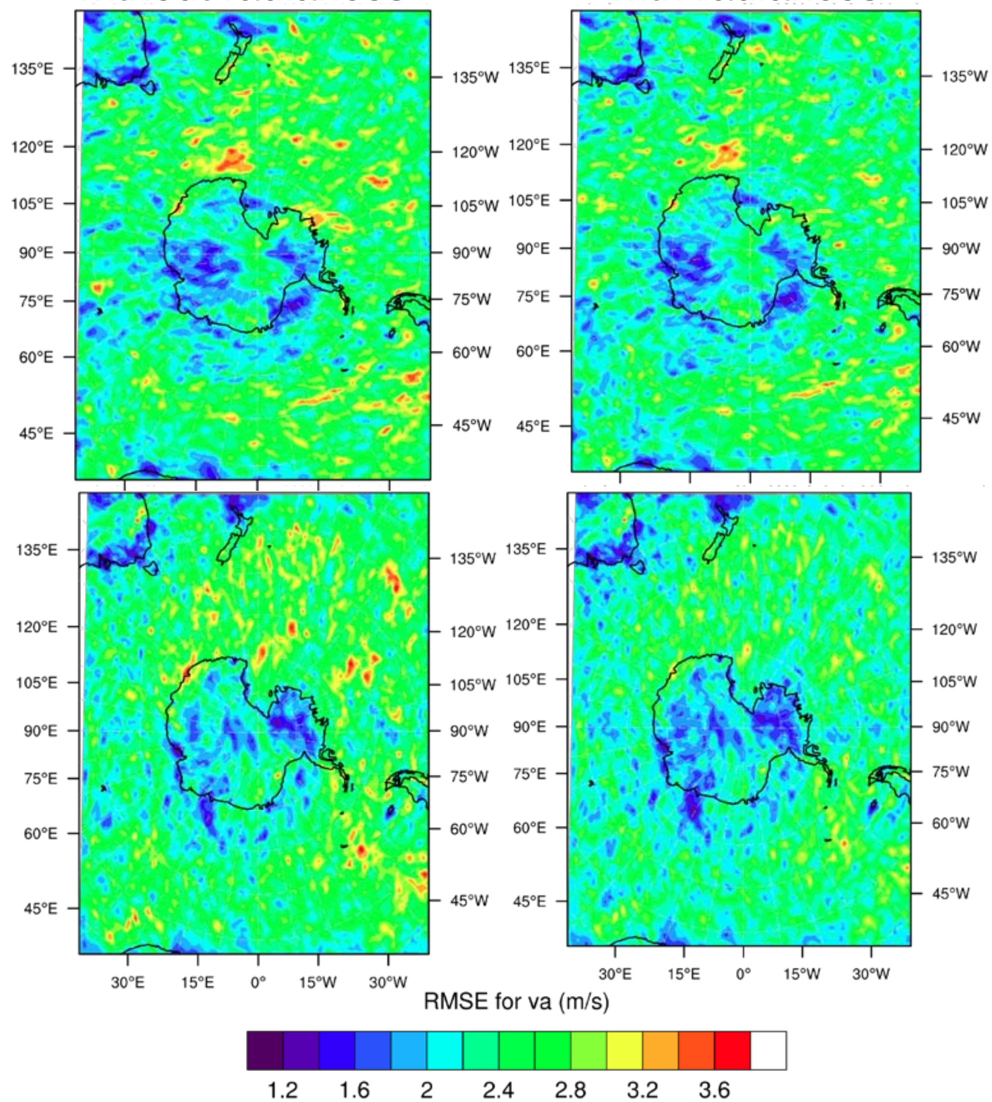
Mean 500 hPa Wind RMSE

- RMSE at the analysis time

without radiances | with radiances

u-wind

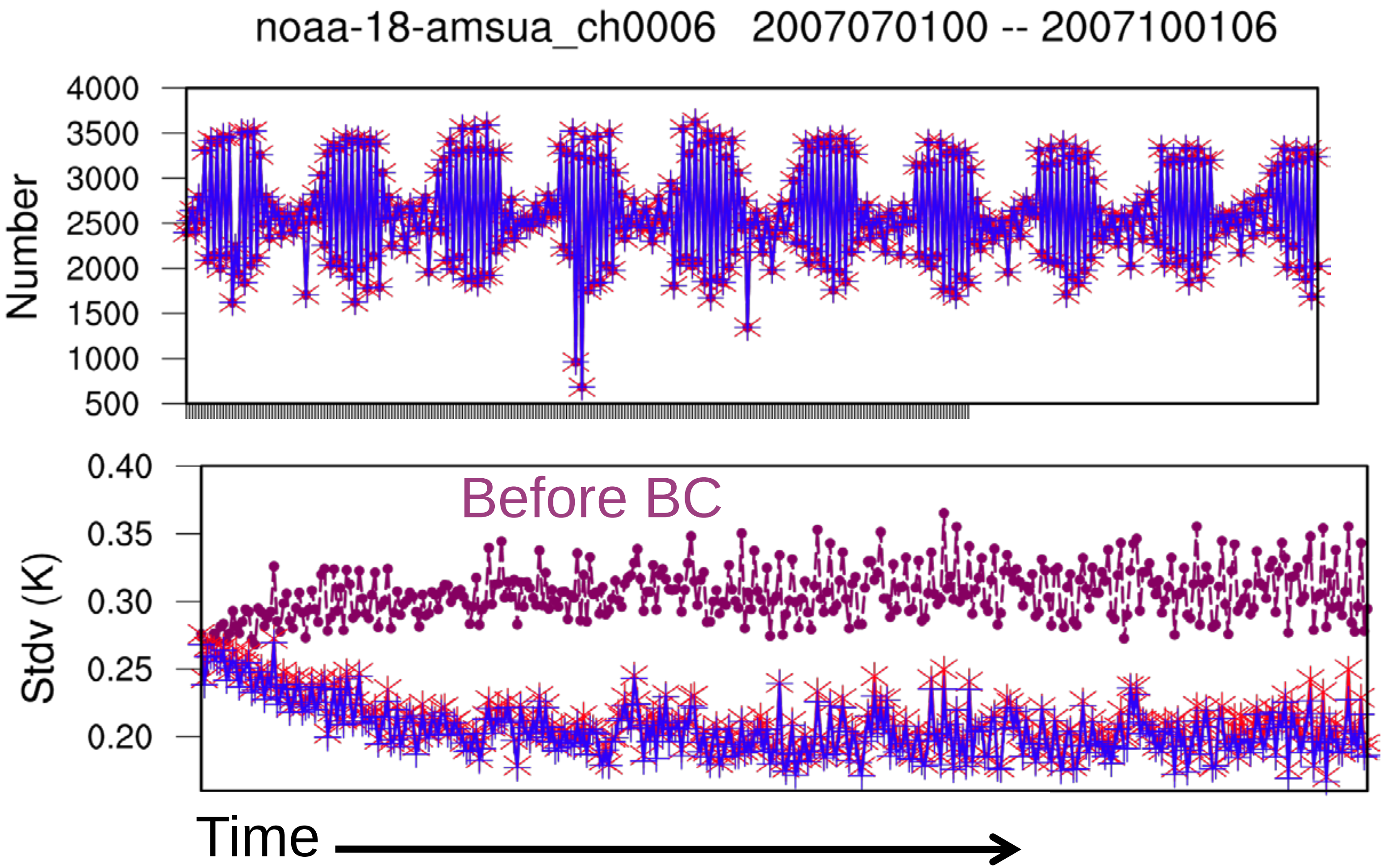
v-wind



Offline Monitoring Statistics

Number of assimilated radiances

Standard deviation



obs - analysis

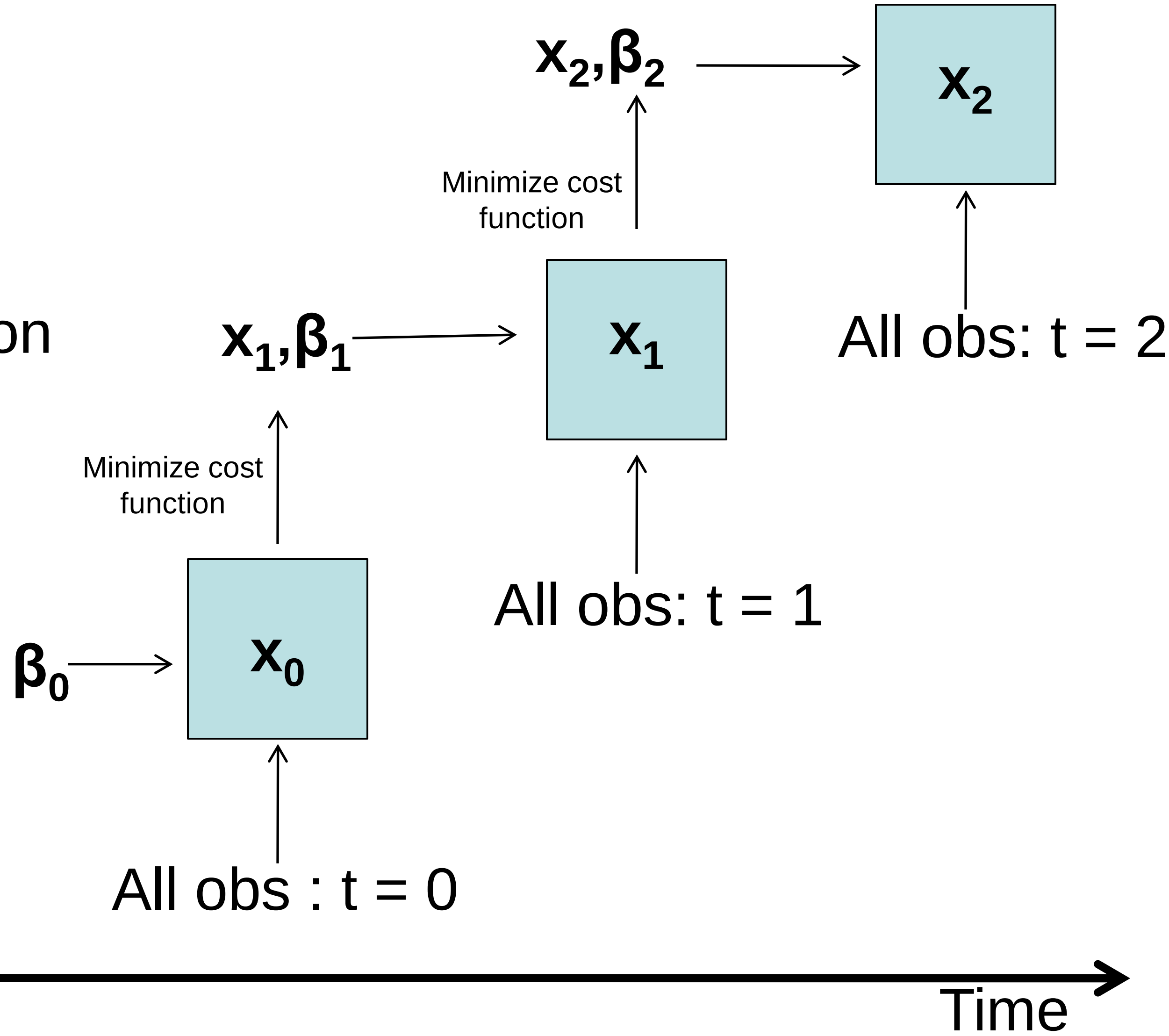
obs – background (with bias correction)

obs – background (no bias correction)

Variational BC Procedure

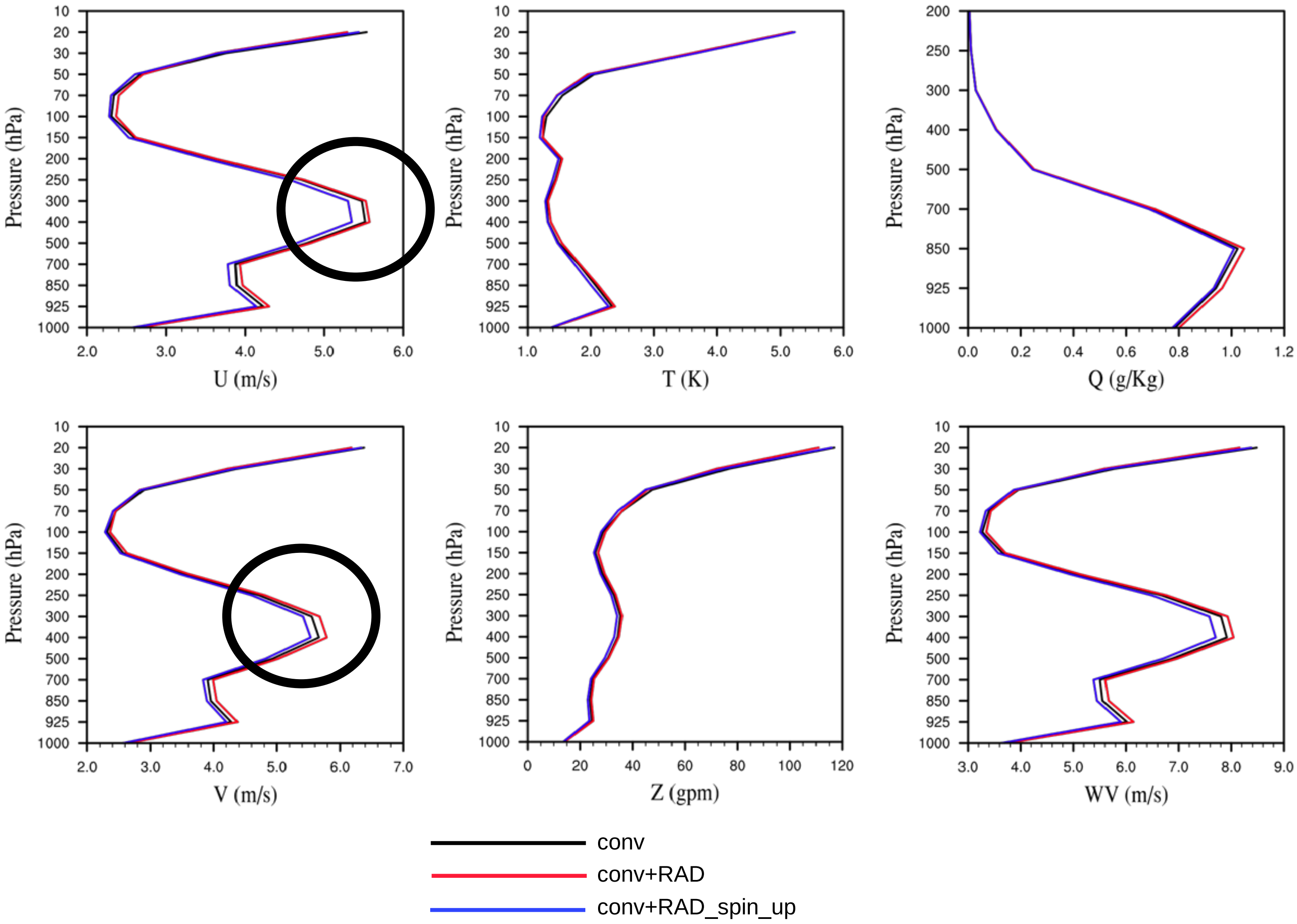
- "Cycle" the coefficients (**β**), *and* (optionally) the background

- Minimize cost function with **x** *and* **β** as dependent variables



Aggregate RMSE

- RMSE for 48-hr forecasts



Predictor-based BC

- Specify N_p predictors (p_i; $i = 1 \ldots N_p$) to perform BC
- Each predictor has a corresponding coefficient (β_i) that determines its weight
- Based on these predictors, modify the observation operator (H) for radiance observations:

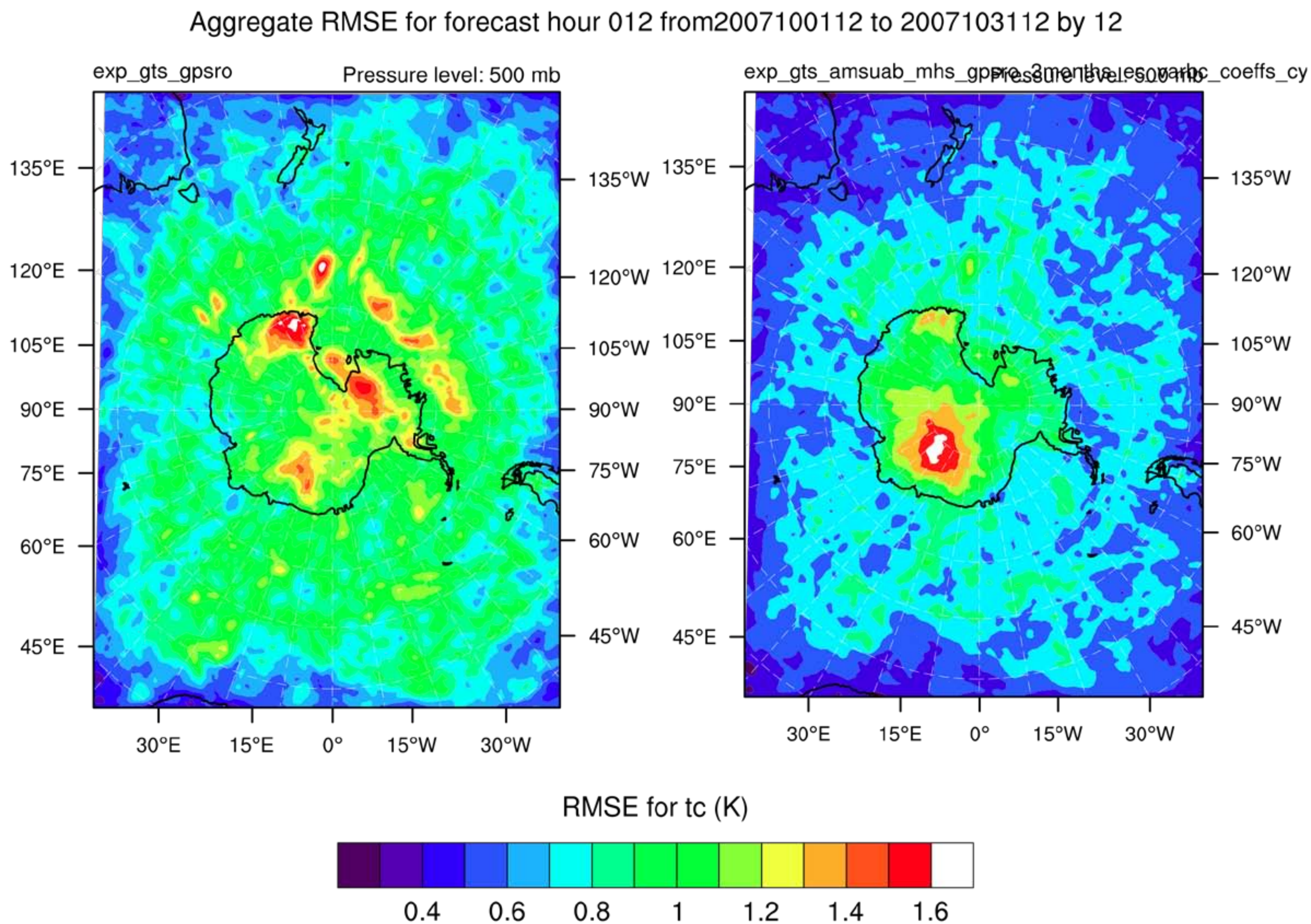
$$\tilde{H}(\mathbf{x_B}, \beta) = H(\mathbf{x_B}) + \sum_{i=1}^{N_p} \beta_i p_i(\mathbf{x_B})$$

Bias corrected radiance

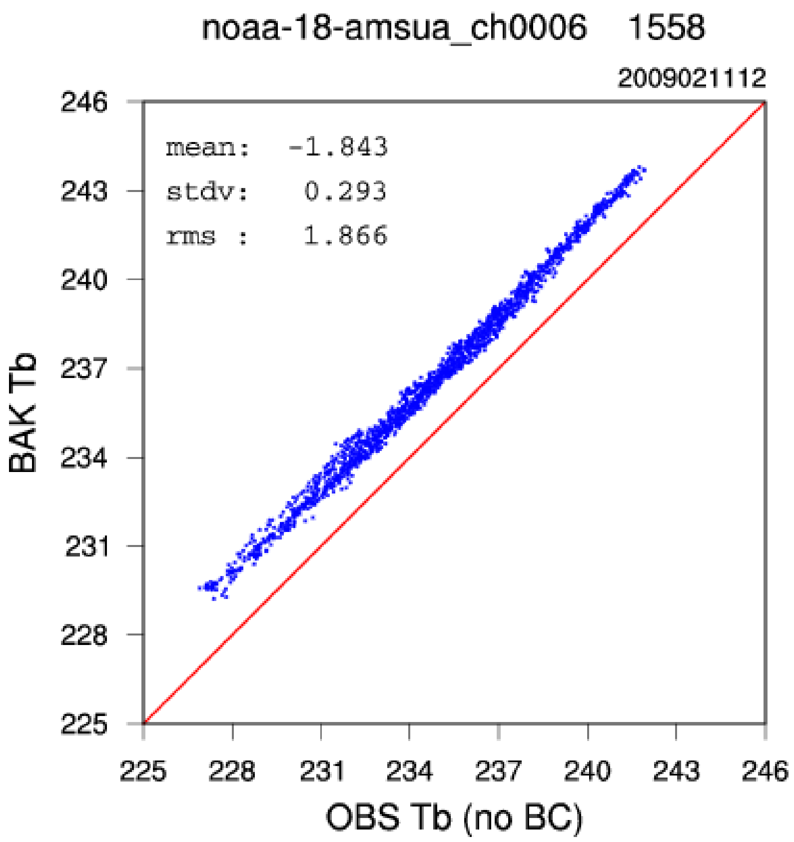
Model-simulated brightness temperature from radiative transfer model

Correction for bias

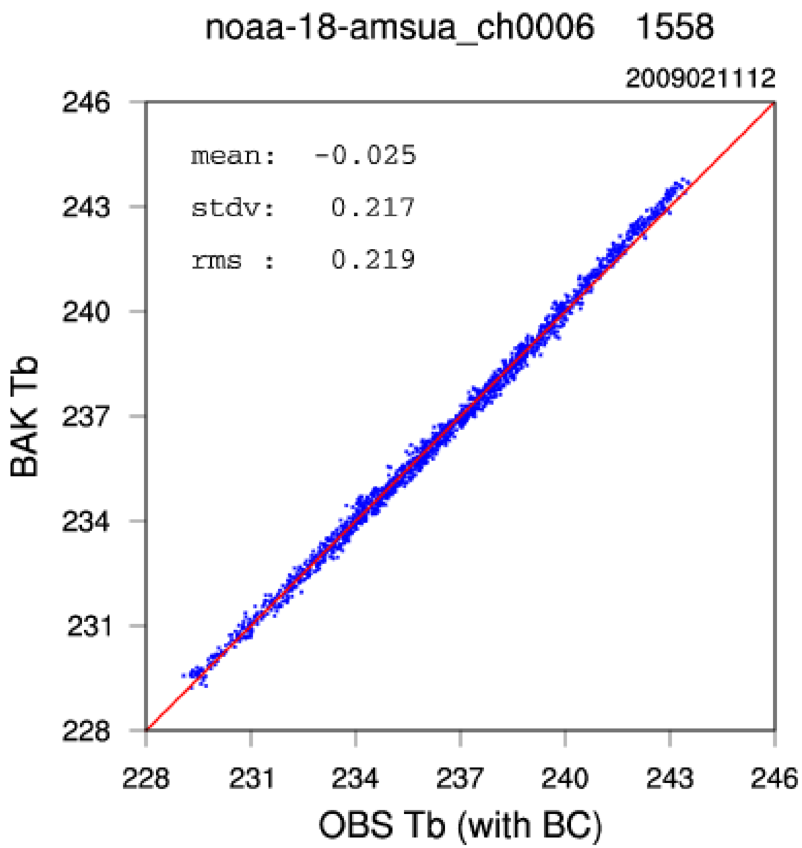
- Values of p_i are known, but we do NOT know the values of β_i


Aggregate RMSE for forecast hour 012 from2007100112 to 2007103112 by 12
exp_gts_gpsro
Pressure level: 500 mb
135°E
120°E
105°E
90°E
75°E
60°E
45°E
135°W
120°W
105°W
90°W
75°W
60°W
45°W
30°E
15°E
0°
15°W
30°W
exp_gts_amsuab_mhs_gpsro_3months_es_varbc_coeffs_cy
RMSE for tc (K)
0.4
0.6
0.8
1
1.2
1.4
1.6

Bias Correction



No bias correction



With bias correction

3DVAR Formulation

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x_b})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \frac{1}{2}(\mathbf{y}-H(\mathbf{x}))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y}-H(\mathbf{x}))$$

$J(\mathbf{x})$**:** Scalar cost function

x: The analysis: *primary field of interest!*

$\mathbf{x_b}$**:** Background field

y: Observations

***H*:** Observation operator: *includes radiative transfer model*

R: Observation error covariance matrix

B: Background error covariance matrix

Predictor-based Bias Correction

- Specify N_p predictors (p_i; i = 1…N_p) to perform bias correction (BC)

- WRFDA uses the following predictors:

  1) 1000-300 hPa thickness
  2) 200-50 hPa thickness
  3) Surface skin temperature
  4) Total column precipitable water
  5) Satellite scanning angle

  (Predictors 1–4: State-dependent)

- Each predictor has a corresponding coefficient (β_i) that determine its weight

Variational Bias Correction

- Satellites move in and out of limited-area domains
- Not always enough data to perform meaningful bias correction
- Can overcome this problem by "spinning-up" the BC coefficients for an extended period of time before the assimilation using "offline monitoring"
  - "Offline" because we do not make a complete analysis considering other data (i.e., the background, non-radiances observations)

Variational Bias Correction

- Augment state vector with the BC coefficients (**β**), which introduces another term in the 3D-VAR cost-function:

$$J(\mathbf{x},\beta)=\frac{1}{2}(\mathbf{x}-\mathbf{x_b})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b})+\boxed{\frac{1}{2}(\beta-\beta_{\mathbf{b}})^{\mathrm{T}}\mathbf{B}_{\beta}{}^{-1}(\beta-\beta_{\mathbf{b}})}+\frac{1}{2}(\mathbf{y}-\tilde{H}(\mathbf{x},\beta))^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{y}-\tilde{H}(\mathbf{x},\beta))$$

- New term for the bias-correction coefficients
- $\mathbf{B}_{\boldsymbol{\beta}}$ determines how much new coefficients depend on the old ones

Bias-corrected radiances

- This method determines **β** while considering the entire model state and other non-radiance observations

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To provide facility support to the wider community; and,
To apply the results to benefit society.