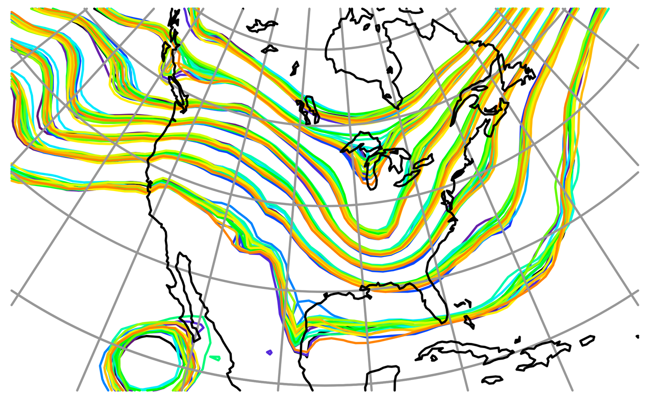

Assimilation of GPS radio occultation refractivity with WRF using a non-local observation operator

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1. GPS Radio Occultation (RO) Refractivity

1.1 What is RO refractivity?

When radio signals from GPS satellites pass through the atmosphere, the raypaths are bent and the signal is slowed. The changes depend on the atmosphere's density along the path. Low-Earth-orbiting (LEO) satellites intercept the signals just above Earth's horizon and measure the bend and signal delay. The profiles of atmospheric refractivity as a function of height can be derived.

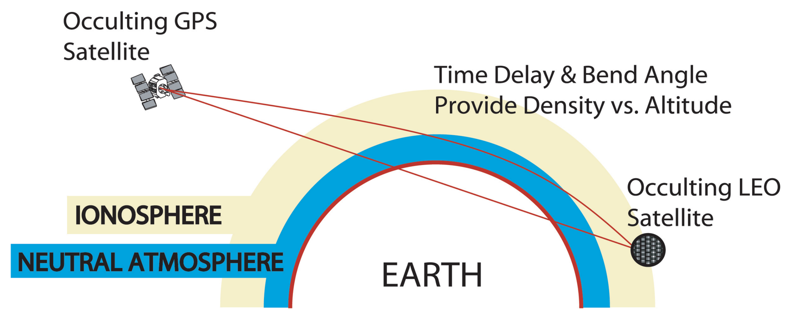

Figure 1: *Illustration of Radio Occultation.*

1.2 Reasons to use refractivity:

- high vertical resolution ($\sim$100m near the surface) information about water vapor and temperature distribution,
- not contaminated by precipitation or thick clouds, and
- global coverage.

2. Assimilation of GPS RO refractivity with WRF model

2.1 Purpose

To demonstrate that assimilation of GPS RO data using the non-local RO operator will improve:

- analyses of water vapor and temperature, and
- forecasts of high impact weather, (i.e. winter storms, hurricanes).

2.2 Assimilation System

The Data Assimilation Research Testbed (DART) ensemble data assimilation system (http://www.image.ucar.edu/DAReS/DART) is used to assimilate the observations. The system uses flow-dependent forecast error covariances, which are important for mesoscale forecasts and analyses. NCAR's Weather Research and Forecast (WRF) model is used with a 50km resolution configuration for the North American domain.

2.3 Experiments

We examine the impact of the RO refractivity on the analyses of water vapor and temperature in these three cases:

- Exp I: Assimilate only satellite cloud drift wind observations,
- Exp II: Exp I plus RO refractivity using the non-local operator,
- Exp III: Exp II, but using the local refractivity operator.

Assimilations are done continuously for January 2003. Analyses are generated every 6 hours. Radiosondes within 200km and $\pm$ 3 hours are used for verification.

3. The RO observations

In January 2003, there were 536 RO refractivity profiles available over the North American domain (the data is 7 times denser since 2007).

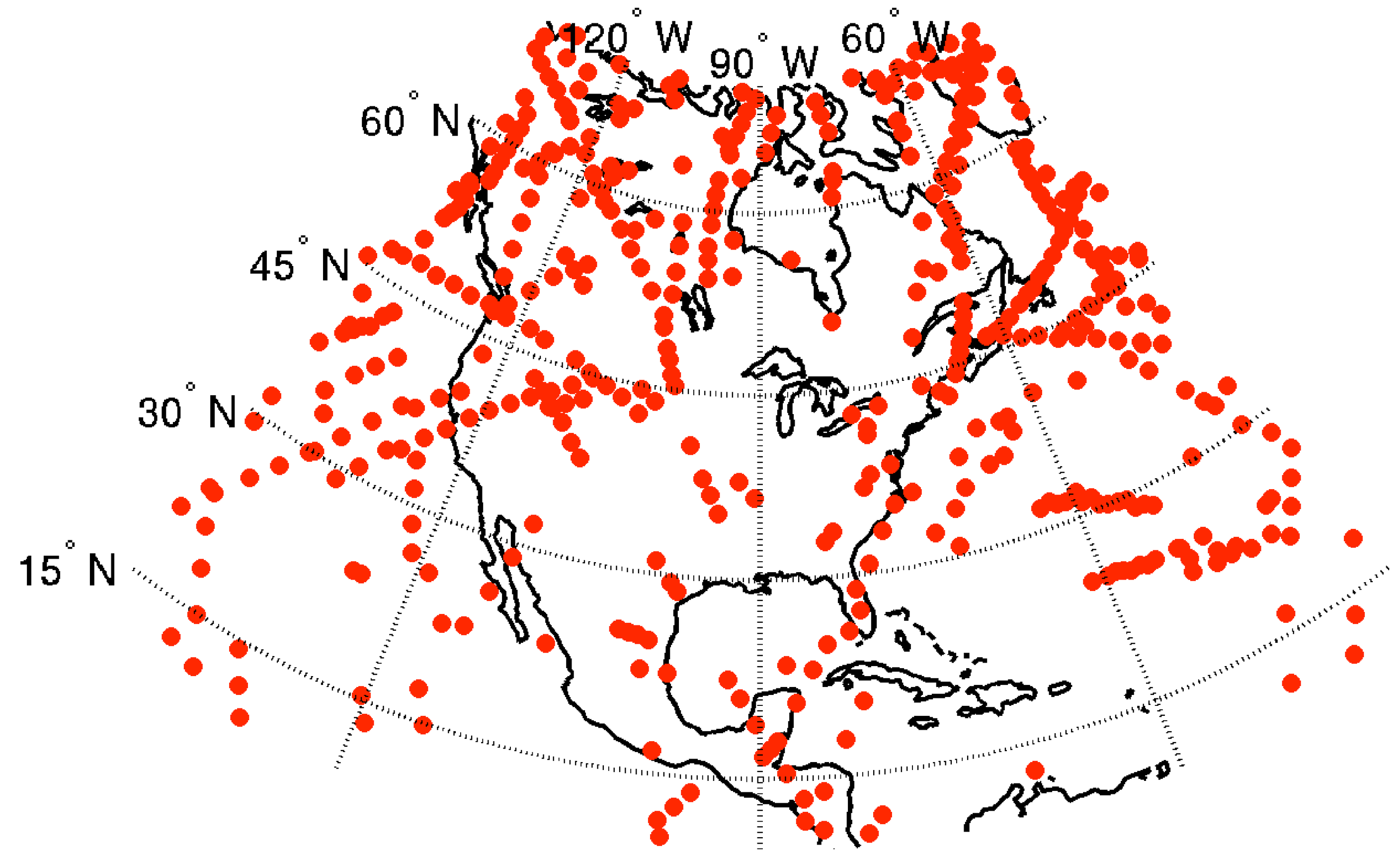

Figure 2: *Locations of RO profiles over the North American domain during January 2003.*

4. Non-local vs. local RO operators.

In the lower troposphere, atmospheric density may have large mesoscale variations along the raypath. Ignoring these variations can result in large forward modeling error of refractivity. Use of non-local operators will reduce the error.

4.1 The non-local operator

The neutral atmosphere's refractivity is defined as:

$$\mathbf{N} = (n-1) * 10^6 = 77.6 \times P/T + 3.73 * 10^5 \times e/T^2 \qquad (1)$$

where, P is pressure, T is temperature, and e is water vapor partial pressure. The non-local operator (Sokolovskiy et al. 2005) defines a new variable S as an integration of the refractivity along the raypath:

$$\mathbf{S}_{\mathbf{guess}} = \int_{raypath} \mathbf{N}_{\mathbf{guess}}(x, y, z)dl \qquad (2)$$

A similar calculation is done for the observation and the variable S is assimilated.

4.2 A local operator

For comparison, a local operator is also evaluated. It linearly interpolates the model refractivity in the vertical and horizontal directions to the observed location. This is a frequently used forward operator.

5. Results

It can be seen from Fig.3 that in the presence of satellite wind observations, the assimilation of GPS RO data using the non-local operator reduced both bias and RMS error of the temperature and water vapor analyses compared with the use of the local operator, especially in the lower troposphere.

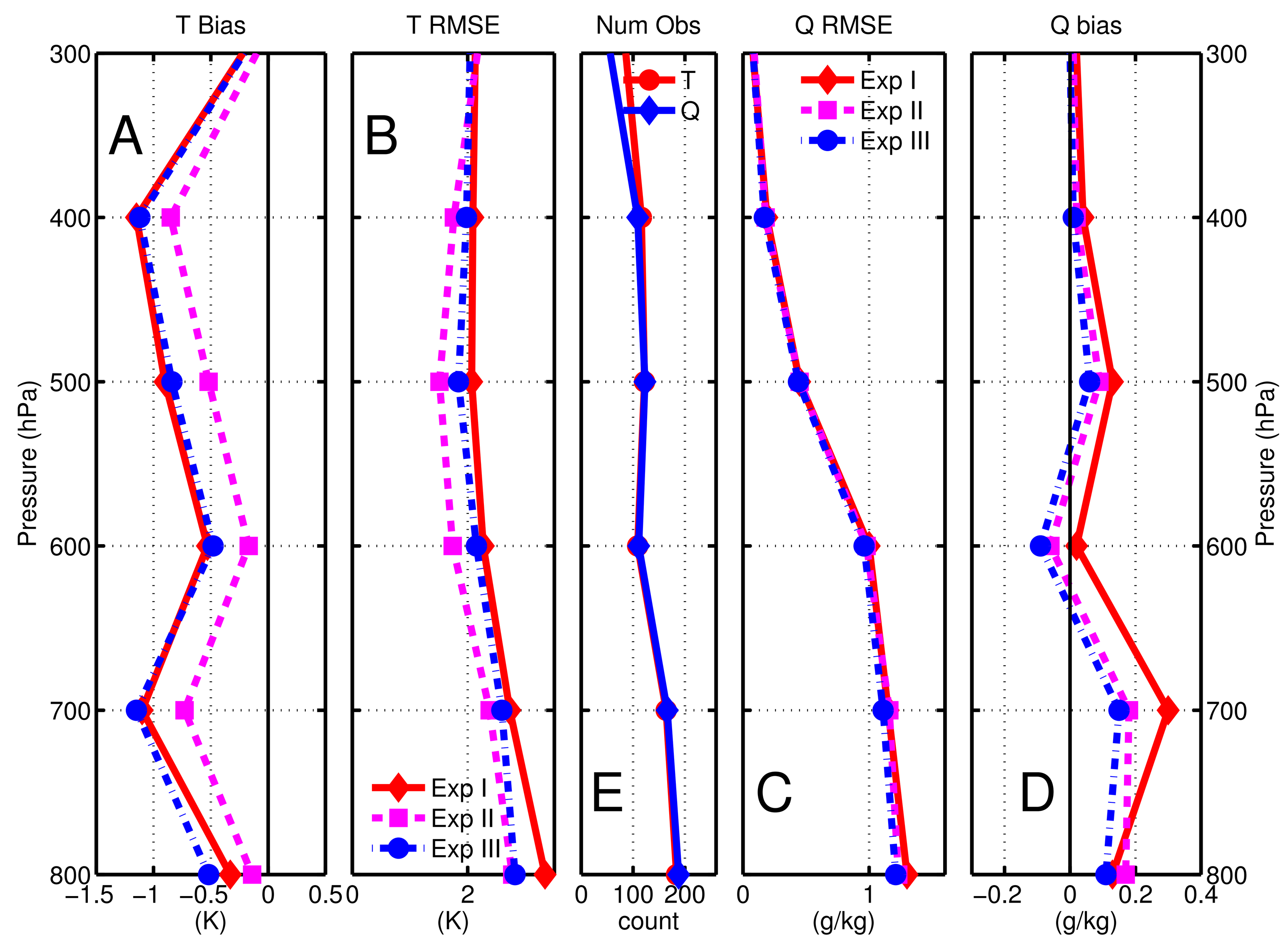

Figure 3: *Panel A shows the vertical distribution of mean error (i.e. bias) of the temperature analyses with respect to the co-located radiosondes (withheld from the experiments) for all three experiments. Panel B is the RMSE of the temperature analyses. Panel C is the RMSE for water vapor, panel D is the bias for water vapor. Panel E (middle) shows the number of verifying radiosonde observations.*

References

[1] Anderson, J., 2003, A Local Least Squares Framework for Ensemble Filtering, *Mon. Wea. Rev.*, **131**, 634-642.

[2] Liu H., J. Anderson, Y.-H. Kuo, C. Snyder, and A. Caya, Evaluation of a non-local quasi-phase observation operator in assimilation of CHAMP radio occultation refractivity with WRF, *Mon. Wea. Rev.*, (In press).

[3] Sokolovskiy S., Y.-H. Kuo and W. Wang. 2005, Evaluation of a Linear Phase Observation Operator with CHAMP Radio Occultation Data and High-Resolution Regional Analysis, *Mon. Wea. Rev.*, **133**, 3053-3059.

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