Performance of a local ensemble transform Kalman filter for the analysis of atmospheric circulation and distribution of long-lived tracers under idealized conditions

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Atmospheric tracer simulations

- Numerical simulations (e.g., transport models, CTMs) have been widely used for investigating chemical constituents variations in the atmosphere.
- These simulations can be improved through the use of advanced data assimilation technique (high-quality met. analysis, efficient concentration assimilation)
- The quality of meteorological analysis significantly affects these simulation results. The physically imbalanced analysis increment may lead to unrealistic circulations.
- EnKF allows the production of physically balanced analysis fields, similar to the 4D-VAR system. It may have advantages to analyze atmospheric transport properties.
- Chemical constituent data assimilation systems have recently been developed. The

This study evaluates the performance of the EnKF in the analysis of atmospheric circulation and long-lived tracer distributions, and shows how EnKF data assimilation improves the long-lived tracer analysis.

Local ensemble transform Kalman filter (LETKF, Ott et al., 2004; Hunt et al., 2007) has conceptual and computational advantages over the original EnKF.

$$\mathbf{x}_{n,i}^{b} = M\left(\mathbf{x}_{n-1,i}^{a}\right).$$

In the forecast step, a background ensemble is obtained from each ensemble member according to the model,

$$\mathbf{y}_{i}^{b} = H\left(\mathbf{x}_{i}^{b}\right),$$

$$\mathbf{Y}^{b} = \mathbf{y}_{i}^{b} - \overline{\mathbf{y}^{b}},$$

In the analysis step, background observation vectors and background perturbations in the observation space are obtained

The local analysis error covariance in the ensemble space is expressed by

$$\tilde{\mathbf{P}}^{a} = \left[(k-1)\,I + \left(\mathbf{Y}^{\mathrm{b}}\right)^{T}\mathbf{R}^{-1}\mathbf{Y}^{\mathrm{b}}\right]^{-1},$$

The analysis weights and perturbation analysis matrices of weights are

$$\overline{\mathbf{w}^{a}} = \tilde{\mathbf{P}}^{a}\left(\mathbf{Y}^{\mathrm{b}}\right)^{T}\mathbf{R}^{-1}\left(\mathbf{y}^{o} - \overline{\mathbf{y}^{b}}\right),$$

$$\mathbf{W}^{a} = \left[(k-1)\,\tilde{\mathbf{P}}^{a}\right]^{1/2},$$

Finally, the new analysis mean and ensemble analyses in the model space are obtained

$$\overline{\mathbf{x}}^{a} = \overline{\mathbf{x}}^{b} + \mathbf{X}^{b}\overline{\mathbf{w}^{a}},$$

$$\mathbf{x}_{i}^{a} = \overline{\mathbf{x}}^{b} + \mathbf{X}^{b}\mathbf{w}_{i}^{a},$$

The LETKF solves the analysis equation in a local volume centered on each grid point.

Perfect model experiments

Assume that forecast models provide a perfect representation of the atmosphere

•Models: FRCGC transport model coupled toT42L32 CCSR/NIES AGCM

•Transport (CO2): Grid-scale & sub grid-scale transport, 10 min interval

•No chemistry, Surface flux: anthropogenic, biospheric, and oceanic components

•A reference solution ← Forecast model simulation

•Artificial observational data ← Reference solution + obs. error (U,V,T,Q,PS,CO2)

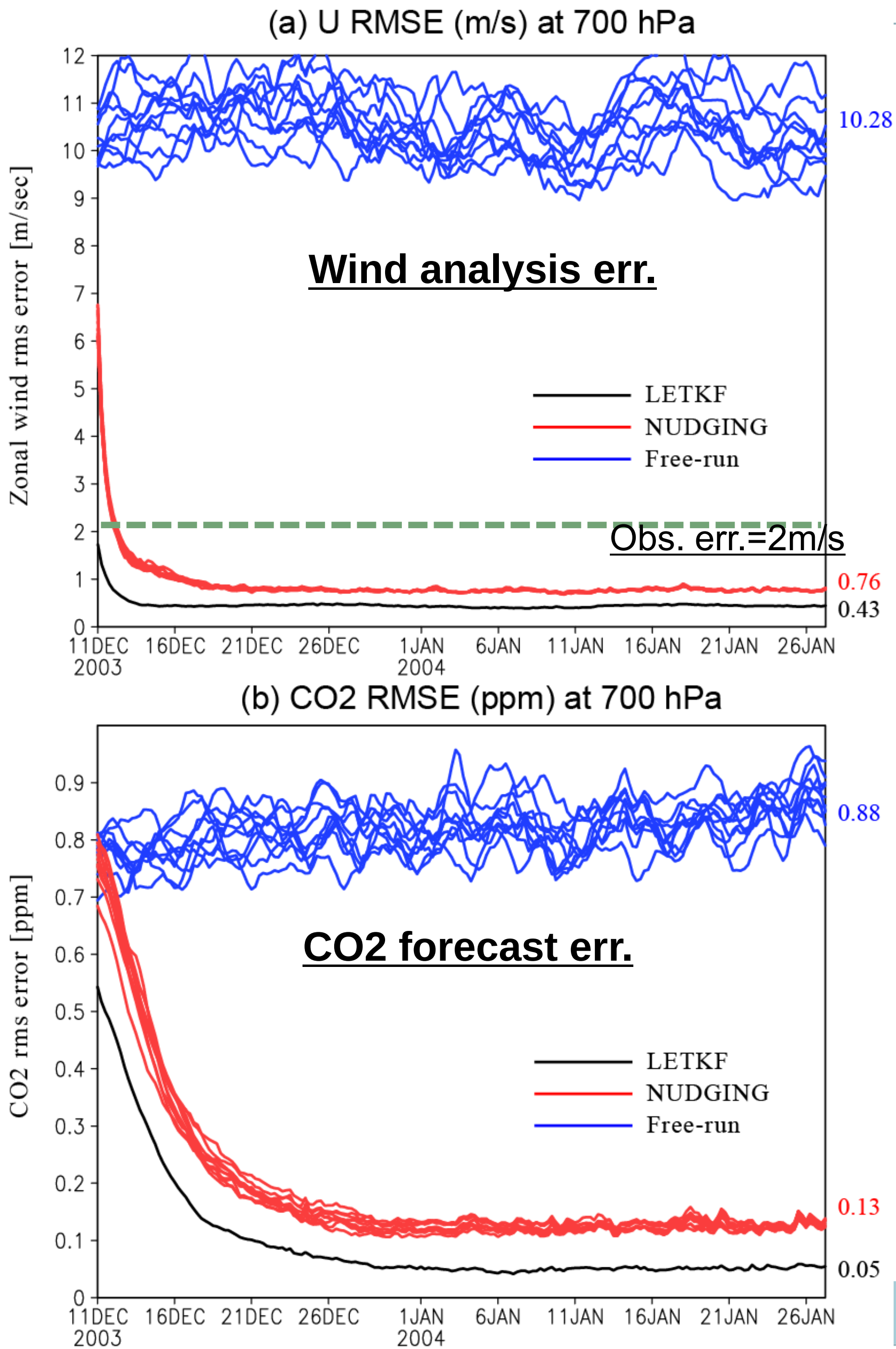
• Analyzed meteorological fields → Atmospheric transport model

•50 members, covariance inflation=8%, local patch grid size =3*3*3

•Observations were located at 25% of the model grid points

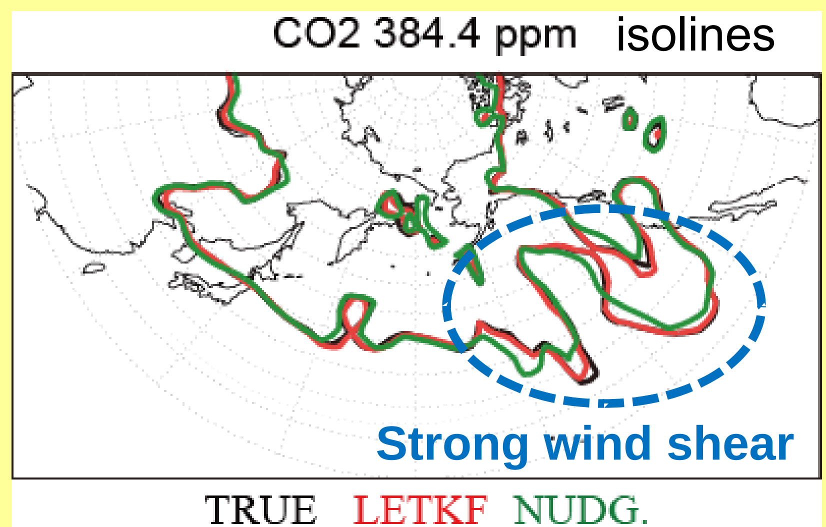
•Background error covariance for initial assimilation ← Lagged average forecast

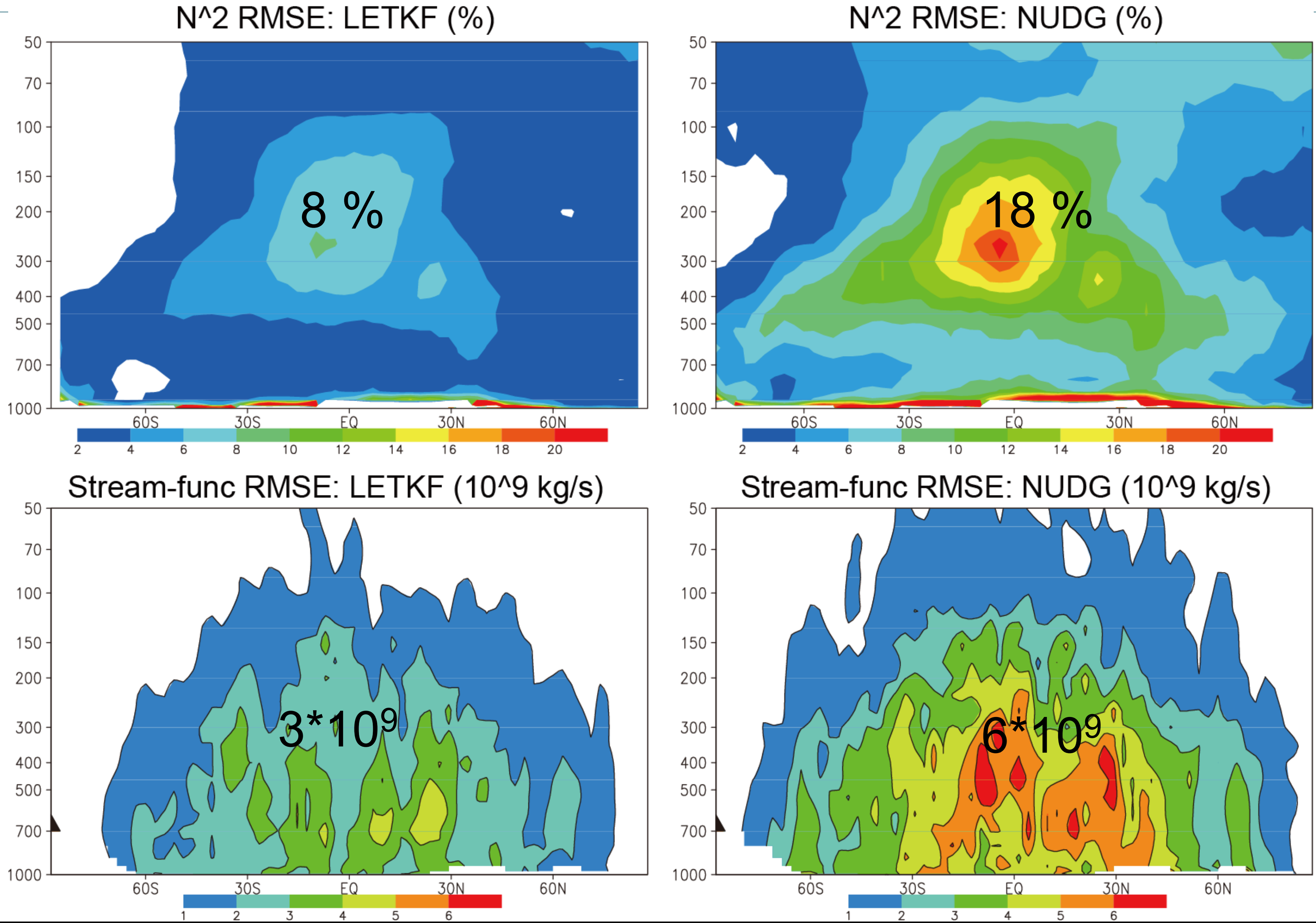
Performance of the atmospheric circulation analysis system



A greater improvement in LETKF meteorological analysis both for wind analysis and tracer forecast.

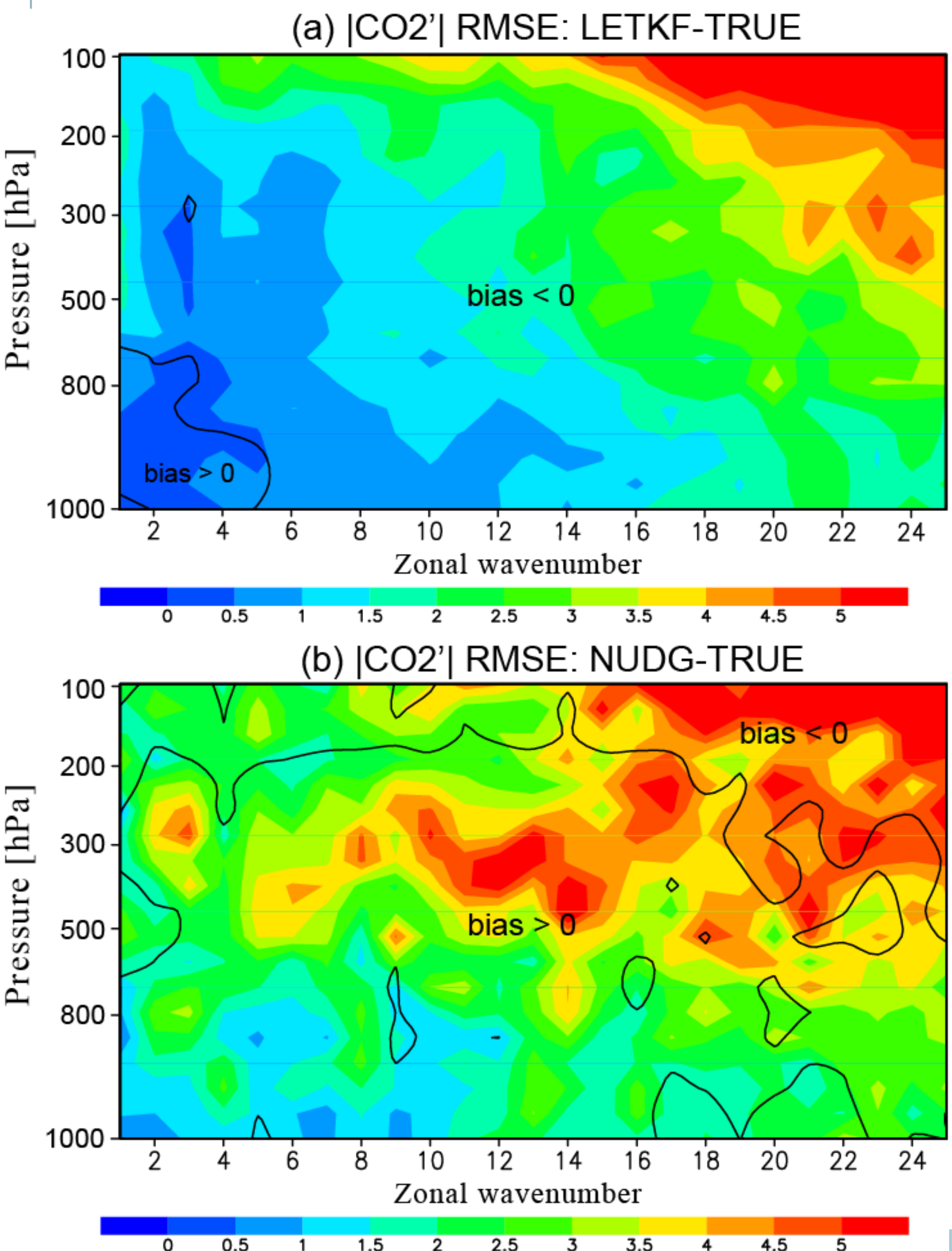
Significant improvement : around the region with strong wind shear.





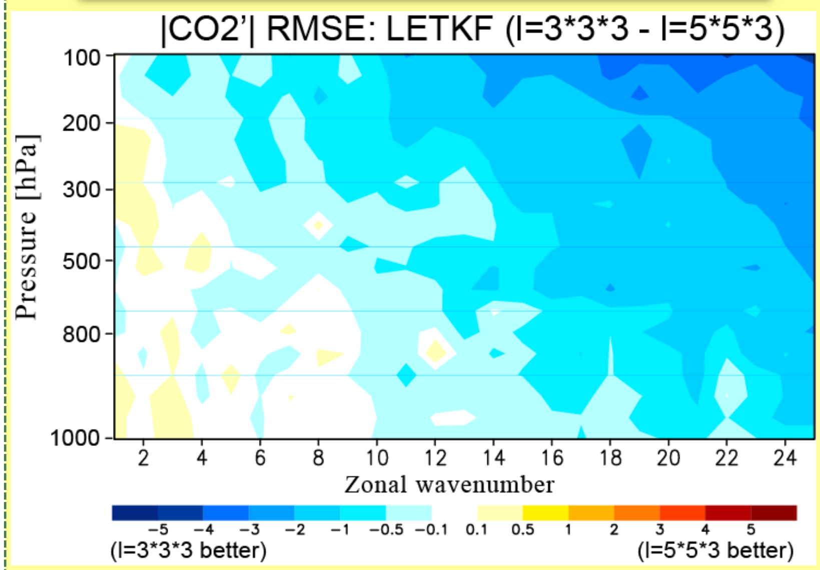
Improvements in the tracer simulation are possible through better balancing assimilation schemes (i.e., LETKF) for meteorological analysis.

Zonal CO2 variation errors at different horizontal scales



The LETKF captures atmospheric transport properties, particularly those related to large-scale motions.

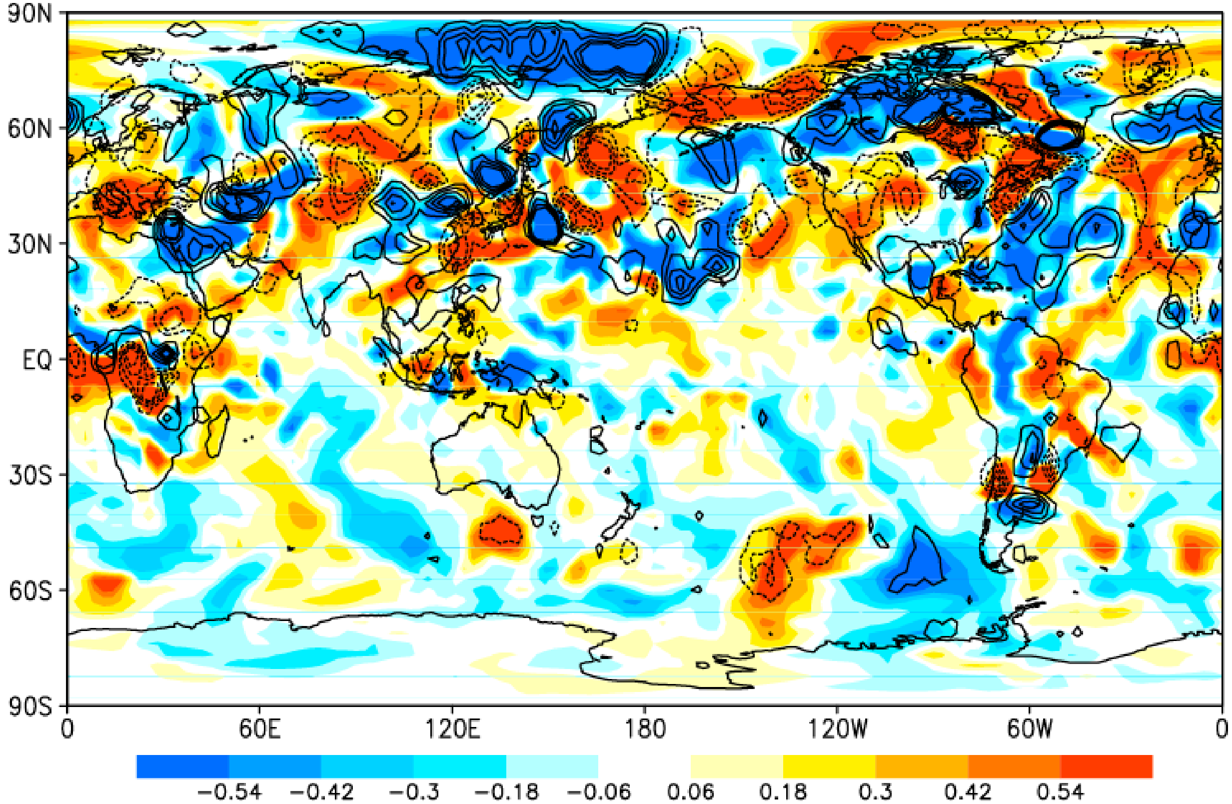
Local patch size dependence



Increasing the horizontal local length degraded the small-scale variations

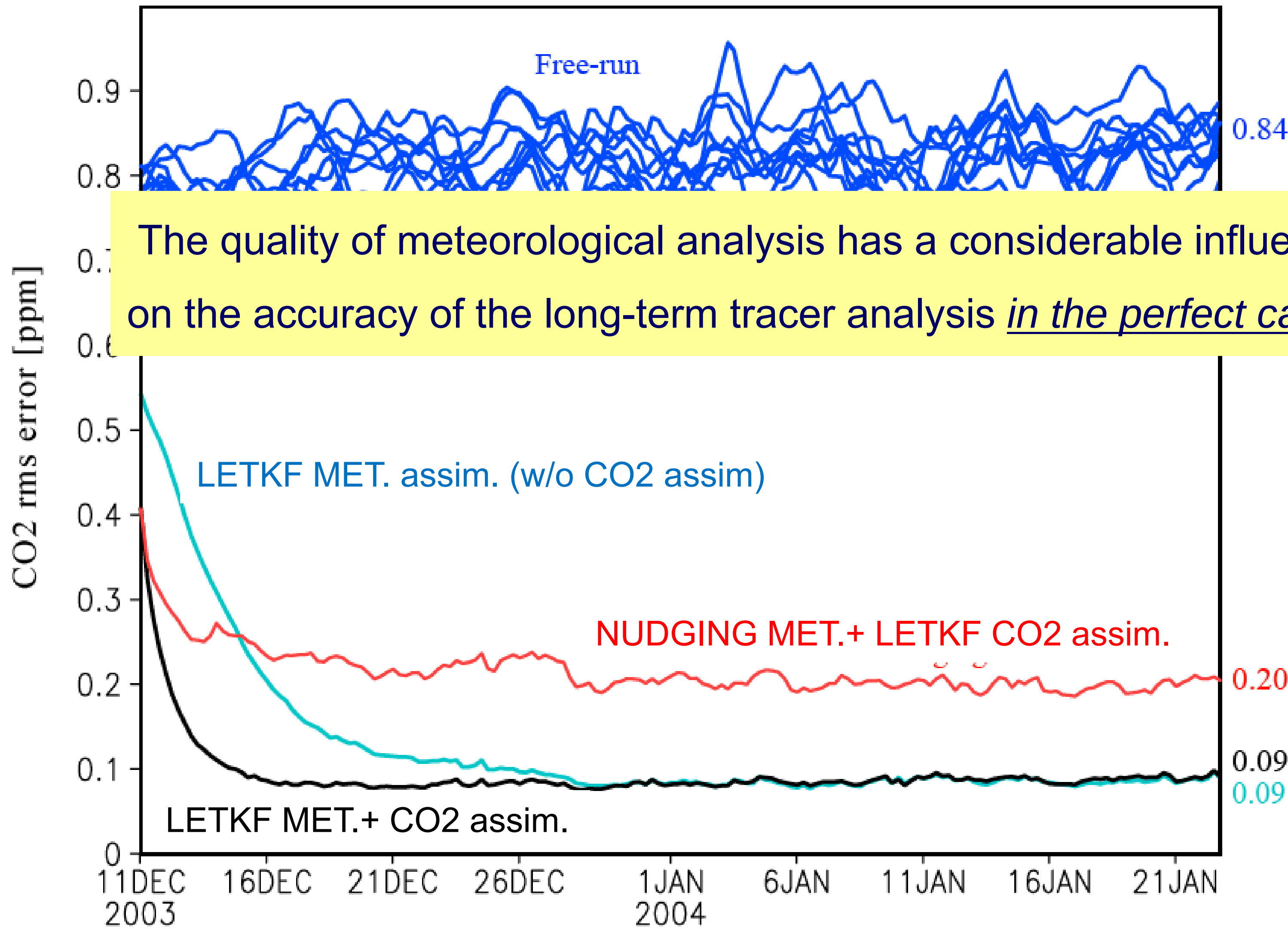
Performance of the tracer concentration assimilation system

(b) Analysis increment & background error [ppm] at 700 hPa



The LETKF concentration assimilation effectively corrected the background CO2 error where the ensemble spread was large.

Performance of the tracer concentration assimilation system



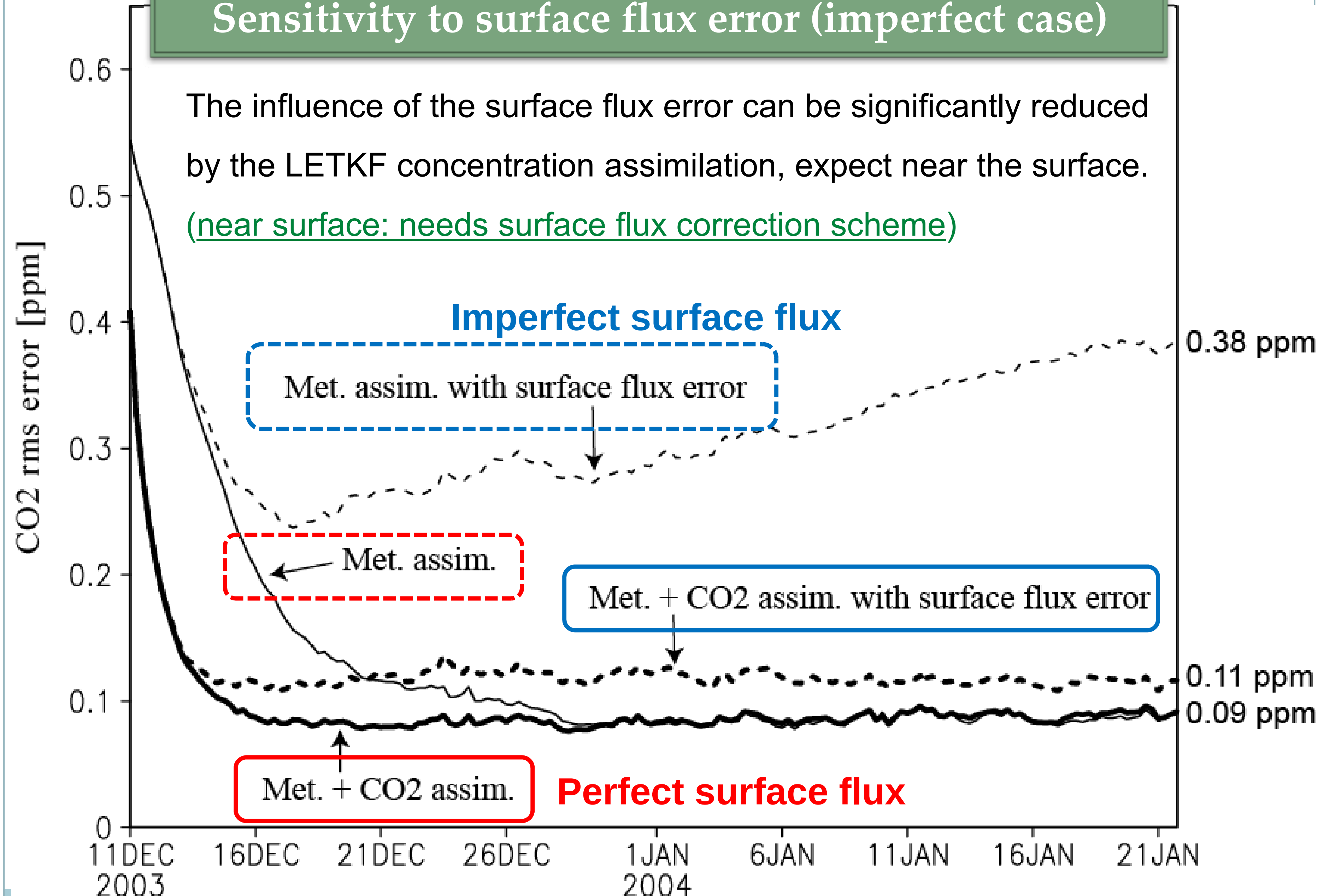
The quality of meteorological analysis has a considerable influence on the accuracy of the long-term tracer analysis *in the perfect case*.

700 hPa CO2 Global-mean RMSE [ppm]

Sensitivity to surface flux error (imperfect case)

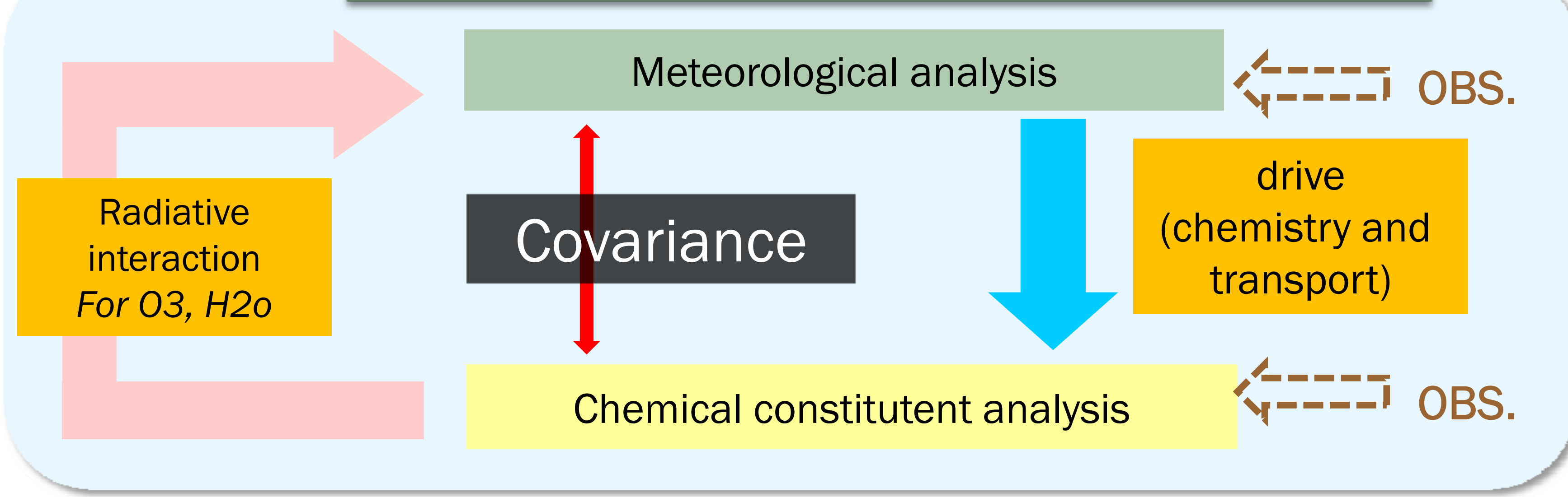
The influence of the surface flux error can be significantly reduced by the LETKF concentration assimilation, expect near the surface.

(near surface: needs surface flux correction scheme)



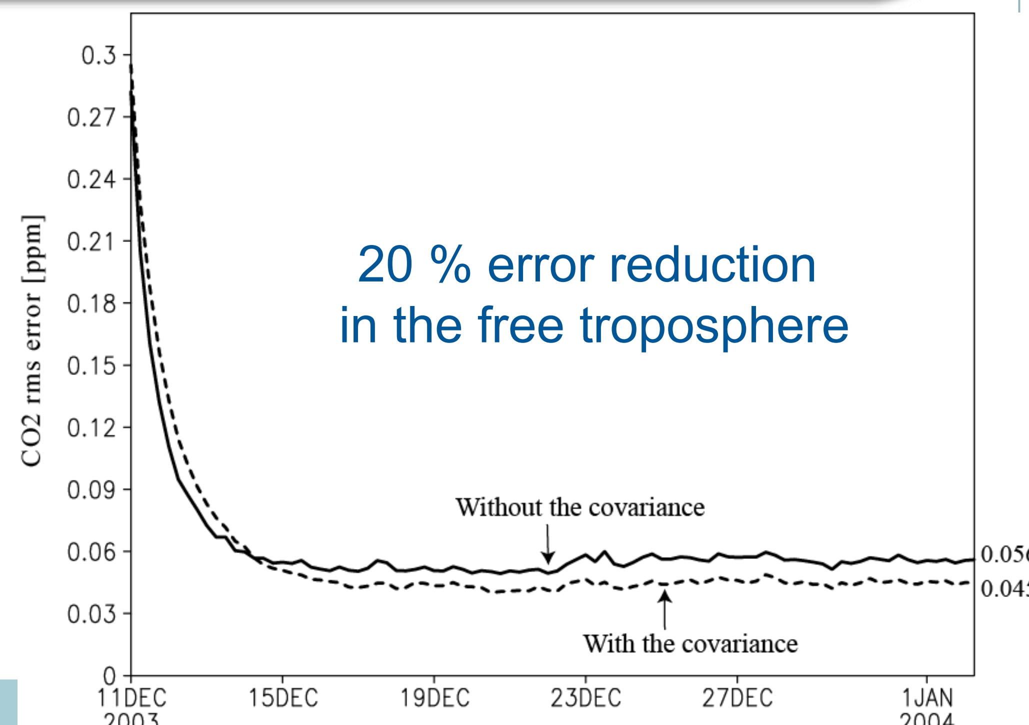
700 hPa CO2 Global-mean RMSE [ppm]

Coupling data assimilation system



High-quality meteorological data can improve the tracer estimates in two ways,

1) by improving the transport simulation, and
2) by considering the covariance to the tracer distribution.



Conclusions

(1) LETKF meteorological analysis facilitates the study of atmospheric transport characteristics (e.g., eddy mixing features, mean-meridional circulation) and provides high-quality tracer transport simulations, reflecting its flow-dependent and physically well-balanced analysis.

(2) The tracer concentration assimilation effectively reduces the tracer background error caused by initial distribution and surface flux errors. Influences of model bias were more significant (not shown here).

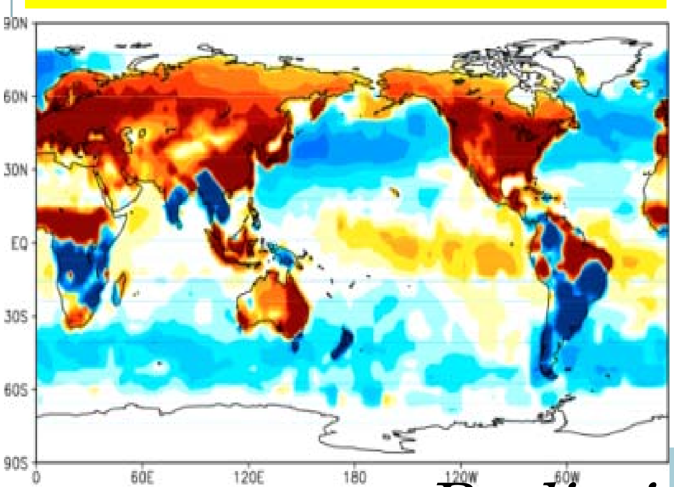
(3) Tracer analysis can also be improved by considering the covariance with wind fields in a background error matrix, in which wind observation directly impacts the tracer states.

These findings are of great value for future developments of high quality reanalysis system for atmospheric constituents with LETKF.

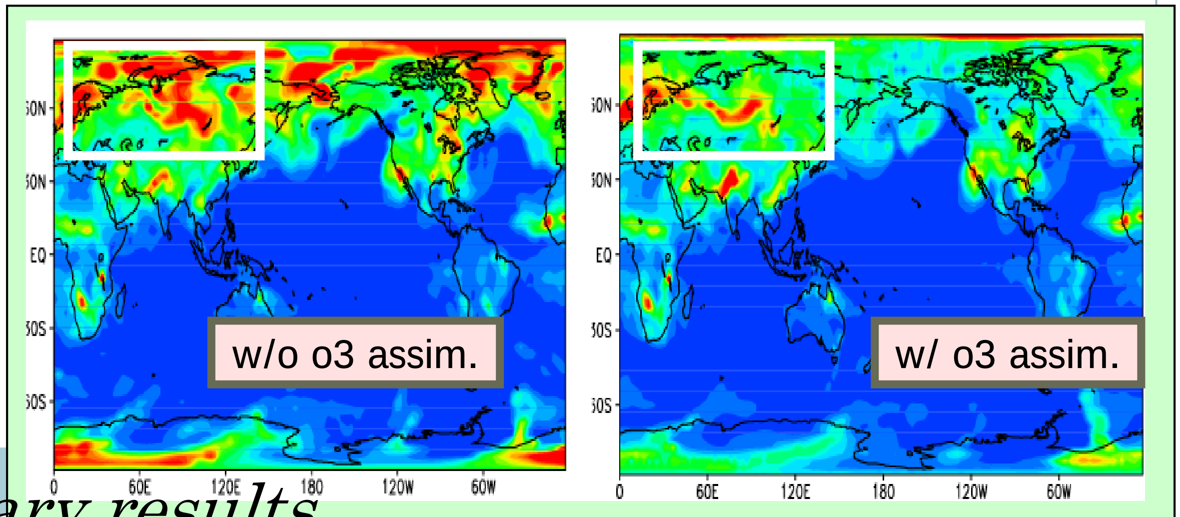
The future directions are focused toward the application of the developed LETKF data assimilation system to;

- estimate surface fluxes of CO2 with satellite observations (GOSAT)
- assimilate chemically active species (e.g., O3) into a full-chemistry CTM (CHASER) with satellite observations (e.g., GOME-II).
- compare with variational data assimilation systems

Surface CO2 flux estimation



Tropospheric O3 assimilation



Preliminary results