CO2 fluxes estimated with satellite, aircraft, and surface observations using an ensemble-based 4D data assimilation system

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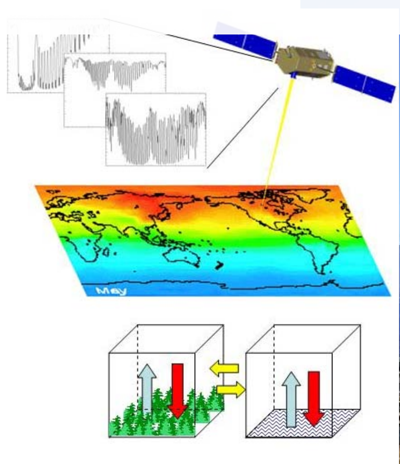
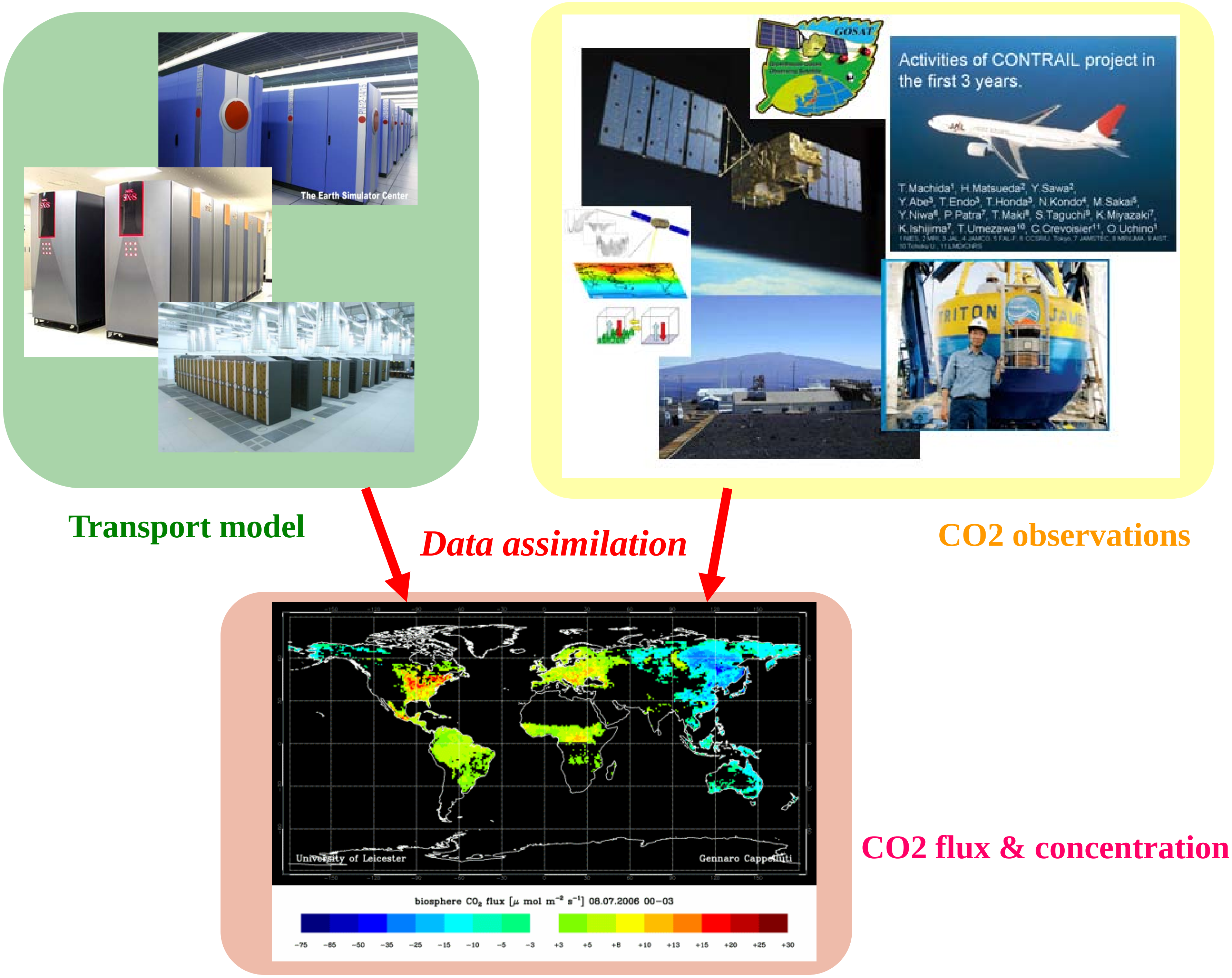
submitted to JGR-Atmosphere

This study discusses a method to efficiently utilize various observations to estimate surface CO2 flux estimations, and investigate the relative importance of different platform observation data (satellite, aircraft, and surface observations).



Various type data sets are available for CO2 !!!


The Earth Simulator Center
GOSAT
Activities of CONTRAIL project in the first 3 years.
T.Machida1, H.Matsueda2, Y.Sawa2, Y.Abe3, T.Endo3, T.Honda3, N.Kondo4, M.Sakai5, Y.Niwa6, P.Patra7, T.Maki8, S.Taguchi9, K.Miyazaki7, K.Ishijima7, T.Umezawa10, C.Crevoisier11, O.Uchino1
TRITON
Transport model
Data assimilation
CO2 observations
University of Leicester
Gennaro Cappelluti
biosphere CO_2 flux [μ mol m^{-2} s^{-1}] 08.07.2006 00–03
−75 −65 −50 −35 −25 −15 −10 −5 −3 +3 +5 +8 +10 +13 +15 +20 +25 +30
CO2 flux & concentration

4D data assimilation system for carbon cycle

- *Forecast model:*

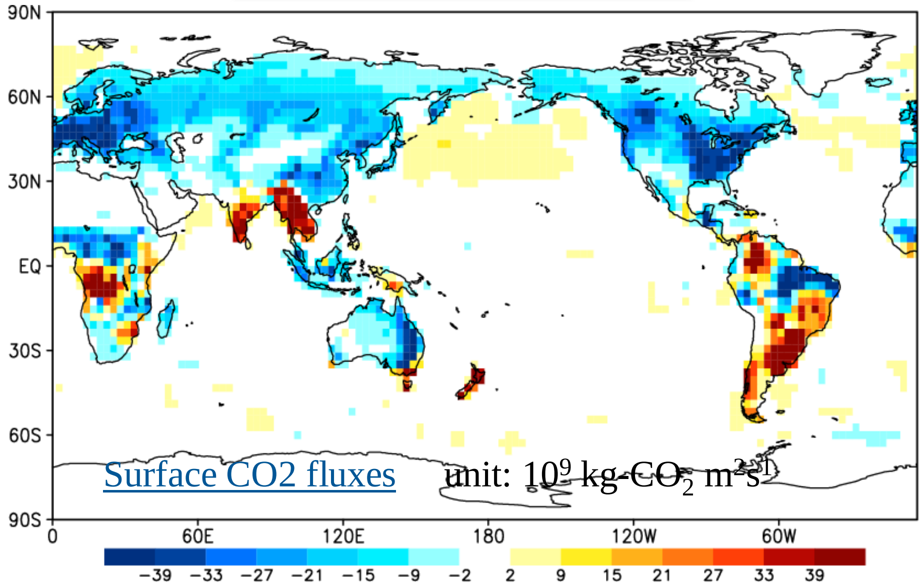
FRCGC transport model coupled to CCSR/NIES AGCM @ T42L32

(transport = grid-scale + parameterized convection and diffusion)

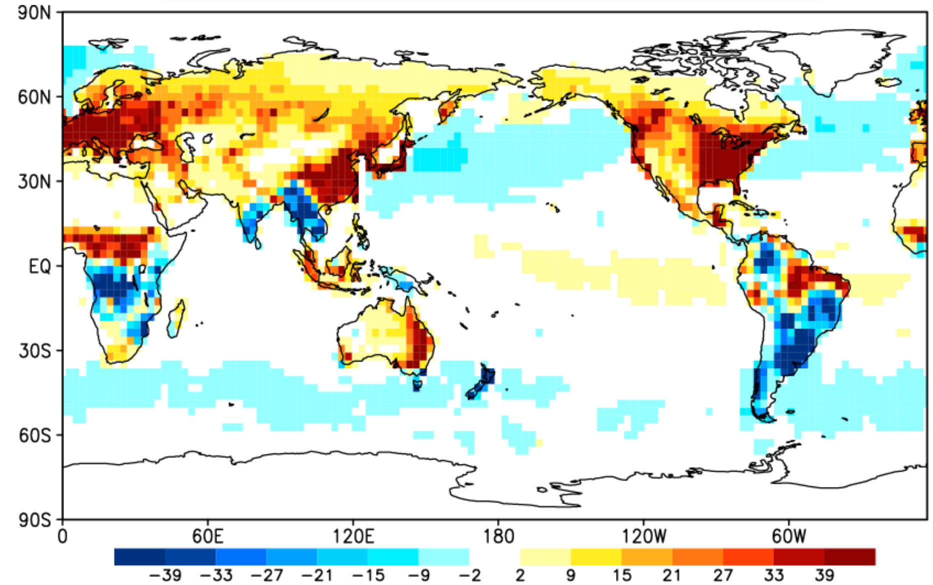
- *Data assimilation*:

Local ensemble transform Kalman filter (LETKF) with state augmentation technique

A priori error



True flux (Nov.-Dec)



The ensemble spread for CO2 flux is initialized such that
the standard deviation is equal to the initial error

Local ensemble transform Kalman fiter (Hunt et al. 2007)

The LETKF is one of the ensemble square root filters in which the observations are assimilated to update only the ensemble mean by

$$\overline{\mathbf{x}}^a = \overline{\mathbf{x}}^f + \mathbf{K}[\mathbf{y}^o - H(\overline{\mathbf{x}}^f)], \qquad \mathbf{K} = \mathbf{X}^f \tilde{\mathbf{P}}^a (\mathbf{H}\mathbf{X}^f)^{\mathrm{T}} \mathbf{R}^{-1}$$

The ensemble perturbations are updated by transforming the background perturbations through a transform matrix T

$$\mathbf{X}^a = \mathbf{X}^f \mathbf{T}, \qquad \mathbf{T} = [(K-1)\tilde{\mathbf{P}}^a]^{1/2},$$

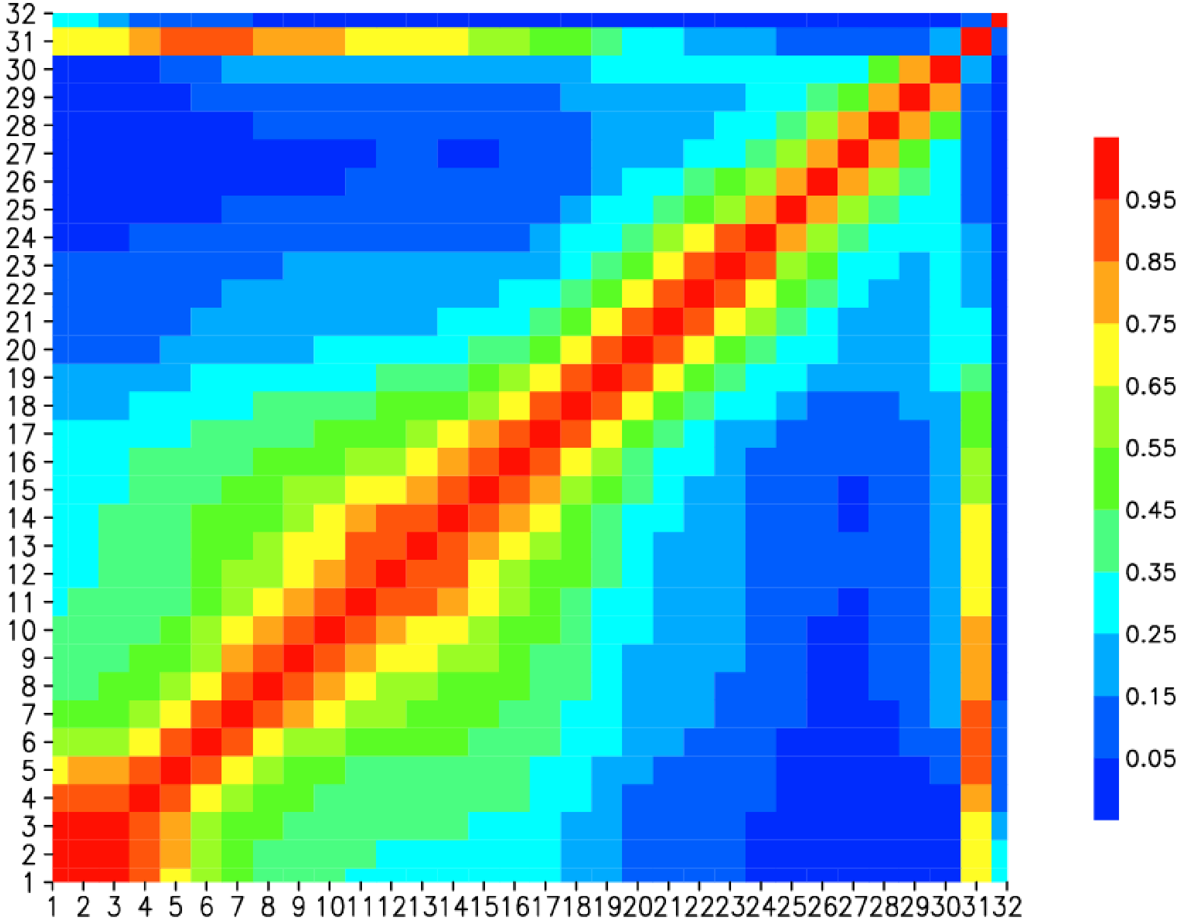
The analysis error covariance in ensemble space is given by

$$\tilde{\mathbf{P}}^a = [(K-1)\mathbf{I} + (\mathbf{H}\mathbf{X}^f)^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{H}\mathbf{X}^f)]^{-1},$$

The LETKF performs the analysis in ensemble space (rather than in model or obs space), which greatly reduces the computational cost.

Simultaneous estimation of state and parameter

Background covariance structure



1-30: CO2 conc. at each model level,
31:CO2 column, 32:surface flux

New state vector

$$z = \begin{pmatrix} \boxed{x} \\ \boxed{flux} \end{pmatrix}$$

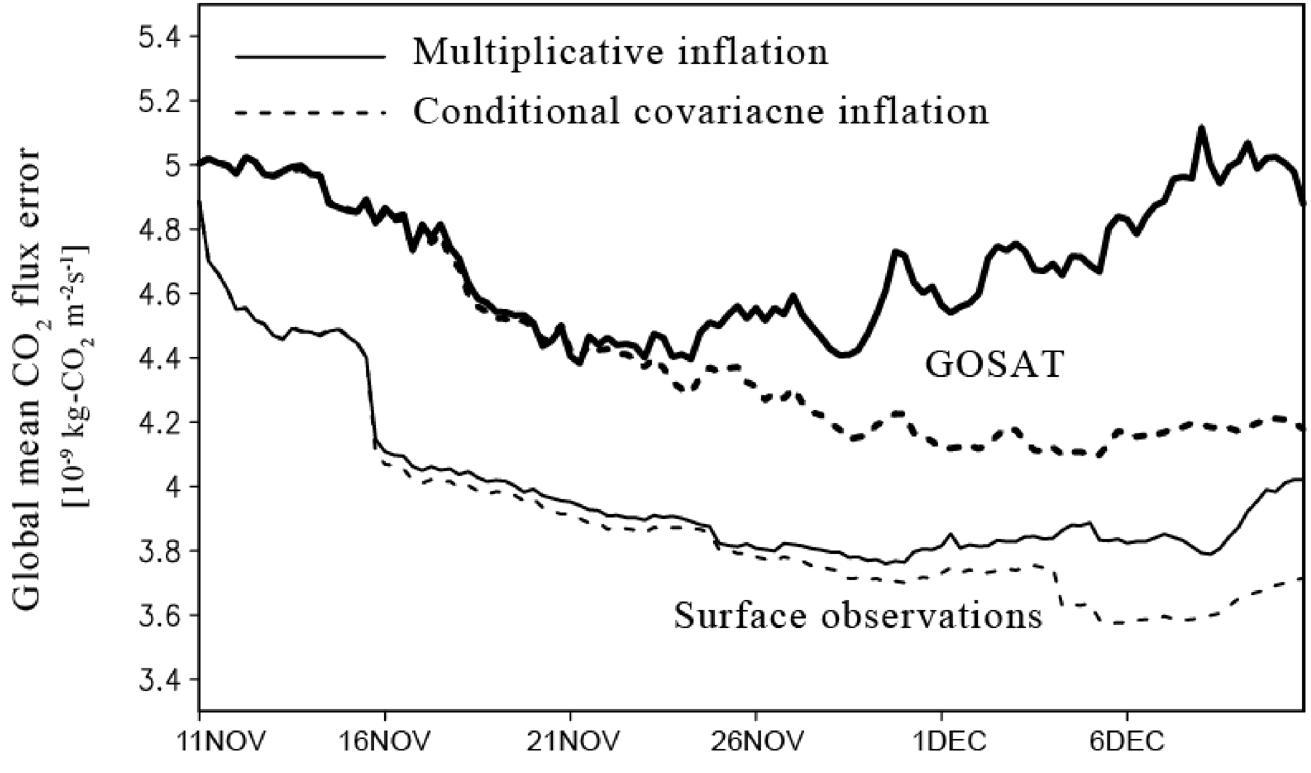
The state vector augmentation method has been applied to simultaneously estimate the model state (met. & CO2 conc.) and the uncertain model parameter (surface CO2 flux).

Covariance inflation technique

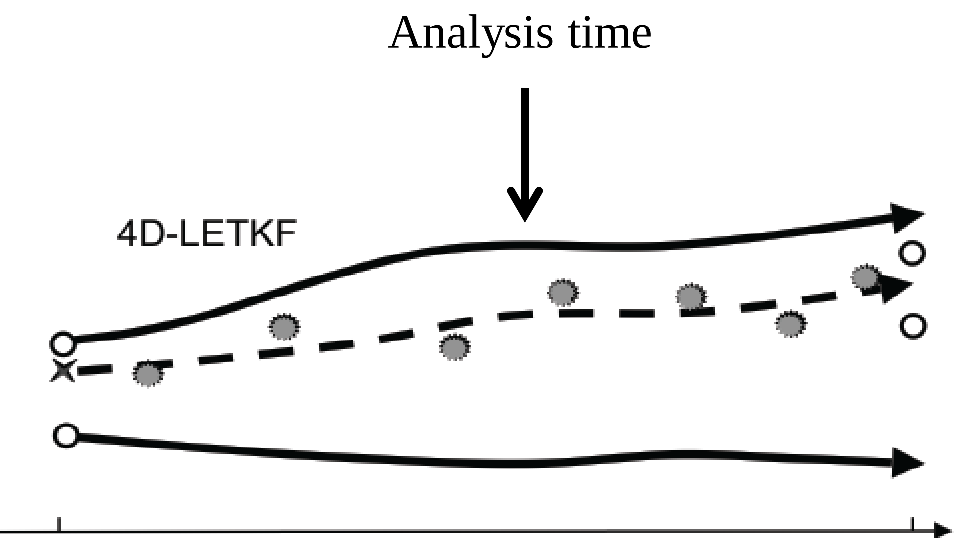
Covariance inflation technique is used to avoid filter divergence caused by progressive underestimation of the model error covariance magnitude.

- Multiplicative inflation (Anderson and Anderson ,1999)
- Additive inflation (Whitaker et al., 2008)
- **Conditional covariance inflation (e.g., Aksoy et al., 2006)**

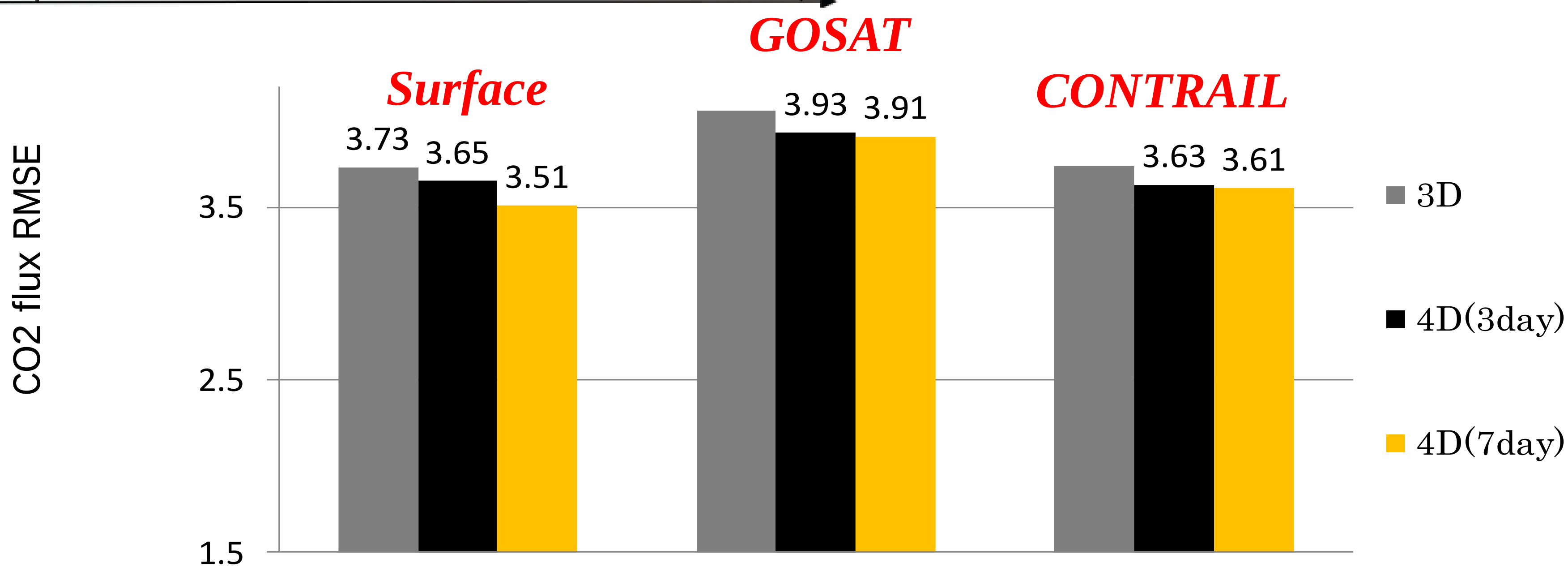
The analyzed standard deviation is inflated back to a minimum or maximum predefined value



4D-LETKF vs. 3D-LETKF



A 4D EnKF data assimilation system uses a trajectory that best fits all the observations in a data assimilation window. It provides an analysis in terms of the weights of the ensemble forecast members at the analysis time.

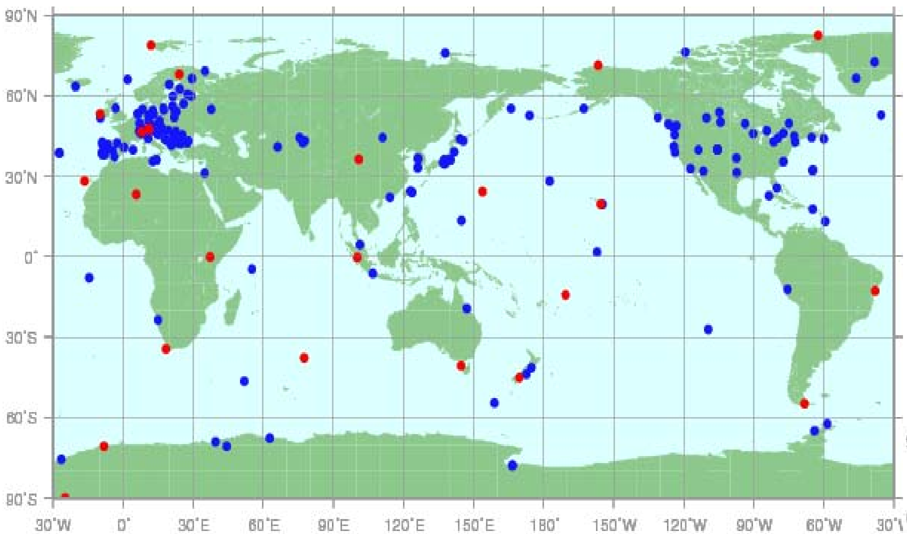


4D-LETKF vs. 3D-LETKF

Data	3D	4D (3-day)	4D (7-day)	
Surface (h=600 km)	3.94	3.94	3.81	
Surface (h=900 km)	3.66	3.65	3.53	
Surface (h=1200 km)	3.70	3.61	3.46	
GOSAT (h=600 km)	4.51	4.43	4.38	
GOSAT (h=900 km)	4.36	4.13	4.64	
GOSAT (h=1200 km)	4.17	3.78	4.54	bad
CONTRAIL (h=600 km)	4.04	4.04	4.89	
CONTRAIL (h=900 km)	3.88	3.85	3.69	
CONTRAIL (h=1200 km)	3.68	3.56	5.43	bad

When a long assimilation window (i.e., a 7-day window) or a long localization length (i.e., 1200 km) is used, the surface flux analysis suffers from large (both temporal and spatial) spurious correlations and is degraded

Observation system simulation experiments (OSSEs)



Continuous and flask surface observations

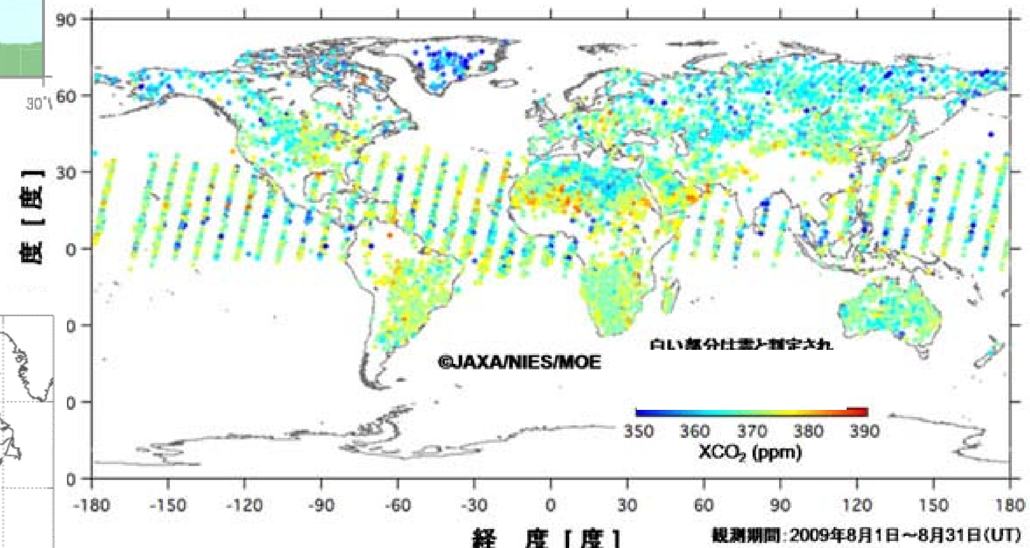
Density: low

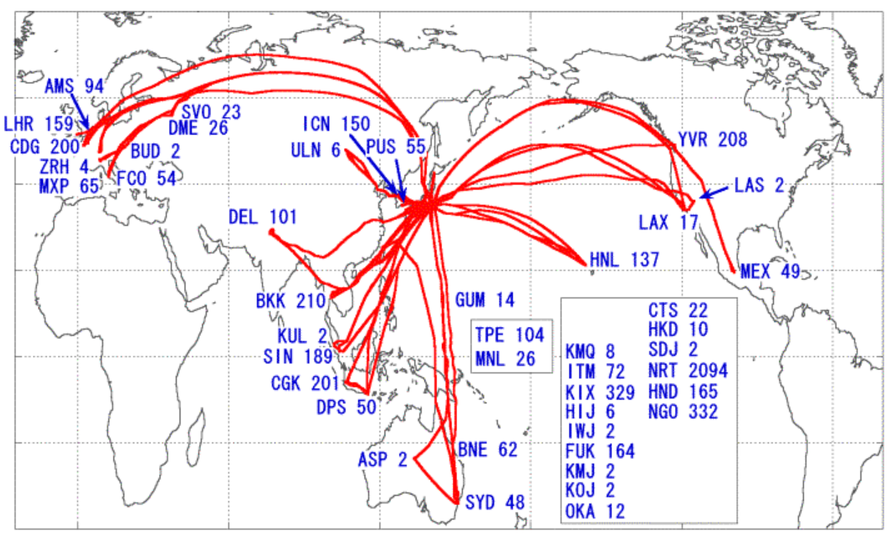
Error: small

GOSAT observations

Density: high

Error: relatively large





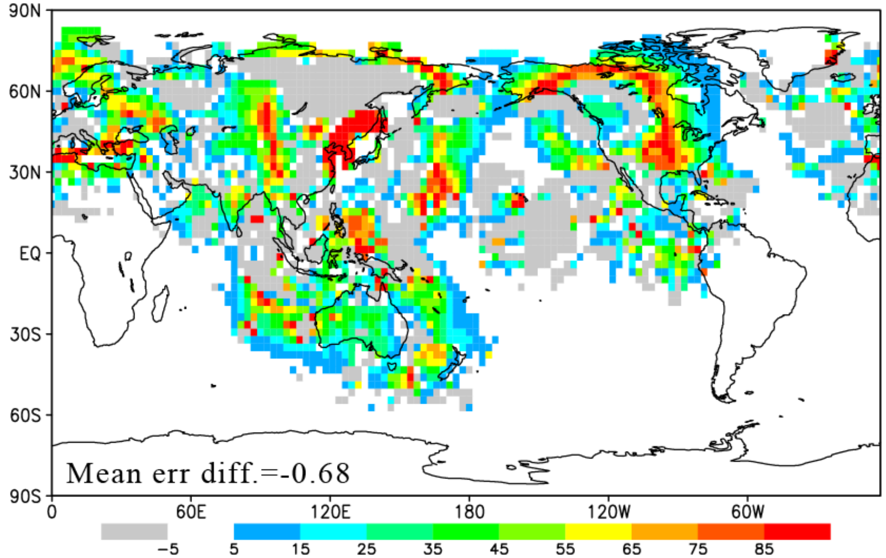
CONTRAIL aircraft observations

Density: high (+vertical profile)

Error: small

Localization: CONTRAIL data assimilation

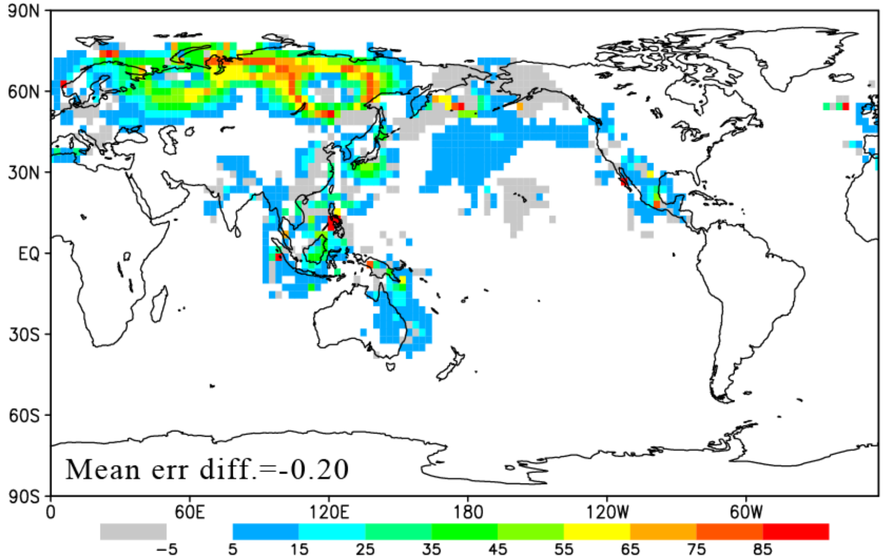
(a) CONTRAIL h=1200-600 km 3D



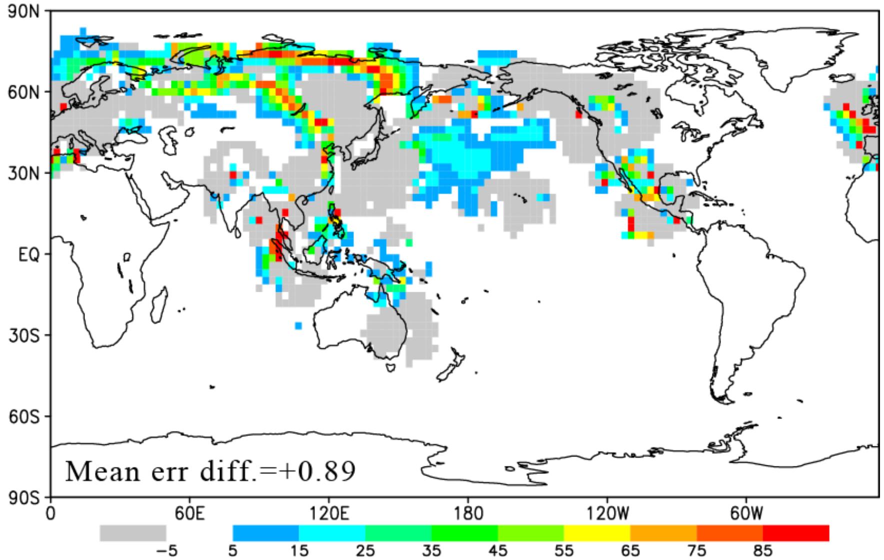
The increase in the vertical localization length allows an increased use of the upper tropospheric data in surface flux estimates, reducing the surface flux analysis error.

In contrast, because of significant spurious correlations between variations in surface fluxes and lower stratospheric concentrations , the increase of the vertical localization length to lnP=1 has an adverse impact.

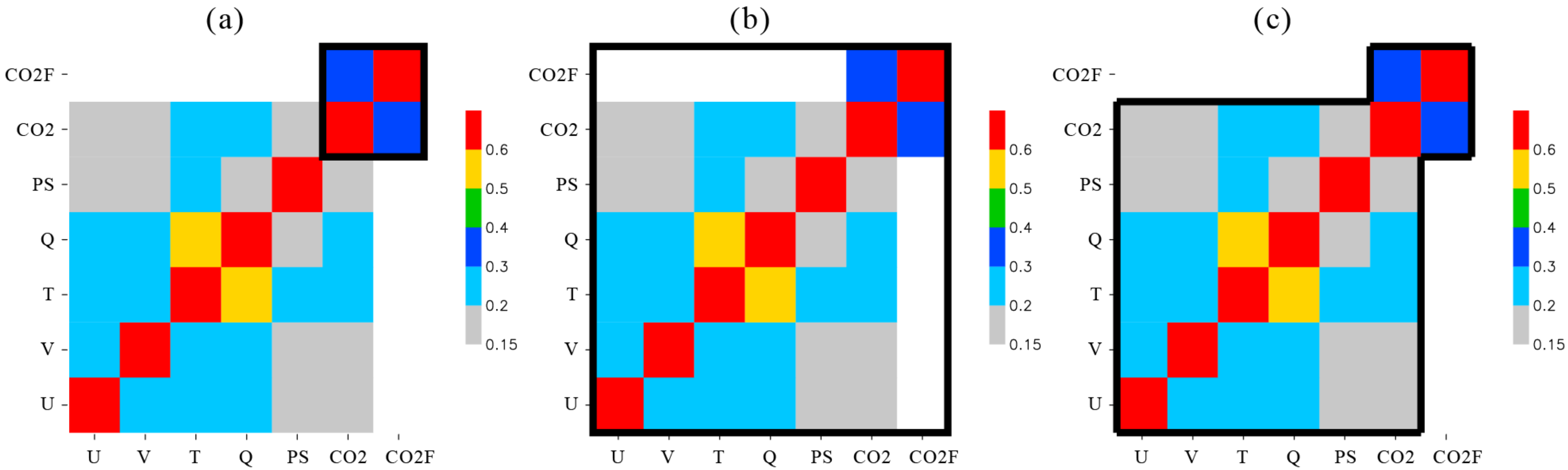
(b) CONTRAIL p-top=250-500 hPa 3D



(c) CONTRAIL p-top=100-500 hPa 3D



Design of the state vector: coupling data assimilation



(Mean absolute error=4.45) (Mean absolute error=5.32) (Mean absolute error=4.10)

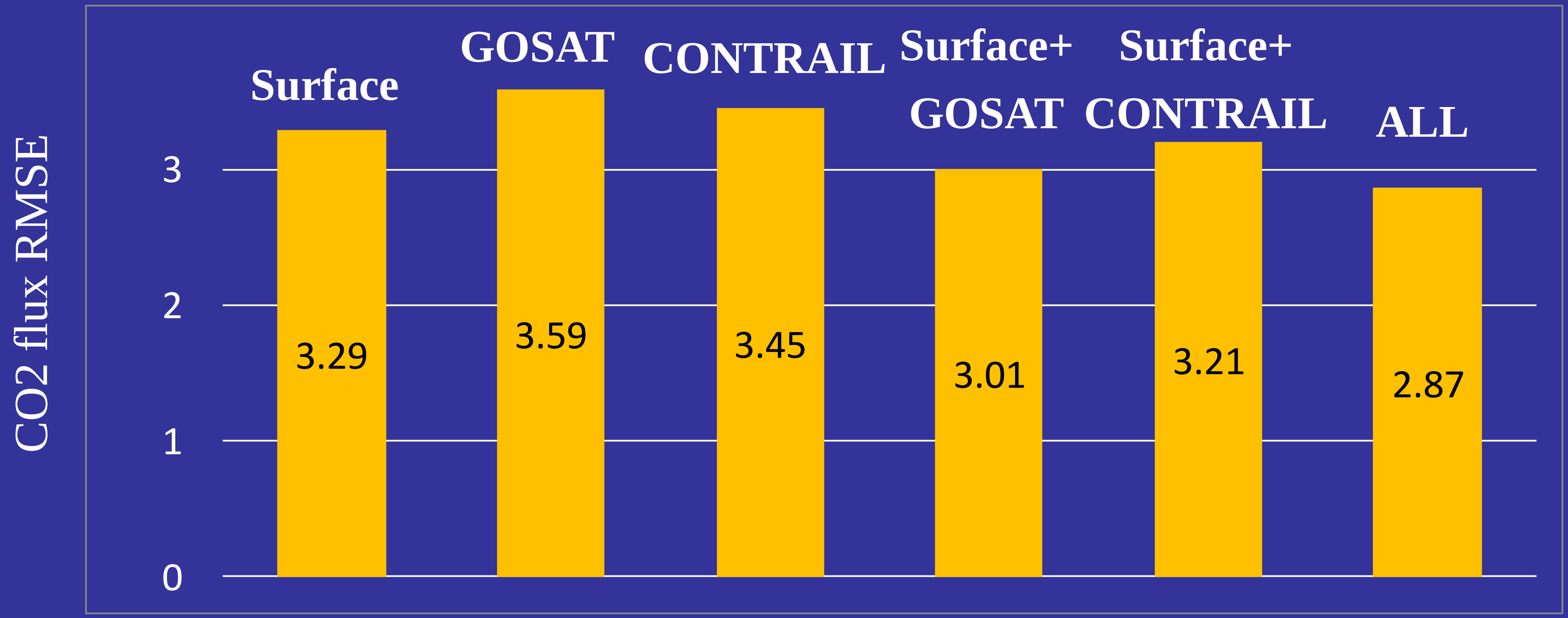
Background error covariance structure @ bottom level

Although meteorological data assimilation can provide more constrains on the flux estimation, spurious correlations among meteorological variables and CO2 flux significantly degraded the flux analysis in (b). By considering variable localization, it's possible to stabilize and improve the CO2 flux analysis in (c)

Relative importance of different platform data

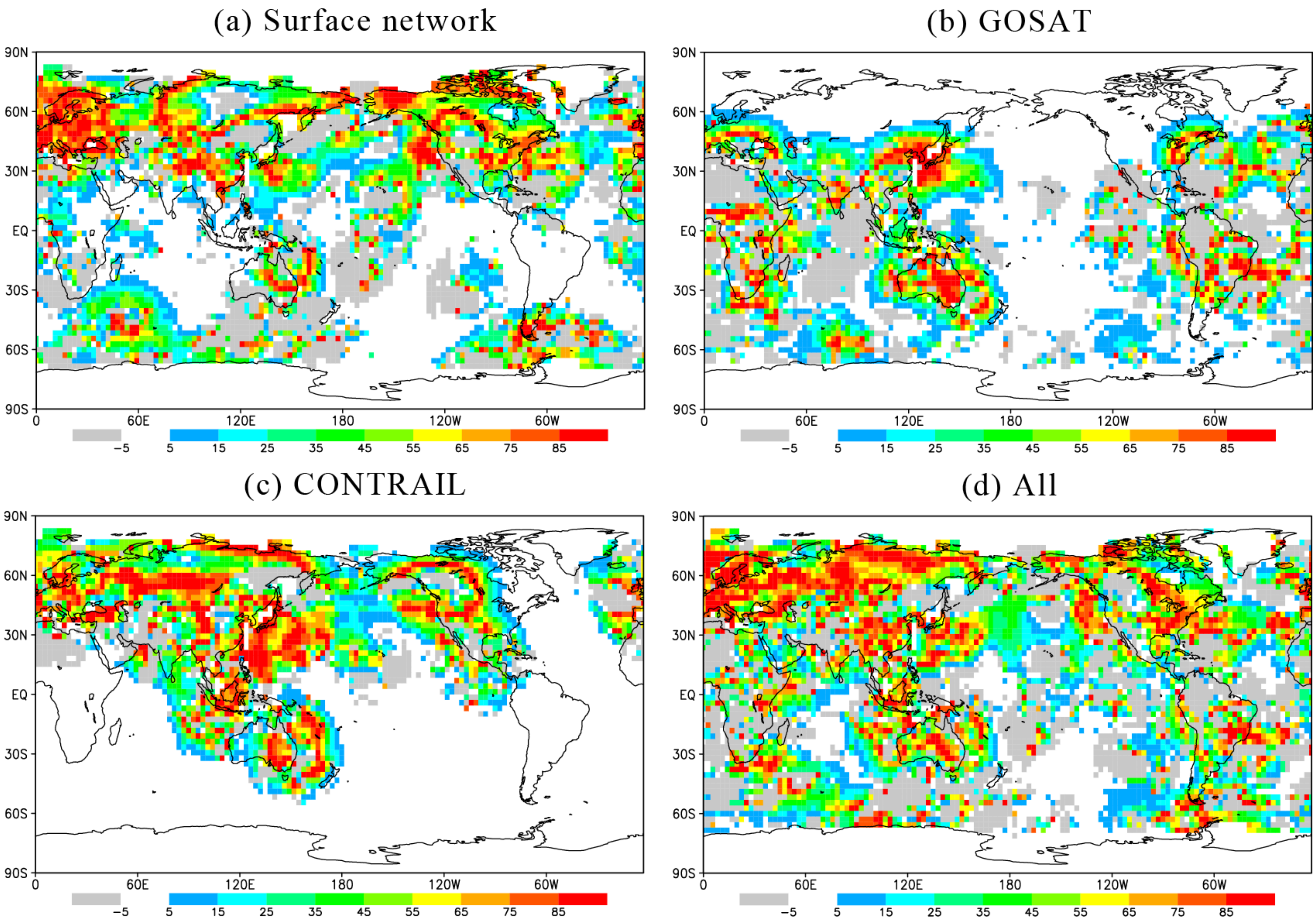
Optimal data assimilation system

- State augmentation method for parameter (i.e., surface flux estimations)
- Localization: h=1200 km, logP=0.75 hPa
- Conditional covariance inflation
- Weight-interpolated column data assimilation
- 4D data assimilation with 3-day window

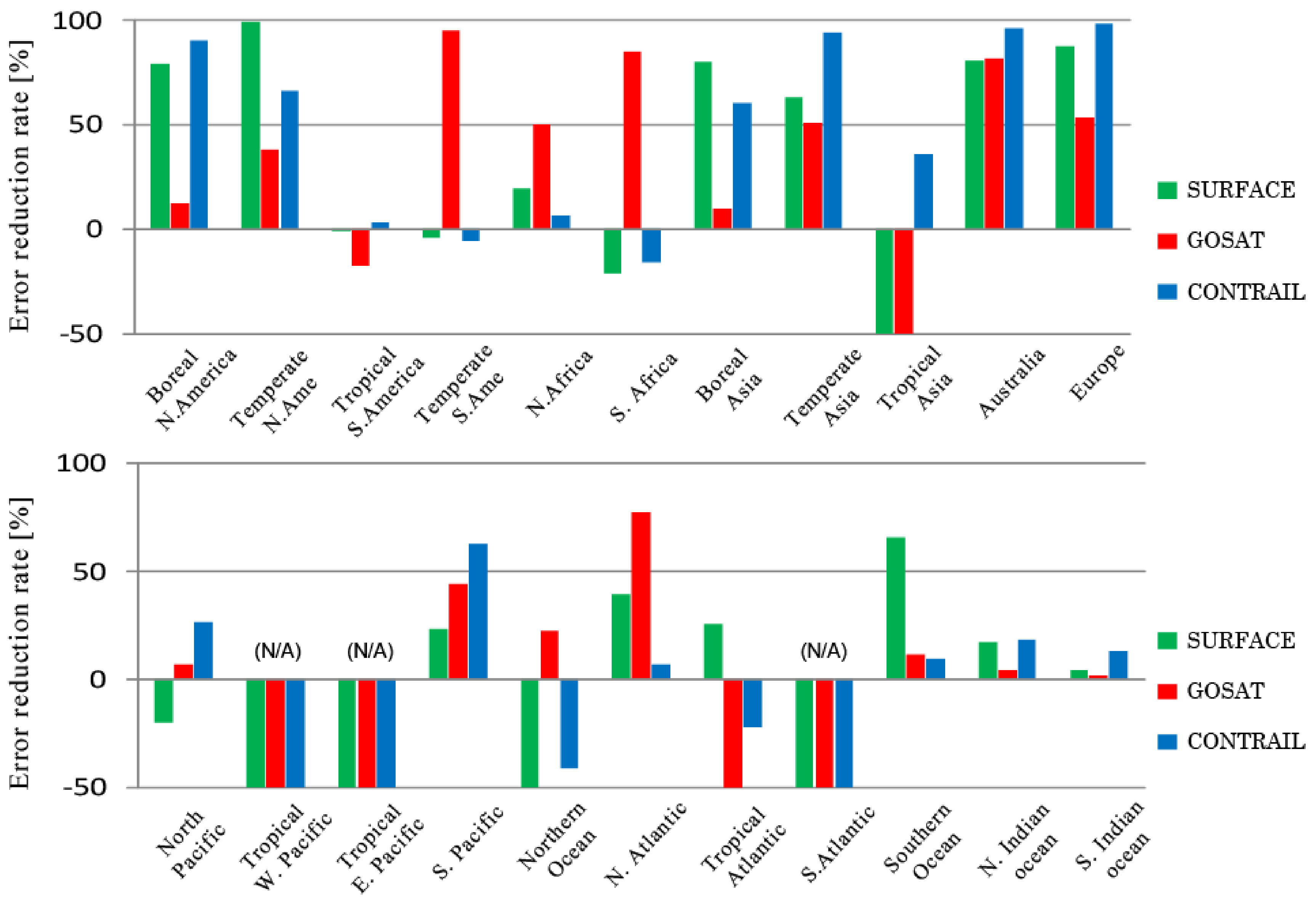


Initial RMSE = 5.4, Global mean absolute flux = 6.2

Surface flux error reduction rate [%]

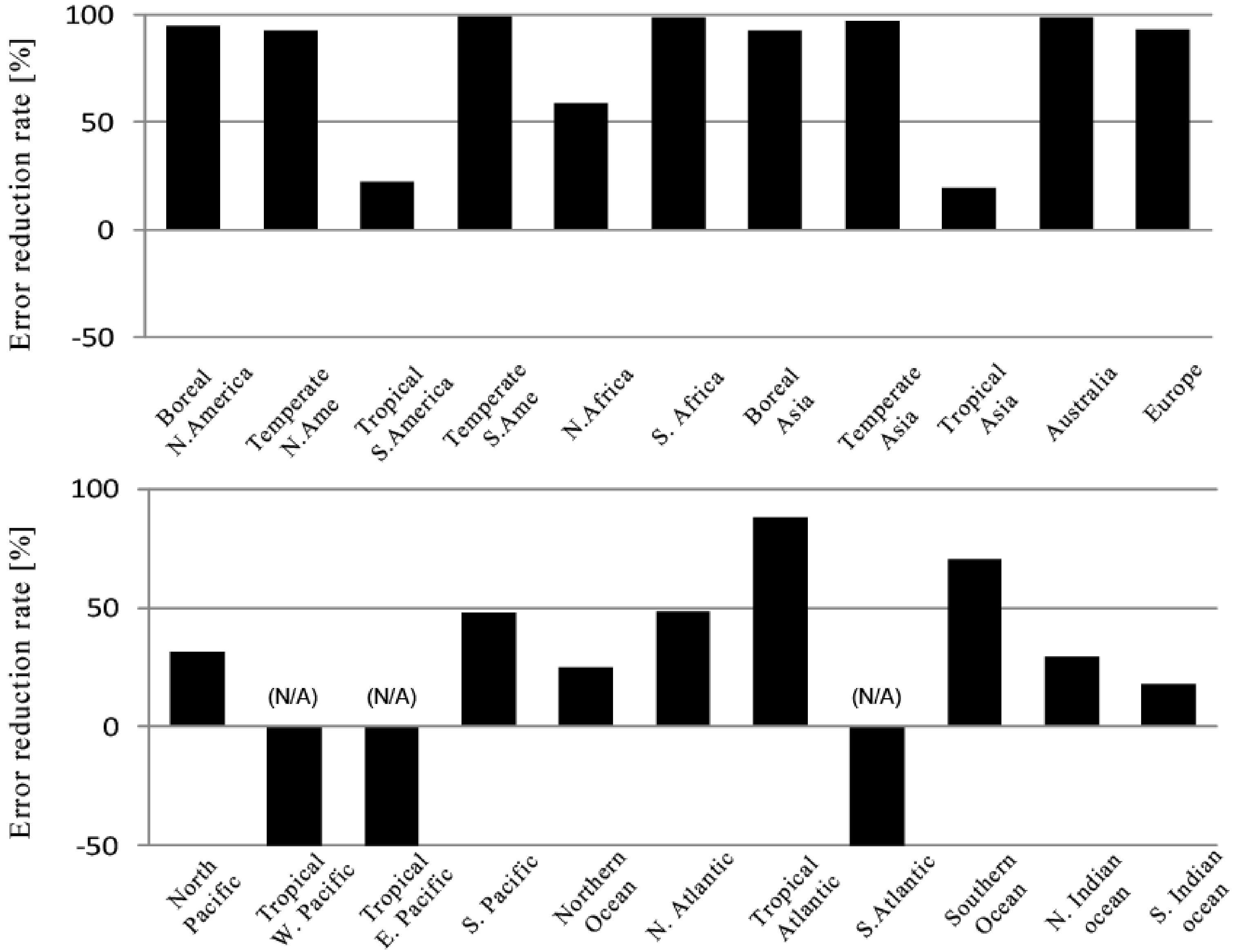


Surface flux error reduction rate [%]



GOSAT XCO2 and CONTRAIL vertical profile data provide strong additional constraints on the surface flux estimation.

Surface flux error reduction rate [%]



By combining all the platform datasets, the data assimilation system significantly improved the global estimation of the surface CO2 fluxes by compensating for the unobserved areas.

Conclusions

The potential impacts of various types of CO2 concentration data obtained from surface, satellite (by the GOSAT project), and aircraft (by the CONTRAIL project) measurements on the estimation of surface CO2 fluxes have been investigated using an EnKF DA system.

- **Conventional surface network data contributes to largest error reductions.**
- **GOSAT gives large flux error reduction over south-America and Africa.**
- **The impacts of CONTRAIL data are large over Europe, Australia, trop.-temp. Asia, and North America, where many vertical profiles data exist.**
- **By combining information obtained from all the data sets, the data assimilation system significantly improves the flux estimation globally.**
- ***The simultaneous data assimilation system for all types of data is expected to improve our knowledge of the carbon cycle.***