Recent developments in chemical data assimilation for atmospheric gases and aerosols in Japan

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Motivations/Purposes

- **We have developed chemical data assimilation systems for monitoring atmospheric environment in East Asia since 2009. - CO2, aerosols, and ozone.**
- **The data assimilation systems developed by four Japanese research institutes employ a same data assimilation scheme, a localized EnKF (LETKF).**
- **The data assimilation approach allows to simultaneously optimize forecast variables (i.e., concentrations) and parameters (i.e., emissions).**
- **This presentation: introduction of our recent activities on chemical data assimilation for atmospheric gases and aerosols.**

Ensemble Kalman Filter

	4D-Var	**4D-EnKF**
Background error statistics	Flow-dependent	Flow-dependent
Program code	Complicated	**Simple**
Adjoint matrix	Necessary	**Unnecessary**
Observation operator	Requires tangent linear & adjoint operators	**Requires only a forward transform operator**
Asynchronous observations	Handles at each observational time	Handles at each observational time
Analysis error covariance	Not provided	Explicitly provided

1. Stratospheric ozone

(MLS, OMI)

2. Aerosols

(CALIPSO, ground-based lidar)

Japanese CTMs/CCMs

& 3D/4D-LETKF

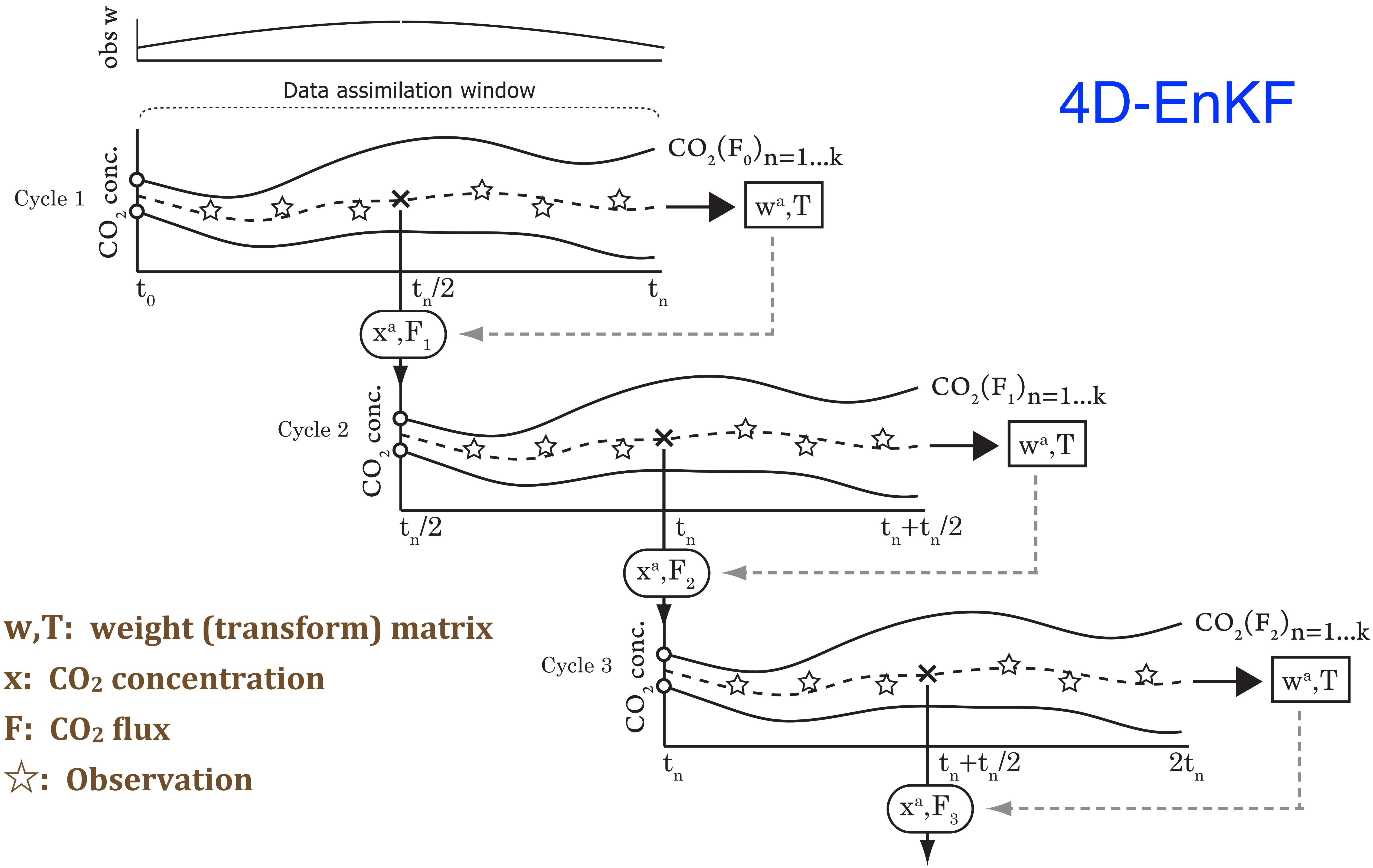
3. Surface CO2 flux

(GOSAT, CONTRAIL)

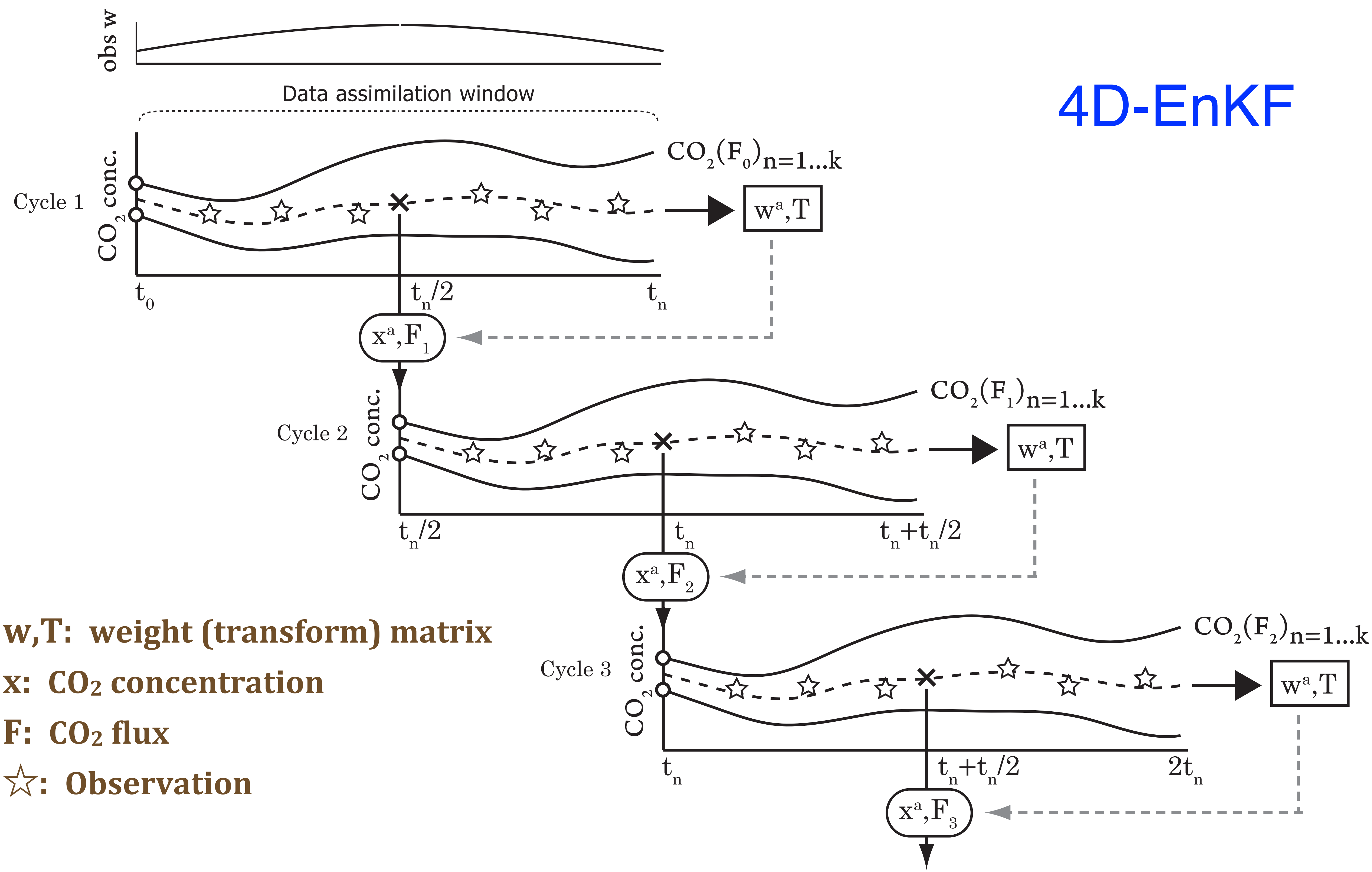
4. Air quality

(OMI, SCIAMACHY...)

4D-EnKF



In a 4D EnKF, the observations in a data assimilation window are simultaneously assimilated, and the assimilation window includes analysis time.



w,T: weight (transform) matrix

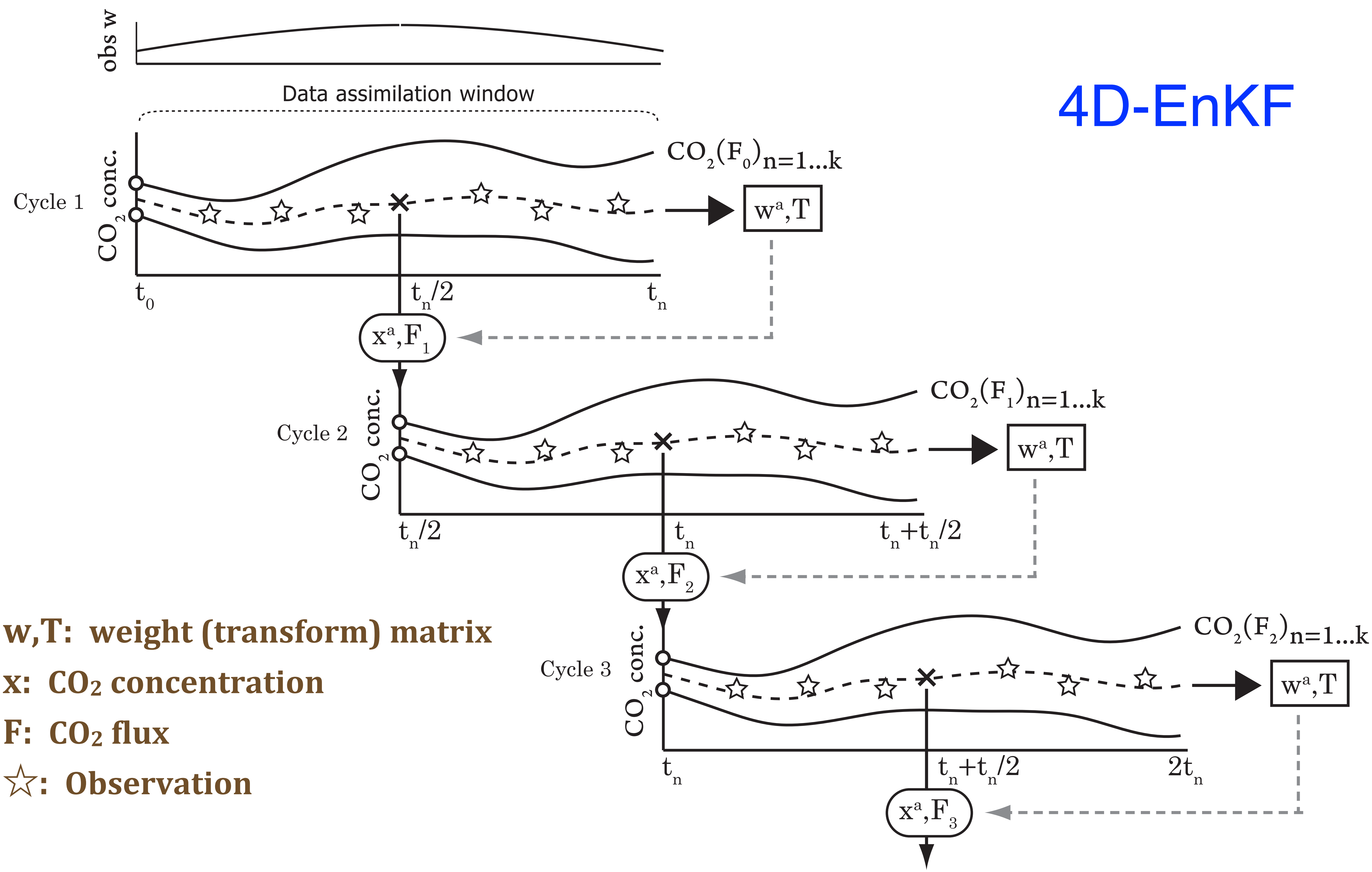
x: CO_2 concentration

F: CO_2 flux

☆: Observation

A weight matrix (w, T) used to obtain the local analysis increment is estimated at the end of the window using all observations and the corresponding background perturbations within the window.

4D-EnKF



w,T: weight (transform) matrix

x: CO_2 concentration

F: CO_2 flux

☆: Observation

The weight (w) is valid at any time in the assimilation window.

Comparison with the fixed lag Kalman Smoother

- Fixed lag Kalman smoother (e.g., Peters et al., 2005) uses the expanded state vector and the multiple time analysis.
  - has major advantages in analyzing long term variations of global surface fluxes at a large scale.
  - since the approach allows the use of large constraints obtained from a long data assimilation window (possibly) w/o serious model error growth with time and sampling errors.
- It might be difficult to obtain meaningful constrains from remote data on surface flux variations especially at a fine scale.

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  - since the approach allows the use of large constraints obtained from a long data assimilation window (possibly) w/o serious model error growth with time and sampling errors.
- It might be difficult to obtain meaningful constrains from remote data on surface flux variations especially at a fine scale.
- Our method, with localized analyses, has advantages in analyzing fine scale structures in surface fluxes, if provided sufficient observational information is available in a localized space. However, when the analysis increment is too localized, some areas are possibly under-constrained.

1. Stratospheric ozone

Forecast models:

(1) **CCSR/NIES CCM** (Akiyoshi et al., 2009) T42L34 p-top=0.01 hPa	
(2) **MRI CCM2** (Shibata and Deushi, 2008, Deushi and Shibata 2011) T42L68 p-top=0.01 hPa	
(3) **CHASER** (Sudo et al., 2002) T42L32 p-top=3 hPa	*not shown here*

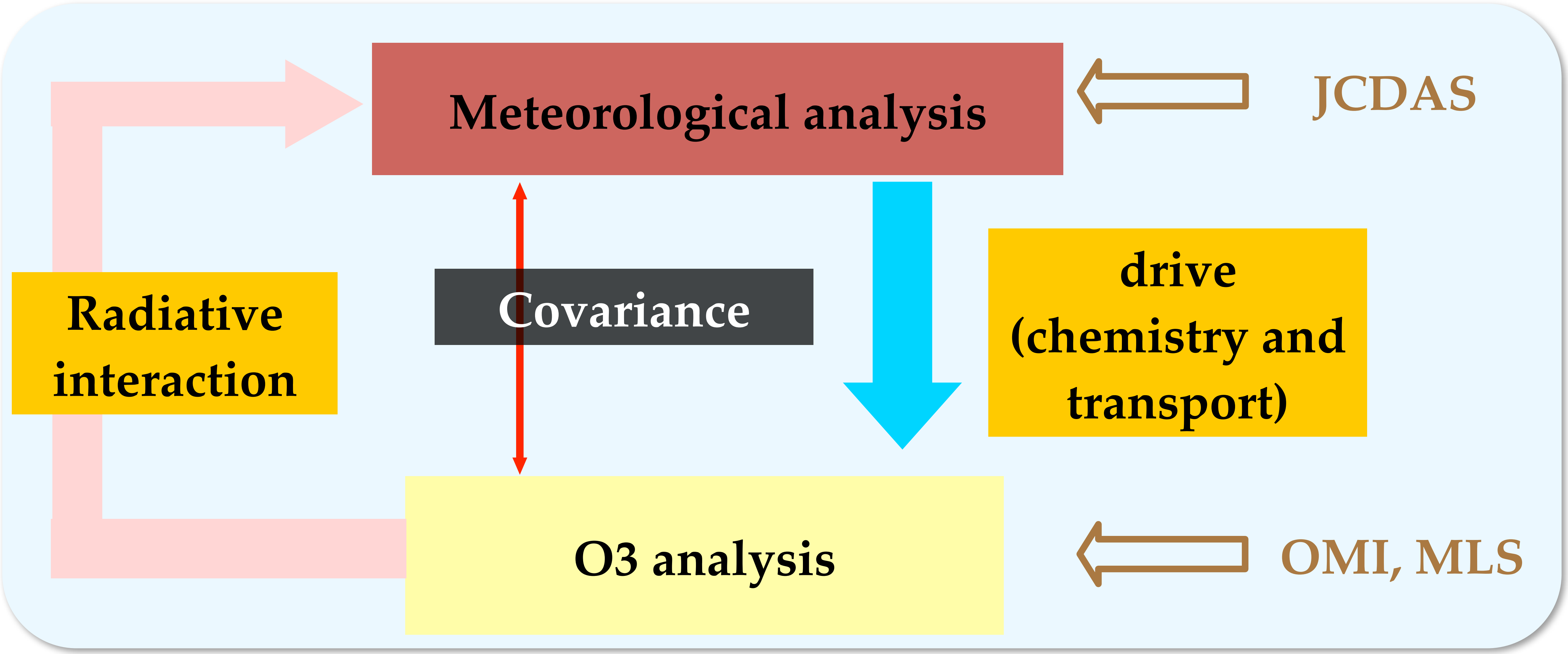
A multi-model comparison provides an opportunity to examine the effects of the model bias on the assimilation performance.

Assimilated data: **MLS O3 profile, OMI O3 column, JCDAS (regarded as met. data, simplifying the system)**

Control variables: **O3, U, V, T**

Assimilation setting: **3D analysis with 6-hourly cycle**

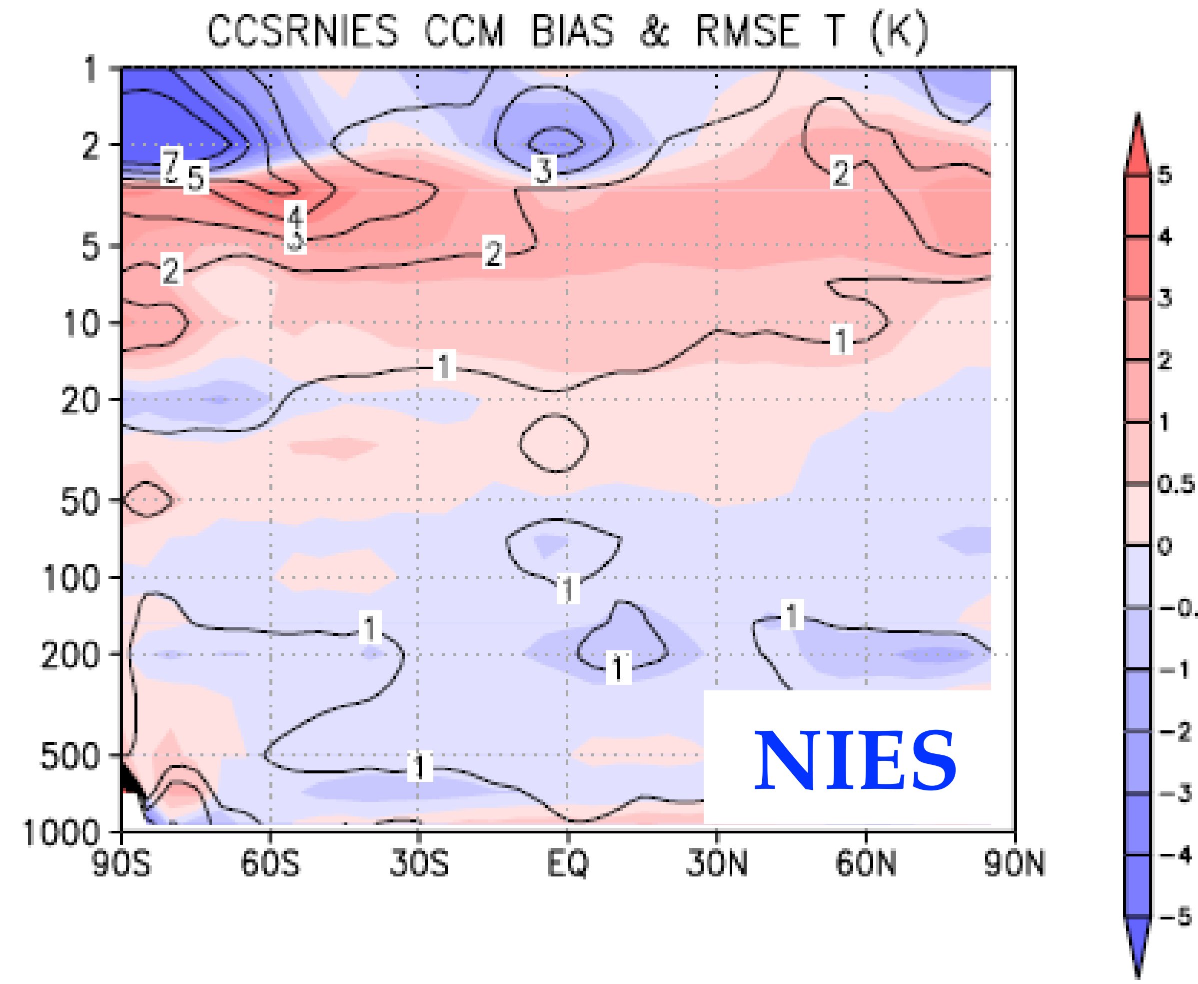
Meteorology-chemistry coupling data assimilation



How does the ozone data assimilation improve the meteorological analysis?

Chemistry-climate models:

Ozone forecast error →
Temperature analysis error



- **Without** ozone data assimilation (only met. data are assimilated)

→ Large T errors of the models still exists in upper stratosphere in both models.

- Need to correct ozone/radiation.

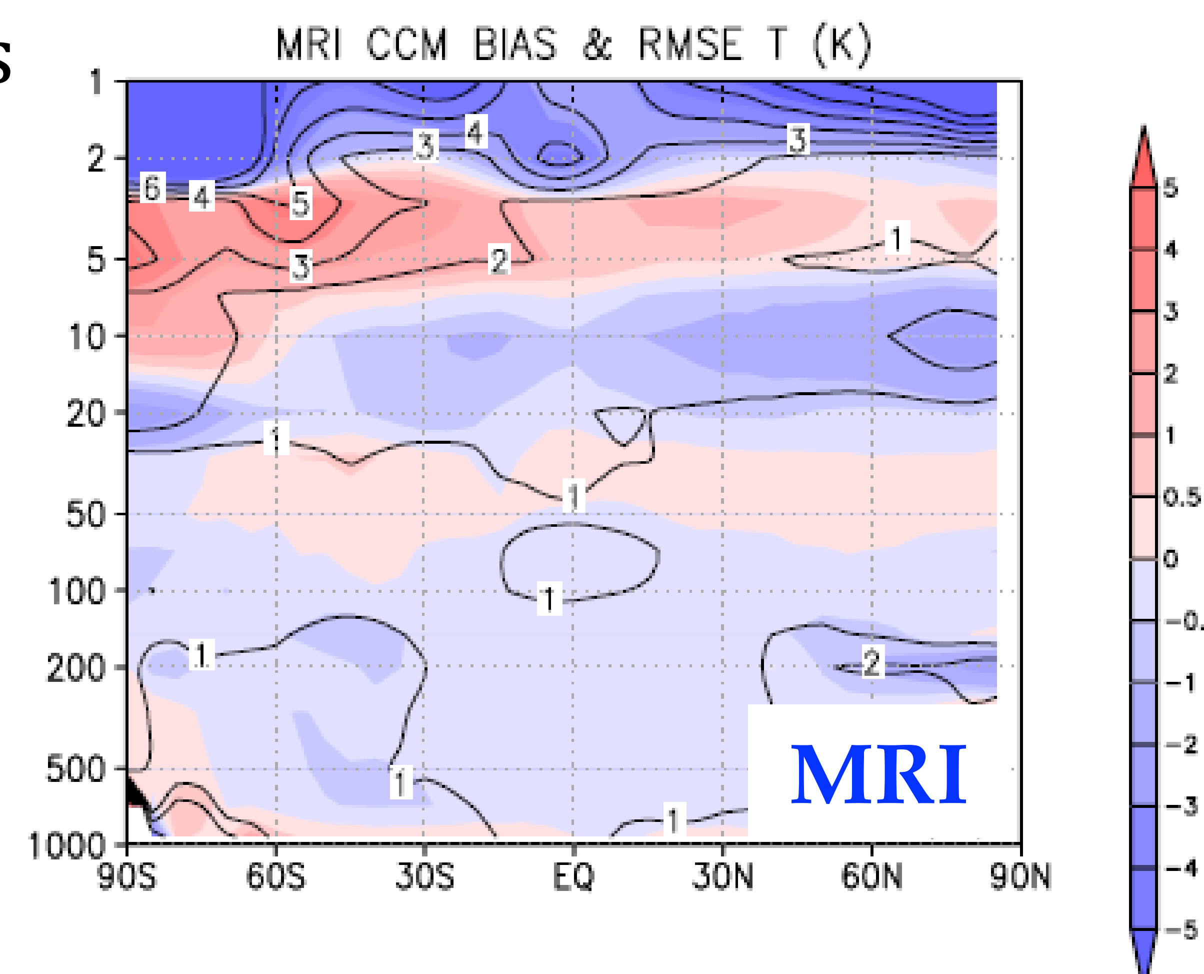
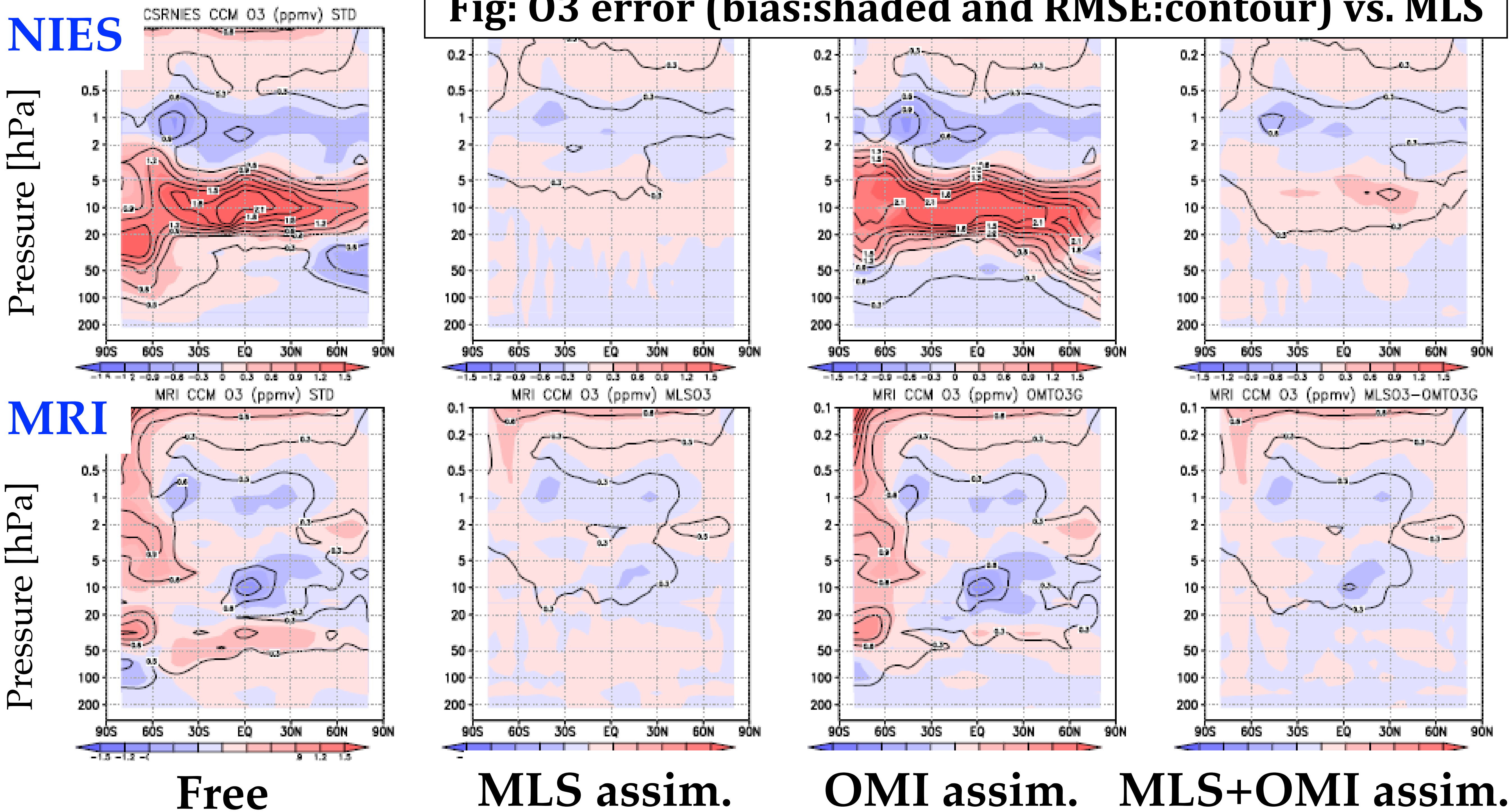


Fig: Temperature error (bias:shaded and RMSE:contour) compared to (assimilated) JCDAS.

Ozone data assimilation

- ***Improvements by MLS O3 assimilation***: throughout the stratosphere.
- ***Improvements by OMI-TO3 assimilation***: only in the lower stratosphere.
- No improvement in the mesosphere due to too small ensemble spread.

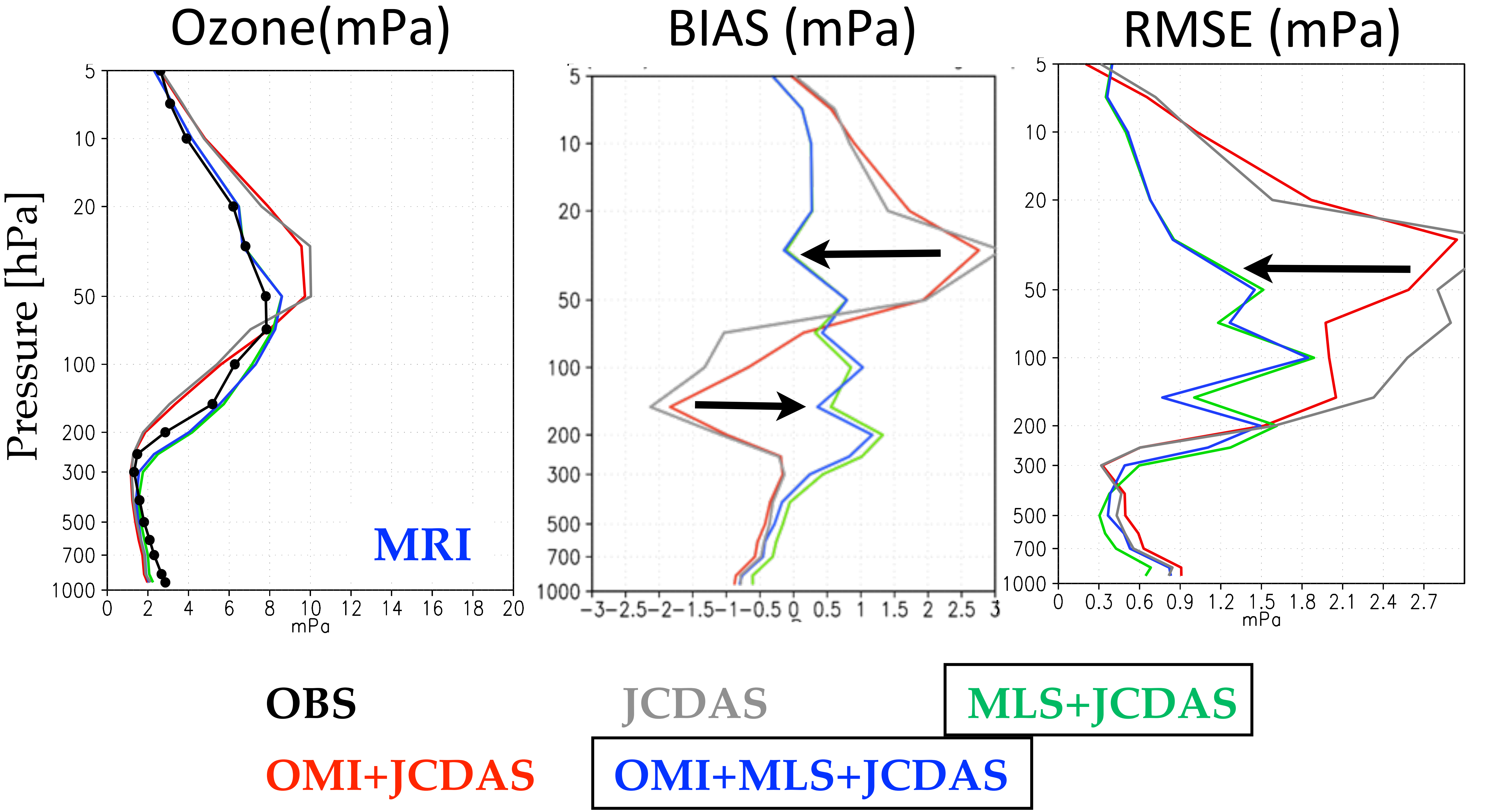
Fig: O3 error (bias:shaded and RMSE:contour) vs. MLS



Ozone data assimilation

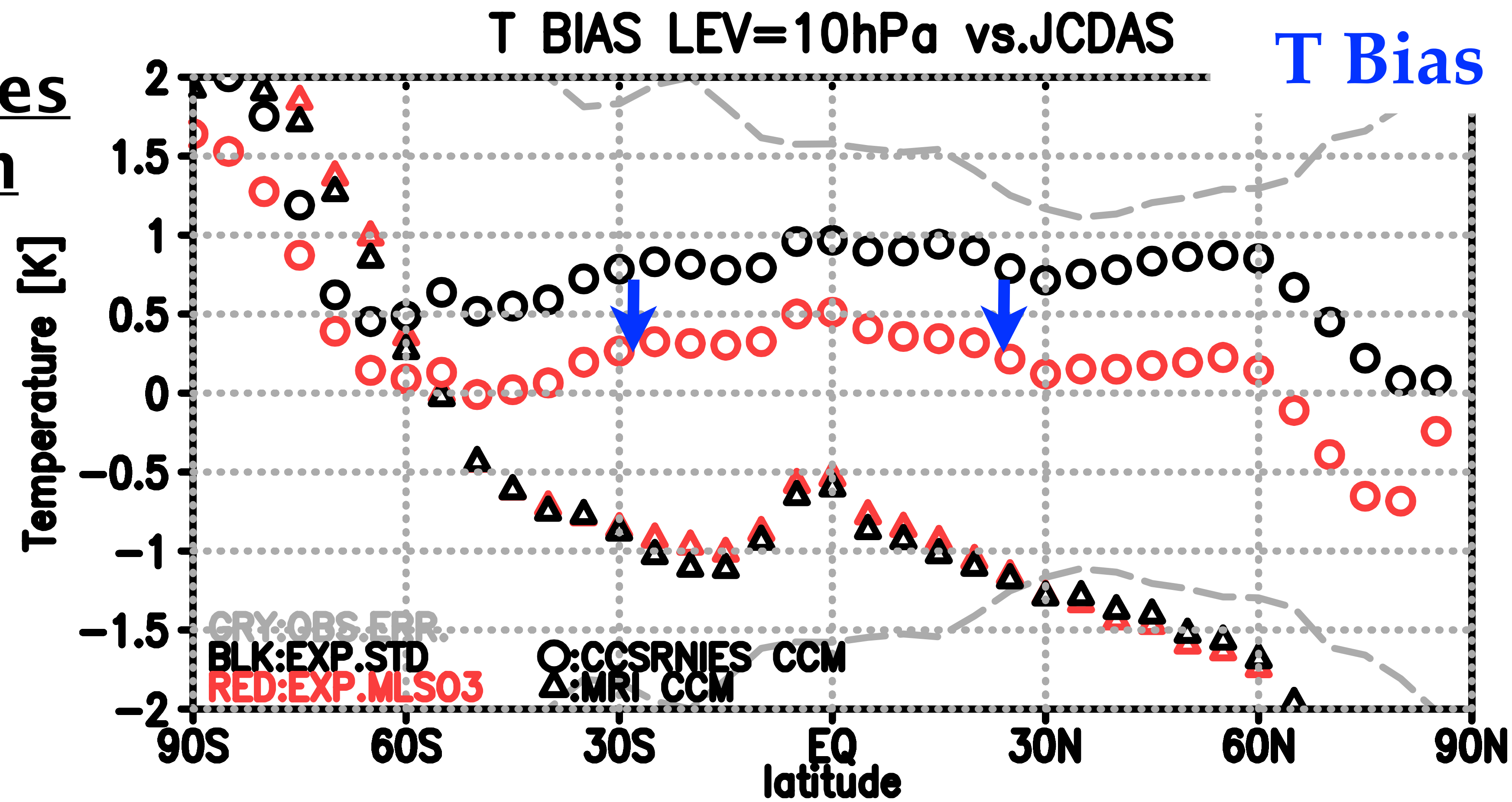
(vs. Sonde, 60S-90S)

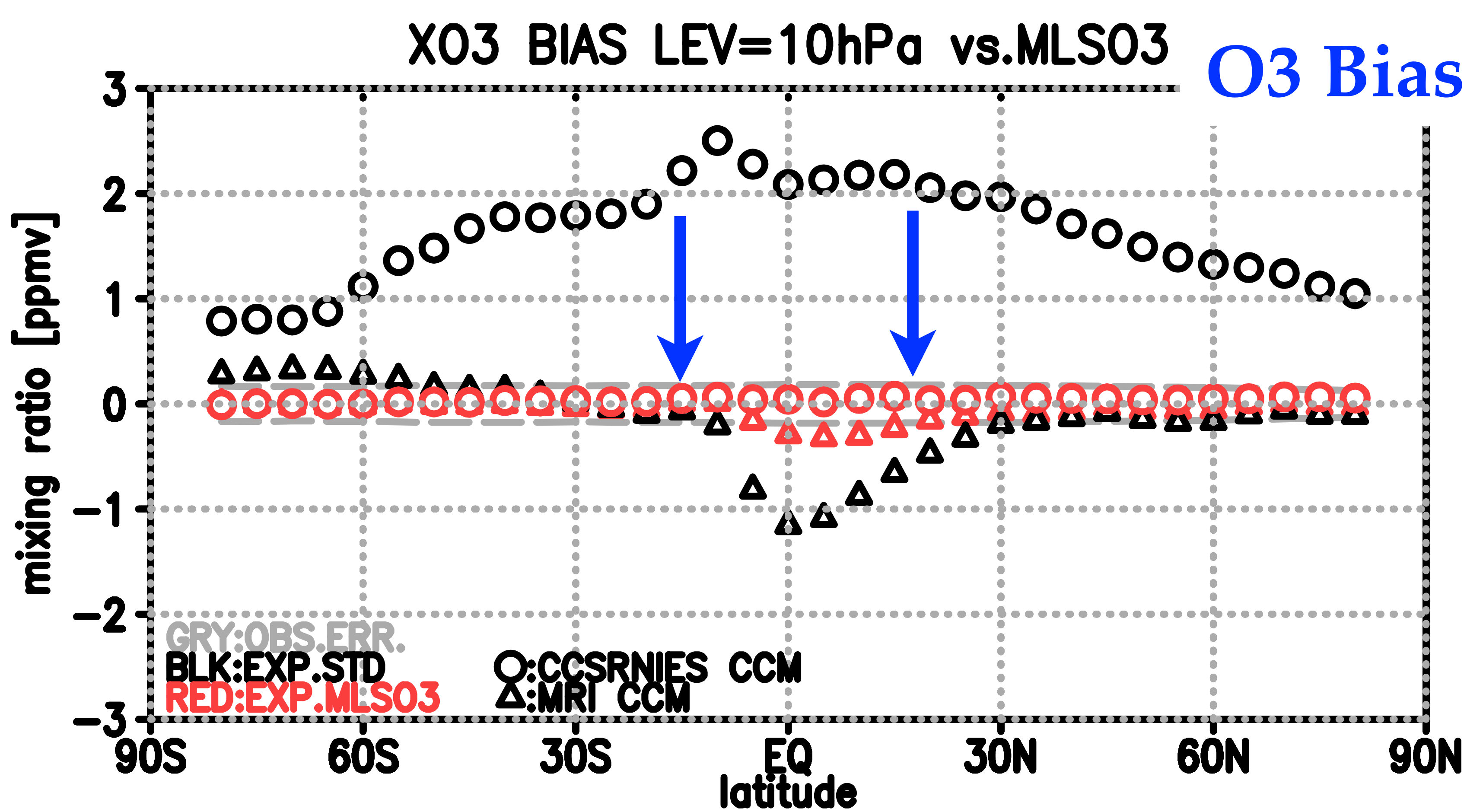
August-September, 2006



Improvements of temperature and o3 biases by O3 data assimilation

○ NIES: simulated o3
○ NIES: w/ o3 assim.
△ MRI: simulated o3
△ MRI: w/ o3 assim.



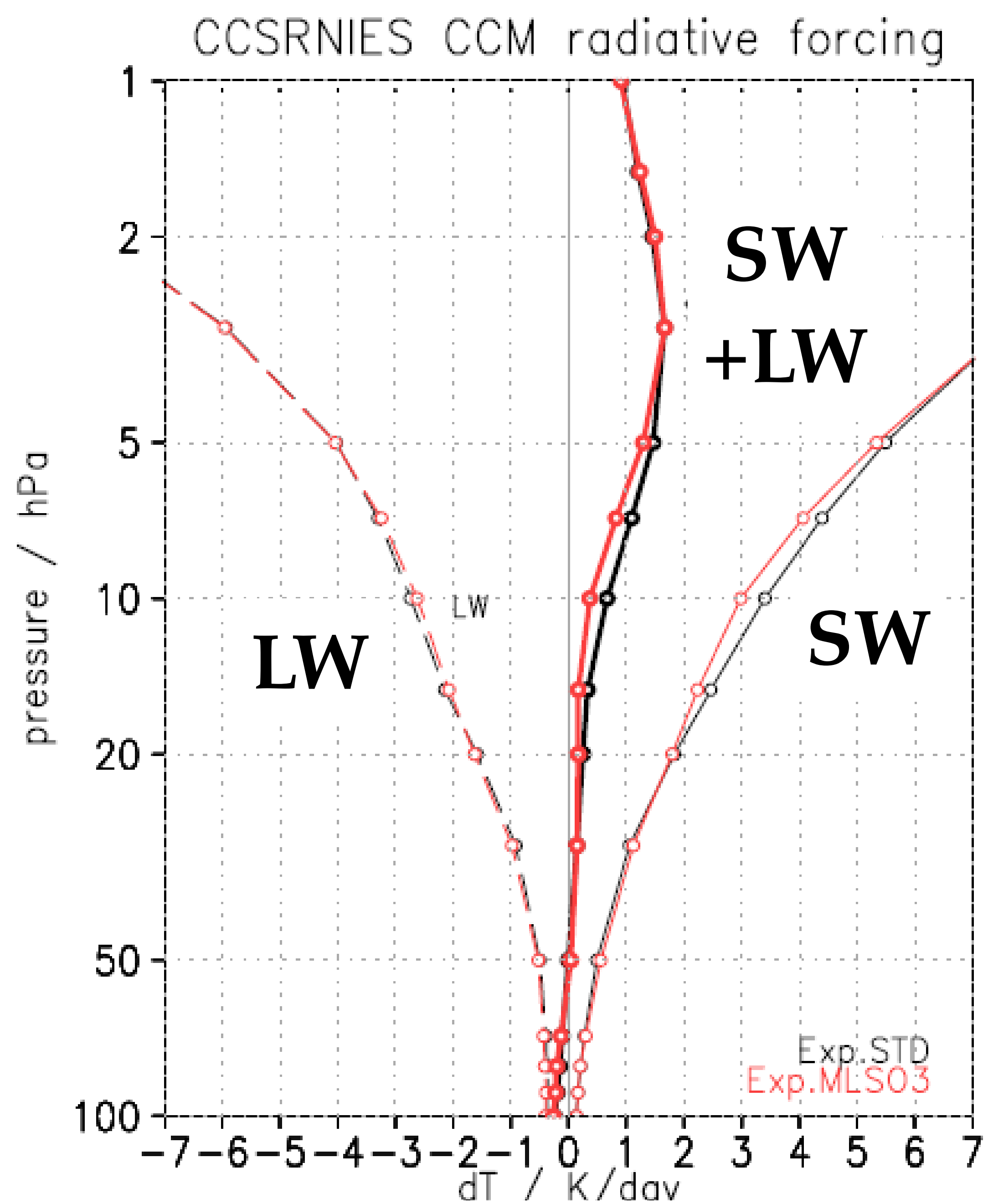


- The temperature bias of the NIES model has been mostly (about 50 %) removed by ozone data assimilation.
- The impact is not obvious in MRI model, since the MRI model has very small bias in the forecasted ozone fields.

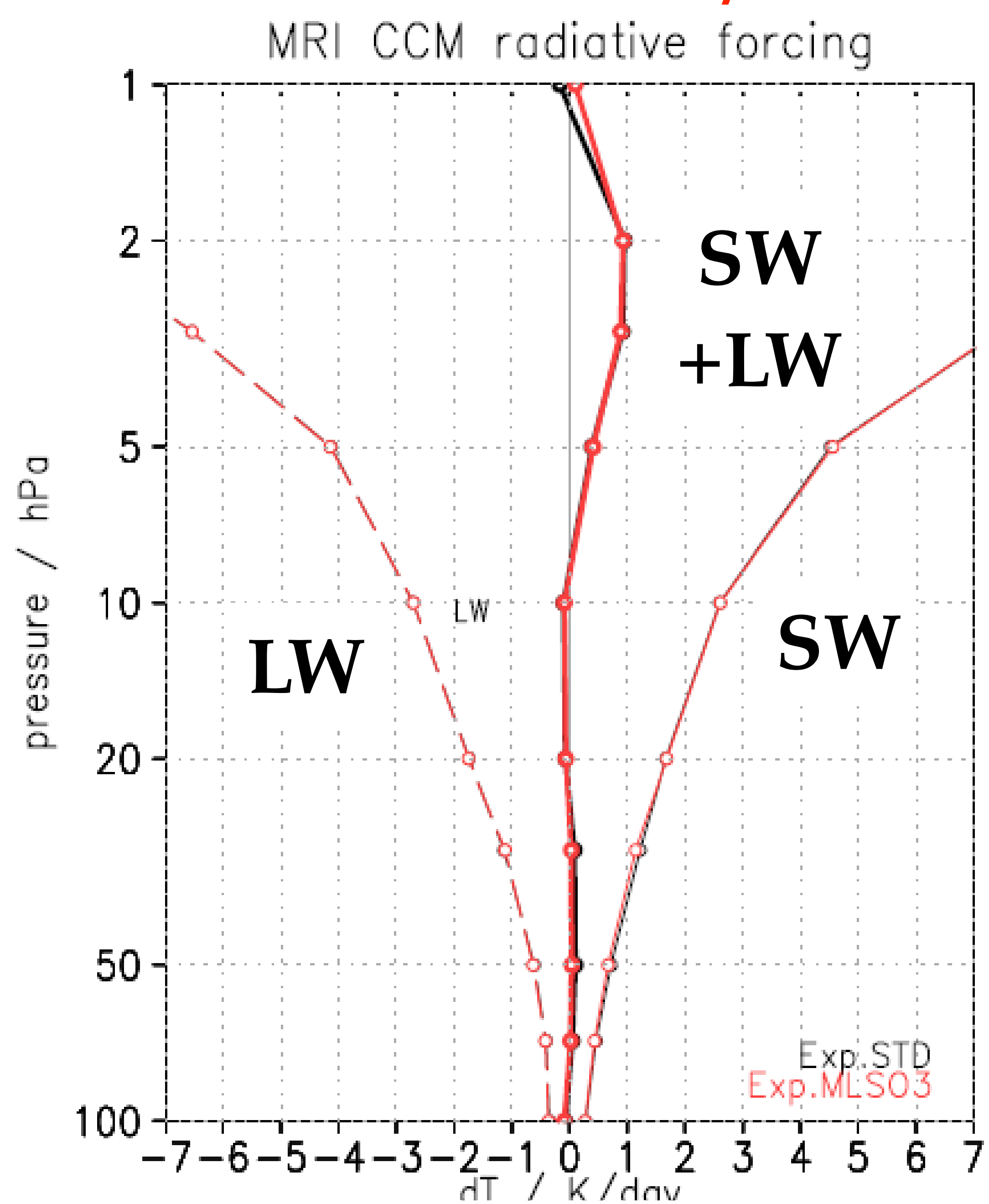
- **NIES in the middle stratosphere:** O_3 data assimilation → less positive O_3 bias → 10 % reduction in SW heating → 40% reduction in net radiative heating
- **MRI:** Almost no impact on the heat budget. The radiative scheme needs to be improved to remove the cold bias.

Fig: Radiative forcing by SW & LW

Simulated o3 w/ O3 assim.



NIES



MRI

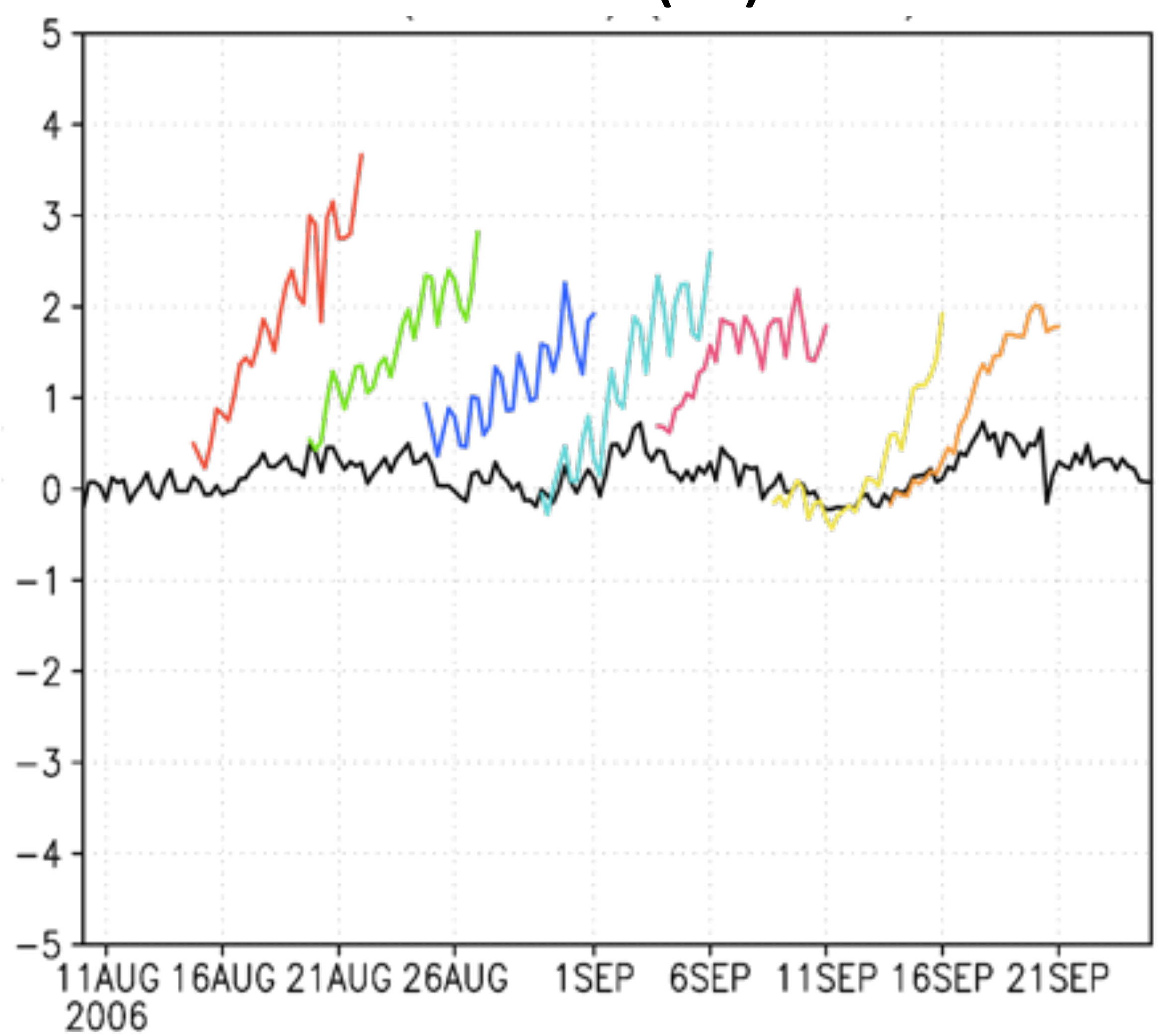
7-days Hindcast experiments using the assimilated field

- **Initialization with assimilated fields.**

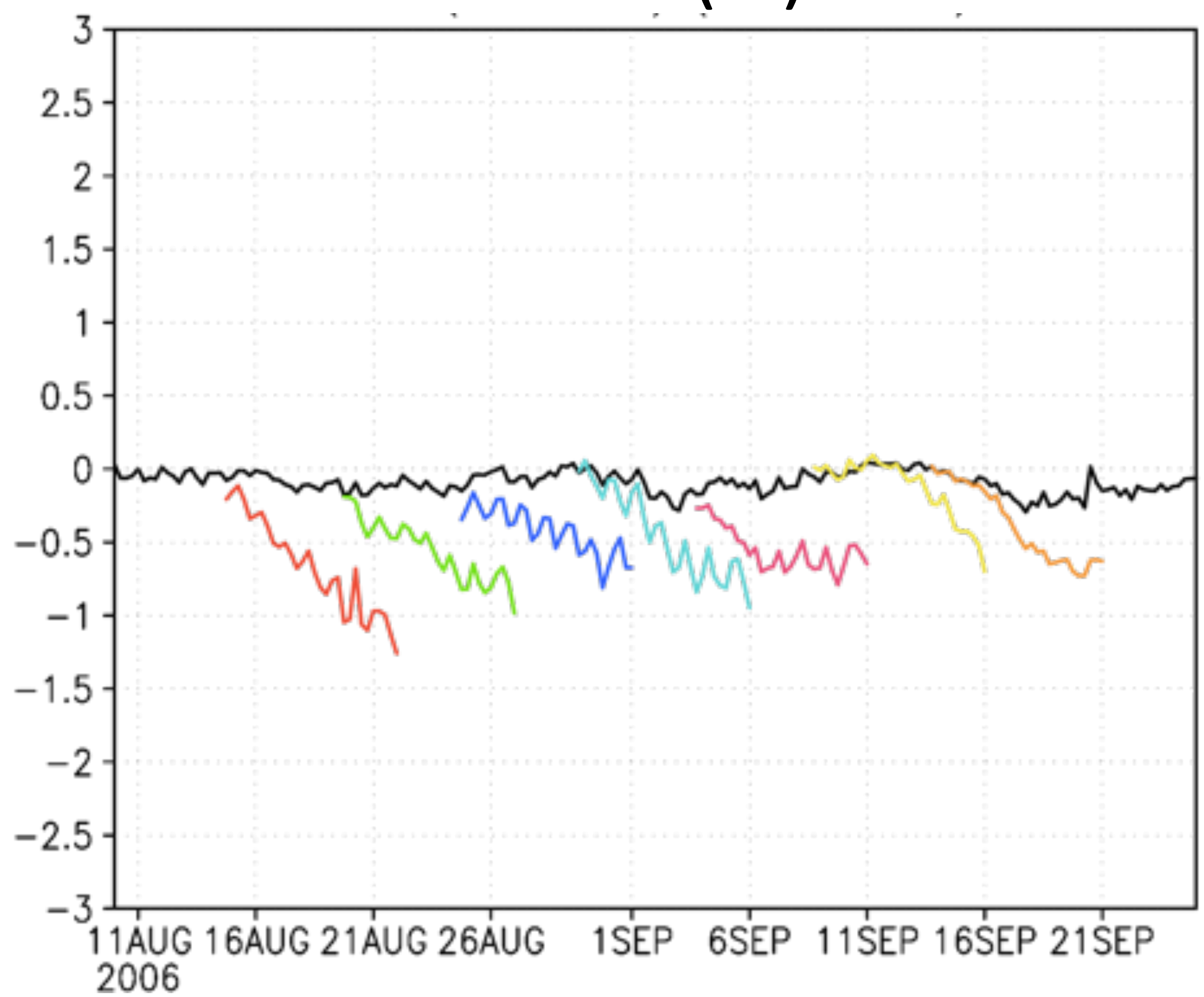
  → High quality forecast (< 3% RMSE, < 1% bias)

Performance of the total ozone hindcast runs (vs. OMI, 30N-60N)
2006 08.10 – 2006 09.25

RMSE(%)



BIAS (%)



2. Aerosols

under development by JMA (T. Sekiyama)

- **Asian Dust**
  - seasonal phenomenon sporadically affecting East Asian countries during the springtime,
  - causes health and aviation problems,
  - originates in the deserts of Mongolia and China.

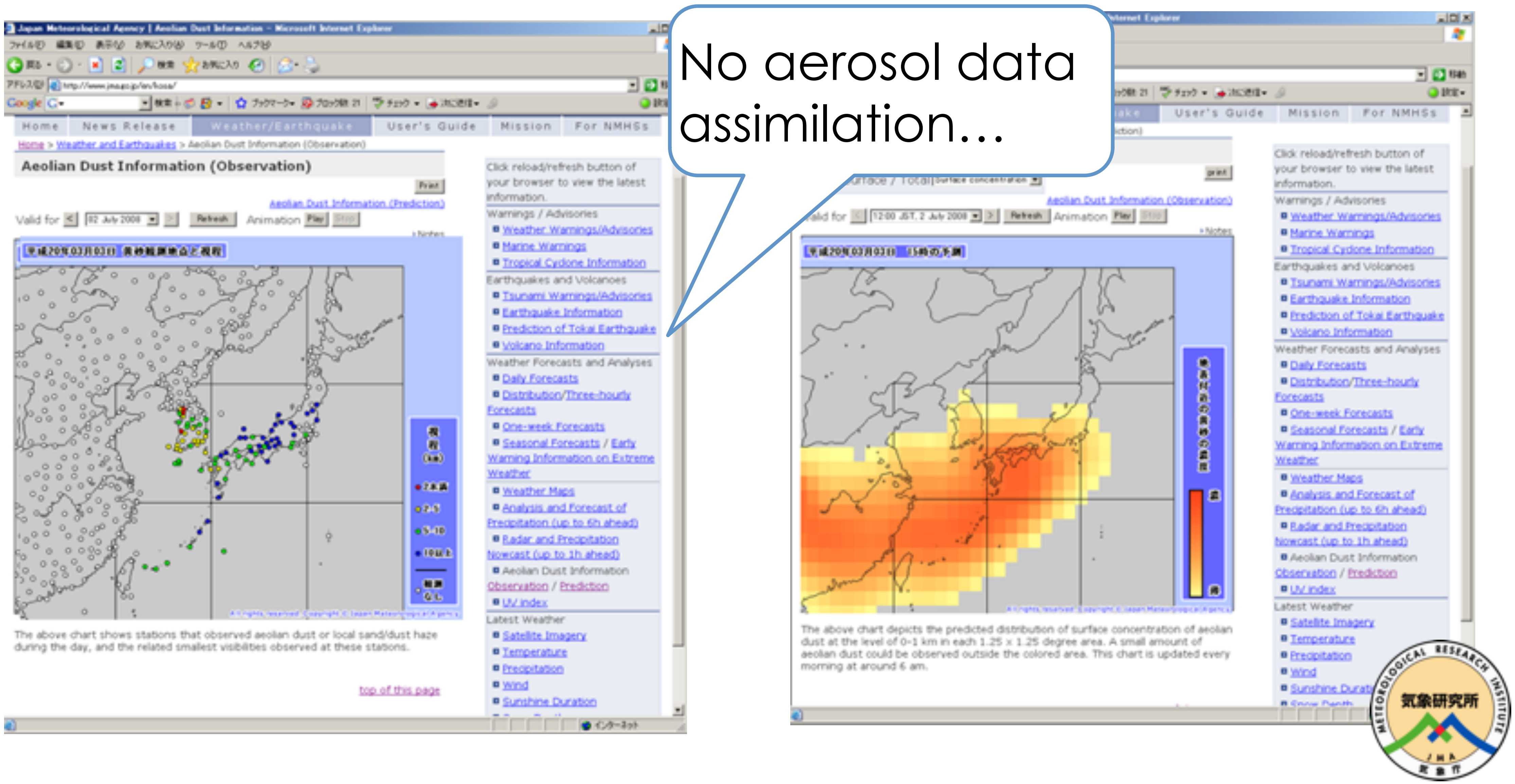
Forecast models: **MASINGAR**

Assimilated data: **Satellite (CALIPSO/CALIOP) and ground-based lidar**

Control variables: **dust (partitioned into 10-size bins), dust flux, sea-salt, OC, BC, and sulfate aerosols**

Assimilation setting: **4D analysis with 48-h time window**

Operational dust prediction

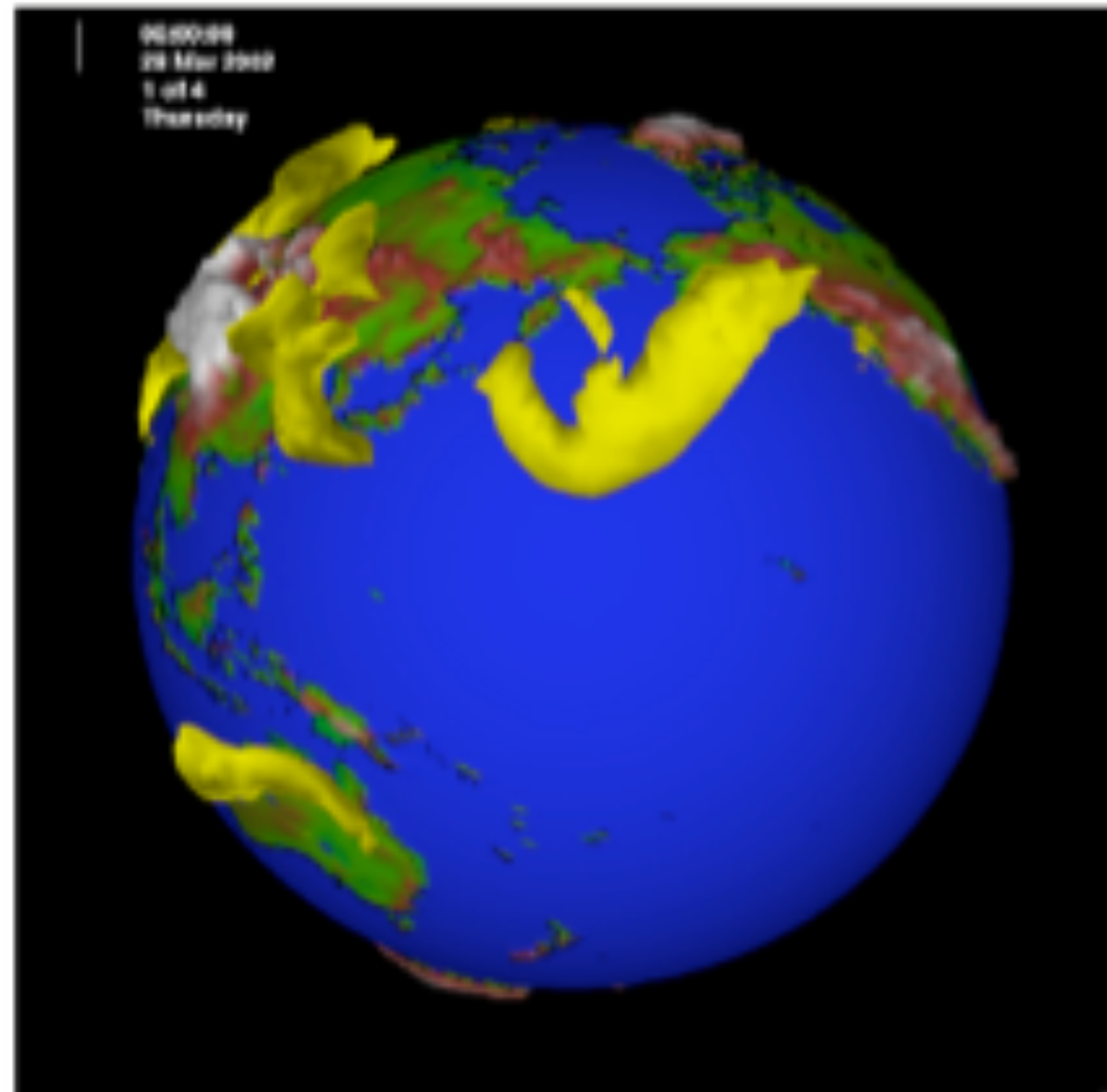


- JMA wants to utilize aerosol data assimilation for improving their operational dust prediction.
- If possible, they want to use the aerosol analysis for their NWP and climate simulations.

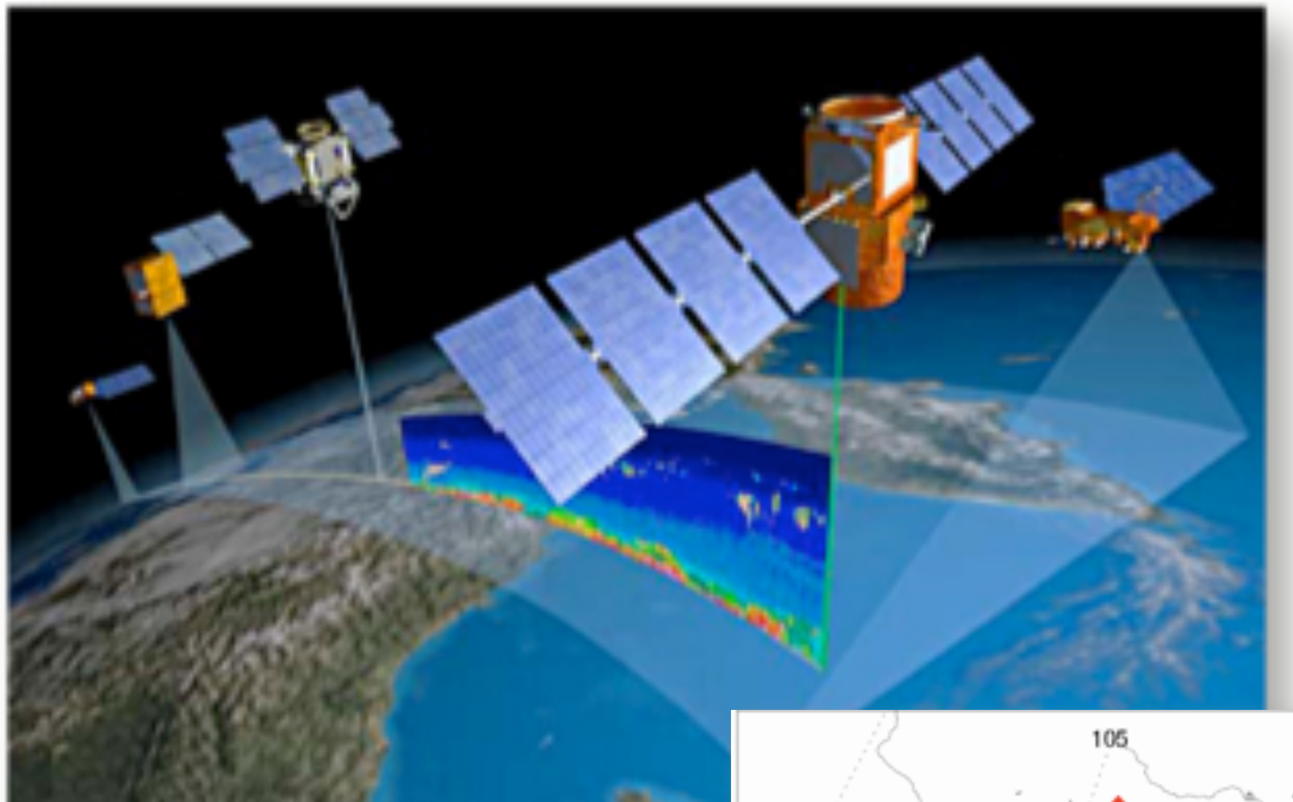
EnKF for aerosol analysis

- The Model of Aerosol Species in the Global Atmosphere (**MASINGAR**) of MRI/JMA simulates…

- **dust** (partitioned into 10-size bins), sea-salt, OC, BC, and **sulfate** aerosols

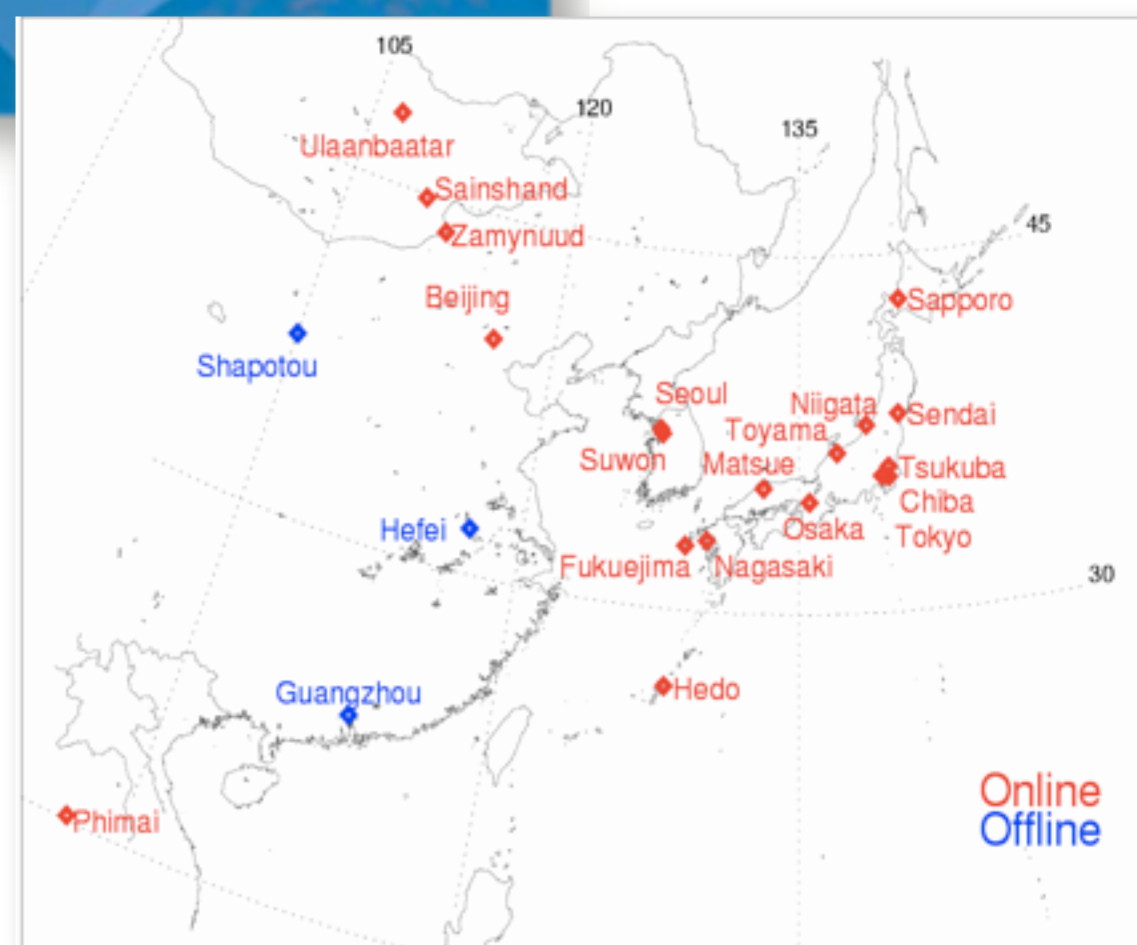


EnKF for aerosol analysis

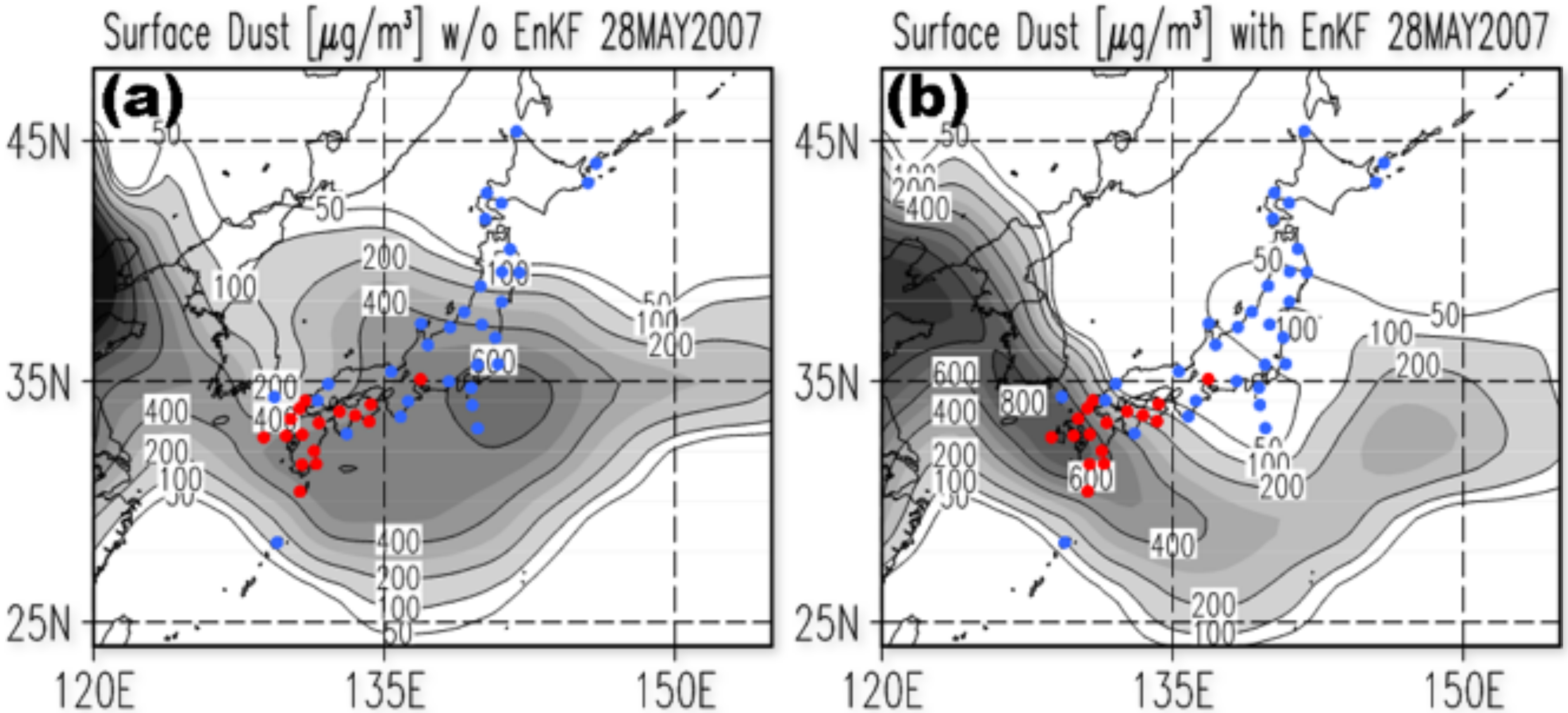


Satellite Lidar observation (CALIPSO/CALIOP): NASA launched the polar-orbit satellite in 2006.

Ground-based lidar network (NIES AD-Net): NIES Japan is operating more than 20 lidar stations in East Asia.

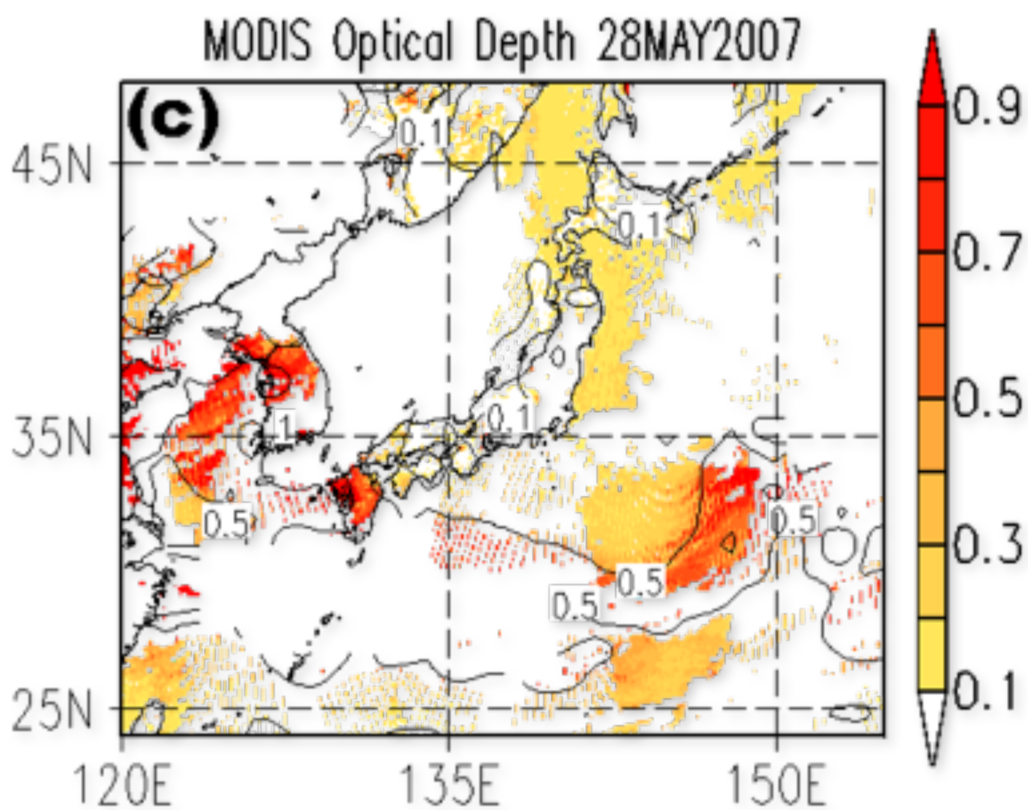


EnKF for aerosol analysis



Contours and gray shades are **surface dust concentrations**.

(a) Free model-run result without data assimilation.
(b) CALIPSO data assimilation result.



Sekiyama et al., ACP (2010)

Red and blue circles are weather stations.

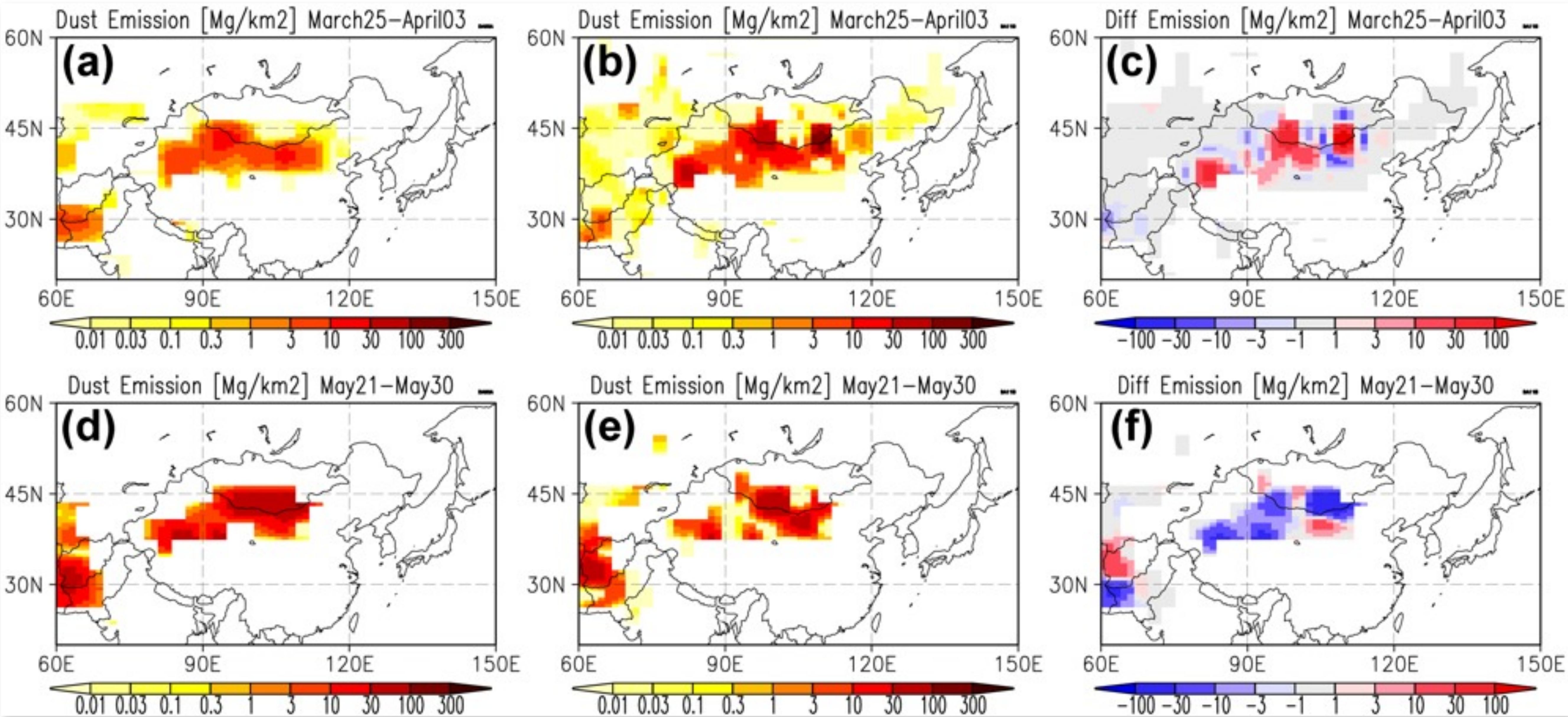
Red ones observed aeolian dust.

Blue ones did not observe any dust events.

The data assimilation result makes the dust plume mostly limited to the area of the red weather stations, in contrast to the free model-run result in which the dust plume covers both red and blue stations.

EnKF for aerosol analysis

- Dust emission inverse analysis by EnKF



Sekiyama et al., SOLA (2011)

The dust concentrations in the downwind region are evidently improved when this dust emission analysis is installed to the model simulation.

JMA's plan for aerosol prediction

- **The EnKF aerosol analyses as initial conditions of aerosol prediction.**
  (hopefully, in practical use by 2014…)
- Aerosol **reanalysis**:
  available for climate modeling?
- Aerosol **climatology** (detailed):
  available for NWP?
- Ideally, **weather-chemistry** coupled DA…

3. Surface CO_2 flux

- establish a 4D-EnKF data assimilation system to estimate global surface CO_2 fluxes from various data.
- evaluate the potential impacts of various data obtained from the surface network measurements, GOSAT measurements, and CONTRAIL aircraft measurements (OSSEs).
- Real data assimilation with a bias-corrected GOSAT data.

Forecast models: MJ98-CDTM, FRCGC ACTM

Assimilated data: Satellite (GOSAT), Aircraft (CONTRAIL), Ground-based network

Control variables: Surface CO_2 flux, Atmospheric CO_2 concentration

Assimilation setting: 4D analysis with 72-h time window

4D data assimilation system for carbon cycle

- Simultaneously estimate atmospheric concentrations and surface fluxes of CO_2 at high spatial (2.8°) and temporal (1.5 days) resolution.

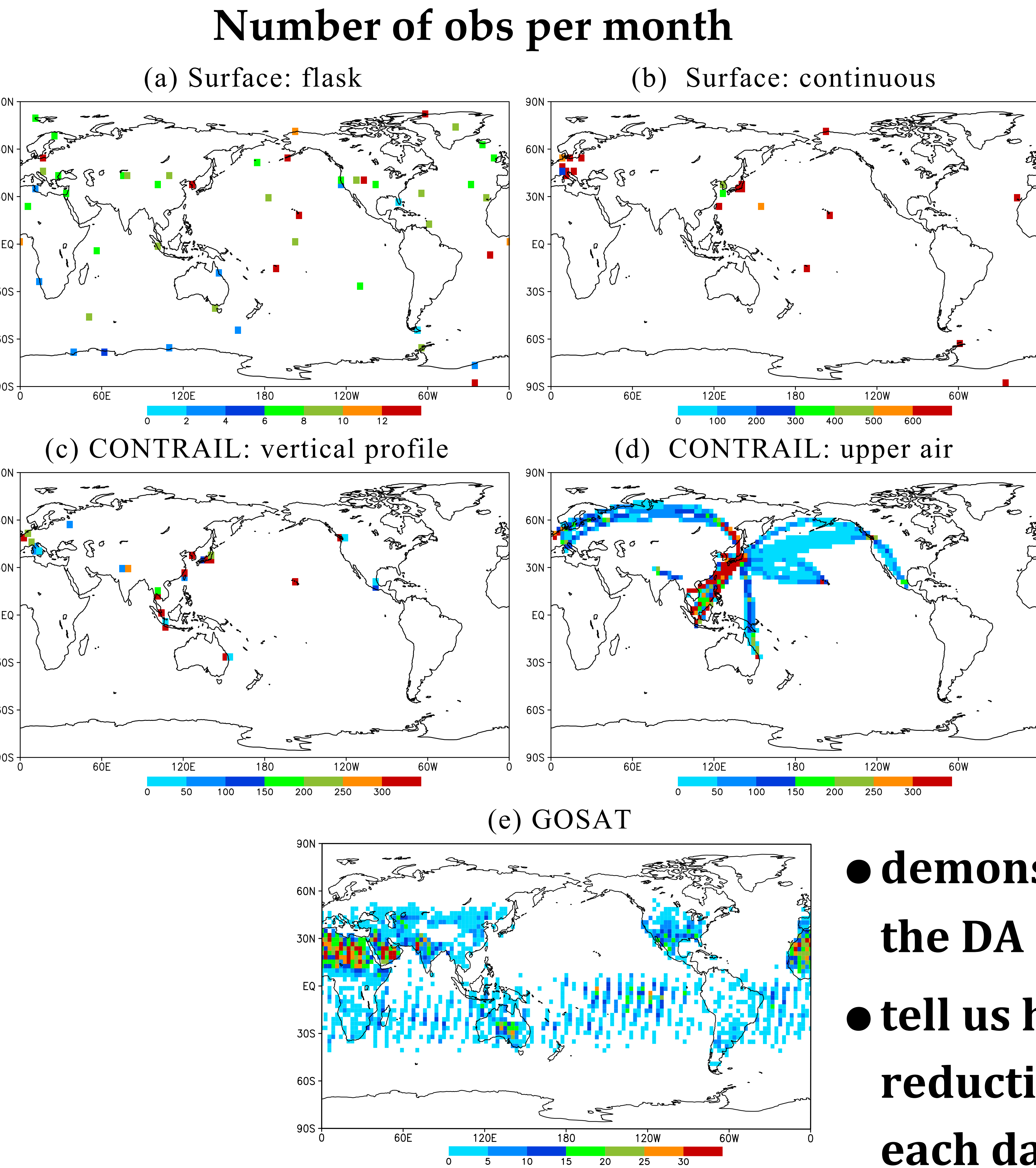
***Forecast models*: (1) FRCGC ACTM (Miyazaki et al., 2008)**

(2) MJ98-CDTM

***Data assimilation*: 4D-EnKF with localization (LETKF, Hunt et al., 2007)**

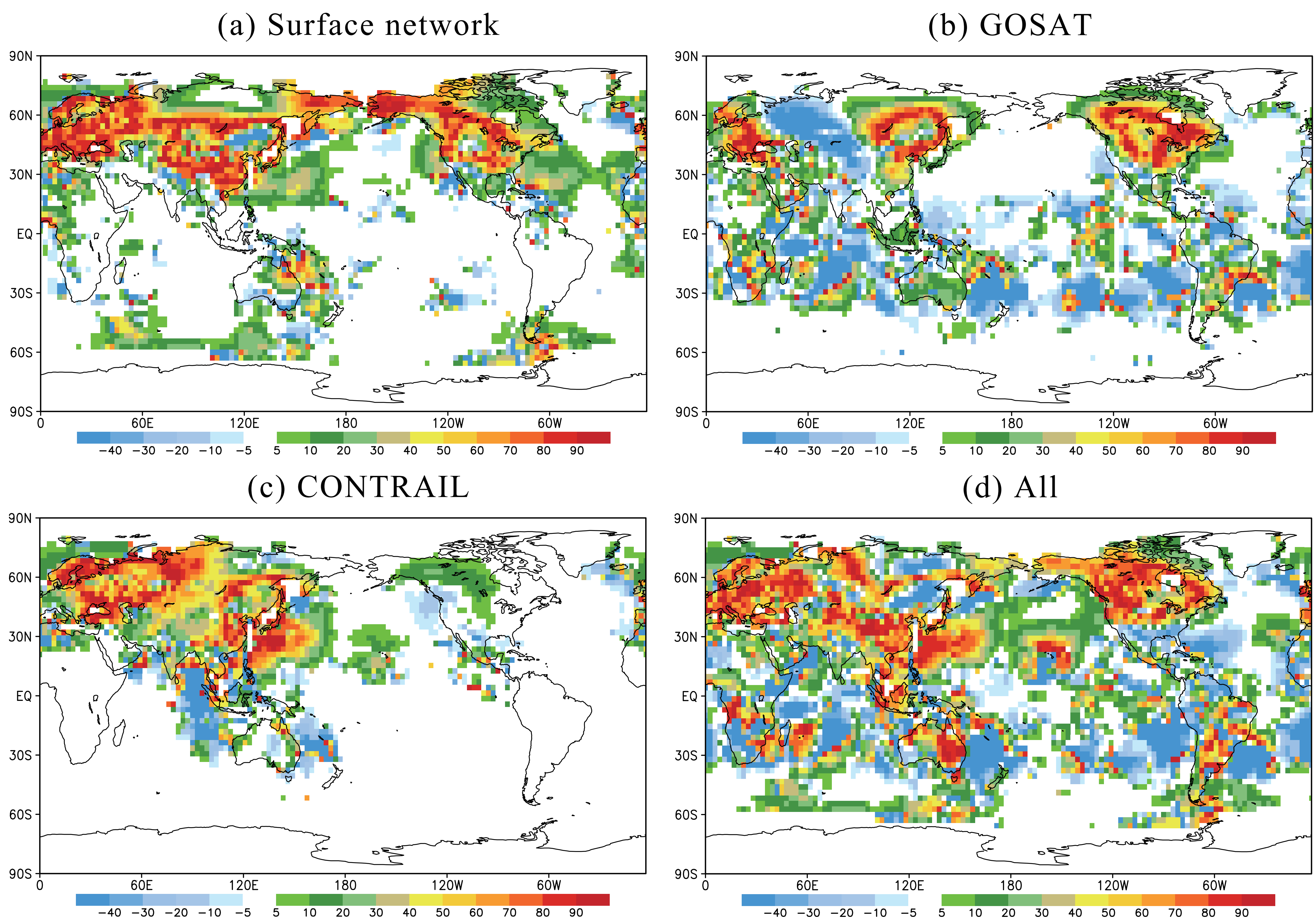
- **State augmentation approach**
- **Conditional inflation for surface flux**
- **Data assimilation window: 3-day**
- **Super observation for CONTRAIL data**
- **Long vertical localization length for CONTRAIL**
- **48 ensemble members**

Observation system simulation experiments (OSSEs)

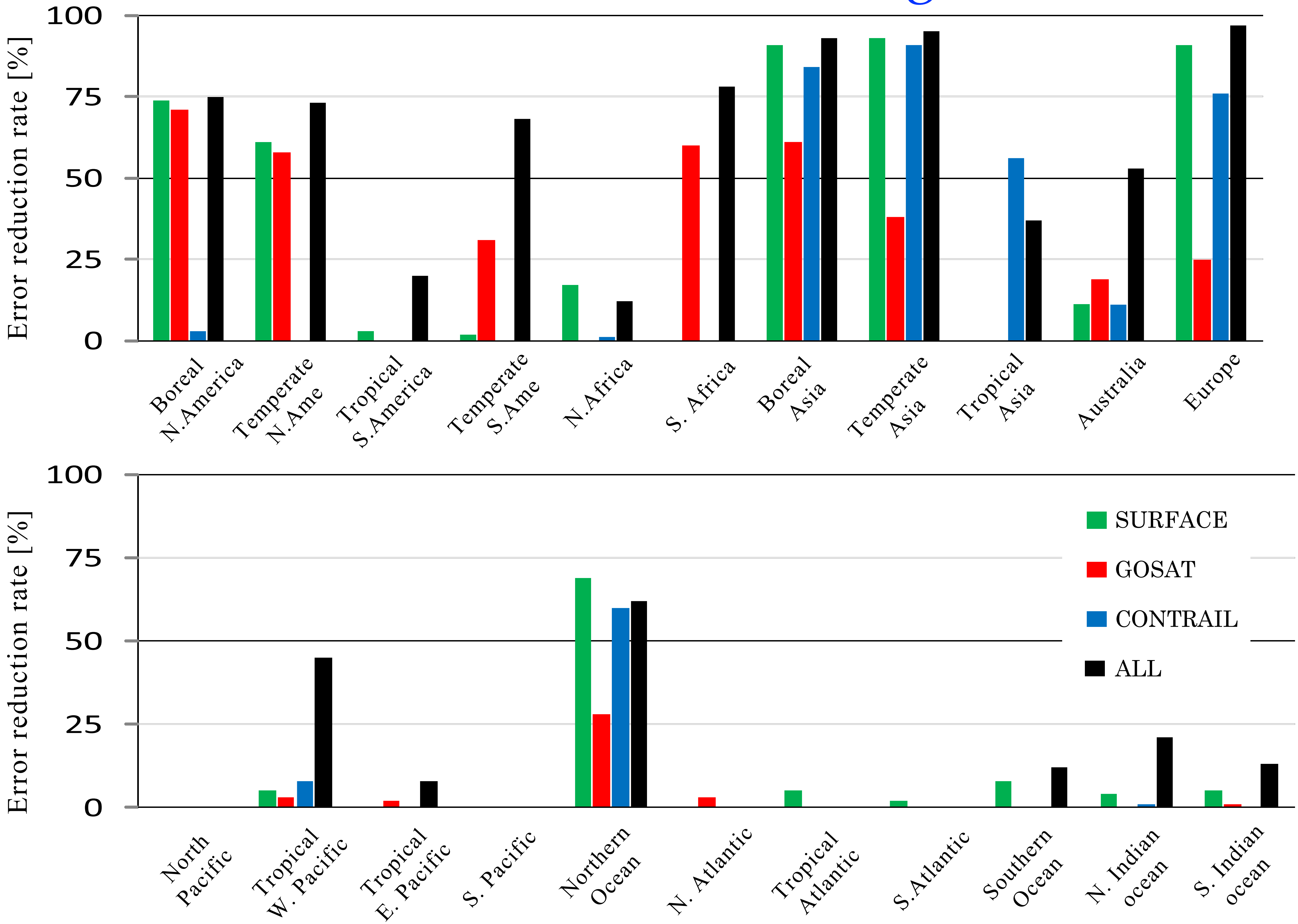


- **demonstrate the performance of the DA scheme**
- **tell us how much error reductions can be expected by each dataset**

Flux error reduction rate [%]: grid-scale



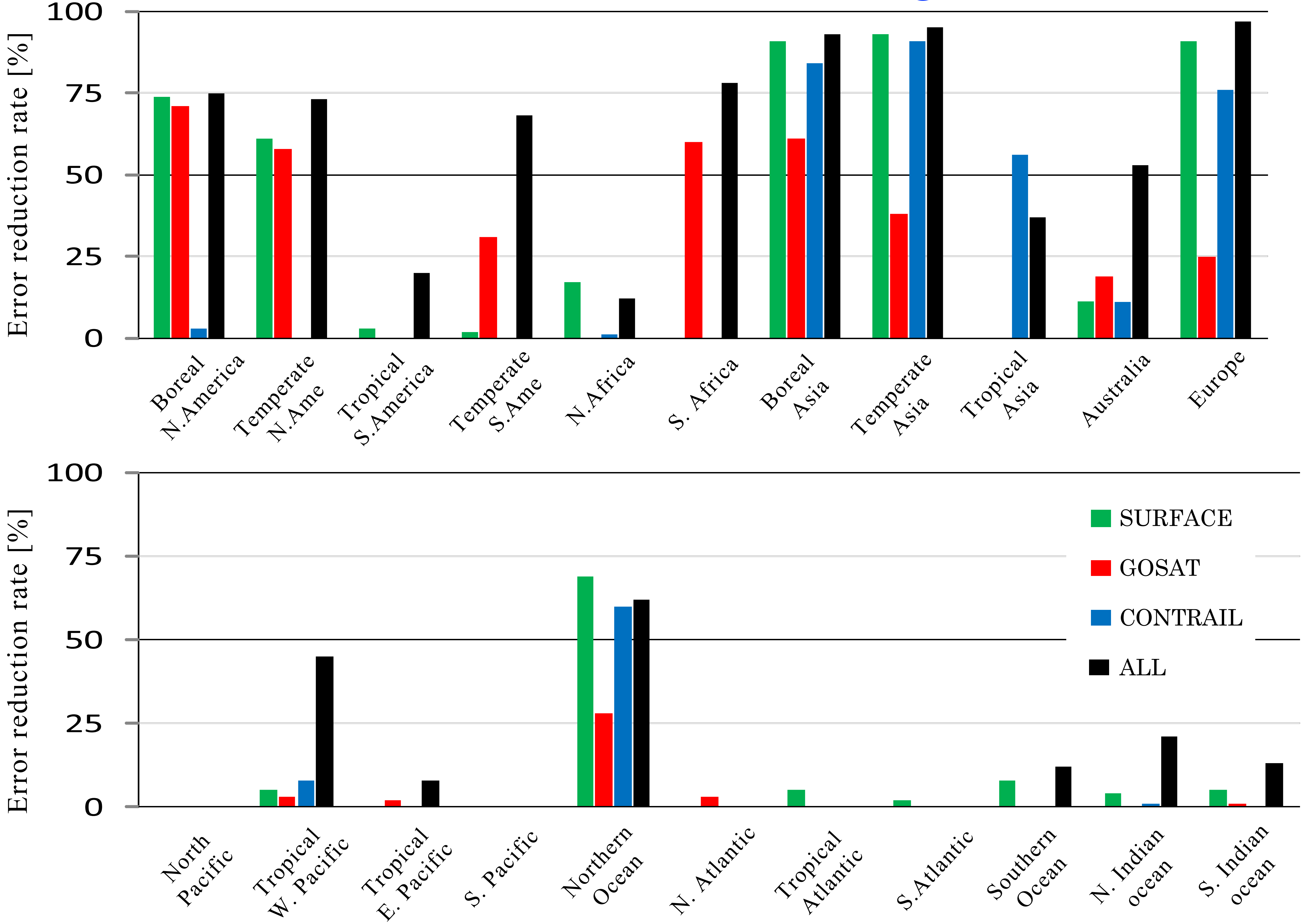
Flux error reduction rate [%]: regional-fluxes



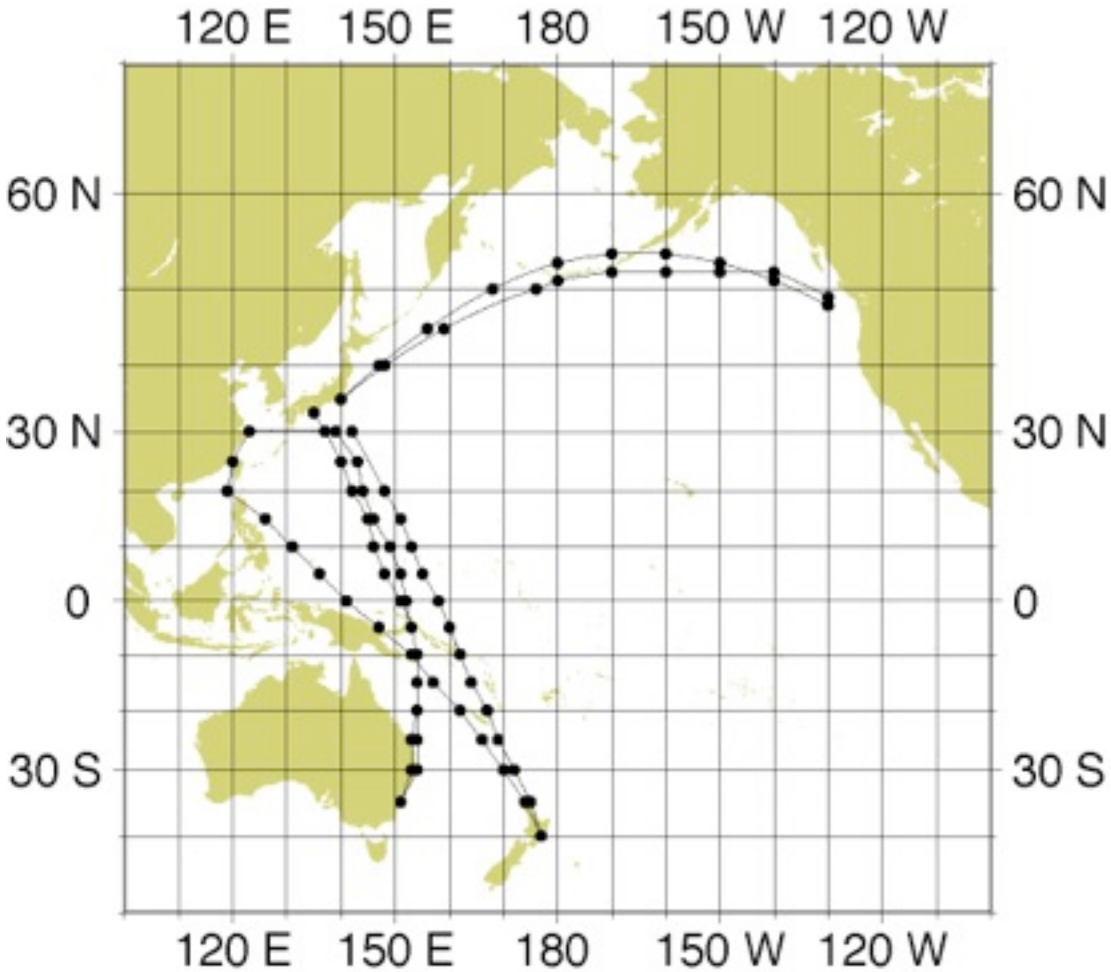
CONTRAIL data: Europe and Asia.

GOSAT data: North and South America, South Africa, Asia, and Europe

Flux error reduction rate [%]: regional-fluxes

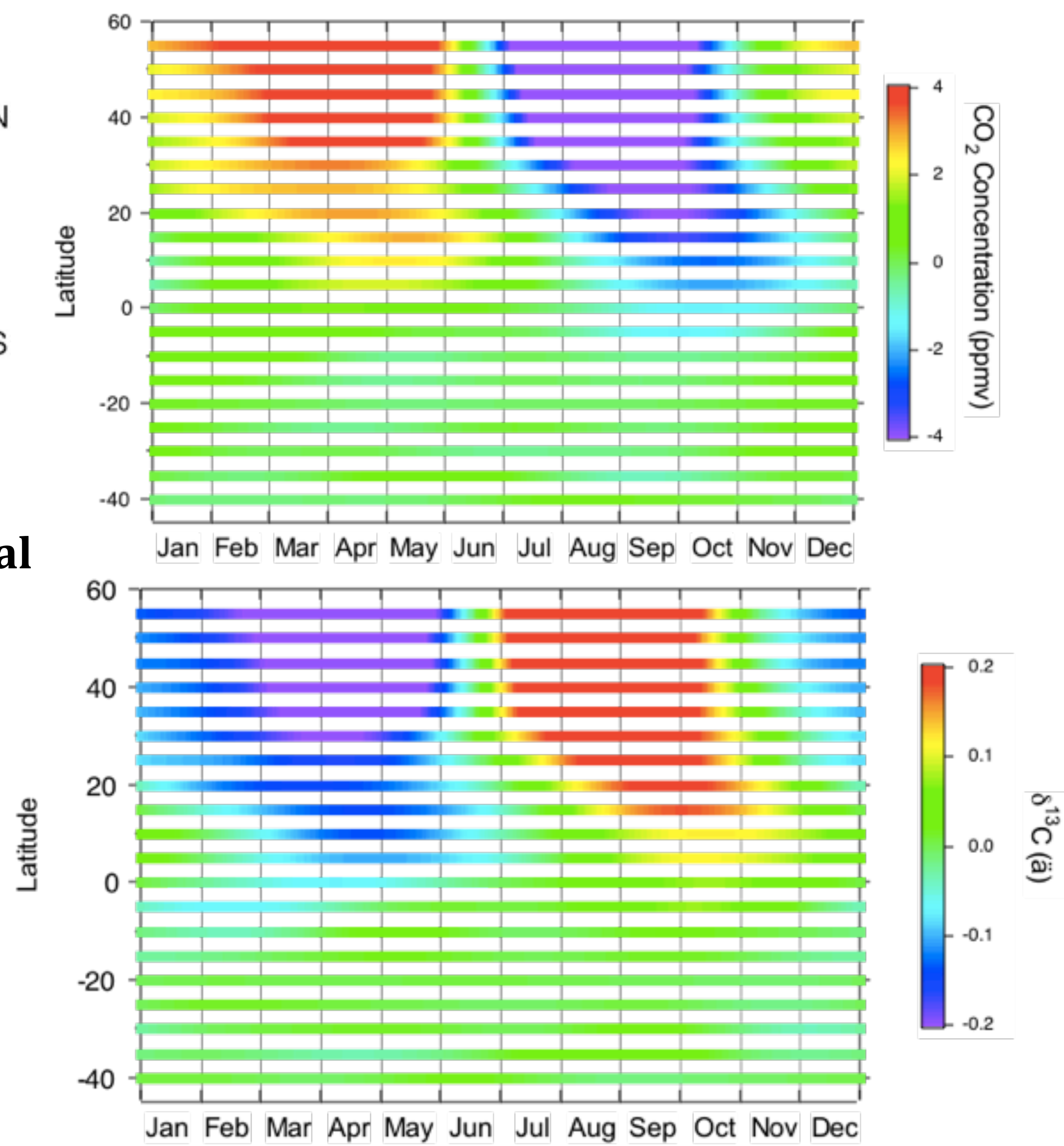


Additional constraints are required especially over North Africa, tropical South America, southern North America, and the oceans.



Air sampling on board commercial container ships since 1984.

Fig: Mean seasonal cycles of CO_2 concentration and $\delta^{13}C$ at each latitude band.



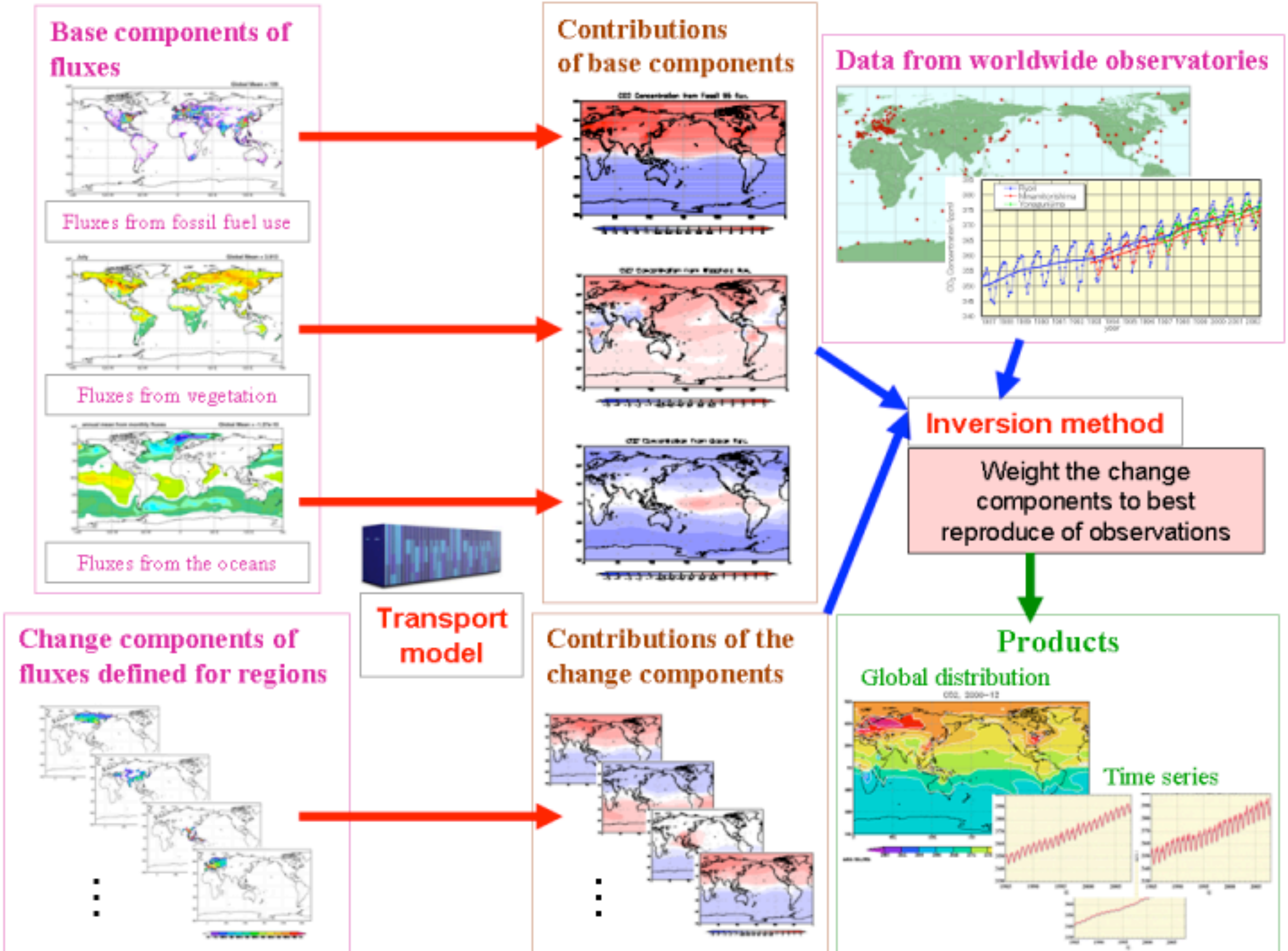
Further constraints will be added...

Sensitivity to OSSE settings and model/obs errors

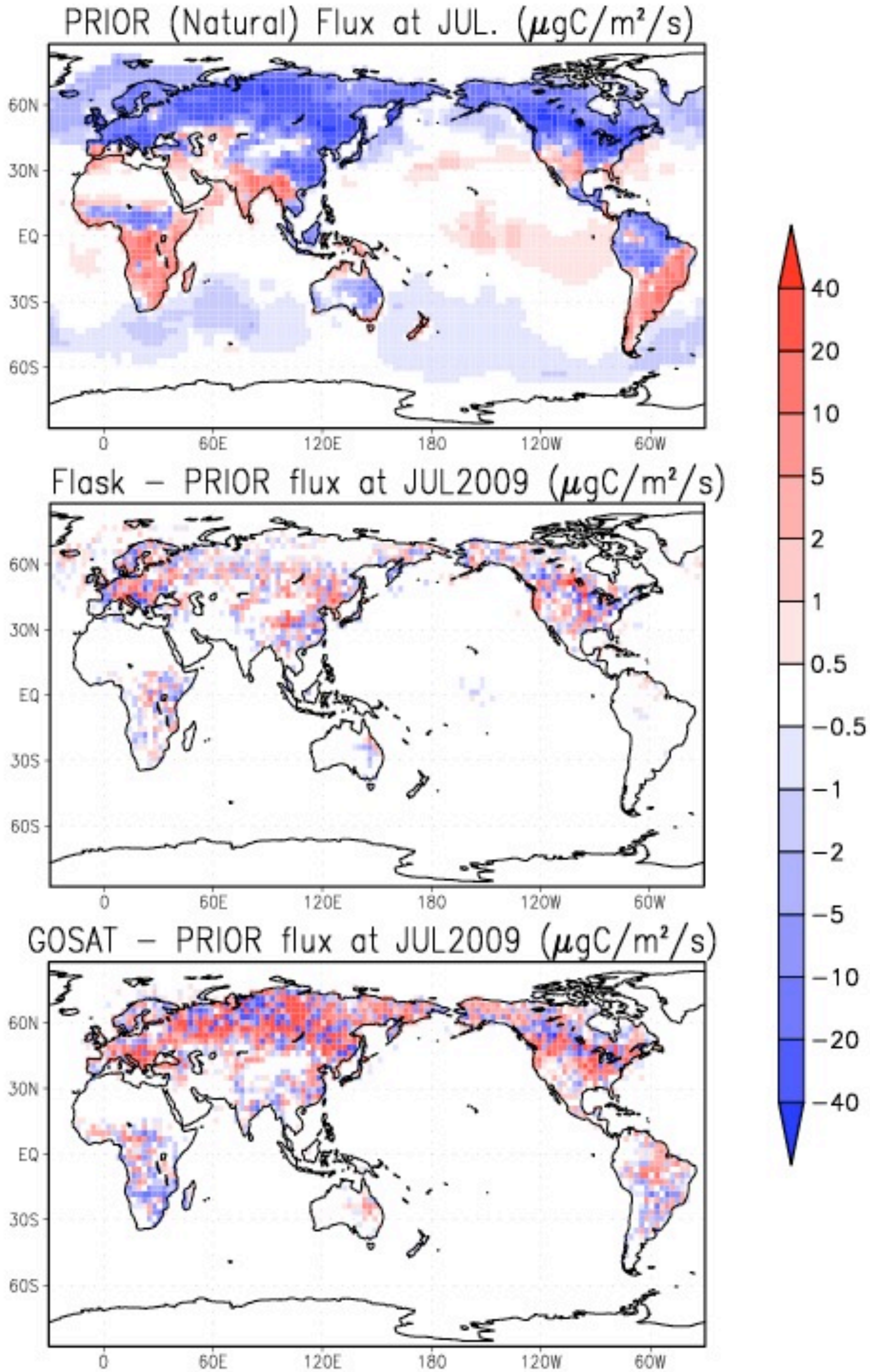
- **The OSSE results are sensitive to its settings (e.g., initial and true fluxes, and observation errors).**
- **Many sources of error associated with the observations and the transport model will strongly decrease the usefulness of each observation; this could become a limiting factor in the data assimilation that involves real data (Miyazaki et al., 2011).**
- **E.g., realistic systematic errors in the GOSAT data can reduce the usefulness of the observations by a factor of 2.**

A bias correction scheme for GOSAT

- **Monthly mean bias of GOSAT is estimated by comparing GOSAT XCO_2 (L2SWIR) with JMA CO_2 analysis (based on surface observations).**
- **Hot spot fluxes are further adjusted using surrounding data.**



Real data assimilation



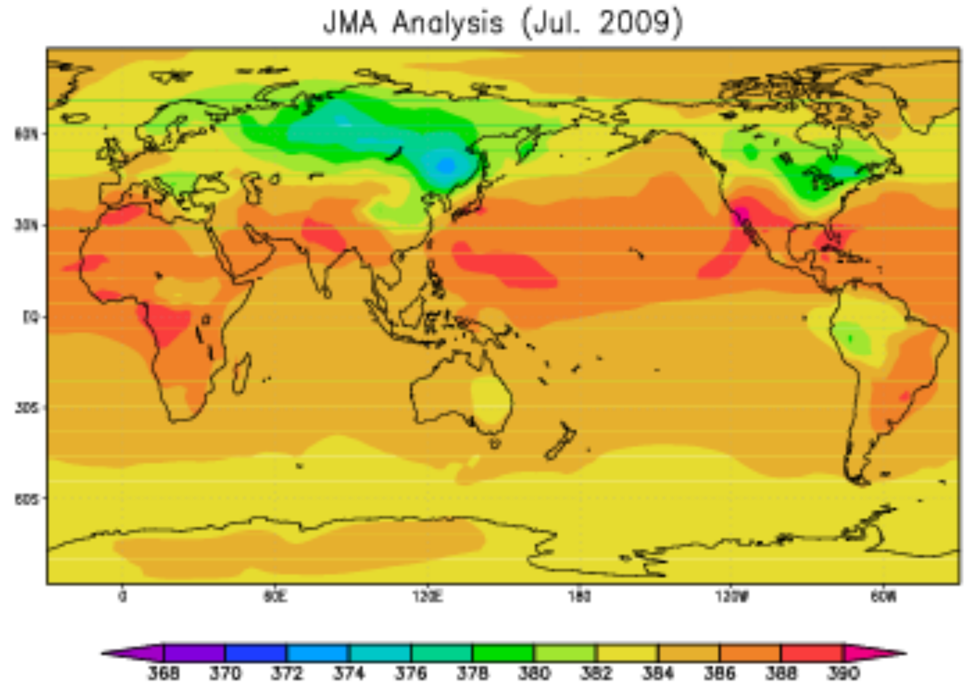
- Bias-corrected GOSAT data provide additional corrections and improve the agreement with independent data.

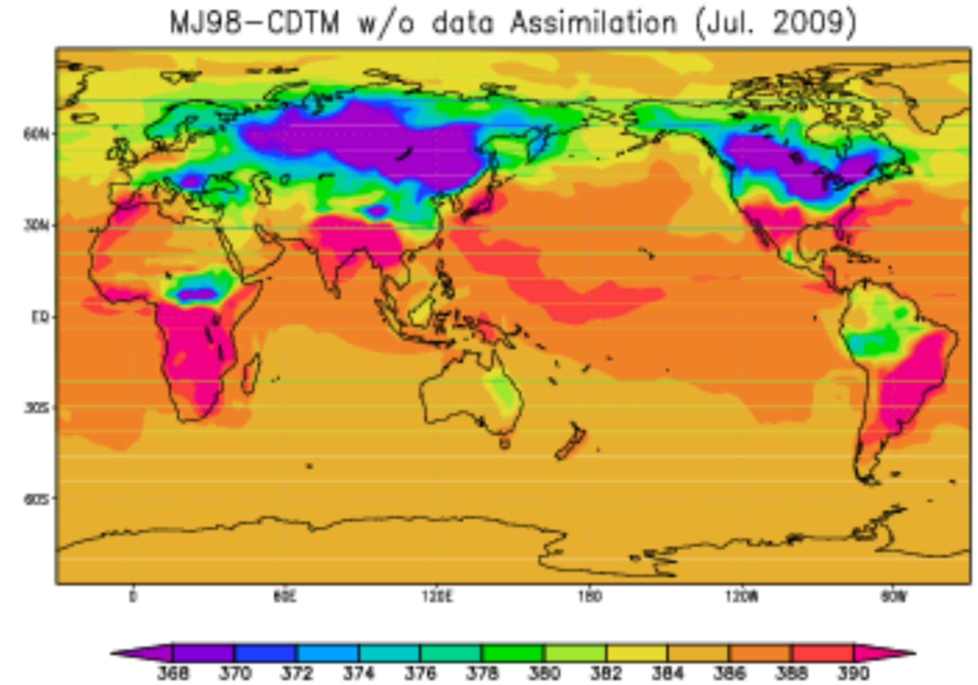
CO_2 Analysis Results（Jul 2009）

Surface CO2 concentrations

RMSE=3.96ppm

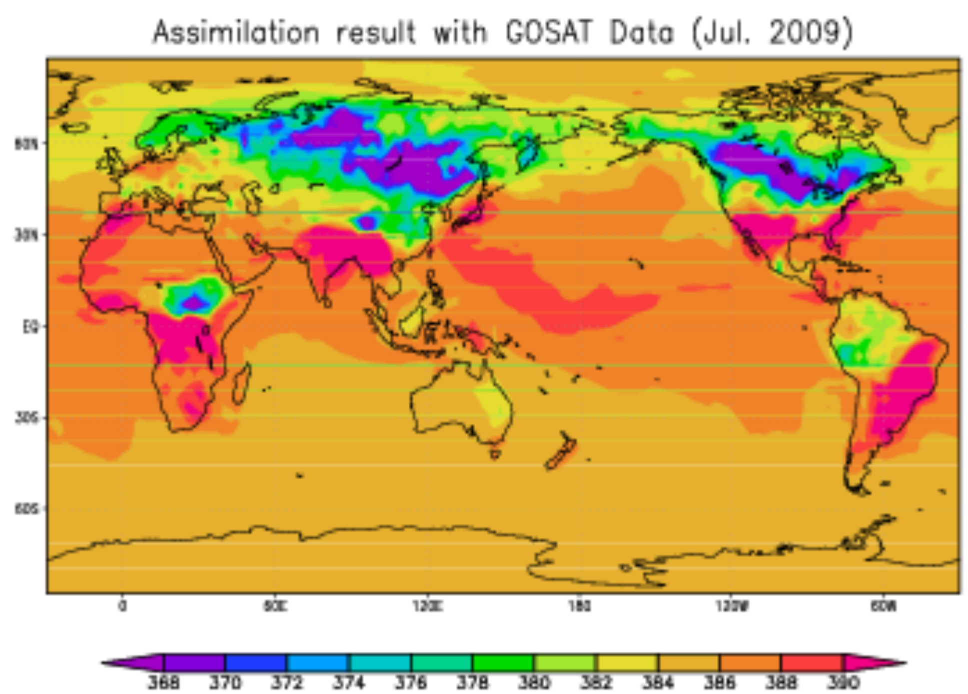
JMA Analysis

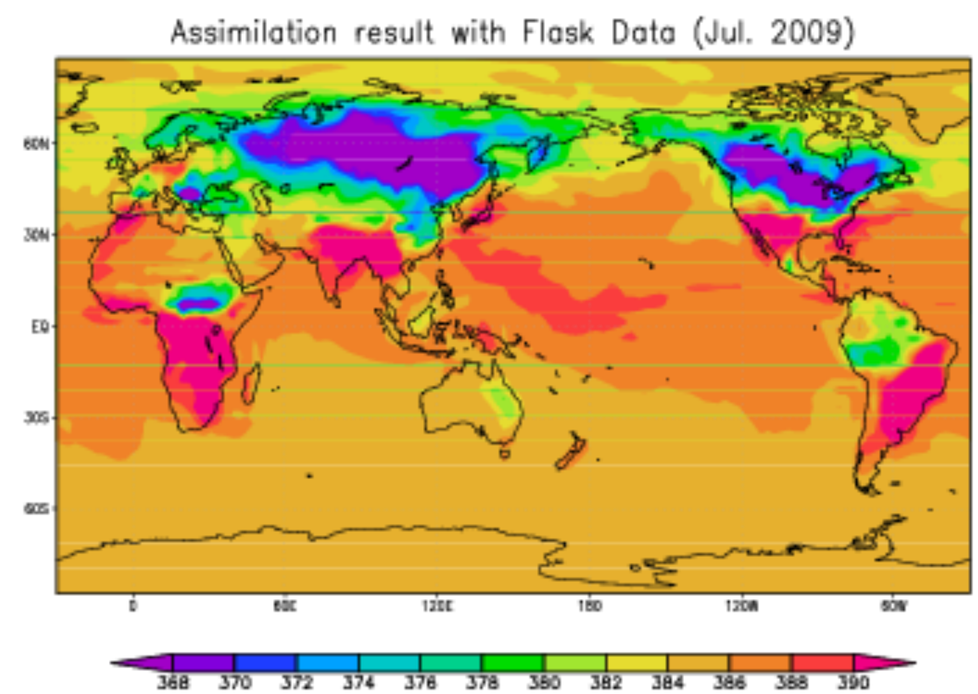




w/o assim.

GOSAT assim.





Flask assim.

RMSE=3.12ppm

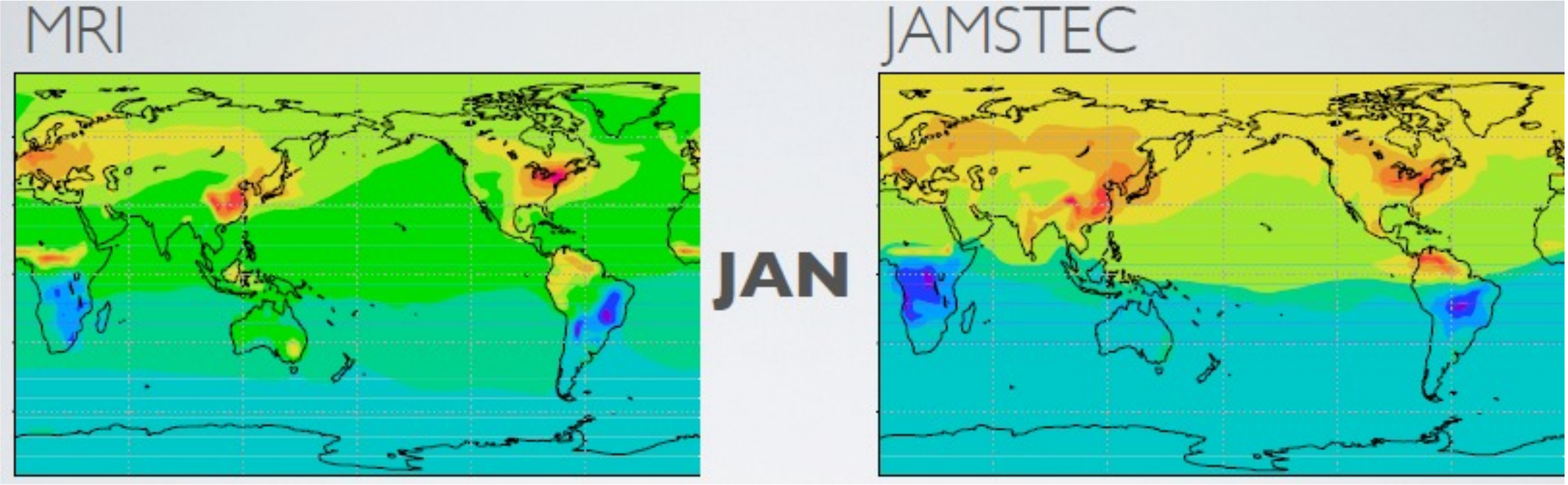
RMSE=3.83ppm

Multi-model comparison of surface CO_2 flux estimates

Forecast models:

(1) **MRI CDTM** (Maki et al., 2010)
(2) **JAMSTEC ACTM** (Miyazaki et al, 2008)

Fig: CO2 Mixing Ratio Anomaly in the lower troposphere



e.g., choice of vertical diffusion scheme largely affects simulation/assimilation results.

4. Air quality

Forecast models:

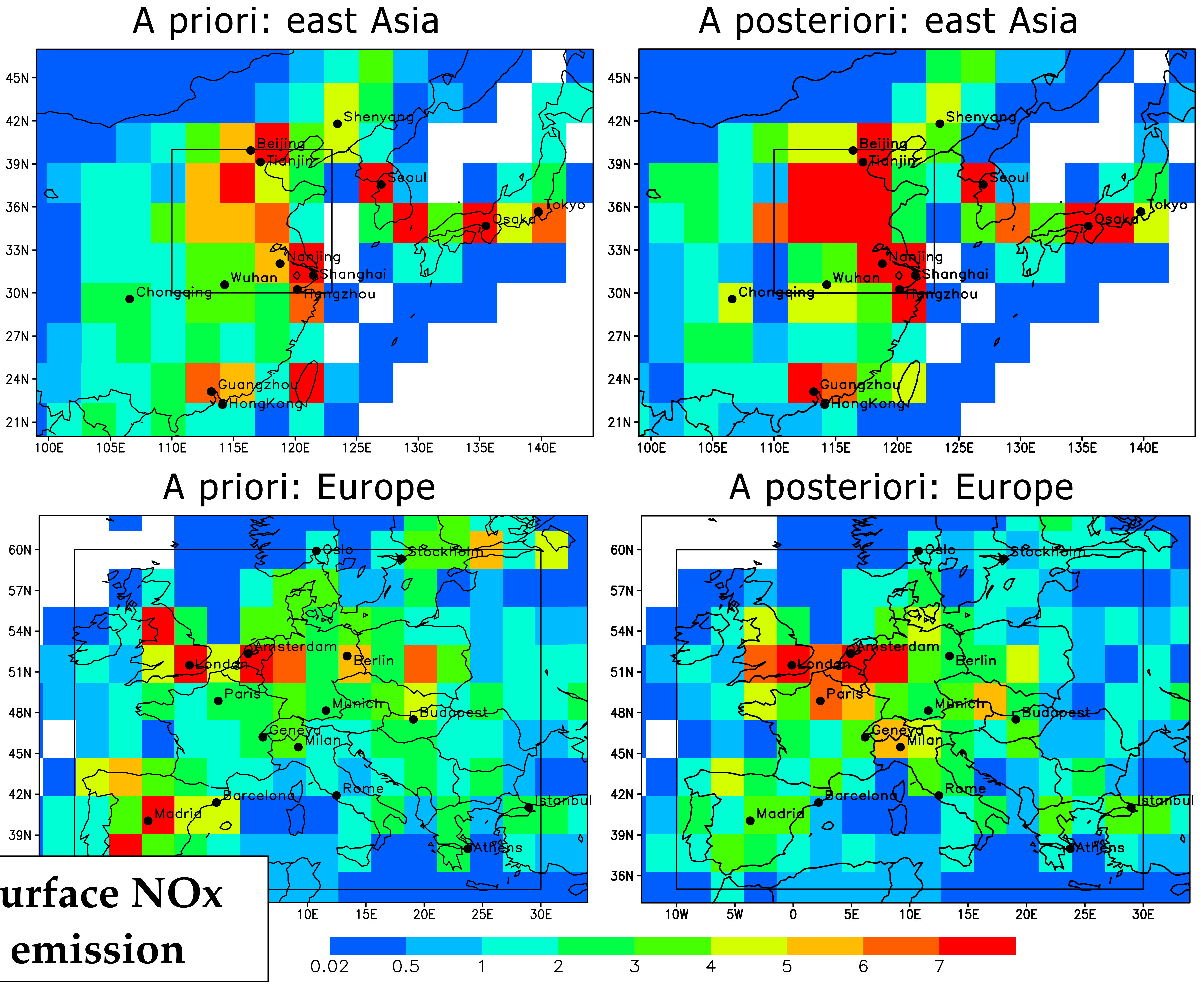
(1) **CHASER** (Sudo et al., 2002) T42L32 p-top=3 hPa
(2) **MRI CCM** (Shibata and Deushi, 2008) T42L68 p-top=0.01 hPa

- **for reanalysis/monitoring of Asian/global atmospheric environment**

Assimilated data: **OMI NO2, SCIAMACHY NO2, TES O3, etc...**

Control variables: **NOx emission, NO2, O3, HNO3, etc...**

Assimilation settings: **3D-analysis**



Surface NOx emission

Summary

We have developed chemical data assimilation systems to analyze Asian/global atmospheric environment, using a same scheme.

- **Meteorology-chemistry coupling data assimilation**
  - **for better understanding stratospheric processes/ stratospheric reanalysis??**
- **Aerosols analysis/forecast**
  - **for operational use at JMA…?**
- **High resolution surface CO_2 flux estimates**
  - **(the knowledge obtained from the OSSEs will help to interpret the real data assimilation results)**
- **atmospheric concentrations and emissions of polluted gasses**
  - **for monitoring Asian/global atmospheric environment.**

… more data will be included …

- Miyazaki et al., Assessing the impact of satellite, aircraft, and surface observations on CO_2 flux estimation using an ensemble-based 4D data assimilation system, JGR, 2011. **(CO$_2$ DA system, OSSE study)**
- Miyazaki, Performance of a local ensemble transform Kalman filter for the analysis of atmospheric circulation and distribution of long-live tracers under idealized conditions, JGR, 2009. **(CO$_2$ DA system, OSSE study)**
- Miyazaki et al., Formation mechanisms of latitudinal CO_2 gradient in the upper troposphere over the subtropics and tropics, JGR., 2009 **(CO$_2$ transport/CONTRAIL analysis)**
- Miyazaki, et al., Global-scale transport of carbon dioxide in the troposphere, JGR, 2008. **(CO$_2$ transport/modeling)**
- Miyazaki et al., Global NOx emission estimates from data assimilation of OMI tropospheric NO_2 columns, to be submitted **(air quality DA)**
- Maki et al., New techniques to analyze global distributions of CO_2 concentrations and fluxes from non-processed observational data, Tellus, 2010. **(QC processes)**
- Maki et al., The Impact of Ground-Based Observations on the Inverse Technique of Aeolian Dust Aerosol, SOLA, 2011. **(Dust inversion)**
- Sekiyama et al., Data assimilation of CALIPSO aerosol observations. ACP, 2010. **(Aerosols assimilation)**
- Sekiyama et al., The Effects of Snow Cover and Soil Moisture on Asian Dust: II. Emission Estimation by Lidar Data Assimilation, SOLA, 2011. **(Aerosols assimilation)**
- Iwasaki et al., Comparisons of Brewer-Dobson Circulations diagnosed from Reanalyses, JSMJ, 2009. **(BD inter-comparison among reanalyses)**
- Presentation at IUGG: Nakamura et al., Data Assimilation session (JM02). **(Strat. O$_3$)**
- **and more soon... (hopefully!!)**