Experiences from several data assimilation methods:

- 4D-Var and EnKF -
- Satellite and in-situ measurements -
- Regional and global models -

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Just have moved to AEAM department, MRI

Ph.D at Kyushu Univ.

CFORS/CTM

4D-Var

Lidar

CALIOP

2010.06 Harvard Univ.

(D. Jacob Group)

EnKF

GEOS-Chem

OSSE

MODIS

Inversion

SPRINTARS

2011.03 MRI

(Typhoon Res. Dep.)

MASINGAR

2013.04

(Atmos. Env. and
App. Meteorol. Res. Dep.)
working with
Takashi Maki,
Thomas T. Sekiyama and
Taichu Y. Tanaka

DA experiments with various models, observations and methods

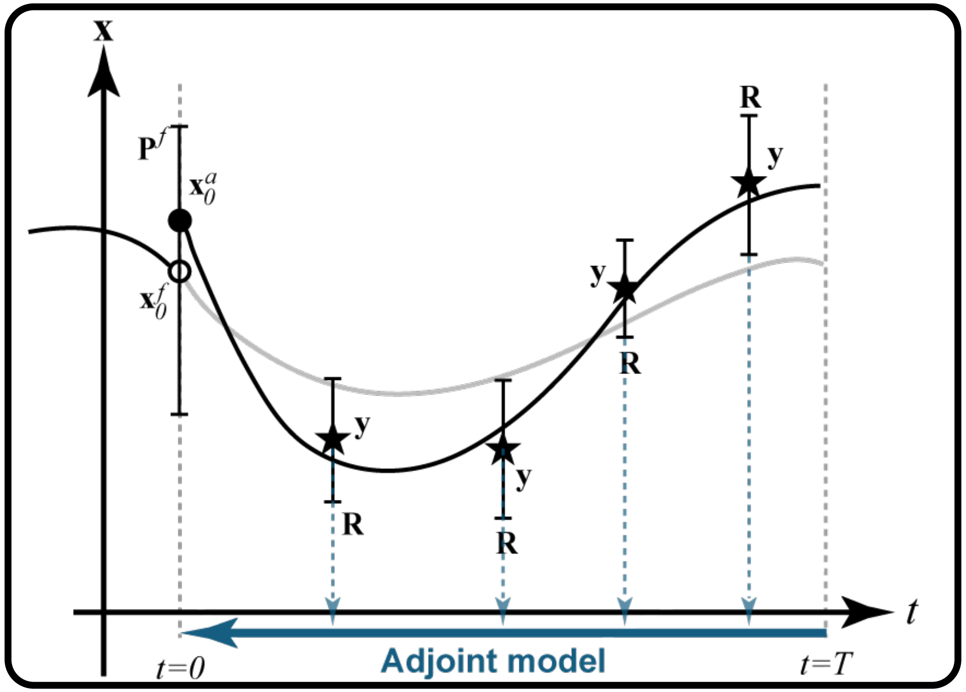
Today's contents

1. CFORS (regional)	4D-Var	in-situ measurements
2. CFORS (regional)	4D-Var	Lidar
3. GEOS-chem	EnKF	satellite (MOPITT)
4. SPRINTARS	EnKF	satellite (MODIS)
5. SPRINTARS	4D-Var	satellite (MODIS)

- Concluding remarks

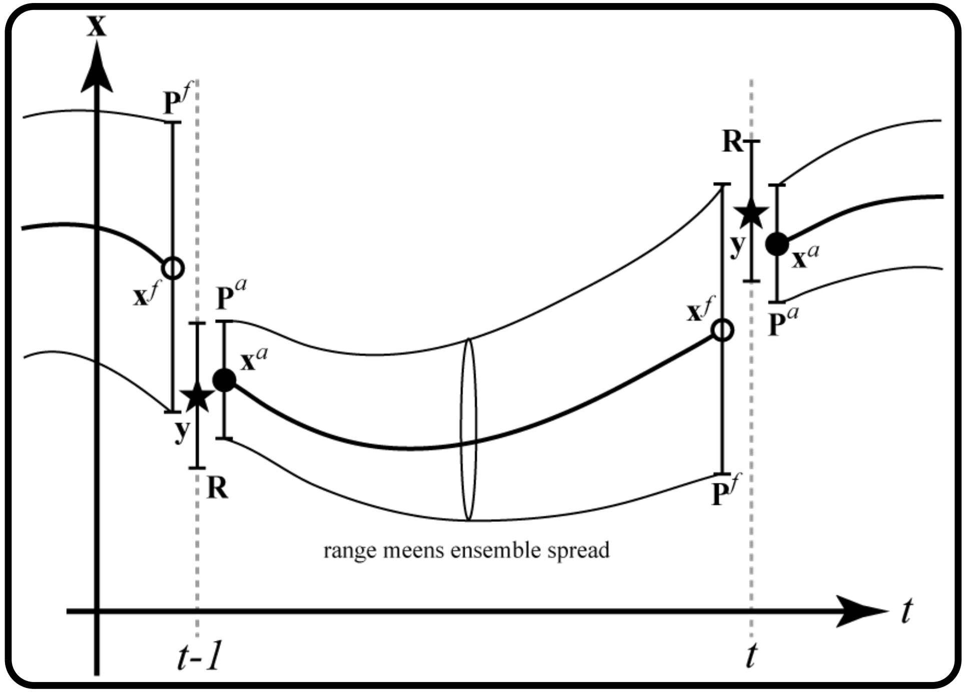
Introduction: 4D-Var and EnKF

❖ 4D-Var



Use adjoint model

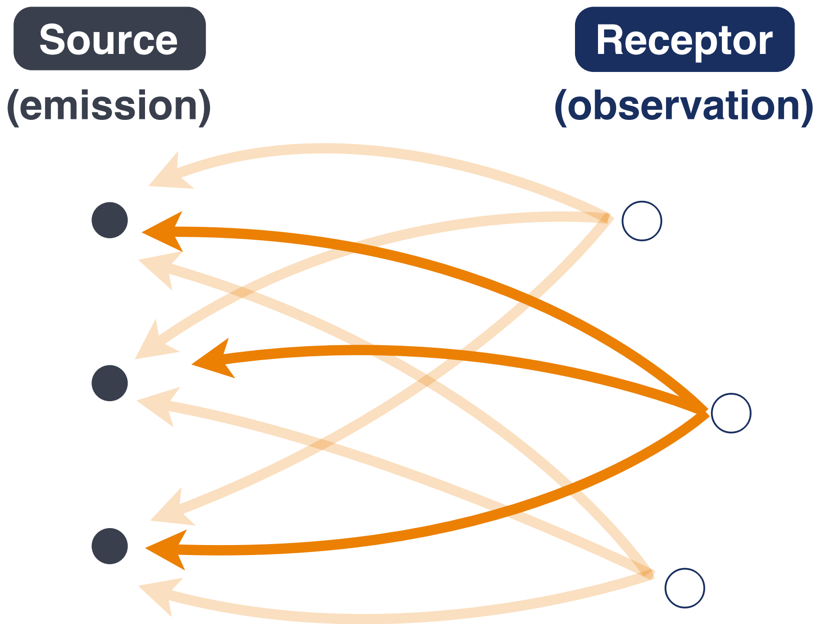
❖ EnKF



Use ensemble simulation

Introduction: Backward and Forward methods

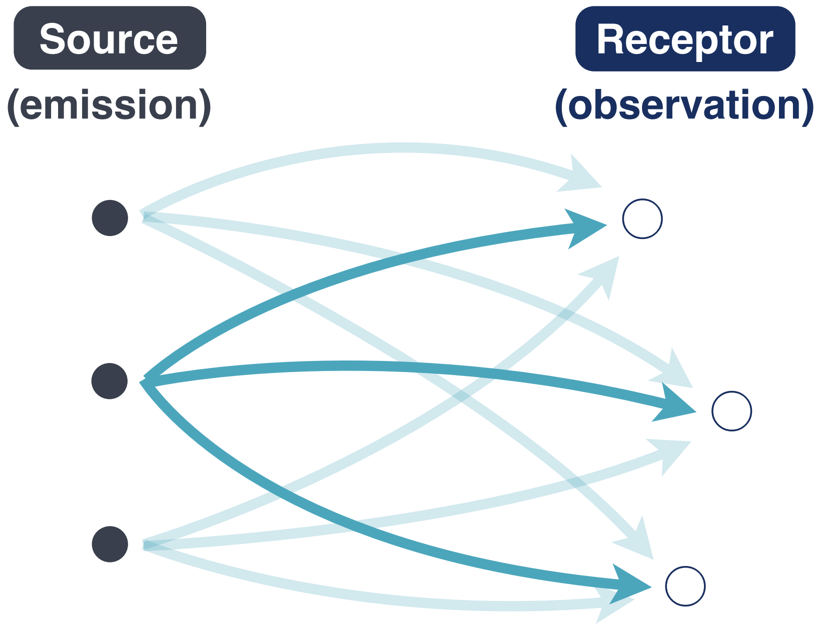
Adjoint (Backward)



Backward method calculates sensitivities of receptors (observations) to sources (emissions).

※We need an adjoint model.

Forward



Forward method calculates sensitivities of sources (emissions) to receptors (measured concentrations).

※We need a set of 'ensemble' simulations.

Today's contents

1. CFORS (regional) **4D-Var** <u>in-situ measurements</u>
2. CFORS (regional) **4D-Var** <u>Lidar</u>
3. GEOS-chem **EnKF** <u>satellite (MOPITT)</u>
4. SPRINTARS **EnKF** <u>satellite (MODIS)</u>
5. SPRINTARS **4D-Var** <u>satellite (MODIS)</u>

- Concluding remarks

1. CFORS x 4D-Var x in-situ measurements

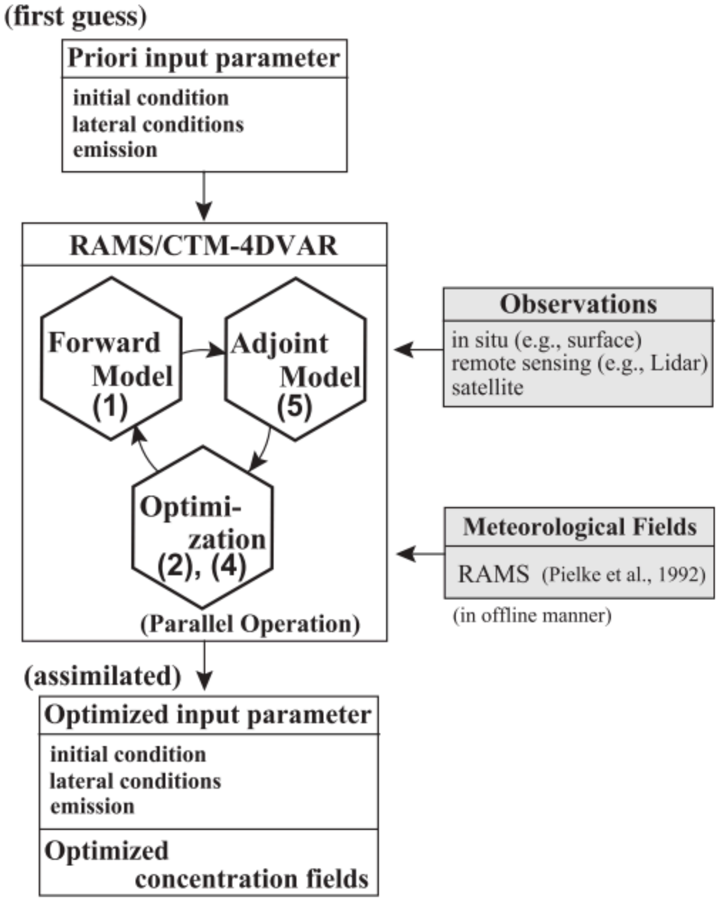


Fig. 1. Schematic of the RAMS/CTM-4DVAR data assimilation system. The numbers correspond to the equation numbers in the text.

(Yumimoto and Uno, 2006)

- **Goals**

Developing a 4D-Var DA system with CTM in 2-year master’s program (including an adjoint of the CTM)

* No TAMC. Line by line.

1. CFORS x 4D-Var x in-situ measurements

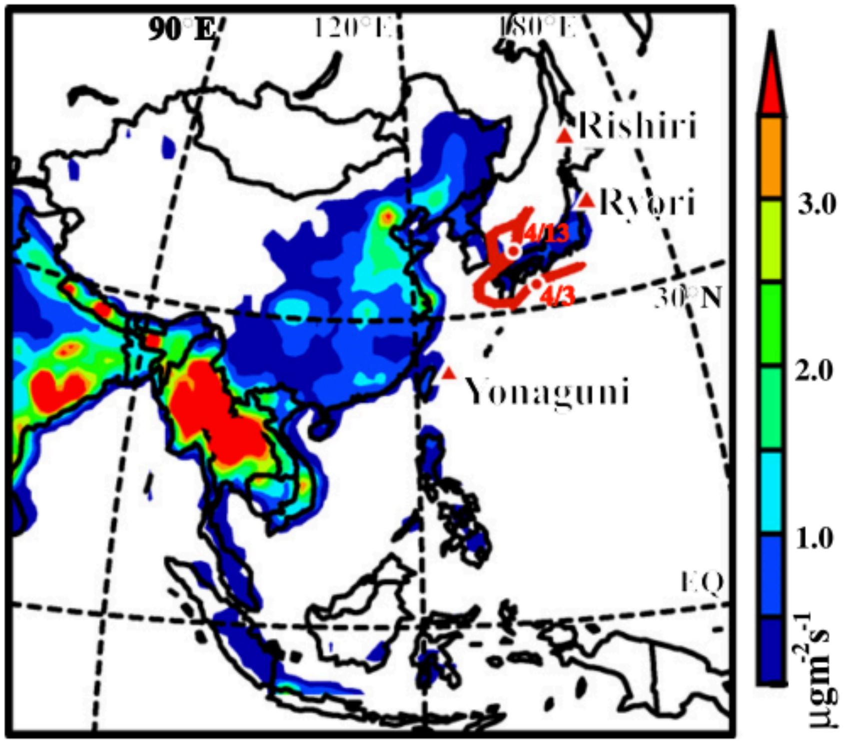


Fig. 2. Modeling domain and spatial distribution of the basic (priori) emissions of CO. Red triangles show observation sites; the red solid line is the R/V *Ronald H. Brown* ship track.

- **Regional CTM (CFORS)**
- **4D-Var**
- **Observational constraints**

  in-situ (surface) measurements of CO
- **Goals**

  Optimize CO emission in East Asia

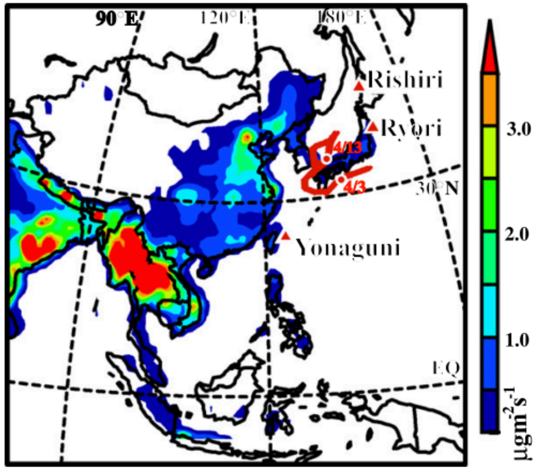
  Validate the DA system

  Show the capability of 4D-Var

  for chemical DA and inverse modeling.

1. CFORS x 4D-Var x in-situ measurements

a priori



a posteriori

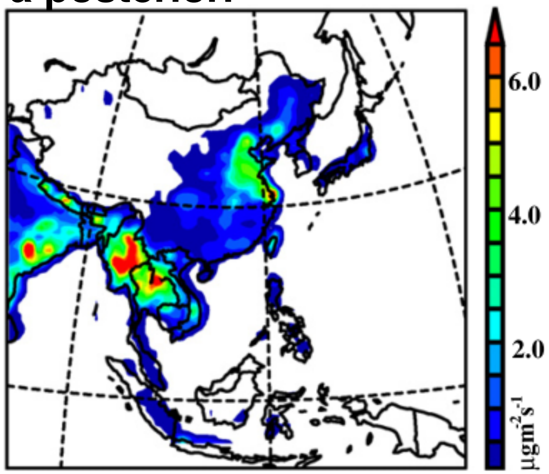


Table 2
Recent estimates of annual anthropogenic CO emissions from China (Tg CO year^{-1})

Study	China (Tg year^{-1})	
	Anthropogenic	Biomass burring
Bottom up estimate		
The priori (Streets et al., 2003)	100	16
REAS[a]	148	
Streets et al. (2006)	142	16
Top down (inverse) estimate		
Palmer et al. (2003)	163–173	12
Pétron et al. (2004)	132–194[b]	
Arellano et al. (2004)	195–222[b]	
Wang et al. (2004)	166	
Heald et al. (2004)	173	
This study	147	
Modeling		
Allen et al. (2004)	113–177[b]	
Carmichael et al. (2003b)	169–228	

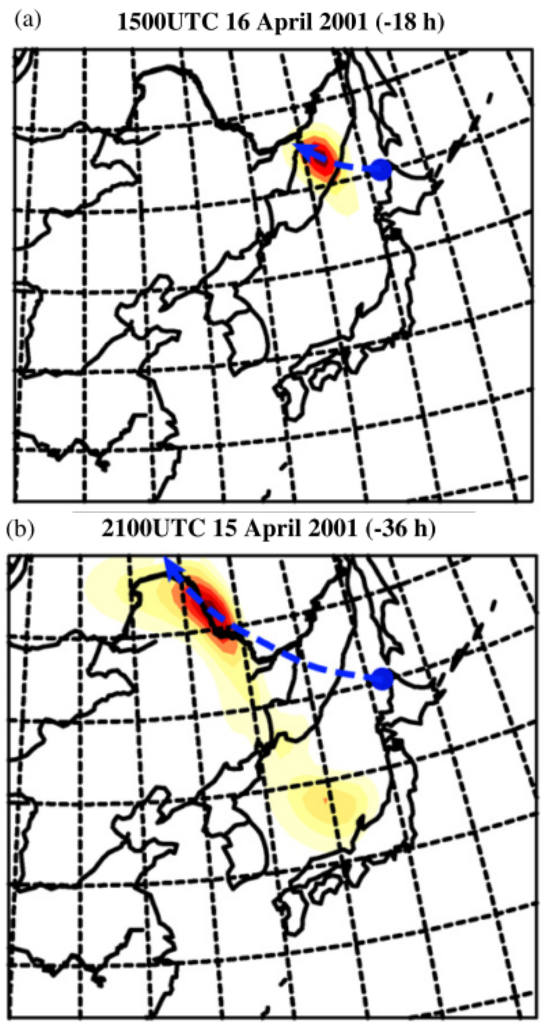
(Yumimoto and Uno, 2006)

▪ Results

The DA system worked well

Our posteriori CO emission is consistent with results from other inversions

1. CFORS x 4D-Var x in-situ measurements



(Yumimoto and Uno, 2006)

- **Results**

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Adjoint model is also useful for backward sensitivity analysis

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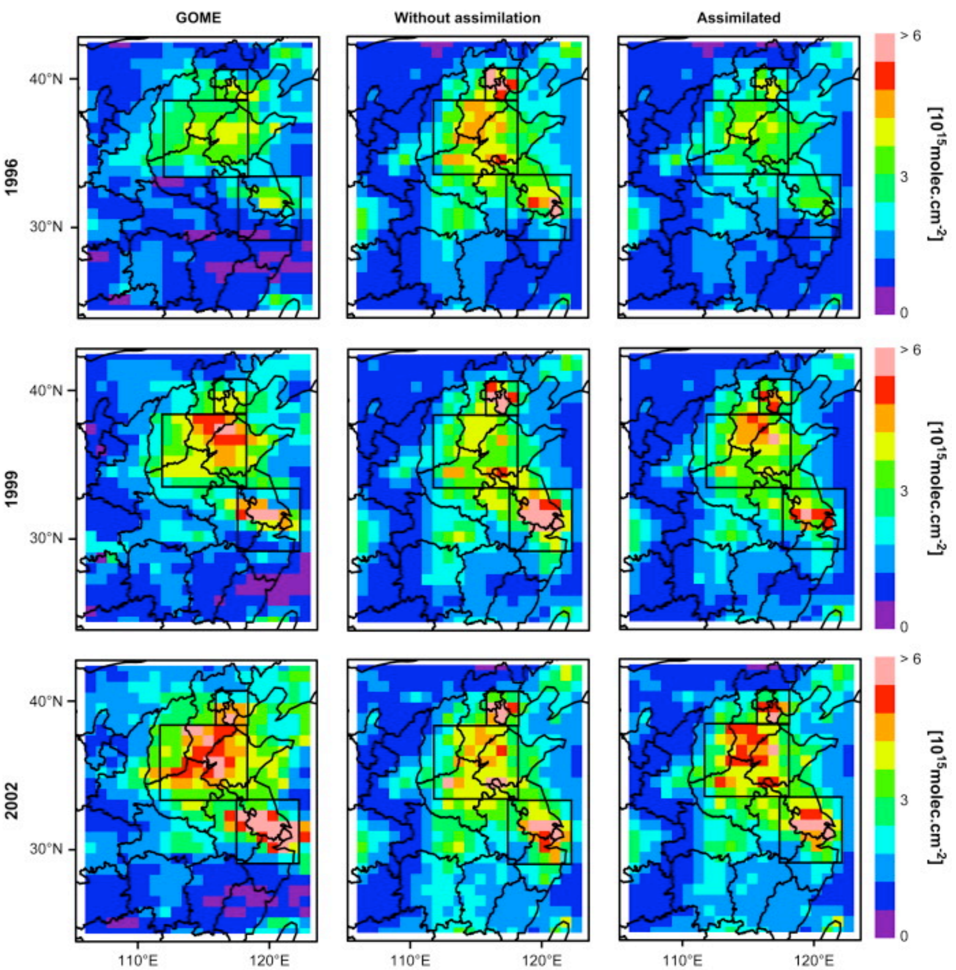


(Kurokawa et al., 2009)

▪ Results

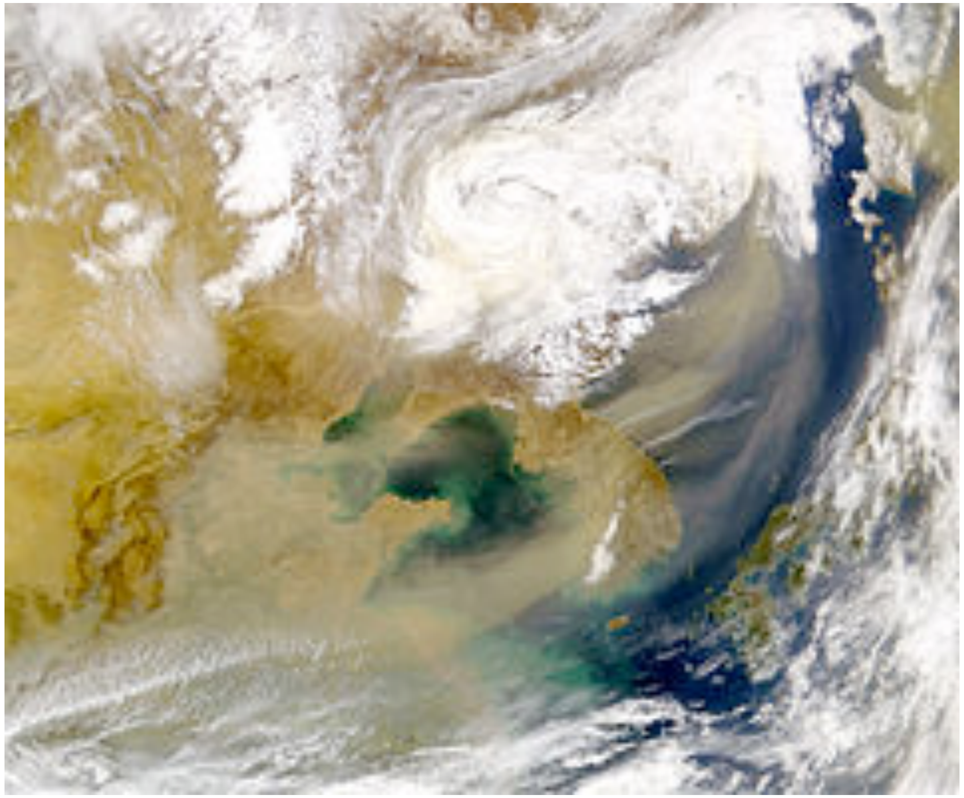
The DA system worked well

Our posteriori CO emission is consistent with results from other inversions

Adjoint model is also useful for backward sensitivity analysis

The DA system is used for optimizing NOx emission over China

2. CFORS x 4D-Var x Lidar


Asian dust attacked the Korean Peninsula

- **Regional CTM (CFORS)**

  8 bins

- **4D-Var**
- **Observational constraints**

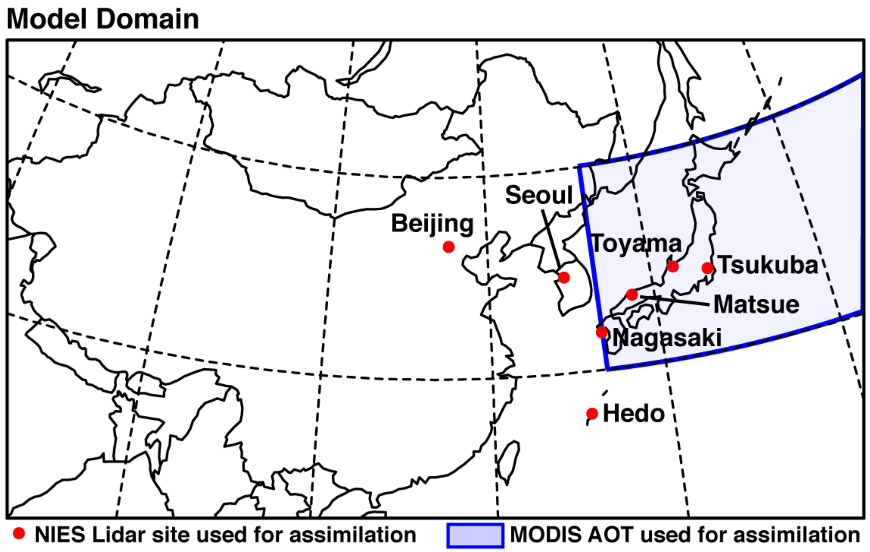
  NIES Lidar network

- **Goals**

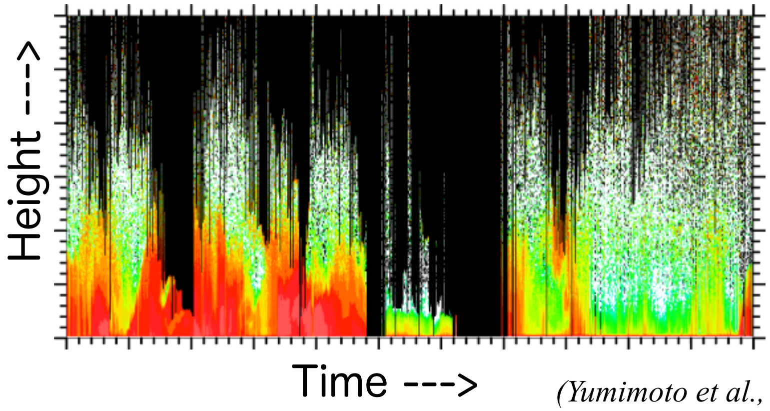
  Optimize dust emission (the Gobi desert)

  Show the capability for assimilating remote sensing measurements.

2. CFORS x 4D-Var x Lidar



Example of Lidar measurement



(Yumimoto et al., 2007, 2008)

- **Regional CTM (CFORS)**

  8 bins

- **4D-Var**
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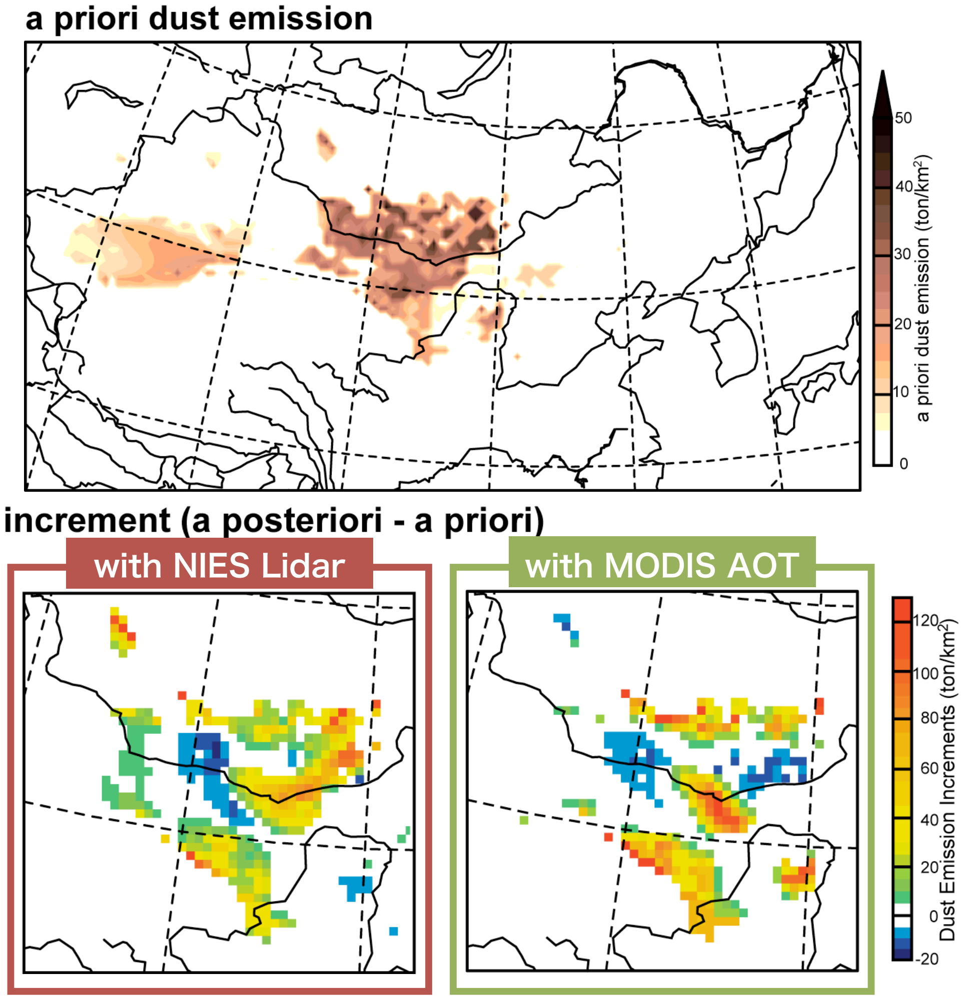


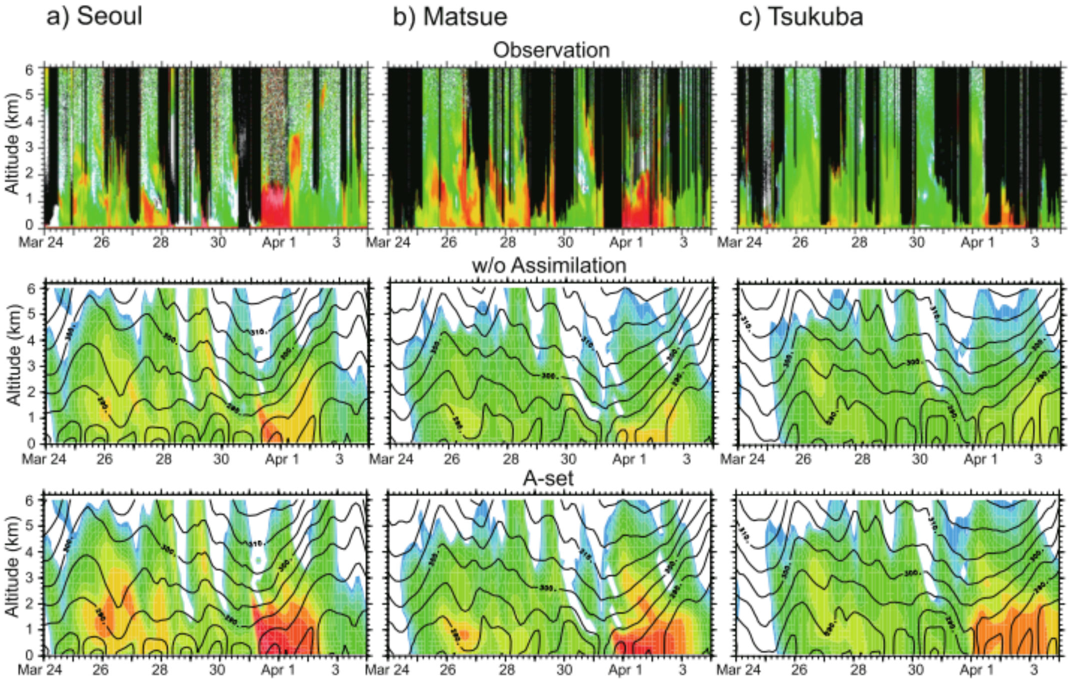
(Yumimoto et al., 2007, 2008)

▪ Results

We obtained the optimized dust emission of about 57 Tg/event.

The Lidar inversion is consist with an inversion with MODIS AOT.

2. CFORS x 4D-Var x Lidar



Comparison with NIES Lidar

■ Results

We obtained the optimized dust emission of about 57 Tg/event.

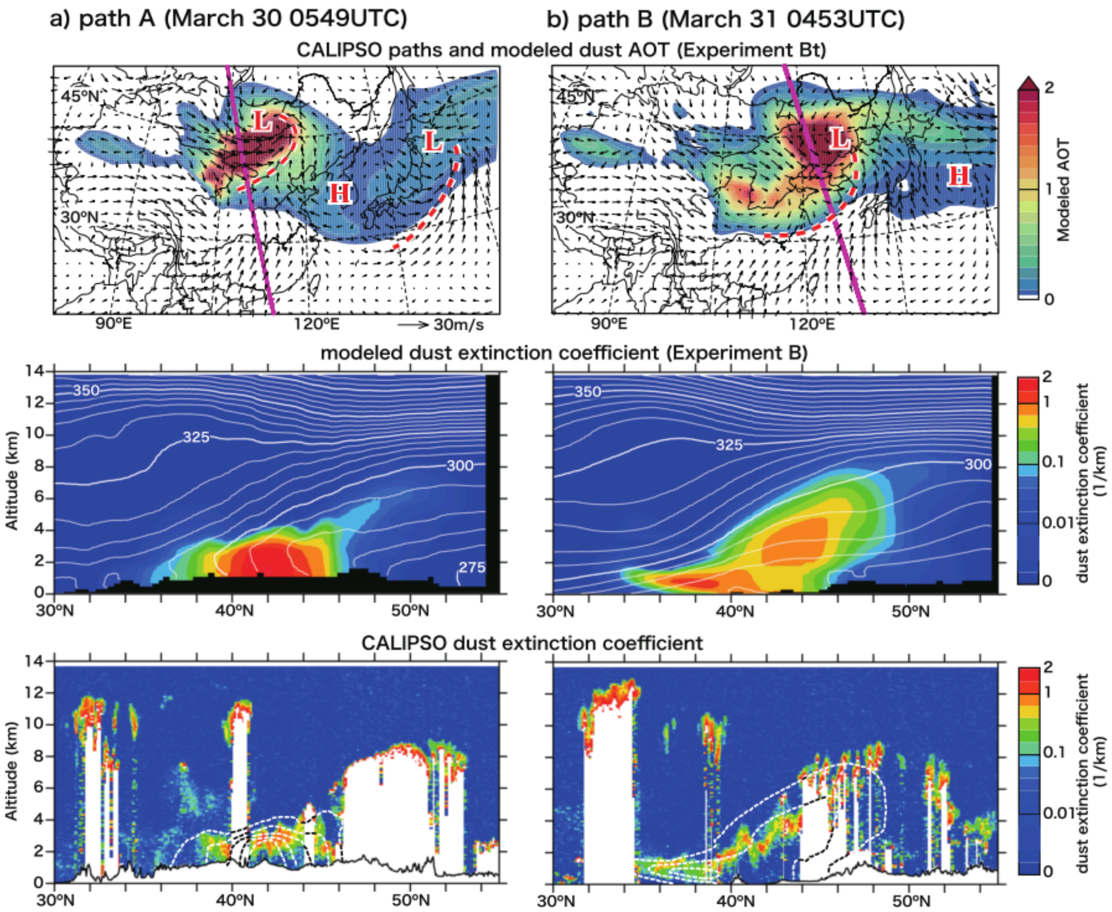
The Lidar inversion is consist with an inversion with MODIS AOT.

Assimilation results are validated by

NIES Lidar
in-situ PM10 measurements
CALIPSO and MODIS

(Yumimoto et al., 2007, 2008)

2. CFORS x 4D-Var x Lidar



(Yumimoto et al., 2007, 2008)

▪ Results

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NIES Lidar

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CALIPSO and MODIS

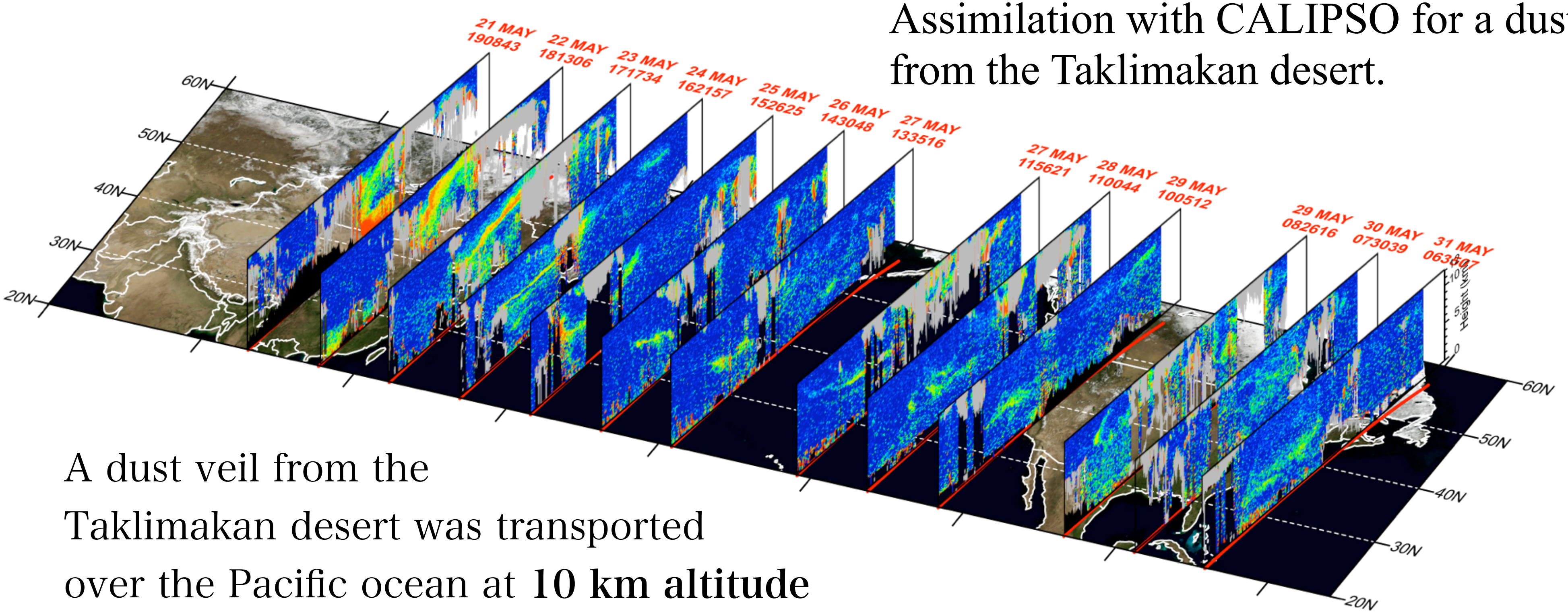
Various applications

Yumimoto et al., 2008b, Iwamoto et al. 2011, Hara et al,, 2009, Uno et al., 2008

2. CFORS x 4D-Var x Lidar

▪ Progresses

Assimilation with CALIPSO for a dust veil from the Taklimakan desert.



(Yumimoto et al., 2010)

A dust veil from the Taklimakan desert was transported over the Pacific ocean at **10 km altitude** with **1 km thickness.**

2. CFORS x 4D-Var x Lidar

- **Progresses**

Assimilation with CALIPSO for a dust veil from the Taklimakan desert.

Size-resolved adjoint inversion of Asian dust

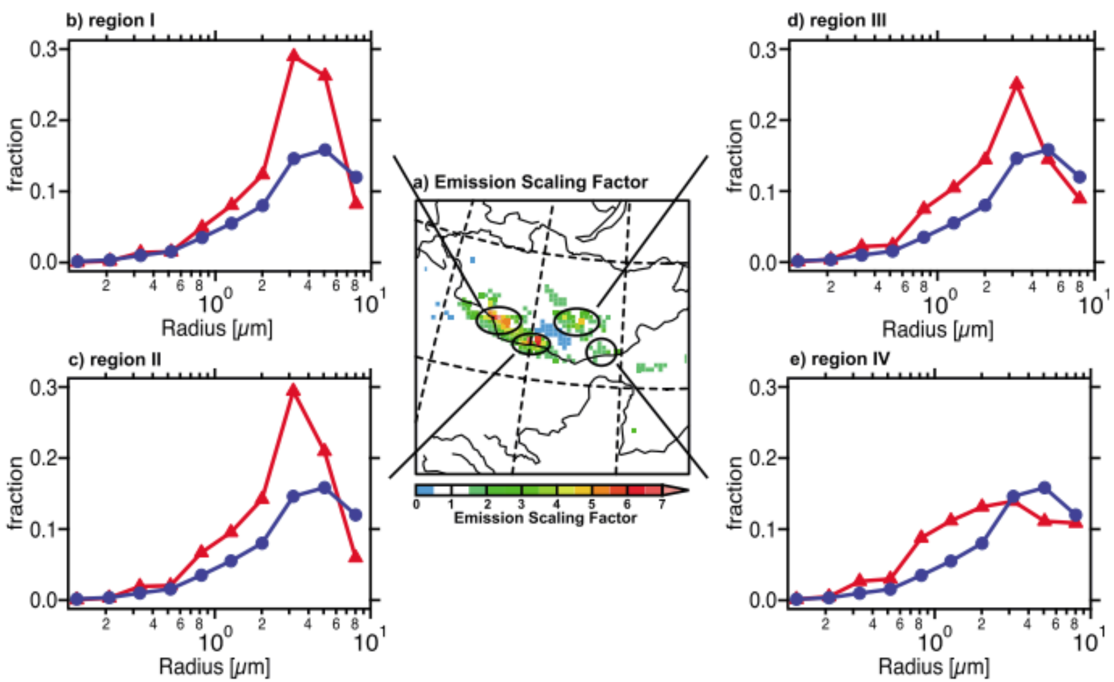


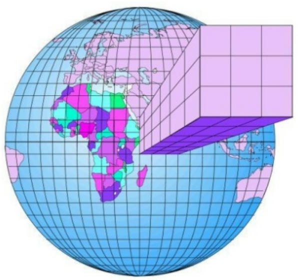
Figure 2. (a) Horizontal distribution of the emission scaling factor (ratio of the a posteriori emission flux to the a priori flux). (b–d) Y2007 or a priori (blue lines) and a posteriori (red lines) size distributions of dust emission fluxes in regions I–IV.

(Yumimioto et al., 2012)

3. GEOS-Chem x EnKF x satellite (OSSE)

Input data
- NASA GEOS meteorological fields
- other

Modules
▪ emissions ▪ transport
▪ chemistry ▪ aerosols
▪ deposition ▪ sub-surface



Applications
▪ chemical processes, transport, budgets
▪ inverse analyses ▪ radiative forcing
▪ air quality ▪ biogeochemistry

- **GEOS-Chem**
- **EnKF (LETKF)**
- **Observational constraints**

  Satellite (LEO and imaginary GEO)
- **Goals**

  Implement LETKF in GEOS-chem

  Perform OSSE for geo-stationary satellite

  Estimate impacts of satellite observation on CO forecasting in East Asia.

3. GEOS-Chem x EnKF x satellite (OSSE)

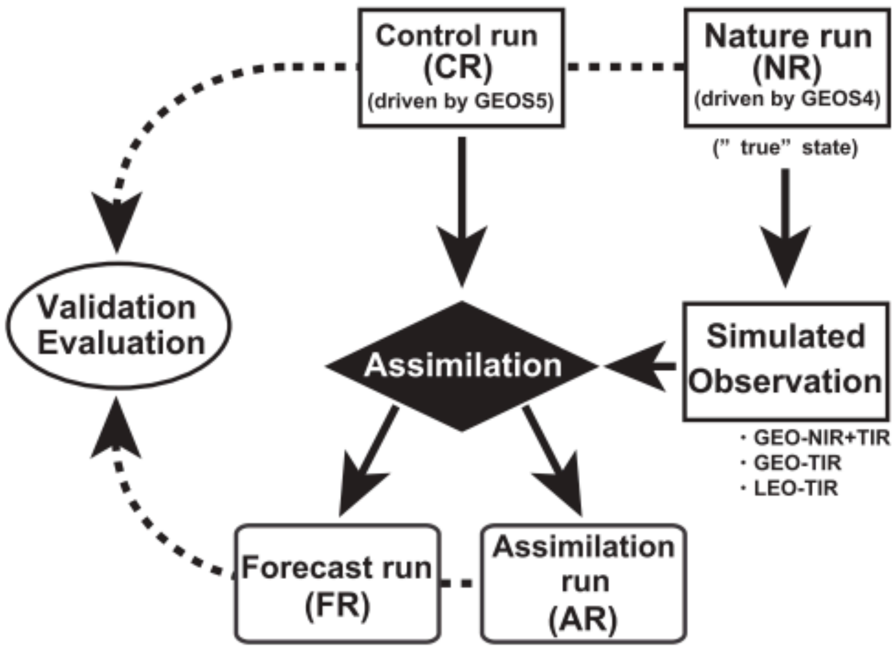


Fig. 1. Schematic diagram of the observing system simulation experiment (OSSE) framework.

Table 1
Sets of simulated observations used in the OSSE.

Obs. Set	GEO-NIR+TIR	GEO-TIR	LEO-TIR
Orbit	Geostationary	Geostationary	Low Earth orbit
Frequency	3-h interval	3-h interval	Twice a day
Sensprs	Near Infra Red Thermal Infra Red	Thermal Infra Red	Thermal Infra Red

(Yumimoto, 2013)

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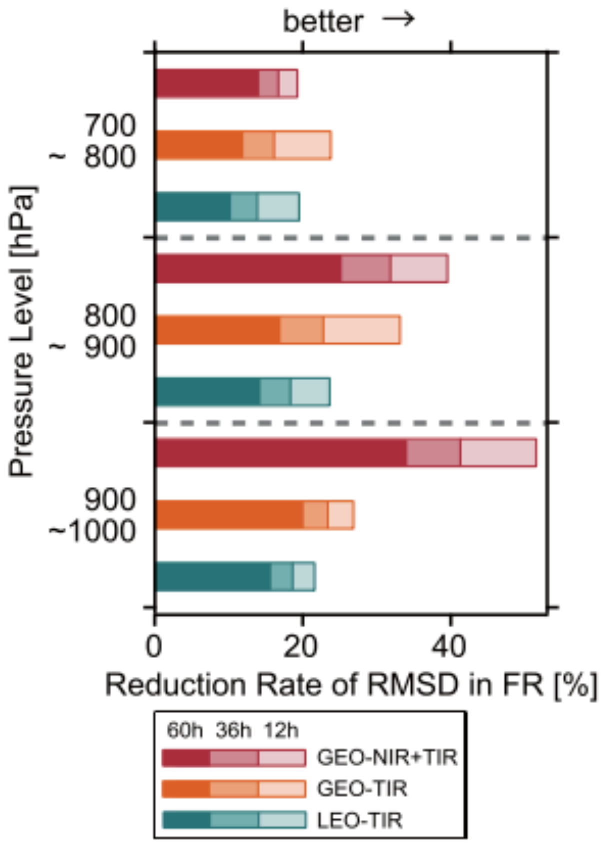


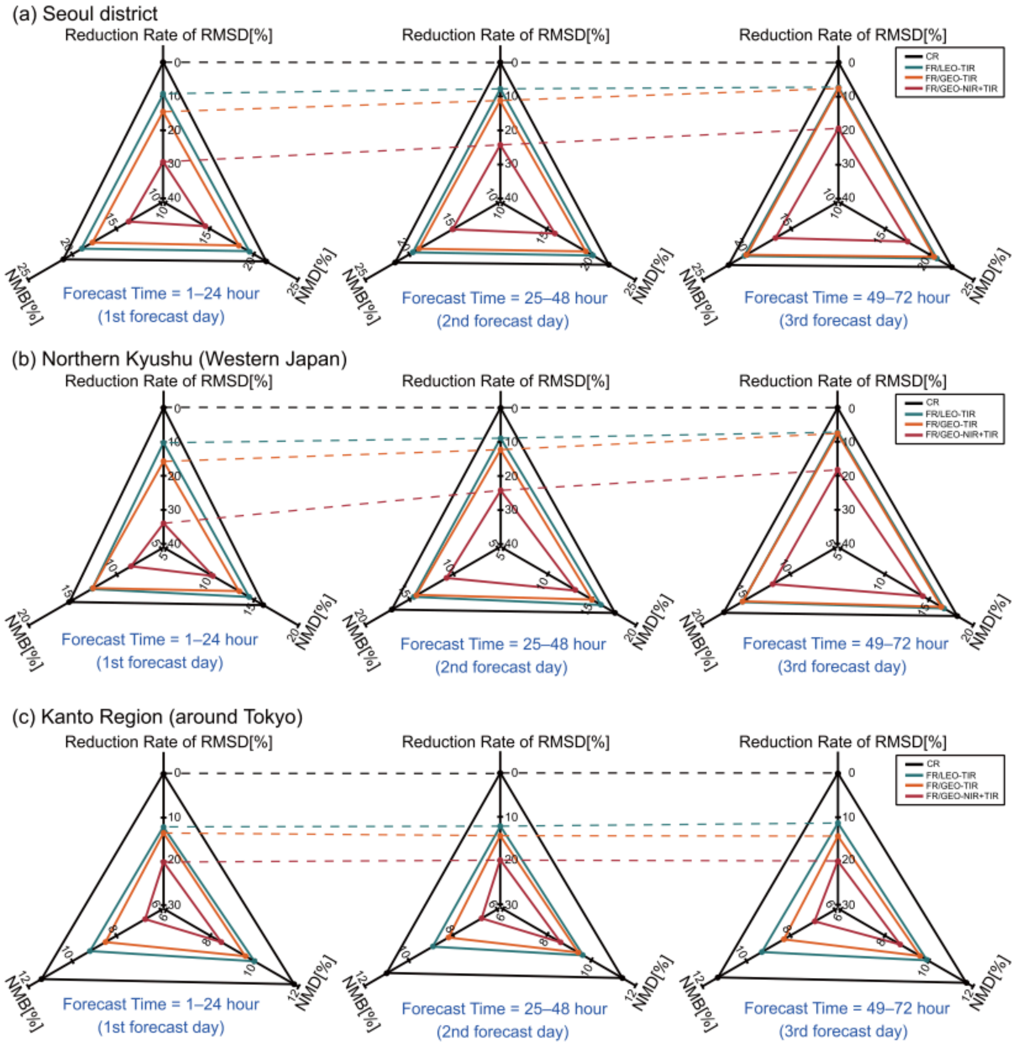
Fig. 8. RMSD reduction rates of the FR compared with the CR for three vertical levels. The color shades represent forecast times: light, moderate, and dense shades denote 12-, 36-, and 60-h forecast times. The RMSDs were calculated from 27 FRs in the downwind region (20–50°N, 120–155°E). Red, orange and green bars denote RMSD reduction rates from GEO-NIR + TIR, GEO-TIR, and LEO-TIR, respectively. Higher reduction rate means greater positive impact on the FRs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this

(Yumimoto, 2013)

- **Results**

GEO-satellite with two sensors achieved much better forecasts even in 60-h forecast.

3. GEOS-Chem x EnKF x satellite (OSSE)



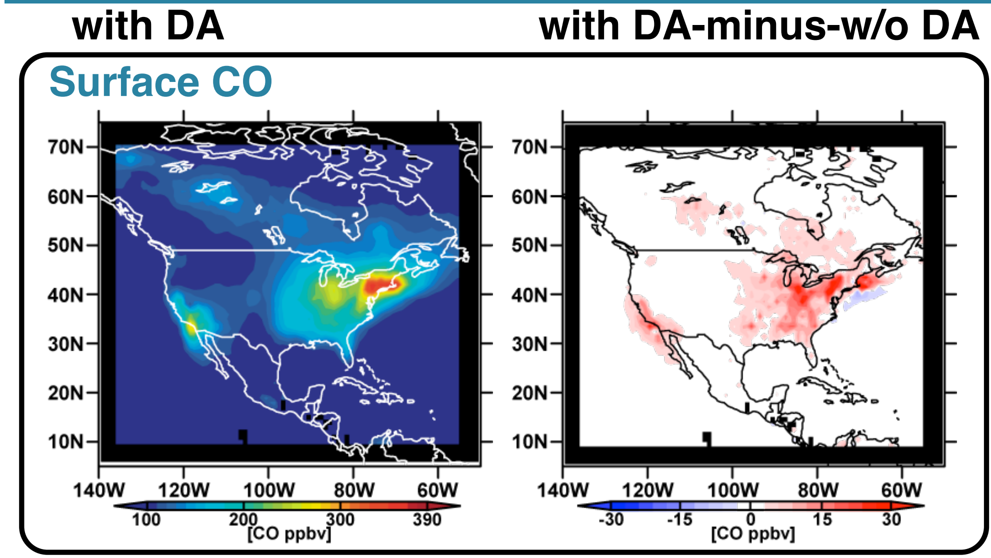
▪ Results

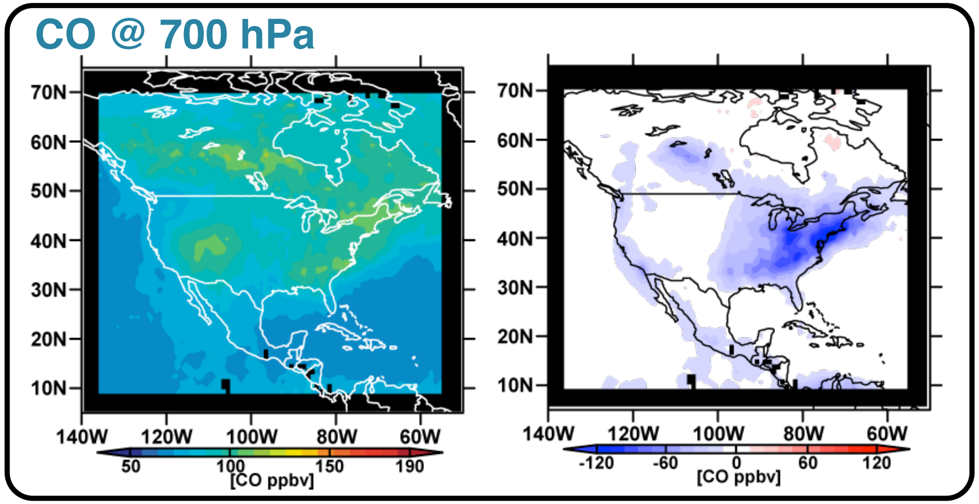
GEO-satellite with two sensors achieved much better forecasts even in 60-h forecast.

and has big impact on forecast of trans-boundary CO over the downwind region

(Yumimoto, 2013)

3. GEOS-Chem x EnKF x satellite (OSSE)



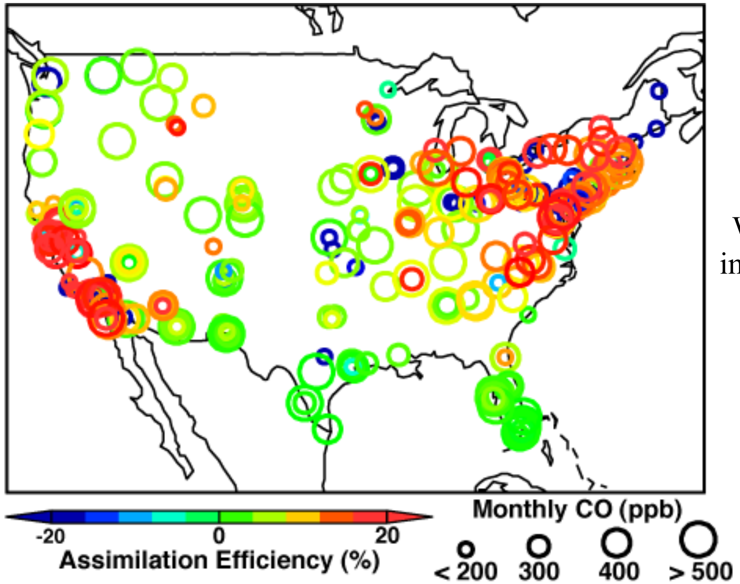


- **Progresses**
  - One month CO DA experiment in US with MOPITT/TERRA measurements

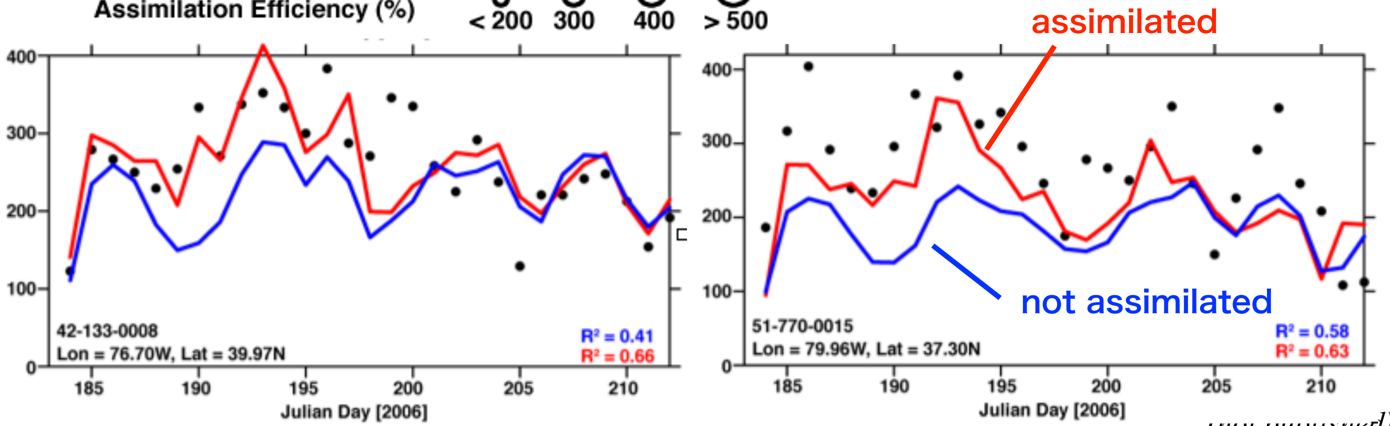
(not published)

3. GEOS-Chem x EnKF x satellite (OSSE)

Compared with EPA insitu measurements



Warm color shows improvement by DA



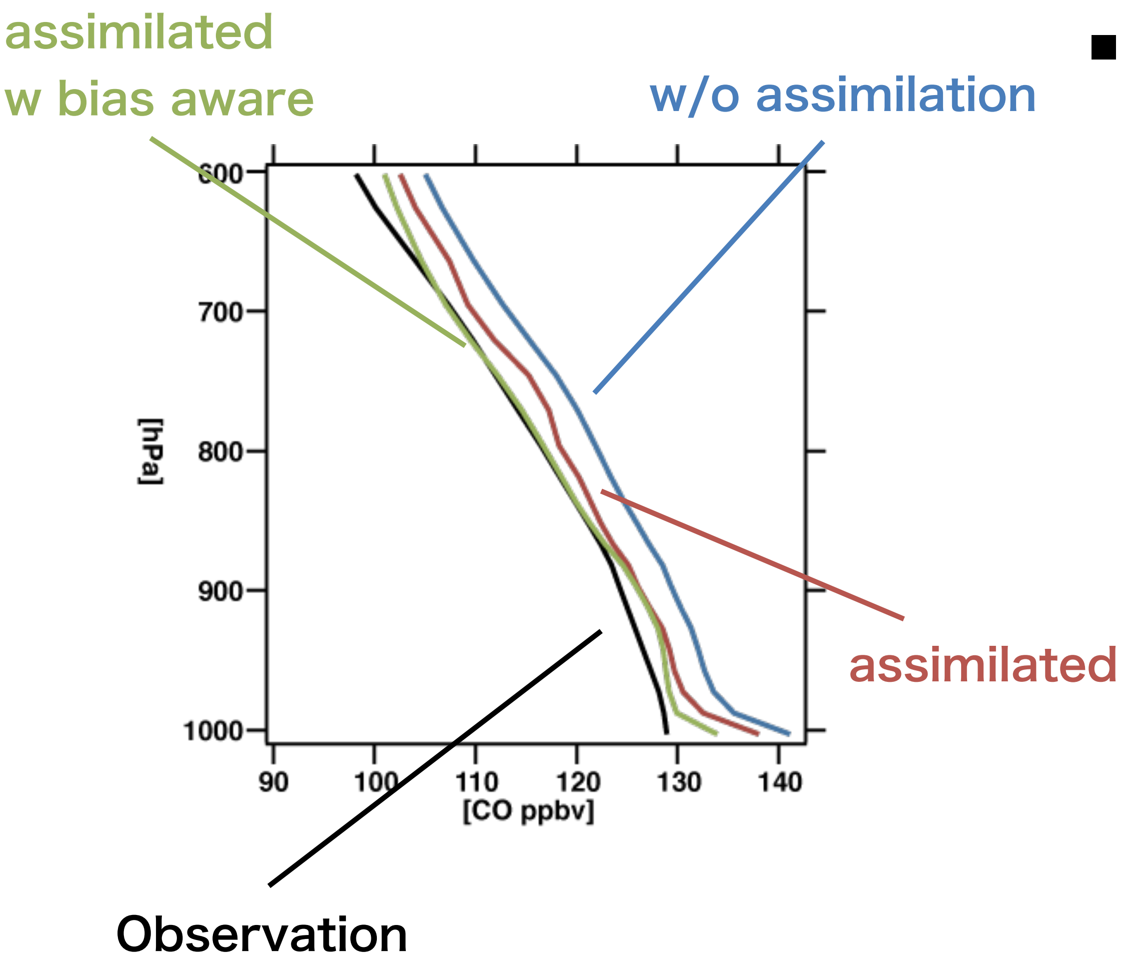
(not published)

▪ Progresses

- One month CO DA experiment in US.

  with MOPITT/TERRA measurements

3. GEOS-Chem x EnKF x satellite (OSSE)



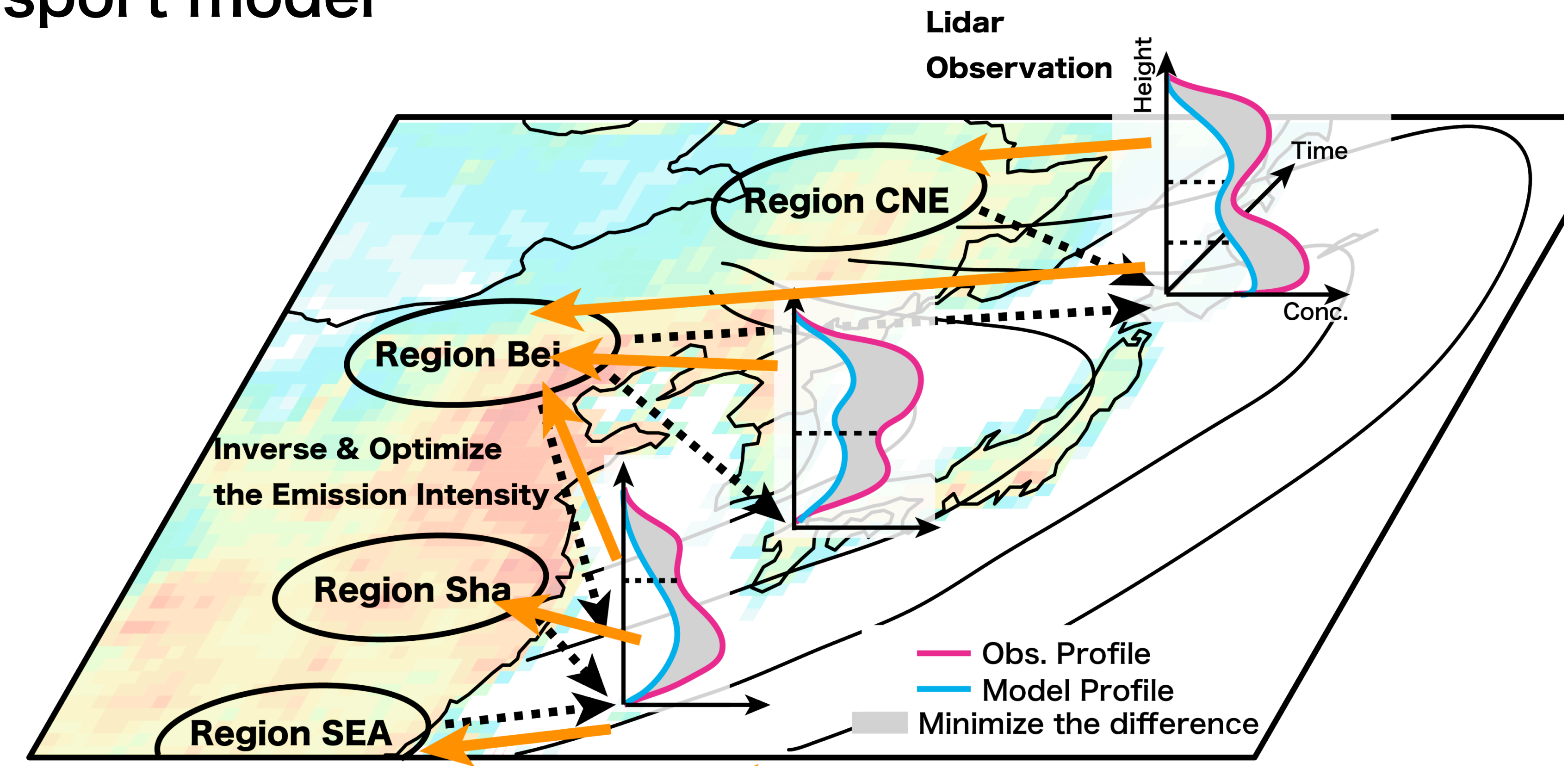
(not published)

■ Progresses

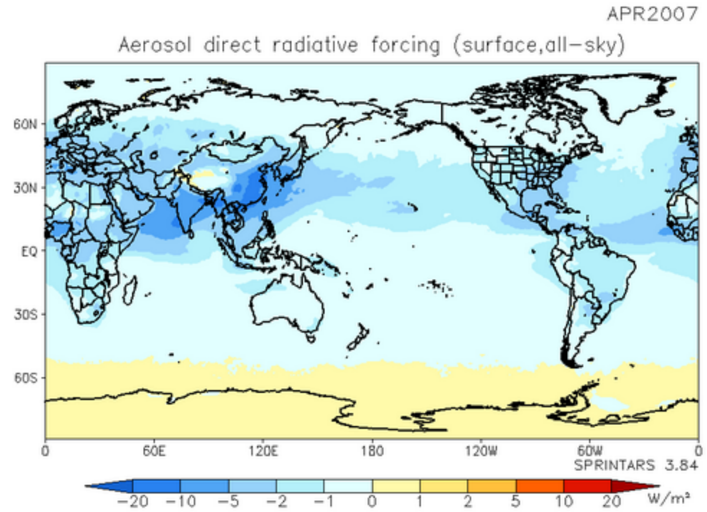
- One month CO DA experiment in US with MOPITT/TERRA measurements
- Bias aware method has capability for introducing better DA performance
- GEOS-Chem/LETKF is capable for assimilating various chemical component and aerosols

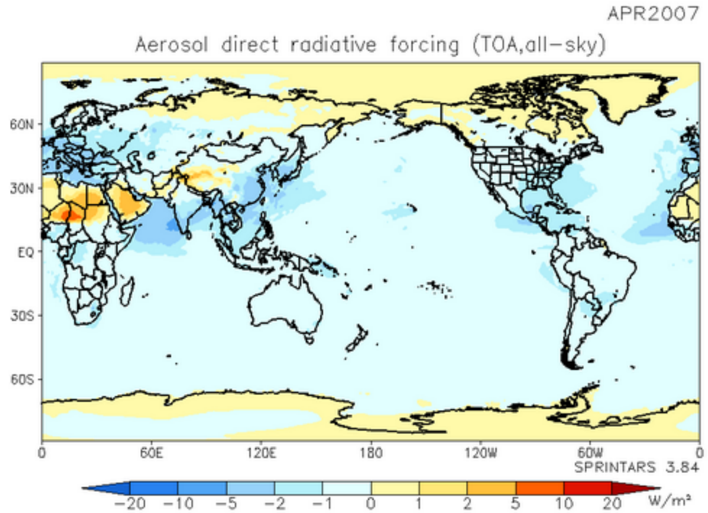
3. GEOS-Chem x EnKF x satellite (OSSE)

■ Five-dimensional data assimilation of aerosol based on integrated analysis of multi-wavelength lidar and chemical transport model



4. SPRINTARS x EnKF x satellite (MODIS)





- **SPRINTARS**
- **EnKF (LETKF)**
- **Observational constraints**

  Satellite (MODIS AOT)
- **Goals**

  Implement LETKF in SPRINTARS

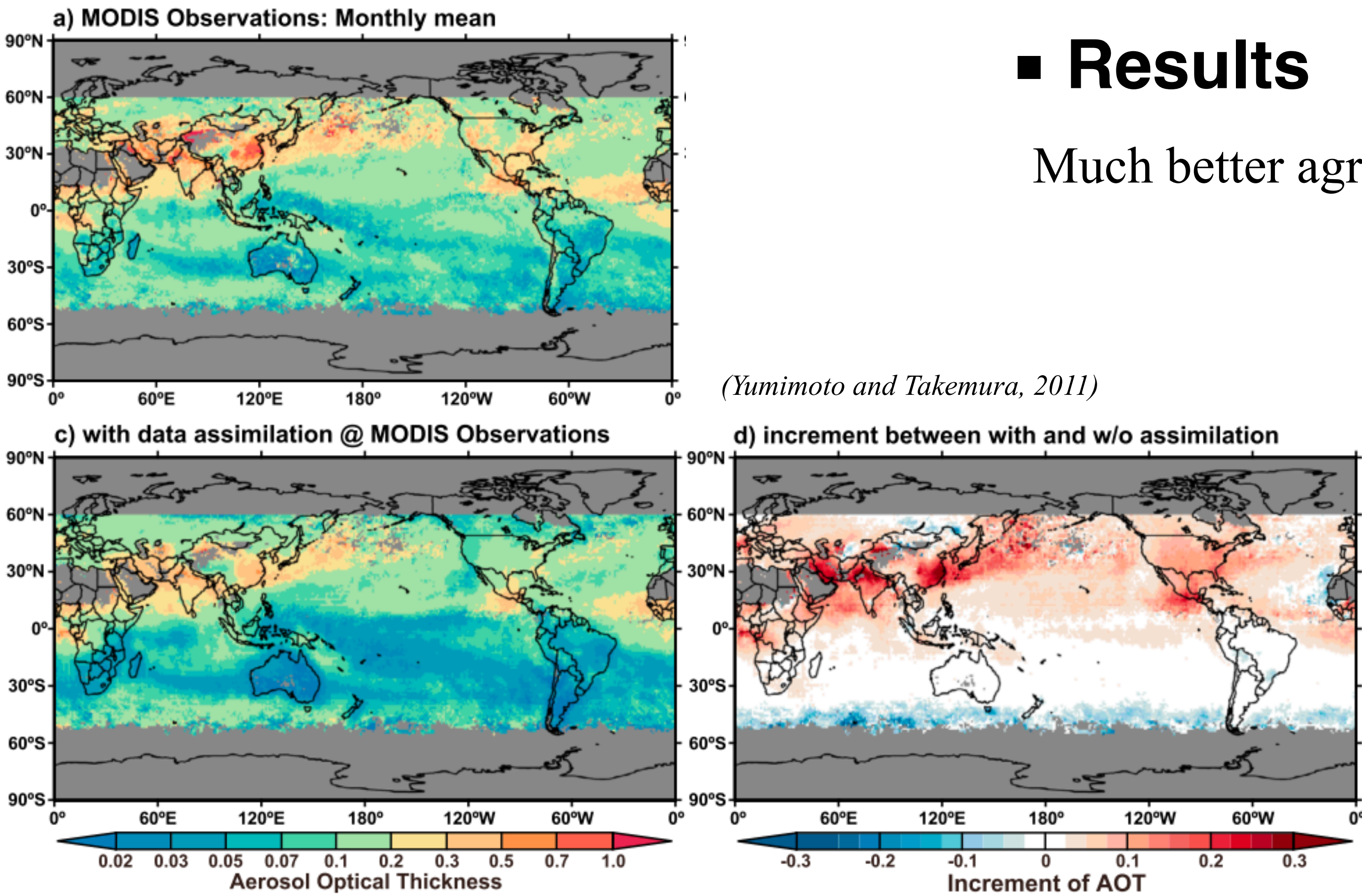
  One-month DA experiment and validation

  Estimate impacts of DA on radiative forcing.

4. SPRINTARS x EnKF x satellite (MODIS)

- **Results**

Much better agreement with MODIS



(Yumimoto and Takemura, 2011)

Figure 2. Spatial distributions of monthly mean AOT in May 2007. (a) MODIS/TERRA and AQUA, (b) *a priori*, (c) *a posteriori*, and (d) increment between *a posteriori* and *a priori*. Modeled results were sampled and interpolated at the times and locations of MODIS AOT availability.

4. SPRINTARS x EnKF x satellite (MODIS)

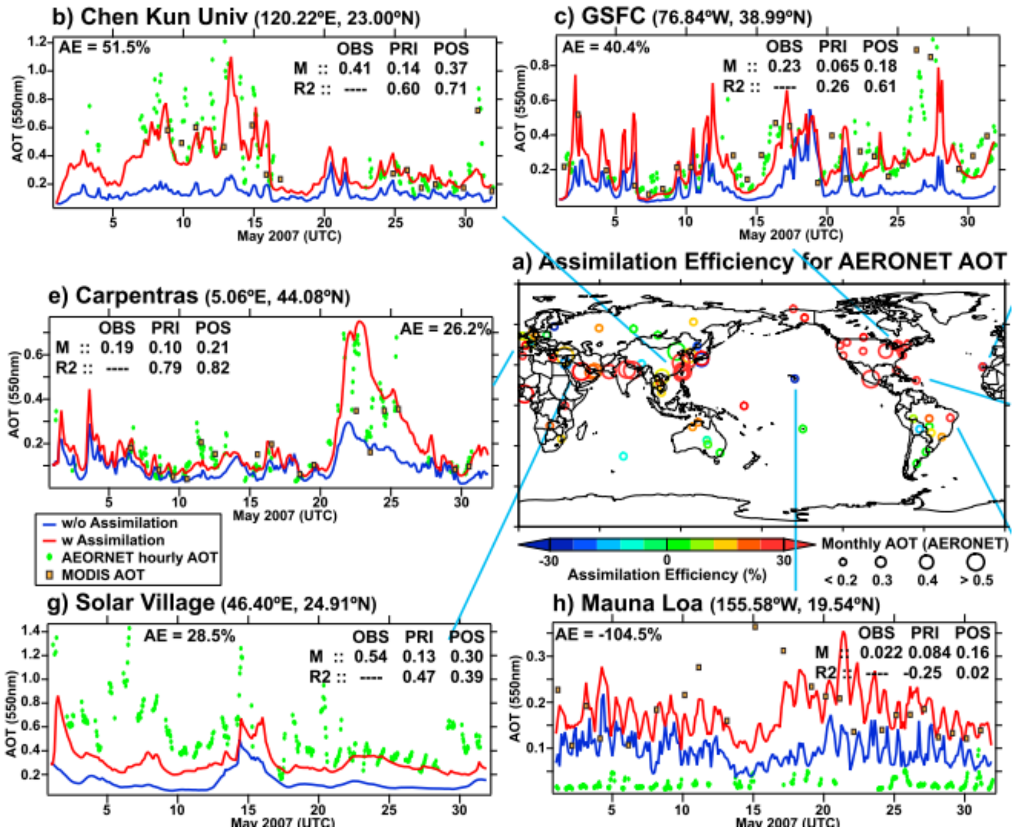


Figure 3. Comparisons between AERONET measurements and modeled results (a) showing the global distribution of assimilation efficiencies (AE) based on AERONET data. Color and size show AE values and observed monthly AOT, respectively. (b–i) AOT time series at AERONET sites. AERONET and MODIS observations are shown as green circles and orange cubes, respectively. *A posteriori* and *a priori* AOTs are shown with red and blue lines, respectively. AE, mean AOT (M) and correlation coefficients (R2) are also shown for observation (OBS), *a priori* (PRI) and *a posteriori* (POS).

(Yumimoto and Takemura, 2011)

▪ Results

Much better agreement with MODIS

Validated by AERONET

4. SPRINTARS x EnKF x satellite (MODIS)

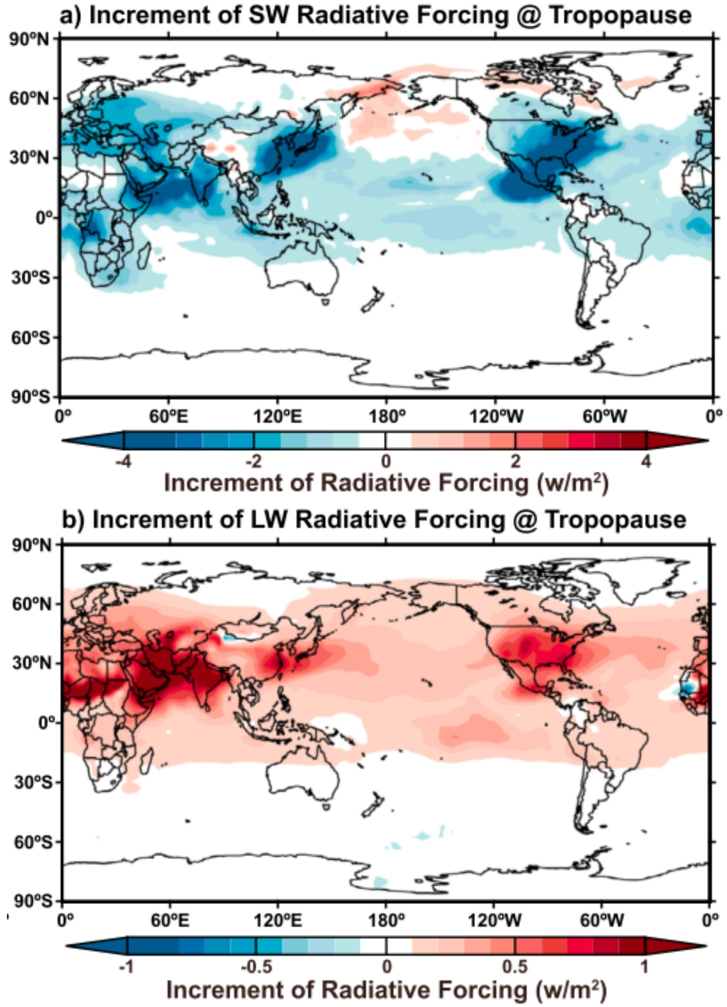


Figure 4. Increment of whole-sky TOA direct aerosol effect (DRE) of anthropogenic and natural aerosols between *a posteriori* and *a priori* (a) shortwave and (b) longwave radiation.

▪ Results

Much better agreement with MODIS

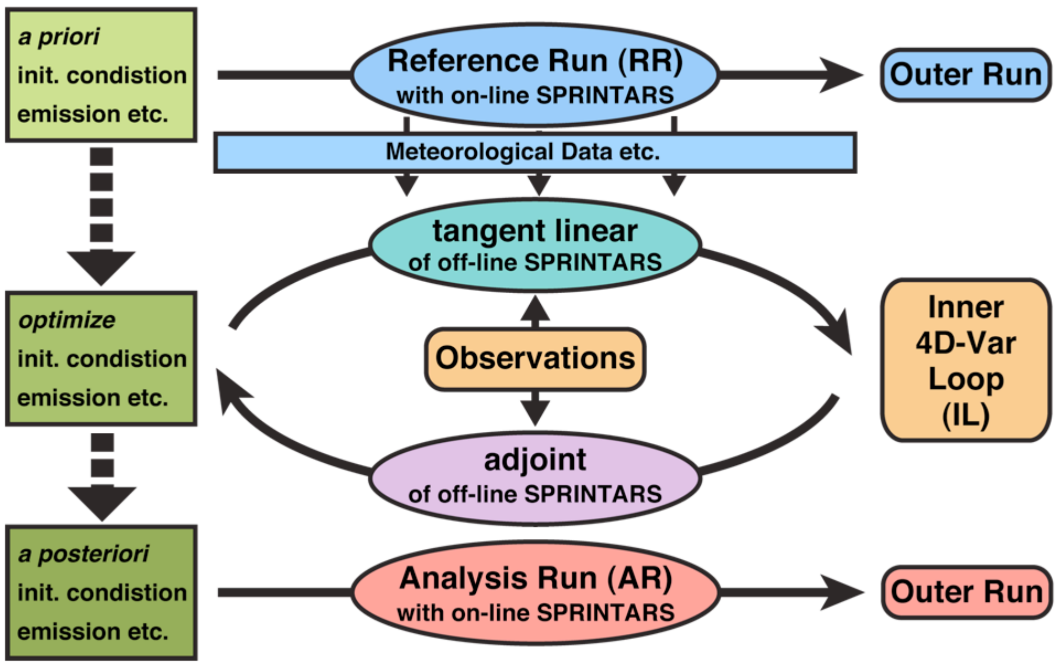
Validated by AERONET

Assimilated aerosol field modified direct radiative forcing

	a priori	a posteriori
Whole Sky @ TOA	-0.56 W/m^2	-1.1±0.35 W/m^2
Clear Sky @ TOA		
Ocean	-1.4 W/m^2	-2.5±0.47 W/m^2
Land	-1.5 W/m^2	-2.7±0.52 W/m^2

(Yumimoto and Takemura, 2011)

5. SPRINTARS x 4D-Var x satellite (MODIS)



Schematic diagram of SPRINTARS/4D-Var data assimilation system

(Yumimoto and Takemura, 2013)

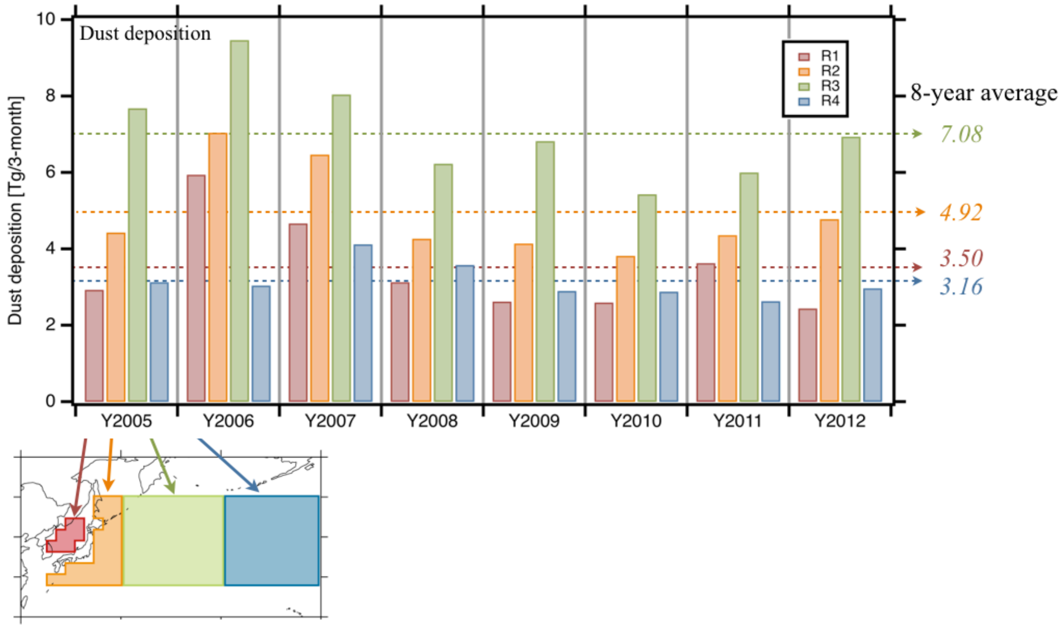
- **SPRINTARS**
- **4D-Var**
- **Observational constraints**

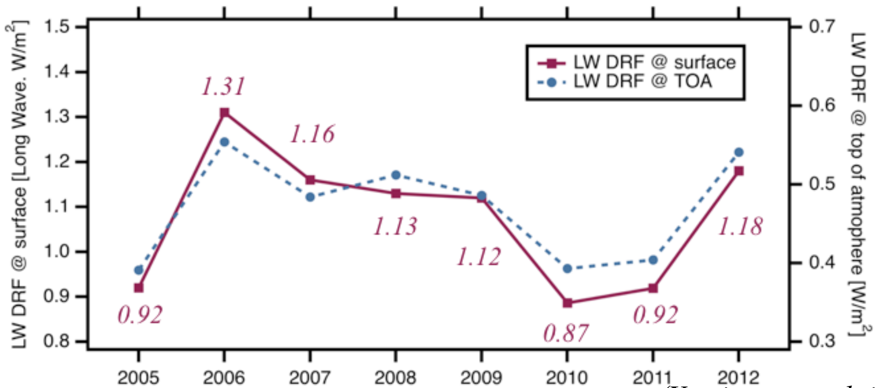
  Satellite (MODIS coarse-mode AOT)
- **Goals**

  Implement 4D-Var in SPRINTARS

  8-year inversion experiment of Asian dust

5. SPRINTARS x 4D-Var x satellite (MODIS)





(Yumimoto et al, in prep.)

- **Results**

Inverse estimate of 8-year dust emissions

(a posteriori emission shows significant correlations with snow cover and SLP)

Analyzed dust deposition and radiative forcing

Concluding remarks

・Assimilation is a powerful tool for CTMs.

・Both 4D-Var and EnKF have their distinctive advantages.

・Accurate estimates of background covariance and its structure are important.

・Comprehensive DA, which assimilates observations from various platforms, is required.

(Strong co-operation between model and observation)

・DA works with MASINGAR (with JMA and JAXA) will be shown in the next ICAP meeting.