Ensemble Data Assimilation for Aerosol Prediction

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Agenda

- Introduction (data assimilation)
- Ensemble Kalman filter (EnKF)
- EnKF for aerosol analysis
- JMA's plan for aerosol prediction
  - How to collaborate with NWP

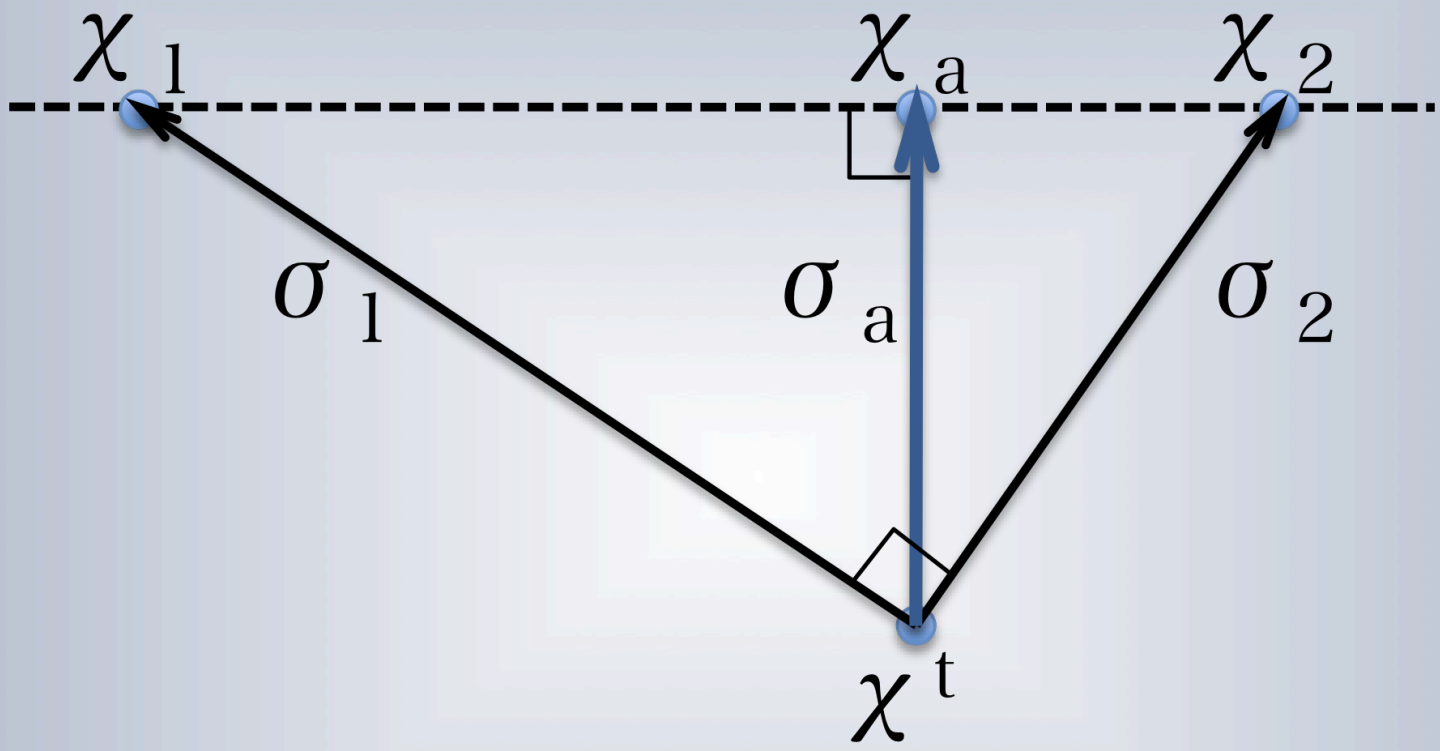
Introduction

- Data Assimilation for geophysics
  - Optimal Interpolation (OI)
  - Variational Method (3D-Var, 4D-Var)
  - Kalman Filter (KF)

minimum variance estimation

    - **Ensemble Kalman Filter**
      - Perturbed Observation KF
      - Square Root KF
  - Particle Filter

Optimal Interpolation (OI)

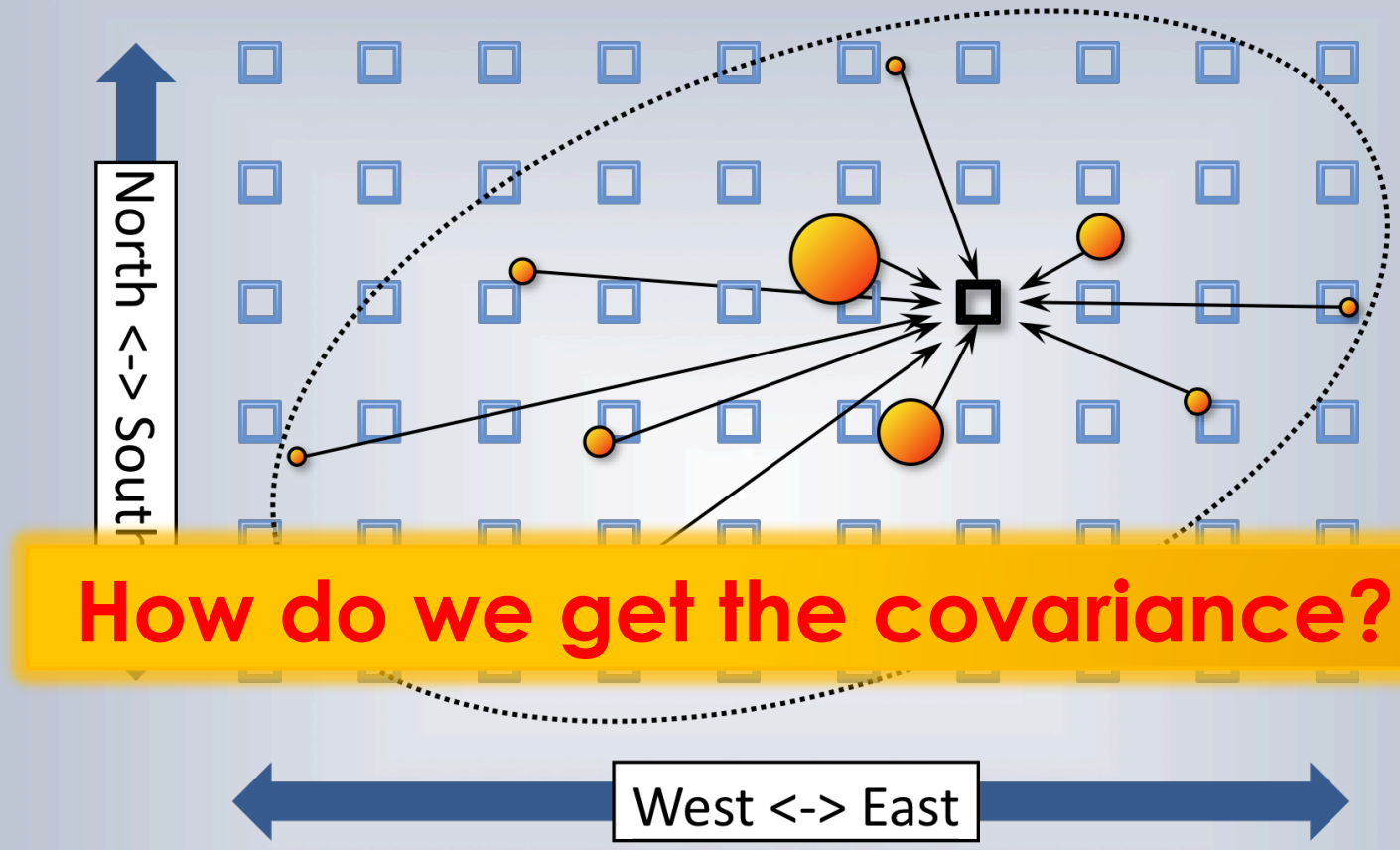


Weighted Average

$$\chi_a = \omega\chi_1 + (1-\omega)\chi_2 = \chi_2 + \omega(\chi_1 - \chi_2)$$

$$\omega = \sigma_2^2 / (\sigma_1^2 + \sigma_2^2)(0 \leq \omega \leq 1)$$

Optimal Interpolation (OI)



How do we get the covariance?

$$\chi_a = \chi_b + \mathbf{W}(\psi_o - \mathbf{H}\chi_b)$$

$$\mathbf{W} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$$

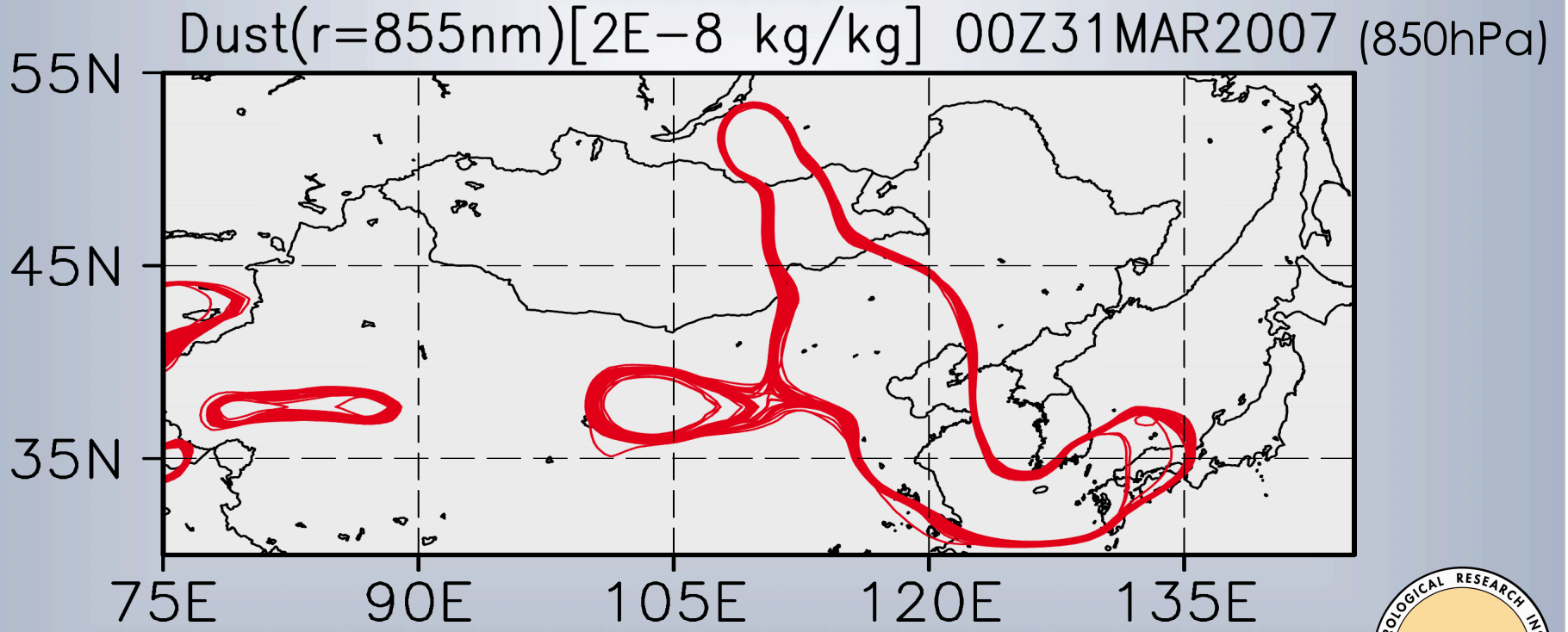
B: error covariance matrix

Introduction

- In OI or 3D-Var, the error covariance between two points is assumed **homogeneous** and **isotropic**.
- 4D-Var **implicitly** finds the optimal error covariance by using a maximum likelihood approach.
- What else could we do?
  - What we need is the covariance…

Introduction

* Stochastic or "ensemble" forecasting is used to account for **uncertainty**.



32-member spaghetti plot

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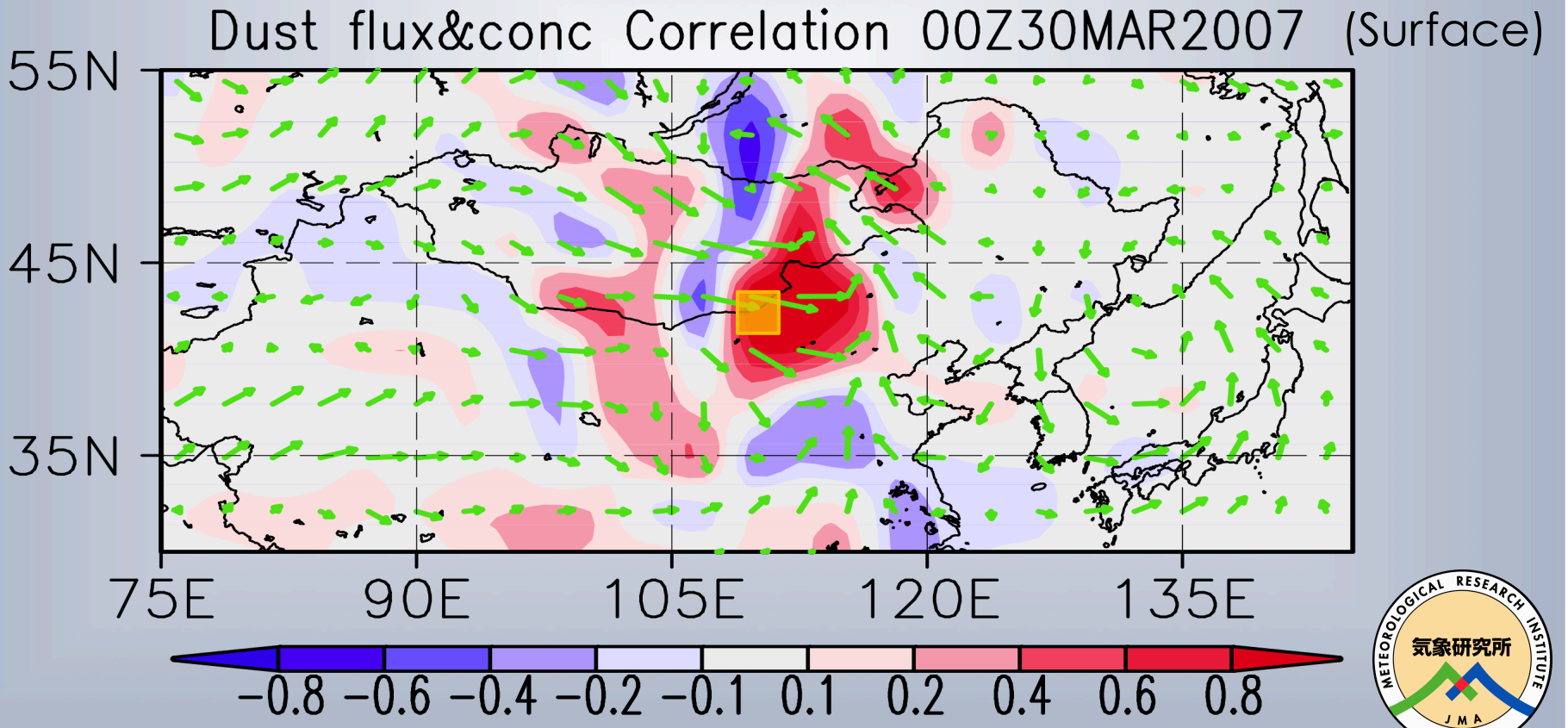
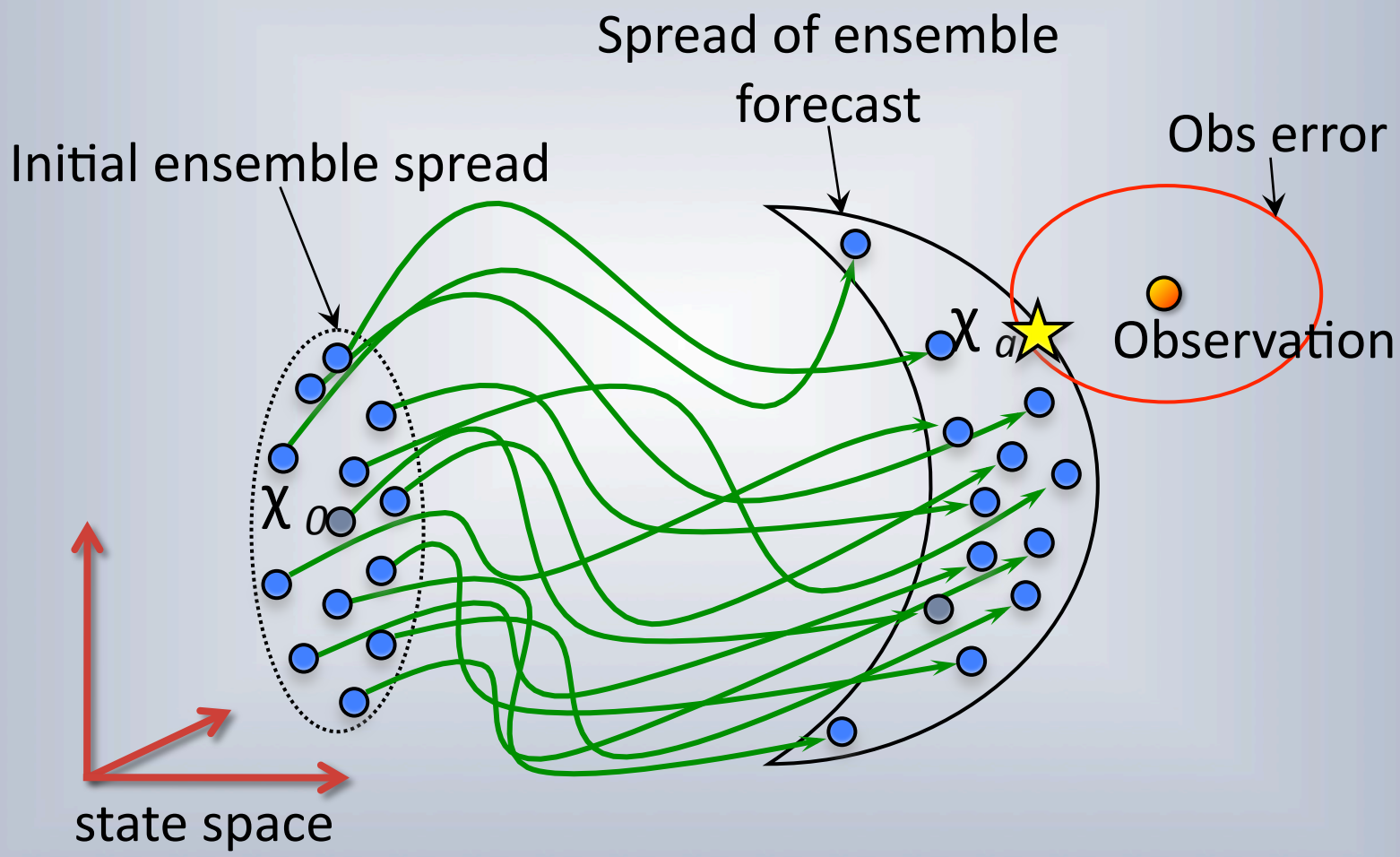
Introduction

* Uncertainty = forecast **error**

  ➔ $\Sigma\, \text{error}_1 \times \text{error}_2$ = **covariance**



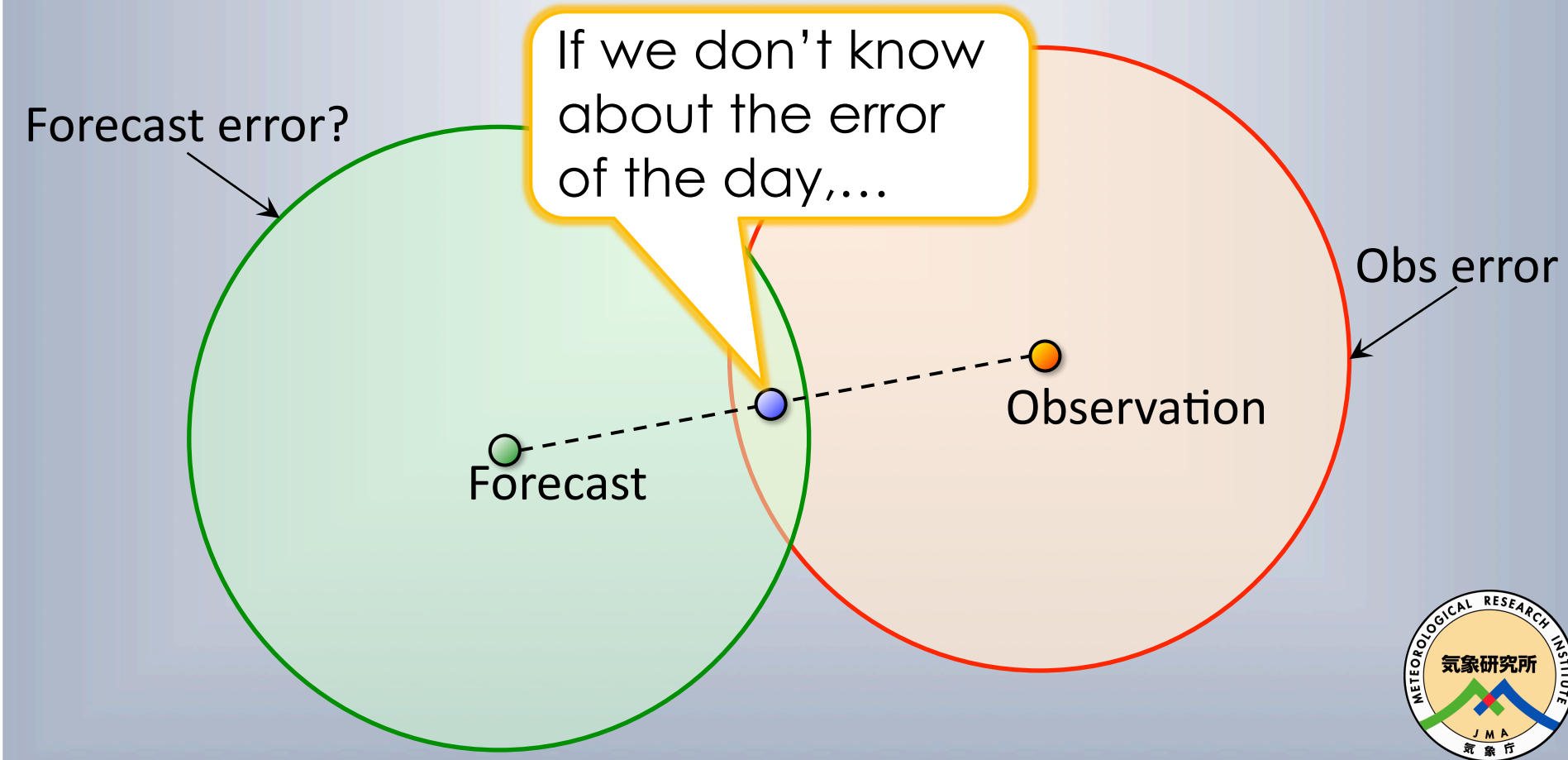
Ensemble Kalman Filter



Monte Carlo method

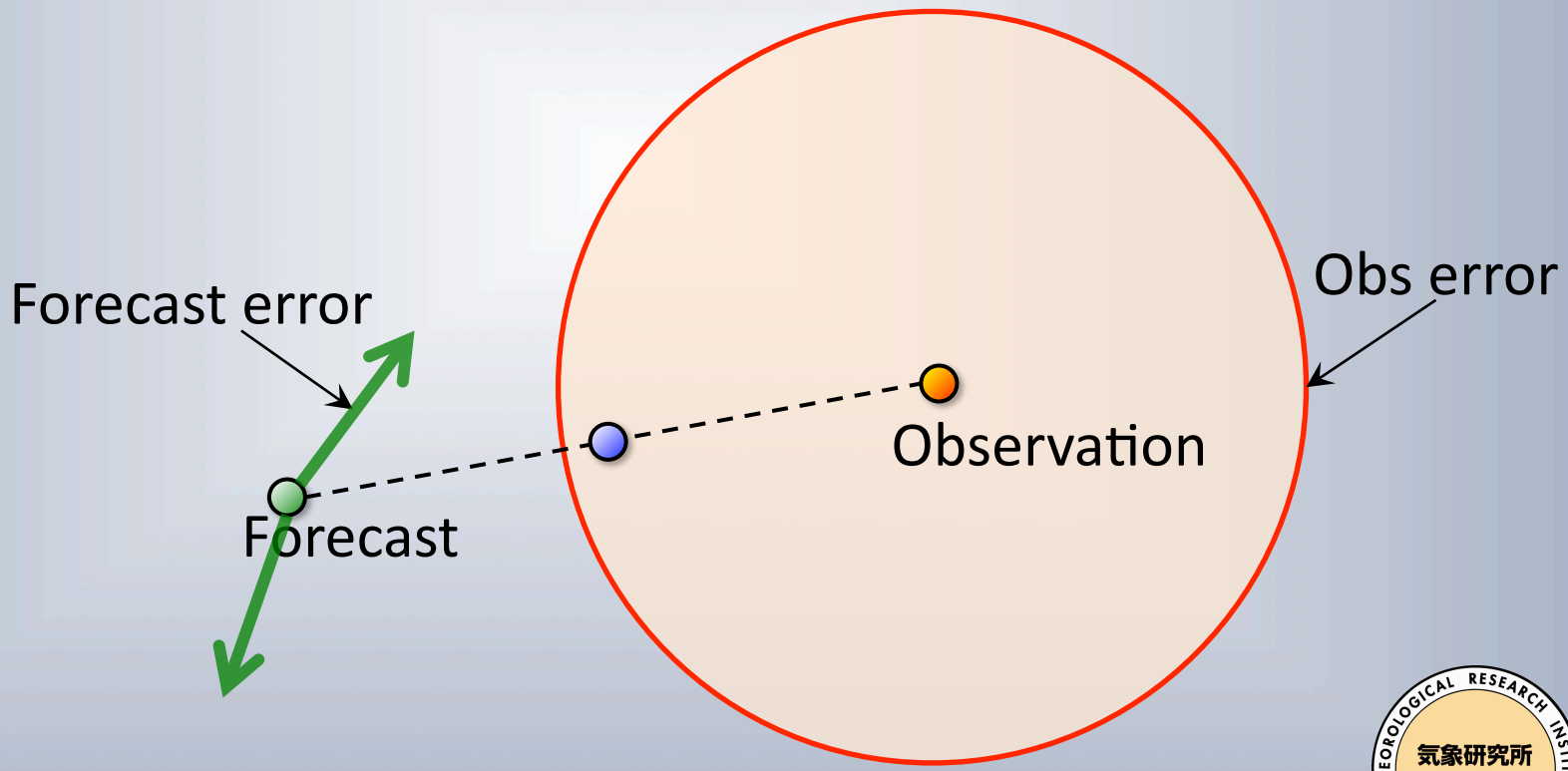
Ensemble Kalman Filter

* Suppose we have a forecast (back-ground) and an observation.



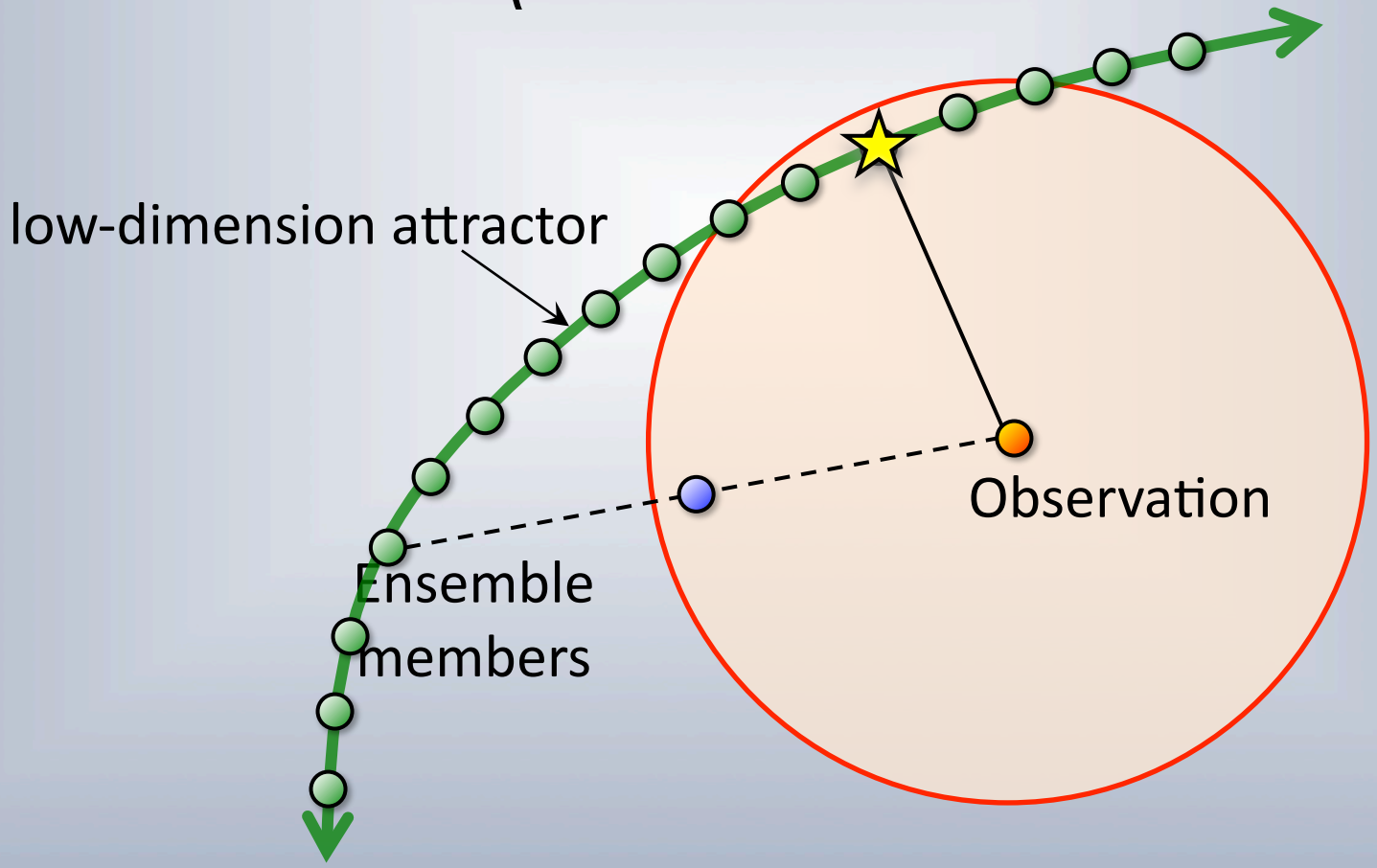
Ensemble Kalman Filter

* Generally, forecast errors lie on a low-dimension attractor, so…



Ensemble Kalman Filter

* Kalman filter finds the forecast error covariance (= attractor's structure).



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

Ensemble Kalman Filter

- Which is better, EnKF or 4D-Var, for atmospheric chemistry?
- The two have even performance, but 4D-Var has a longer history.
- 4D-Var has compatibility with NWP.
- Are you "chemists who are interested in Met" or "meteorologists who are interested in chemistry"?

Aerosol data assimilation
under development by JMA

Why JMA predicts dust?

- **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.
- JMA has to predict it.

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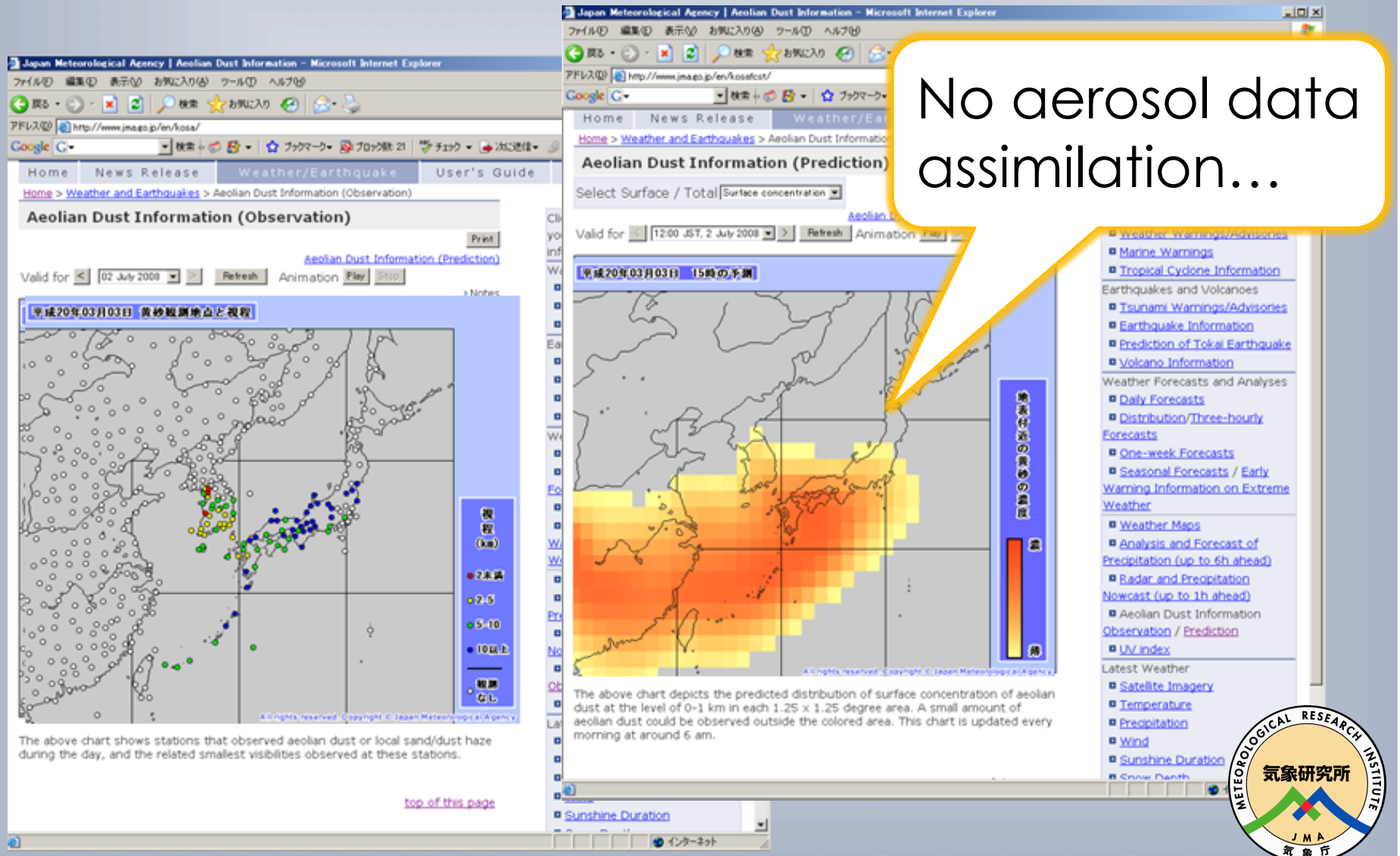
Operational dust prediction



JMA's dust prediction

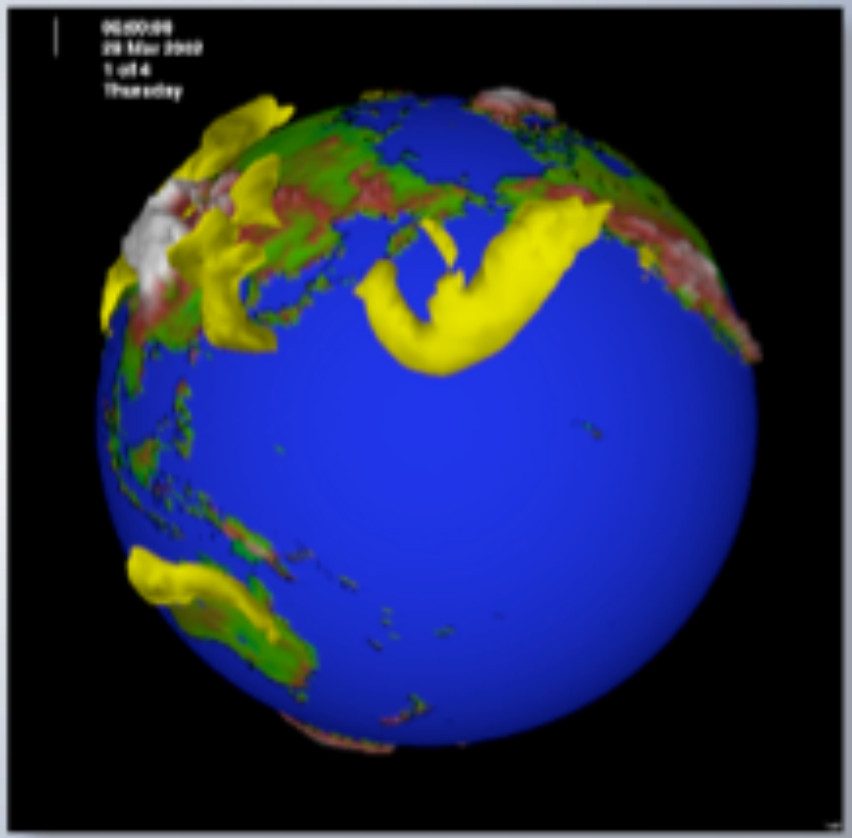
- JMA wants to utilize aerosol data assimilation for improving their operational dust prediction.
- If possible, they want to use the aerosol analysis for their NWP and climate simulations.

EnKF for aerosol analysis

Methodology

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
- The meteorological components are **nudged** to 6-hourly JMA reanalysis.



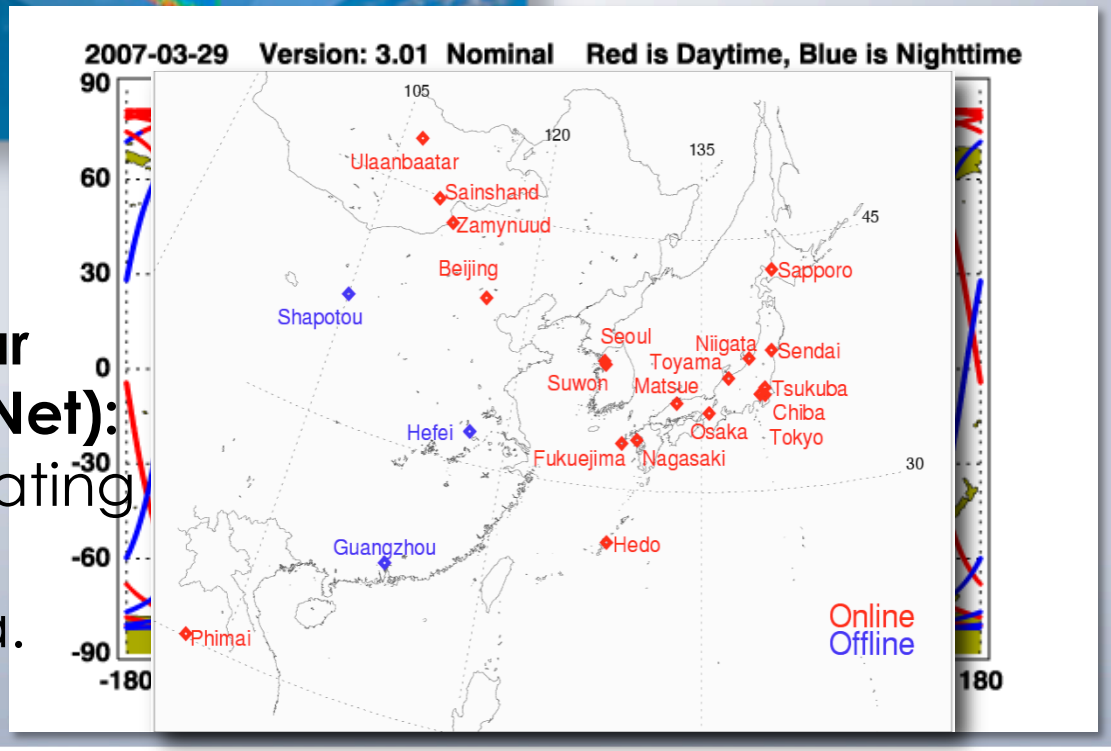
EnKF for aerosol analysis

model variables

	U&V wind	SO4	Dust	Dust Flux	Sea Salt	BC OC
U&V wind	**Nudged**	Yes	Yes	Yes	No	No
SO4	Yes	**Control**	Yes	Yes	No	No
Dust	Yes	Yes	**Control**	Yes	No	No
Dust Flux	Yes	Yes	Yes	**Control**	No	No
Sea Salt	No	No	No	No	**N/C**	No
BC OC	No	No	No	No	No	**N/C**

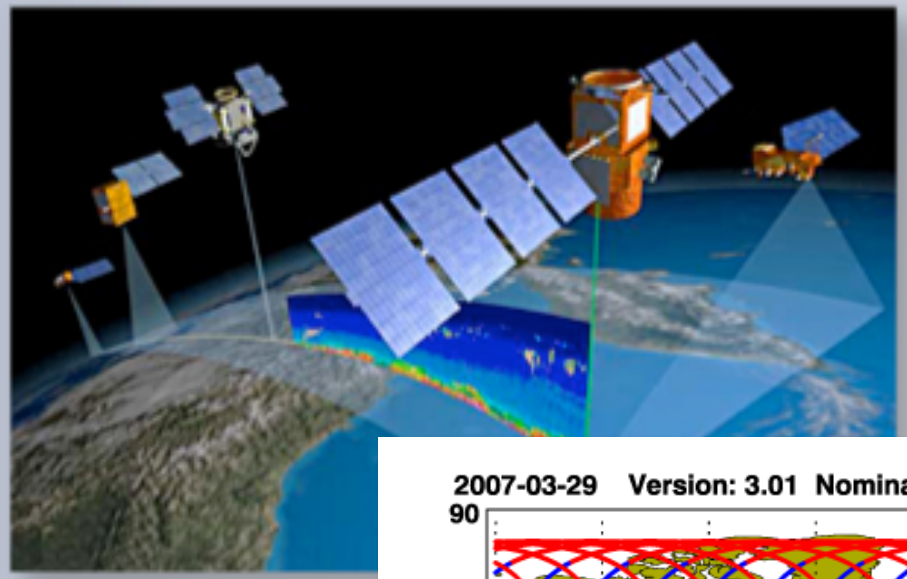
EnKF for aerosol analysis

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

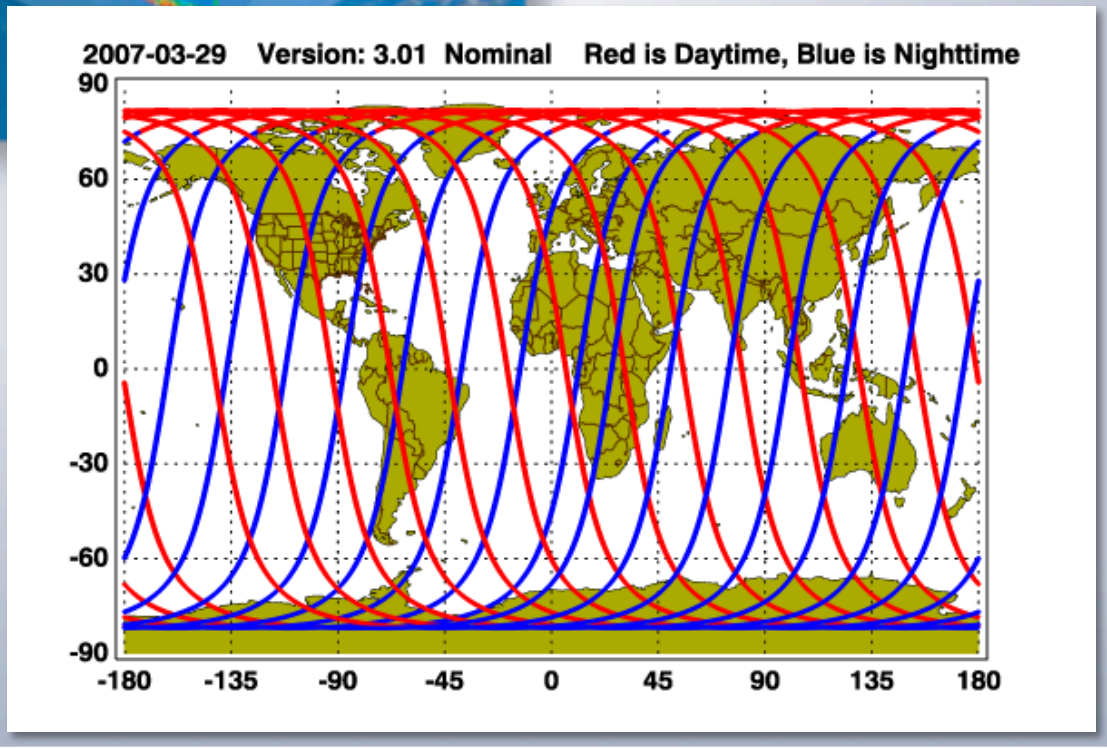


Ground-based lidar network (NIES AD-Net):
NIES Japan is operating more than 20 lidar stations in East Asia.

EnKF for aerosol analysis



The CALIPSO orbit has an about 1000 km longitudinal interval per day at mid-latitudes.



Lidar view angle: almost zero…

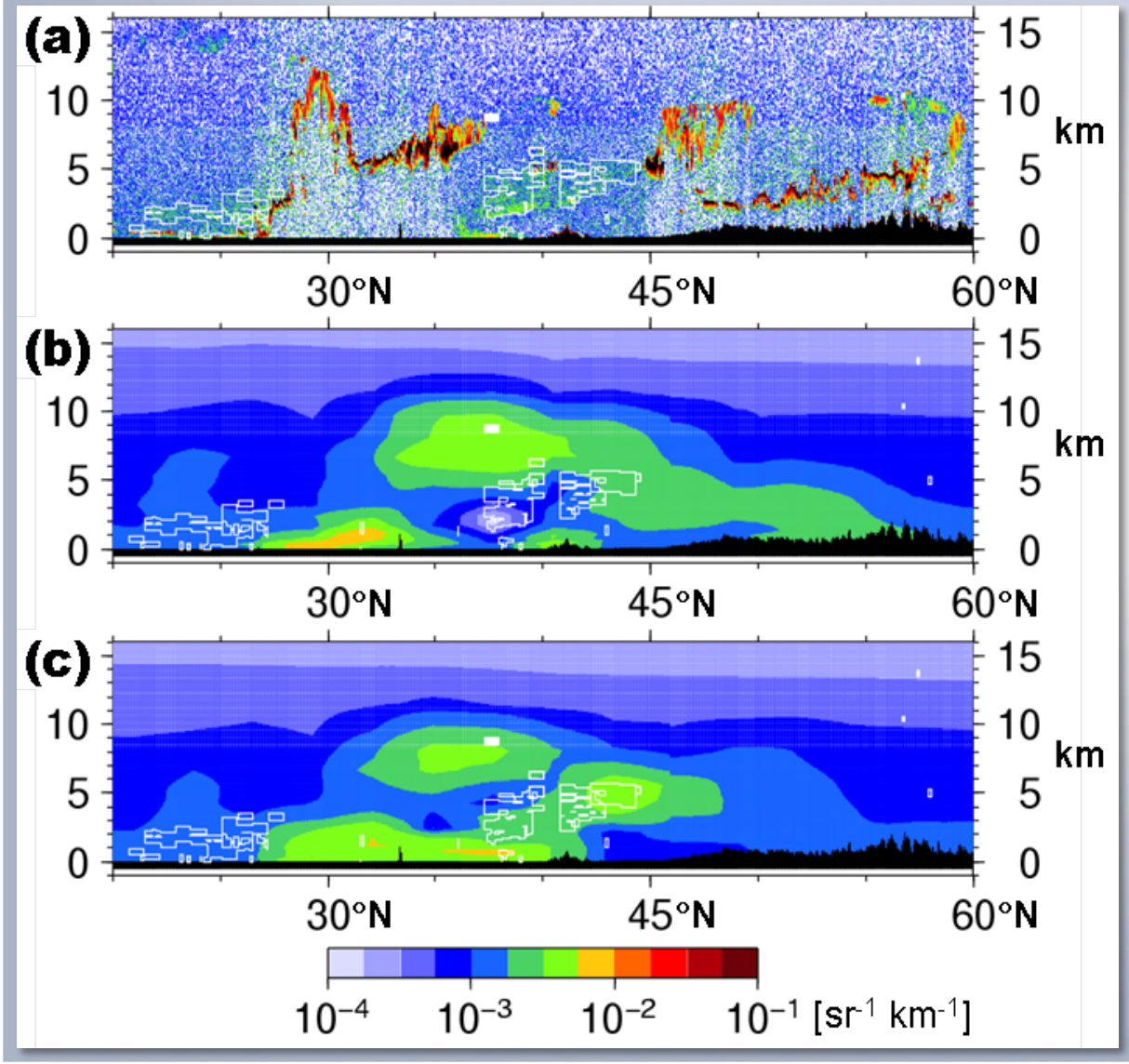
Data density: very sparse…

But it has vertical profiles.

EnKF for aerosol analysis

Results

EnKF for aerosol analysis



Observation Variables: attenuated backscattering coeff. at 532 nm;

a) CALIPSO/CALIOP;

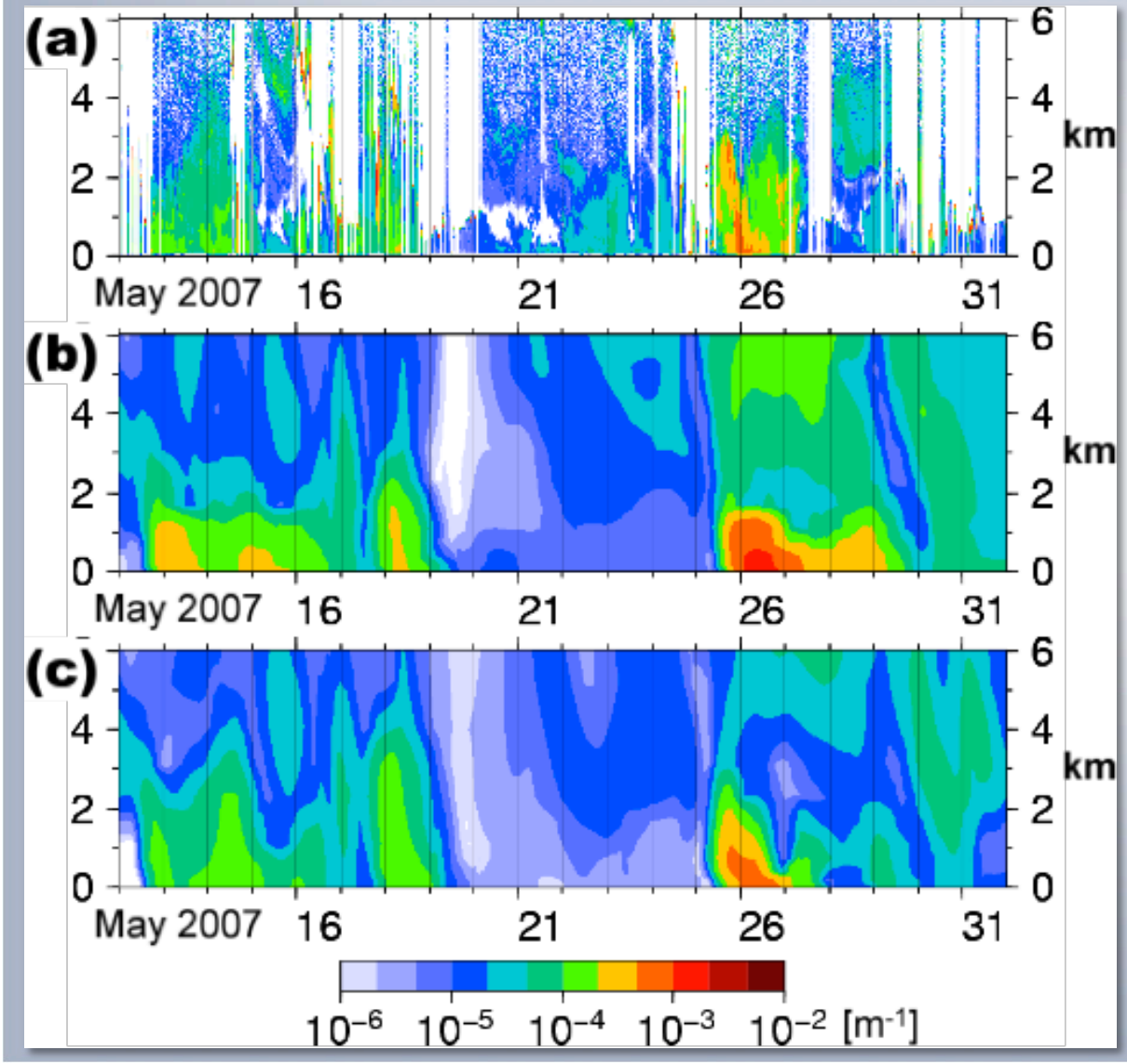
b) model **without** data assimilation;

c) model **with** data assimilation.

White squares: aerosol plumes.

Sekiyama et al., ACP (2010)

EnKF for aerosol analysis



Comparison of 532nm extinction coefficients for dust aerosol.

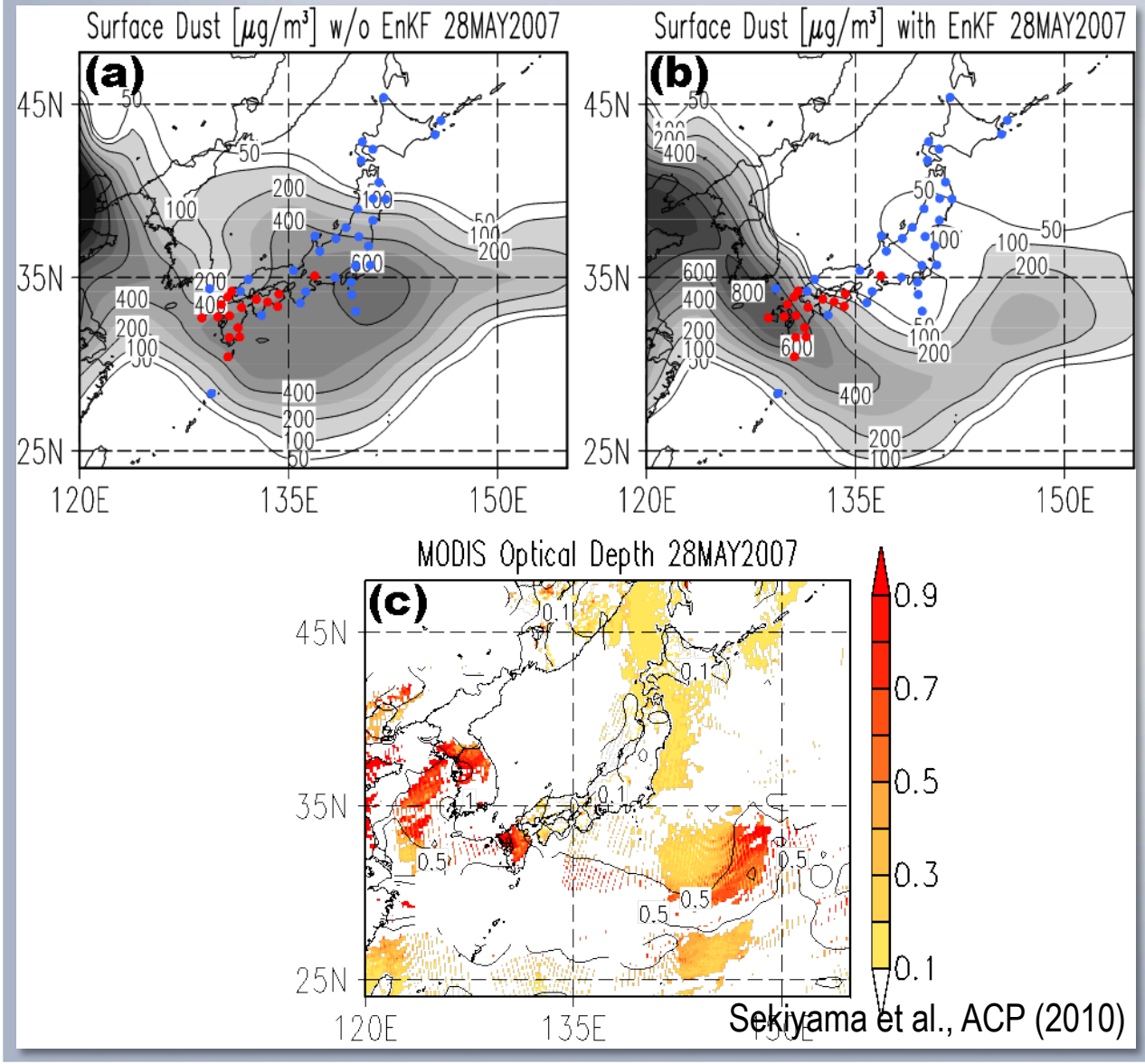
(a) Independent ground-based lidar observation;

(b) free model-run results without data assimilation;

(c) CALIPSO data assimilation results.

Sekiyama et al., ACP (2010)

EnKF for aerosol analysis



Sekiyama et al., ACP (2010)

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

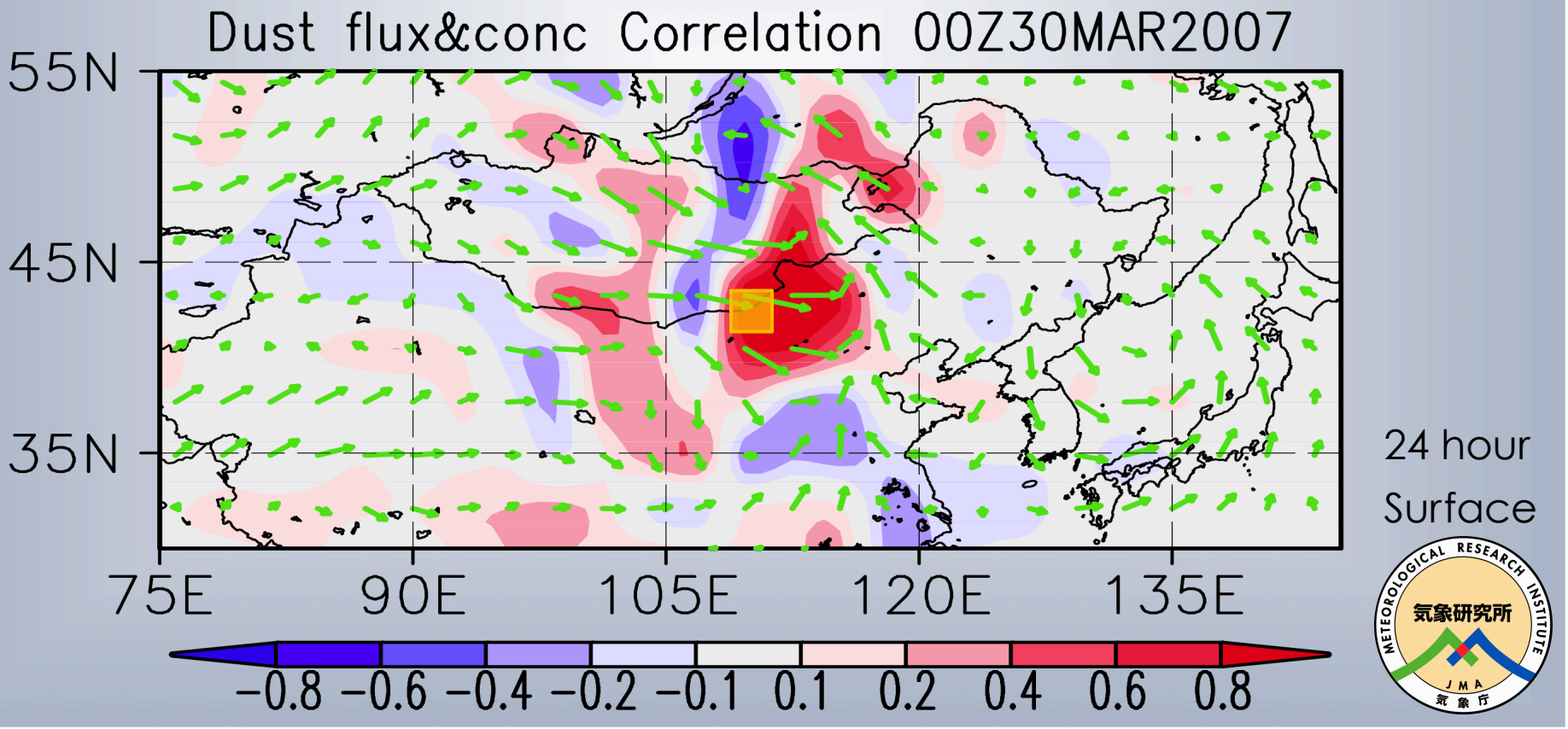
(a) Free model-run result without data assimilation.

(b) CALIPSO data assimilation result.

Red and blue circles are weather stations. The Red ones observed aeolian dust on the day. Blue ones did not observe any dust events.

EnKF for aerosol analysis

* Correlation between dust flux & conc enables inverse analysis.



24 hour
Surface

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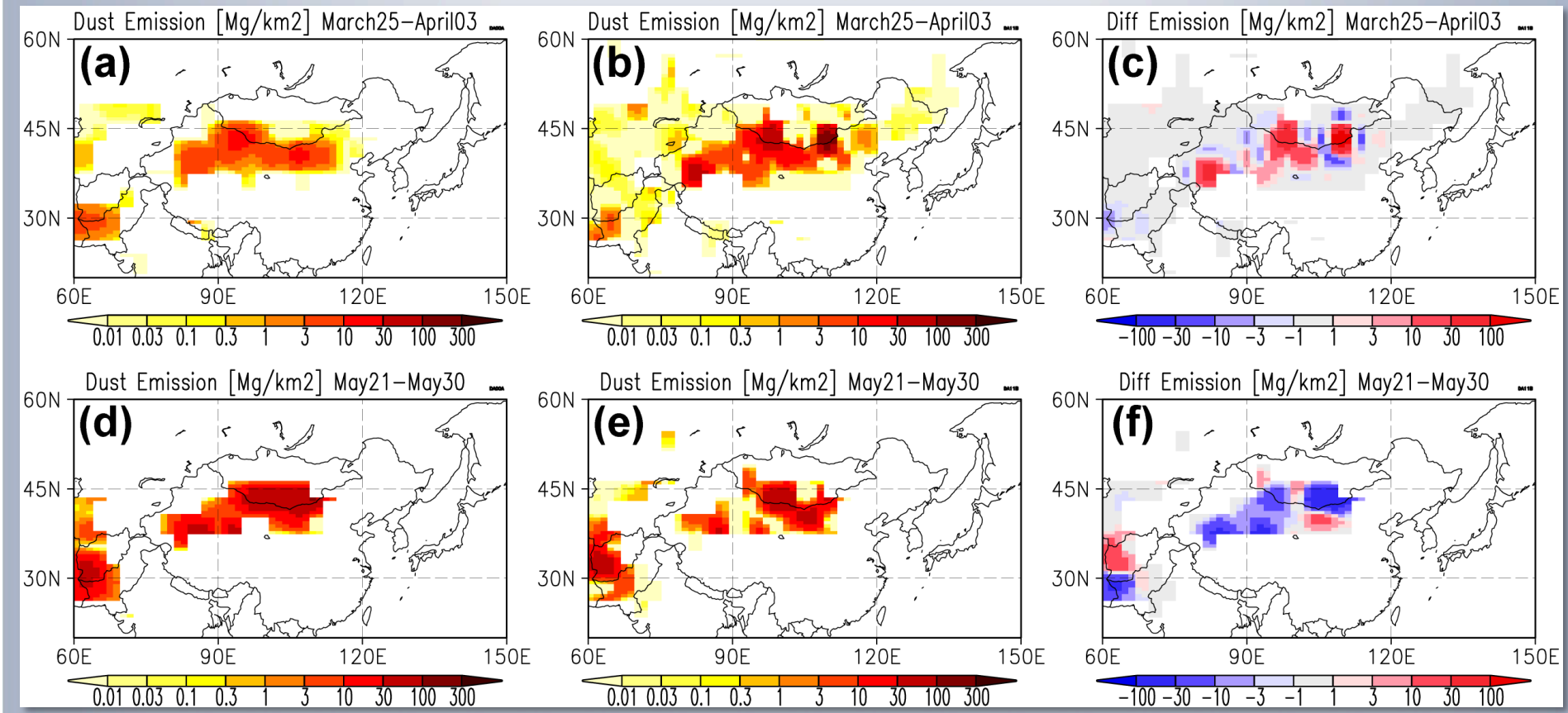
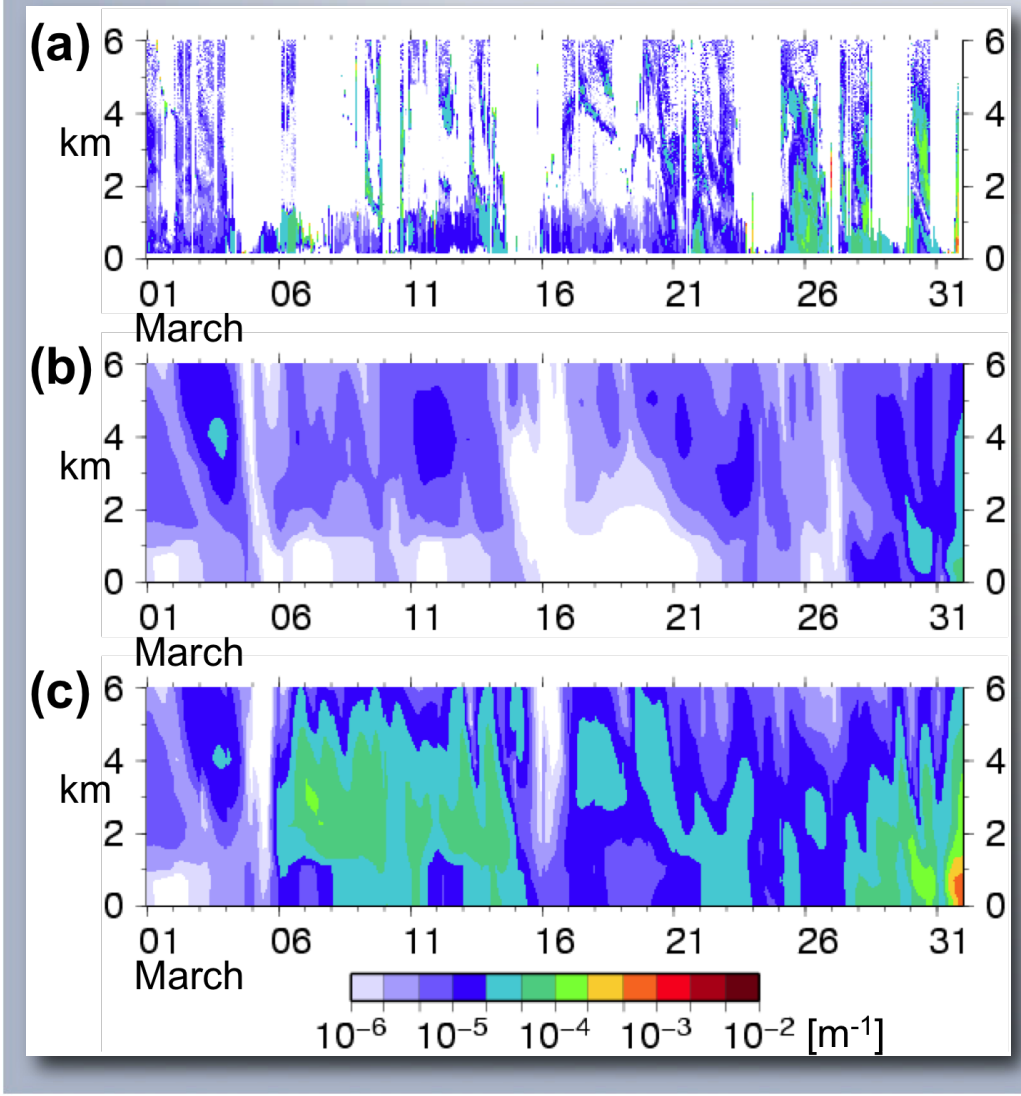
EnKF for aerosol analysis

* Dust emission inverse analysis by EnKF



Sekiyama et al., SOLA (2011)

EnKF for aerosol analysis

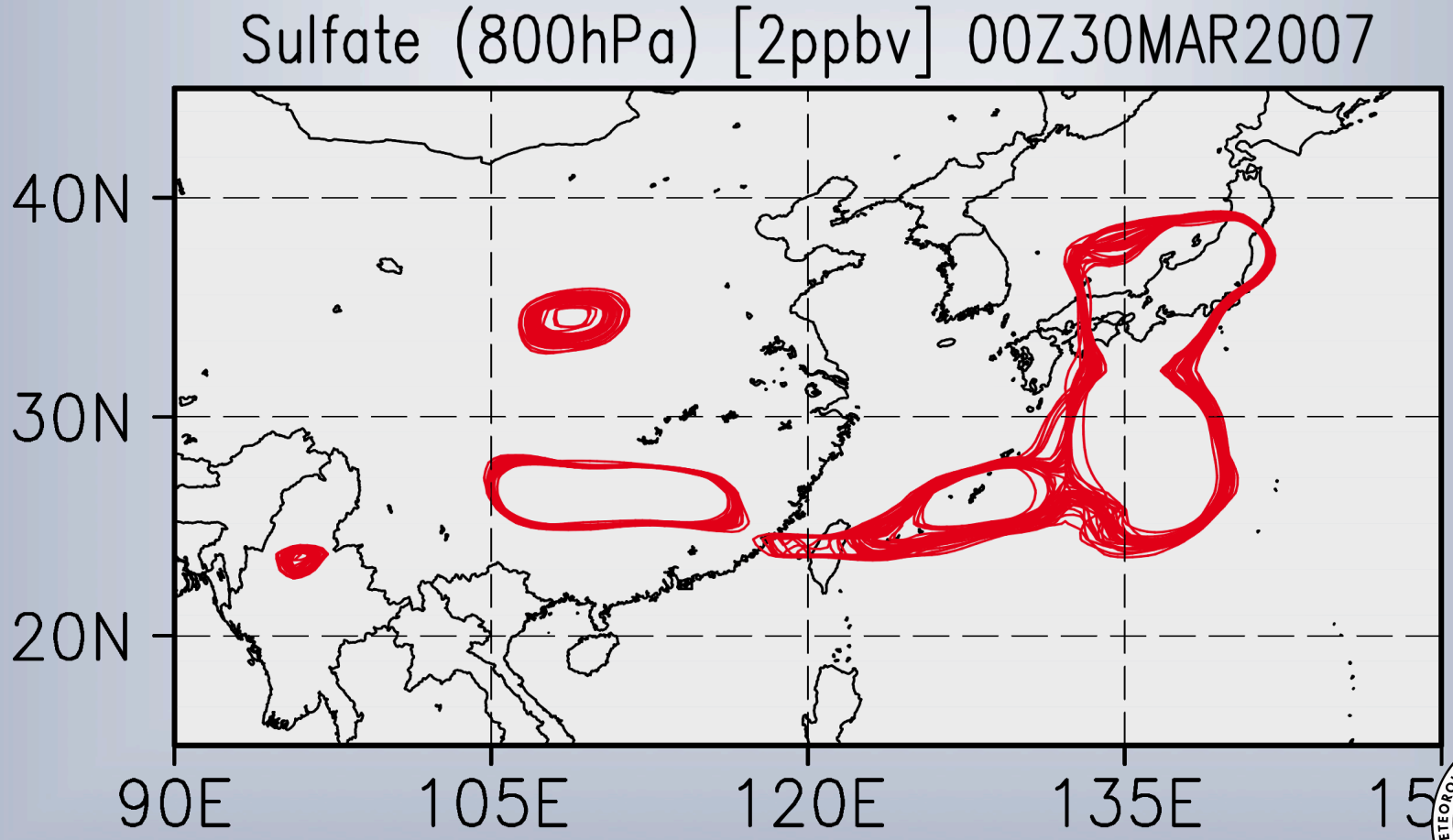


* Asian dust source regions are often covered with snow.
* It's difficult for models to simulate dust outbreaks (Fig. b).
* EnKF improves dust flux estimation and dust concentration (Fig. c).

Sekiyama et al., SOLA (2011)

EnKF for aerosol analysis

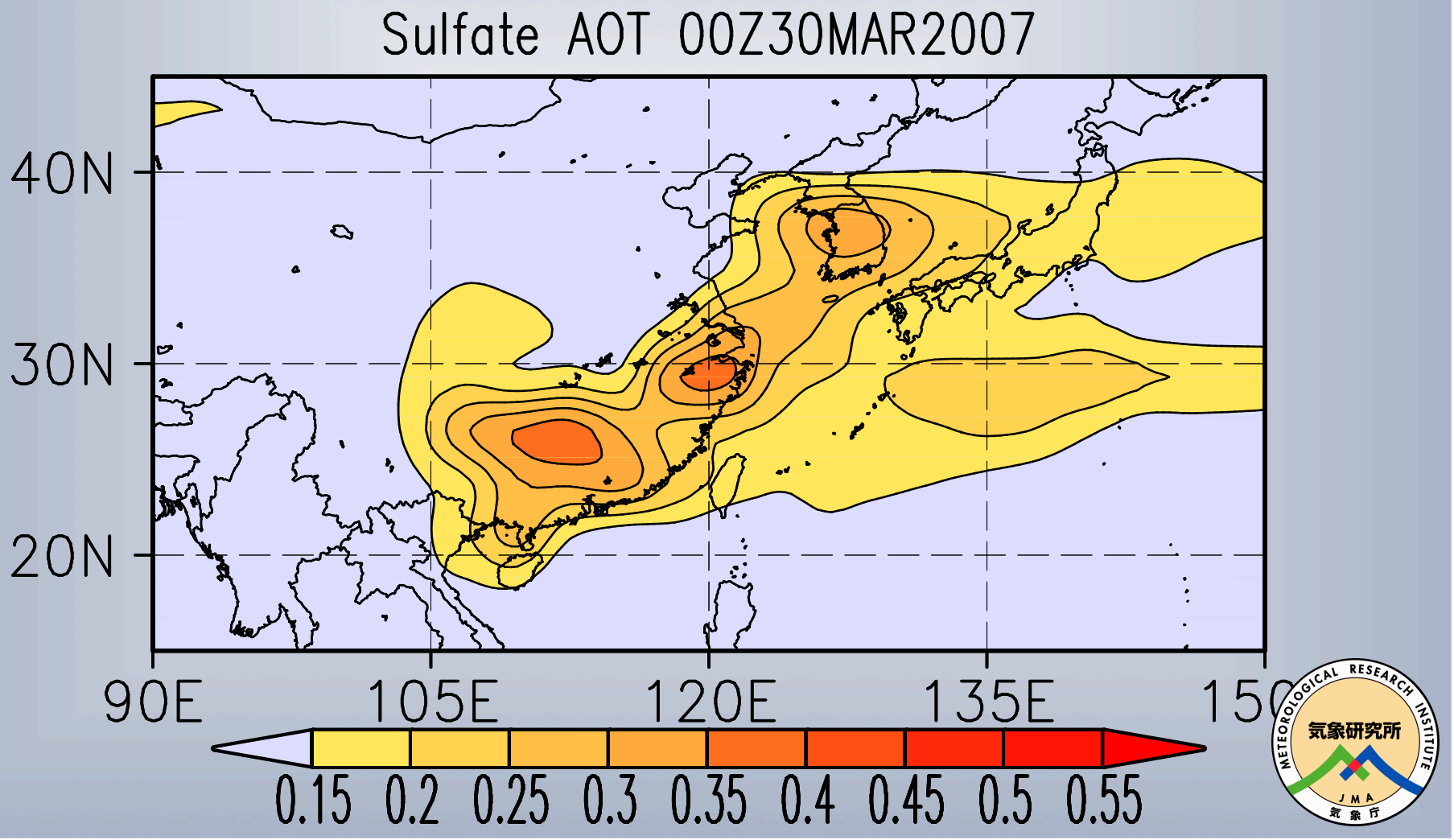
* Not only dust, but **sulfate aerosol…**



32-member spaghetti plot

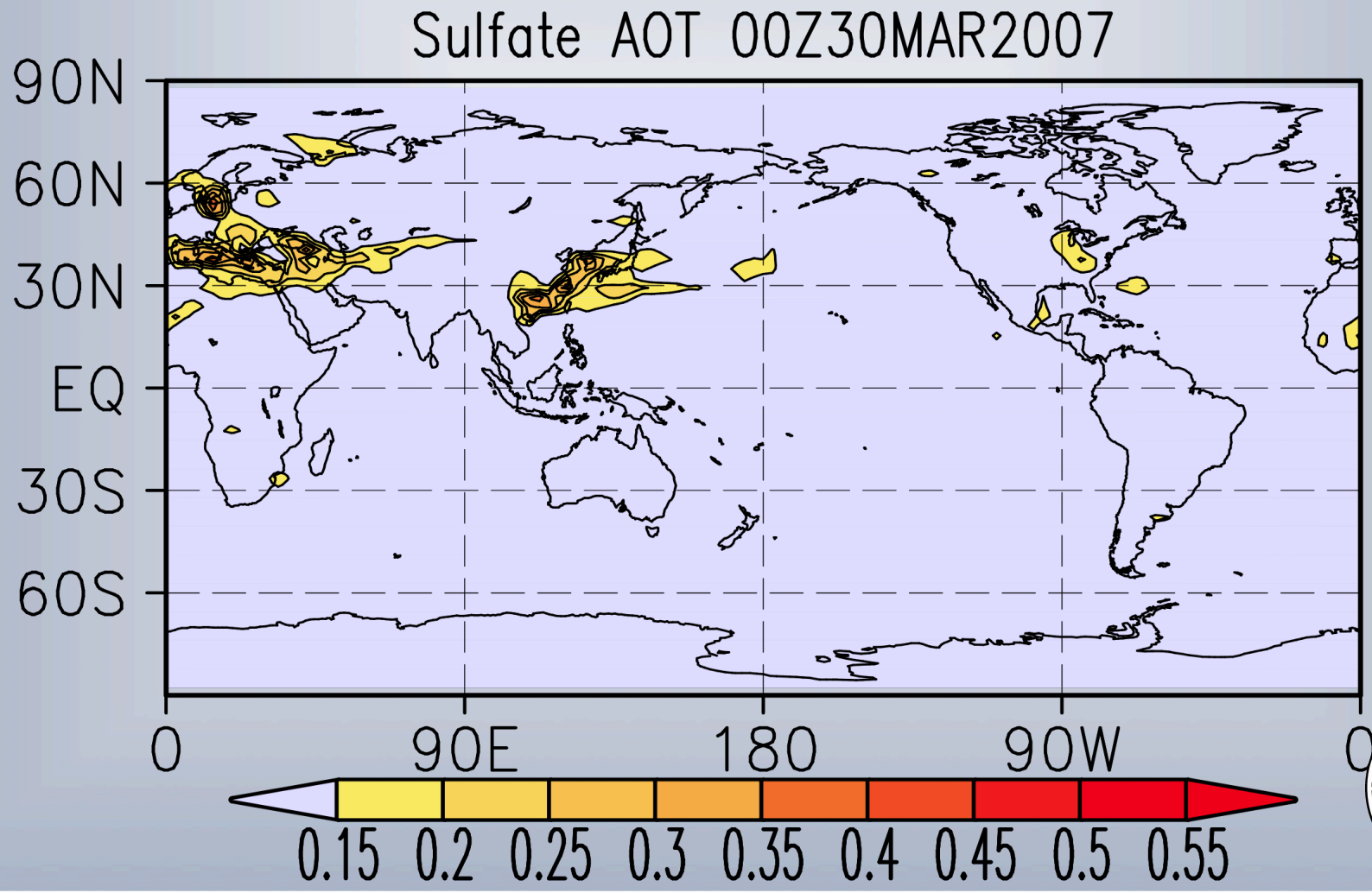
EnKF for aerosol analysis

* Assimilation result of sulfate AOT



EnKF for aerosol analysis

* Assimilation result of sulfate AOT



JMA's plan for aerosol prediction

JMA's plan for aerosol prediction

- JMA's dust prediction doesn't include a data assimilation procedure.
- **JMA wants to use the EnKF aerosol analyses as initial conditions of aerosol prediction.**
  (hopefully, in practical use by 2014…)
- But, the JMA aerosol prediction has no interaction with NWP…

JMA's plan for aerosol prediction

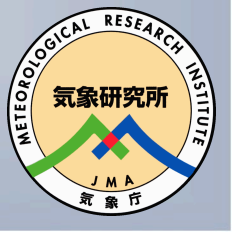
- JMA is operating a 4D-Var system for NWP.
- JMA weather/climate models have **no interaction** with aerosol **chemistry**.
- We should collaborate with NWP.
- How?
- EnKF data assimilation have **no compatibility** with the current NWP.

JMA's plan for aerosol prediction

- JMA aerosol data assimilation:
  currently available only for environmental predictions…
- Aerosol **reanalysis**:
  available for climate modeling?
- Aerosol **climatology** (detailed):
  available for NWP?
- Ideally, **weather-chemistry** coupled DA…
- Still, many challenges…

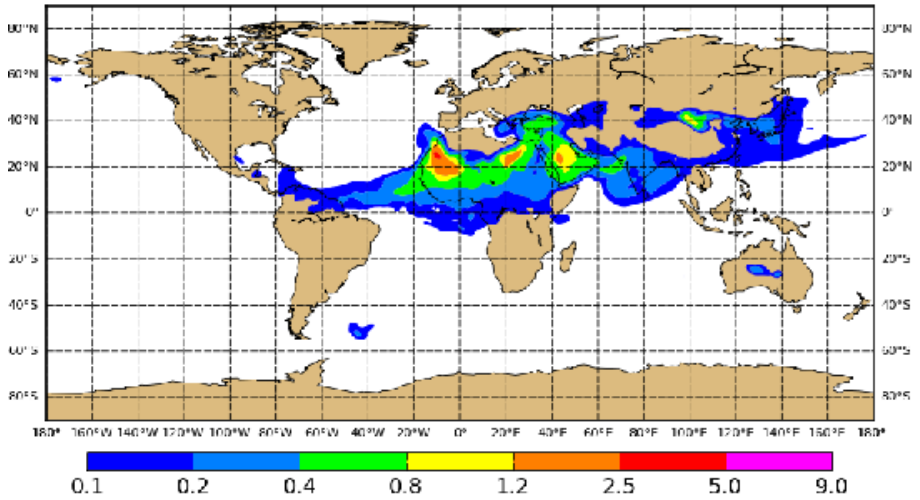
Thank you.

Model Ensemble



Dust

Friday 1 April 2011 00UTC NAAPS Forecast t+006
Friday 1 April 2011 06UTC Valid Time
Dust Aerosol Optical Depth at 550nm



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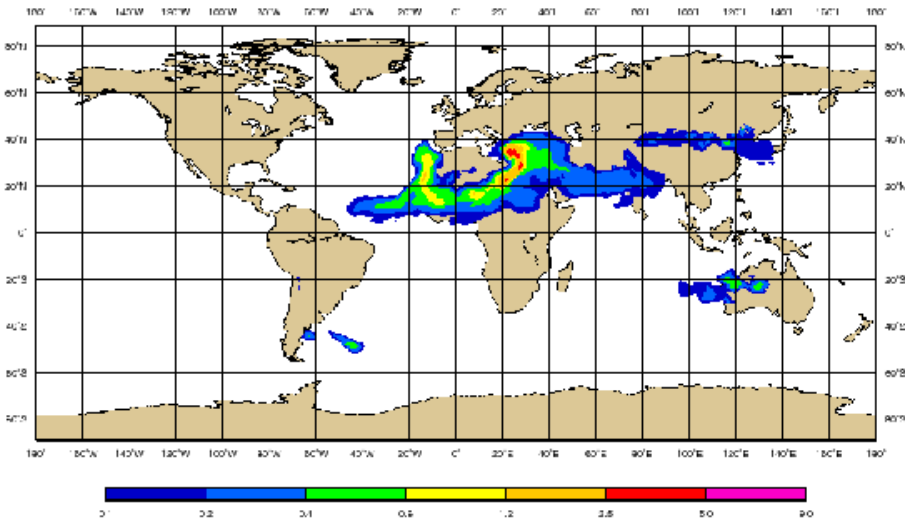
Friday 01 April 2011 00UTC MASINGAR Forecast t+006 VT: Friday 01 April 2011 00UTC
Dust Aerosols Optical Depth at 550 nm



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Friday 1 April 2011 00UTC GEOS 5 Forecast t+006
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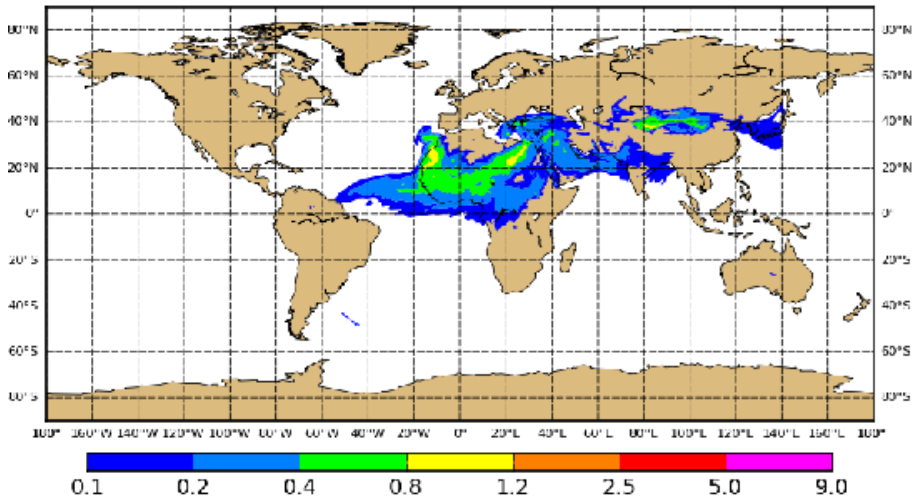

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GEOS–5

Friday 1 April 2011 00UTC MACC Forecast t+006
Friday 1 April 2011 06UTC Valid Time
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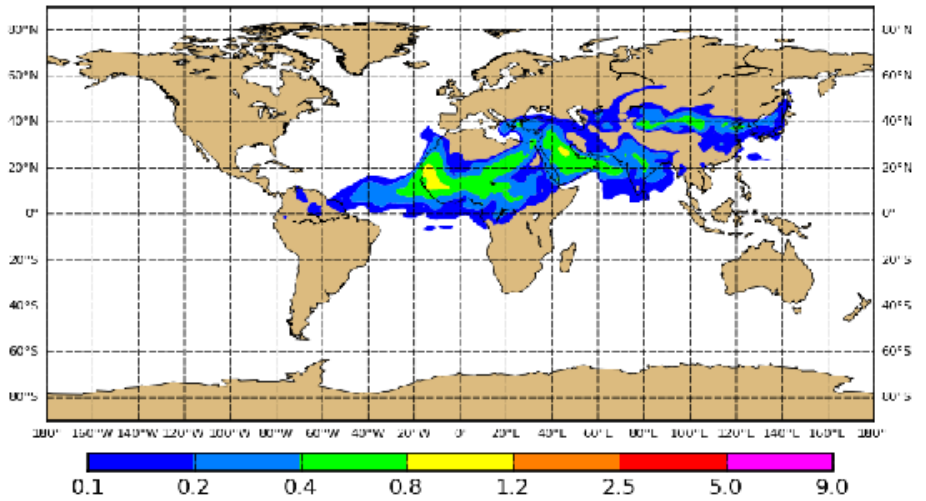

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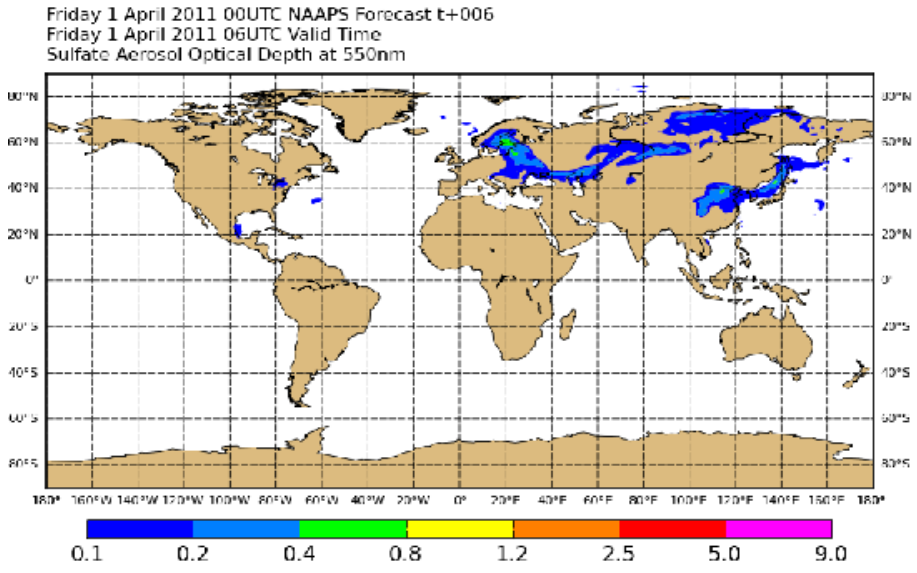
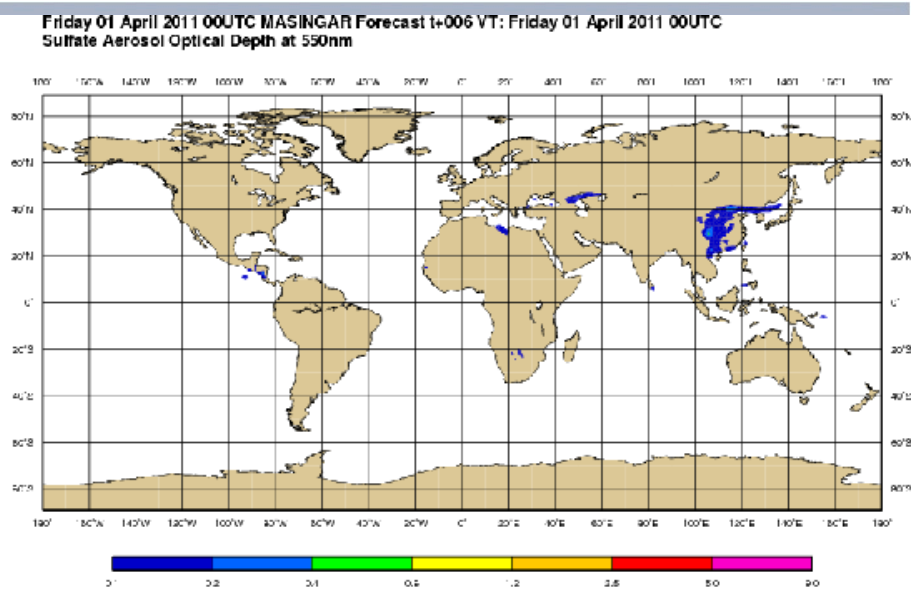
Sulfate



NAAPS



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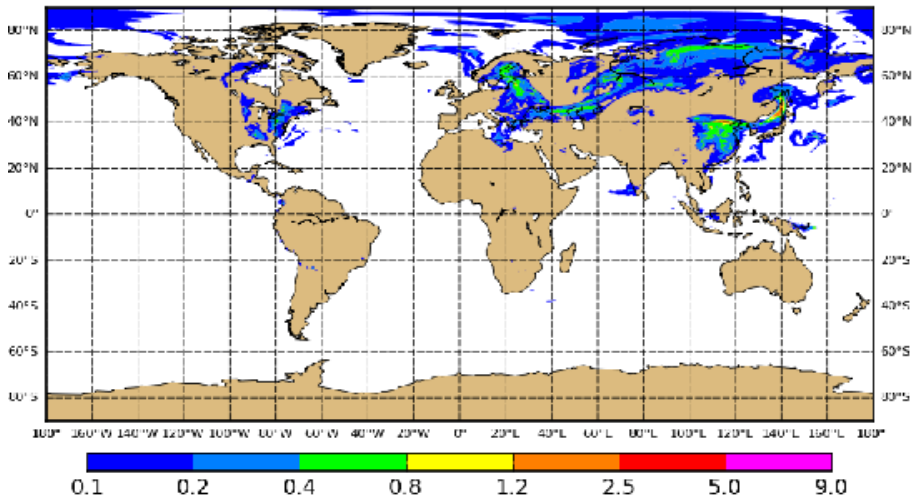

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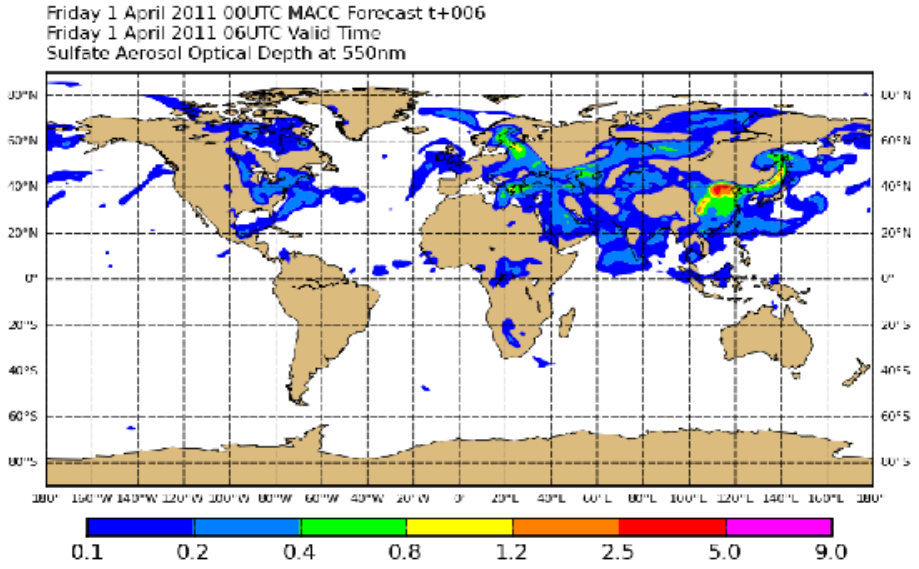

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Sea Salt

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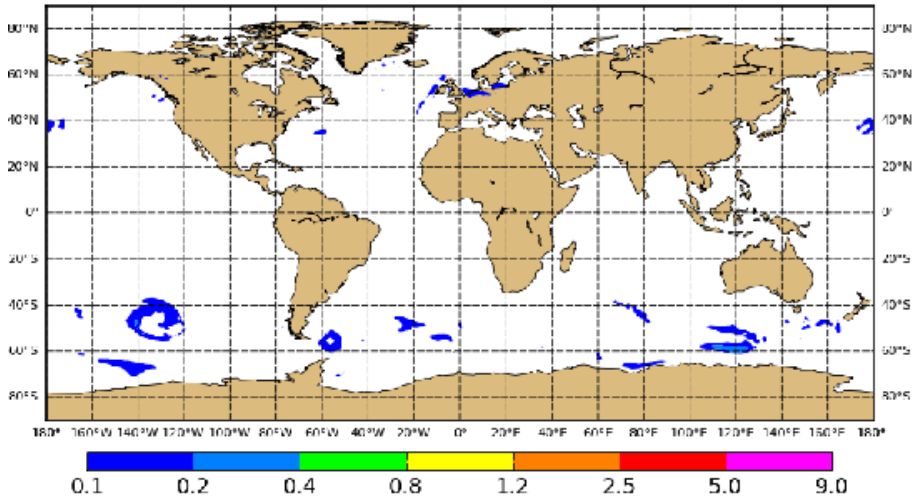
SeaSalt Aerosol Optical Depth at 550nm



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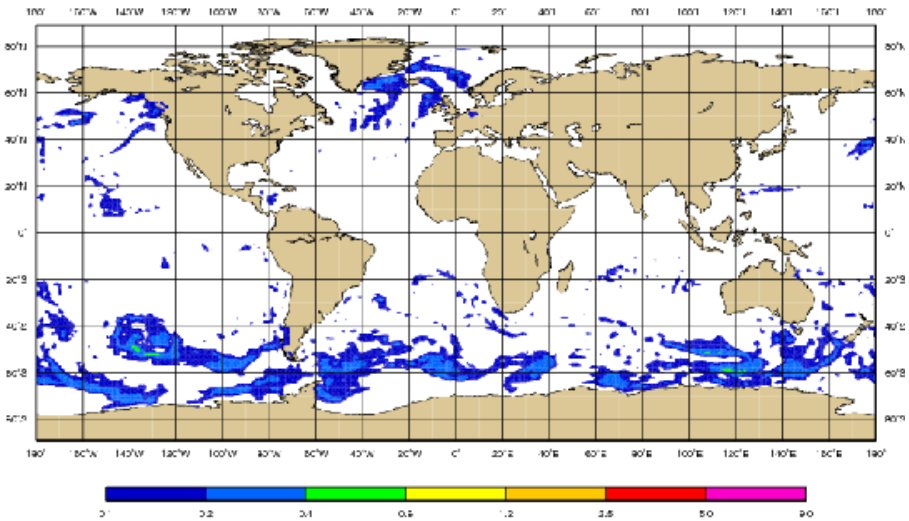
SeaSalt Aerosol Optical Depth at 550nm



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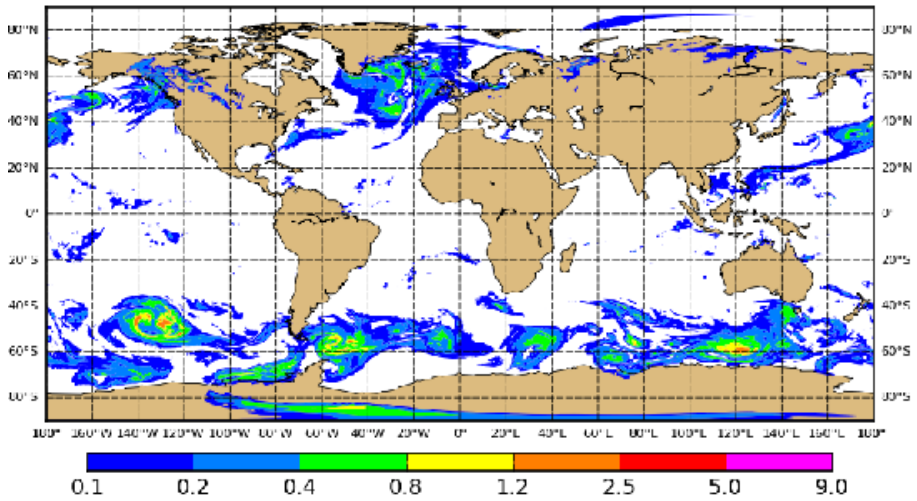

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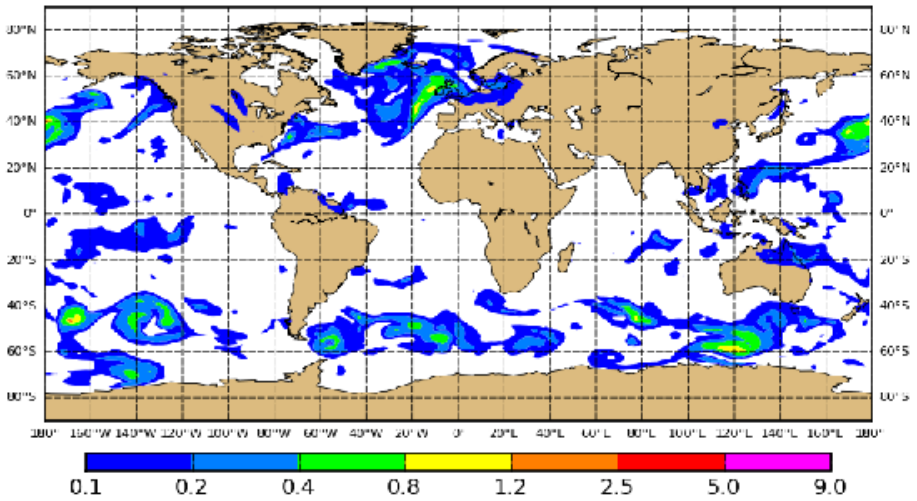

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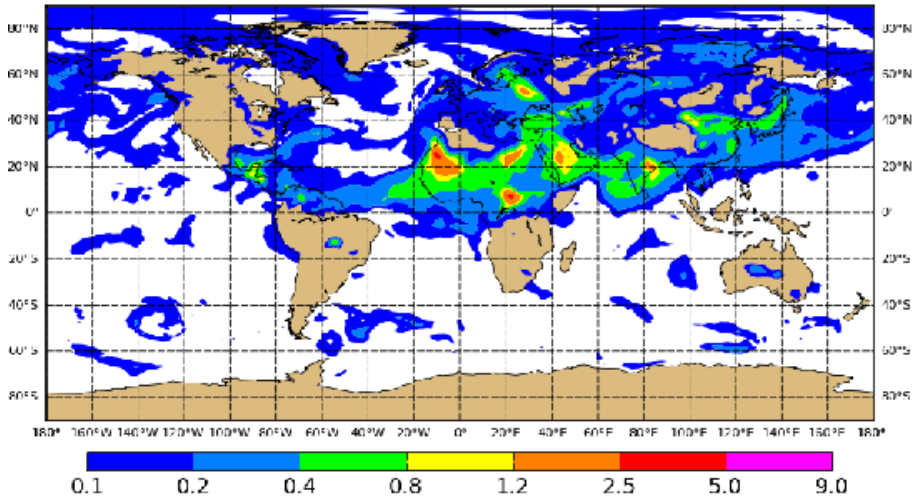
Friday 1 April 2011 06UTC Valid Time
Total Aerosol Optical Depth at 550nm



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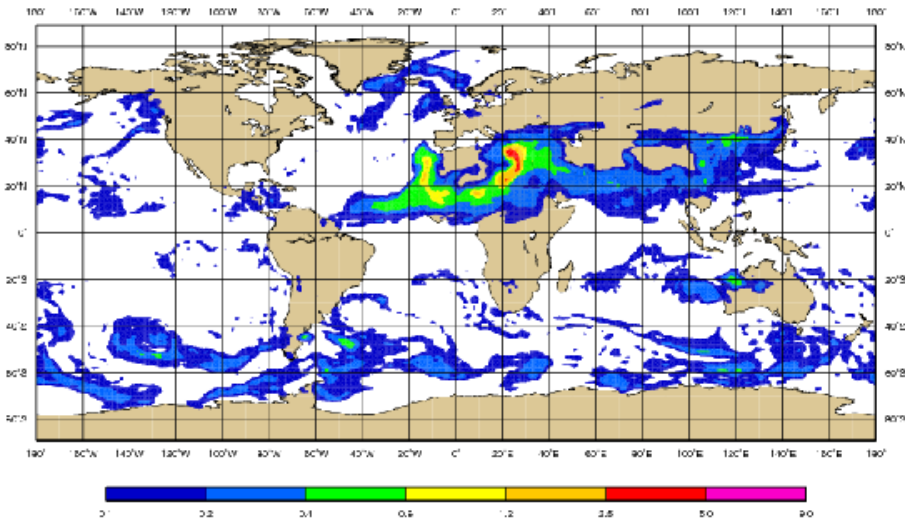
Friday 01 April 2011 00UTC MASINGAR Forecast t+006 VT: Friday 01 April 2011 00UTC
Total Aerosol Optical Depth at 550nm



MRI/JMA MASINGAR

Total

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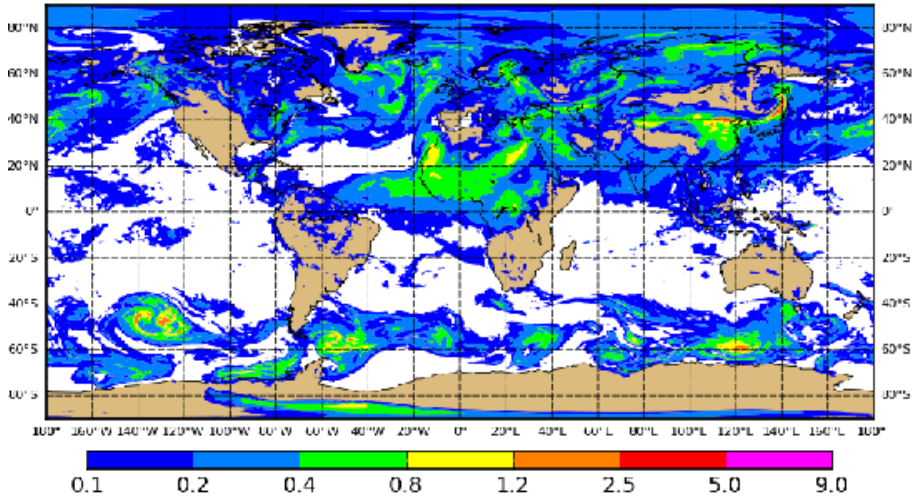

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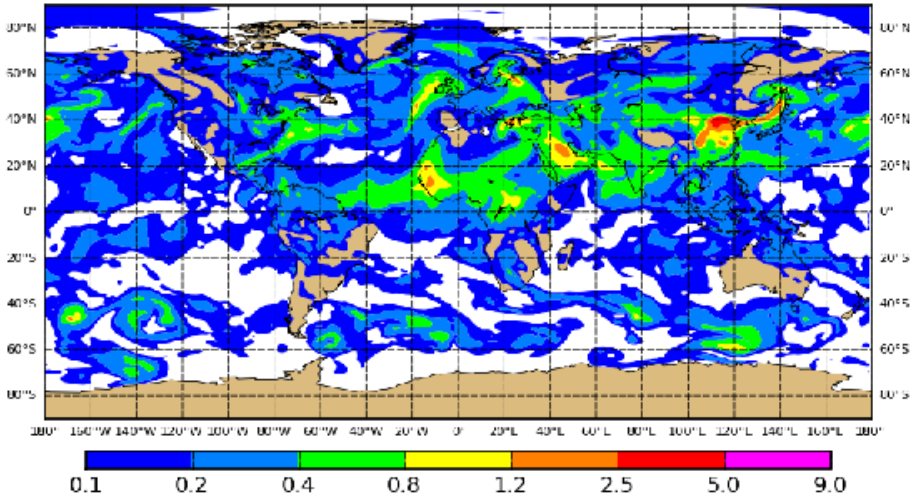

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