Adjoint data assimilation of black carbon during ACE-ASIA

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Outline

Objective: Investigate the applicability of adjoint data assimilation with real-world data.

- Background
  - Adjoint analysis
  - STEM-III application in ACE-ASIA
- Results
  - Black carbon adjoints and gradients
  - Assimilation results
    - Concentrations
    - Scaled parameters
- Summary, conclusions, and future work

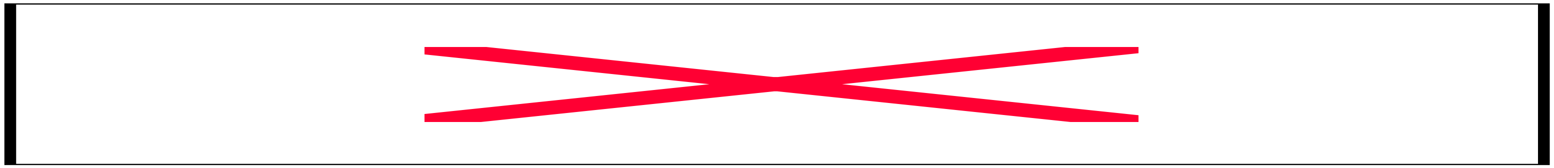
Background

Forward/backward sensitivity analysis

Complementary methods for sensitivity analysis

- Forward (direct) sensitivity analysis: Propagating a perturbation from its source (emission, initial or boundary condition, etc.) forward in time and space

- Backward (adjoint) sensitivity analysis: Propagating a perturbation from its receptor (or receptors) backward in time and space

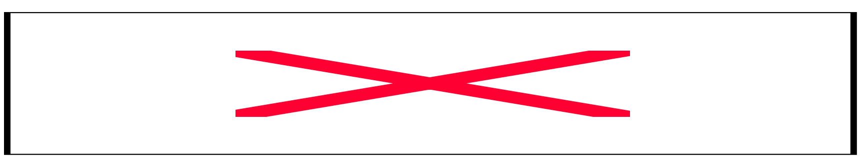


Adjoint formulation

- Forward and adjoint equations (Sandu *et al.*, in preparation; Vukicevic *et al*., 2000; Vautard *et al*., 2000; *Elbern et al*., 2000; Sandu *et al.*, 2003) for the transport of the non-reactive black carbon:

$$\frac{\partial C}{\partial t} = -\nabla \cdot (\mathbf{u}C) + \nabla \cdot (\mathbf{K}\nabla C) + E$$

$$\begin{cases} C(x,0) = C^0(x) & \Leftarrow \quad (\mathrm{t}=0) \\ C(x^b,t) = C^b(x^b,t) & \Leftarrow \quad (\mathrm{Inflow}) \\ K\dfrac{\partial C}{\partial z} = v_d C - E_0 & \Leftarrow \quad (\mathrm{z}=0) \end{cases}$$



$$\begin{cases} \lambda(x,T_{end}) = 0 & \Leftarrow \quad (\mathrm{t}=\mathrm{T}_{end}) \\ \lambda(x^b,t) = 0 & \Leftarrow \quad (\mathrm{Inflow}) \\ K\dfrac{\partial \lambda}{\partial z} = v_d \lambda & \Leftarrow \quad (\mathrm{z}=0) \end{cases}$$

Adjoint formulation (cont'd)

$$\delta J = \int\limits_{x,t=0} \lambda C^0 \delta\varepsilon^0 + \iint\limits_{x^b,t} \mathbf{u}\lambda C^b \delta\varepsilon^b + \iint\limits_{x,t,z=0} \lambda E^0 \delta\varepsilon_{E^0} + \iint\limits_{x,t} \lambda E \delta\varepsilon_E$$

In discrete form:

$$\frac{\partial J}{\partial \varepsilon^0}(x,0) = \lambda(x,0)C^0(x)$$

$$\frac{\partial J}{\partial \varepsilon_{E^0}}(x,t) = \sum_{x,z=0}\sum_t \frac{\lambda(x,t)E^0(x,t)}{\Delta z}\Delta t$$

$$\frac{\partial J}{\partial \varepsilon_E}(x,t) = \sum_x \sum_t \frac{\lambda(x,t)E(x,t)}{\Delta z}\Delta t$$

$$\frac{\partial J}{\partial \varepsilon^b}(x^b,t) = \sum_{x^b}\sum_t \left[\left(\frac{\mathbf{u}(x^{b1},t)}{\Delta x} + \frac{\mathbf{K}(x^{b1},t)}{\Delta x^2}\right)\lambda(x^{b1},t) + \left(\frac{\mathbf{u}(x^{b2},t)}{6\Delta x}\right)\lambda(x^{b2},t)\right]\Delta t$$

STEM-III and modeling domain

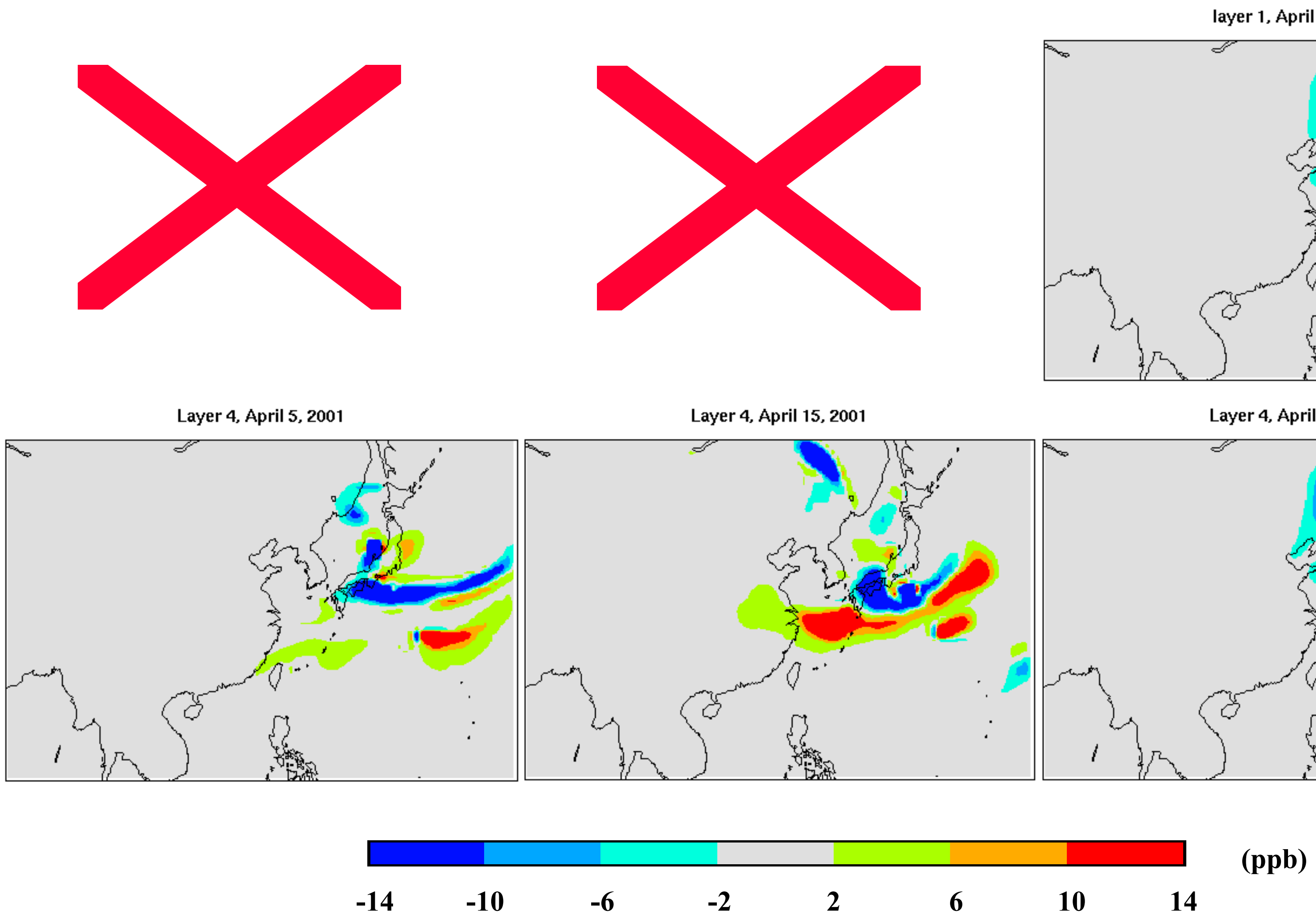
- Regional scale model; previously applied to the ACE-ASIA domain (Carmichael *et al.*, 2003)
- 90x60 grid cells and 18 vertical layers
- Month of April, 2001
- The inventory for the anthropogenic (hourly) and biomass burning (daily) black carbon emissions is similar to that used in Carmichael *et al.*, 2003

Assimilation experiment

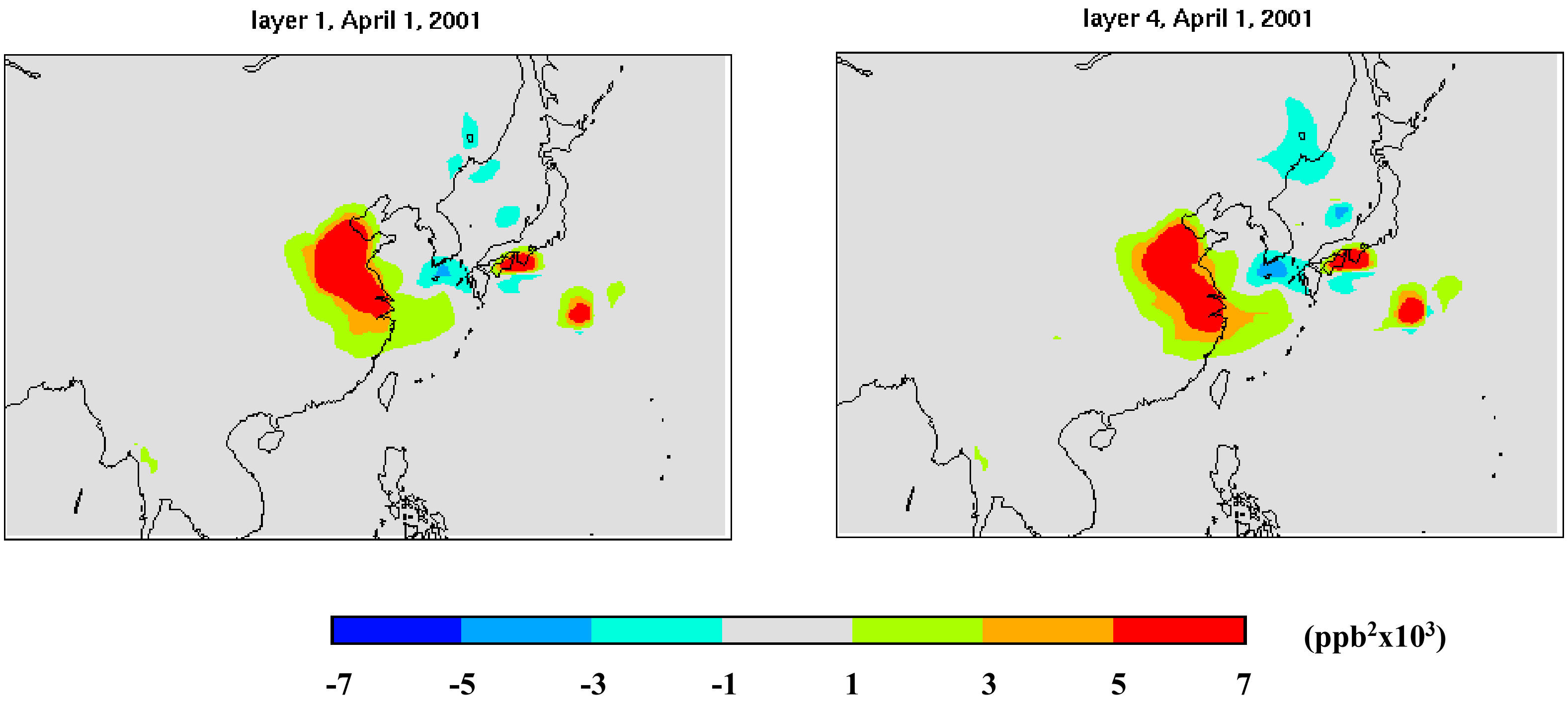
- Black carbon mass measurements at 4 Japanese Islands are assimilated. The measurements are made every 4 hours, and provide ~680 data points.
  - No chemistry
  - Assimilation window is one month
- Emissions (biomass burning and other anthropogenic emissions), initial and boundary conditions are scaled .
- No a-priori information (about the scaled parameters) is included in the cost function.
- For each parameter, grid cells/days are scaled in groups (of 500) based on their daily gradient.
- Because of dynamic grouping, Newton’s method is not applicable for the optimization.

Results

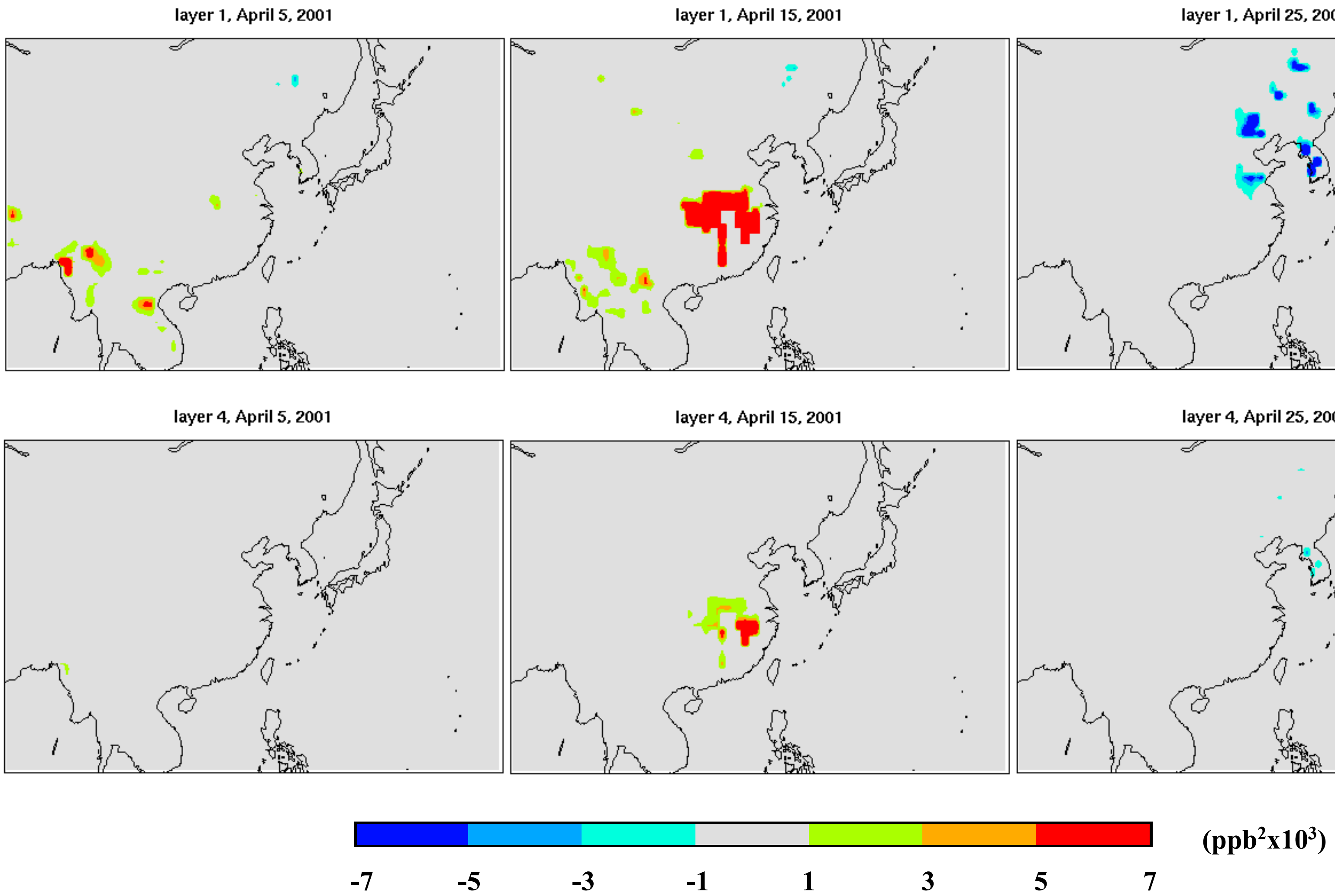
Adjoints and regions of influence



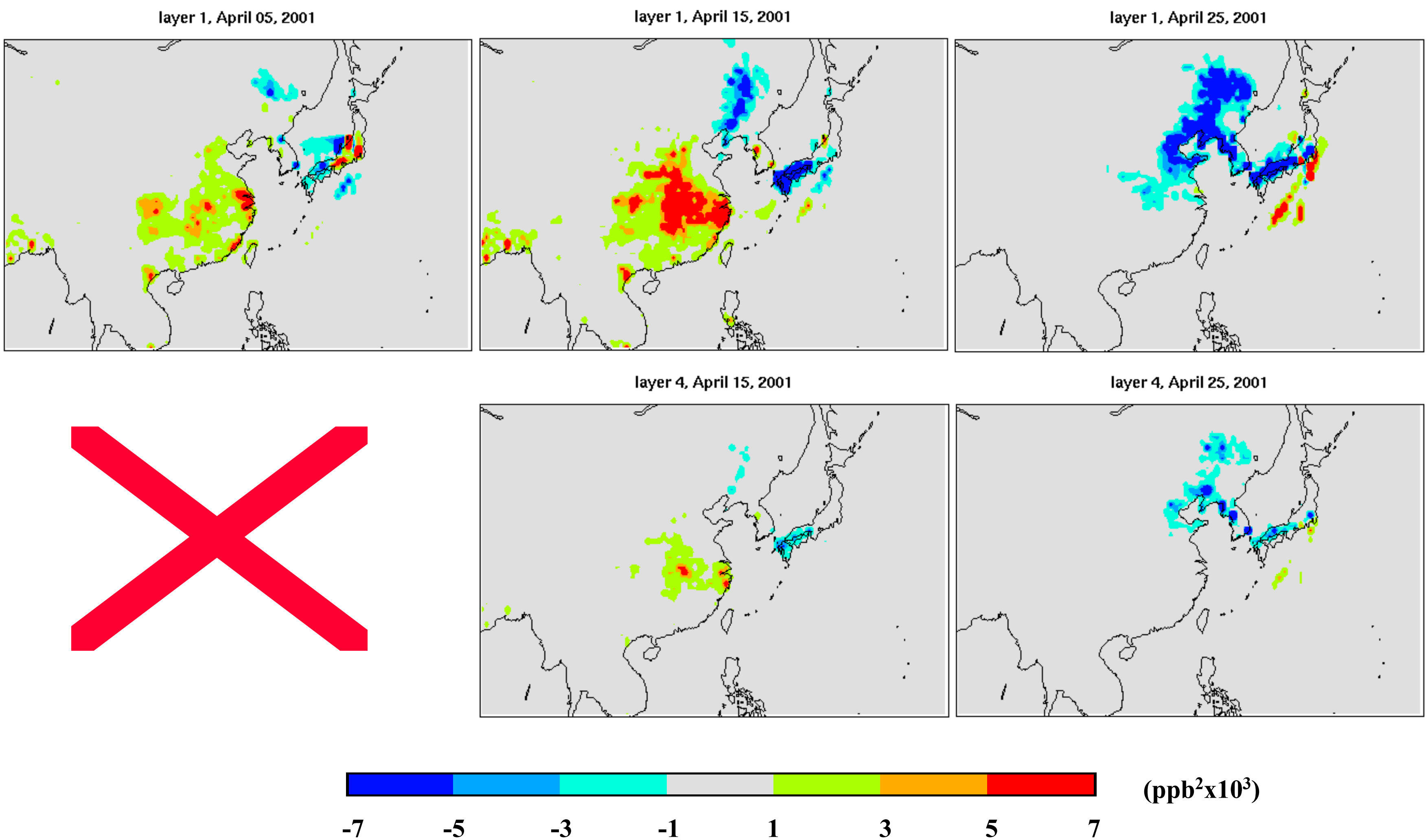
Daily gradients: initial conditions



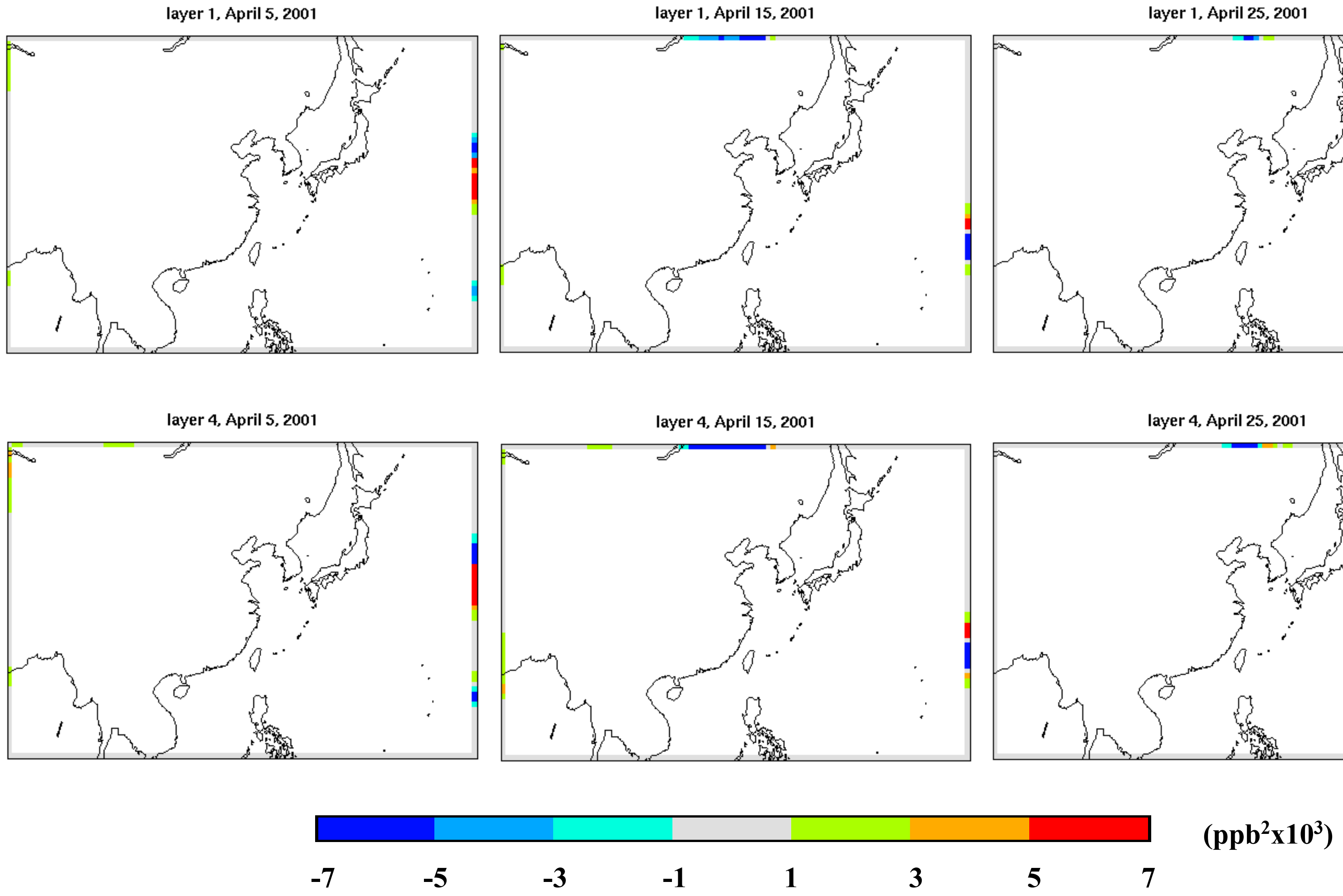
Daily gradients: biomass burning



Daily gradients: anthropogenic emissions

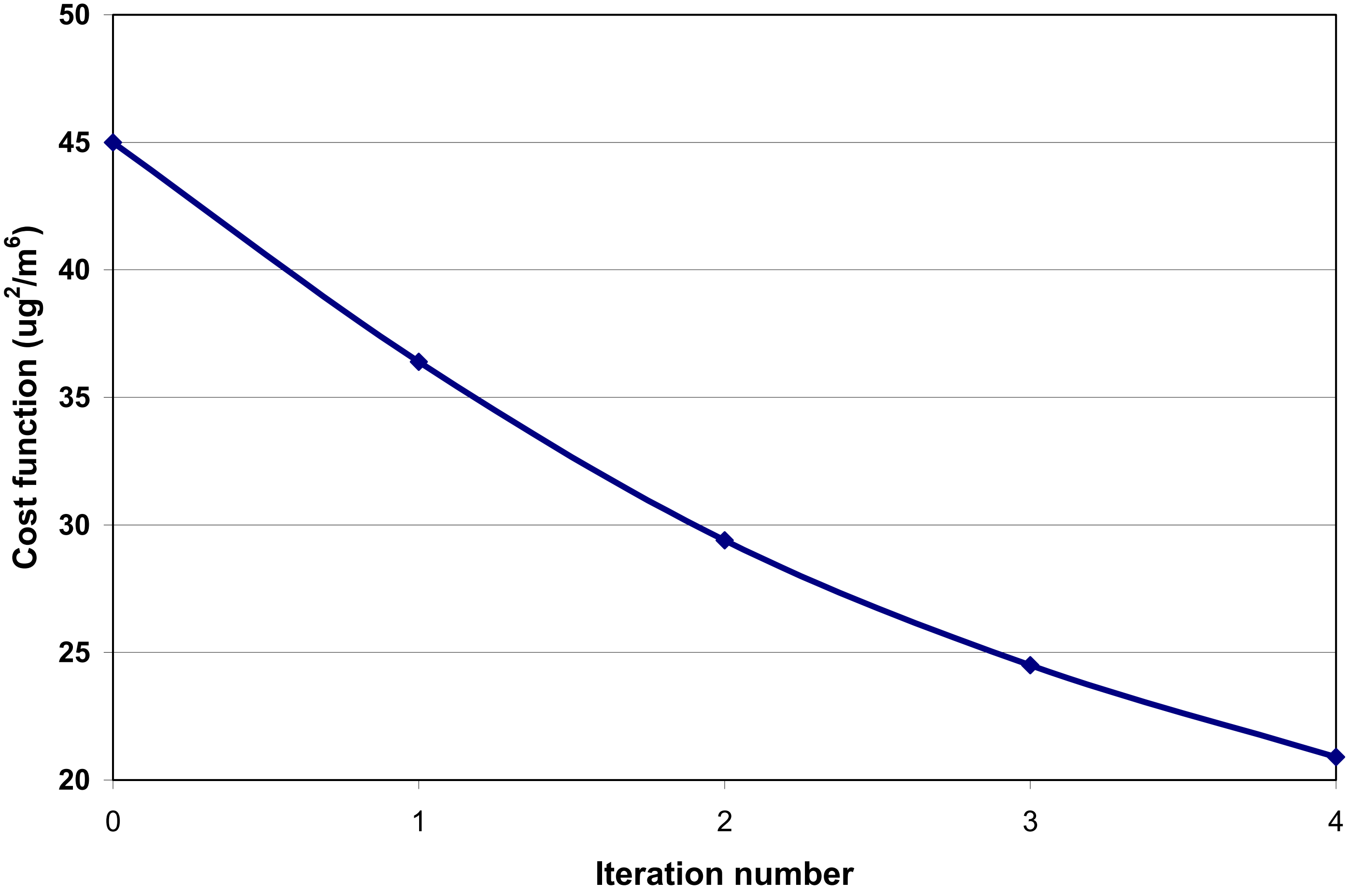


Daily gradients: boundary conditions

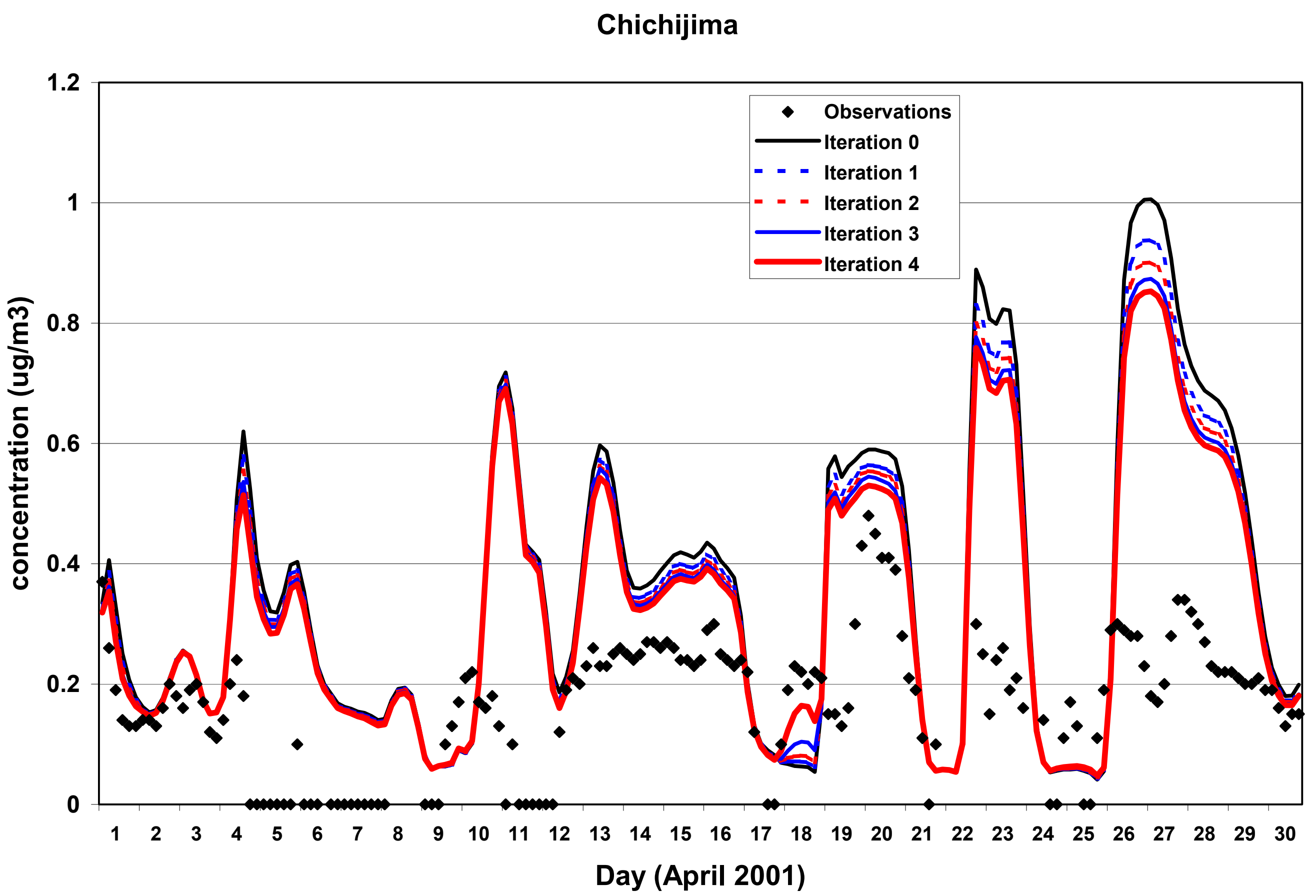


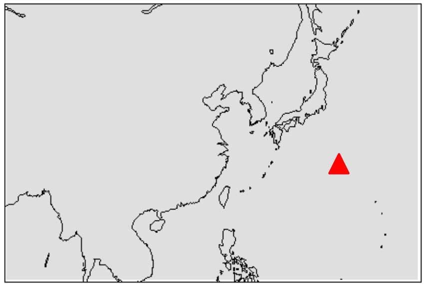
Daily gradients: distributions

Cost function reduction

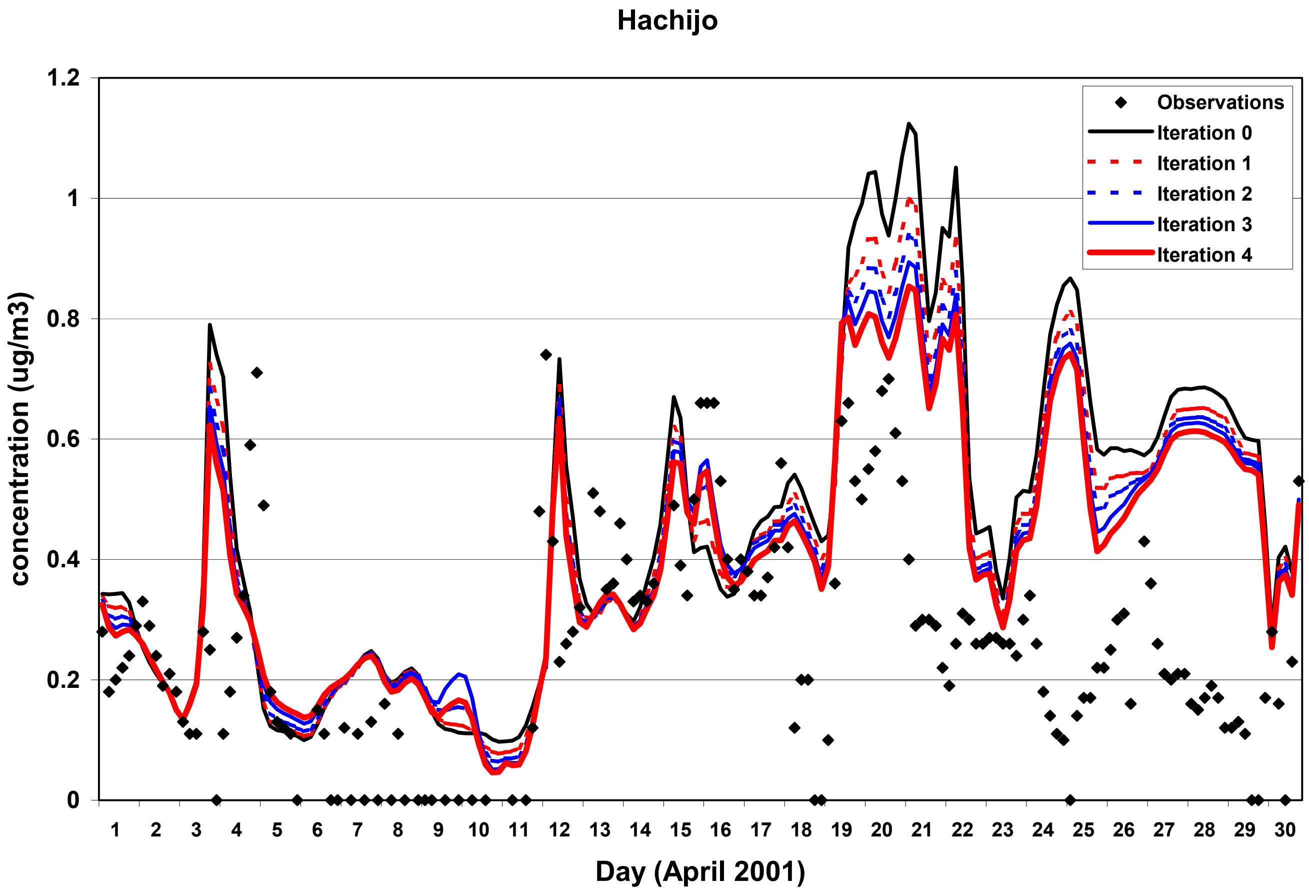


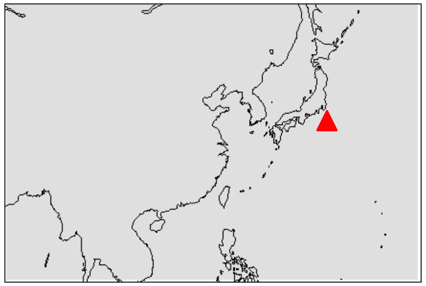
Time series: Chichijima



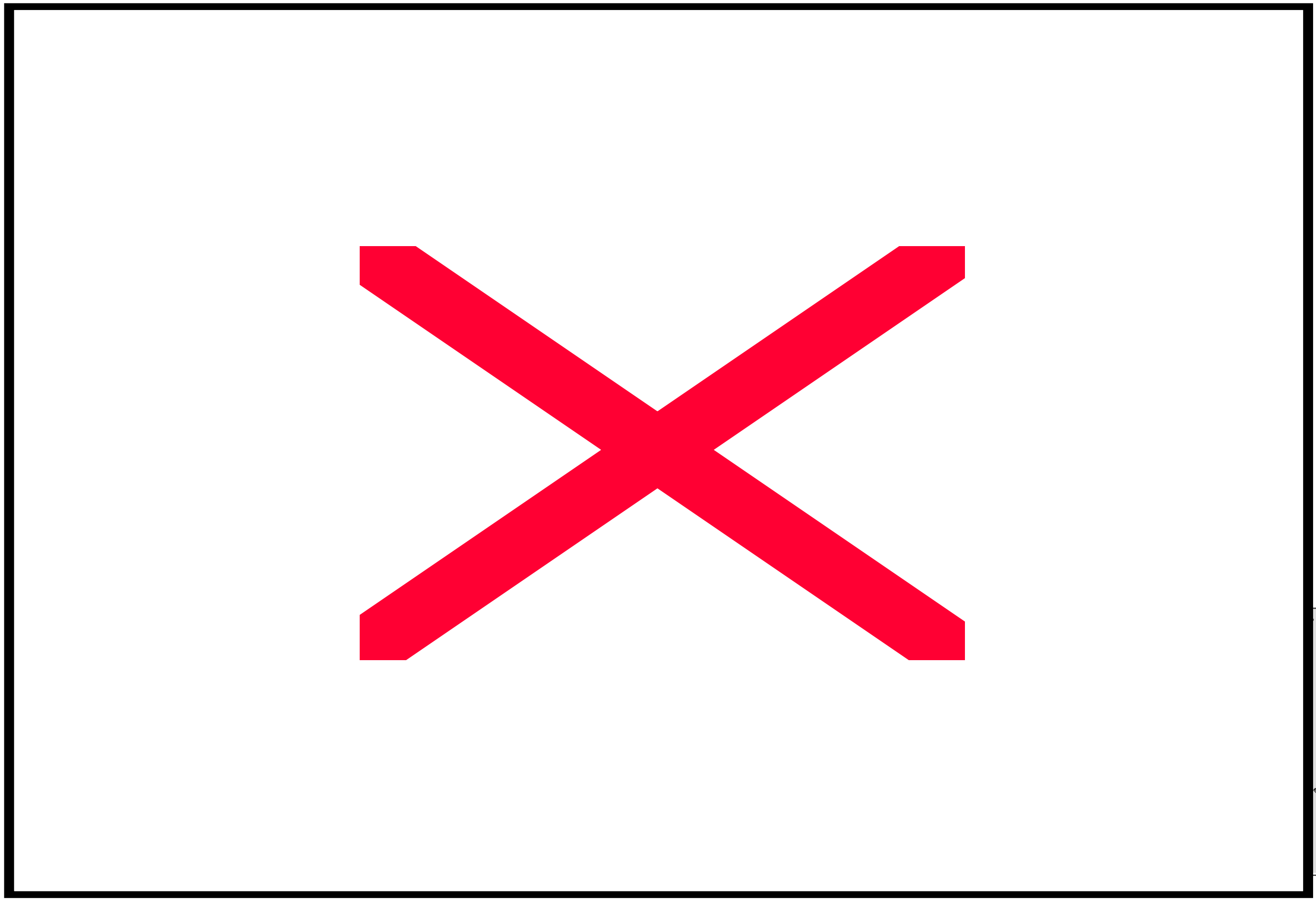


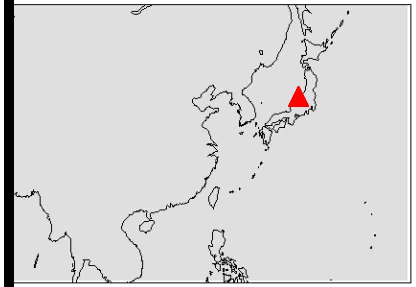
Time series: Hachijo



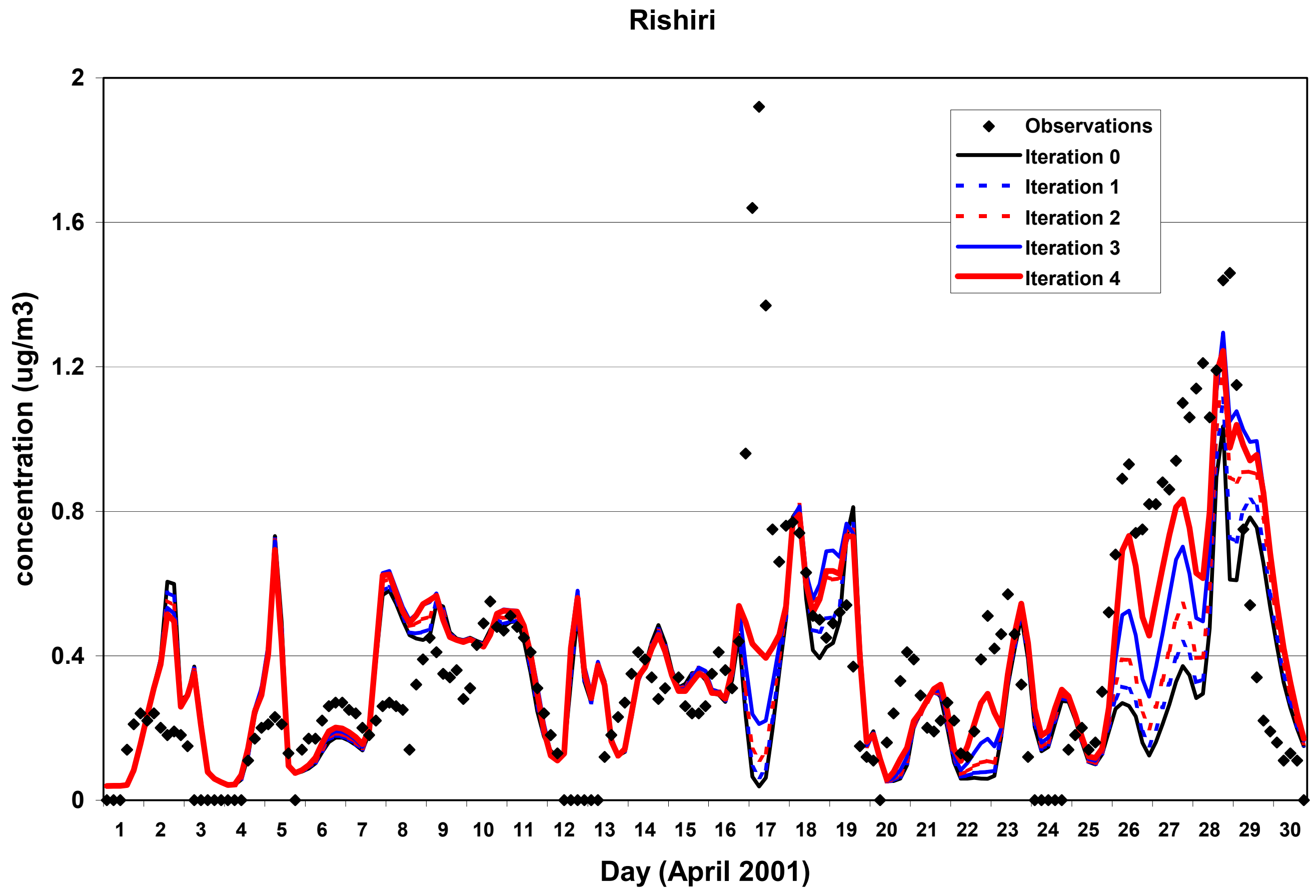


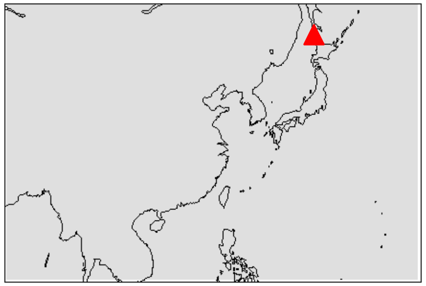
Time series: Sado





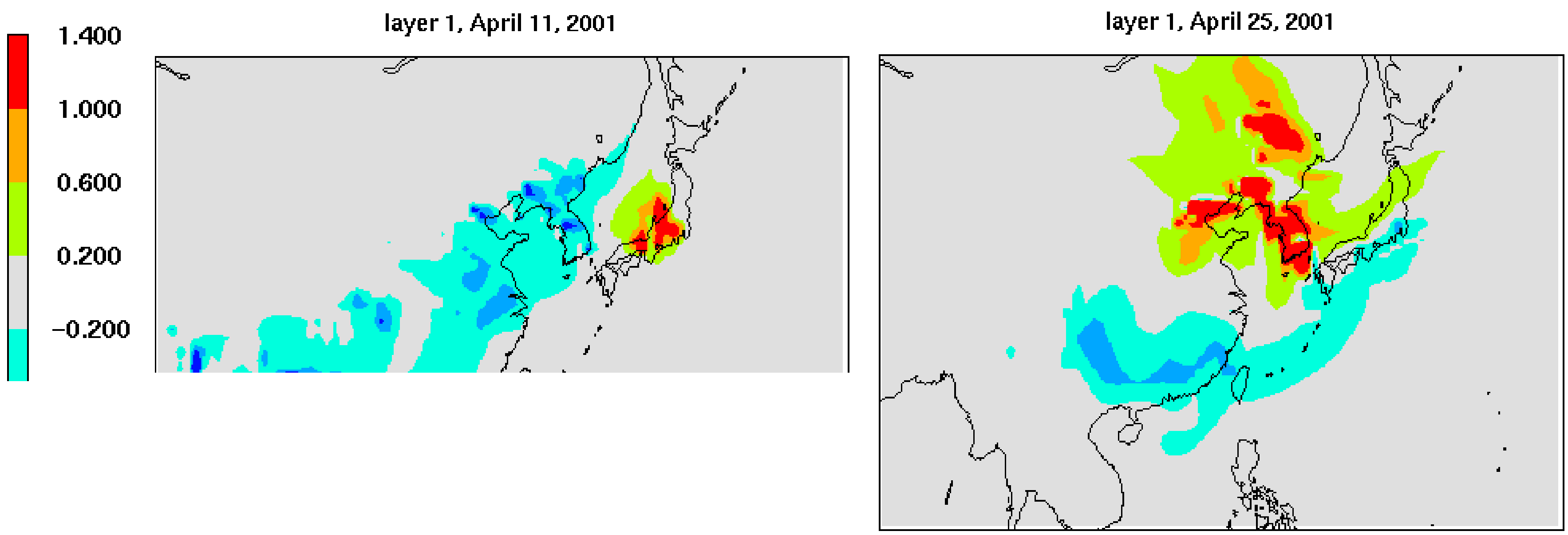
Time series: Rishiri



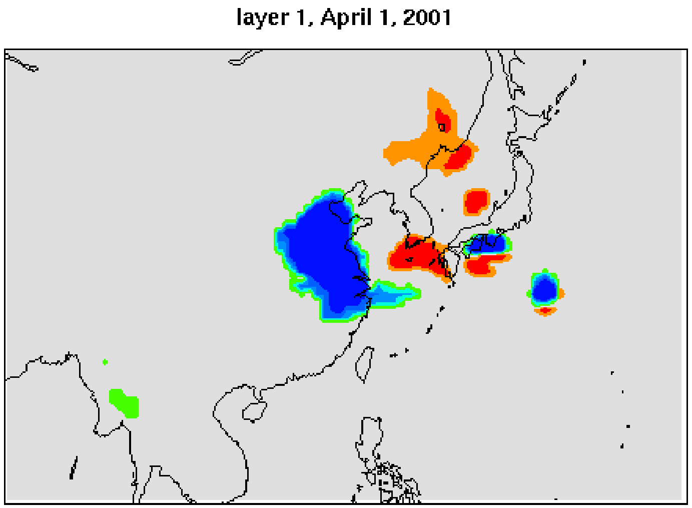


Scaled vs. original concentrations

Scaled - Original



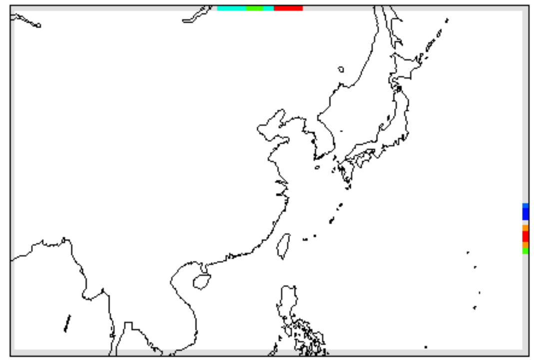
Final scaling: initial conditions



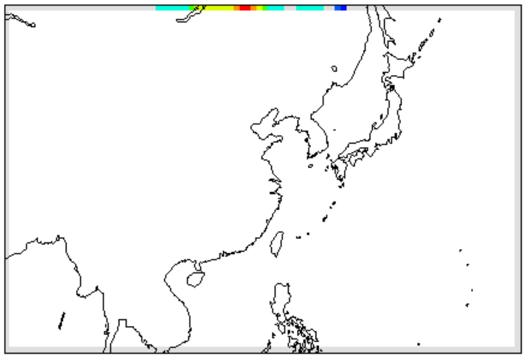
Final scaling: boundary conditions

layer 1, April 8, 2001

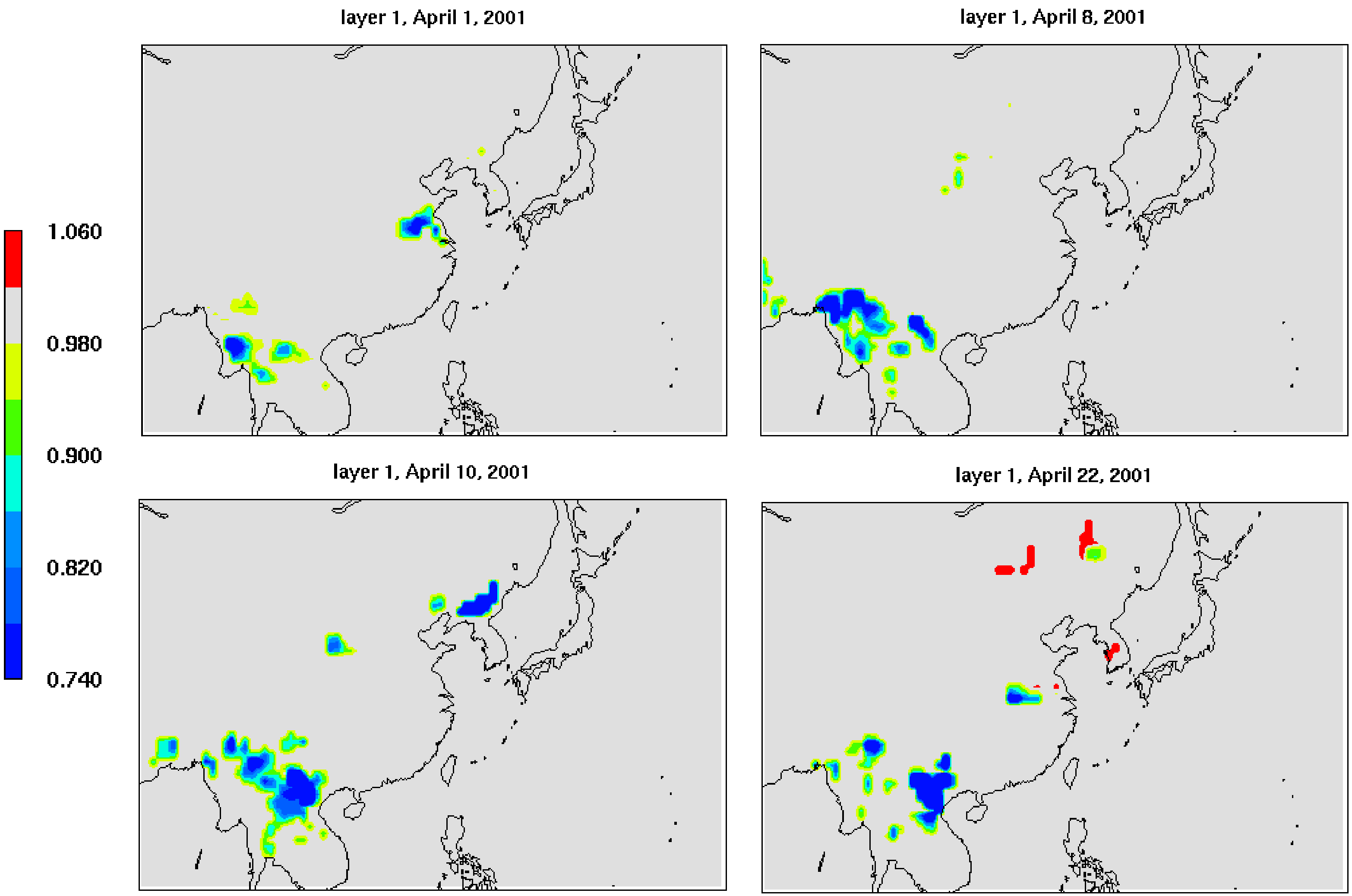
layer 1, April 15, 2001



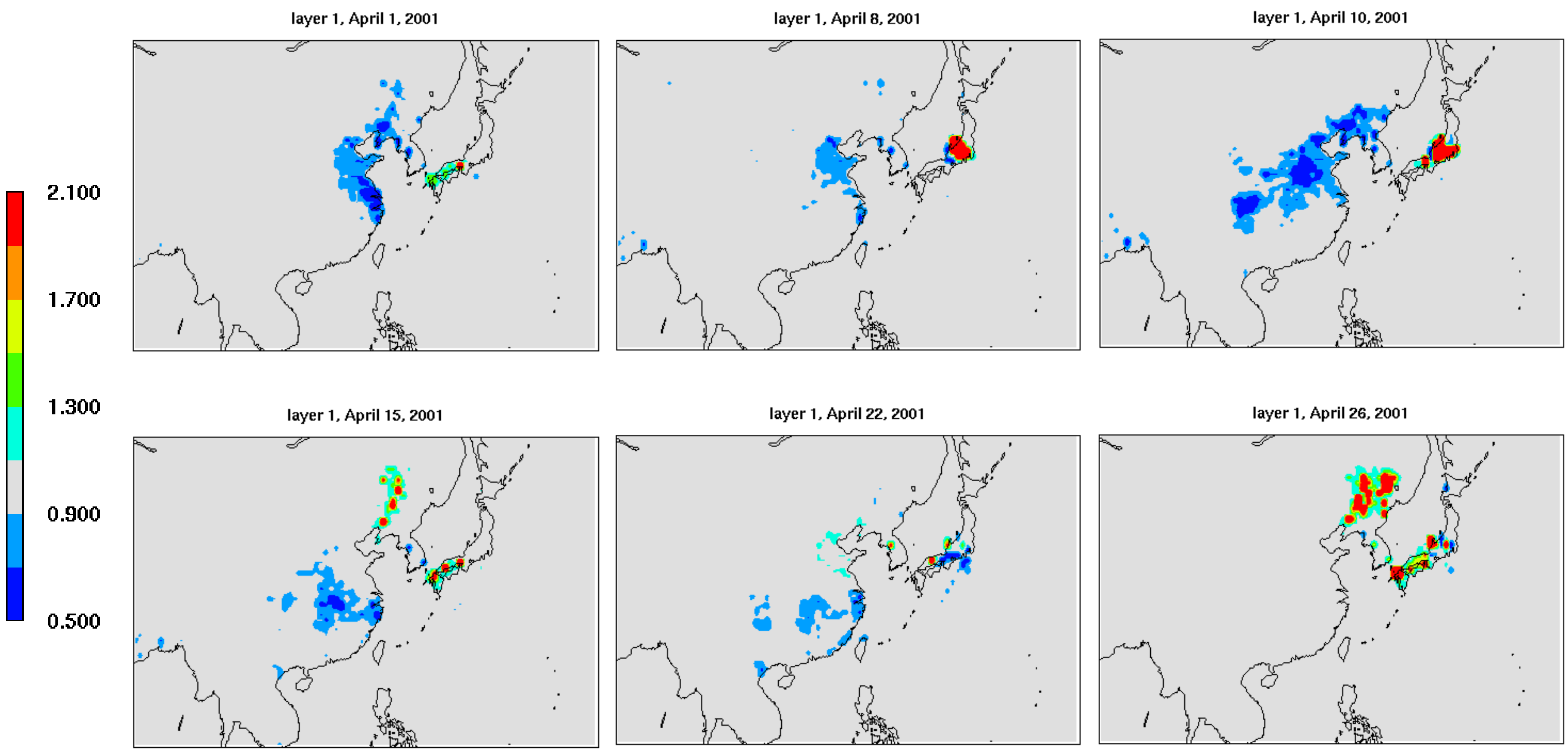
layer 1, April 22, 2001



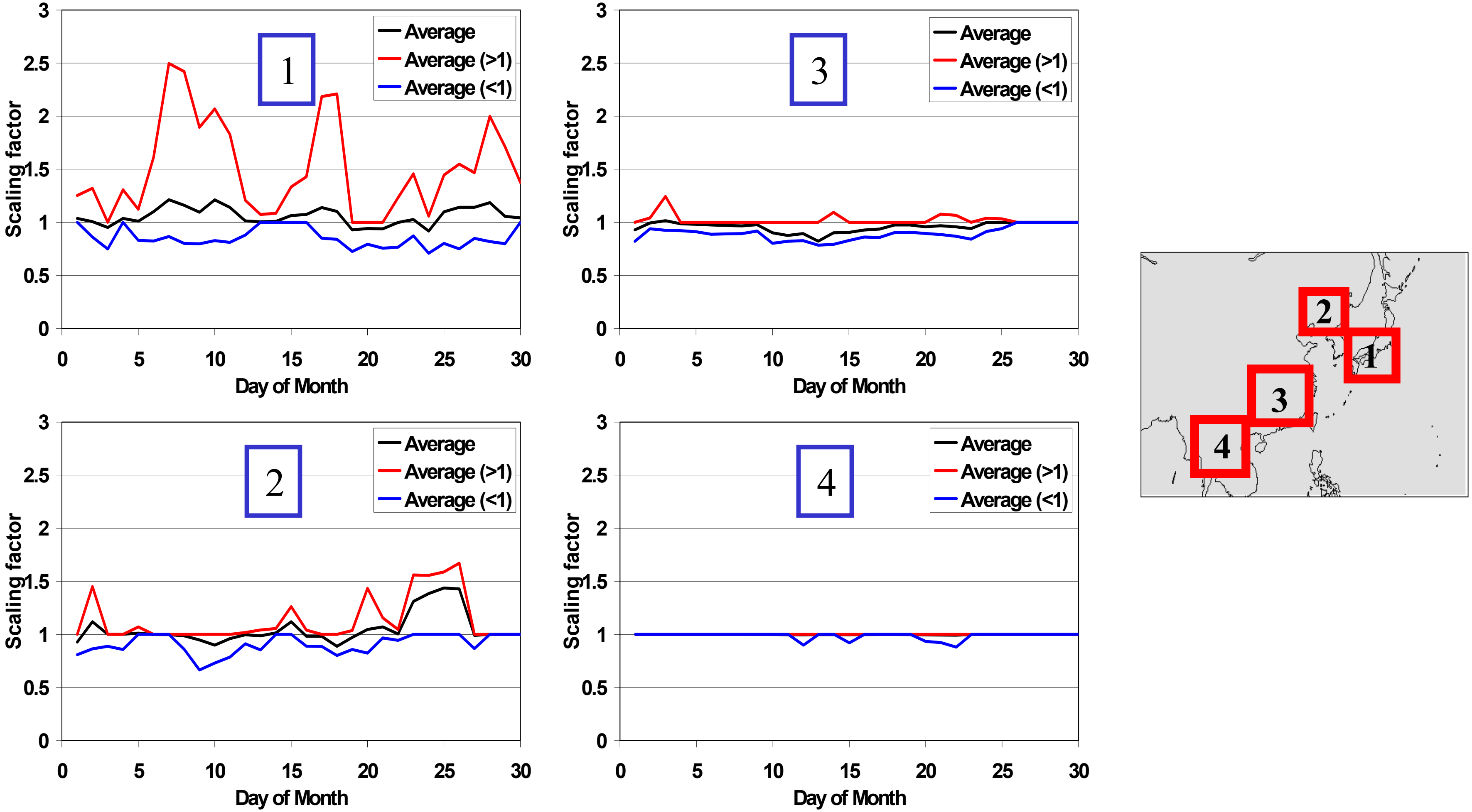
Final scaling: biomass burning



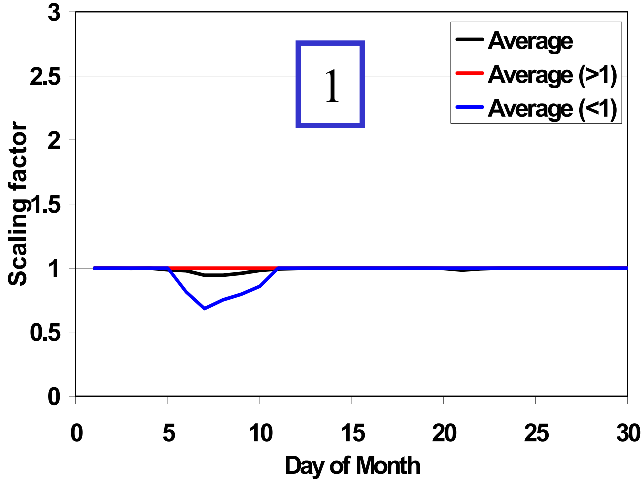
Final scaling: anthropogenic emissions

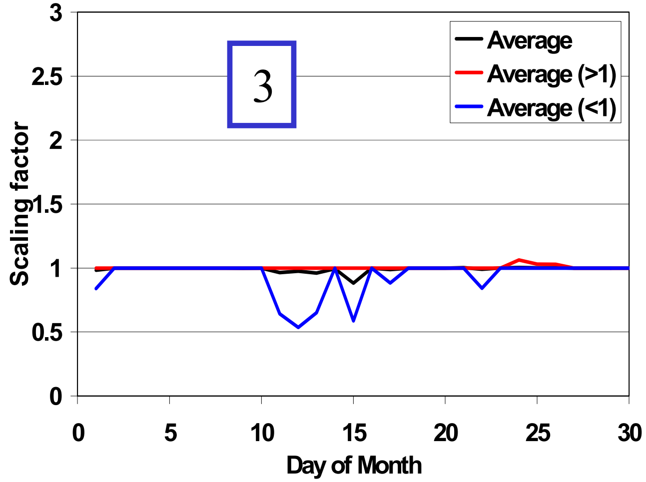


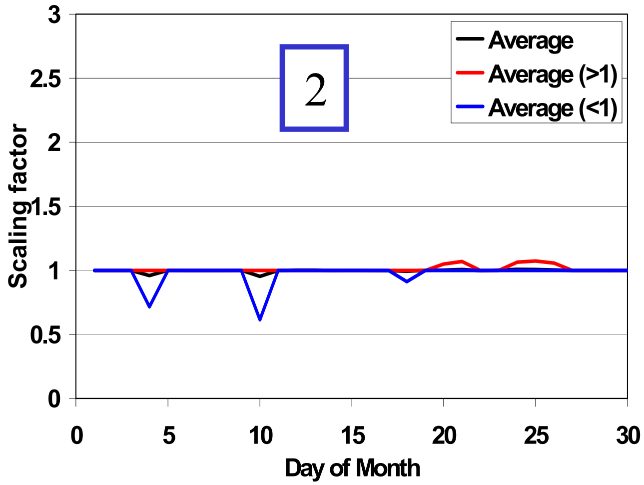
Regional scaling factors: anthropogenic emissions

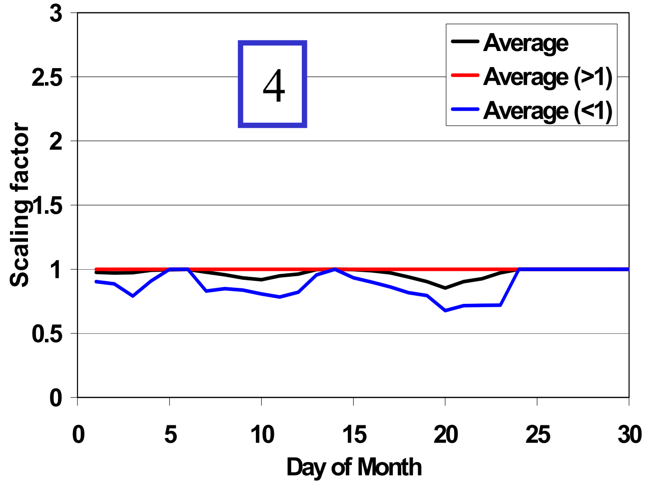


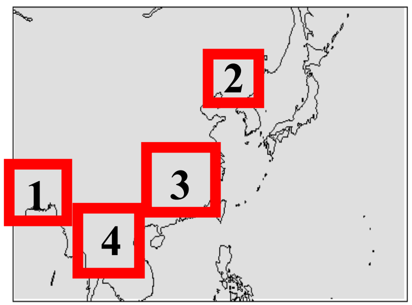
Regional scaling factors: biomass burning



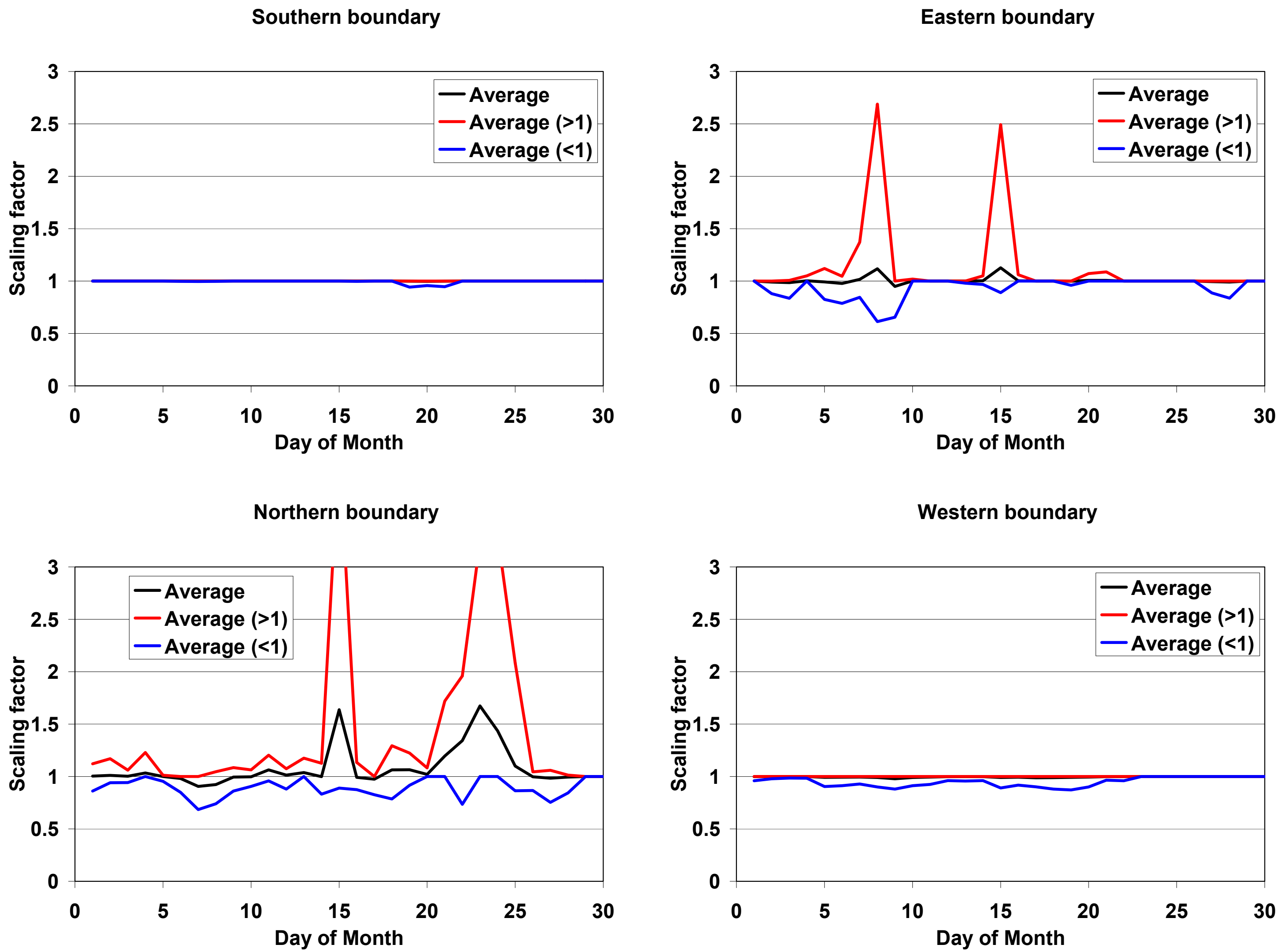








Regional scaling factors: boundary conditions



Summary

- Assimilation is fairly successful as the cost function is reduced by ~55% (32% reduction in RMSE).
- For assimilation, the grid cells and days are grouped based on their daily gradients.
- Anthropogenic emissions are the main factor affecting the cost function. Those emissions are scaled (mostly down-scaled; 0.4-4.0) primarily in the first layer, and both locally and over the long range.
- Biomass emissions are primarily down-scaled (0.5-1.1) over the region and in the first layer.
- Boundary conditions (inflow) are scaled (0.4-9.0) more aggressively in layers 3-7.

Conclusions

- Adjoint analysis provides a robust method for data assimilation. 4-D data assimilation is inherently expensive, however, our application is relatively inexpensive as it involves a non-reactive species and linear processes.

- Adjoint results provide unique insight into the temporal and spatial distribution of the regions of influence.

- Limited data readily translates into limited success for the assimilation. The Japanese stations are well located to monitor mid- to long-range transport, however, more data is needed for such a vast domain.

- These results indicate (uncertainties notwithstanding) that for much of the month, biomass burning is overestimated.

(Not very distant) Future work

- Incorporate more data (suggestions?)
  - In the assimilation
  - In the analysis of the assimilated concentrations (if the data are deemed not quite suitable for use in the assimilation)
- Other parameters/processes to scale; primarily wet removal
- Add a-priori information to the cost function
- Work on the optimization (suggestions?)
  - How to compensate for the loss of 2^{nd} order information in Newton's method?
  - Other scaling options?

Possible future work (more distant)?

- Inverse modeling of summer 2004 ICARTT aerosol (sulfate, BC, and OC) and gas-phase data based on a regional model for the northeast U.S. (CMAQ?)