Inverse modeling of long-term CO emission in China with Green's function method and forward sensitivity

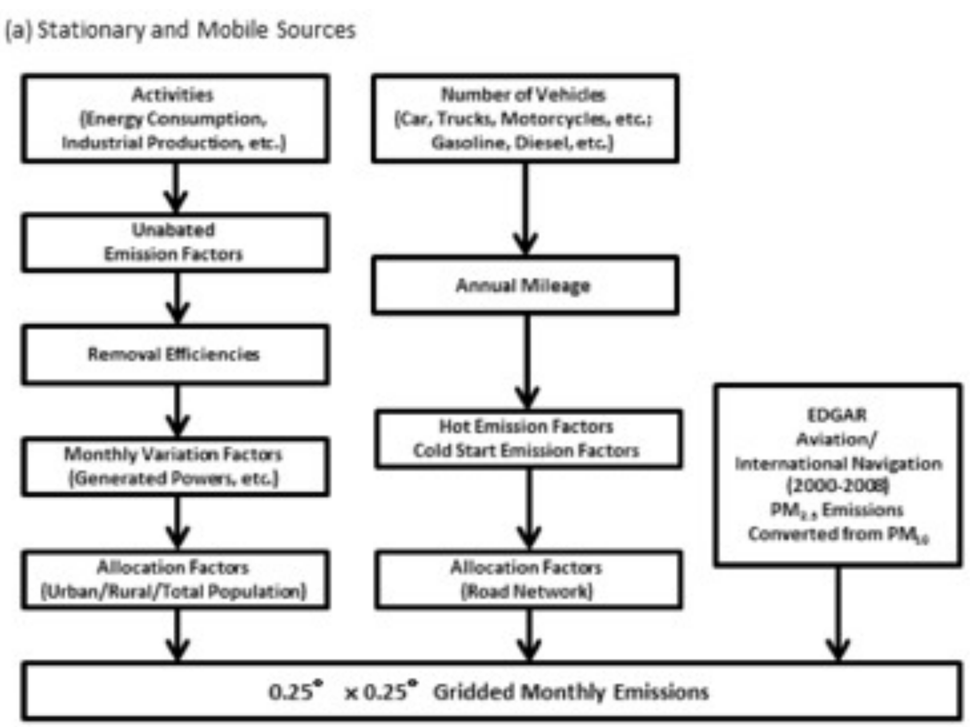
Keiya YUMIMOTO

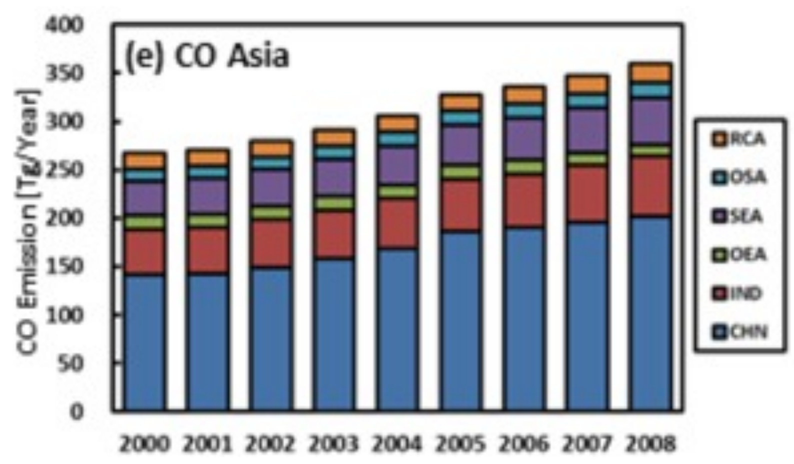
Meteorological Research Institute (MRI), Japan Meteorological Agency, Japan

Itsushi UNO

Research Institute for Applied Mechanics, Kyushu University, Japan

1. Introduction





Kurokawa et al. 2013

Emission Inventory

INPUT

CTM

statistics and emission factors etc.

events and time variations
(biomass burning and socioeconomic conditions etc.)

Uncertainties
±70% (CO), ±31% (NOx), ±208% (BC), ±258% (OC)
Zhang et al. 2009

Inverse Estimate
(Top-down)

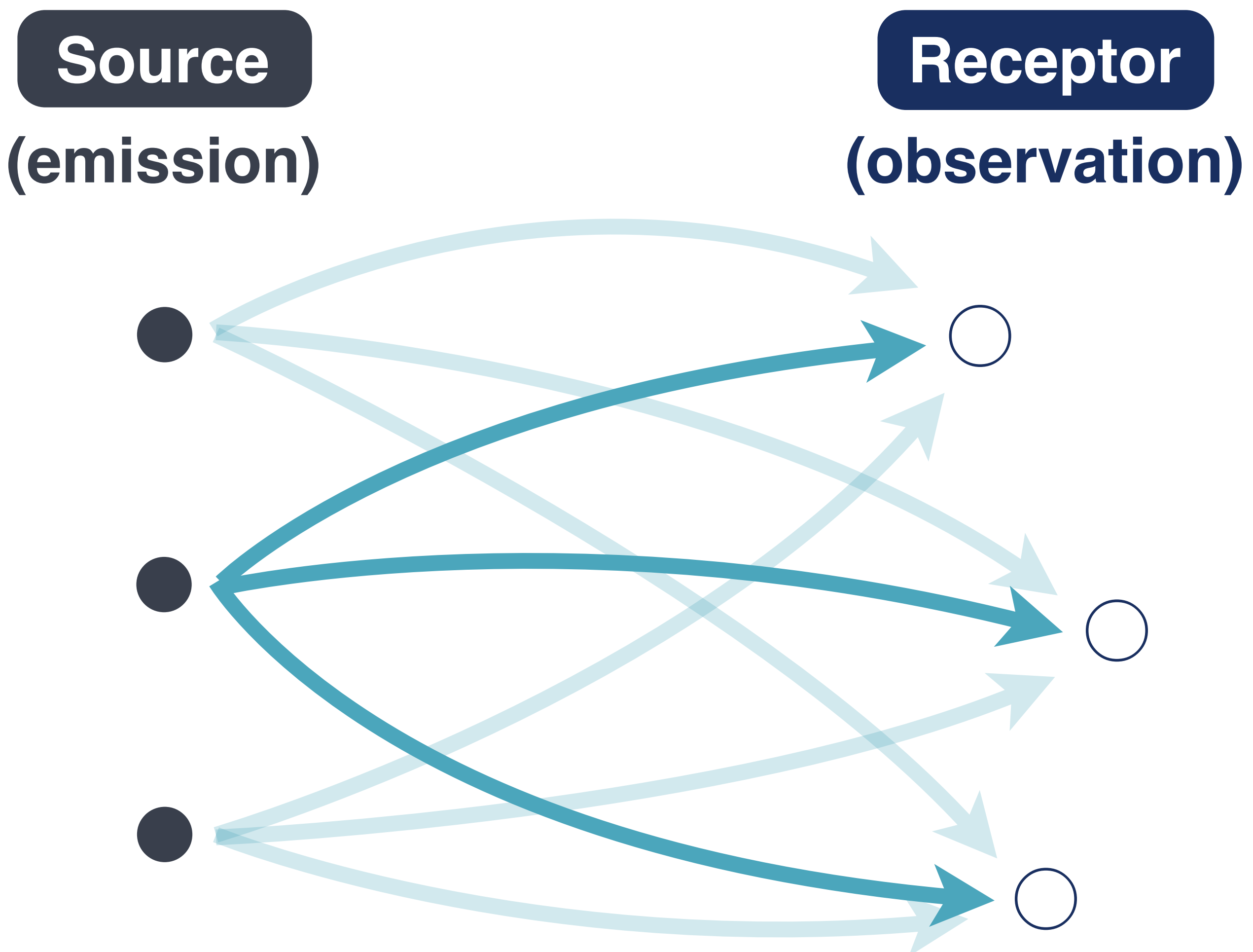
- interactive
  (with observations and model)
- compensating

2. Inversion Methods

Species	**CO**	**CO2**	**NOx** / **Methane** / **aerosols**
Spacial Resolution	**regional** *Heald et al., 2004* *Fotems-Cheiney et al., 2011* *Arellano et al., 2004*	**gridded** *Yumimoto and Uno, 2006* *Stabrakou and Müller, 2006* *Kopacz et al., 2010*	*Tanimoto et al., 2008*
Time Period	**month** *Yumimoto and Uno, 2006* *Tanimoto et al., 2008* *Wang et al., 2004*	**year** *Stabrakou and Müller, 2006* *Kopacz et al., 2010* *Arellano et al., 2004*	**years** *Fotems-Cheiney et al., 2011*
(Time Resolution)	**monthly**	**daily**	**diurnal**
Observation	**in-situ** *Yumimoto and Uno, 2006* *Tanimoto et al., 2008*	**air craft** *Wang et al., 2004*	**satellite** *Stabrakou and Müller, 2006* *Kopacz et al., 2010* *Arellano et al., 2004* *Fotems-Cheiney et al., 2011*
Method	**Forward** *Wang et al., 2004* *Arellano et al., 2004* *Heald et al., 2004*	**Adjoint (Backward)** *Yumimoto and Uno, 2006* *Tanimoto et al., 2008*	*Stabrakou and Müller, 2006* *Kopacz et al., 2010* *Fotems-Cheiney et al., 2011*

2. Inversion Methods

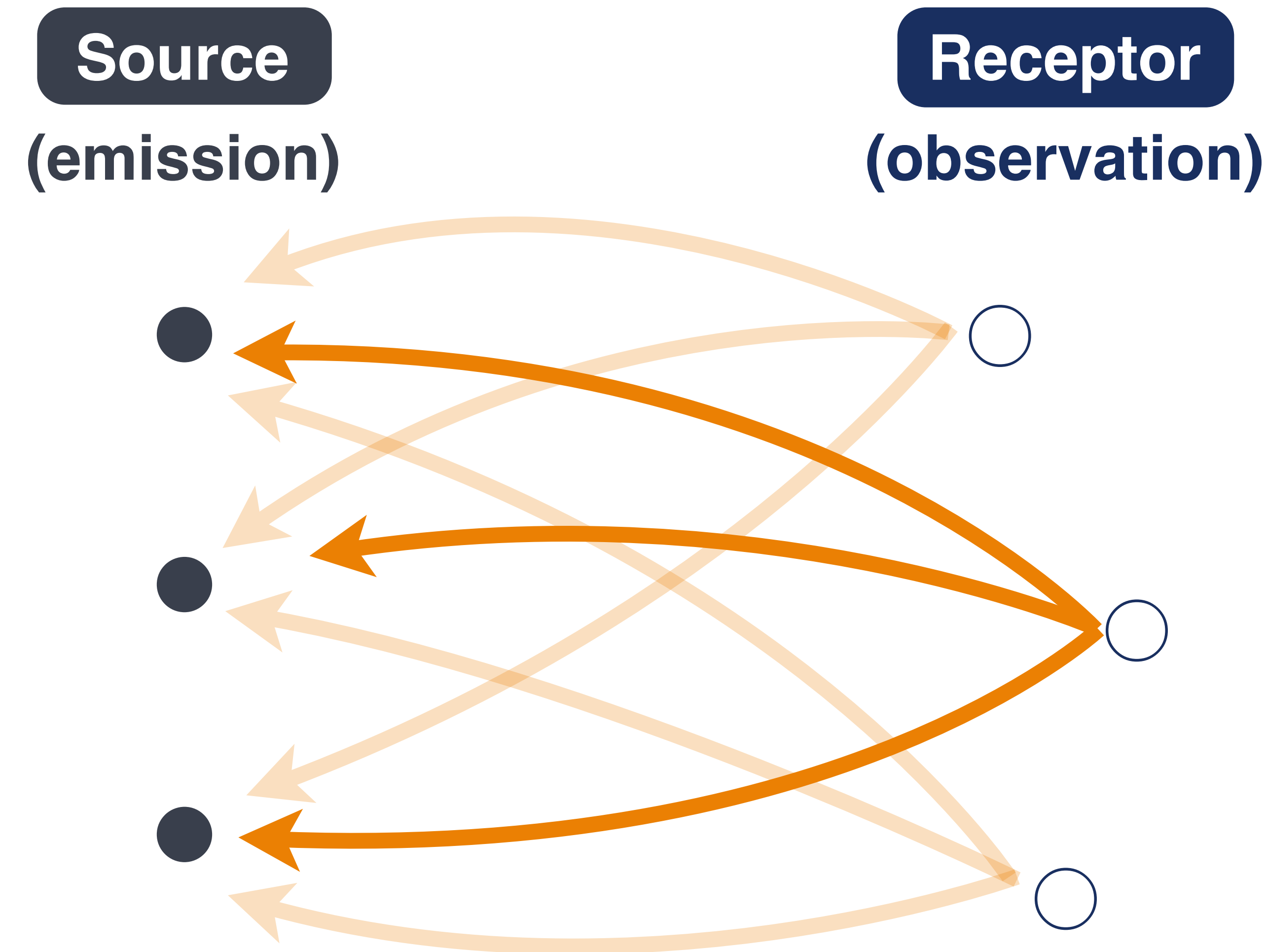
Forward



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

※We need ‘ensemble’ simulation for each source.

Adjoint (Backward)



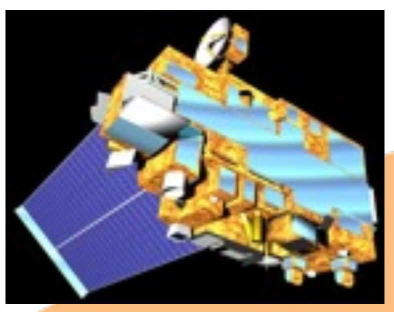
Backward method calculates sensitivities of receptors (observations) to sources (emissions).

※We need adjoint of the forward model.

2. Inversion Methods

- **In this study...**

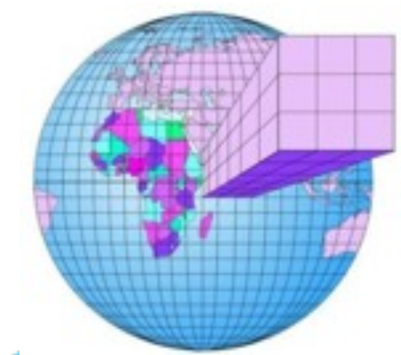
Green's Function method



MOPITT/TERRA
CO measurement

Information Constraint

Forward Sensitivity



GEOS-Chem
Chemical Transport Model

Inversely optimized CO emission

- China emission
- Recent 6 years (2005–2010)
- Vertical profiles
- Tagged simulation

2. Inversion Methods

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3. Method (Green's Function Method)

Menemenlis et al., 2005

Yumimoto and Uno., 2012

- **Observation**

$$\mathbf{y}^{o} = H_{i}[\mathbf{x}^{t}] + \boldsymbol{\varepsilon} \qquad (1)$$

$\mathbf{y}^{o}$: observation, $\boldsymbol{\varepsilon}$: noise process

- **Model**

$$\mathbf{x}^{t}(t_{i+1}) = M_{i}[\mathbf{x}^{t}(t_{i}), \boldsymbol{\eta}] \qquad (2)$$

$\mathbf{x}^{t}$: true state, $\boldsymbol{\eta}$: control parameter

- **Convolution**

$$\mathbf{y}^{o} = G(\boldsymbol{\eta}) + \boldsymbol{\varepsilon} = G(\mathbf{0}) + \mathbf{G}\boldsymbol{\eta} + \boldsymbol{\varepsilon} \qquad (3)$$

G: convolution of H and M

assuming G is linear

$\mathbf{G}$: Green's function matrix, **forward sensitivity**

jth column vector of $\mathbf{G}$: $$\mathbf{g}_{j} = \frac{G(\mathbf{e}_{j}) - G(\mathbf{0})}{e_{j}}$$

- **miss-fit between observations and model**

$$\mathbf{d} = \mathbf{y}^{o} - G(\mathbf{0}) = \mathbf{G}\boldsymbol{\eta} + \boldsymbol{\varepsilon}$$

3. Method (Green's Function Method)

Menemenlis et al., 2005, MWR

- miss-fit between observations and model

$$\mathbf{d} = \mathbf{y}^o - G(\mathbf{0}) = \mathbf{G}\boldsymbol{\eta} + \boldsymbol{\varepsilon} \qquad (4)$$

- Cost function (to be minimized)

$$J = \boldsymbol{\eta}^T\mathbf{Q}^{-1}\boldsymbol{\eta} + \boldsymbol{\varepsilon}^T\mathbf{R}^{-1}\boldsymbol{\varepsilon} \qquad (5)$$

- Solution

$$\boldsymbol{\eta}^a = (\mathbf{Q} + \mathbf{G}^T\mathbf{R}^{-1}\mathbf{G})^{-1}\mathbf{G}^T\mathbf{R}^{-1}\mathbf{d} \qquad (6)$$

- We set η as scaling factor for emissions

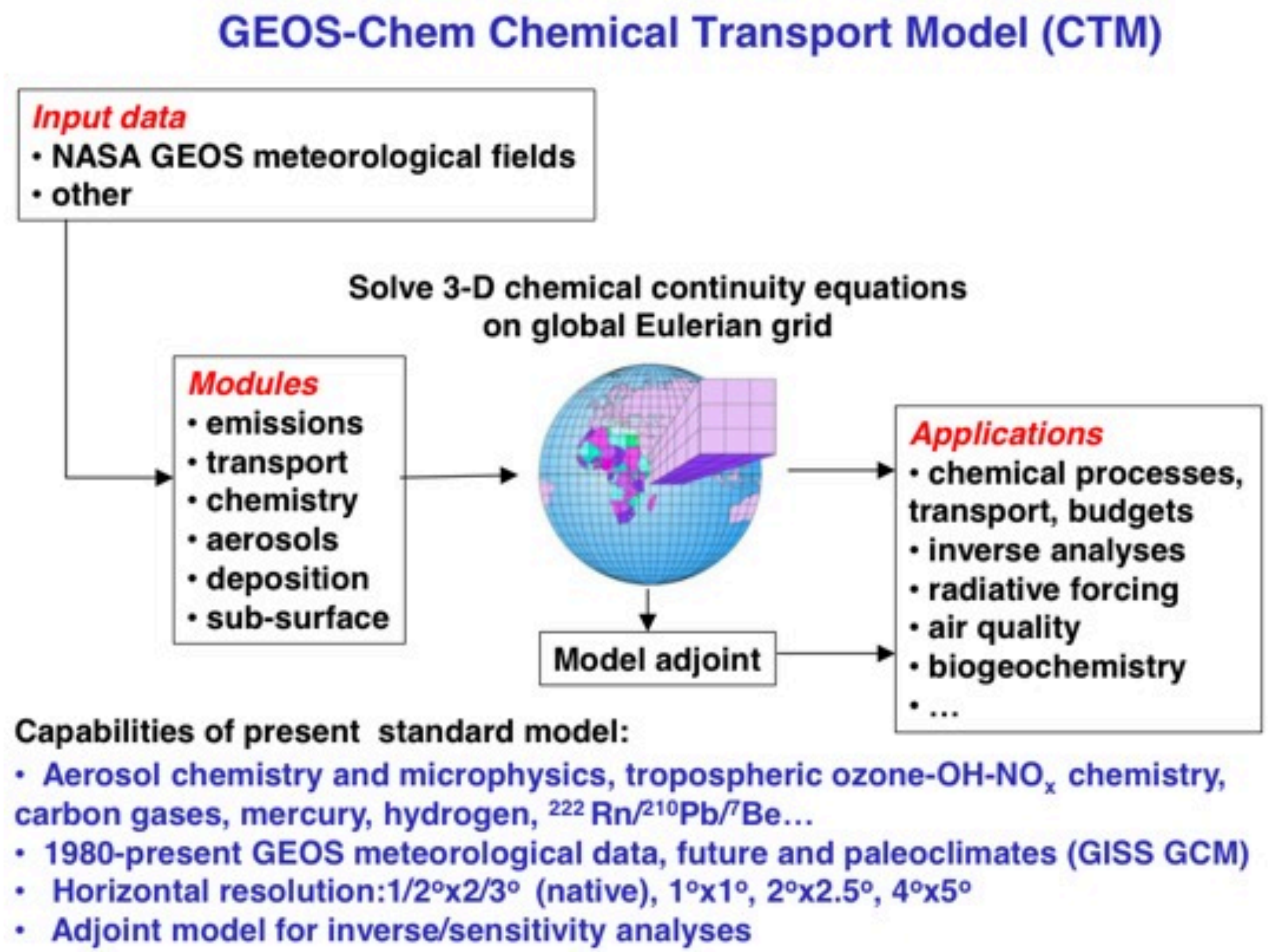
$$\mathbf{E}^a = (\mathbf{1} + \boldsymbol{\eta}^a)\mathbf{E}^f \qquad (7)$$

a posteriori

a priori

4. Experiment Setting

- **Model (Chemical Transport Model; CTM)**



- GEOS-Chem v9-01-01
- GEOS5 Met. fields
- a priori (base) emission

  FF (Fossil Fuel): EDGAR (2005)

  BF (Bio-Fuel) : Yevich and Logan (2003)

  BB (Biomass Burning): Duncan et al. (2003)

  = 117.8 Tg/year from China

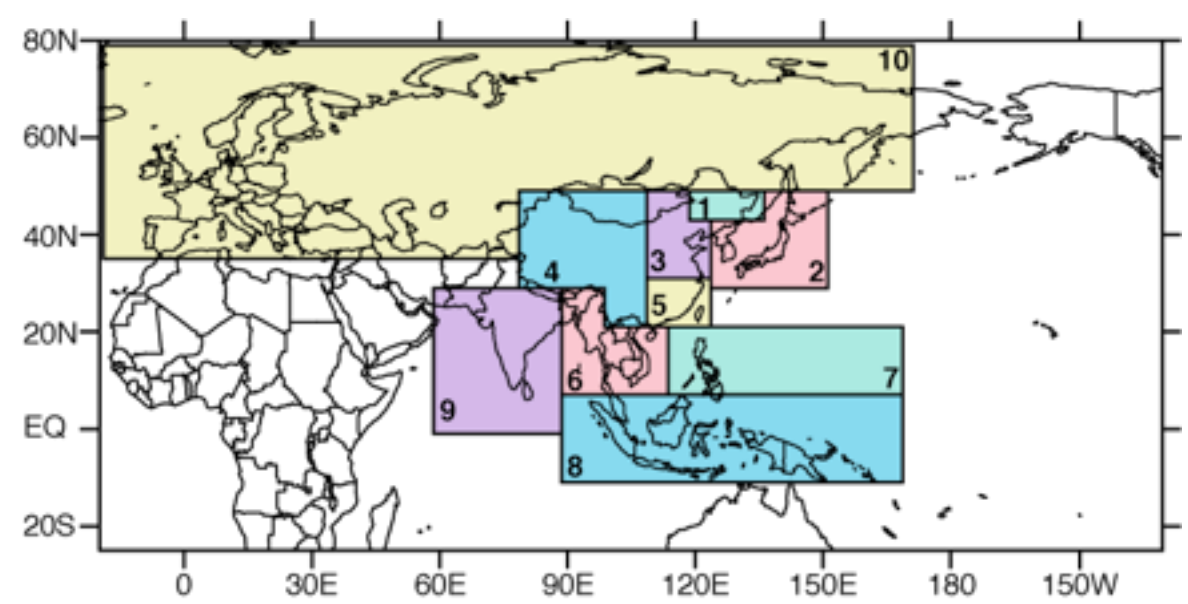
- Tagged CO simulation

  calculate Green's function matrix by one integration

  11 geographical tagged region

  4 tags (regions) in China

emissions from the 11 geographical regions are inversely optimized



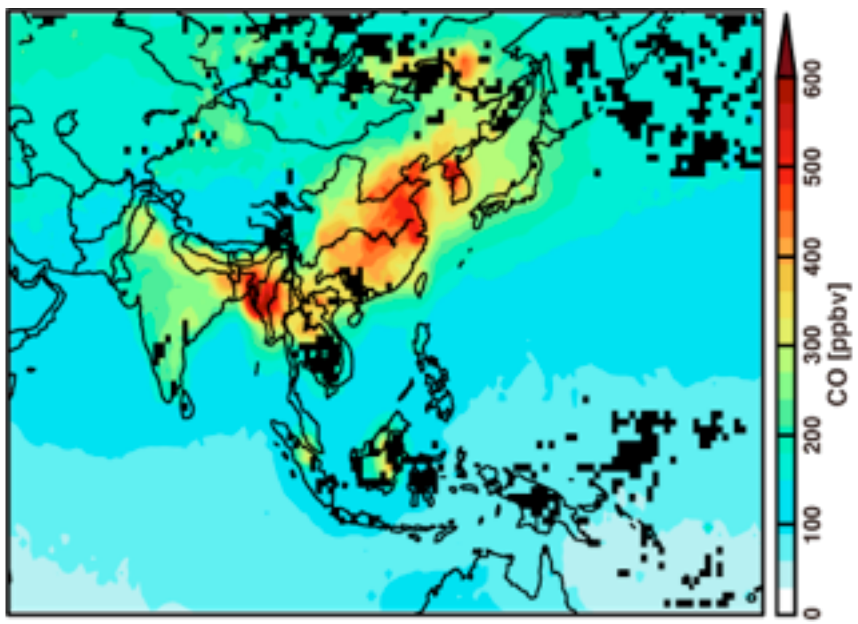
4. Experiment Setting

- **Observation (Constraint)**

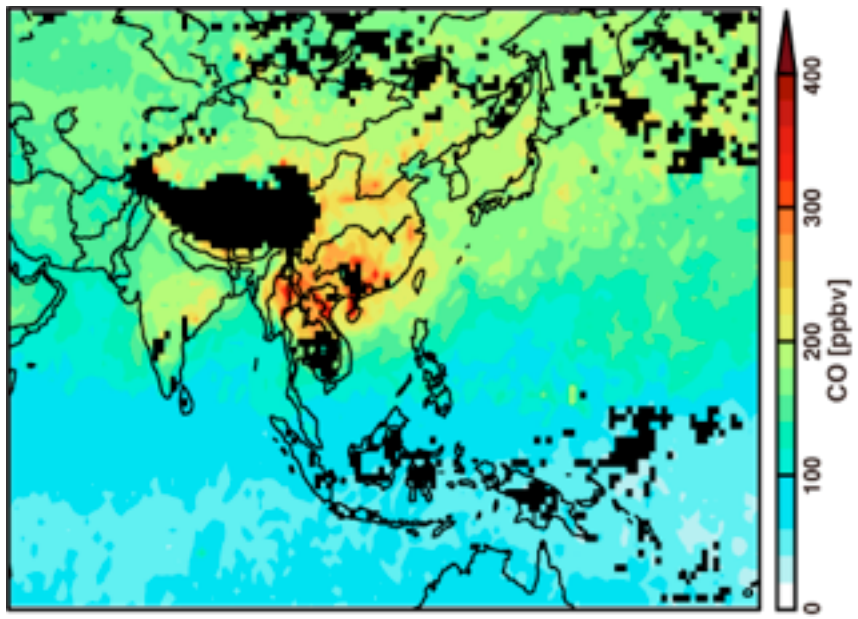
  MOPITT CO profile (V4)

  - on board TERRA satellite
  - 10:30 Local Time
  - over 10-year continuous observation (2-month lack in Aug. and Sep. 2009)

200501 @ surface



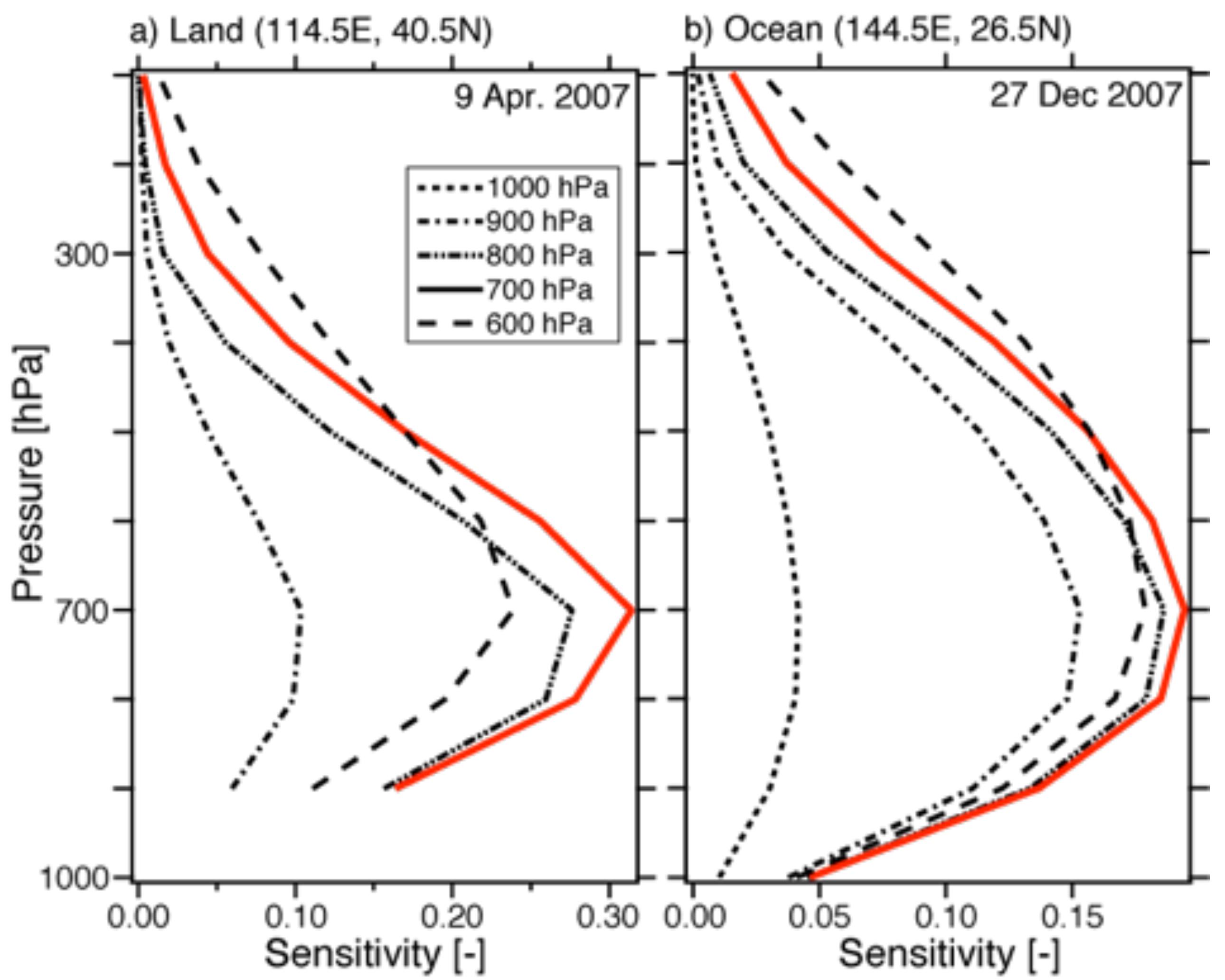
200501 @ 700hPa



Monthly-averaged CO distribution from MOPITT

4. Experiment Setting

- **Observation (Constraint)**
  MOPITT CO profile (V4)
  - on board TERRA satellite
  - 10:30 Local Time
  - over 10-year continuous observation (2-month lack in Aug. and Sep. 2009)
  - the highest sensitivity at 700 hPa



Example of averaging kernels of 1000, 900, 800, 700 and 600 hPa.

4. Experiment Setting

- **Observation (Constraint)**

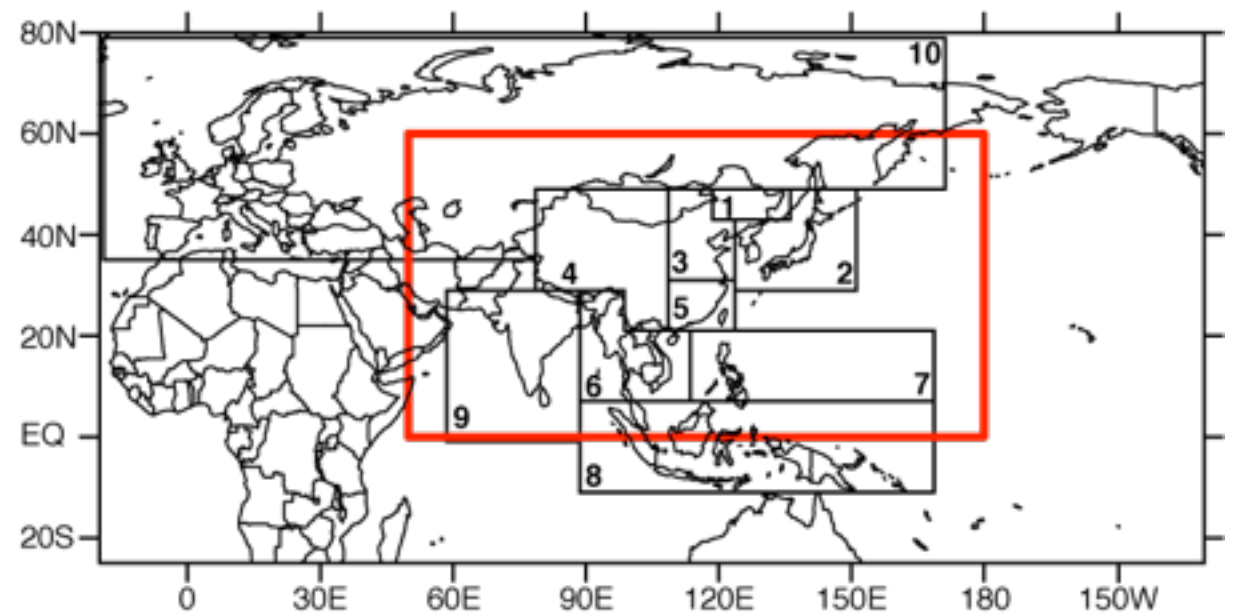
MOPITT CO profile (V4)

- on board TERRA satellite
- 10:30 Local Time
- over 10-year continuous observation (2-month lack in Aug. and Sep. 2009)
- the highest sensitivity at 700 hPa

We use MOPITT measurements

- monthly-averaged
- measured at 4 vertical levels (surface, 900, 800, 700 hPa)
- corrected assuming 5% positive bias (Kopacz et al., 2009)
- through averaging kernel (*H* includes operation of AK)

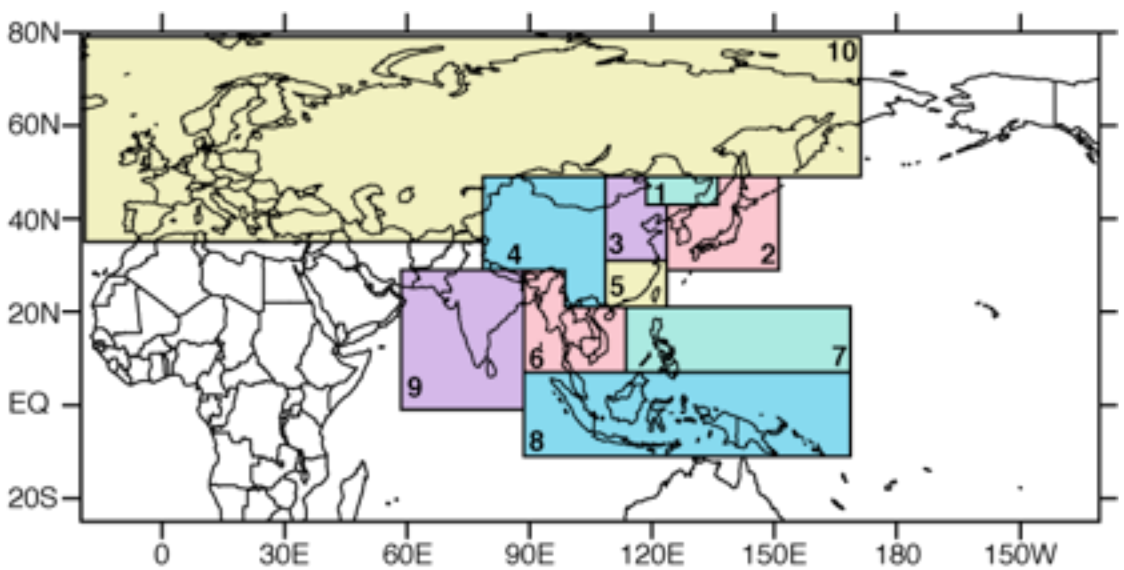
※25,000–30,000 data/month used in the inversion



MOPITT data region used in the inversion

4. Experiment Setting

Global 2x2.5



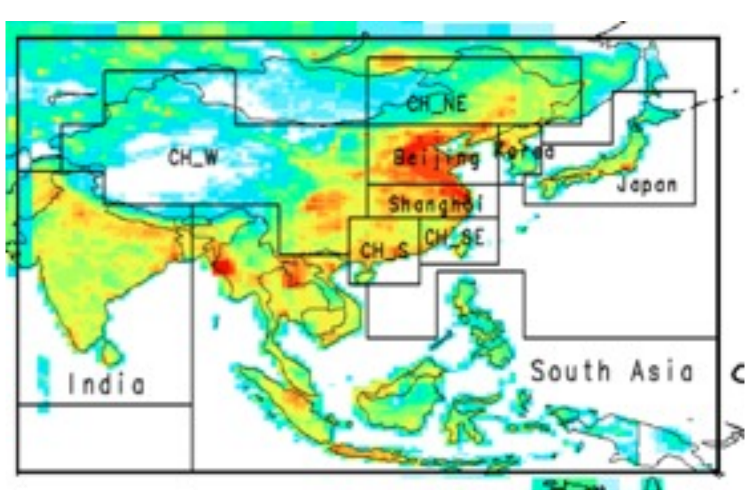
- 11 regional tags
- a priori = EDGAR

MOPITT V4 TIR Only

- **Thermal Infrared Only** Product
- the highest sensitivity around 700 hPa
- lower 4 vertical levels
  (Surface 900, 800, 700)
- through averaging kernel
- ~30,000 data/month used

Yumimoto and Uno, 2012

China Nest 0.5x0.667



- finer China tags
- REAS V2

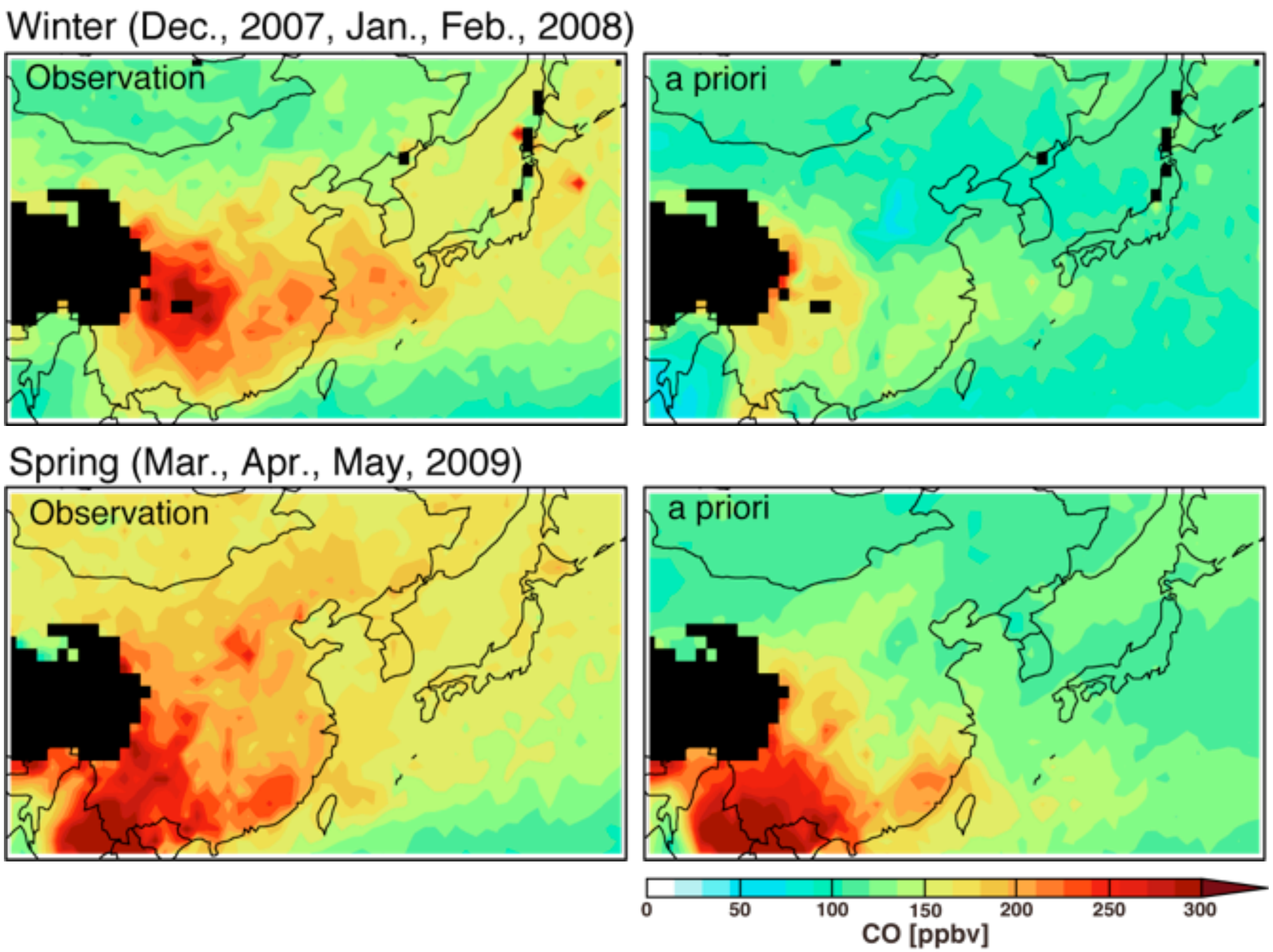
MOPITT V5 TIR/NIR

- **Thermal Infrared**
  + Near Infrared Product
- additional sensitivity near surface

Yumimoto et al., in prep.

5. Inversion Results

- **vs. MOPITT (ppbv, 2D-distribution, season)**

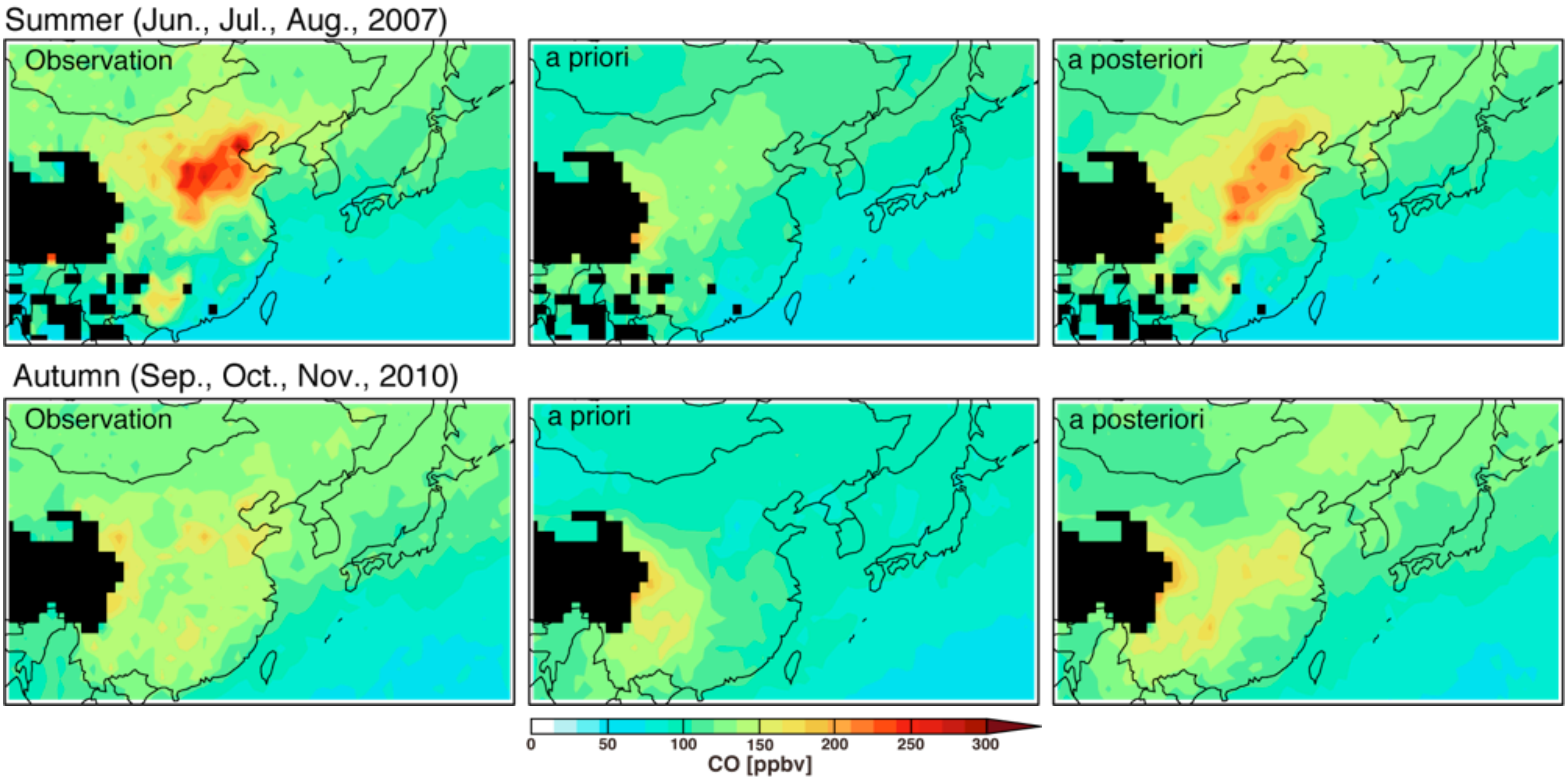


CO mixing ratio (ppbv) at 700 hPa from MOPITT, a priori, and a posteriori

A posteriori successfully re-produce CO outflows from China to Japan

5. Inversion Results

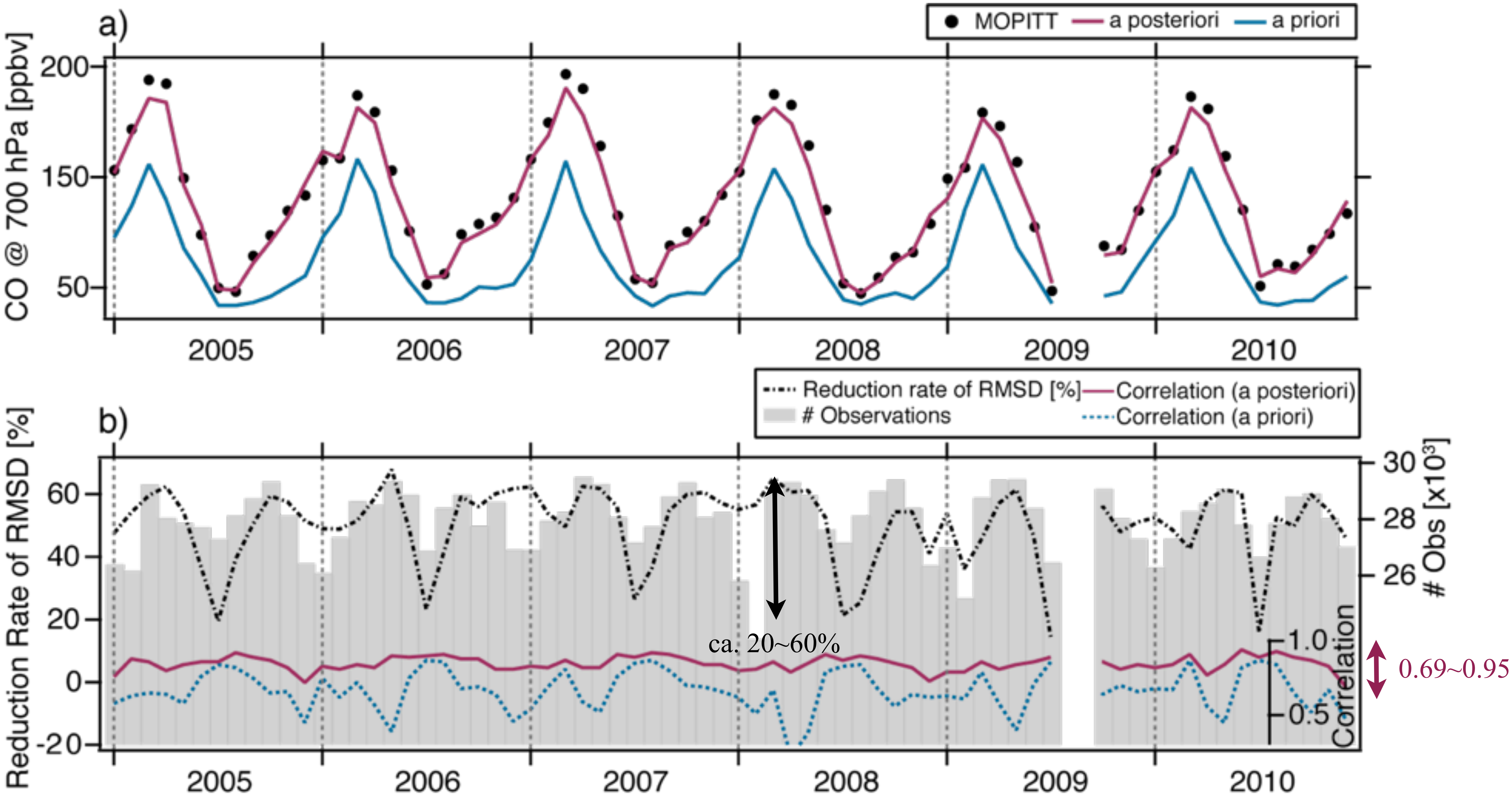
- **vs. MOPITT (ppbv, 2D-distribution, season)**



CO mixing ratio (ppbv) at 700 hPa from MOPITT, a priori, and a posteriori

5. Inversion Results

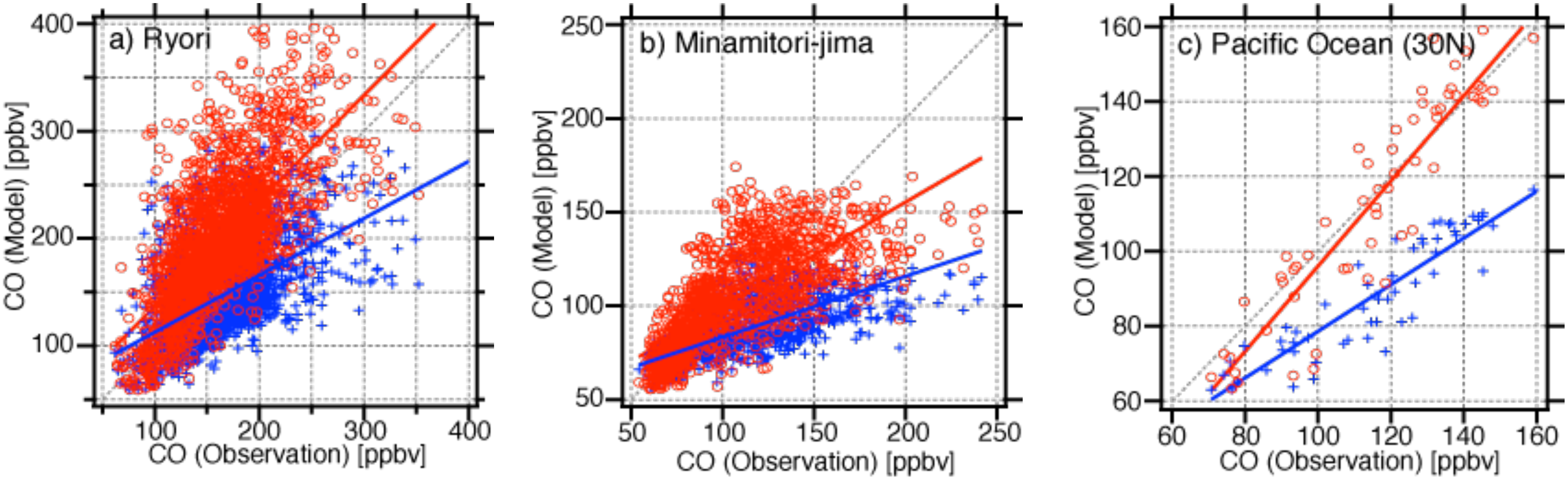
- **vs. MOPITT (Time-Series, Statistics)**

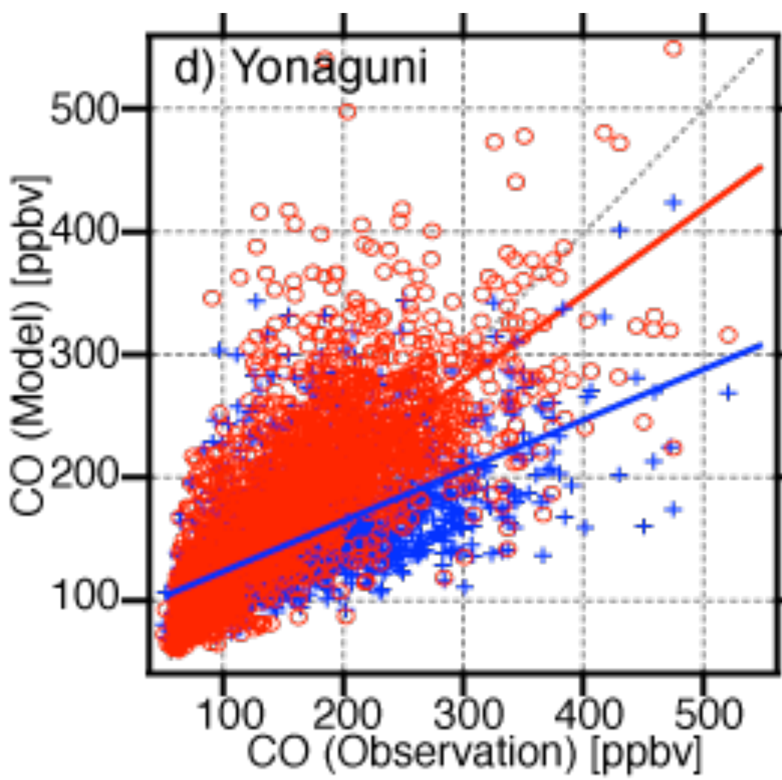


Time series of (a) monthly-averaged CO concentration and (b) statistics

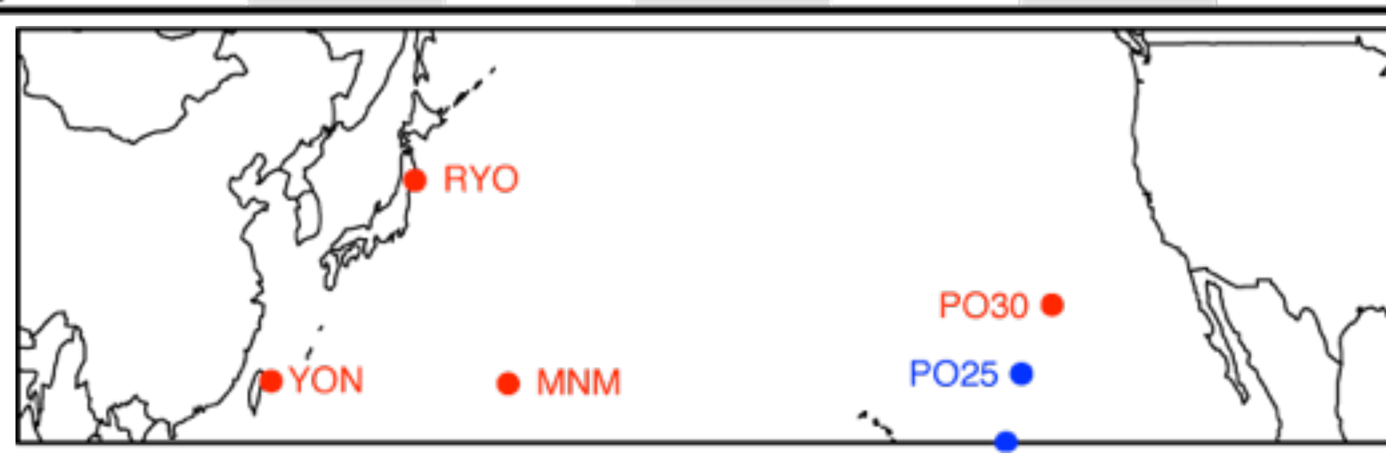
5. Inversion Results

- **vs. in-situ measurements (independent validation)**





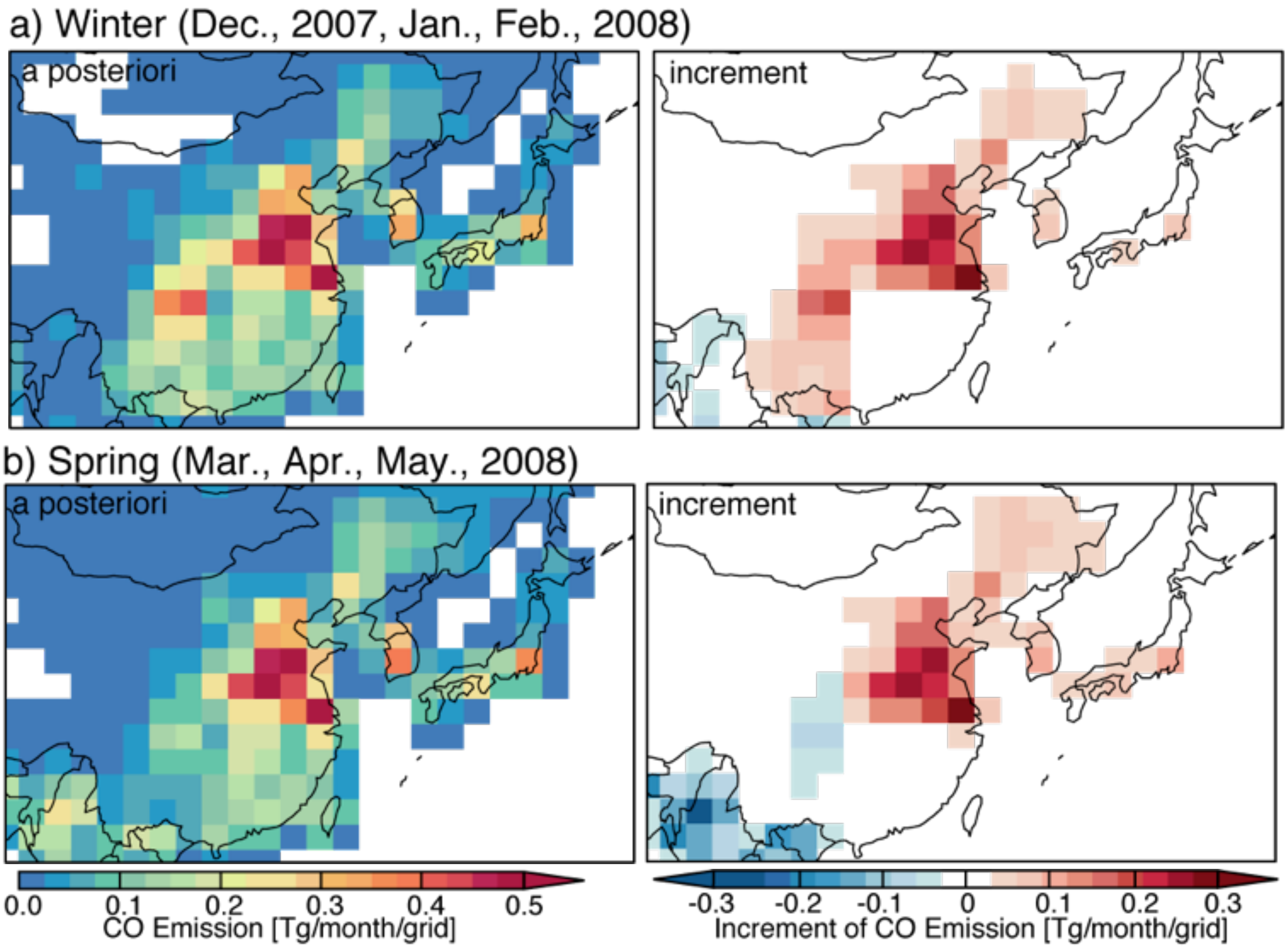
	Ryori (R)		P30N (P)		Yonaguni (Y)		Minamitori-jima (M)	
Location[a]	141.82E	39.03N	135.00W	30.00N	123.02E	24.47N	153.98E	24.28N
# Observations	2107		59		2087		1418	
	a priori	a posteriori	a priori	a posteriori	a priori	a posteriori	a priori	a posteriori
AE [%]	-29		61		3		29	
Correation Coef.	0.55	0.69	0.91	0.92	0.63	0.73	0.73	0.74
Slope	0.53	0.98	0.62	1.13	0.41	0.70	0.32	0.56
Bias [ppbv]	59.28	38.54	16.92	-16.90	83.86	69.96	50.58	41.80



Scatter plots of in-situ measurements vs. model

5. Inversion Results

- **a posteriori emission (2D-distribution, season)**

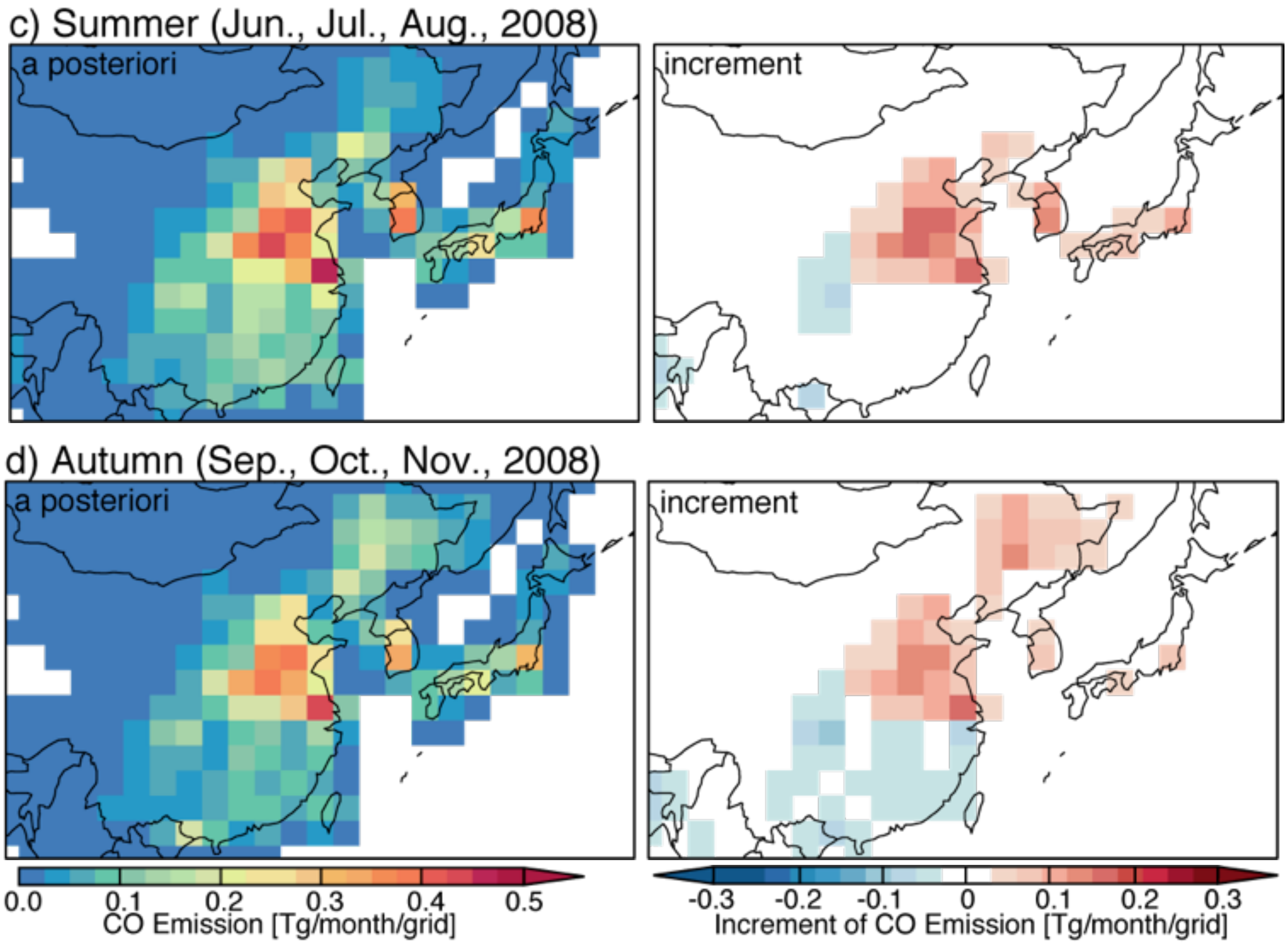


A posteriori emission and increment between a posteriori an d a priori

Emission in central eastern China is increased.

5. Inversion Results

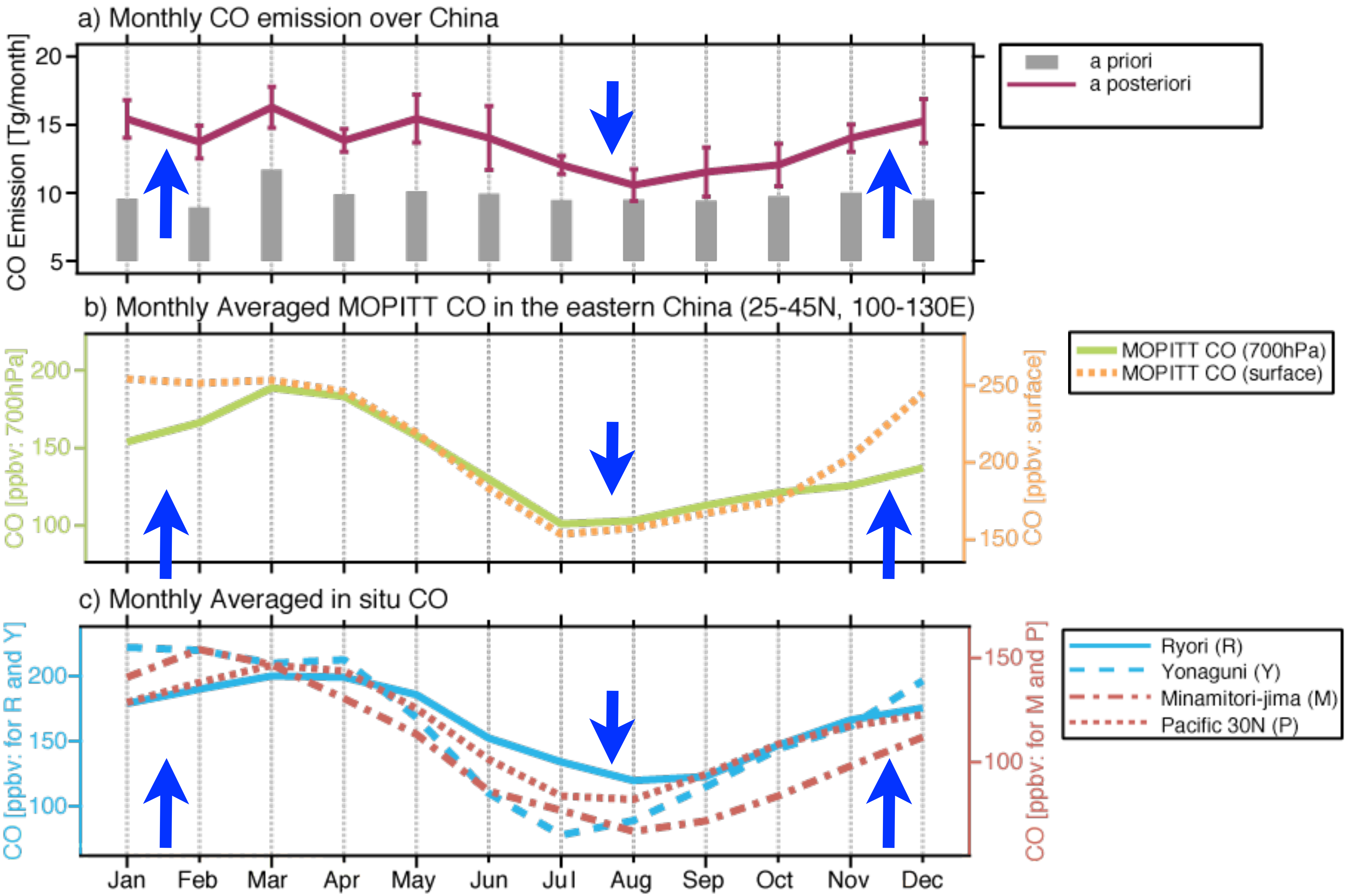
- **a posteriori emission (2D-distribution, season)**



A posteriori emission and increment between a posteriori an d a priori

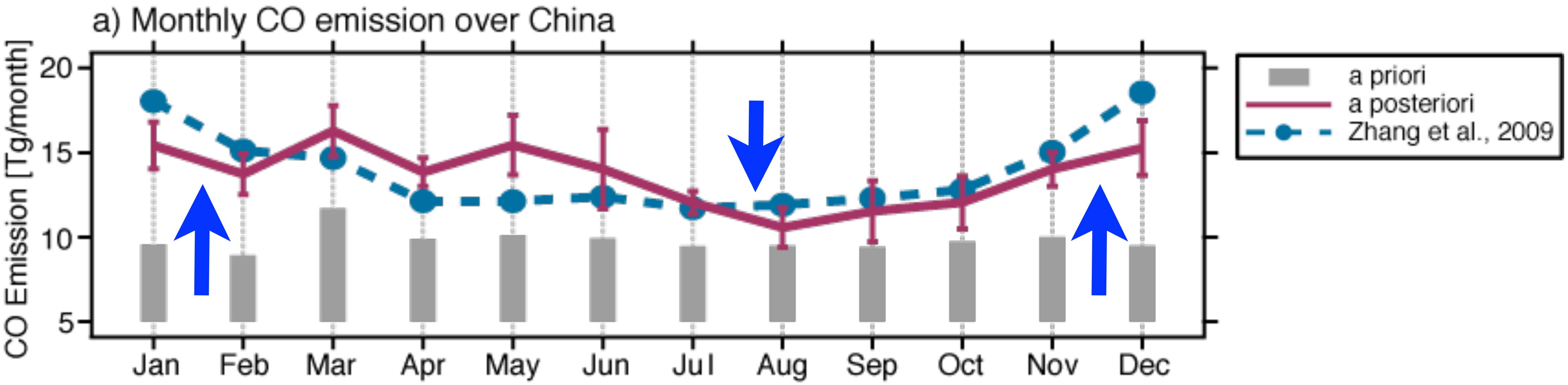
5. Inversion Results

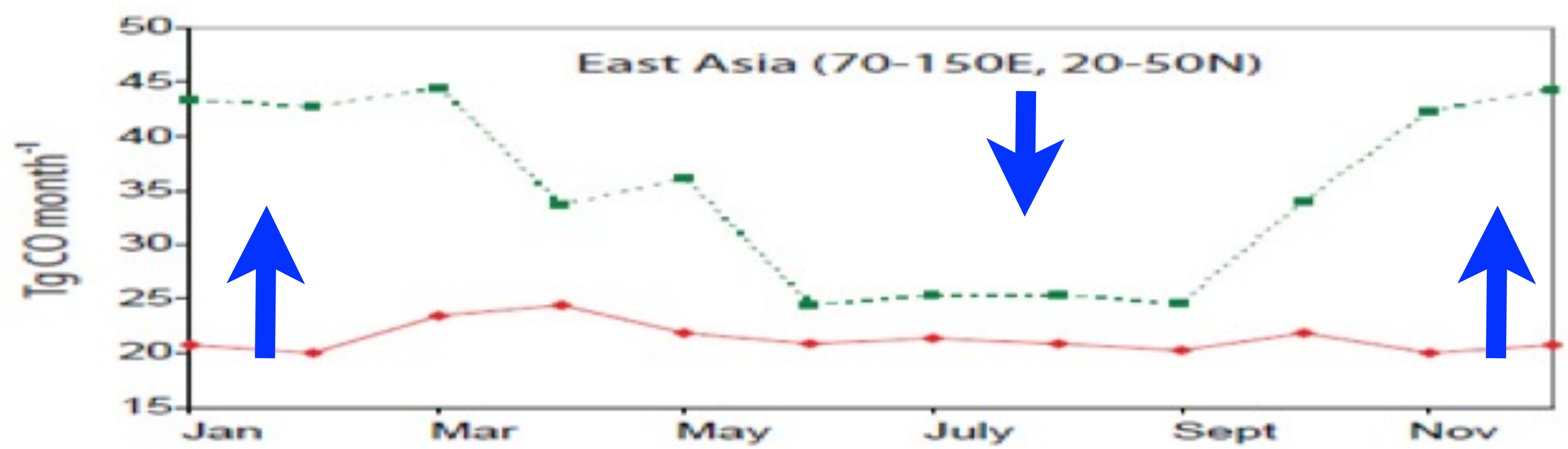
- **a posteriori emission (seasonal cycle)**



5. Inversion Results

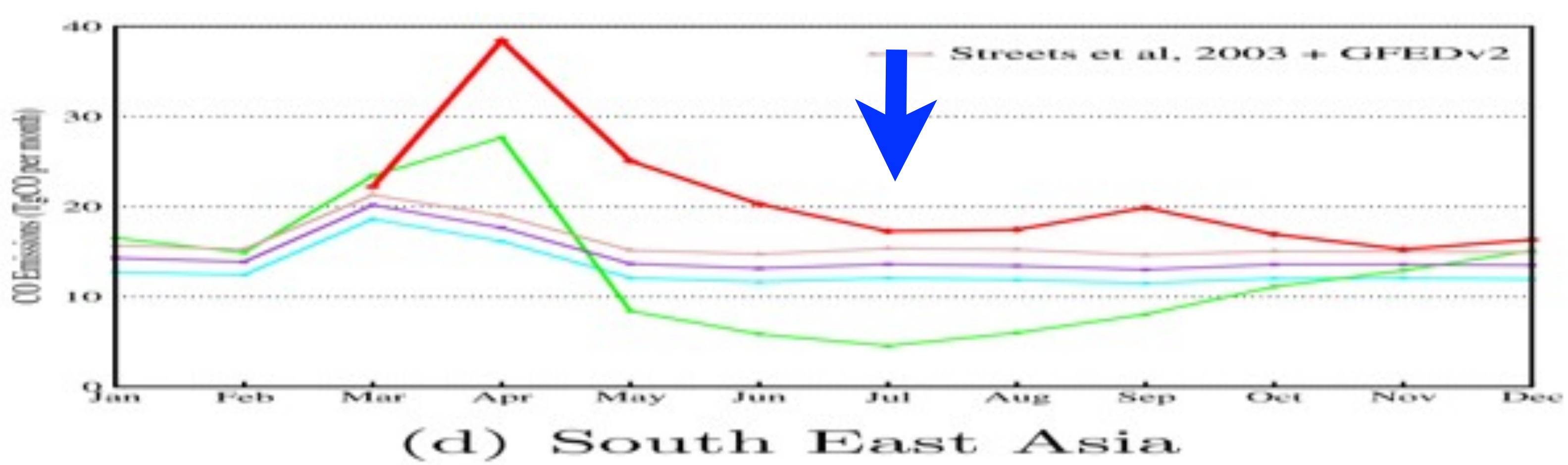
- **a posteriori emission (seasonal cycle)**





Kopacz et al. 2010(Figure 2)

China + Japan + Korea + part of Indea

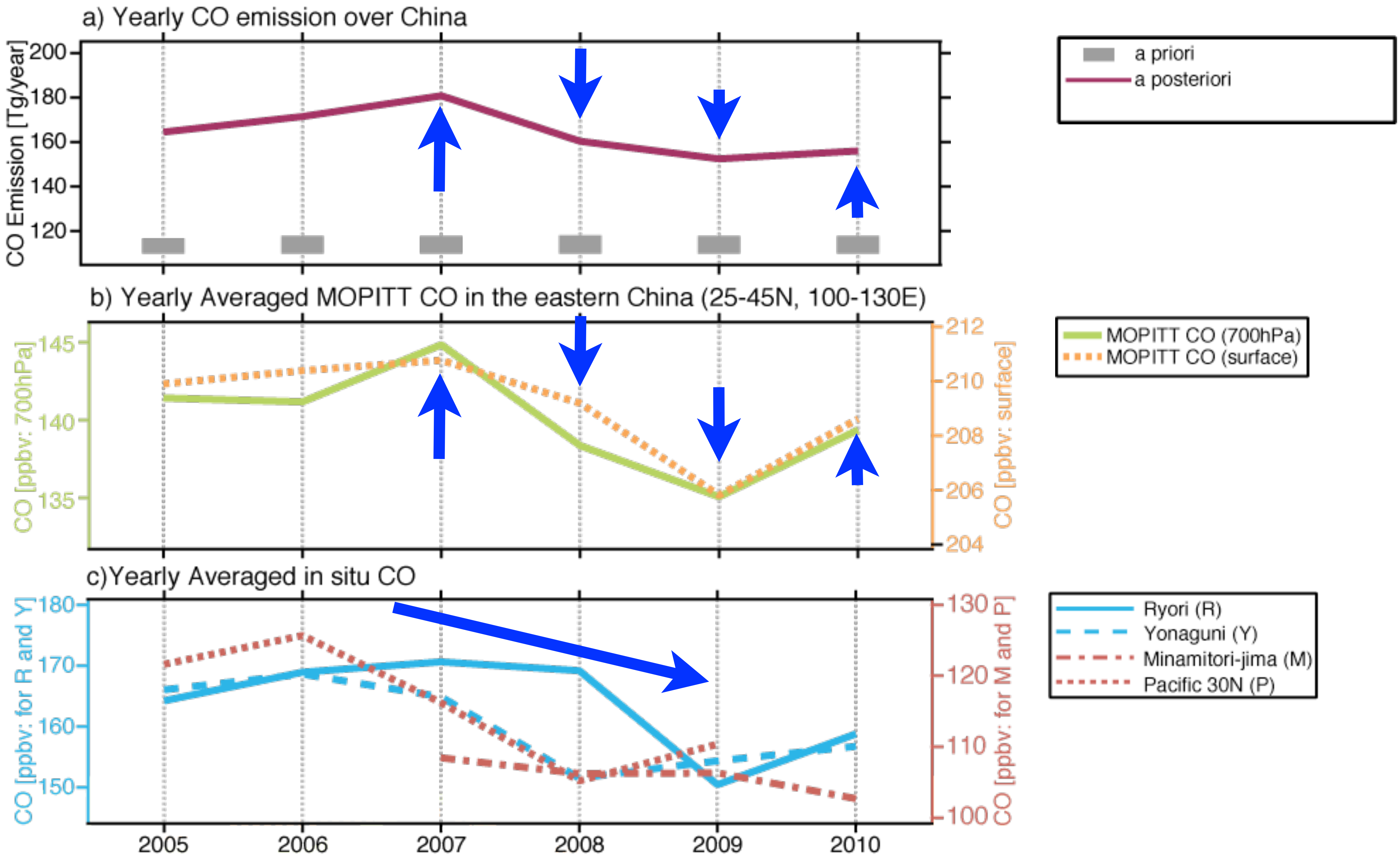


Fortems-Cheiney et al. 2011

China + Japan + Korea + south eastern Asia

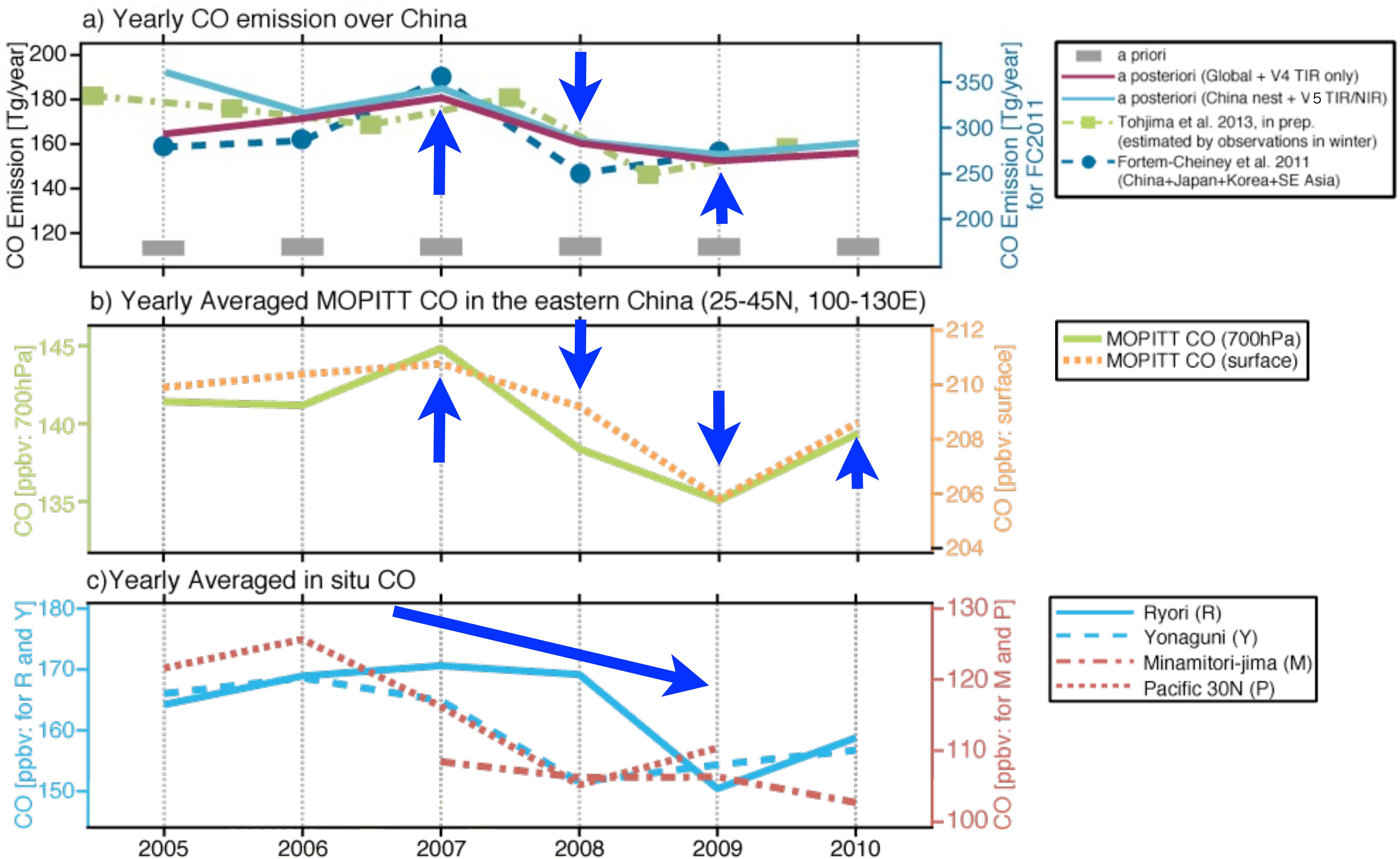
5. Inversion Results

- **a posteriori emission (annual variation)**



5. Inversion Results

- **a posteriori emission (annual variation)**



6. Summary

- **In this study,**
  - CO emissions in China are inversely optimized with Green's function method, MOPITT vertical profiles, and GEOS-Chem for the recent 6 years.

- **We found that**
  - a posteriori emissions successfully reproduce

    (1) CO outflows from China to East China Sea and the Japanese archipelago in winter and spring.

    (2) high CO over the central eastern China region.

  - a posteriori emissions exhibit significant variation

    (peak in winter-–spring, bottom in summer)

  - a posteriori Chinese CO sources range from 156.1 to 180.8 Tg/year, representing inter-annual variations due to socioeconomic conditions