NANJING UNIVERSITY

Development of CMAQ for East Asia CO_2 data assimilation under an EnKF framework: Methodology and first results

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Outline

- 1. Background and motivation
- 2. Assimilation system and validation experiment
- 3. Impact of wind field uncertainty and variation
- 4. Conclusion and future work

Background

- CO_2 flux inversion depends on observations and reasonable CO_2 transport models.

- For accurate CO_2 flux estimation,

GEMS (Hollingsworth et al., 2008) adopts a two-step approach:

(1). Obtain consistent CO_2 concentration fields.

(2). Inverse CO_2 flux based on (1).

- Several studies have assimilated CO_2 satellite products to transport model for better CO_2 concentration fields, through 4DVar, 3Dvar, EnKF or LETKF .

  (e.g., Engelen et al., 2009; Tangborn et al., 2013; Liu et al., 2012).

Motivation

- Continuous surface CO_2 observations
  - Engelen et al. (2009) point out that, in situ data in the previous studies are used only for verification of assimilation systems, even though the data can be assimilated.
  - Being accumulated and becoming available over East Asia.
- Regional CO_2 data assimilation
  - To adequately describe all CO_2 transport processes involved, models from global to local scales would be necessary (Chevillard, et al., 2002).
  - Previous studies mainly focus on a global scale.

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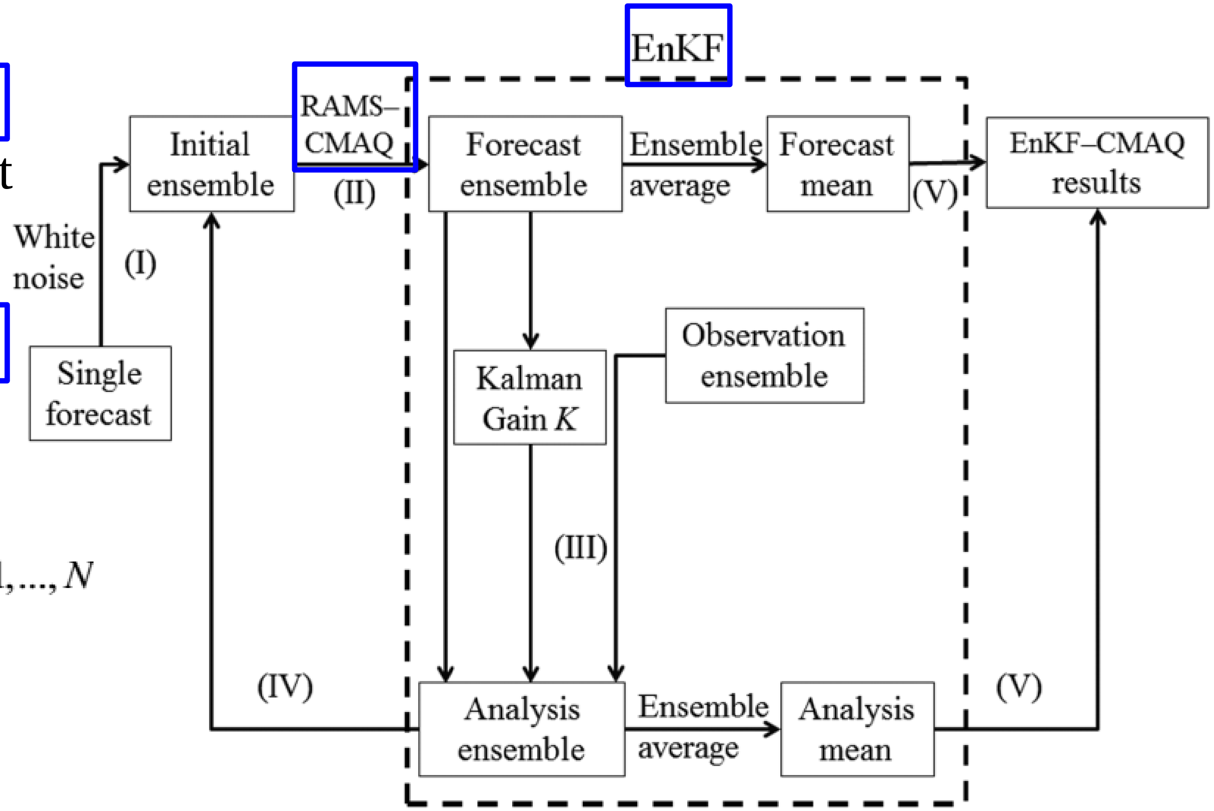
CO_2 assimilation system

- CO_2 transport model: RAMS–CMAQ (Zhang et al., 2002)
- Assimilation scheme: EnKF (Evensen, 2009)

$$K = P^b H^T (HP^b H^T + R)^{-1}$$

$$X_i^a = X_i^b + K(Y_i - HX_i^b) \qquad i = 1, \ldots, N$$

$$P^b = \frac{1}{N-1}\left[\sum_{i=1}^{N}(X_i^b - \bar{X}^b)(X_i^b - \bar{X}^b)^T\right]$$



Huang et al., 2014

- Assimilation variable: CO_2 concentration
- Covariance inflation method: Additive covariance inflation (Houtekamer & Mitchell, 2005)

$$\Delta X_i^b = X_i^b + q_i \qquad i = 1, \ldots, N$$

$$q_i \sim N(0, Q)$$

CO_2 transport model

RAMS–CMAQ:

(1) The Community Multi-scale Air Quality (CMAQ) modeling system (Byun at al., 1999):

- offline chemical transport model, treating CO_2 as a tracer
- driven by meteorology fields.

(2) The Regional Atmospheric Modeling System (RAMS) (Pielke et al., 1992):

- meteorology model
- provides meteorology fields to CMAQ.

Thanks to Xingxia Kou for her help on the research of this part.

Wind uncertainty

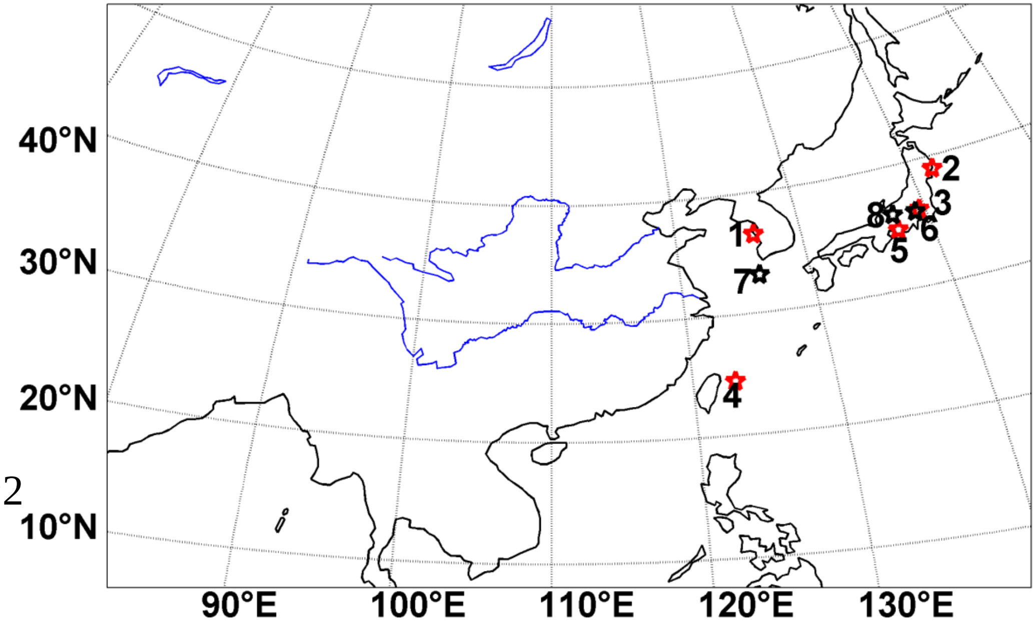
- Considerable CO_2 transport uncertainties come from the uncertainties in meteorological fields, particularly the wind fields (Liu et al., 2011).

- Ensemble RAMS meteorology fields with wind perturbations
  - drive ensemble CMAQ simulation
  - from historical RAMS simulations

Thanks to Chu-Chun Chang and Cheng-Chieh Kao for their help on the research of this part.

Experiment setting

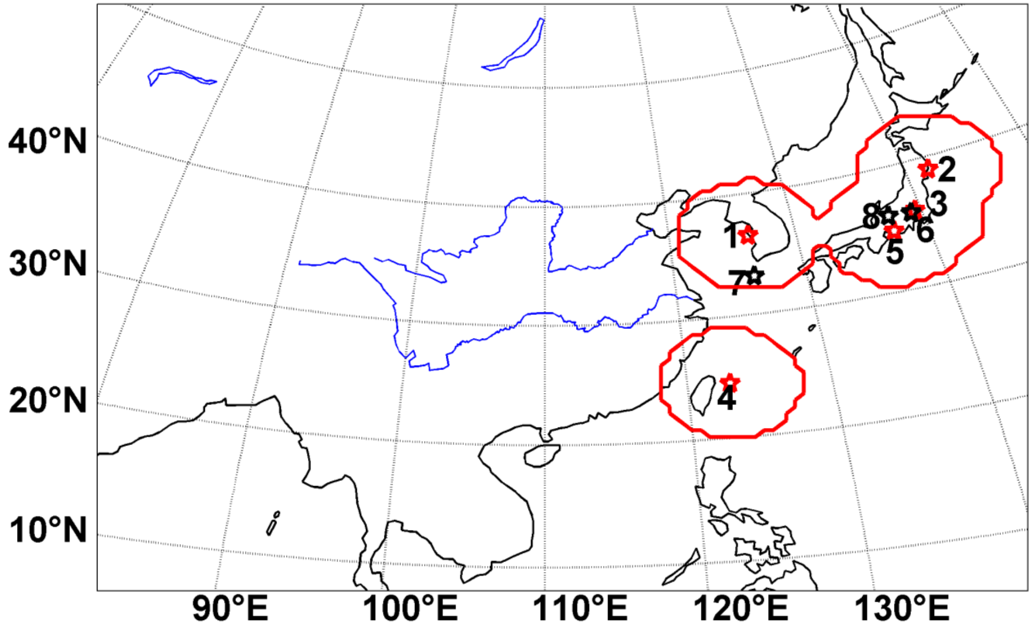
- Period:
  Jan. 23rd to Feb. 7th, 2007, including several synoptic-scale weather processes
- Control run (Control):
  Single RAMS–CMAQ simulation
- Observation
  Hourly continuous surface CO_2 observing records
- Site classification
  - Assimilation sites (Asites)
    1.AMY, 2.RYO, 3.KIS, 4.YON, 5.MKW
  - Reference sites (Rsites):
    6.DDR, 7.GSN, 8.TKY



Observations are from World Data Centre for Greenhouse Gases (WDCGG) website, http://ds.data.jma.go.jp/gmd/wdcgg/

Experiment run (EnKF–CMAQ)

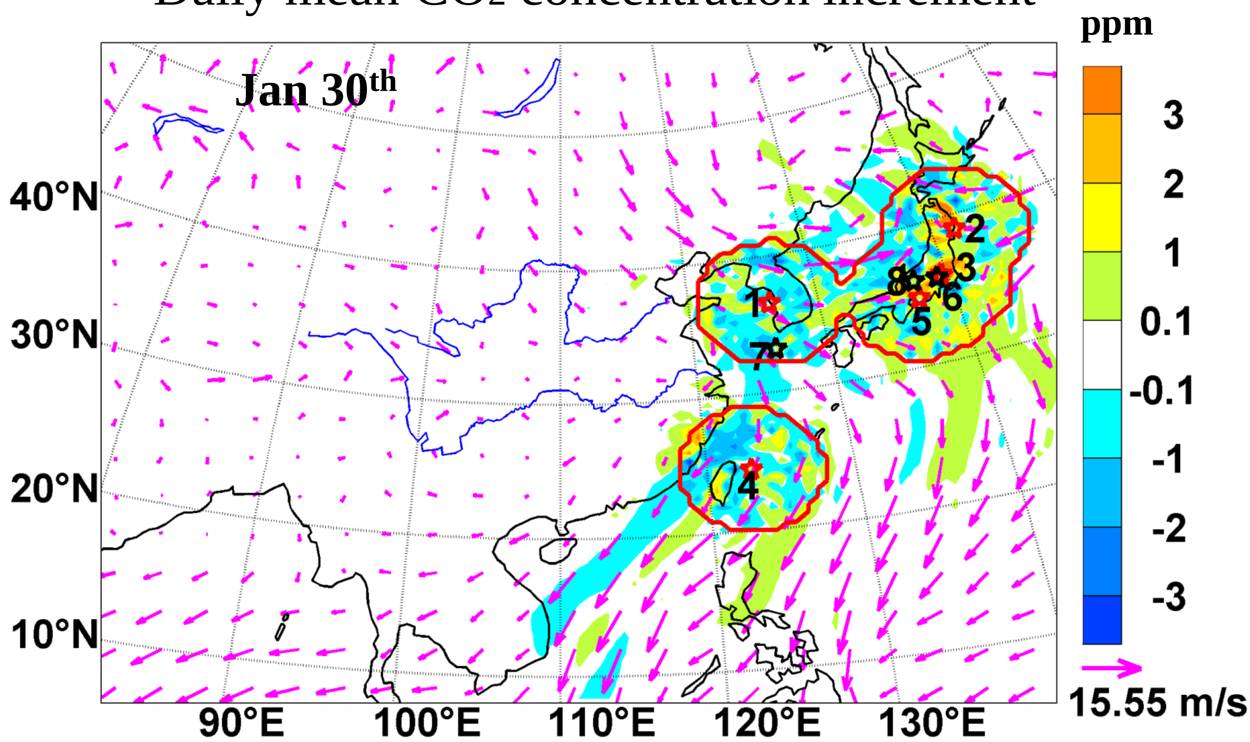
- Ensemble size
  40-member ensemble
- Assimilation frequency
  every 3 hours
- Analysis region
  the model vertical level 1
- Additive covariance inflation
  white noise ~ $N(0,(4\%\overline{X}^b)^2)$,
  $4\%\overline{X}^b \approx 15$ ppm, confined to the nearby areas of Asites
- Observation perturbations
  white noise ~ $N(0,(0.2\%Y)^2)$,
  $0.2\%Y \approx 0.8$ ppm



Results: update distribution

- Flow-dependent distribution.
- Confined assimilation impact:
  - downwind areas
  - nearby areas

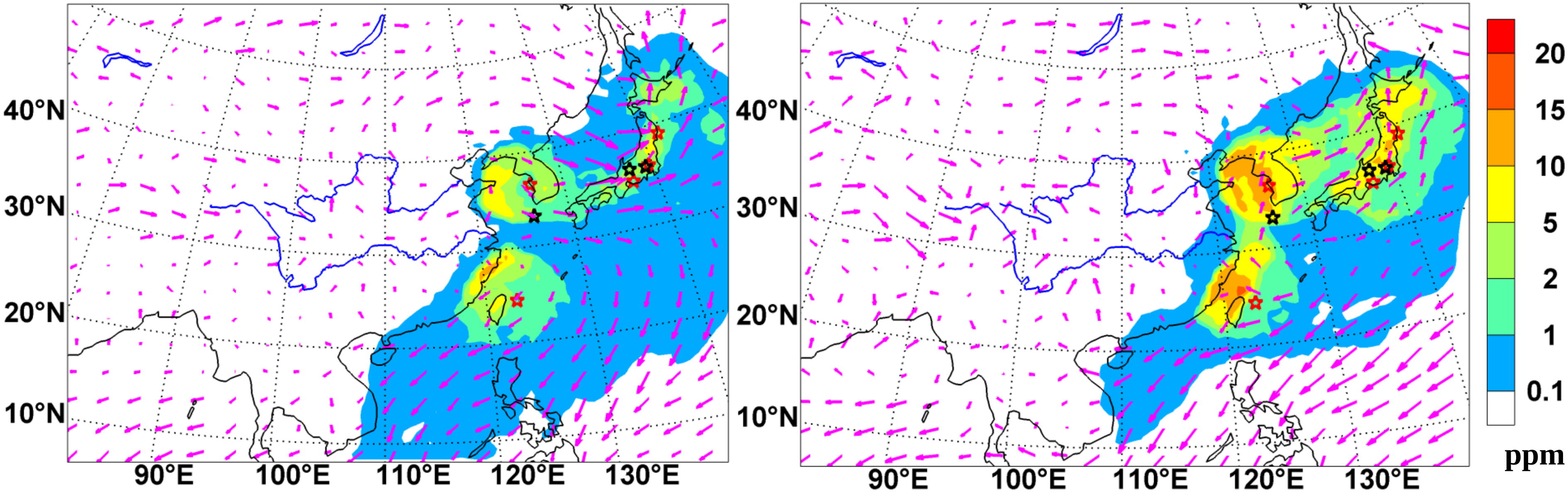
Daily mean CO_2 concentration increment



Increment = EnKF–CMAQ results – Control results

Results: CO_2 ensemble spread

CO_2 background ensemble spread



1200 UTC+8 Feb. 2rd

1200 UTC+8 Feb. 4th

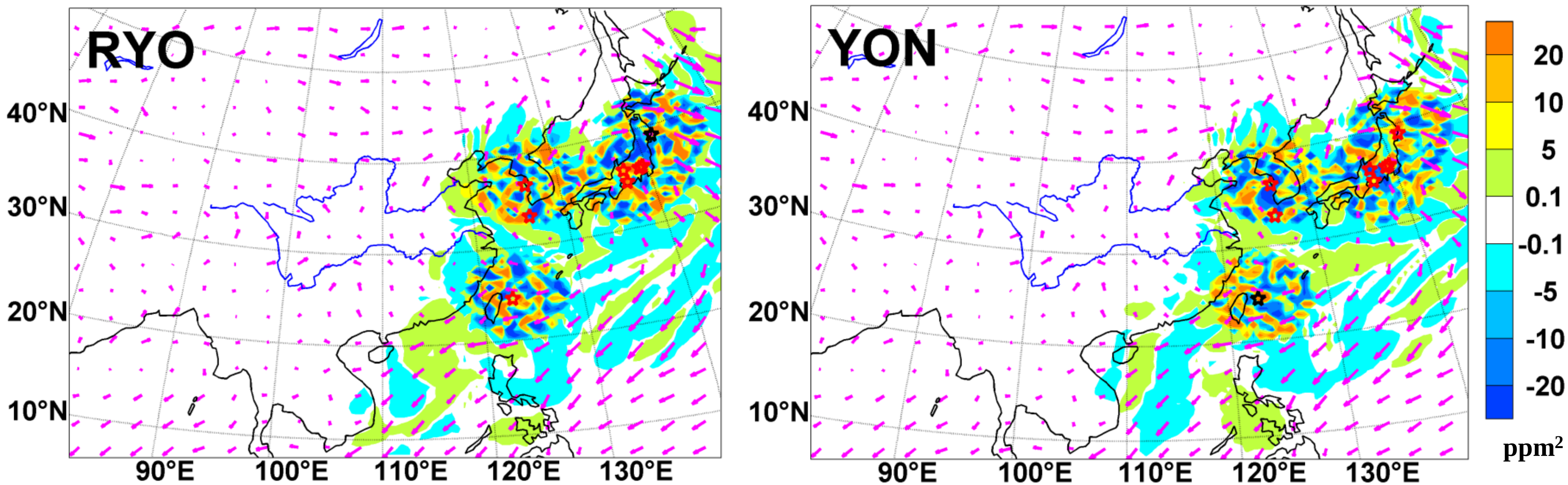
Flow-dependent CO_2 uncertainty:

- Give weight to observations in data-related areas
- Reject observation information in data-avoid areas

ppm

Results: CO_2 error covariance

CO_2 background error point-covariance



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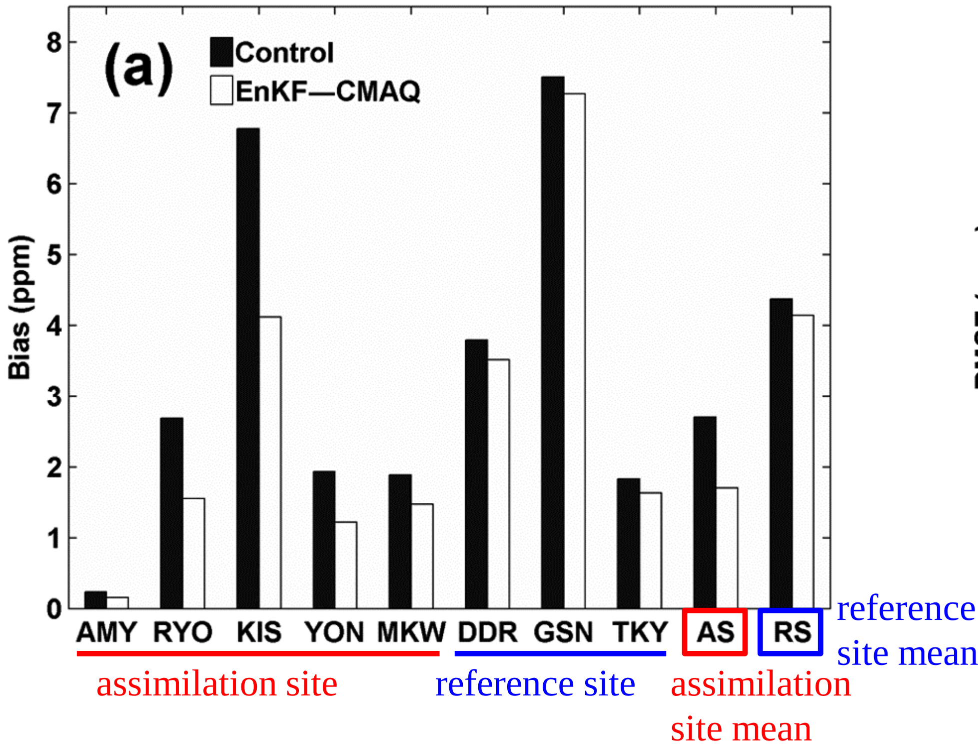
Flow-dependent error covariance:

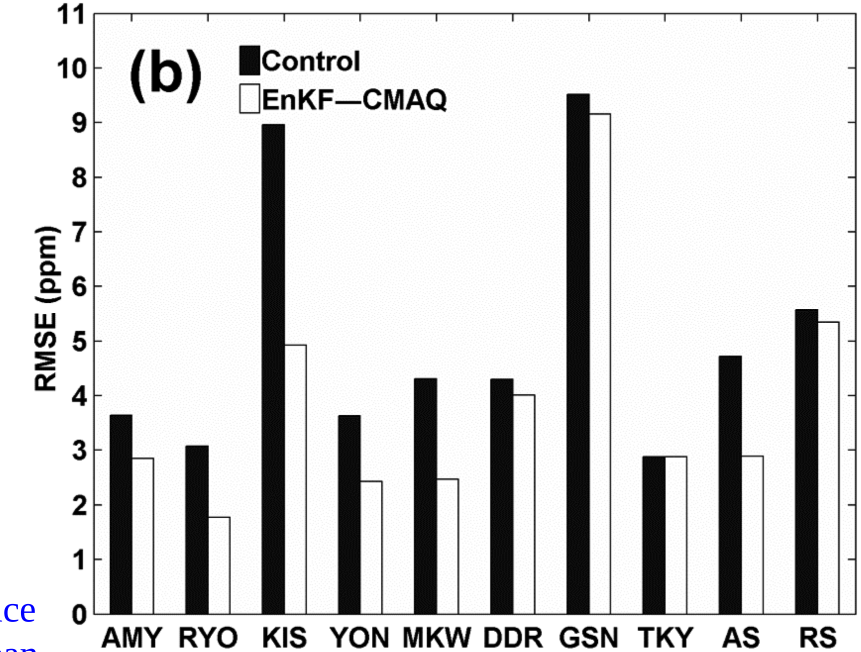
- Information is propagated from assimilation sites
- Covariance inflation damages original background error covariance structure

Results: simulation accuracy

The daily mean CO2 concentration Bias



The daily mean CO2 concentration RMSE



(Huang et al., 2014)

Positive analysis impact

- To Asite:
  - introduced through analysis
  - sustain during model intergreation
- To Rsites:
  - propagated through analysis
  - transported by model integration.

Brief Summary

- A CO_2 concentration assimilation system EnKF–CMAQ is developed, through coupling RAMS–CMAQ and EnKF.

- The performance of EnKF–CMAQ system for assimilating continuous surface CO_2 observations is satisfactory:
  - impact of assimilation analysis is confined within proper areas
  - simulation accuracy of synoptic timescale CO_2 variation is improved.

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Background

- Synoptic-scale weather systems make a substantial contribution to the day-to-day variations of CO_2. (Parazoo et al., 2008; Patra et al., 2008)

- Liu et al. (2011) show, on a global scale, considerable CO_2 transport uncertainties come from the uncertainties in meteorological fields, particularly the wind fields.

Motivation

On a synoptic timescale and regional scale:

- Impact of wind uncertainty on the performance of an EnKF assimilation system?
- Contribution of wind field variation to the variation of CO_2 simulation uncertainty?
- Variation of the adjustment of wind uncertainty on CO_2 simulation uncertainty?

Experiment Setting

ExpWind:

- A 32-member ensemble EnKF–CMAQ assimilation run.

ExpNoWind:

- The same as ExpWind, but EnKF–CMAQ uses single meteorology field, instead of ensemble meteorology fields with wind perturbations.

EnWind:

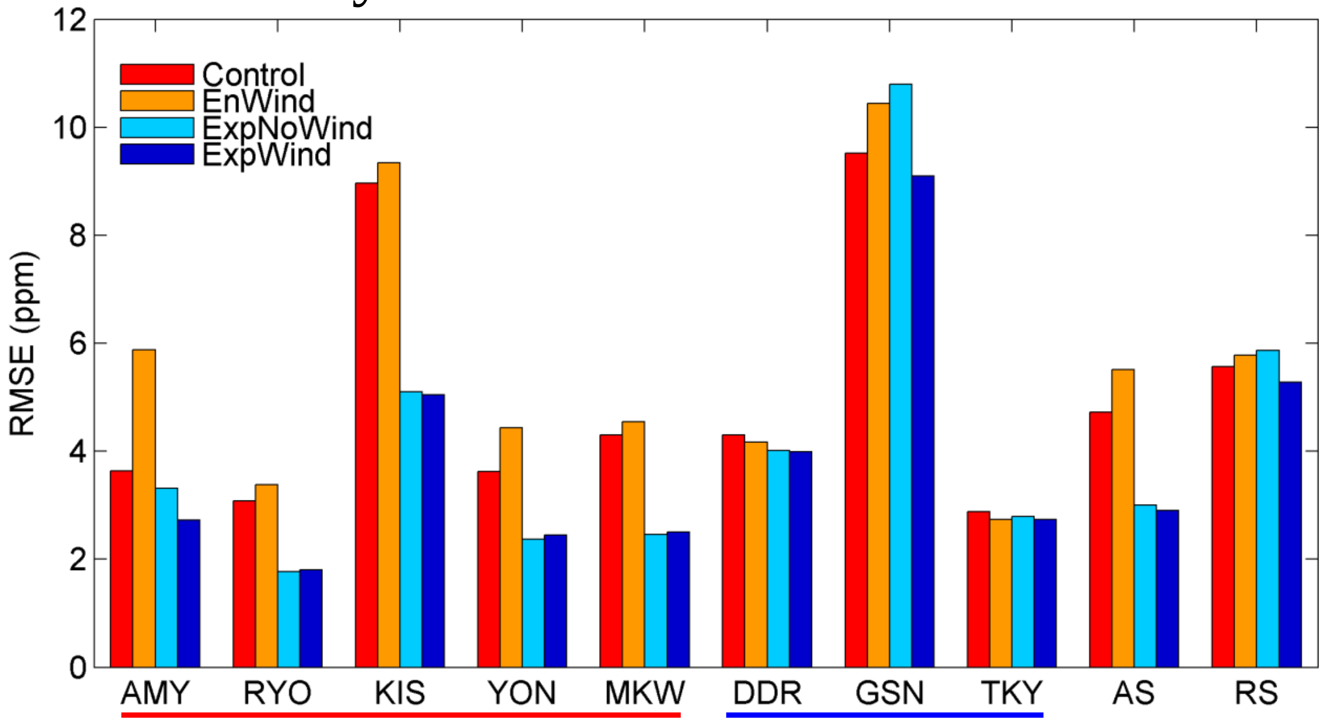
- Ensemble RAMS–CMAQ simulation, i.e., the same as ExpWind, but no assimilation analysis is performed.

Control:

- The single RAMS–CMAQ simulation in the validation experiment.

Results: simulation accuracy

The daily mean CO_2 concentration RMSE



ExpWind V.S. Control and EnWind

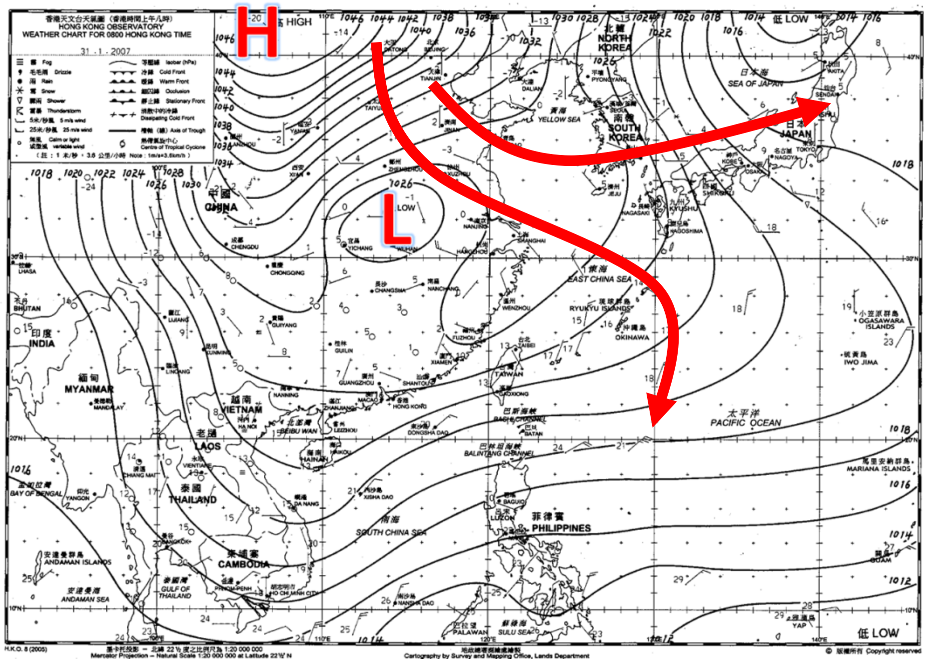
- Assimilation improves the simulation accuracy

ExpWind V.S. Control and ExpNoWind

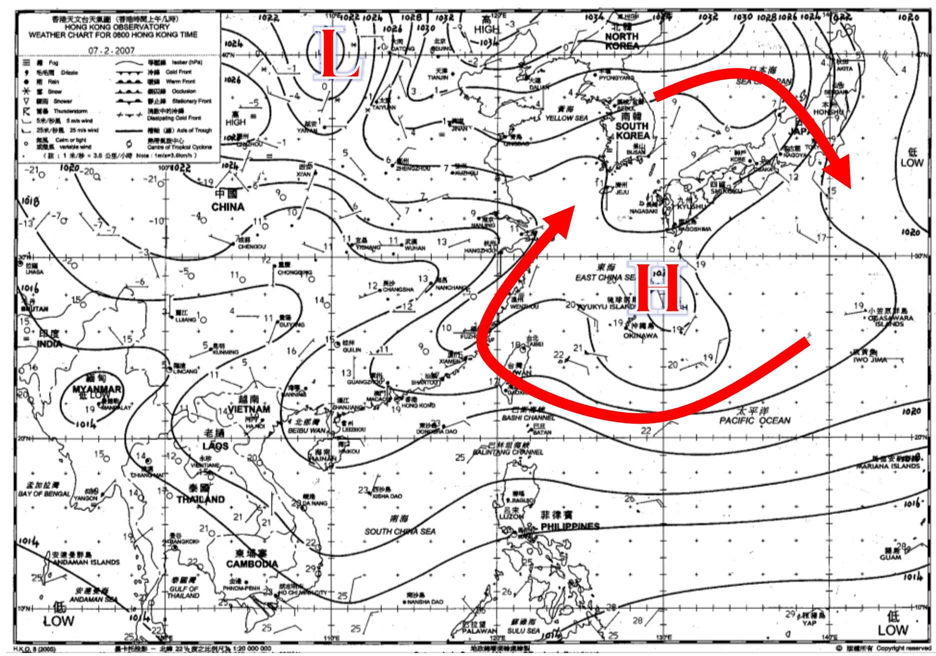
- Wind perturbations are important to improvement at Rsites.

Synoptic condition

0800 UTC+8 Jan. 31st



0800 UTC+8 Feb. 7th



(Surface Weather Charts from IENV, the Hong Kong University of Science and Technology)

Consistent strong winds

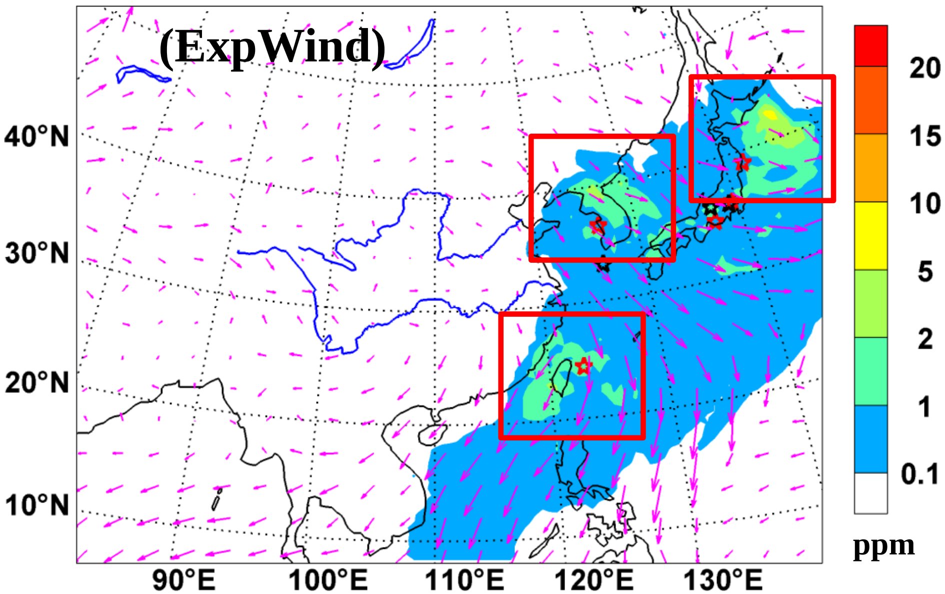
- Low pressure system
- Strong wind transport

Inconsistent weak winds

- High pressure system
- Weak wind transport

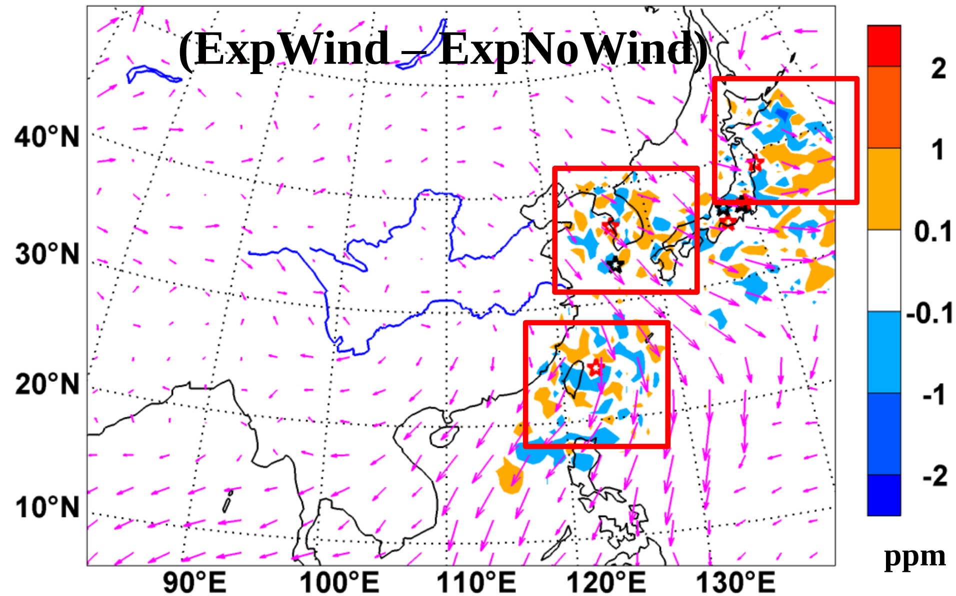
Consistent strong winds

CO_2 background ensemble spread



0900 UTC+8 Jan. 31st

CO_2 ensemble spread difference



0900 UTC+8 Jan. 31st

Ensemble spread

- decays sharply,

  from ~15 to < 5 ppm

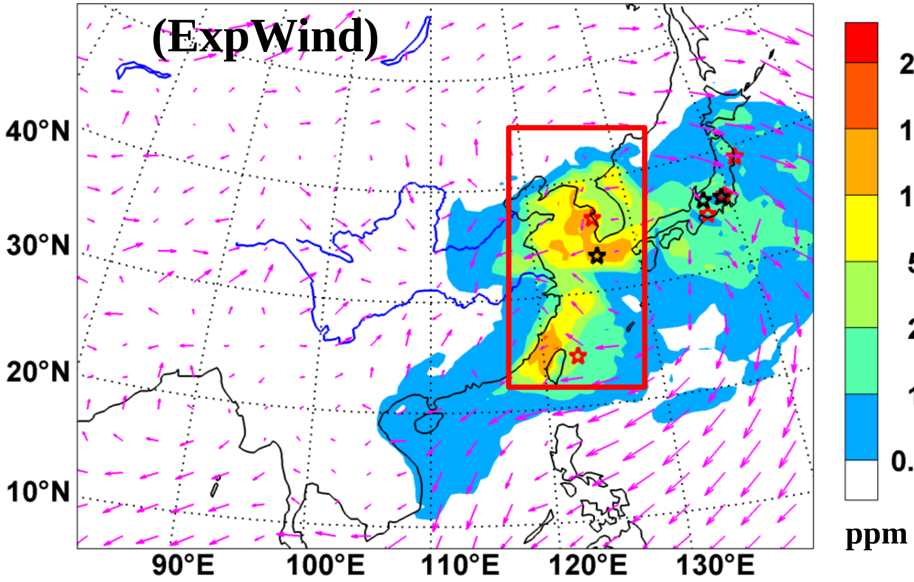
Adjustment on CO_2 uncertainty

- wind perturbations slightly adjust ensemble spreads..

concentrate over wind convergence areas

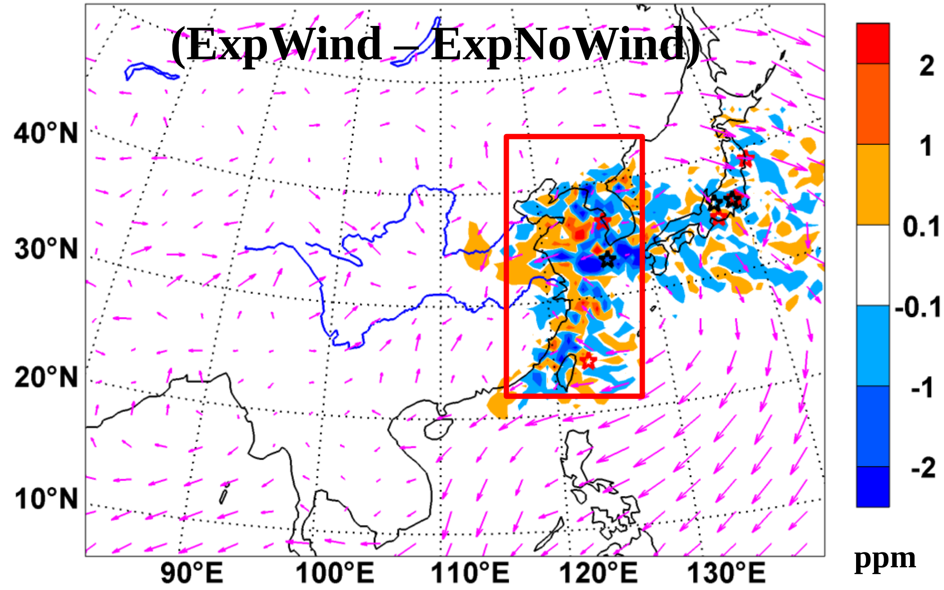
Inconsistent weak winds

CO2 background ensemble spread



0900 UTC+8 Feb. 7th

CO2 ensemble spread difference



0900 UTC+8 Feb. 7th

Ensemble spread

- sustains or decays moderately, 5 ~ 15 ppm

Adjustment on CO_2 uncertainty

- wind perturbations obviously adjust ensemble spreads.

concentrate over wind convergence areas

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Conclusion

- Development and verification of the EnKF-CMAQ CO_2 concentration assimilation system.

- Feasibility of assimilating continuous surface CO_2 concentration observations to improve CO_2 simulation accuracy in the lower troposphere.

- Substantial contribution of wind field variation associated with synoptic-scale weather systems to:
  - the variation of CO_2 simulation uncertainty
  - the adjustment of wind uncertainty on CO_2 simulation uncertainty

Future work

- For a longer timescale, the fixed additive covariance inflation
  - becomes inconsistent with variation of CO_2 concentration uncertainty
  - intensifies the damage on the original background error covariance structure constructed by model integration.

- Future EnKF–CMAQ:
  - an adaptive background error covariance inflation technique similar to Miyoshi (2011)
  - an Kalman Filter updating inflation parameters based on the “observed” inflation parameters computed from model outputs

Thank you for your attention

Observation stations

Table 1 Location of Continuous CO_2 Observing Stations

Station Name (GAW ID)	Longitude(°E)	Latitude(°N)	Altitude(m)	Institution[a]	Category	Reference
Anmyeon-do (AMY)	126.32	36.53	47	KMA	Coastal	Lee, et al. [2012]
Gosan (GSN)	126.12	33.15	72	NIER	Coastal	Yu and Kim [2011]
Ryori (RYO)	141.82	39.00	260	JMA	Coastal	Kawasato [2012]
Takayama (TKY)	137.42	36.13	1420	AIST	Mountain	Murayama [2009]
Mt.Dodaira (DDR)	139.18	36.00	840	Saitama	Mountain	Muto [2009]
Kisai (KIS)	139.55	36.08	13	Saitama	Continental	Muto [2009]
Mikawa-Ichinomiya (MKW)	137.43	34.85	50	Aichi	Continental	Ohno [2008]
Yonagunijima (YON)	123.02	24.47	30	JMA	Coastal	Kawasato [2012]

[a] Aichi: Aichi Air Environment Division; AIST: Research Institute for Environmental Management Technology, National Institute of Advanced Industrial Science and Technology; JMA: Atmospheric Environment Division, Global Environment and Marine Department, Japan Meteorological Agency; KMA: Korea Global Atmosphere Watch Center, Korea Meteorology Administration; NIER: National Institute of Environmental Research; Saitama: Center for Environmental Science in Saitama.

The category is based on Patra et al. (2008). TransCom model simulations of hourly atmospheric CO_2: Analysis of synoptic-scale variations for the period 2002–2003

We express deep gratitude to the dedicated principal investigators, research teams and support staff of the stations for providing their CO_2 observation records on the World Data Centre for Greenhouse Gases (WDCGG) website.

More experiment setting

- The study domain for RAMS–CMAQ is 6654 × 5440 km^2 on a rotated polar stereographic map projection centered at (35° N, 110° E) with 64 × 64 km^2 grid resolution.
- Biospheric CO_2 flux is generated by a vegetation photosynthesis and respiration module (VPRM). The emission inventory also consisted of anthropogenic emissions, biomass burning emission and sea-air exchange. The setting flows that of Kou et al. (2013).
- The EnKF–CMAQ, which has a 7 d spin-up run, is integrated from the initial condition on January 15 provided by the RAMS–CMAQ.
- CarbonTracker results used to generate the initial condition are provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov.

Adaptive inflation

In Miyoshi (2011), the adaptive multiplicative error covariance inflation updates the multiplicative inflation factor α by a Kalman Filter (KF) as:

$$\alpha_i^a = \frac{v_i^o}{v_i^o + v_i^b}\alpha_i^b + \frac{v_i^b}{v_i^o + v_i^b}\alpha_i^o$$

a refers to analysis, *b* refers to background and *o* refers to observation. *v* denotes the variance and *i* denotes time.
v_i^b is given by first guess, and α_i^o and v_i^o is computed from model outputs.

Similar to the method of Miyoshi, future EnKF–CMAQ will update the additive inflation factor σ (standard deviation of the white noise) by a KF as:

$$\sigma_i^a = \frac{v_i^o}{v_i^o + v_i^b}\sigma_i^b + \frac{v_i^b}{v_i^o + v_i^b}\sigma_i^o$$