Simulation of CO₂ Concentration over East Asia Using the Regional Transport Model WRF- CO₂

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Abstract

The Weather Research and Forecasting (WRF) model is used for regional transport simulations of atmospheric carbon dioxide (referred to as WRF-CO₂) for the East Asia region at the horizontal resolution of 27×27 km. The domain extends from 18°N to 51°N in latitude and 101°E to 165°E in longitude, including the islands of Japan, South Korea, North Korea and a part of China. The simulation period is limited to the year 2002. To understand the role of surface fluxes and transport, we have simulated atmospheric CO₂ using 5 different CO₂ fluxes from ocean, fossil fuel and terrestrial biospheres at various horizontal resolutions, and at hourly to monthly time intervals. The model simulations are compared with observed time series at 9 stations, which are located under different ecological and climate

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conditions. The model simulations are evaluated at different seasonal, synoptic and diurnal time scales for CO₂ and meteorological parameters, such as air temperature, relative humidity, wind speed and direction. The performance of WRF-CO₂ model is found to be satisfactory in all aspects when compared to global model simulated results obtained under the TransCom (Transport Model Intercomparison Project) continuous experiment. The WRF-CO₂ model is shown to have the ability to resolve distinct concentration variations, both diurnal and synoptic, at two closely spaced stations within 25 km. The diurnal cycles of terrestrial biospheric fluxes and the planetary boundary layer are found to be most dominant controls for CO₂ diurnal variations, whereas the surface fluxes horizontal distributions and wind directions are identified as the dominant controls for CO₂ synoptic variations. Further increase in horizontal resolution of biospheric fluxes and meteorology in WRF-CO₂ simulation is required for improving the model-observation agreement.

1. Introduction

It is well known that more than half of the total emitted CO₂ is taken up by natural absorbers like land biosphere and ocean. The rest remains in the atmosphere (Keeling et al. 1995). This fraction shows large diurnal, synoptic, seasonal and inter-annual variability, mainly over land. It happens because of the complex nature of source and sink distribution, and atmospheric transport over the land. Quantifying the behaviour of these sources and sinks is highly challenging, and precise prediction of the future growth of CO₂ over the globe demands accurate estimation of CO₂ sources and sinks at sub-continental scales. Large uncertainty persists in the estimated CO₂ fluxes by inverse modeling of atmospheric CO₂ due to the transport/forward modeling errors (e.g., Gurney et al. 2002), in particular at the continental sites (Patra et al. 2006).

Since the 1990s, different global models have been used to simulate CO₂ concentration over land and ocean (Law et al. 1996; Law et al. 2008; Patra et al. 2008). Most of these models had not only coarse resolution, but some also did not include complete meteorology for realistic representation of boundary layer height or deep cumulus convection (e.g., Taguchi et al. 2011). This is particularly important if the terrain changes sharply with different vegetation types, changing topography and human concentration. In recent years, various regional transport models with high spatial resolution have been developed (Sarrat et al. 2007; Ahmadov et al. 2009; Corbin et al. 2010). However, simulation of CO₂ using regional model has not been previously conducted over the Asia region.

Our main objective in the present study is to understand the performance of the model in relation to the observed data. We evaluate the WRF-CO₂ model performance through: (i) presentation of Pearson correlation coefficient (r) and normalized standard deviation (ω) of daily averaged observed and modeled

time series; (ii) comparison of meteorological products, (iii) comparison of diurnal variation of seasonally averaged data and (iv) study of synoptic variation of hourly data during short span of time. All evaluations are made at 9 observation stations. In the next section, the model configuration, materials and methods are given, followed by the results and discussions. Conclusions are given in Section 4.

2. Model description, emission inventory and sources of observed data

The CO₂ tracer model is implemented in WRF, jointly by the Research Institute for Global Change/Japan Agency for Marine-Earth Science and Technology (RIGC/JAMSTEC), Japan and Jadavpur University (JU), India. Our model domain extends from 18°N to 51°N in latitude and 101°E to 165°E in longitude (Fig. 1), covering all but one (Minamitorishima) of the continuous CO₂ monitoring sites in Asia (WDCGG 2011). A large part covers the Pacific Ocean, littered with a good number of islands. The Islands of Japan occupy the central part. South Korea, North Korea and a part of China are also in the western part of the domain. The majority of the observation stations are located within the Japanese archipelago, which has a very complex terrain and long coastline, highly varying topography with flat to high hill regions. Thus the 9 observation stations are located in such diverse environments as remote ocean, coastal ocean, coastal land, inland and high hills.

2.1 Model description

The WRF-Chem, Version 3 (Grell et al. 2005) has been modified for simulating atmospheric CO₂, which is an inert gas in the troposphere (Takigawa et al. 2007; Ballav and De 2012). WRF-Chem is a mass and scalar conserving air quality model dealing with transport and transformation of chemically reactive aerosol and gases. In this study, we used the ARW (Advance

Fig. 1. (a; left) Model domain with terrain height in meter (colour bar) and nine observation stations (marked by alphabet; Y: YON, H: HAT, R: RYO, C: COI, A: AMY, K: KIS, M: MKW, T: TKY, D: DDR) are shown. The alphabets K and D overlap due to the proximity of the sites. (b; right) Average distribution of CASA 3-hourly flux for 31 July 2002 is shown (in $\text{gC}/\text{m}^2/\text{day}$), and location of two big cities, Tokyo (black circle) and Nagoya (black triangle) are also marked. White areas along the coastal area, denoting no CO_2 flux are due to poor representation of the continental boundary by CASA fluxes at $1^\circ \times 1^\circ$ resolution. This problem is particularly severe for Taiwan and the Korean peninsula.

Research WRF) core model. This is the key component of the modeling system to having fully compressible non-hydrostatic equations. The grid structure is Arakawa C-grid staggering and it has terrain following

Eta ($\eta = \frac{P - P_t}{P_s - P_t}$) coordinate along the vertical direction for the purpose of meteorology. Here P is the hydrostatic pressure, P_t is the top pressure and P_s is the surface pressure.

Because the original version of WRF-Chem does not include CO_2 species, the model has been modified to incorporate anthropogenic, biogenic and oceanic CO_2 fluxes as tracers, and thus referred to as WRF- CO_2 . For our simulation, WRF- CO_2 was configured with a 27 km grid spacing domain over East Asia. Our domain has 165 grid points in the east west direction and 132 grid points in north south direction. The domain is centered at (35°N , 133°E), which is near Tokyo (Fig. 1). The model has 30 vertical layers up to 100 hPa, and 11 layers are located within 2 km above the ground level. We choose Lambert Conformal map projection for the model domain.

WRF-Chem has multiple physical, dynamical and chemical options suitable for a broad spectrum of applications. Table 1 summarizes the WRF- CO_2 configuration options selected for various atmospheric processes, adopted from Takigawa et al. (2007) and

Niwano et al. (2007) with a validation of surface concentration and vertical ozone profiles over the Kanto area in Japan. Global land use and terrain data are used from the 30 second USGS (U. S. Geological Survey) data with 24 land use categories, initial and lateral boundary conditions for the meteorological variables are used from FNL (final analysis) data of the NCEP (National Centers for Environmental Prediction; www.nomad3.ncepnoaa.gov/ncep_data) at 6-hourly interval with $1^\circ \times 1^\circ$ grid resolution. The initial and boundary conditions for five tracer CO_2 components (details in Subsection 2.2) are obtained from the Center for Climate System Research/National Institute for Environmental Studies/Frontier Research Center for Global Change (CCSR/NIES/FRCGC) atmospheric general circulation model (AGCM)-based Chemistry-Transport Model (ACTM) (Patra et al. 2008; 2009). Initial background concentrations for CO_2 tracer components is set at about 370 ppm as simulated by the ACTM.

Three dimensional grid analysis nudging available in WRF core meteorological model is used to nudge meteorological fields such as wind, temperature, and the concentration of water vapour towards NCEP FNL data to reproduce the transport of tracers during observational period. For u , v components of wind, nudging is applied for all model levels. But, in the case of temperature and water vapour, nudging is applied

Table 1. WRF model configuration used in the work.

Atmospheric Processes	WRF-CO ₂ Option
Microphysics	Cowry Single-Moment 3-Class scheme
Longwave Radiation	RRTM scheme
Shortwave Radiation	Goddard shortwave
Surface Layer	Eta similarity
Land Surface	Noah Land Surface Model (Chen and Dudhia, 2001)
Planetary Boundary Layer	MYJ scheme (Mellor and Yamada, 1982)
Cumulus Parameterisation	Grell-Devenyi ensemble scheme
Chemistry	Run five CO ₂ tracers for prescribed fluxes
Photolysis	Off
Dry Deposition	Off
Gas Phase Chemistry	Off
Aerosol Chemistry	Off
Wet Scavenging	Off
Cloud Chemistry	Off
Vertical Turbulent Mixing	On
Subgrid Convective Transport	On

for the model layers above the planetary boundary layer though the model top is 100 hpa. Folding time for nudging is chosen to be 2.8×10^{-4} second⁻¹ for all four parameters. We note here that WRF-CO₂ is an online tracer transport model in which the transport and diffusion processes of tracers are calculated using the meteorological fields at every model time step (90 seconds in this study). The CO₂ emissions are updated every hour. The first 5 days of model simulations are discarded as model spin up. Model simulations are samples at the nearest grid point of the measurement site horizontally. In vertical, when a site lies in between two model levels, linear interpolation has been done and when the site altitude is below the first model level, output at layer 1 is chosen.

2.2 Emission inventory

The input for flux data is given in three categories, namely ocean flux, fossil flux and terrestrial biosphere flux as obtained from various data inventories. The ocean flux (referred to as OC) input is given as monthly-mean air-sea exchange rate of CO₂ (Takahashi et al. 2002). Emissions due to fossil fuel burning (FS) are prepared by combining values from two sources. (1) Over Japan, the industrial emissions are taken from the Japan Clean Air Program (JCAP) at a horizontal resolution of 1×1 km (Kannari et al. 2007) and the emissions from automobiles are based on the East Asian Air Pollutant Emissions Grid Inventory (EAGrid, version: 2000). Diurnal and seasonal variations of these emissions are parameterized by an average variation prescribed in JCAP. The EAGrid 2000 automo-

bile emission data also contain variations between the weekdays and weekends (Takigawa et al. 2007). (2) The fossil fuel emissions outside the Japan area are taken from the Regional Emission inventory in ASia (REAS), which is available at $0.5^\circ \times 0.5^\circ$ horizontal resolution and without any temporal variations for 2002 (Ohara et al. 2007). The terrestrial biogenic flux input is given from two biogeochemical model simulations: (1) the Carnegie-Ames-Stanford-Approach (CASA) model (Olsen and Randerson 2004), simulated fluxes are available at $1^\circ \times 1^\circ$ horizontal resolution, and time resolution of 3-hourly (CH) and monthly (CM) intervals. (2) Terrestrial ecosystem flux is also available from the Simple Biosphere Model (SiB3) model (Baker et al. 2007) at $1^\circ \times 1^\circ$ horizontal and hourly time resolutions (SH). These CASA and SiB3 fluxes are taken from the TransCom continuous experiment.

All these fluxes are converted to WRF model grid using 5-point stencils (Krishnamurti et al. 1998) before the transport simulation. Based on our experience in an earlier study using fossil fuel emissions at two horizontal resolutions (Ballav and De 2012), diurnally varying terrestrial ecosystem fluxes at higher resolution (of the order of WRF model grid size) is desired for further improvement in the quality of WRF-CO₂ simulations. The fossil fuel emission distribution and temporal variations as used in this study always produce better model-observation agreement compared to the other fossil emission at $1^\circ \times 1^\circ$ horizontal resolution over the whole domain, as in the TransCom experiment. In this study we have chosen only the best flux combinations with FS as found by Ballav and De (2012),

Table 2. Correlation coefficient and normalized standard deviation of daily average observed and model simulated CO₂ concentration variability over the year 2002 for different tracer combinations. The r and ω for raw data, including seasonal cycle, are given within parenthesis.

Station category	Station	r			ω		
		FS+OC+CM	FS+OC+CH	FS+OC+SH	FS+OC+CM	FS+OC+CH	FS+OC+SH
Remote ocean	YON (24.47°N, 123.02°E, 30 m)	0.58 (0.56)	0.58 (0.52)	0.62 (0.68)	1.18 (0.96)	1.21 (0.98)	1.34 (1.18)
	HAT (24.05°N, 123.8°E, 10 m)	0.67 (0.60)	0.65 (0.56)	0.70 (0.73)	1.14 (0.91)	1.16 (0.94)	1.25 (1.13)
Coastal ocean	RYO (39.09°N, 141.8°E, 260 m)	0.53 (0.73)	0.53 (0.65)	0.52 (0.69)	0.67 (0.92)	0.91 (0.86)	0.94 (1.41)
	COI (43.15°N, 145.5°E, 45 m)	0.5 (0.87)	0.57 (0.81)	0.50 (0.81)	0.90 (0.87)	1.21 (0.84)	1.44 (1.53)
Inland	MKW (34.85°N, 137.4°E, 50 m)	0.59 (0.53)	0.56 (0.54)	0.55 (0.46)	0.60 (0.78)	0.72 (0.8)	0.67 (0.95)
	KIS (36.08°N, 139.6°E, 13 m)	0.40 (0.42)	0.41 (0.42)	0.41 (0.45)	0.88 (0.88)	0.90 (0.89)	0.91 (0.93)
High hill	DDR (36.13°N, 139.2°E, 840 m)	0.57 (0.57)	0.58 (0.55)	0.56 (0.53)	0.65 (0.67)	0.68 (0.68)	0.74 (0.86)
	TKY (36.13°N, 137.4°E, 1420 m)	0.34 (0.52)	0.36 (0.50)	0.39 (0.60)	0.63 (0.72)	0.72 (0.76)	0.79 (1.03)
Coastal land	AMY (36.53°N, 126.32°E, 47 m)	0.53 (0.54)	0.53 (0.54)	0.53 (0.56)	0.68 (0.74)	0.75 (0.75)	0.75 (0.83)

and focus on the analysis of processes governing the synoptic and diurnal variations in CO₂ concentrations.

Concentrations obtained from WRF-CO₂ outputs for three flux components are then added for calculating atmospheric CO₂ concentrations (e.g., FS+OC+CM, FS+OC+CH, or FS+OC+SH), which are then compared with observations. To avoid negative tracer concentrations, the initial values of WRF-CO₂ simulations have about 370 ppm as stated earlier, which were provided as initial and boundary conditions from ACTM. An offset of ~750 ppm is subtracted from the combined CO₂ tracer fields for comparison with the observed time series.

2.3 Sources of observational data

We classify the 9 sites (ref. Table 2 for locations) used in this study into 5 categories:

a. Remote ocean stations: (i) Yonagunijima (YON) is located near the northern coast of a small Japanese island and about 100 km east of Taiwan (Sasaki 2006; Tsutsumi et al. 2006). (ii) Hateruma (HAT) is located on a small Japanese island of area 12.5 km² and about 220 km east of Taiwan (Mukai et al. 2001). CO₂ concentrations at both the stations are dominated by oceanic flux during boreal summer and flux from

mainland Asia during the boreal winter (Tohjima et al. 2010).

b. Coastal ocean stations: (i) Ryori (RYO) is located halfway up a mountainous cape facing the Pacific Ocean (Sasaki 2006). (ii) Cape Ochi-ishi (COI) is located at the base of Nemuro Peninsula on the north-eastern edge of Hokkaido at the tip of a cape (Tohjima et al. 2006). Both the stations are situated in Japanese main island and are under the influence of land and ocean fluxes.

c. Coastal land station: Anmyeon-do (AMY) is located in the west coastal peninsula of Korea. It has an abundance of pine trees in the vicinity (Kim and Park 2006). The station is influenced by the land and ocean fluxes.

d. Inland stations: (i) Kisai (KIS) is located in a rural area about 50 km north-northwest of Tokyo (Muto 2006). (ii) Mikwa-Ichinomiya (MKW) is located in a plain suburban area surrounded by mountains in the north and north-east, and about 60 km south-east of Nagoya city in Japan (Iwata 2006). Both stations are mainly dominated by land flux.

e. High hill stations: (i) Takayama (TKY) is located about 15 km east of Takayama city in Japan in a cool-temperate mountainous forest area having an alti-

Fig. 2. FS component of WRF-CO₂ concentration (in ppm) at 03 UTC (a) and at 15 UTC (d); CH component of WRF-CO₂ concentration over the domain at 03 UTC (b) and 15 UTC (e) of 01 July, 2002; background level (about 375 ppm) CO₂ is cut off from both FS-CO₂ and CH-CO₂. The locations of measurement sites are marked by numbers in panel (b). Panel (c) and (f) show the PBL Height (in meter) and wind speed (in m s⁻¹) together at 03 UTC and 15 UTC respectively of the same date.

tude of 1420 m from sea level (Murayama et al. 2003). Kondo et al. (2001) have suggested that the effect of anthropogenic sources from Takayama city is less significant at the observation point compared to the anthropogenic emission signals arriving from Nagoya or Tokyo, located about 150 and 300 km southeast of Takayama respectively. (ii) Mt. Dodaira (DDR) is located about 60 km north-west of Tokyo near the east end of Sotochichibu mountain range (Muto 2006) with an altitude of 840 m. Both stations are influenced by upper air land flux.

The observed data at hourly time intervals for all these stations were obtained from WDCGG (2011), except the meteorological data for TKY (accesses through the AsiaFlux website; <http://asiaflux.net/>). The hourly-mean values are created from continuous in situ measurement of CO₂ every few minutes.

3. Results and discussion

3.1 Day-night variations of selected model products over the domain

Model simulated CO₂ concentration signals due to fossil fuel emissions are shown in Figs. 2a and d corresponding to 03 and 15 UTC (Universal Time or Z) (12 and 24 Japan standard time, JST) respectively, of 01 July 2002. During the day, FS-CO₂ component is higher by about 17 ppm around the main city of Tokyo, Japan and Busan, South Korea compared to the surrounding regions. In the night, FS-CO₂ is higher than its daytime value over most landmass regions. On the other hand, the horizontal wind pattern does not change much from day to nighttime, as the mean flow is under the influence of a slowly moving cyclonic system in the southern part of the domain (Figs. 2c, f). Variation in FS-CO₂ and wind pattern satisfies the commonly understood interactions between the net

sources of a chemical species and day-night variations in planetary boundary layer (PBL) height. The PBL generally extends up to about 1000 m over Japanese main islands and higher than 2000 m over the mainland China during the day (Fig. 2c). During the night (Fig. 2f), PBL heights are typically lower than 400 m in latitudes north of 30°N. However, over the sea, the PBL height does not change significantly between day and night, as the sea-surface temperature does not show strong diurnal variation. The PBL heights are always higher (~1000 m) in the southern latitudes of 25°N compared to the northern latitudes over the sea.

The WRF model simulated biological tracer CH is shown in Figs. 2b and e. The CH fluxes over land are strongly negative during the mid-day due to the draw-down of atmospheric CO₂ by the terrestrial ecosystem during photosynthesis, while the nighttime respiration (i.e., release of CO₂ to the atmosphere) dominates the carbon exchange by the ecosystem. Thus the WRF-CO₂ simulated CH tracer shows less value over the land regions at daytime compared to the oceanic surroundings. However, during the night most land regions exhibit accumulation of ecosystem respired CO₂, up to about 15 ppm, trapped within the shallow PBL.

3.2 Model performance for daily-average CO₂ concentration

In this section we analyze the correlation coefficient (r) and normalized standard deviation (ω) between daily averaged observed data and model output for the entire year 2002. The ω is calculated by normalizing the modeled variability (1σ) with the observed variability. In case of model output, 3 tracer combinations are prepared, i.e. FS+OC+CM/CH/SH, by combining oceanic and fossil CO₂ signals with three different terrestrial biosphere signals (CM, CH and SH, respectively). The results obtained in respect of the 9 observation stations are presented in Table 2, where the actual time series as well as its deseasonalized data are used for the calculation. We find that for the actual time series, $0.42 \leq r \leq 0.87$ and each of the r in Table 2 holds in 99% of cases (i.e. statistically 1% significant) following Student t-test with almost 360 data points. The correlation is best for all combinations at COI for the raw time series due to the presence of a deeper seasonal cycle there, and for its northern-most location among all sites. The correlations for raw time series are also impressive at RYO.

After deseasonalizing of the time series using the Nakazawa et al. (1997) filtering technique, we obtain the synoptic variations in CO₂ concentrations (as defined in Patra et al. 2008). Examples of deseasonal-

ized time series for observed and model data are shown in Figs. 3a to 3d for the 4 stations RYO, AMY, KIS and MKW respectively. In all the stations, synoptic variations become stronger during the summer months (June-August) compared to the other seasons at most sites. Maximum synoptic variations occur at KIS without significant seasonal differences in the amplitudes of variability because this site is located close to strong fossil fuel emission signals around Tokyo. Of these four sites, the lowest amplitude of synoptic variation is observed at RYO, which is a high latitude station located in a desolate area. In case of AMY and MKW, synoptic variations are greater during the summer season, and the variations are weakest in winter. The correlations for simulated and observed daily average CO₂ concentrations are of similar order at all sites, ranging from ~0.4 at TKY to a maximum of 0.7 at HAT. One can note from Table 2 that r does not differ much for CM, CH or SH combinations. This is because the synoptic variations in CO₂ are produced by large-scale meteorological/frontal systems. As we are using daily average values for this analysis, the diurnal fluxes show even lower impact. The synoptic changes in winds bring different flux signals from different areas around a measurement site.

Correlation coefficients for the TransCom global models (Patra et al. 2008) may be compared with our results using a regional model. Six stations are common to their analysis, and the r at these stations for WRF-CO₂ is always higher or close (Table 2) to the maximum r obtained for 19 global models (range of r at YON = 0.37 to 0.61, RYO = 0.01 to 0.50, MKW = 0.10 to 0.51, DDR = 0.04 to 0.60, TKY = 0.00 to 0.45 and AMY = 0.13 to 0.55 for the CH combination) in the TransCom-continuous experiment. This is expected, as the resolution of global models is much poorer compared to WRF.

We further present comparison of correlation coefficients with ACTM, which was used for supplying boundary conditions to the WRF-CO₂. The highest r in cases of ACTM for all the combinations of terrestrial flux (CH, CM and SH) combinations are 0.47 at YON, 0.33 at RYO, 0.30 at MKW, 0.29 at DDR, 0.29 at TKY, 0.34 at AMY. These correlation coefficients are lower than the lowest r obtained for regional model WRF-CO₂ (ref. Table 3).

As ω is the ratio of standard deviations between the model and observed data, the value of 1 represents the situation when both have similar fluctuations. The values are not far from 1 at all observation stations either for actual or deseasonalized data (Table 2). One can note that, ω generally increases gradually as one

Fig. 3. Time series of deseasonalized observed and model CO₂ concentration (in ppm) using FS+OC+CH fluxes for the year 2002 at (a) RYO, (b) AMY (c) KIS and (d) MKW.

moves from CM to CH and then to SH tracer combination. The possible reason is time resolution in input biospheric flux because time averaging decreases from monthly to 3-hourly and then to hourly values.

When we consider the global models, ω is much less than 1 in a majority of the cases for two seasons, summer and winter. This shows that the global models give, in general, much less synoptic variation compared to the observations. For deseasonalized time series at the two remote ocean stations, ω is conspicuously greater than 1 for all biological tracer combinations in case of WRF. Observed synoptic variation at these two remote stations are quite low, but the model cannot reproduce this low synoptic variation. Our results

suggest that horizontal resolution for both CO₂ fluxes and transport models have equally important contributions in improving the model-observation synoptic variability agreement (as shown in Patra et al. 2008).

3.3 Meteorology

In order to understand the role of meteorology in simulating atmospheric-CO₂, we consider 3 significant meteorological parameters, i.e. Air Temperature (AT), Relative Humidity (RH) and Wind Speed (WS), which are available at 9 observation stations. The wind direction contributes significantly to CO₂ concentration, as transport is determined by it. As wind direction is a highly fluctuating parameter, we are not comparing

Table 3. Correlation coefficient and Root Mean Square Error of different daily averaged meteorological parameters, relative humidity (RH, in %), air temperature (AT, in °C) and wind speed (WS, in m s^{-1}) at 9 observation stations (blank fields are due to unavailable measurements).

	Station	Winter			Summer		
		RH	AT	WS	RH	AT	WS
<i>r</i>	YON	0.81	0.94	0.95	0.54	0.63	0.94
	HAT	–	0.92	0.96	–	0.54	0.97
	RYO	0.65	0.93	0.82	0.83	0.95	0.76
	COI	–	0.93	0.89	–	0.87	0.87
	MKW	0.72	0.91	0.89	0.83	0.93	0.63
	KIS	0.89	0.83	0.8	0.84	0.93	0.66
	DDR	0.79	0.95	0.58	0.84	0.97	0.34
	TKY	0.45	0.97	0.64	0.84	0.97	0.58
	AMY	0.77	0.91	–	0.57	0.82	–
RMSE	YON	6.39	1.48	0.91	6.5	0.71	0.87
	HAT	–	1.52	1.47	–	0.9	1.6
	RYO	19.1	2.17	1.34	7	1.45	1.15
	COI	–	1.91	2.21	–	1.92	1.51
	MKW	15.83	2.95	2.88	7.64	1.91	2.66
	KIS	13.75	1.66	1.63	6.32	2.31	1.2
	DDR	9.35	1.1	6.55	7.67	1.33	4.35
	TKY	18.24	1.03	6.38	12.65	1.13	4.04
	AMY	8.71	3.23	–	8.78	1.67	–

it here. Correlation coefficient and Root Mean Square Error (RMSE) are evaluated between observed values and model meteorological output, as simulated by the WRF dynamical core. The results are presented in Table 3 for two extreme seasons, namely the boreal summer and winter. However, our study covers all four seasons of the year 2002.

We find that the AT has the best and a very regular r in all seasons and at all observation stations. Correlation varies from 0.83 to 0.99 if that of two remote ocean stations in summer is neglected. AT has also low RMSE (average being 1.62, considering all four seasons). The second best r comes in case of WS. If we neglect two high hill stations, r varies from 0.63 to 0.97 throughout the four seasons. Also, r for WS is, in general, much higher in winter. RMSE of WS (average comes to 1.77) is not much different from that of AT if we neglect the two high hill stations (DDR and TKY). Though r of RH is quite close to that of WS, its RMSE is slightly higher (average rises to 10.52). However, the average RMSE of RH as a fraction of absolute magnitude is less than that of the wind speed (15% for RH and 32% for WS), both lie within the range of their variability (1- σ standard deviations are 20% and 45% for RH and WS, respectively). Here, all the r are accepted in 99% of cases using Student t-test for almost 90 samples. In

order to understand the performance of the model in respect of wind direction, one can compare the wind pattern from model and observation. In Fig. 4, wind patterns have been presented for the station KIS, where the match is good in all four seasons. However, the magnitude does not always match well. An example is the station MKW, where match is quite poor in all four seasons, which is likely to be due to the complex coastline around the measurement point. On the whole, WRF model produces realistic simulation of meteorology over this domain.

3.4 Diurnal variation of hourly data

The diurnal CO_2 concentration cycle is directly dependent on the diurnal cycle of some of the meteorological parameters, like temperature vertical profile and wind vectors. In winter, the diurnal cycle is strongly determined by the meteorological parameters, whereas in summer the biological fluxes also have equally large contributions. In this section, we consider the seasonal average diurnal variations in CO_2 concentration from hourly data. All 9 stations are considered and all four seasons are studied; and it should be mentioned that all cases with an absolute magnitude of r above 0.51 are acceptable in 99% of cases according to Student t-test with 24 samples. Figure 5 shows the average

Fig. 4. Observed wind rose plot at the station KIS for the season (a) winter, (b) spring, (c) summer and (d) autumn. Model produced wind rose plot at the station KIS for the season: (e) winter, (f) spring, (g) summer, and (h) autumn. Wind speed is given by different color codes: yellow (0–1.5), orange (1.5–3.0), green (3.0–5.0), cyan (5.0–8.0), blue (8.0–10.0) and red > 10.0. All measures are in m s^{-1} . The bigger circle gives the maximum frequency of occurrence in time.

diurnal cycle for two seasons at 6 stations only i.e. RYO (Figs. 5a, b), AMY (Figs. 5c, d), KIS (Figs. 5e, f), MKW (Figs. 5g, h), DDR (Figs. 5i, j) and TKY (Figs. 5k, l), for observations and model (FS+OC+CH). On the other hand, the average diurnal cycle amplitude for model (FS+OC+CH/SH) and observations at four different stations is presented in Fig. 6a and 6b for the two extreme seasons, namely the boreal summer and winter respectively.

At MKW and KIS, the model produces very high r (0.95 to 0.99 for MKW and 0.79 to 0.92 for KIS) and the amplitude of mean diurnal cycle of CO_2 concentration at MKW comes closest for CH tracer in summer (22.3 ppm and 35.1 ppm for observation) as shown in Fig. 6a and for SH tracer in winter (Fig. 6b; 12.5 and 10.8 ppm for observation). In the case of KIS, the model produced the highest amplitude variation in summer is 31.4 ppm (37.4 ppm observed), and that in winter is 20.4 ppm (23.7 ppm observed). Both these model amplitudes occur for SH flux combinations, and

the results are also similar for CH flux combinations. In winter, KIS has a rise in CO_2 in the morning, which is captured partially by the model. In the model, it is due to contribution from fossil fuel and may be due to transport from Tokyo, which is only 50 km away. The next in line, in order of observed CO_2 amplitude, is AMY (12.0 ppm in summer and 4.8 ppm in winter), whereas, the model produces a highest amplitude of 6.6 ppm in summer and 3.3 ppm in winter.

The above results may be compared with the corresponding simulated amplitudes by TransCom global models (Law et al. 2008). In case of MKW and KIS, a majority of the TransCom models have produced much weaker mean diurnal cycle amplitude in summer. On the other hand, a majority of the models at AMY have produced much higher values compared to the observed magnitude. The model WRF- CO_2 can capture the diurnal amplitude to a reasonable extent and phase to a large extent at these 3 stations, displaying distinct characteristics.

Fig. 5. Seasonally averaged diurnal amplitude of CO_2 variation (in ppm) about the mean for observed and model output at (a) RYO in summer, (b) RYO in winter, (c) AMY in summer, (d) AMY in winter, (e) KIS in summer, (f) KIS in winter, (g) MKW in summer, (h) MKW in winter, (i) DDR in summer, (j) DDR in winter, (k) TKY in summer and (l) TKY in winter.

The observed diurnal amplitude variation is quite low at HAT, YON and COI stations both in summer and winter, though YON has highest diurnal amplitude in summer among the three, which cannot be captured by the model. In all three stations, the model has no biological flux and only small amplitude of fossil flux. So the observed amplitude at YON in summer is due to

local causes, which the model cannot identify. In case of HAT and COI, the amplitude of the mean diurnal cycle of the WRF model CO_2 in winter is higher than the amplitude in summer, contrary to the observations. At RYO, the regional model is excellent both in phase and amplitude (Figs. 5a, b and Figs. 6a, b). In case of DDR, WRF- CO_2 captures the diurnal amplitude well

Fig. 6. Amplitudes of mean diurnal cycle for model (FS+OC+CH/SH) and observation at different observation stations for two seasons: (a) boreal summer (b) boreal winter.

in both the seasons, though the phase matching is sufficiently poor in summer (Figs. 5i, j). On the other hand, the diurnal amplitude simulation is poor at TKY in both the seasons, though r is high (≥ 0.96) in summer (Figs. 5k, l).

3.5 Case studies for synoptic variation of CO_2 concentration

In this section we present two case studies, mainly to examine the performance of the model over a short duration in two extreme seasons, namely winter and summer. In the first case (Fig. 7), we consider 6 days in winter (05 to 10 February) when the sky is almost clear. The model simulated CO_2 concentration for the tracer combination FS+OC+CH and wind are presented in Figs. 7a to 7c for three successive days at the same hour of 15 UTC (midnight for JST). In Fig. 7a, wind speed is low over Japan and Korea, so the concentra-

tion is high (~ 408 ppm) over the two countries. But, the wind strengthens over Korea and the concentration also falls by 10 ppm over a large part of the country in the next 24 hours (Fig. 7b). On the other hand, the wind continues to be poor over Japan and the concentration also remains high. At 15 UTC, 07 February, the wind becomes strong ($\sim 10 \text{ m s}^{-1}$) over major parts of Japan (Fig. 7c) and the concentration falls sharply (by 20 ppm), but elevated CO_2 concentrations are seen on the eastern side of Japan over the Pacific Ocean. The change in CO_2 is not significant during this period over the ocean because the emissions are much lower compared to the land regions.

Next, to examine the model performance for synoptic variation over the individual stations, we consider the time series of hourly CO_2 concentrations at 9 individual stations for the 6 days mentioned above. Here, the concentration and wind direction are plotted

in the same figure so as to examine any inter-relation between the two. Measurements of wind directions are not available at AMY. Over 3 stations, namely HAT, YON and COI (Figs. 7d, e, i), the observed as well as model simulated CO_2 concentration does not vary much, and the average r and ω for three stations are 0.54 and 1.27 respectively. To a lesser extent, the observed variation has been captured at RYO, with r being 0.48, and for TKY, the same is 0.31. Both the model and observed data have shown synoptic variability, but clear matches in phase of the variabilities led to poor correlation at TKY. Average ω for the two stations is relatively high at 1.97. The observed time series at AMY (Fig. 7l) begins with a large amplitude variation that is not so strong on other days; the initial high variation is captured well by the model, though the smaller observed oscillations afterward are not captured very well. Despite that high correlation and close unity NSD are obtained at this location ($r = 0.84$ and $\omega = 0.82$). The model also has largely captured the synoptic variations at DDR (Fig. 7h), in spite of some shift in phase in places ($r = 0.76$ and $\omega = 0.62$). Very strong synoptic fluctuation is observed at KIS and MKW (Figs. 7k, j). The model is able to capture the synoptic variation, both in magnitude (up to 50 ppm) and phase at KIS ($r = 0.57$ and $\omega = 1.04$) and at MKW ($r = 0.6$ and $\omega = 0.68$).

Simulation of wind direction is reasonably well at 7 available stations (Fig. 7). We now show two specific examples of how the wind direction plays an important role in changing CO_2 concentration at the sites. At 00 JST of 09 February, a large drop in observed CO_2 concentration (389.3 ppm) is observed at MKW, but the concentration was much higher at 20 JST, 08 February (417.3 ppm) and again at 03 JST, 09 February (408.2 ppm). These changes on CO_2 variations correspond to wind direction shift from south-east to north and again to south-east. When the wind direction is southeasterly, there is strong possibility of transport from a big city, Nagoya, which vanishes when the wind direction is changed towards North. The second example is that of the variations at KIS. Incidentally, all peaks in CO_2 concentration are linked with southeasterly or southerly wind directions. Under these wind regimes, transport of CO_2 emissions from Tokyo is observed at KIS.

The second case study is carried out for 6 days in the summer month of July (from 08 to 13). During this period two closely located cyclonic systems enter the domain. Model produced CO_2 concentrations for the combination FS+OC+CH and the wind are presented over the entire domain for 3 successive days at the same time of 15 UTC, starting from 09 July (Figs.

8a to c). In Fig. 8a, one cyclonic system has reached the southern part of Japan on 09 July. Strong wind (15 m s^{-1}) is affecting the Japanese land area and in its wake, CO_2 concentration gets dispersed. Tokyo and the surrounding areas are showing the highest CO_2 concentration (~ 408 ppm) of the entire country. The center of the system moved close to Tokyo on 10 July (Fig. 8b). The concentration over the region tends to go up as wind is calm over the center of the cyclonic system, presumably due to trapping of emissions within it. The difference in concentration between the low and high wind regimes is about 30 ppm. Strong wind affects only the north-central ($\sim 40^\circ\text{N}$) part of Japan on 11 July and the concentration falls substantially (by 18 ppm), though it increases by 14 ppm at the center of the cyclonic system. Concentration over Korea increases by 18 ppm during 9–11 July. The other cyclonic system located at the south western corner of the domain does not move much during these 3 days, so its impact on CO_2 concentration is not visible.

Time series of hourly CO_2 concentrations along with the wind direction over 9 stations are presented in Fig. 8d to 8i for 6 days from 08 to 13 July. In general, the relative variation pattern in concentration remains almost the same over 9 stations as in the previous case, though the summer shows higher amplitude variabilities if compared with winter. Again, the observed concentration does not vary much over the 3 stations, namely HAT, YON and COI (Figs. 8d, e, i). The model gives less diurnal variation compared to the observations, the average ω is 0.6. At HAT, the model can pick up most of the crests and troughs of the time series ($r = 0.45$), with relatively poor performance at YON and COI (r is 0.14 and 0.26 respectively). Both HAT and YON showed a drop in concentration on 12 July, which was captured by the model in both the places. On that day, a high pressure existed at both places, which drove away the wind along with CO_2 . The next high order of diurnal variation is found at TKY and RYO, and further higher variation occurs at DDR and AMY. This order is maintained as in the previous case. Performance of the model is quite good at these four stations, as a majority of crests and troughs in the present time series are captured well by the model (r varies from 0.44 to 0.60). Except at AMY ($\omega = 1.22$), ω is less than 1 (varying from 0.45 to 0.73) at the three other stations. Here, very high diurnal variation is also observed at MKW and KIS (Figs. 8j, k). Performance of the model in capturing the diurnal variation phase is quite good (average $r = 0.51$), though the amplitude of variation cannot be reproduced on many occasions, particularly at MKW ($\omega = 0.42$). The maximum observed

Fig. 7. Model simulation of CO₂ concentration (in ppm) for the combination FS+OC+CH and vector winds over the domain for 3 consecutive days of (a) 05 February, (b) 06 February and (c) 07 February 2002 at the identical hour of 15 UTC. Observed and model simulated CO₂ concentrations (in ppm) and wind direction (in degree) are presented for 6 consecutive days during 05–10 February 2002 at all the sites are shown in panels d–l. The time along the x-axis for panels d–l are in JST.

Fig. 8. Model simulation of CO₂ concentration (in ppm) for the combination FS+OC+CH and vector winds over the domain for 3 consecutive days of (a) 09 July, (b) 10 July and (c) 11 July 2002 at the identical hour of 15 UTC. Observed and simulated CO₂ concentration (in ppm) and wind direction (in degree) are presented for 6 consecutive days from 08–13 July 2002 at the sites (panels d–i). The time along the x-axis for panels d–i are in JST.

diurnal amplitude at MKW is 70 ppm, which occurs on 09 July and falls to barely 10 ppm on the next day, when the system comes close. In case of KIS, normal day diurnal amplitude is nearly 40 ppm, but it drops to 20 ppm at the time of impact of the system. Here, the model largely captures the pattern of variability at KIS ($\omega = 0.89$), but the amplitude of variation cannot be captured at MKW. Again the wind direction simulation is reasonably well, though the model cannot reproduce the high fluctuations.

All the r mentioned above for the two cases are acceptable in 99% of cases (except r at YON during 08–13 July) according to Student t -test the number of data points are either 144 or slightly less. One important achievement of the model WRF-CO₂ is its ability to resolve different CO₂ concentration variations at KIS and DDR, though they are located within 25 km, and at height of 13 and 840 m above the mean sea level, respectively. This has occurred because of higher resolution of the regional model along with high resolution of fossil fuel emissions input, which has high intensity around the Tokyo area. This shows that the regional model is capable of capturing the mesoscale systems well. From these two case studies, we find that the model has poor capability in capturing phase in summer, though it can reproduce the high diurnal variation and effect of meteorological parameters on its transport. The model produced diurnal amplitude in winter time is mostly on the higher side. The poor diurnal cycle simulation in summer could thus be attributed to the low spatial resolution ($1^\circ \times 1^\circ$) in terrestrial ecosystem fluxes.

4. Conclusions

The regional model WRF-CO₂ has been developed jointly by the RIGC/JAMSTEC and JU for simulating CO₂ concentrations at high spatial resolutions (presently set at 27×27 km) over the East Asian domain. The model contains WRF-ARW meteorology at its core, and 5 different CO₂ fluxes are transported using standard set of dynamical parameterizations. The results are compared with observed time series meteorological parameters and CO₂ concentrations at 9 sites and hourly/daily time intervals. This model setup can reproduce the significant meteorological parameters quite well, which are fundamental for better reproduction of tracer transport in the model. The regional model has higher resolution than the global models, e.g., in TransCom continuous experiment, and this helps to capture sharp change in diurnal variability in concentration within a much shorter spatial distance. This aspect is clearly demonstrated in case of simu-

lating CO₂ concentration variations at DDR and KIS sites, which are separated by approximately 25 km. This leads to the expectation that, as the resolution of the model increases with availability of higher resolution data for input (meteorological and surface fluxes), performance of the model in simulating chemical will increase.

For simulating diurnal and synoptic variations, model errors can be attributed to site locations, model resolution, choice of land surface flux and spatial-temporal homogeneity in surface fluxes. These errors are supposed to amplify in the nocturnal boundary layer when surface emissions of CO₂ become strongly stratified in the vertical, resulting in difficulty for the coarse resolution models to simulate diurnal cycle accurately. WRF-CO₂ model is shown to overcome some of these limitations through realistic representation of meteorology, e.g., the air temperature and winds. However, further improvement in representation of the terrestrial biosphere fluxes by increasing horizontal resolution is required (Fig. 1b) for simulating the diurnal and synoptic variations accurately. In addition, the horizontal and vertical resolution of the WRF-CO₂ model should also be increased for realistic representation of the complex coastline and orography of the Japanese archipelago, respectively.

We considered 5 different types of station and two extreme seasons for evaluating the model performance. The model simulated synoptic variability correlated well (r in the range of 0.36 to 0.65 for FS+OC+CH combination) for all sites and normalized standard deviations in the range of 0.68 to 1.21 for the whole year of 2002. The highest correlation coefficients found at each sites for ACTM simulations (among 3 different flux combinations) are lower than the lowest r calculated using WRF-CO₂ at each site for the same 3 sets of fluxes, though the simulation of mean diurnal cycles is not uniform across the sites. However, an excellent match (r over 0.9) is obtained at several sites. Out of the two case studies, there was a system in one case, and in the other the weather was clear. Performance of the regional model is quite satisfactory under all situations. Where meteorology fails, performance of the model also deteriorates. In particular, failure to simulate the wind direction precisely causes poor simulation of synoptic variations in CO₂. A possible example may be MKW when the system comes closest to the station.

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