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Technical Information

Development of an Emissions Processing System for Climate Scenario Inventories to Support Global and Asian Air Quality Modeling Studies

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ABSTRACT

Climate change is an important issue, with many researches examining not only future climatic conditions, but also the interaction of climate and air quality. In this study, a new version of the emissions processing software tool - Python-based PRocessing Operator for Climate and Emission Scenarios (PROCES) - was developed to support climate and atmospheric chemistry modeling studies. PROCES was designed to cover global and regional scale modeling domains, which correspond to GEOS-Chem and CMAQ/CAMx models, respectively. This tool comprises of one main system and two units of external software. One of the external software units for this processing system was developed using the GIS commercial program, which was used to create spatial allocation profiles as an auxiliary database. The SMOKE-Asia emissions modeling system was linked to the main system as an external software, to create model-ready emissions for regional scale air quality modeling. The main system was coded in Python version 2.7, which includes several functions allowing general emissions processing steps, such as emissions interpolation, spatial allocation and chemical speciation, to create model-ready emissions and auxiliary inputs of SMOKE-Asia, as well as user-friendly functions related to emissions analysis, such as verification and visualization. Due to its flexible software architecture, PROCES can be applied to any pre-gridded emission data, as well as regional inventories. The application results of our new tool for global and regional (East Asia) scale modeling domain under RCP scenario for the years 1995-2006, 2015-2025, and 2040-2055 was quantitatively in good agreement with the reference data of RCPs.

Key words: Emissions processing, Climate scenario, Air quality, Global and Asia modeling

1. INTRODUCTION

Comprehensive atmospheric chemistry transport models (CTMs) are an essential tool for understanding the interactions between emissions and atmospheric chemistry, under various meteorological conditions. The performance of comprehensive air quality models has been gradually improved over the past few decades. A coordinated set of emission inputs need to be supplied, based on the air quality modeling framework, such as spatio-temporal distribution and chemical mechanism, for each CTM. Emission processing systems that can transform emissions data into specific formats required by CTMs are needed. Recently, some of these tools have been developed and implemented for emissions processing, in addition to being widely used for air quality simulations (UNC, 2012; Woo *et al*., 2012; Wang *et al*., 2011; Baldasano *et al*., 2008; Borge *et al*., 2008; Samaali *et al*., 2007).

Climate change is becoming an increasingly important global issue, with scientists working towards understanding not only the climate change scenario in future, but also the interaction between climate and air quality. The Special Report on Emissions Scenarios (SRES), published by the Intergovernmental Panel on Climate Change (IPCC), was used in the IPCC's Third Assessment Report (TAR) and the Fourth Assessment Report (AR4; Nakicenovic *et al*., 2000). The emissions scenarios in SRES have been widely used to create potential climate change scenarios for future, through comprehensive integrated modeling systems. The new set of climate change scenarios, namely the Representative Concentration Pathways (RCPs), has been provided in support of IPCC's Fifth Assessment Report (AR5). The RCPs have been selected from existing literature to span the full range of possible trajectories for future greenhouse gas concentration through the year 2100 (van Vuuren *et al*., 2012, 2011; Moss *et al*., 2010). In total, 4 scenarios were developed, leading to radiative forcing levels of 8.5, 6.0, 4.5 and 2.6 W/m^2, by the end of the 21st century.

The main purpose of this paper is to present the development of a new emissions processing system (Python-based PRocessing Operator for Climate and Emission Scenarios; PROCES) for climate scenario inventories, to support climate and CTM modeling studies. This tool covers a global scale modeling domain, which mainly supports the GEOS-Chem model, and regional scale modeling domain that supports comprehensive air quality models, such as the Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006; Byun and Ching, 1999) and the Comprehensive Air Quality Model with Extensions (CAMx; ENVIRON, 2013) for Asia.

PROCES is composed of one main system and two units of external software. One of the external software for this processing system was developed using the GIS commercial program, which was only used to create an auxiliary database, such as spatial allocation profiles. The other external software is the SMOKE-Asia modeling system (Woo *et al*., 2012) that allows the creation of model-ready emissions for regional scale models in Asia. The main system was coded using Python version 2.7, with an extension module (numpy, scipy, etc.). In this respect, the main software module would be virtually running in all the operating systems (OS), being available free of cost with GNU, the General Public license. To demonstrate the applicability of PROCES, RCP scenario inventories were applied for the years 1995-2006, 2015-2025 and 2040-2055.

The structure of this paper is as follows. In Section 2, the methodology of developing global and Asian emission processing systems is described, including its main processing capabilities, the parameters, inputs and outputs. The application results of our tool on global and regional (East Asia, in this case) scale modeling domain under RCP scenarios are presented in Section 3. Finally, the summary and conclusions are presented in the last section.

2. METHODOLOGY

PROCES is an open source software, created with the GIS commercial program and SMOKE-Asia (Woo *et al*., 2012) modeling system. We classified the main software into two major systems, depending on the modeling scale. Each module in the global scale processing system offers the ability to edit the input inventory, eventually creating model-ready emissions to support the GEOS-Chem model. The general framework for global scale processing is illustrated in Fig. 1. The regional scale processing system for Asia was designed to create SMOKE-ready inventory and other

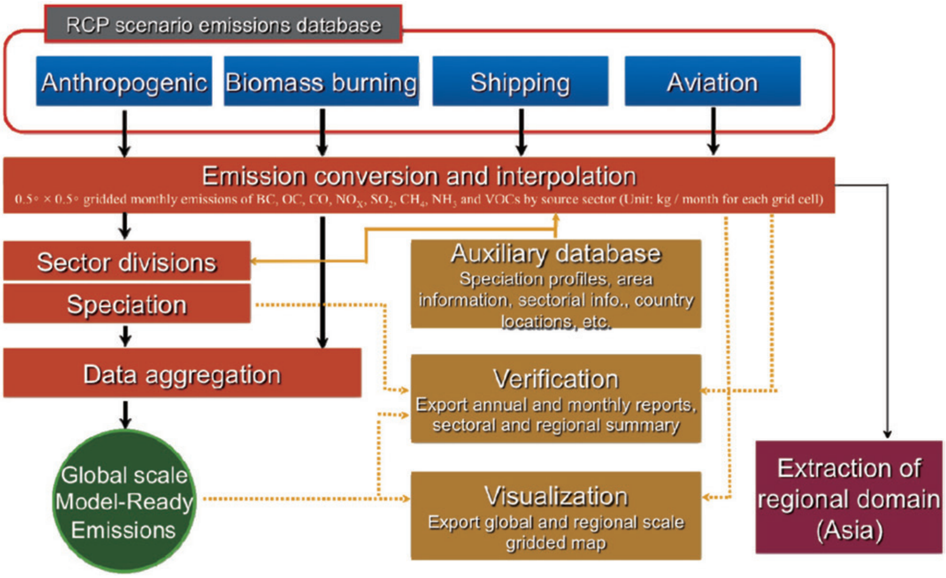

Fig. 1. Detailed schema of global emissions processing.

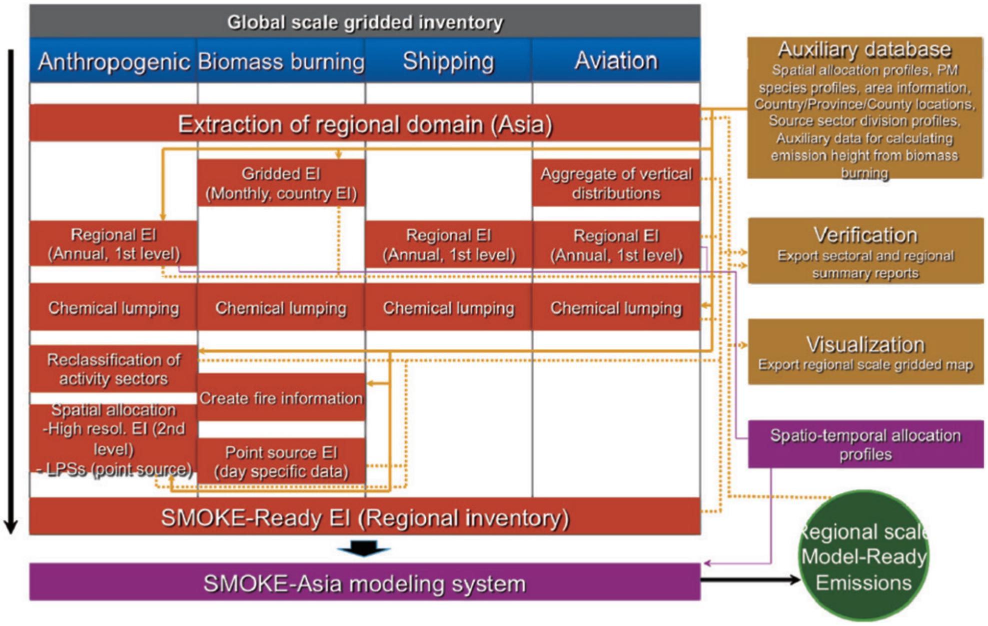

Fig. 2. Detailed schema of Asia emissions processing.

Table 1. Summary of the RCPs emission inventory dataset.

Item	Description
Domain	40 regions of the globe
Species	BC, OC, CO, NO_x, SO_2, CH_4, NH_3, VOCs
Spatial resolution	0.5° × 0.5° grid resolution
Temporal resolution	Monthly
Sectors	*Anthropogenic: ENE, IND, SLV, DOM, TRA, WST, AGR, AWB Biomass burning: Forest fire, Glass fire International shipping and Aviation
Period	2000-2100, every 10 years
Data availability	RCPs database available online at http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=about

*ENE (Energy production and distribution), IND (Industrial processes and combustion), SLV (Solvent production and use), DOM (Residential and commercial comb.), TRA (Land transport), WST (Waste treatment and disposal), AGR (Agricultural sector), AWB (Agricultural waste burning)

necessary input files. The regional scale CTM model-ready emissions in the Asian domain are subsequently created by SMOKE-Asia modeling system (Fig. 2). The parameters (speciation profiles, spatial allocation profiles, source sectors mapping table, change factors, etc.) are calculated before emissions processing and included in the auxiliary database of this system. The output files are in text format by default. However, they can be extended to create NetCDF (Network Common Data Form) format, to meet the requirements specific to a particular model, such as CMAQ.

The key elements of the RCPs inventory are listed in Table 1. The RCPs inventory, being the input file of our system, covers 40 regions across the globe. Emissions are provided for eight major pollutants, with a monthly resolution grid of 0.5° × 0.5°, in NetCDF format. Within the RCP scenario period, RCP inventories are provided every 10 years. Therefore, filling the gap between subsequent decadal emissions by annual ones is also required for supporting seamless CTM simulations.

We summarize the following major improvements and changes in PROCES thought to be necessary. First, future emissions under climate scenarios are easily calculated in the system. Unlike previous processing systems that require user specific pre-processing to project future emissions, PROCES allows the emission projection or interpolation using the gridded dataset as well as projection parameters within the model domain. Second, Climate scenario datasets may have its limitations for directly applying air quality modeling studies. Complementation of insufficient information for emission processing, such as detailed level of emission sectors and point source information, is systemically conducted. In order to make sufficient details, assistance functions, such as subdivision of emission sectors, grid emission to regional inventory, extraction of monthly profiles, allocation of point source parameters, are consisted in PROCES. Third, verification functions are involved in the processing system, which easily verify quantitative changes for each processing steps and visualize for intermediate and final outputs. Detailed processing functions in PROCES are described below sub-chapters.

2. 1 Global Scale Emissions Processing

A detailed description of all the processing functions, inputs, outputs, and parameters is provided in this subsection.

2. 1. 1 Emission Conversion and Sector Allocation

The conversion and interpolation function allows calculating and converting the emission sources in each grid cell of the entire gridded inventory for the target years. The interpolation method described in formula (1) was used to generate data for missing years from the input scenario inventory. To maintain the detailed spatial variation, it was applied at each grid-cell level. Even if the emissions from a specific sector in a certain grid were newly added or eliminated for the next decade, it was estimated to proportionally increase or decrease every year. For a given pollutant from each source sector, the following calculation was carried out:

$$E_{Y_mP,S,ij} = E_{Y0_m,P,S,ij} + \left(\frac{Y - Y0}{Y1 - Y0}\right)(E_{Y1_m,P,S,ij} - E_{Y0_m,P,S,ij})(TF \cdot AF), \tag{1}$$

where $E_{Y_mP,S,ij}$ is the emission from source sector S, for pollutant P, during the target month of year Y_m at each grid cell (i, j). Y0 and Y1 are the representative years provided by the input scenario inventory, which is generally at 10-year intervals. TF and AF are the time and area unit conversion factors, respectively.

The enhanced level of detail in the source sectors is important because they represent different types of emission activities, connected to emissions processing. Prior to the chemical speciation process, six simple RCP emission sectors for VOCs were mapped to a more detailed level. The details of the sectors were obtained from the EDGAR 3.2 FT 2000 inventory (Olivier *et al*., 2005). Table 2 describes the source sector mapping between RCPs and the EDGAR inventory. The transportation sector for Asia in particular, was mapped into the sectors in the regional inventory, TRACE-P 2000 (Streets *et al*., 2003), which would be more representative of Asian activities.

2. 1. 2 Chemical Speciation

Emissions speciation is required for CTMs that use “model species” to conduct atmospheric chemistry calculations. These functions in our system should be applied to monthly gridded inventories after sector division calculations. The chemical speciation function consists of two steps. Firstly, VOC emissions for each detailed source sector were speciated according to the SAPRC99 chemical mechanism. We used a method similar to that applied by the US EPA, as we mainly used their speciation profile and reference table, with US source classification scheme. Moreover, the source mapping methods between EDGAR and US source sectors was the same as in Woo *et al.* (2012). The VOC species obtained by the SAPRC99 mechanism were reclassified into GEOS-Chem species to support the specific requirement for that model. To link both of the chemical species, the method described in Moon *et al.* (2005) was used.

2. 1. 3 Data Aggregation

After the completion of the main processing for each source category and source sector, the entire speciated detail inventory derived from the final process had to be gathered, followed by the export of the model-ready emissions inventory. This module provides total emissions as a set of gridded inventory, with monthly temporal resolution. The data aggregation was carried out for a given emission species as follows:

$$E_{Y_mP,ij} = \sum_{S=1}^{n} E_{Y_m,P,S,ij} \tag{2}$$

where $E_{Y_mP,ij}$ is the emission of a given chemical species P, during the target month of year Y_m in each grid cell (i, j). S and n indicate the source sectors and the total number of source categories, respectively.

2. 2 Emissions Processing for Asia

2. 2. 1 Creation of Regional EI (Emissions Inventory)

To create a regional inventory, two modules were sequentially carried out. The domain extraction module allows extracting a selected range of regional domain emissions (Asia, in this case) from the gridded global inventories. The inputs of this module were derived from the intermediate results of emission conversion and interpolation module in the global-scale emissions processing system, which is classified by pollutant, source sector, month, and year. The Asia domain in our

Table 2. Mapping table between RCPs and the PROCES source sectors.

RCP sector	PROCES sector	Sector description
ENE	B20 F20 B30 F30 F80 F90	Power generation (Biofuel use) Power generation (Fossil fuel use) Charcoal production OTS(ALL)- Other transformation sector Oil production Gas production
IND	B10 F10 I10 I20 I30 I40 I50 I60 I90	Industry (Biofuel use) Industrial sector (Fossil fuel use) IRO: Iron & steel NFE: Non-ferro CHE: Chemicals Building materials PAP: Pulp & paper FOO: Food (Beer & Wine) MIS: ind. Miscellaneous
SLV	I70	SOL: Solvent use/ Misc.
DOM	B40 F40	RCO: Residential (Biofuel use) RCO sector (RES + COM + OTH) (Fossil fuel use)
*TRA for Globe	B51 F51 F54	Road transport (Biofuel use) Road transport (Incl. Evaporation) (Fossil fuel use) Trans. Land Non-road
WST	W40 W50	Waste incineration (non-energy) Misc. waste handling
AGR AWB		
*TRA for Asia	Non-road LDGV LDDV HDGV HDDV LDGT LDDT MTCC	Non-road vehicle Light duty gas vehicle Light duty diesel vehicle Heavy duty gas vehicle Heavy duty diesel vehicle Light duty gas truck Light duty dissel truck Motorcycle

*Note that transportation sector emissions for Asia are independently mapped onto regionalized information to represent Asian activities

exercise covers the continent from Pakistan to Japan and from Indonesia to Mongolia, by latitude and longitude bands, respectively. Fig. 3 shows the countries and sub-regions that are defined in this system.

The regional summation module is a unique feature of our system, since it allows the aggregation of gridded emissions by region, which is required for the SMOKE-Asia modeling system. For this module, an input reference table that links each grid cell to first level administrative divisions is needed. This reference table was generated during the creation of auxiliary datasets for our processing system. The regional summation module also aggregates monthly resolution emissions to an annual inventory for the entire Asia region, in addition to exporting spatial (specially for international shipping and aviation sources) and temporal (monthly data only) allocation profiles used in the SMOKE-Asia modeling system. The following equation explains the summation module, which creates the annual total emissions inventory for each emission source and first level administrative region.

$$E_{C_kY,P,S} = \sum_{ij\subset C_k} \sum_{m=1}^{12} E_{Yij,Y_m,P,S}, \tag{3}$$

where $E_{CkY,P,S}$ is the emission of a given source sector S, for pollutant P, relative to year Y in country C_k. Y_m indicates the target month of year Y, while i and j are the grid cell coordinates.

2. 2. 2 Pre-processing for SMOKE-Ready EI

A set of emissions inventory that consists of air pollutants classified by detailed emission activities and

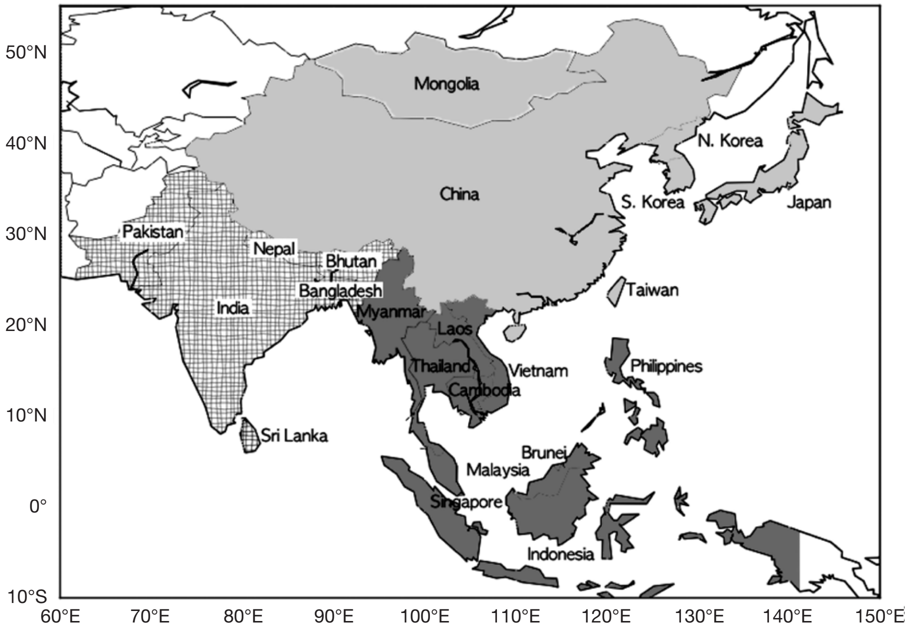

Fig. 3. Definition of the emissions domain for Asia (light gray shading, East Asia; dark gray shading, South East Asia; cross stripes, South Asia).

source regions is required for SMOKE processing. The climate scenario emissions generally provide speciated carbonaceous emissions (e.g., Black Carbon and Organic Carbon) for climate and air quality modeling purposes. However, it should generate data for a specific pollutant, such as $PM_{2.5}$, because the SMOKE system must have the pollutant in the inventory, for outputting speciated compounds, as referred to in model chemistry. To generate PM_{10} and $PM_{2.5}$ by the chemical lumping module, the ratio of PM compounds for each country derived from the Asian inventory (Zhang *et al.*, 2009 for anthropogenic sources), US EPA speciation profiles (for biomass burning, international shipping and aviation sources), as well as carbonaceous species emissions were applied. PM species profiles derived by the chemical lumping module were subsequently exported to the auxiliary database to prepare for SMOKE-Asia processing.

The reclassification of activity sector module provides simplified emission sectors for each pollutant, extended to detailed levels. The detailed sectors were obtained from the EDGAR 3.2 FT 2000 inventory (Olivier *et al.*, 2005), which is the same as the sector division module in the global scale processing system. However, it can be applied to all the pollutants, including VOCs, for emissions processing.

The emissions inventory available at the first level administrative region (77 units) from the regional summation module is further allocated to the second level sub-region (2752 units), by the spatial allocations module in the regional scale processing system. The spatial allocation factors that allow the distribution of regional emissions across sub-regions were calculated by spatial surrogates in the auxiliary database. We followed the definitions of first and second level administrative regions and spatial surrogates for Asia as per Woo *et al.* (2012).

2. 2. 3 Create Fire Information for Biomass Burning Inventories

Biomass burning (BB) emissions are essentially treated as day-specific point-source inventory in SMOKE modeling systems combined with BlueSky framework (Pryden, 2008), which allows the plume-rise scheme for biomass burning activities. To consider the effect of emission injection height on the long-range transport in CTMs, this module allows the calculation of the day-specific point-source inventory that includes not only the emission amounts, but also other parameters related to plume rise calculation, such as heat flux and burning area information for each point source. We assumed that each grid cell emission has a point source location at the center of the grid. The auxiliary data for calculating the injection height of BB emissions was derived from the 2009 BB inventory, which was estimated by BlueSky-Asia (Choi *et al.*, 2013).

2. 2. 4 Applying the SMOKE-Asia Modeling System

SMOKE-Asia is an emissions processing system for supporting air quality modeling and analysis over Asia (Woo *et al*., 2012). In this study, this system, as an external software, was selected to create model-ready emissions at a regional scale for Asia. For this process, the regional scale processing system in the main software calculates not only a set of regional inventory, compatible with SMOKE-Asia, but also auxiliary data, such as spatio-temporal allocation profiles and PM speciation profiles.

2. 3 Verification and Visualization of the Processes

Model-ready emissions are one of the critical inputs for CTMs. Since emission processing is a complex procedure that includes several processing steps with various types of data, it is important to verify quantitative changes in not only the total amounts of each pollutant, but also the model species and their spatio-temporal distributions for reducing the uncertainty of emissions processing. The verification steps in PROCES consist of three major components: 1) exporting log files on errors or warnings related to inputs and application issues, 2) exporting summary reports of emission amounts, and 3) exporting spatio-temporal plots of emissions after the processing steps.

In order to achieve these components, the verification module carries out a consistency check for emission mass and spatio-temporal processing operations for each processing step, highlighting abnormal processing results. This module also exports an emission summary report for each processing result, so that users can clearly find and correct the problematic inputs or processing steps, using both of the module outputs.

Since the results of this system are created in the form of ASCII text, it can virtually be visualized with any software. Nevertheless, we have created a visualization module using intermediate data, as well as the final model-ready inventory for users' convenience. The visualization module is also available for exporting multiple figures by year, month, source sector, pollutant and geographical domain, as well as for carrying out simple calculations such as pollutant ratio, above-criteria pollutant concentration, and average values.

3. APPLICATION ACROSS THE GLOBE AND IN EAST ASIA

PROCES allows the performance of the required applications, simultaneously with emissions processing for CTMs. To support modeling experiments and illustrate the performance of this system, we chose a specific set of application periods required by global and regional scale modeling domains - the present (1995-2006), near future (2015-2025) and mid-term future (2040-2055) periods. The four RCP scenarios were applied to this system, with the results being compared against the RCP reference data for global data and previous SRES study (Lee *et al*., 2015) for Asia. The modeling emission inventories for global and Asian scales in this study are described in this chapter.

3. 1 Illustrations of Global Scale Emissions Processing Results

The application of PROCES allows us to generate the monthly 0.5°×0.5° gridded emissions data during the modeling period across the world. The results of the model-ready global emissions were subsequently used for GEOS-Chem model to estimate the global air quality. Fig. 4 shows the global emission trends of BC and NO_x, derived from PROCES, as well as the sectoral composition of source categories for the years 2000, 2020 and 2050 as the central years for each period. For quantitative verification, the calculation results were also compared with the reference data of RCP emissions (RCP Database online at http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=compare), which are indicated by circles in Fig. 4. The results appear to be quantitatively in good agreement with the reference data for all of the pollutants and source sectors.

In general, the lowest emissions are found for the scenario with the most stringent climate policy (RCP2.6), while the highest are for the scenario without a climate policy (RCP8.5), although this does not apply to all regions, at all times (van Vuuren *et al*., 2011). The results for RCPs in this study also show different patterns for each pollutant, prior to the mid-term future (2050) period, in spite of the total global emissions. For example, the highest scenario of BC emissions for 2020 is RCP2.6, which is the lowest emissions scenario for 2050, as it dramatically decreases after 2020. Anthropogenic source is a major contributor, as more than half of the total emissions come from the source of all RCPs, which therefore, is a key driver for future emissions trend in this study. The emissions of BC for RCP2.6 and NO_x for RCP8.5 rapidly decrease from 2020s to 2050s, mainly due to the rapid decrease in anthropogenic emissions during that period. The emissions from aviation sources, except RCP2.6, significantly increase, despite little contribution from the total emissions during the modeling period. The aviation emissions in RCP2.6 also increase until 2020, decreasing subsequently until 2050.

The anthropogenic NO_x emissions from different RCPs for global scale modeling domain are shown in

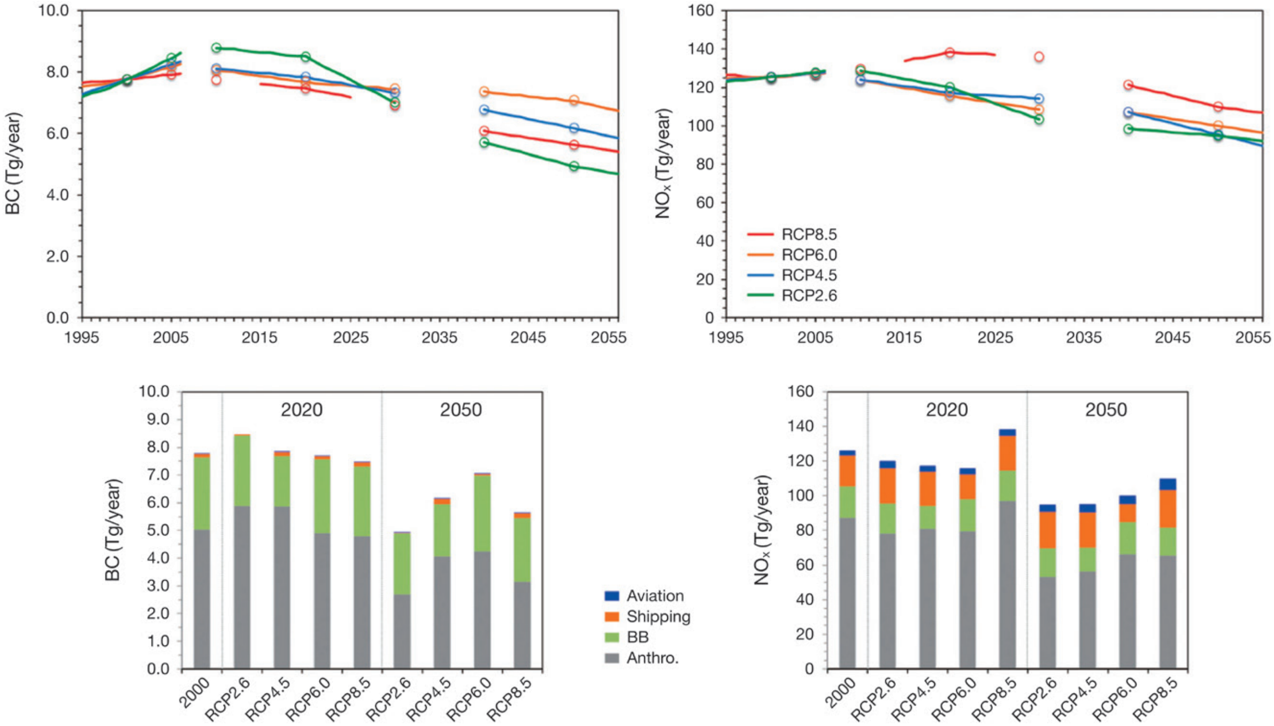

Fig. 4. Comparison of global BC and NO_x emissions trend from all source categories with reference data (circle marker) for the different RCPs during the modeling periods. The lower panel shows portion of source categories for the central year emissions for each periods.

Fig. 5. The emission hotspots, such as large cities and developing countries, are distinguished in the domain. The results show that emissions from North America and Europe continuously decrease in all of the RCP scenarios, while those from East Asia show an upward trend until 2020, especially for RCP8.5, subsequently decreasing. The future emissions of NO_x for India are projected differently based on the scenarios.

The amounts of total emission derived from PROCES are fundamentally equal to reference RCP datasets, whereas chemical species estimated by emission processing that could influence the quantity of emission in the specific area, such as subdivision of emission sectors and chemical speciations, can be different. As an example, the emission trends of total anthropogenic NMVOC and its speciated components, derived from PROCES, under RCP 8.5 scenario are shown in Fig. 6(a). Most speciated NMVOCs have similar trend that decrease after 2020s, whereas the MEK (Methyl ethyl ketone) consistently increases by 2.5 times from the year 2000 to 2050 even it is major species in NMVOC (Fig. 6(b)). The reason of opposite trend in the MEK is that the activities of solvent use, which is a major contributor of the MEK, have increasing tendency in RCP 8.5 scenario. The both of total NMVOC and MEK emissions from North America, Europe and Australia show decreasing (Fig. 6(c) and (d)). In the other hand, Asia except Japan, Africa, Central and South America lead to increase the MEK over the globe.

3. 2 Illustrations of Regional Scale Emissions Processing Results for Asia

PROCES allows the creation of regional scale model-ready emissions through the SMOKE-Asia modeling system. The applied regional modeling domain covers East Asia, including eastern China, parts of Taiwan, Mongolia, North and South Korea, and Japan at a horizontal resolution of 54 km, with 58 × 46 grid cells. Fig. 7 and Table 3 show the example of spatial distribution of model-ready NO_x emissions from four source categories over the East Asia modeling domain and summary of regional emissions for each representative year under RCPs scenario in Asia, respectively. Eastern China generally shows higher emission rates throughout the modeling period compared to other regions, with a rapidly increasing rate until 2020, especially at RCP8.5, and it tends to decrease by 2050 without RCP 6.0. These trends are also showed in other pollutants, such as CO, SO_2, VOC and $PM_{2.5}$, except NH_3. The NH_3 emissions show continuously increasing trends in

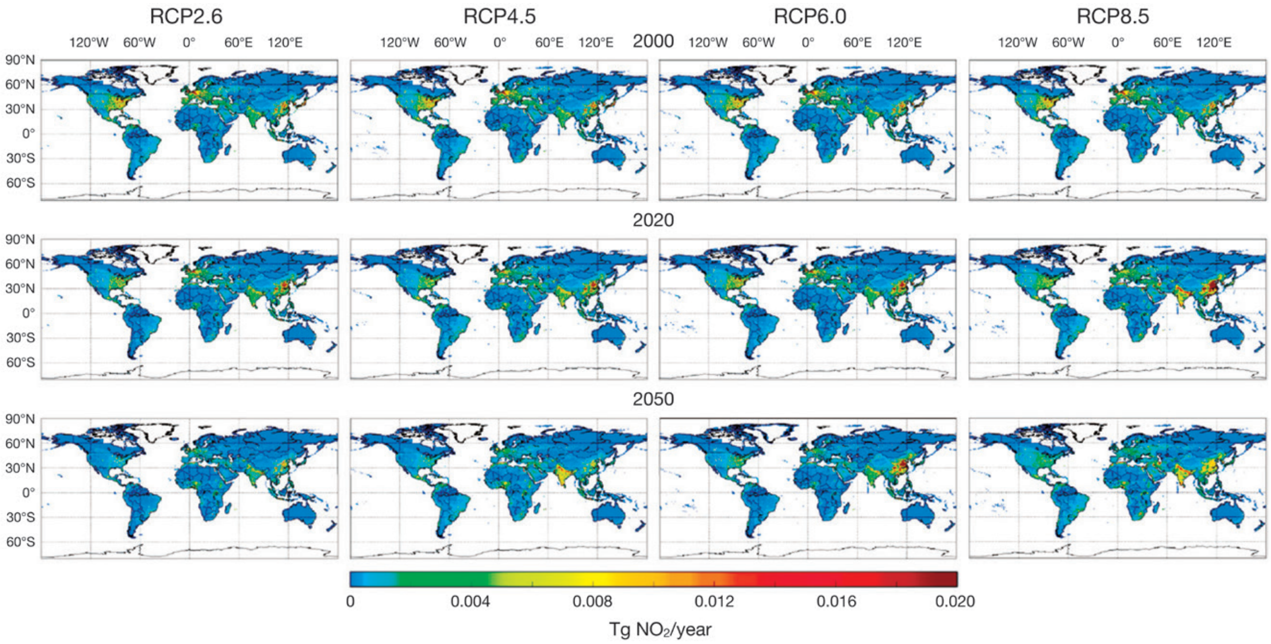

Fig. 5. Spatial distribution of NO_2 emissions from anthropogenic sources over the globe for the different RCPs at each representative year.

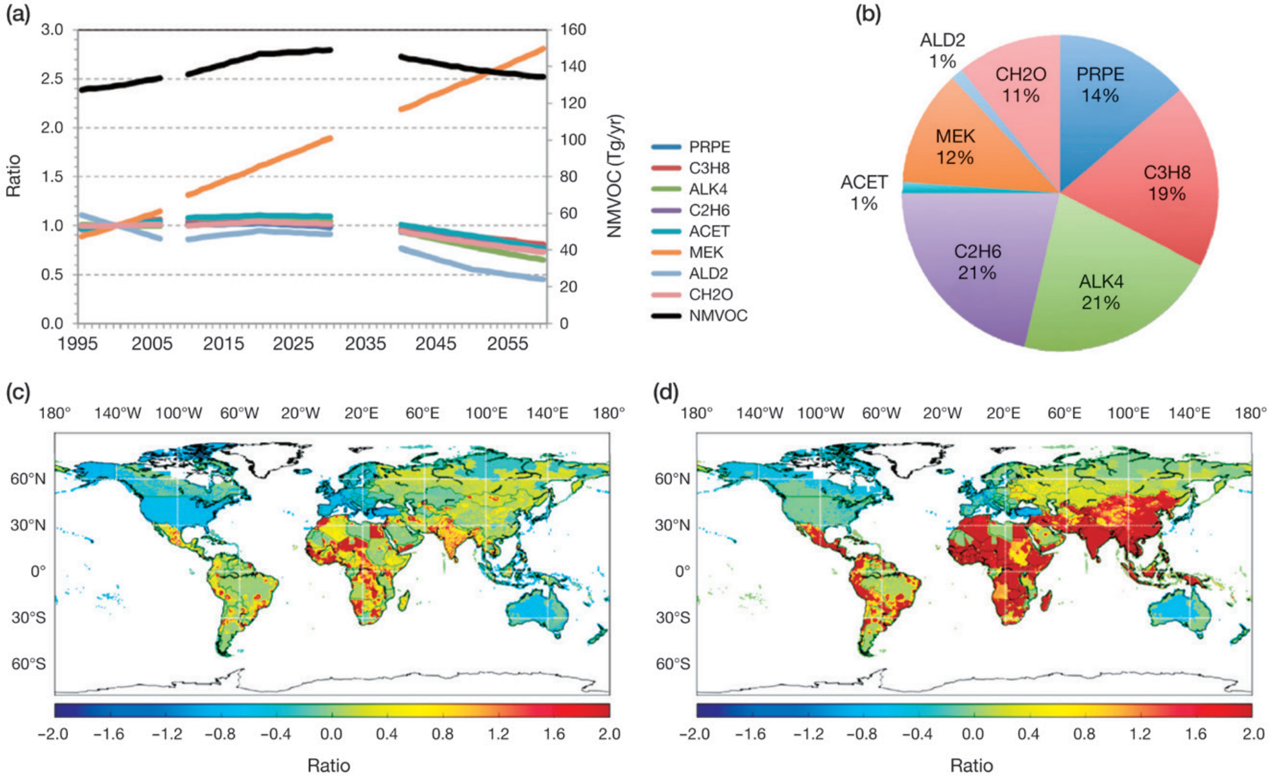

Fig. 6. Comparison of (a) annual variations between total NMVOC emissions and speciated NMVOC (for GEOS-Chem) under RCP 8.5 scenario, and (b) portion of speciated NMVOC (% in moles) for the year 2000 over the globe. Spatial distribution of increasing rate under RCP 8.5 scenario from the year 2000 to 2050 for (c) total NMVOC and (d) MEK, respectively (ACET: Acetone, ALD2: Acetaldehyde, ALK4: ≥C4 alkanes, C2H6: Ethane, C3H8: Propane, CH2O: Formaldehyde, MEK: Methyl ethyl ketone, PRPE: ≥C3 alkenes).

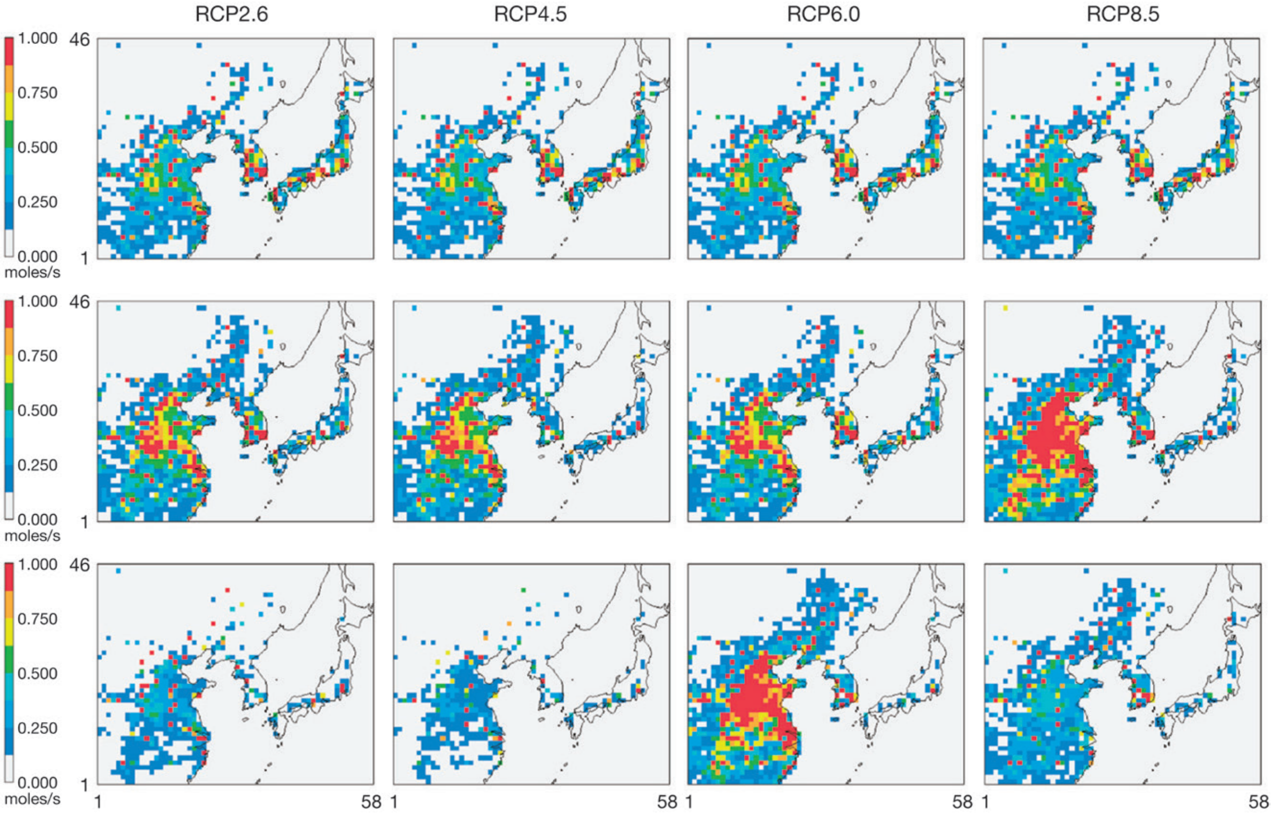

Fig. 7. Spatial distribution of NO_2 emissions from four source categories over the East Asia modeling domain for the different RCPs at each representative year.

Table 3. Summary of regional anthropogenic emissions for each representative year under RCPs scenario in Asia. (Unit: Tg/yr)

Pollutant	YEAR	S.KOREA	CHINA	JAPAN	OEASIA	SEASIA	SASIA
			RCP 8.5				
CO	2000	4.89	121.51	6.85	7.89	50.28	97.21
	2020	4.10	156.48	1.95	7.12	41.44	130.41
	2050	1.90	101.58	0.59	4.22	24.41	142.85
NO_x	2000	1.37	11.73	2.35	0.88	3.79	5.93
	2020	1.10	27.61	0.90	0.99	4.34	11.79
	2050	0.65	11.62	0.55	0.43	2.41	10.43
SO_2	2000	0.89	18.74	0.89	0.77	4.17	6.55
	2020	0.84	28.70	0.34	1.01	5.55	11.46
	2050	0.30	5.80	0.07	0.36	2.00	10.25
NH_3	2000	0.13	6.66	0.39	2.29	2.58	4.34
	2020	0.19	8.10	0.43	2.79	3.57	5.45
	2050	0.24	8.97	0.66	3.14	4.43	7.49
VOC	2000	1.53	23.40	2.13	1.67	10.23	12.01
	2020	1.77	34.46	1.18	2.03	13.33	17.25
	2050	0.76	27.92	0.60	1.45	8.73	23.47
$PM_{2.5}$	2000	0.55	10.12	0.51	0.33	3.44	6.13
	2020	0.44	11.34	0.13	0.34	3.16	8.02
	2050	0.18	5.13	0.05	0.16	1.77	9.67

Table 3. Continued.

Pollutant	YEAR	S.KOREA	CHINA	JAPAN	OEASIA	SEASIA	SASIA
RCP 6.0							
CO	2000	4.89	121.48	6.85	7.88	50.19	97.30
	2020	5.37	165.36	4.68	6.86	44.05	76.76
	2050	3.46	267.36	2.02	4.32	31.79	70.66
NO$_x$	2000	1.37	11.73	2.35	0.88	3.78	5.94
	2020	1.44	17.56	1.43	0.78	4.52	6.54
	2050	0.76	25.72	0.42	0.40	4.67	6.82
SO$_2$	2000	0.89	18.74	0.89	0.77	4.16	6.56
	2020	0.93	24.75	0.50	0.60	4.92	7.34
	2050	0.38	26.17	0.15	0.23	4.50	9.78
NH$_3$	2000	0.13	6.66	0.39	2.29	2.57	4.35
	2020	0.14	8.69	0.43	1.82	2.94	5.99
	2050	0.15	10.95	0.52	2.57	3.55	7.38
VOC	2000	1.53	23.40	2.13	1.66	10.20	12.03
	2020	1.69	25.74	1.50	1.80	10.45	10.79
	2050	1.21	39.65	0.73	1.48	10.67	11.69
PM$_{2.5}$	2000	0.56	10.16	0.53	0.36	3.77	6.20
	2020	0.51	10.55	0.34	0.31	6.85	6.06
	2050	0.26	14.66	0.12	0.13	5.14	6.22
RCP 4.5							
CO	2000	4.89	121.47	6.85	7.88	50.18	97.29
	2020	2.69	175.39	1.94	11.78	67.05	134.33
	2050	1.52	61.96	0.67	4.13	60.11	173.85
NO$_x$	2000	1.37	11.73	2.35	0.88	3.78	5.94
	2020	0.49	17.97	0.79	1.42	6.10	10.27
	2050	0.21	5.73	0.46	0.45	4.92	13.22
SO$_2$	2000	0.89	18.74	0.89	0.77	4.16	6.56
	2020	0.33	29.48	0.41	1.18	4.24	10.87
	2050	0.16	3.69	0.27	0.17	2.57	9.08
NH$_3$	2000	0.12	6.65	0.38	2.29	2.54	4.35
	2020	0.20	8.63	0.38	2.47	2.99	7.67
	2050	0.21	9.60	0.35	1.70	3.18	9.36
VOC	2000	1.53	23.40	2.13	1.66	10.20	12.03
	2020	0.62	32.43	1.04	2.98	14.23	17.99
	2050	0.30	14.42	0.72	1.71	13.98	24.90
PM$_{2.5}$	2000	0.56	10.16	0.53	0.36	3.77	6.20
	2020	0.23	11.86	0.25	0.51	5.76	7.75
	2050	0.13	3.15	0.16	0.19	3.88	7.31
RCP 2.6							
CO	2000	4.88	121.38	6.82	7.88	50.08	97.25
	2020	3.50	126.21	3.97	5.12	58.29	121.62
	2050	1.68	61.44	1.79	2.41	39.52	102.05
NO$_x$	2000	1.37	11.72	2.34	0.88	3.78	5.94
	2020	1.18	18.42	1.30	1.01	5.22	9.44
	2050	0.27	7.62	0.57	0.35	6.32	11.73
SO$_2$	2000	0.89	18.73	0.89	0.77	4.15	6.55
	2020	0.61	24.45	0.59	0.90	5.45	11.38
	2050	0.08	2.71	0.19	0.13	2.83	5.56
NH$_3$	2000	0.12	6.61	0.36	2.26	2.43	4.33
	2020	0.12	8.97	0.34	2.33	3.32	6.48
	2050	0.13	11.94	0.33	1.60	3.96	9.25
VOC	2000	1.53	23.39	2.12	1.66	10.18	12.03
	2020	1.36	29.25	2.04	1.51	11.86	15.67
	2050	0.50	11.96	1.13	0.57	8.11	15.08
PM$_{2.5}$	2000	0.56	10.15	0.53	0.36	3.76	6.20
	2020	0.54	13.87	0.40	0.43	4.70	7.87
	2050	0.11	4.35	0.09	0.10	3.01	6.04

OEASIA: Other East Asia, SEASIA: South East Asia, SASIA: South Asia

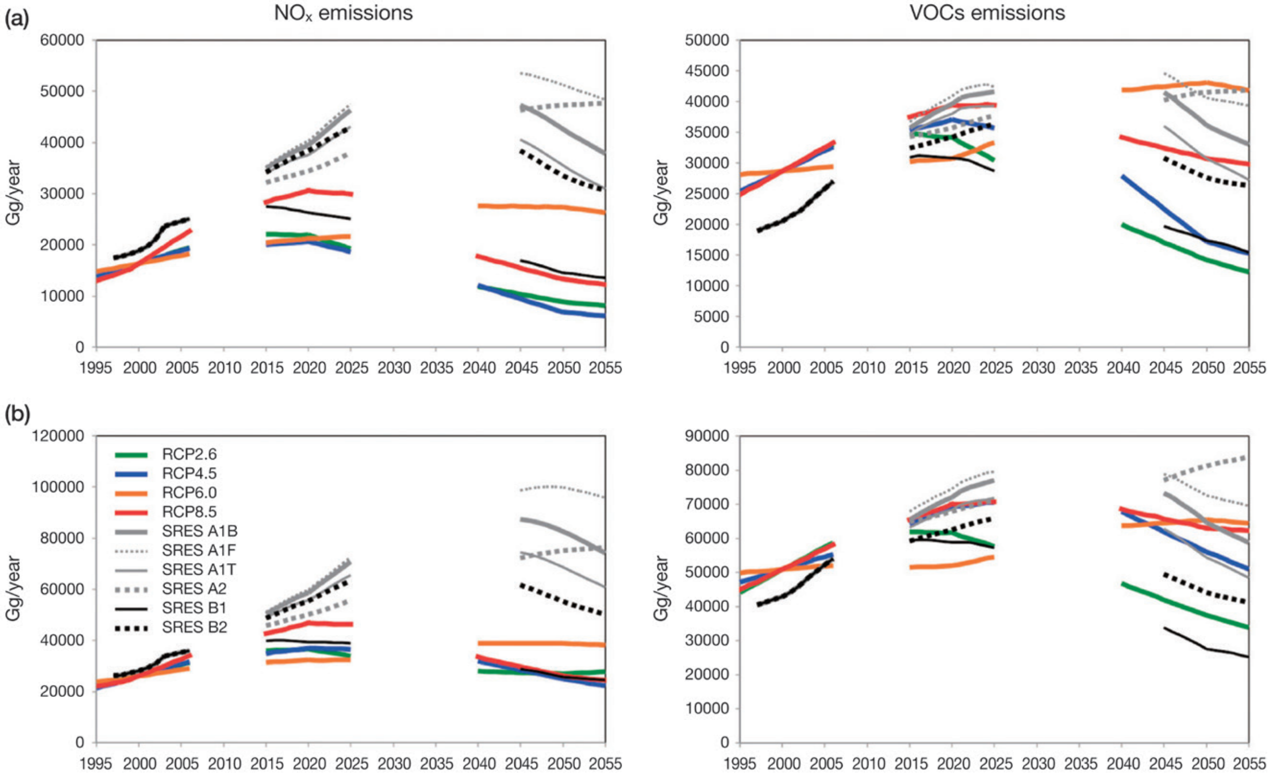

Fig. 8. Emissions of NO_x and VOC trend during the modeling period over the (a) East Asia and (b) entire Asia region. For a comparison the trends of RCPs emissions from this study described with a previous study for SRES scenario emissions in Asia region.

most of Asia regions as well as China. The emissions from developed countries, such as South Korea and Japan, mostly decrease during this period without RCP 6.0. RCP 6.0 scenario shows only increasing emission rates to the year 2020, and decrease for South Korea except $PM_{2.5}$. The SASIA including India shows generally increase trends of emissions to the year 2020, except RCP 6.0 scenario that presents decrease trends for CO, VOC and $PM_{2.5}$. The RCP 6.0 scenario also shows unusual trends in SEASIA. General trends of emission from SEASIA in other RCPs show increasing rate until 2020 then decrease. Whereas emissions from SEASIA under RCP 6.0 scenario show continual increases in NO_x, VOC and NH_3, decrease in CO. The regional model-ready emissions derived from our system could be directly used in CMAQ model, as well as other air quality models, such as MAQSIP (Multiscale Air Quality Simulation Platform), REMSAD (Regulatory Modeling System for Aerosols and Deposition) and CAMx (Comprehensive Air Quality Model with Extensions), through the SMOKE-Asia modeling system.

Fig. 7 presents the anthropogenic emission trends of NO_x and VOCs, derived from PROCES and a previous study (Lee *et al.*, 2015), for different RCPs and SRESs in East Asia and across Asia. Lee *et al.* (2015) estimates the present and future emissions under six SRES scenarios using the best available regional emissions studies (Zhang *et al.*, 2009; Ohara *et al.*, 2007; Streets *et al.*, 2003) to create base-year emissions. The NO_x and VOCs trends in Fig. 7 generally show that the highest RCP emission scenario is RCP8.5 for the year 2020, while it is RCP6.0 for the year 2050, due to the rapidly decreasing RCP8.5 emissions after 2020, which is different from the global emission trends. The six SRES scenario emissions from a previous study generally show a higher range of emissions than RCPs, especially NO_x emissions over East Asia and Asia. Moreover, the six emission scenarios under SRES continuously increase and decrease close to 2040, although the turning point of RCPs is around 2020. One explanation is that all RCPs assumed air pollution control becomes more stringent, over time, as a result of rising income levels (van Vuuren *et al.*, 2011). This assumption may have effectively led to the decrease in emissions from developing countries such as China in a shorter time, which influences the downward trend of air pollution across Asia.

4. CONCLUSION

A new version of the emissions processing software tool - Python-based PRocessing Operator for Climate and Emission Scenarios (PROCES) - was developed to support climate and atmospheric chemistry modeling studies. PROCES was coded using Python version 2.7. The GIS commercial software and SMOKE-Asia were selected as the external support programs for creating spatial allocation profiles and model-ready emissions over the Asian domain, respectively. This tool offers the possibility of performing several calculations related to emissions processing, such as emissions interpolation, spatial allocation, chemical speciation, etc. However, specific parameters are required for most of these modules.

For the sector division process, EDGAR 3.2 FT 2000 (Olivier *et al*., 2005) and TRACE-P 2000 (Streets *et al*., 2003) inventories were included in the auxiliary database of this system. A linking method between SAPRC99 and GEOS-Chem species (Moon *et al*., 2005) was applied to support the GEOS-Chem model. The INTEX 2006 inventory (Zhang *et al*., 2009), as a set of speciation profiles for carbonaceous emissions over Asian countries, was used for the Asian study. Other parameters, such as spatial allocation profiles, were calculated using the available spatial information, gathered in the auxiliary database.

As an emission processing system, major improvements and changes in PROCES are 1) future emissions under climate scenarios are easily calculated in the system, 2) complementation of insufficient information, such as detailed level of emission sectors and point source parameters, required by emission processing steps is systemically conducted, 3) verification functions are involved in the processing system.

The results of the model-ready emissions under RCP scenarios were successfully achieved, with the outputs being quantitatively in good agreement with the reference data of RCPs. Inter-annual emissions showed different patterns for each pollutant before the mid-term future (2050s) period, in spite of the total global emissions. Regionally, emissions from North America and Europe continuously decreased in all of the RCP scenarios. Meanwhile, East Asia showed an increase in emissions until 2020, especially at RCP8.5, subsequently decreasing. The future emissions of NO_x for India are projected differently based on the scenarios.

PROCES is not limited to a specific emissions inventory or spatial coverage. Therefore, it could be applied to any pre-gridded emissions, as well as regional inventories. This tool can provide better modeling input data under multiple climate scenarios. We hope it will be widely used in various climate and air quality studies.

REFERENCES

Baldasano, J.M., Güereca, L.P., López, E., Gassó, S., Jimenez-Guerrero, P. (2008) Development of a high-resolution (1 km × 1 km, 1 h) emission model for Spain: The High-Elective Resolution Modelling Emission System (HERMES). Atmospheric Environment 42, 7215-7233.

Borge, R., Lumbreras, J., Rodríguez, E. (2008) Development of a high-resolution emission inventory for Spain using the SMOKE modelling system: A case study for the years 2000 and 2010. Environmental Modeling & Software 23, 1026-1044.

Byun, D.W., Ching, J.K.S. (1999) Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-/600/R-99/030.

Byun, D.W., Schere, K.L. (2006) Review of the governing equations, computation algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. Applied Mechanics Reviews 59, 51-77.

Choi, K., Woo, J., Kim, H.K., Choi, J., Eum, J., Baek, B.H. (2013) Modeling of Emissions from Open Biomass Burning in Asia Using the BlueSky Framework. Asian Journal of Atmospheric Environment 7, 25-37.

ENVIRON International Corporation (2013) User's Guide - Comprehensive Air Quality Model with Extensions Version 6.0.

Lee, J.B., Cha, J.S., Hong, S.C., Choi, J.Y., Myoung, J.S., Park, R.J., Woo, J.H., Ho, C., Han, J.S., Song, C.K. (2015) Projections of summertime ozone concentration over East Asia under multiple IPCC SRES emission scenarios. Atmospheric Environment 106, 335-346.

Moon, N.K., Song, C.K., Park, R.J., Byun, D.W. (2005) Geos2CMAQ User Guide (Linking CMAQ with GEOS-Chem).

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A. (2000) Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge.

NIER (National Institute of Environmental Research) (2010) The Integrated Climate and Air quality Modeling System. NIER.

Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., Hayasaka, T. (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980-2020. Atmospheric Chemistry and Physics 7, 4419-4444.

Olivier, J.G.J., Van Aardenne, J.A., Dentener, F., Ganzeveld, L., Peters, J.A.H.W. (2005) Recent trends in global greenhouse gas emissions: regional trends and spatial distribution of key sources. A. van Amstel (coord.). In: Non-CO_2 Greenhouse Gases (NCGG-4). Millpress, Rotterdam, ISBN 90 5966 043 9, pp. 325-330.

Pryden, A.D. (2008) Getting started with the BlueSky Framework version 3.0. Sonoma Technology, Inc.

Samaali, M., François, S., Vinuesa, J.-F., Ponche, J.-L. (2007) A new tool for processing atmospheric emission inventories: Technical aspects and application to the ESCOMPTE study area. Environmental Modeling & Software 22, 1765-1774.

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H., Yarber, K.F. (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research 108(D21), 8809.

UNC (2012) SMOKE v3.1 User's Manual.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. (2011) The representative concentration pathways: an overview. Climate Change 109, 5-31.

Wang, S., Zheng, J., Fu, F., Yin, S., Zhong, L. (2011) Development of an emission processing system for the Pearl River Delta Regional air quality modeling using the SMOKE model: Methodology and evaluation. Atmospheric Environment 45, 5079-5089.

Woo, J.-H., Choi, K.-C., Kim, H.K., Baek, B.H., Jang, M., Eum, J.-H., Song, C.H., Ma, Y.-I., Sunwoo, Y., Chang, L.-S., Yoo, S.H. (2012) Development of an anthropogenic emissions processing system for Asia using SMOKE. Atmospheric Environment 58, 5-13.

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., Duan, L., Lei, Y., Wang, L.T., Yao, Z.L. (2009) Asian emissions in 2006 for the NASA INTEX-B mission. Atmospheric Chemistry and Physics 9, 5131-5153.

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