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ORIGINAL ARTICLE

An Integrated Framework for MOSAIC-AQNEA Emission Inventory Development in Northeast Asia

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Abstract
Air pollutant emissions in Northeast Asia play a critical role in regional air quality and transboundary pollution. This study presents the development of the MOSAIC-AQNEA emission inventory framework, integrating country-specific emission inventories for six countries: China, South Korea, Japan, North Korea, Mongolia, and the Asian part of Russia. A mosaic approach was applied to combine nationally developed inventories under a unified sectoral classification scheme. The inventory includes major seven pollutants (SO_2, NO_x, PM_{10}, $PM_{2.5,}$ NH_3, NMVOCs and CO) for the base year 2019. While PM_{10} and $PM_{2.5}$ are explicitly distinguished in the emission inventory and model processing, they are occasionally referred to collectively as PM in the text for brevity. To support air quality modeling, the compiled inventories were processed using the SMOKE-Asia system to generate model-ready inputs. The resulting gridded emissions provide a consistent, high-resolution dataset representing regional emission characteristics. Analysis by sector, pollutant, and intensity metrics (Emissions per GDP and per Population) revealed distinct structural differences among countries, reflecting variations in energy systems, industrial activities, and socioeconomic conditions. This study provides a comprehensively integrated, model-ready emission inventory framework that consistently integrates national inventories across Northeast Asia under a unified processing structure. The framework ensures cross-country comparability through systematic sector mapping, bottom-up emission based downscaling, and consistent chemical speciation. The resulting dataset offers a transparent and directly usable emission input for regional air quality modeling and policy-relevant assessments.

Keywords Regional emission inventory integration · Mosaic inventory · Policy-relevant emission assessment · Northeast Asia · SMOKE modeling system · Gridded emissions

1 Introduction

Atmospheric pollutants are emitted into the atmosphere through both anthropogenic activities and natural processes. These pollutants subsequently undergo photochemical reactions and physical processes, leading to the formation of fine particulate matter ($PM_{2.5}$) and ozone (O_3), thereby deteriorating air quality and exerting adverse effects on human health (Ebi and McGregor 2008; Xing et al. 2016). The Asian region has emerged as the largest source of atmospheric pollutant emissions worldwide, driven by the simultaneous progression of rapid industrialization, urbanization, and population growth. This air pollution problem is particularly pronounced in Northeast Asia. Northeast Asia comprises a region centered on China, South Korea, and Japan, and also includes North Korea, Mongolia, and the Asian part of Russia. Owing to rapid industrial development

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and population concentration, this region is recognized as one of the world's largest emitters of greenhouse gases and atmospheric pollutants. According to recent emission statistics, Northeast Asia accounts for approximately 30–40% of global CO_2eq and $PM_{2.5}$ emissions, with South Korea, China, and Japan contributing the majority of regional emissions (Crippa et al. 2023).

Northeast Asian countries have implemented a wide range of emission control policies aimed at improving domestic air quality (Botta and Yamasaki 2020; Trnka 2020; Yang 2020). In the policy-making process for air quality management, it is essential to quantitatively characterize emission conditions based on scientific analyses and to evaluate the impacts of policy implementation (Jafari et al. 2021). The starting point of such analyses is the systematic identification of emission sources and the accurate estimation of emissions by source category. Subsequently, effective management strategies are established by assessing the atmospheric behavior of emitted pollutants, their chemical transformation processes, and their impacts on climate and the environment. In this context, one of the most critical foundational datasets is the emission inventory, which provides source-specific emission information. In particular, for regions such as Northeast Asia, where countries with substantial emission levels are geographically clustered and exert transboundary influences on one another, the development of emission inventories within an integrated framework is of critical importance.

Methodologies for developing air pollutant emission inventories are generally classified into bottom-up and top-down approaches. The bottom-up approach estimates emissions using activity data (e.g., energy and fuel consumption) and emission factors (Akyuz et al. 2024; Ibarra-Espinosa et al. 2018), whereas the top-down approach infers emissions by inversely estimating them from observed atmospheric pollutant concentrations, such as those derived from satellite observations. Fundamentally, the top-down approach is based on the concept of allocating emissions by disaggregating emission data from large areas to smaller areas using surrogate variables (Marinello et al. 2024; Park et al. 2023, 2024). Countries develop and utilize emission inventories to manage their national emissions. Additionally, the mosaic approach has been widely adopted in regional and global emission inventories covering Asia and beyond (Hoesly et al. 2018; McDuffie et al. 2020). This method has been shown to significantly improve emission accuracy and model performance by incorporating more locally specific information (Li et al. 2017). However, since the inventories are developed by various independent groups, achieving consistency in sectoral classification and spatial/temporal resolution across datasets remains a key challenge.

Recognizing Asia's critical role in regional and global air pollution, a variety of emission inventories have been developed over the past decades (Roy et al. 2023). Previously developed emission inventories for the Asian region include Transport and Chemical Evolution over the Pacific (TRACE-P) (Streets et al. 2003), Regional Emission inventory in Asia (REAS) (Kurokawa et al. 2013; Kurokawa and Ohara 2020), Comprehensive Regional Emissions Inventory for Atmospheric Transport Experiment (CREATE) (Woo et al. 2020), Model Inter-Comparison Study for Asia (MICS-Asia) (Li et al. 2017), and The Korea–United States Air Quality (KORUS-AQ) (Crawford et al. 2021) inventory. In addition to inventories based on bottom-up methodologies, such as TRACE-P, CREATE, and REAS, research applying mosaic approaches that integrate country or region-specific datasets, such as KORUS-AQ and MICS-Asia, have also been reported. Previous mosaic emission inventories for Northeast Asia have often been developed upon existing inventories such as REAS rather than the latest national-specific datasets. This approach may carry over uncertainties from the original source inventories, as the underlying assumptions and data limitations are not fully resolved in subsequent updates. Furthermore, many recent studies have extended their scope beyond emission inventory development to include emission processing for chemical transport model (CTM) applications. These studies aim to provide spatially, temporally, and chemically refined information by incorporating locally specific parameters and datasets (Choi et al. 2017; Kim et al. 2023).

In this study, an integrated air pollutant emission inventory for Northeast Asia was developed by combining the strengths of bottom-up approaches based on activity data and emission factors reported in previous studies with a mosaic approach that integrates national emission inventories developed by country experts under a unified sectoral definition framework. Furthermore, to effectively support scientific and policy modeling, an integrated emission inventory framework was presented that encompasses not only emission inventory development but also processing steps for model application. Through this framework, both the spatiotemporal distribution characteristics and the atmospheric chemical composition of pollutants emitted from individual sources were considered in a manner reflecting the regional characteristics of Northeast Asia. Importantly, the framework is designed to support regional environmental cooperation initiatives in Northeast Asia, analogous to the role of the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model in Europe's Clean Air Outlook (CAO). In particular, it aims to provide a scientific foundation for regional cooperative programs such as the

Northeast Asian Clean Air Partnership (NEACAP) under the North-East Asian Subregional Programme for Environmental Cooperation (NEASPEC), which operates across the same six Northeast Asian countries considered in this study. This approach aims to more realistically represent regional emission characteristics and to provide a reliable foundational dataset for air quality modeling and policy assessment studies.

Unlike previous studies that rely on single-source or globally harmonized inventories, this study develops a region-specific integration framework that preserves national data characteristics while ensuring regional consistency. The novelty of this work lies in combining national inventories, standardized sector mapping, and activity-based emission downscaling within a unified processing system. This approach enables more policy-relevant and regionally representative emission estimates for Northeast Asia. The study therefore fills a critical gap between national reporting systems and model-ready regional inventories.

2 Methodology and Models

2.1 Research Framework

The emission framework developed in this study encompasses the process of constructing an integrated air pollutant emission inventory by combining national emissions across six Northeast Asian countries under a common sectoral classification scheme, as well as processing the inventory for use as model input. Figure 1 presents the geographical locations of the six Northeast Asian countries considered in the development of the integrated emission inventory. The Northeast Asian countries examined in this study correspond to the regions shaded in green in the figure, including China, South Korea, Japan, North Korea, the Asian part of Russia, and Mongolia.

Figure 2 presents an overview of the process of combining and processing emission inventories from multiple countries within a unified framework. Figure 2-a) illustrates the overall framework for estimating mosaic emissions. The

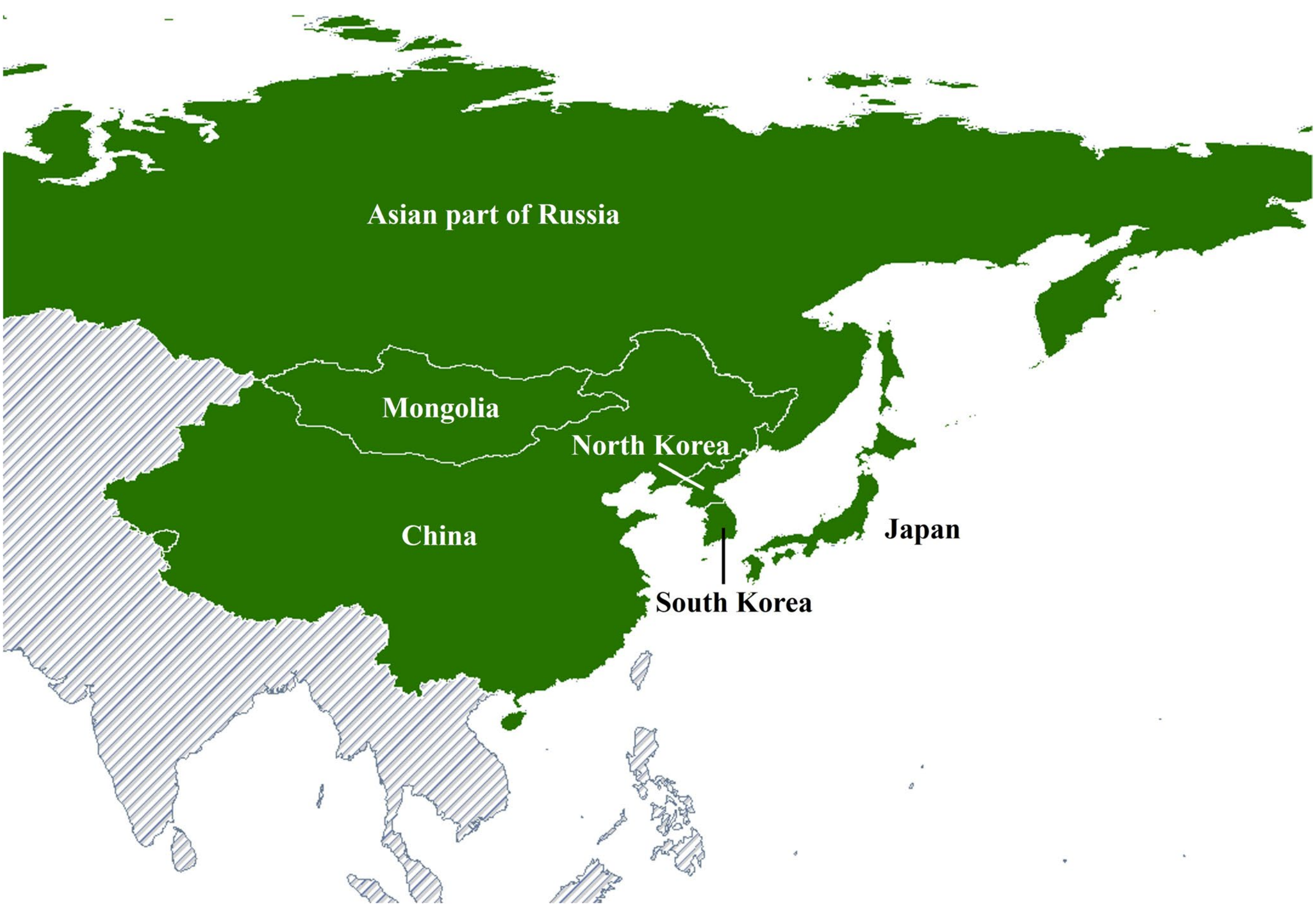


Fig. 1 Research Domain and Target Northeast Asia Countries

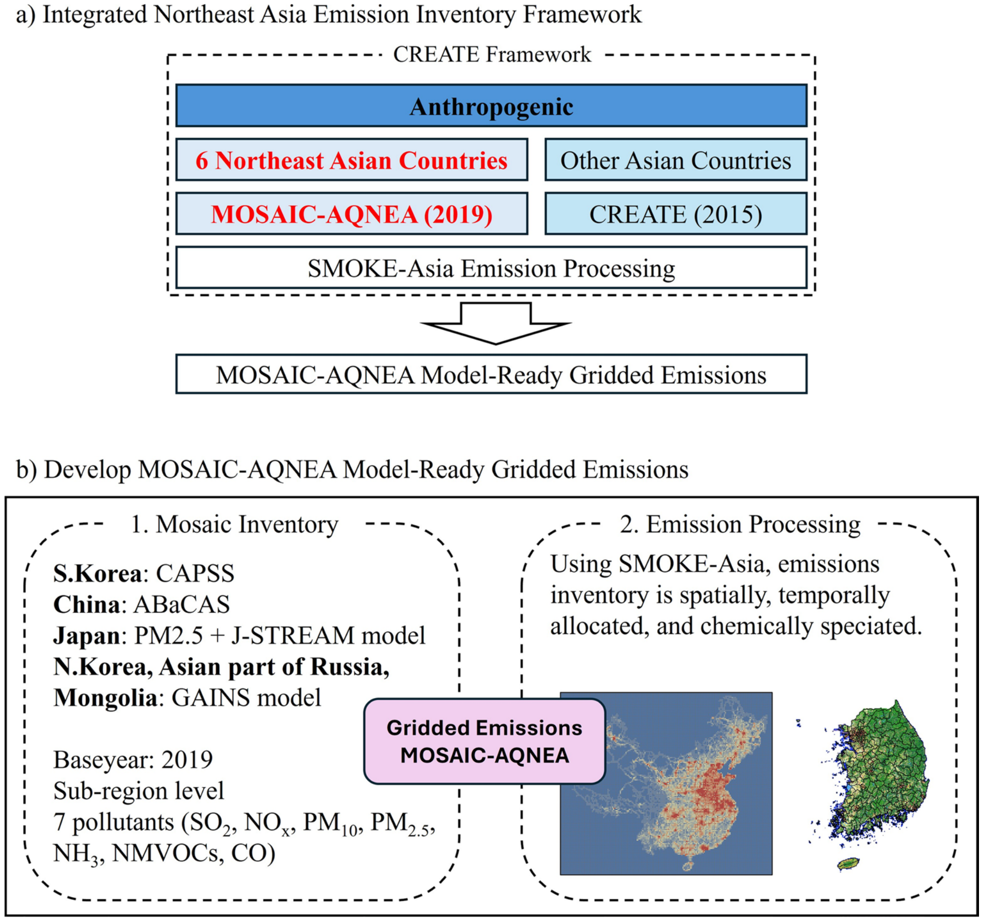


Fig. 2 Research framework

MOSAIC-AQNEA emission inventory was fundamentally developed based on the framework of the CREATE emission inventory (Woo et al. 2020), which was originally established for the Asian region. Because the CREATE emission inventory estimates emissions using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-Asia model (Amann et al. 2008), an integrated assessment model developed by the International Institute for Applied Systems Analysis (IIASA), the MOSAIC-AQNEA inventory was likewise constructed by mapping emissions from representative national inventories to align with the major emission sectors defined in GAINS.

Additionally, Fig. 2-b) describes the detailed methodology used to develop the MOSAIC-AQNEA emissions. The base year of the integrated MOSAIC-AQNEA emission inventory is 2019, and the inventory was developed at the sub-national administrative level. The inventory covers seven air pollutants (SO_2, NO_x, PM_{10}, $PM_{2.5}$, NH_3, NMVOCs, and CO). Although PM_{10} and $PM_{2.5}$ are explicitly distinguished in the inventory, they are occasionally referred to collectively as PM in the text for simplicity. Emissions prepared in inventory format at the administrative level, representing annual total amounts, underwent processing to generate high-resolution gridded emissions suitable for use as input data for atmospheric chemical transport models, using emission processors such as Sparse Matrix Operator Kernel Emissions (SMOKE) (Houyoux et al. 2000; US EPA 2023).

The MOSAIC-AQNEA gridded emission inventory developed through this integrated methodology was structured to enable straightforward updates of Northeast Asian emissions in accordance with revisions of the base year. This framework provides a foundation for subsequent applications, including updating the emission base year using a mosaic approach and incorporating policy-driven future emission projections based on bottom-up methodologies that utilize detailed sector-specific emission factors, activity data, and policy-related parameters.

2.2 Develop Integrated Northeast Asia Emission Framework

2.2.1 Emission Framework: CREATE

The CREATE emission framework refers to an integrated emission inventory development system designed to support comprehensive climate–air quality linkage analyses for the Asian region. This framework was developed primarily to address limitations of existing Asian emission inventories, including insufficient information, low transparency, and constraints in sectoral, fuel-type, and pollutant-level representations (Woo et al. 2020). The CREATE framework encompasses a comprehensive set of methodological components for bottom-up anthropogenic emission estimation, including sectoral and fuel classification schemes, and regional coverage definitions. Within this framework, emission inventories are constructed based on the reference year of the activity data used, resulting in base-year inventories such as CREATE (2010), CREATE (2015). In this study, the CREATE framework is utilized as the methodological basis for emission estimation.

Within the CREATE framework, anthropogenic emission estimates are derived using the internationally validated GAINS model. This design enables a simultaneous consideration of air pollutants and greenhouse gases. The GAINS-based approach estimates emissions by combining activity data, uncontrolled emission factors, removal efficiency, and control technology penetration. This methodology expresses emissions of pollutant p in region i as a function of activity type k and control technology m, thereby allowing quantitative interpretation of how emission changes respond to variations in policy, technological, and socioeconomic conditions (Amann et al. 2008).

Such a structure represents a key characteristic of the CREATE framework, as it enables not only the estimation of base-year emissions but also the evaluation of emission changes under policy scenarios or socioeconomic transitions. Woo et al. (2020) presented the emission calculation formulation as follows.

$$E_{i,p} = \sum_{k}\sum_{m} A_{i,k} \cdot ef_{i,k,m,p} \cdot x_{i,k,m,p} \quad (1)$$

In this formulation, A denotes activity data, ef represents the emission factor after the application of control technologies, and x indicates the penetration rate of control technologies. This equation structure enables systematic representation of the effects of control technology adoption and variations in activity levels on emissions. The CREATE inventory was developed for 22 Asian countries and 99 sub-regions, incorporating 54 fuel groups and 201 detailed sectors. Beyond the integration and development of MOSAIC-AQNEA emissions based on the CREATE emission framework, the bottom-up structure of the framework provides advantages for subsequent applications, including policy-driven emission projections for additional research and the continuous updating of emission inventories (Woo et al. 2020).

2.2.2 Emission Inventory: MOSAIC-AQNEA

The MOSAIC-AQNEA emission inventory is an integrated emission inventory for Northeast Asia developed using a mosaic methodology under the project entitled "Development of mid- and long-term integrated management strategy for future fine particle Air Quality improvement in NorthEast Asia (AQNEA)". As shown in Fig. 3, MOSAIC-AQNEA inventory covers six Northeast Asian countries, including China, South Korea, Japan, North Korea, Asian part of Russia, and Mongolia, and incorporates emission inventories developed at the national level for each country.

National emission inventories were compiled based on the most recent officially available datasets and internationally validated emission estimation frameworks. For South Korea, the 2019 emission inventory from the Clean Air Policy Support System (CAPSS), provided by the National Institute of Environmental Research was utilized (Lee et al. 2011). For China, the emission inventory developed under the Air Benefit and Cost and Attainment Assessment System (ABaCAS) by Tsinghua University was adopted (Li et al. 2023a, b b). For Japan, a national emission inventory developed by the National Institute for Environmental Studies (NIES), integrating the PM2.5 emission inventory and outputs from Japan's Study for Reference Air Quality modeling (J-STREAM), was applied (Chatani et al. 2023). Emissions for North Korea, Asian part of Russia, and Mongolia were estimated using the GAINS-Asia, which is the Asia specific version of GAINS–Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE) framework (Stohl et al. 2015), constructed following a bottom-up approach reflecting energy consumption structures and technology penetration levels. Each emission inventory was harmonized according to a unified sectoral definition, as summarized in Table 1.

The sectoral classification of MOSAIC-AQNEA was developed for anthropogenic emission sectors, enabling emission estimation for seven air pollutants (SO_2, NO_x, PM_{10}, $PM_{2.5}$, NH_3, NMVOCs, and CO) across eight sectors: power, industry, residential, on-road, non-road, agriculture, solvent use, and other (e.g., waste). For countries within the modeling domain not explicitly covered by MOSAIC-AQNEA inventories, country-level emission data provided by the CREATE v3.0 emission inventory were utilized.

Emission inventories developed by each country in accordance with the sectoral classification presented in Table 1 undergo a downscaling process based on activity-based allocation to ensure consistency with the detailed sectoral and fuel structures defined in the CREATE emission framework. In this process, aggregated sectoral emissions from national inventories are redistributed according to the emission shares estimated bottom-up within the CREATE framework, which

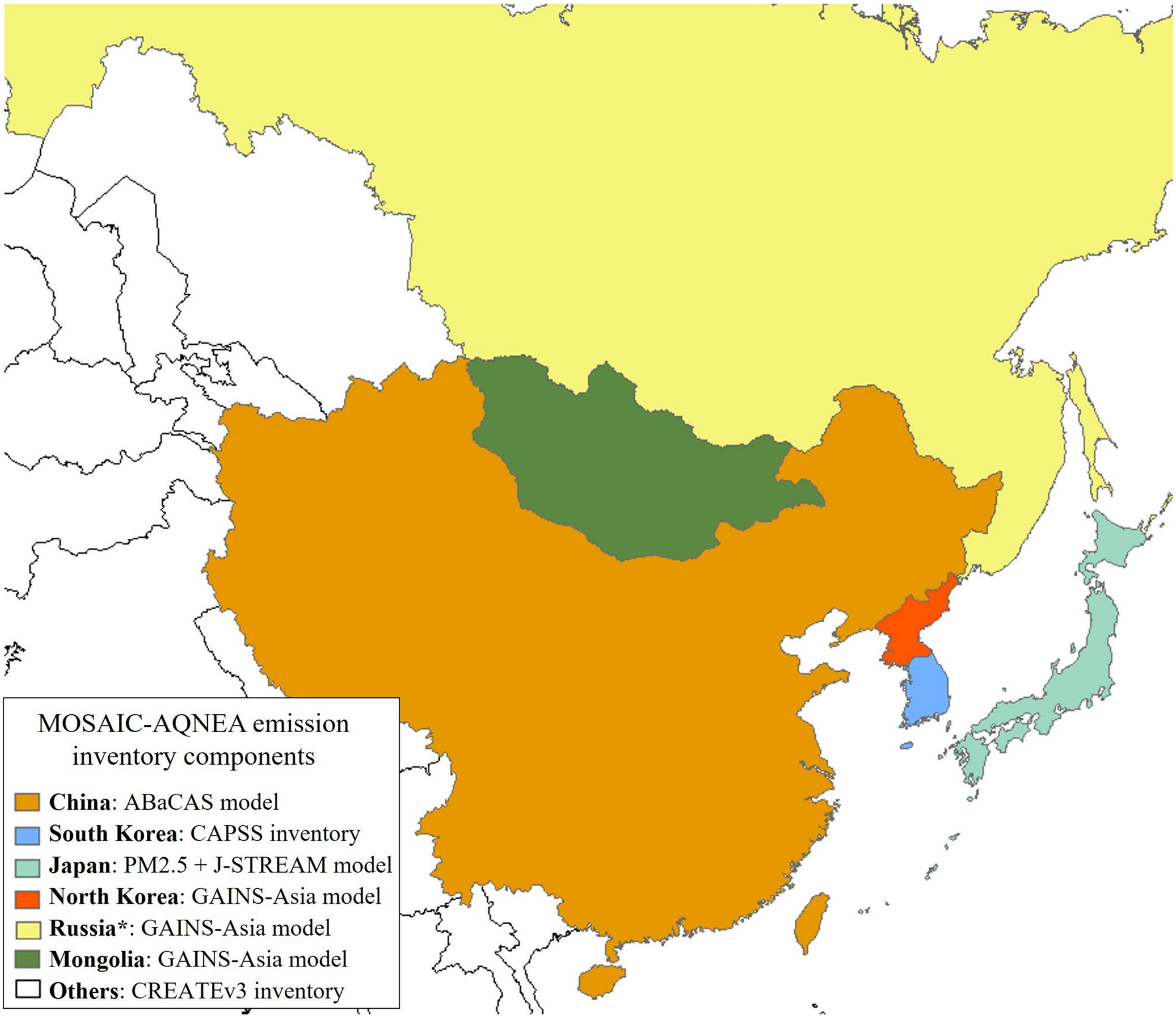


Fig. 3 The national emission inventories used in the development of the MOSAIC-AQNEA (Russia*: Asian part of Russia)

Table 1 MOSAIC-AQNEA inventory sector classification

Tier 1	Tier 2
Power	Power, Energy
Industry	Industrial (Combustion + Process), Fugitive (incl. refinery and gas stations)
Residential	Residential + Commercial
On-road	Road transport
Non-road	Off-road vehicles and other machinery + Railways
Agriculture	Agriculture
Solvents	Solvent use + Paint use + etc.
Other	Waste (incl. incineration facility) + etc.

are themselves derived from sector-specific activity data. For the energy sector, energy statistics from international databases such as the International Energy Agency (IEA) are used as the primary activity data, while non-energy sectors employ a range of activity indicators including population, livestock headcounts, fuel consumption, and industrial production volumes. This activity-based redistribution ensures that the disaggregation reflects the underlying structural drivers of emissions in each country, rather than relying on simple proportional adjustments or empirical scaling. The sectoral downscaling of MOSAIC-AQNEA emissions presented in Table 1 is performed according to Eq. 2.

$$M_{r,s,f} = M_{r,S} \times \frac{C_{r,s,f}}{\sum_{s,f} C_{r,s,f}} \tag{2}$$

Where *M* and *C* denote emissions from the MOSAIC-AQNEA and CREATE inventories. The subscripts *r*, *S*, *s* and *f* refer to region, major sector, sub-sector, and fuel type, where *s* belongs to major sector *S*. Following the CREATE framework described in Sect. 2.2.1, *s* and *f* are classified into 201 detailed sectors and 54 fuel groups. Emissions reconstructed through activity-based allocation are subsequently reorganized according to fuel type, technological characteristics, and usage sectors, ensuring that emission characteristics remain internally consistent among pollutants within identical activity units. This approach mitigates potential inconsistencies in sector definitions arising from differences in national statistical systems, while explicitly capturing the effects of policy or technological changes at specific activity levels. Consequently, the MOSAIC-AQNEA emission inventory downscaled to the CREATE framework preserves the heterogeneity of national data sources and estimation methodologies, while being harmonized under a unified sectoral structure and pollutant definition. This structure ultimately enables the construction of a consistent integrated emission inventory for Northeast Asia and provides input data suitable for cross-country comparisons and scenario-based air quality assessments. In the model processing steps, PM_{10} and $PM_{2.5}$ are treated separately to ensure compatibility with chemical transport models, while aggregated references to PM are used only for concise discussion in the text.

2.2.3 Emission Processing: SMOKE-Asia

Following the preparation of annual emissions in inventory format at the administrative level, emission processing is required to generate gridded emission fields suitable for scientific and policy-oriented modeling studies. In this study, the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system developed by the United States Environmental Protection Agency (US EPA) was employed for this purpose (Houyoux et al. 2000; US EPA 2023). The SMOKE system processes emission inventories into grid-based emission fields for use as inputs to three-dimensional air quality models, by spatially, temporally, and chemically allocating emissions through cross-reference input files. These cross-reference files can incorporate a range of allocation surrogates, such as NMVOCs speciation profiles, land use and land cover data, and traffic volume statistics. Emission processing represents a critical step beyond simple data transformation, as it converts inventories into forms capable of reflecting high-resolution characteristics for scientific and policy applications. Through this procedure, atmospheric chemical transport models are able to account for spatial emission patterns, temporal variability across monthly, weekly, and hourly scales, and chemical reactivity.

Emission processing was conducted by improving SMOKE-Asia (Woo et al. 2012), a database-driven emission processing system developed for the Asian region. Since its development, SMOKE-Asia has been widely applied in major international observation–modeling studies, including KORUS-AQ Campaign (Crawford et al. 2021), and the Satellite Integrated Joint monitoring of Air Quality (SIJAQ) Campaign (Cha et al. 2025), and its input datasets have undergone continuous refinement (Park et al. 2021). While supporting various campaigns, previous studies were reviewed and incorporated to accurately reflect temporal allocation factors and chemical speciation for the Northeast Asian region. Using this framework, the emission inventories constructed for Northeast Asia were spatially and temporally allocated and chemically speciated according to the workflow illustrated in Fig. 4, based on previous studies and

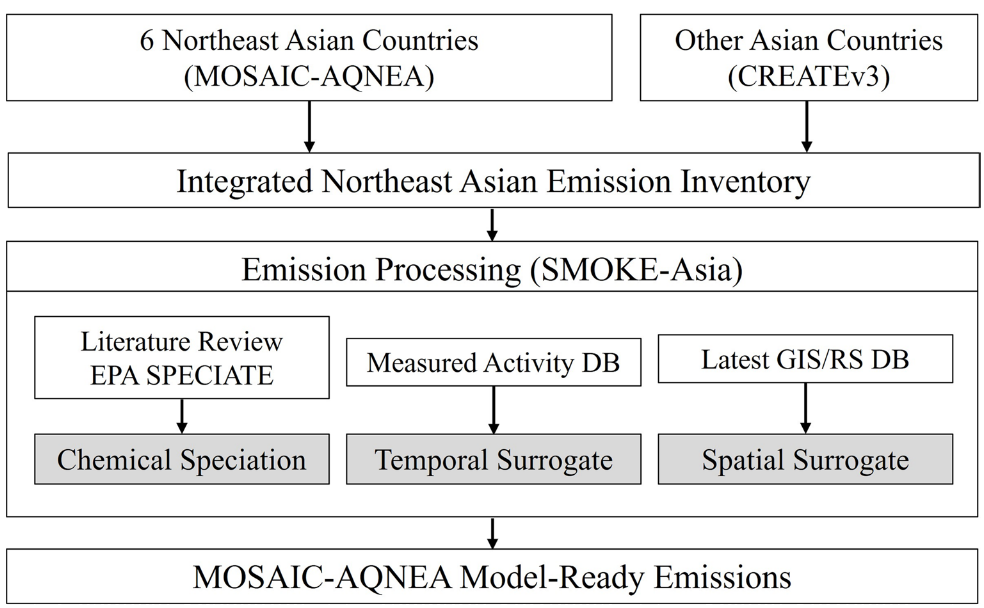


Fig. 4 Emission processing scheme

the latest statistical data. The study primarily incorporated statistical and experimental data from Northeast Asia whenever available. However, for chemical speciation profiles lacking reliable experimental results from Northeast Asia, data from the US EPA SPECIATE were used to fill the gaps. This process resulted in high-resolution gridded emission fields prepared for model input.

The emission inventory processing framework implemented using SMOKE-Asia is summarized in Table 2. During the chemical speciation procedure, gaseous pollutants were processed to ensure compatibility with the Statewide Air Pollution Research Center (SAPRC)07 chemical mechanism (Carter 2010) and the Carbon Bond (CB)06 mechanism (Yarwood et al. 2010) while particulate matter was speciated to maintain consistency with the AERO07 aerosol module. This configuration ensures that key reaction pathways associated with ozone formation and secondary organic aerosol production are represented consistently within atmospheric chemical transport models. The processing domain was defined to encompass all six Northeast Asian countries, thereby providing emission input data suitable for integrated analyses of long-range transport and transboundary air pollution impacts.

Table 2 Emission processing framework

Anthropogenic Emission Processor	SMOKEv4.5
	- Emission Inventory: MOSAIC-AQNEA (2019)
	- Chemical Mechanism: NMVOCs: SAPRC07, CB06 Aerosol: AERO7
Modeling Domain	- Projection Type: Lambert Conformal Conic
	- Grid Resolution (Number of Grid): 27 km x 27 km (270 × 240)
	- Domain Information (Below-Left): (-5,513,000, -2,324,500)
	- Reference Lon., Lat.: (126.0, 38.0)
	- Standard Parallel: (30, 60) North

3 Results

3.1 Northeast Asia Emission Inventory in 2019

3.1.1 Developed MOSAIC-AQNEA Emission Inventory

Table 3 summarizes emissions for the six Northeast Asian countries derived from the MOSAIC-AQNEA emission inventory constructed under the unified sectoral framework. Because the inventory includes only emissions from anthropogenic sources, higher emission magnitudes are observed for countries characterized by large populations or advanced levels of industrialization. This pattern reflects national differences in energy consumption scales and emission characteristics.

Across all pollutants, China exhibits the largest emission share, primarily due to its substantially larger population relative to other countries. Russia, despite inclusion of only its Asian region, shows the second-highest emissions among the six countries, followed by Japan. These relationships are associated with the dominant contribution of fuel combustion processes in power generation, industrial activities, transportation, and residential sectors, which serve as major emission sources of SO_2, NO_x, and CO. Consequently, relative emission patterns among these pollutants provide indirect insights into national energy structures and the effectiveness of air pollution management policies.

Emissions for the six Northeast Asian countries were compared with those reported in existing emission inventories to examine the overall consistency and trends among inventories. Emissions from historical and comparable baseyear (2019) inventories were presented using bar charts, while values from the MOSAIC-AQNEA emission inventory were indicated using star-shaped markers. Overall, emissions show a decreasing tendency as the base year becomes more recent. This pattern reflects the influence of air quality control policies implemented by Northeast Asian countries. The emission inventories considered in this comparison include MICS-Asia (2010), REAS (2010), CREATE (2010, 2015, 2019), ECLIPSE (2015), The Multi-resolution

Table 3 MOSAIC-AQNEA emissions by country (Unit: Gg/Year)

Country	SO_2	NO_x	PM_{10}	$PM_{2.5}$	NH_3	NMVOCs	CO
China	5,982.5	17,003.5	10,340.8	7,616.9	9,341.0	22,259.9	120,180.5
S.Korea	261.7	997.1	156.2	74.7	316.3	1,004.8	710.5
Japan	243.5	1,062.2	104.6	50.2	360.3	1,214.9	2,567.3
N.Korea	87.5	118.2	118.3	67.9	106.4	106.0	243.6
Russia*	1,481.5	1,236.6	803.0	482.4	416.2	1,517.2	2,530.3
Mongolia	176.0	98.3	87.8	56.5	100.5	54.5	547.3
Total	**8,232.7**	**20,515.9**	**11,610.7**	**8,348.6**	**10,640.7**	**26,157.3**	**126,779.5**

* Asian part

Emission Inventory(MEIC) (2017) (Wu et al. 2024), Long-range Transboundary Air Pollutant in Northeast Asia (LTP) (2017) (Kim et al. 2011), and CAPSS (2015).

The results of comparing MOSAIC-AQNEA emissions against existing inventories are presented in Fig. 5. The gray dots, gray shading, and gray horizontal lines represent the pollutant-specific emission estimates, range, and median of the reference inventories, while the red diamond markers indicate MOSAIC-AQNEA emissions. The relative difference between MOSAIC-AQNEA and the reference inventory median, calculated as (AQNEA−Median) / Median × 100%, ranged from −10% to −45% on average across five countries excluding Mongolia, indicating a general tendency for MOSAIC-AQNEA to be lower than the median. This is likely attributable to the declining emission trends reflected in the more recent base year (2019) adopted in this study, where the effects of increasingly stringent air quality policies are captured.

On a country-by-country basis, South Korea (−10%) and Japan (−27%) showed generally good agreement with the reference inventory median across most pollutants, although NH_3 and NMVOCs were slightly higher by approximately +10–11% and +3%, respectively. For China, negative differences were observed across all pollutants except NMVOCs (−5%), with SO_2 showing the largest deviation of −69%, which is likely attributable to substantial emission reductions following the implementation of stringent desulfurization policies after 2010 (Crippa et al. 2023). For the Asian part of Russia and North Korea, CO exhibited particularly large negative differences of −81% and −93%. In contrast, Mongolia showed positive differences across most pollutants, with an average relative difference of +116%, including SO_2 (+133%), $PM_{2.5}$ (+202%), and CO (+244%), suggesting that emissions from domestic coal combustion may have been underestimated in prior inventories. Notably, CO consistently exhibited the widest spread across all countries, indicating that CO emissions are subject to greater uncertainty compared to other pollutants.

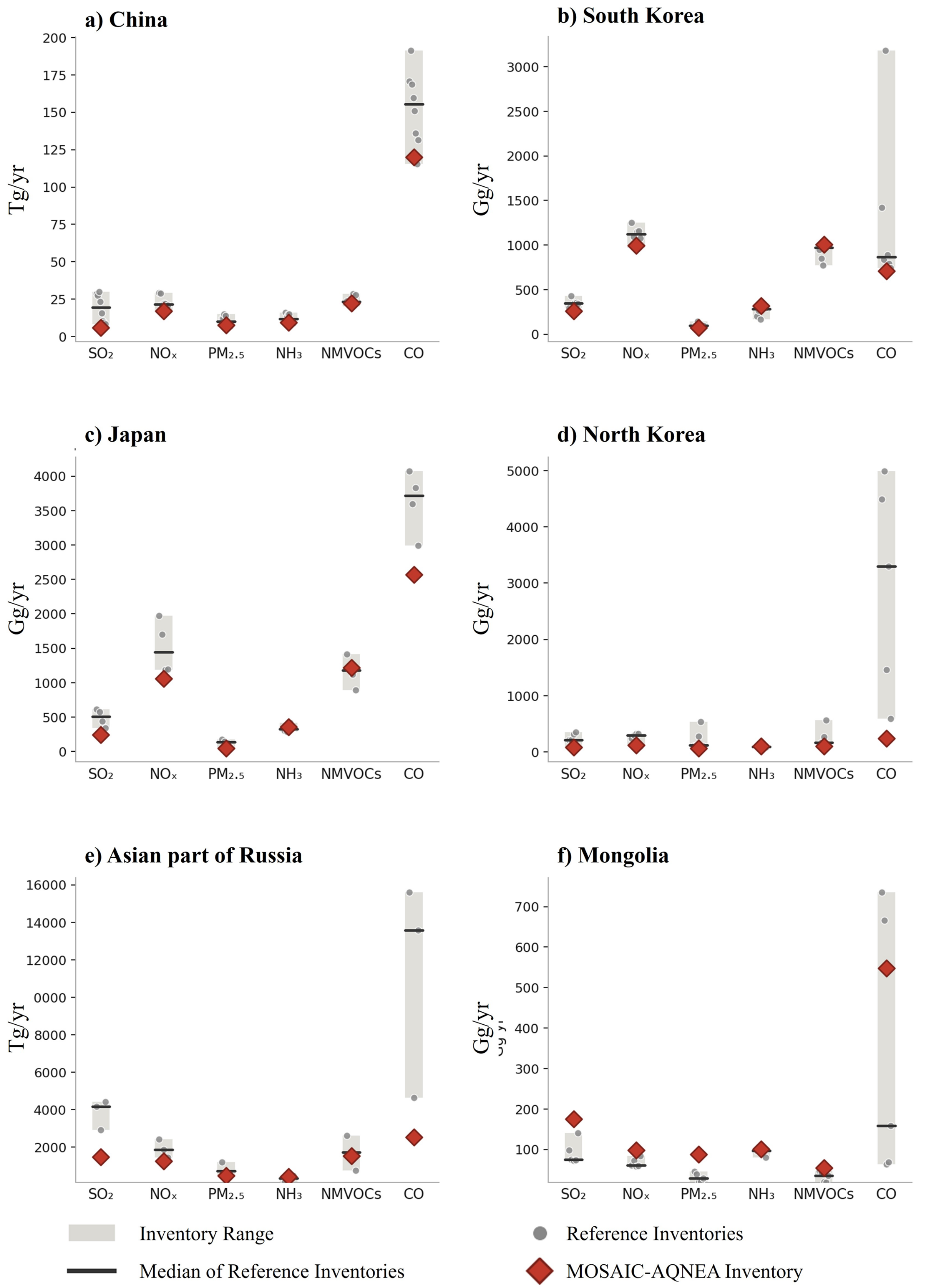
3.1.2 Analysis by Pollutant Level

Northeast Asian countries exhibit distinct emission characteristics driven by differences in population, economic activity, and social structure. At the same time, pollutant-specific emission features are clearly differentiated. SO_2 and NO_x are closely associated with fuel combustion and the industrial and energy sectors, whereas NH_3 is primarily linked to agricultural activities, and NMVOCs are largely governed by solvent use and industrial processes (Dong 2017; McDuffie et al. 2020; Pénard-Morand and Annesi-Maesano 2004). For these reasons, sectoral emission patterns by country were analyzed for each pollutant across the six MOSAIC-AQNEA countries (Fig. 6). Sectoral emission shares by country are shown on the left axis of Fig. 6, while star-shaped markers represent total national emissions on the right axis.

(1) Sulfur Dioxide (SO_2)
SO_2 is a representative combustion-related air pollutant primarily emitted from fossil fuel combustion. Across Northeast Asian countries, SO_2 emissions are mainly concentrated in the power, industry, and residential sectors. China, South Korea, and Japan exhibit emission structures dominated by the power and industry sectors, while the contribution of the residential sector in South Korea is relatively small. North Korea also shows an emission structure dominated by the industry sector, whereas the Asian part of Russia is characterized by emissions mainly from the power sector. In Mongolia, relatively large contributions from the power and residential sectors are observed.

(2) Nitrogen Oxides (NO_x)
NO_x is a representative combustion-related air pollutant primarily formed during high-temperature combustion processes. Across Northeast Asia, NO_x emissions are mainly concentrated in the power, industry, and transportation sectors (on-road and non-road). Compared with SO_2, NO_x emissions show a relatively larger contribution from transportation sources. China, South Korea, and Japan exhibit emission structures characterized by significant contributions from on-road and non-road transportation sources, in addition to the industrial and power generation sectors. This emission structure reflects increasing transportation demand and non-road combustion activities alongside industrial and energy-related activities. North Korea shows an emission structure dominated by the industry sector, whereas the Asian part of Russia is characterized by emissions mainly from the power sector. Mongolia exhibits an emission structure centered on power and non-road sources.

(3) Fine Particle (PM)
The analysis in this study primarily focuses on $PM_{2.5}$, given its dominant role in air quality and health impacts. PM is emitted from a wide range of sources, including fuel combustion, industrial processes, residential heating, and agricultural activities. Across Northeast Asia, PM emissions generally show a concentration in the industry and residential sectors. China exhibits emission structures characterized by major contributions from the industry and residential sectors. Compared with the industry sector, the relatively smaller contribution from the power sector indicates that PM emissions are more strongly associated with distributed combustion sources and diverse non-point emission activities.


a) China
Tg/yr
200
175
150
125
100
75
50
25
0
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
b) South Korea
Gg/yr
3000
2500
2000
1500
1000
500
0
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
c) Japan
Gg/yr
4000
3500
3000
2500
2000
1500
1000
500
0
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
d) North Korea
Gg/yr
5000
4000
3000
2000
1000
0
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
e) Asian part of Russia
Tg/yr
16000
14000
12000
0000
8000
6000
4000
2000
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
f) Mongolia
Gg/yr
700
600
500
400
300
200
100
SO₂ NOₓ PM₂.₅ NH₃ NMVOCs CO
Inventory Range
Median of Reference Inventories
Reference Inventories
MOSAIC-AQNEA Inventory

◀ **Fig. 5** Intercomparison with other inventories. The following inventories were used as reference inventories: MICS (2010), REAS (2010), ECLIPSE (2015), CAPSS (2015), MEIC (2017), LTP (2017), and CREATE (2010, 2015, 2019)

South Korea shows an emission structure mainly driven by the industrial and non-road mobile sectors, while Japan exhibits a relatively balanced distribution across the industry, residential, transportation, and agricultural sectors.

(4) Ammonia (NH_3)
NH_3 is a representative non-combustion air pollutant primarily emitted from agricultural activities, with livestock manure management and fertilizer application serving as the dominant emission sources. Across Northeast Asia, NH_3 emissions are concentrated in the agricultural sector, clearly demonstrating that NH_3 exhibits emission characteristics largely independent of energy-related combustion structures associated with the power generation, industrial, and transportation sectors. In contrast to combustion-related pollutants, the agricultural sector emerges as the principal source of NH_3 emissions consistently across all six countries.

(5) Nonmethane Volatile Organic Compounds (NMVOCs)
NMVOCs represent a complex class of pollutants emitted not only from combustion processes but also from diverse non-combustion sources, including solvent use, industrial processes, and fuel evaporation. Across Northeast Asia, NMVOC emissions are primarily concentrated in the industrial and solvent use sectors, with the solvent sector exhibiting a particularly dominant contribution. This pattern indicates that the use of solvent-based products, such as paints, coatings, adhesives, and cleaning agents, constitutes a major driver of NMVOCs emissions. Although NMVOCs emissions are consistently dominated by solvent use across Northeast Asian countries, substantial contributions are also observed from industrial processes, including petrochemical production activities. These emission characteristics suggest that NMVOCs management cannot be confined to a single sector but requires a combination of industrial process improvements, product use management, and control of evaporative emissions from transportation-related sources.

(6) Carbon Monoxide (CO)
CO is a representative product of incomplete combustion formed under conditions of insufficient oxygen supply. CO emissions sensitively reflect not only fuel type but also combustion efficiency, facility scale, and technological characteristics. Across Northeast Asia, CO emissions are predominantly concentrated in the industrial, residential, and on-road transportation sectors. Because CO emissions are fundamentally combustion-related, their sectoral patterns exhibit tendencies similar to those observed for $PM_{2.5}$.

3.1.3 Relative Emission Indicators Based on CO_2, Population, and GDP

The emission ratios of air pollutants relative to CO_2 serve as indicators of pollutant emission intensity associated with energy consumption activities, indirectly reflecting national combustion technology levels, fuel characteristics, and the effectiveness of emission control policies (Clarke and Faoro 1966; Li et al. 2023a, b a; Lin and Raza 2020; Shpak et al. 2022). Comparison of pollutant-specific emission ratios reveals two contrasting structural patterns among Northeast Asian countries, highlighting a distinction between the China–South Korea–Japan group and the North Korea–Russia–Mongolia group. CO_2 emissions used in Fig. 7 were derived from the Emissions Database for Global Atmospheric Research (EDGAR) inventory (Crippa et al. 2024).

Overall, SO_2 and $PM_{2.5}$ exhibit substantial reductions in China, South Korea, and Japan relative to other pollutants, reflecting the influence of emission control policies. Differences are also observed for NMVOCs, which include significant non-combustion sources. In Japan, recent emission trends for NMVOCs have shown a decreasing pattern compared with China and South Korea (Crippa et al. 2023), resulting in comparatively lower NMVOCs to CO_2 ratios.

To enable a socio-structural comparison of air pollutant emission characteristics (Guo et al. 2017) across Northeast Asian countries, national Gross Domestic Product (GDP) and population statistics were compiled for the base year 2019. GDP and population data were primarily obtained from country statistics provided by the World Bank Group (https://databank.worldbank.org/id/29c4df41, last accessed: 15th Feb.), while estimated data from Statistics Korea were used for North Korea to address gaps in international datasets (https://kosis.kr/bukhan/nkStats/nkStatsIdctChart.do?menuId=M_01_02&listNm=%EA%B5%AD%EB%AF%BC%EA%B3%84%EC%A0%95, last accessed: 15th Feb.). For the Asian part of Russia, the values from the World Bank Group were scaled using the proportion of the Asian region relative to total Russia, as provided by GAINS. Based on these data, national emissions were normalized by GDP and population to derive the indicators *Emissions per GDP* and *Emissions per Population*. These metrics facilitate a relative comparison of emissions across countries.

The *Emissions per GDP* indicator represents emission intensity relative to economic output and can be used to evaluate the environmental burden associated with unit economic activity. This metric reflects multiple structural factors, including national industrial composition, energy

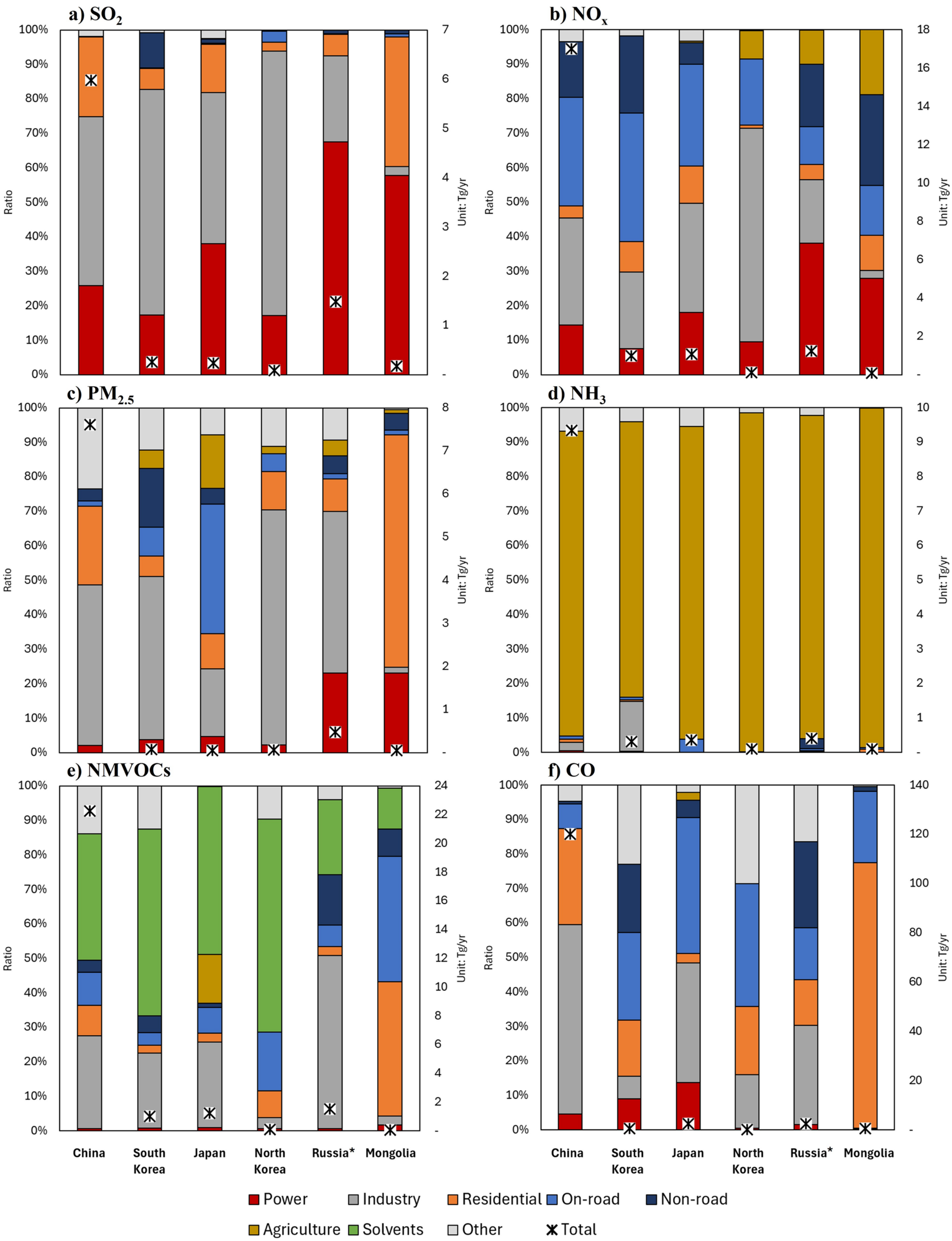


Fig. 6 Sectoral emissions contributions by each country: **a)** SO_2, **b)** NO_x, **c)** $PM_{2.5}$, **d)** NH_3, **e)** NMVOCs, **f)** CO (Russia*: Asian part of Russia)

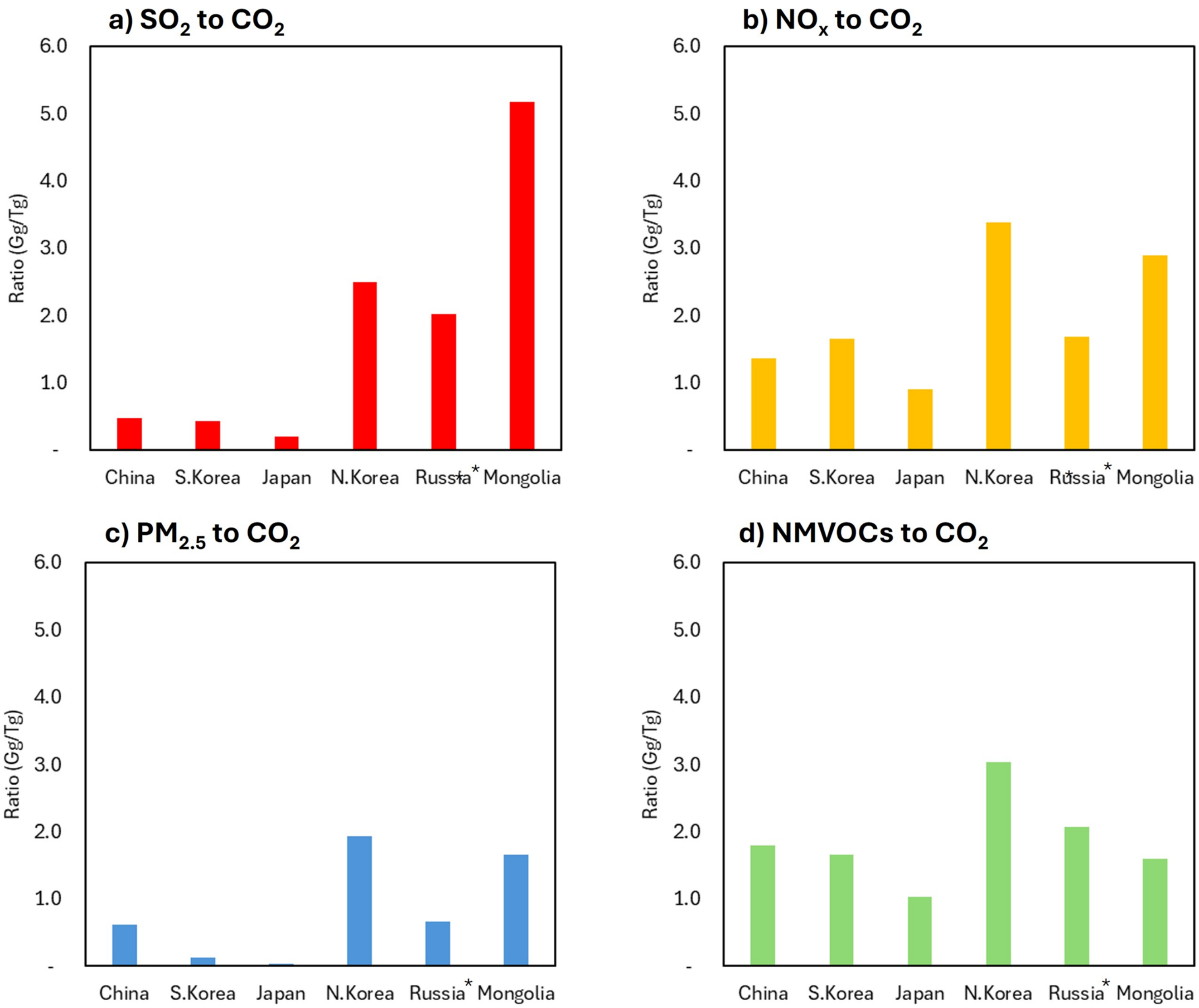


Fig. 7 Pollutants ratio to CO_2 Emissions by each country (Russia*: Asian part of Russia)

efficiency, dependence on fossil fuels, and the extent of air pollution control policies and technologies. For example, even among countries with similar GDP levels, higher values of *Emissions per GDP* may be observed where energy-intensive industries dominate or where emission control technologies are less extensively applied. Accordingly, *Emissions per GDP* functions not as a measure of absolute emission magnitude, but as a structural indicator for interpreting differences in emission characteristics associated with economic and energy system configurations.

The *Emissions per Population* indicator represents average emissions per capita and provides a useful measure for assessing the potential environmental burden linked to national living standards and routine energy consumption and activity patterns. This metric captures emission characteristics associated with population-driven activities, including residential heating, transportation, domestic combustion, and agricultural practices. Differences among countries are often pronounced depending on population density and the degree of urbanization. In general, higher values of *Emissions per Population* tend to be observed in countries with relatively large industrial activity per capita or where heating and energy consumption are concentrated.

A scatter plot was constructed in Fig. 8, with the logarithmic values both of *Emissions per GDP* on the x-axis and *Emissions per Population* on the y-axis. The dotted boundary lines were included solely to facilitate visual interpretation of relative differences among countries and pollutants and do not represent statistical thresholds.

The scatter plot enables simultaneous comparison of emission intensity per unit economic output and per capita emission burden. The upper-right region represents structures characterized by high values of both indicators, while the lower-left region corresponds to relatively low emission

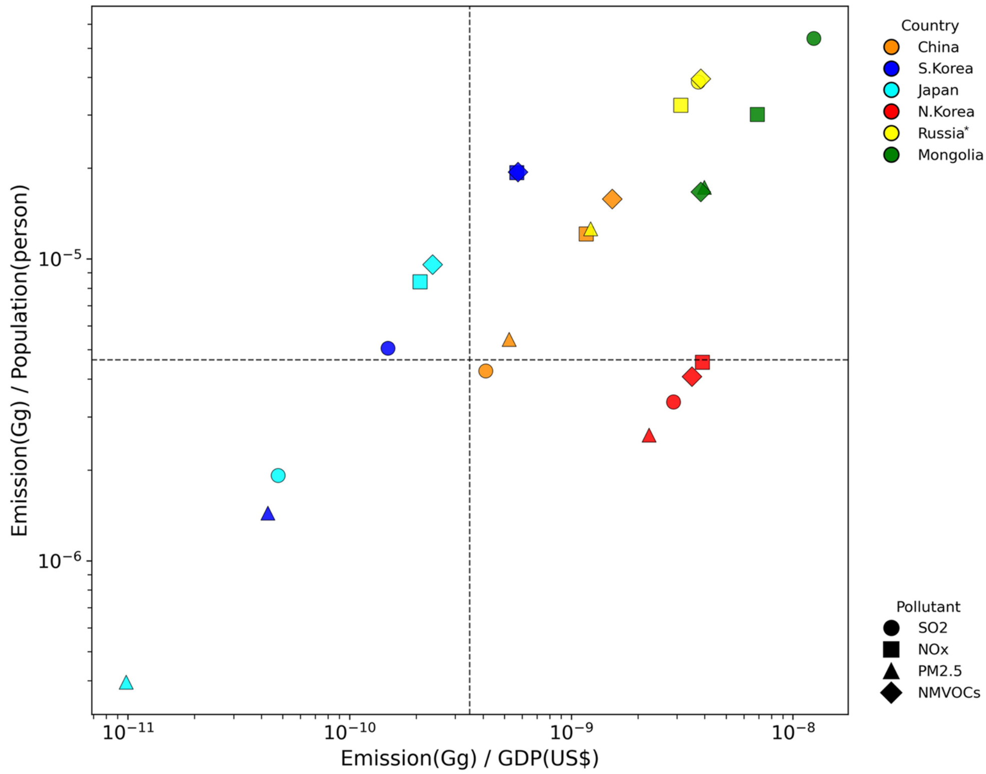


Fig. 8 GDP, Population Indicators (Dashed lines indicate visual partitioning of the plot area and do not represent statistical thresholds) (Russia*: Asian part of Russia)

intensity structures. The slope reflects per capita GDP, resulting in pollutant-specific values being aligned along diagonal patterns for each country. Within this distribution, pollutants located toward the lower-left position represent those with comparatively smaller emission magnitudes for individual countries. For most countries, SO_2 and $PM_{2.5}$ exhibit the lowest emissions relative to GDP and population. The plot also facilitates relative comparisons among countries. South Korea and Japan appear to exhibit lower emissions relative to GDP, whereas North Korea and Mongolia display comparatively higher emission intensities. Japan is distributed within the lowest range of both indicators, indicating consistently low emission intensity characteristics. These results suggest that national emission characteristics are determined not solely by absolute emission amounts but also by the combined influences of economic structure, population attributes, and energy utilization patterns.

3.2 Gridded Model-Ready MOSAIC-AQNEA

3.2.1 Spatial Distribution

The developed emission inventory was processed using SMOKE-Asia to generate model-ready emissions for the base year, and gridded emission maps for major air pollutants are presented in Fig. 9. The gridded emissions indicates elevated emission levels in regions characterized by concentrated human activities, particularly major urban and industrial areas across Northeast Asia. Representative examples include Beijing-Tianjin-Hebei (BTH) and Shanghai in eastern China; the Seoul Metropolitan Area (SMA), including Seoul, Incheon, and Gyeonggi Province, in South Korea; and the Tokyo metropolitan region within the Kanto area of Japan. These regions are associated with high population density and intensive industrial activity, leading to substantial emissions of air pollutants. Emissions in these areas are primarily driven by combustion activities in the residential, transportation, and industrial sectors, resulting in pronounced emissions of SO_2, NO_x and CO.

In contrast, NH_3, a pollutant predominantly emitted from agricultural sources, exhibits spatial distributions concentrated in rural and agricultural regions rather than urban centers. This pattern reflects the dominant contribution of livestock production and fertilizer application. Regions such as inland agricultural areas of China, the Chungcheong and Jeolla regions of South Korea, and Hokkaido and Kyushu in Japan demonstrate comparatively higher NH_3 emission intensities. Higher emission intensities are observed in regions characterized by concentrated livestock operations and fertilizer use, resulting in patterns dominated by area sources. This spatial behavior contrasts with combustion-related pollutants and reflects the fundamental differences in emission mechanisms.

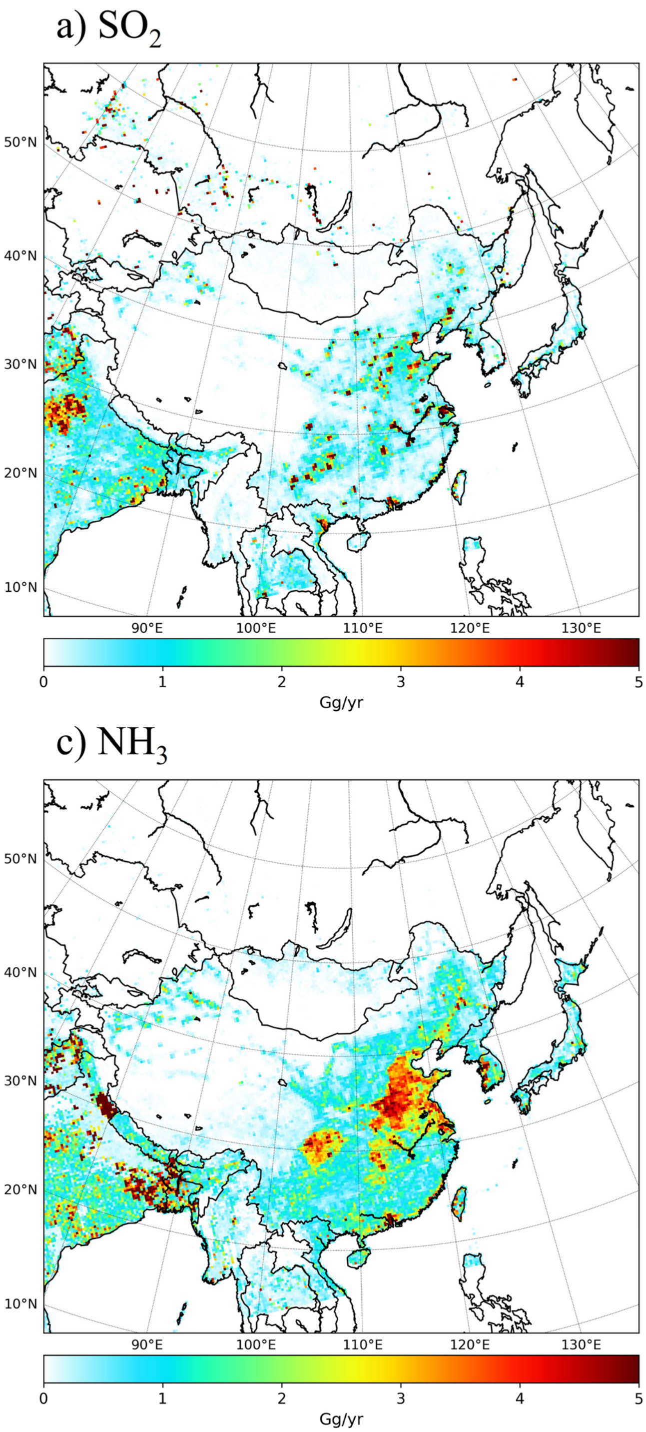


Fig. 9 Gridded emissions spatial distribution

3.2.2 Temporal Allocation

Seasonal variability of emissions in the Northeast Asian region was incorporated using SMOKE-Asia (Fig. 10). The seasonal profiles applied in this study were defined to reflect sector-specific activity characteristics and seasonal differences in energy consumption patterns. This approach enables a more realistic representation of periods of enhanced and reduced emissions at the monthly scale, which cannot be captured by annual mean emission estimates alone.

In the power sector, relatively higher allocation factors are observed during the winter months (January and December) and the summer period (July and August), reflecting seasonal variations in electricity production driven by increased

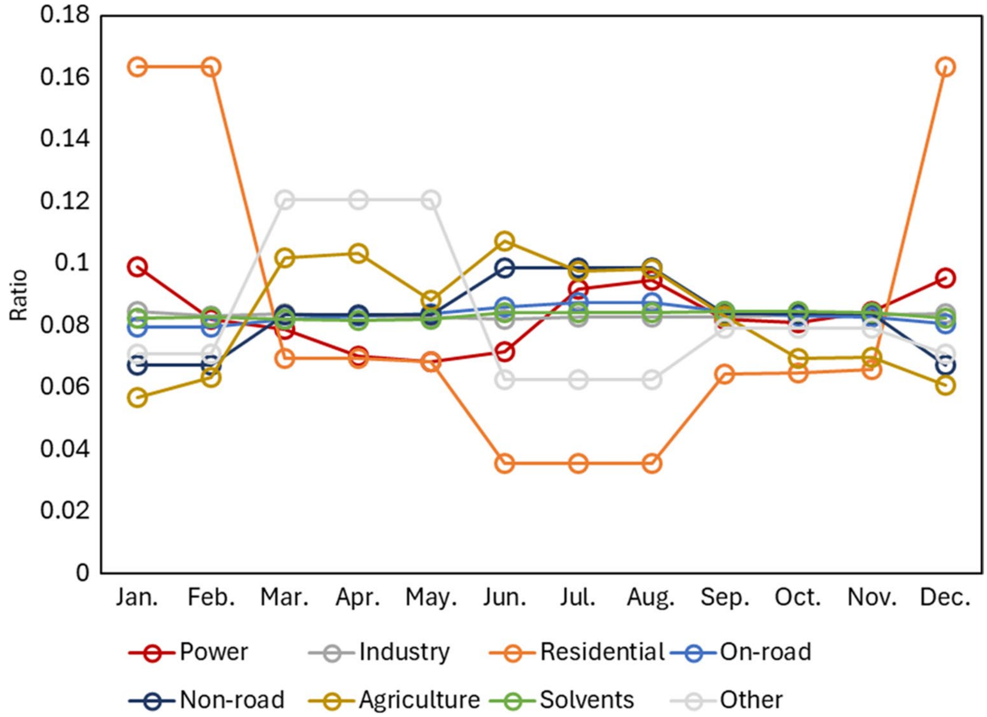


Fig. 10 Temporal allocation by each sector (Averaged profile applied to Northeast Asian countries)

heating and cooling demands. In contrast, lower allocation factors appear during the spring and autumn months, indicating transitional periods characterized by comparatively moderated electricity demand. The residential sector also exhibits pronounced seasonal variability, with the highest allocation factors occurring in winter. This pattern clearly reflects the dominant influence of heating fuel consumption, suggesting that wintertime residential combustion represents a major contributor to seasonal increases in combustion-related pollutants such as $PM_{2.5}$ and CO.

The industrial sector maintains relatively uniform monthly allocation factors throughout the year, reflecting the continuous nature of industrial production activities with limited seasonal fluctuation. The on-road transportation sector displays moderate seasonal variability, with slightly elevated allocation factors during summer. This tendency is associated with increased travel demand and mobility during the summer period.

The agricultural sector shows relatively higher allocation factors in spring and summer, consistent with periods of intensified agricultural activities, including fertilizer application, field operations, and livestock-related processes. Conversely, winter months exhibit reduced emissions due to limited agricultural activity. The solvent use sector demonstrates minimal seasonal variation, indicating that emissions associated with industrial and consumer product usage are not strongly concentrated in specific seasons. A slight increase during summer is attributable to enhanced painting and coating activities and seasonal influences on volatilization conditions.

3.2.3 Speciated NMVOCs Emissions

Chemical speciation of NMVOCs represents a critical factor influencing atmospheric chemical reactivity and secondary pollutant formation. Even for identical total NMVOCs emissions, variations in chemical composition can lead to substantial differences in Ozone Formation Potential (OFP) and Secondary Organic Aerosol (SOA) production. Consequently, differences in country-specific chemical speciation profiles reveal underlying variations in national emission structures (Fig. 11).

Northeast Asian countries generally exhibit NMVOCs composition structures dominated by alkanes and aromatics, indicating that fuel use, industrial processes, and solvent-related activities play central roles in shaping regional NMVOCs emissions. The contribution of aromatic compounds is particularly important, given their strong association with photochemical reactivity and SOA formation, thereby carrying significant implications for air quality impact assessments. China shows comparatively high NMVOCs emission across all other countries. South Korea and Japan display broadly similar composition patterns, although notable differences appear in their relative distributions. South Korea exhibits a relatively higher contribution from aromatics. Japan presents a more balanced distribution between alkanes and aromatics. Asian part of Russia demonstrates a composition structure characterized by a relatively larger contribution from alkanes and a comparatively smaller fraction of aromatics. A measurable contribution from oxygenated volatile organic compounds

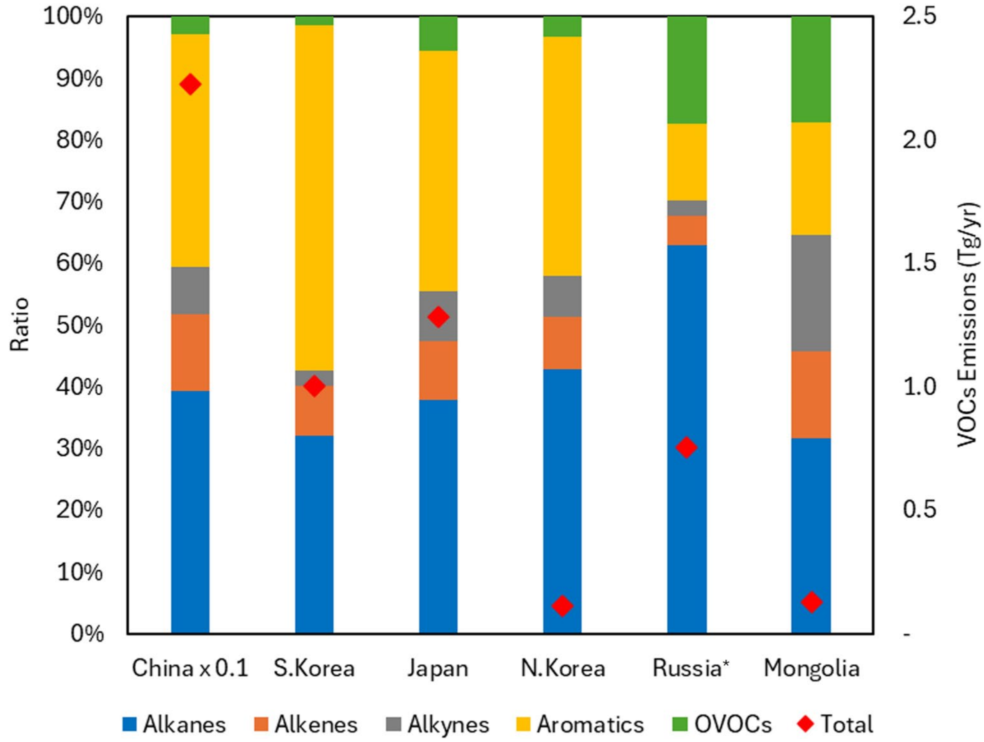


Fig. 11 Speciated emissions by each country

(OVOCs) suggests emissions associated with combustion and oxidation-related processes. North Korea and Mongolia exhibit comparatively low chemical group emission intensities, reflecting lower levels of economic activity and more limited industrial structures.

4 Conclusion

The MOSAIC-AQNEA emission inventory was developed for six Northeast Asian countries (China, South Korea, Japan, North Korea, Asian part of Russia, and Mongolia) by applying a mosaic approach to the national emission inventories under a unified sectoral classification framework. The inventory was further constructed through activity-based downscaling grounded in the detailed activity and fuel categorizations defined within the CREATE framework. In addition, emissions were processed into model-ready formats using refined datasets developed to support major aircraft observation campaigns conducted in the Asian region. Unlike previous regional inventories, this study provides a consistent integration across multiple countries, pollutants, and sectors. The combined use of activity-based bottom-up methodologies and official national inventories enables a more realistic representation of regional emission characteristics.

A principal contribution of this study lies in the establishment of a structural framework supporting atmospheric research in Northeast Asia. Beyond emission inventory development, the framework incorporates emission processing steps required for direct application in atmospheric chemical transport models, facilitated through international collaboration and a shared analytical structure. Northeast Asia represents a region characterized by pronounced long-range transport of air pollutants, where inventories based solely on single-country datasets are insufficient to fully explain regional air quality dynamics. The integrated emission framework presented here provides a foundational dataset for a broad range of applications, including analyses of transboundary emission interactions, source contribution assessments, and scenario-based policy evaluations.

Several directions for future expansion of the framework are evident. First, updates to the base year allow incorporation of evolving energy systems, policy developments, and technological transitions. Such updates are particularly important given the rapid progression of energy transition policies and emission regulations across Northeast Asia. Second, integration with future emission scenarios enables extensions toward climate change and policy-driven air quality projection studies. Third, coupling with multiple atmospheric chemical transport models supports model intercomparison analyses and uncertainty assessments.

In conclusion, the MOSAIC-AQNEA emission inventory and processing framework developed in this study provide an integrated and internally consistent foundation for atmospheric modeling and policy assessment research in Northeast Asia. This approach satisfies both the scientific consistency and policy relevance required for regional-scale air quality investigations.

The key contribution of this study is not only the emission dataset itself but also the transparent framework that enables consistent integration of heterogeneous national inventories. This reduces structural inconsistencies that often limit cross-country comparisons in Northeast Asia. The framework can be extended to future years and scenario analyses, making it relevant for both scientific and policy applications.

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Data Availability The gridded emission datasets generated in this study are publicly available at the Climate change and Air quality Information Systems research group(CAIS) website (URL: http://cais.snu.ac.kr).
The dataset includes model-ready emissions by sector, pollutant, and grid resolution used in this study.
Additional information on processing parameters and sector mappings is provided in the manuscript. Further details can be obtained from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Akyuz, E., Cingiroglu, F., Kaynak, B., Unal, A.: A bottom-up agricultural emissions inventory and its analysis via CMAQ and IASI-NH3. Sci. Total Environ. **950**, 175355 (2024). https://doi.org/10.1016/j.scitotenv.2024.175355

Amann, M., Bertok, I., Borken, J., Chambers, A., Cofala, J., Dentener, F., Heyes, C., Hoglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schöpp, W., Texeira, E., Toth, G., Wagner, F., Winiwarter, W.: A tool to combat air pollution and climate change simultaneously. Methodology (2008)

Botta, E., Yamasaki, S.: Policies, regulatory framework and enforcement for air quality management: The case of Japan (2020)

Carter, W.P.L.: Development of the SAPRC-07 chemical mechanism. Atmos. Environ. **44**, 5324–5335 (2010). https://doi.org/10.1016/j.atmosenv.2010.01.026

Cha, Y., Lee, J.-J., Song, C.H., Kim, S., Park, R.J., Lee, M.-I., Woo, J.-H., Choi, J.-H., Bae, K., Yu, J., Kim, E., Kim, H., Lee, S.-H., Kim, J., Chang, L.-S., Jeon, K., Song, C.-K.: Investigating uncertainties in air quality models used in GMAP/SIJAQ 2021 field campaign: General performance of different models and ensemble results. Atmos. Environ. **340**, 120896 (2025). https://doi.org/10.1016/j.atmosenv.2024.120896

Chatani, S., Kitayama, K., Itahashi, S., Irie, H., Shimadera, H.: Effectiveness of emission controls implemented since 2000 on ambient ozone concentrations in multiple timescales in Japan: An emission inventory development and simulation study. Sci. Total Environ. **894**, 165058 (2023). https://doi.org/10.1016/j.scitotenv.2023.165058

Choi, K.-C., Lee, J.-B., Woo, J.-H., Hong, S.-C., Park, R.J., Kim, M.J., Song, C.-K., Chang, L.-S.: Development of an Emissions Processing System for Climate Scenario Inventories to Support Global and Asian Air Quality Modeling Studies. Asian J. Atmos. Environ. **11**, 330–343 (2017). https://doi.org/10.5572/ajae.2017.11.4.330

Clarke, J.F., Faoro, R.B.: An Evaluation of CO_2, Measurements as an Indicator of Air Pollution. J. Air Pollution Control Association. **16**, 212–218 (1966). https://doi.org/10.1080/00022470.1966.10468465

Crawford, J.H., Ahn, J.-Y., Al-Saadi, J., Chang, L., Emmons, L.K., Kim, J., Lee, G., Park, J.-H., Park, R.J., Woo, J.H., Song, C.-K., Hong, J.-H., Hong, Y.-D., Lefer, B.L., Lee, M., Lee, T., Kim, S., Min, K.-E., Yum, S.S., Shin, H.J., Kim, Y.-W., Choi, J.-S., Park, J.-S., Szykman, J.J., Long, R.W., Jordan, C.E., Simpson, I.J., Fried, A., Dibb, J.E., Cho, S., Kim, Y.P.: The Korea–United States Air Quality (KORUS-AQ) field study. Elementa: Sci. Anthropocene. **9**, 00163 (2021). https://doi.org/10.1525/elementa.2020.00163

Crippa, M., Guizzardi, D., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S., Morikawa, T., Pouliot, G., Racine, J., Moran, M.D., Klimont, Z., Manseau, P.M., Mashayekhi, R., Henderson, B.H., Smith, S.J., Suchyta, H., Muntean, M., Solazzo, E., Banja, M., Schaaf, E., Pagani, F., Woo, J.-H., Kim, J., Monforti-Ferrario, F., Pisoni, E., Zhang, J., Niemi, D., Sassi, M., Ansari, T., Foley, K.: The HTAP_v3 emission mosaic: merging regional and global monthly emissions (2000–2018) to support air quality modelling and policies. Earth Syst. Sci. Data. **15**, 2667–2694 (2023). https://doi.org/10.5194/essd-15-2667-2023

Crippa, M., Guizzardi, D., Pagani, F., Schiavina, M., Melchiorri, M., Pisoni, E., Graziosi, F., Muntean, M., Maes, J., Dijkstra, L., Van Damme, M., Clarisse, L., Coheur, P.: Insights into the spatial distribution of global, national, and subnational greenhouse gas emissions in the Emissions Database for Global Atmospheric Research (EDGAR v8.0). Earth Syst. Sci. Data. **16**, 2811–2830 (2024). https://doi.org/10.5194/essd-16-2811-2024

Dong, G.-H. (ed.): Ambient Air Pollution and Health Impact in China. Springer Singapore, Singapore (2017)

Ebi, K.L., McGregor, G.: Climate Change, Tropospheric Ozone and Particulate Matter, and Health Impacts. Environ. Health Perspect. **116**, 1449–1455 (2008). https://doi.org/10.1289/ehp.11463

Guo, X., Shi, J., Ren, D., Ren, J., Liu, Q.: Correlations between air pollutant emission, logistic services, GDP, and urban population growth from vector autoregressive modeling: a case study of Beijing. Nat. Hazards. **87**, 885–897 (2017). https://doi.org/10.1007/s11069-017-2799-1

Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J.J., Vu, L., Andres, R.J., Bolt, R.M., Bond, T.C., Dawidowski, L., Kholod, N., Kurokawa, J., Li, M., Liu, L., Lu, Z., Moura, M.C.P., O'Rourke, P.R., Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geosci. Model. Dev. **11**, 369–408 (2018). https://doi.org/10.5194/gmd-11-369-2018

Houyoux, M.R., Vukovich, J.M., Coats, C.J., Wheeler, N.J.M., Kasibhatla, P.S.: Emission inventory development and processing for the Seasonal Model for Regional Air Quality (SMRAQ) project. J. Geophys. Res. **105**, 9079–9090 (2000). https://doi.org/10.1029/1999JD900975

Ibarra-Espinosa, S., Ynoue, R., O'Sullivan, S., Pebesma, E., Andrade, M.D.F., Osses, M.: VEIN v0.2.2: an R package for bottom–up vehicular emissions inventories. Geosci. Model. Dev. **11**, 2209–2229 (2018). https://doi.org/10.5194/gmd-11-2209-2018

Jafari, A.J., Charkhloo, E., Pasalari, H.: Urban air pollution control policies and strategies: a systematic review. J. Environ. Health Sci. Eng. **19**, 1911–1940 (2021). https://doi.org/10.1007/s40201-021-00744-4

Kim, C.-H., Chang, L.-S., Kim, J.-S., Meng, F., Kajino, M., Ueda, H., Zhang, Y., Son, H.-Y., He, Y., Xu, J., Sato, K., Song, C.-K., Ban, S.-J., Sakurai, T., Han, Z., Duan, L., Lee, S.-J., Shim, S.-G., Sunwoo, Y., Lee, T.-Y.: Long-term simulations of the sulfur concentrations over the China, Japan and Korea: A model comparison study. Asia-Pacific J. Atmos. Sci. **47**, 399–411 (2011). https://doi.org/10.1007/s13143-011-0025-8

Kim, S., Kim, J., Hu, H., Jang, M., Lee, J.-B., Hong, S.C., Kim, O., Woo, J.-H.: Update of the year 2019 modeling emission inventory in China. Asian J. Atmos. Environ. **17**, 20 (2023). https://doi.org/10.1007/s44273-023-00012-x

Kurokawa, J., Ohara, T.: Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3. Atmos. Chem. Phys. **20**, 12761–12793 (2020). https://doi.org/10.5194/acp-20-12761-2020

Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K., Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2. Atmos. Chem. Phys. **13**, 11019–11058 (2013). https://doi.org/10.5194/acp-13-11019-2013

Lee, D., Lee, Y.-M., Jang, K.-W., Yoo, C., Kang, K.-H., Lee, J.-H., Jung, S.-W., Park, J.-M., Lee, S.-B., Han, J.-S., Hong, J.-H., Lee, S.-J.: Korean National Emissions Inventory System and 2007 Air Pollutant Emissions. Asian J. Atmos. Environ. **5**, 278–291 (2011). https://doi.org/10.5572/ajae.2011.5.4.278

Li, M., Zhang, Q., Kurokawa, J., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., Zheng, B.: MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. Atmos. Chem. Phys. **17**, 935–963 (2017). https://doi.org/10.5194/acp-17-935-2017

Li, J., Irfan, M., Samad, S., Ali, B., Zhang, Y., Badulescu, D., Badulescu, A.: The Relationship between Energy Consumption, CO2 Emissions, Economic Growth, and Health Indicators. IJERPH. **20**(2325) (2023a). https://doi.org/10.3390/ijerph20032325

Li, S., Wang, S., Wu, Q., Zhang, Y., Ouyang, D., Zheng, H., Han, L., Qiu, X., Wen, Y., Liu, M., Jiang, Y., Yin, D., Liu, K., Zhao, B., Zhang, S., Wu, Y., Hao, J.: Emission trends of air pollutants and CO_2 in China from 2005 to 2021. Earth Syst. Sci. Data. **15**, 2279–2294 (2023b). https://doi.org/10.5194/essd-15-2279-2023

Lin, B., Raza, M.Y.: Analysis of energy security indicators and CO2 emissions. A case from a developing economy. Energy. **200**, 117575 (2020). https://doi.org/10.1016/j.energy.2020.117575

Marinello, S., Piccinini, G., Coruzzolo, A.M., Lolli, F., Gamberini, R.: Downscaling atmospheric emission inventories with top–down approach: the support of the literature in choosing proxy variables. Int. J. Environ. Sci. Technol. **21**, 7353–7366 (2024). https://doi.org/10.1007/s13762-024-05490-2

McDuffie, E.E., Smith, S.J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E.A., Zheng, B., Crippa, M., Brauer, M., Martin, R.V.: A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS). Earth Syst. Sci. Data. **12**, 3413–3442 (2020). https://doi.org/10.5194/essd-12-3413-2020

Park, R.J., Oak, Y.J., Emmons, L.K., Kim, C.-H., Pfister, G.G., Carmichael, G.R., Saide, P.E., Cho, S.-Y., Kim, S., Woo, J.-H., Crawford, J.H., Gaubert, B., Lee, H.-J., Park, S.-Y., Jo, Y.-J., Gao, M., Tang, B., Stanier, C.O., Shin, S.S., Park, H.Y., Bae, C., Kim, E.: Multi-model intercomparisons of air quality simulations for the KORUS-AQ campaign. Elementa: Sci. Anthropocene. **9**(00139) (2021). https://doi.org/10.1525/elementa.2021.00139

Park, J., Jung, J., Choi, Y., Lim, H., Kim, M., Lee, K., Lee, Y.G., Kim, J.: Satellite-based, top-down approach for the adjustment of aerosol precursor emissions over East Asia: the TROPOspheric Monitoring Instrument (TROPOMI) NO_2 product and the Geostationary Environment Monitoring Spectrometer (GEMS) aerosol optical depth (AOD) data fusion product and its proxy. Atmos. Meas. Tech. **16**, 3039–3057 (2023). https://doi.org/10.5194/amt-16-3039-2023

Park, J., Choi, Y., Jung, J., Lee, K., Yeganeh, A.K.: First top-down diurnal adjustment to NOx emissions inventory in Asia informed by the Geostationary Environment Monitoring Spectrometer (GEMS) tropospheric NO2 columns. Sci. Rep. **14**, 24338 (2024). https://doi.org/10.1038/s41598-024-76223-1

Pénard-Morand, C., Annesi-Maesano, I.: Air pollution: from sources of emissions to health effects. Breathe. **1**, 108–119 (2004). https://doi.org/10.1183/18106838.0102.108

Roy, S., Lam, Y.F., Chopra, S.S., Hoque, M.M.: Review of Decadal Changes in ASEAN Emissions Based on Regional and Global Emission Inventory Datasets. Aerosol Air Qual. Res. **23**, 220103 (2023). https://doi.org/10.4209/aaqr.220103

Shpak, N., Ohinok, S., Kulyniak, I., Sroka, W., Fedun, Y., Ginevičius, R., Cygler, J.: CO2 Emissions and Macroeconomic Indicators: Analysis of the Most Polluted Regions in the World. Energies. **15**, 2928 (2022). https://doi.org/10.3390/en15082928

Stohl, A., Aamaas, B., Amann, M., Baker, L.H., Bellouin, N., Berntsen, T.K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N., Dusinska, M., Eckhardt, S., Fuglestvedt, J.S., Harju, M., Heyes, C., Hodnebrog, Ø., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K.S., Lund, M.T., Maas, R., MacIntosh, C.R., Myhre, G., Myriokefalitakis, S., Olivié, D., Quaas, J., Quennehen, B., Raut, J.-C., Rumbold, S.T., Samset, B.H., Schulz, M., Seland, Ø., Shine, K.P., Skeie, R.B., Wang, S., Yttri, K.E., Zhu, T.: Evaluating the climate and air quality impacts of short-lived pollutants. Atmos. Chem. Phys. **15**, 10529–10566 (2015). https://doi.org/10.5194/acp-15-10529-2015

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.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. **108**, 2002JD003093 (2003). https://doi.org/10.1029/2002JD003093

Trnka, D.: Policies, regulatory framework and enforcement for air quality management: the case of Korea (2020)

US EPA: SMOKE v4.5 User's Manual: (2023). https://doi.org/10.5281/zenodo.8087514

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.: Development of an anthropogenic emissions processing system for Asia using SMOKE. Atmos. Environ. **58**, 5–13 (2012). https://doi.org/10.1016/j.atmosenv.2011.10.042

Woo, J.-H., Kim, Y., Kim, H.-K., Choi, K.-C., Eum, J.-H., Lee, J.-B., Lim, J.-H., Kim, J., Seong, M.: Development of the CREATE Inventory in Support of Integrated Climate and Air Quality Modeling for Asia. Sustainability. **12**, 7930 (2020). https://doi.org/10.3390/su12197930

Wu, N., Geng, G., Xu, R., Liu, S., Liu, X., Shi, Q., Zhou, Y., Zhao, Y., Liu, H., Song, Y., Zheng, J., Zhang, Q., He, K.: Development of a high-resolution integrated emission inventory of air pollutants for China. Earth Syst. Sci. Data. **16**, 2893–2915 (2024). https://doi.org/10.5194/essd-16-2893-2024

Xing, Y.-F., Xu, Y.-H., Shi, M.-H., Lian, Y.-X.: The impact of PM2.5 on the human respiratory system. J. Thorac. Disease **8** (2016)

Yang, C.: Policies, regulatory framework and enforcement for air quality management: the case of China (2020)

Yarwood, G., Jung, J., Whitten, G.Z., Heo, G., Mellberg, J., Estes, M.: Updates to the carbon bond mechanism for version 6 (CB6) (2010)