JOURNAL OF
HYDRO-METEOROLOGY

Check for updates

Rerearch Article

Exploiting the results of running the GEOS-CF model to evaluate $PM_{2.5}$ concentration in near real-time in Vietnam

Uyen Khanh Le[1], Binh Quoc Pham[2], Long Ta Bui[1]*

[1] Faculty of Environment and Natural Resources, University of Technology, Vietnam National University, Ho Chi Minh City; uyen.le02@hcmut.edu.vn; longbt62@hcmut.edu.vn

[2] Envim Lab, University of Technology, Vietnam National University, Ho Chi Minh City; phamquocbinh2018@gmail.com

*Correspondence: longbt62@hcmut.edu.vn; Tel.: +84–918017376

Received: 12 March 2024; Accepted: 01 May 2024; Published: 25 June 2024

Abstract: Near real-time information about global atmospheric composition, including $PM_{2.5}$ fine dust, is valuable because it helps forecast air quality and manage environmental disasters. Recently, NASA's Global Modeling and Assimilation Office has released a set of near real-time Goddard Earth Observing System models that help analyze and forecast global air quality, named GEOS-CF (GEOS Composition Forecast). In particular, GEOS-CF can simulate the transport from the stratosphere to the troposphere (the stratosphere to troposphere transport) which is technically very difficult. In Vietnam's challenging conditions, research and application of GEOS-CF output results must be made. In this study, the authors developed a tool named ENAR (Envim Nasa Analysis Result) to help interpret GEOS-CF results provided free of charge by NASA to form $PM_{2.5}$ pollution maps for each area hourly across the entire territory of Vietnam. ENAR was applied to build pollution maps for the first three months 2024. The results were analyzed to clarify the range of pollution levels for each area, including the Hoang Sa and Truong Sa archipelagos, Vietnam. These results allow scientific agencies to obtain reliable information for studies predicting this type of pollution.

Keywords: $PM_{2.5}$; GEOS-CF; ENAR tool; NASA; Vietnam.

1. Introduction

Air quality forecasts have recently become increasingly important for Vietnam. Over the past years, rapid economic growth in cities in Vietnam, such as Ho Chi Minh City and Hanoi, has significantly increased the amount of man-made emissions, affecting people's health [1–4]. Among pollutants, fine particulate matter (PM) $PM_{2.5}$ is a significant public health concern [5–7]. Adverse health effects have been associated with short- and long-term exposure to $PM_{2.5}$ [8]. $PM_{2.5}$ is associated with morbidity, mortality, [9] cardiovascular disease, respiratory disease, myocardial infarction, increased hospitalization rates [10] and other diseases [11]. Accurate exposure assessment of $PM_{2.5}$ is a prerequisite for investigating its adverse health effects. Initial studies estimated $PM_{2.5}$ at the nearest monitoring station [12]. However, the closest monitoring devices cannot capture all variations in $PM_{2.5}$ concentrations, and non-differential misclassification occurs [13].

It is essential to predict the scope and level of impact of this type of pollution to protect human health. In recent years, several studies have been conducted on some large urban areas of the country, including the city. Ho Chi Minh city, using models that take into account chemical reactions and regional scales [14–16]. In the study [17], $PM_{2.5}$ pollution forecasts for Southeast Asia, including Cambodia, Laos, Thailand and Vietnam, were made by comparing emission database scenarios for two years, 2019 and 2050. An overview of the research shows that existing studies have not yet produced $PM_{2.5}$ distribution maps for Vietnam at any level. To assess the damage caused by this type of pollution, it is necessary to build a distribution map of this type of pollution [2], which is also why this study was conducted.

In recent times, air pollution modelling research agencies such as universities space research association, goddard earth sciences technology and research, NASA's global modeling and assimilation office, goddard space flight center, TOLNet - tropospheric ozone lidar network ground-based profiling of tropospheric ozone has launched many scientific products, especially the NASA goddard earth observing system composition forecast (GEOS-CF). This product provides users free of charge with 5-day near real-time calculation results of air pollutants, including fine particulate matter ($PM_{2.5}$) [18]. This model combines the GEOS weather analysis and forecasting system with the state-of-the-art GEOS-Chem chemistry module [19, 20]. The complete model and simulation features for the troposphere are given in [21] and provided in [22] for the stratosphere. These models have been calibrated and validated against satellite, balloon, lidar observations of stratospheric composition, including ozone (O_3) measurements and related essential nitrogen and chlorine species related to O_3 recovery in the stratosphere [22]. These products support NASA field missions and evaluate the impact of NASA observations on environmental prediction [22].

In conditions where there are still many difficulties in investment funding, exploiting these results is necessary because they are provided for free, and these results allow research agencies and organizations to access them. latest to quantify the damage caused by pollution and provide long-term plans to reduce pollution. This study aims to exploit the results from running the GEOS-CF model to build $PM_{2.5}$ pollution maps across the entire territory of Vietnam. On that basis, initial assessments are made about the level and scope of impact on different areas of the country.

2. Materials and Methods

2.1. GEOS-CF model

In 2019, NASA's global modeling and assimilation office released a suite of near real-time goddard earth observing system models (GEOS) for analysis and forecasts with delays from one month to two months. This product realizes NASA's field mission, helping the agency predict the global environment. This product is widely available to many users. Version 1.0 was released in September 2019, followed by version 1.1 in March 2020, version 1.2 in February 2022 and version 1.3 in December 2022 [18]. The GEOS-CF system uses the GEOS-Chem chemical scheme version 12.0.1 (http://geos chem.org) [19]. GEOS-Chem includes detailed stratospheric chemistry fully coupled with tropospheric chemistry described in [23]. GEOS-Chem calculated the photolysis rate online using the Fast-JX code [24] implemented in GEOS-Chem [25]. The gas phase mechanism includes 250 chemicals and 725 reactions and is solved using the KPP Rosenbrock Kinetic Preprocessor solver [26].

GEOS-CF uses two independent aerosol schemes run in parallel. The first scheme is the goddard chemistry, transport, aerosol, radiation [27, 28]. The second diagram - mechanism GEOS-Chem aerosol, simulates the mass concentrations of significant aerosol components - dust, black carbon , organic carbon, sea salt, sulfate, nitrate and ammonium and provides up-to-date information on secondary organic aerosol (SOA) chemistry [28].

GEOS-CF uses emissions data from NASA-Harvard, HEMCO [20]. Anthropogenic emissions are monthly averages from HTAP v2.2 [29] and RETRO [30], broken down into hourly values using weekday and day-specific scale factors by industry [31]. Calculations in

GEOS-CF are performed on a cubed-sphere c360 grid [32] (resolution 25 km × 25 km) with 72 vertical layers with pressure values. At the highest level, the pressure is 0.01 hPa. Input data files are provided at ¼ degree horizontal resolution. This global grid has 1440 longitudinal and 721 latitudinal points, corresponding to a resolution of 0.25° × 0.25°. Model output with 1-hour time resolution. The output result is at the altitude closest to the ground at level 72, corresponding to an altitude with a pressure of 985 hPa, equivalent to about 1.2 km [18]. This distance is located in the troposphere, so it directly affects the concentration of $PM_{2.5}$ near the ground and is also the subject of environmental research.

The GEOS-CF model is calibrated, verified, validated by data from NASA, including Satellite, including ACE-FTS v4.1, MLS v5, SAGE III/ISS v5.1, Ozone Watch, OMI "TOMS-like" v3 level 3 products, SBUV Merged Ozone product v8.6; Balloon, including Ozonesondes; Ground-based, including TOLNet Lidar [1].

2.2. Methods and implementation steps

To achieve the set goals, this study uses ENAR software (Envim Nasa Analysis Result), developed by the authors using Python programming, which includes 11 steps. Step 1: perform downloading files, download Netcdf files from the website: https://portal.nccs.nasa.gov/datashare/gmao/geos-cf/v1/ana/Y{year}/M{month}/D{day}. Step 2, the step to search for 24 netCDF files (corresponding to 24 hours) has the following form:GEOS-CF.v01.rpl.htf_inst_15mn_g1440x721_x1.{year}{month}{day}{hour}00.nc4 is performed. After downloading 31×24=744 netCDF files corresponding to 31 days, 24 hours per day, the conversion step from netCDF file (.nc) → geoTIFF file (.tif) is performed (using tools in arcpy to process physical). Step 3: convert the map from this (.tif) format to a point shapefile (Extracting Tif → Points). Step 4: performs interpolation with the IDW Interpolation method, which helps smooth the map. Step 5: cut and merge this Tiff file with the Vietnam map. After the Extracting Map step (the result is that the Tif files have been interpolated and interpolated with the Vietnam map), they are converted into a .png file. Step 6 performs a colour change to identify the level of pollution.

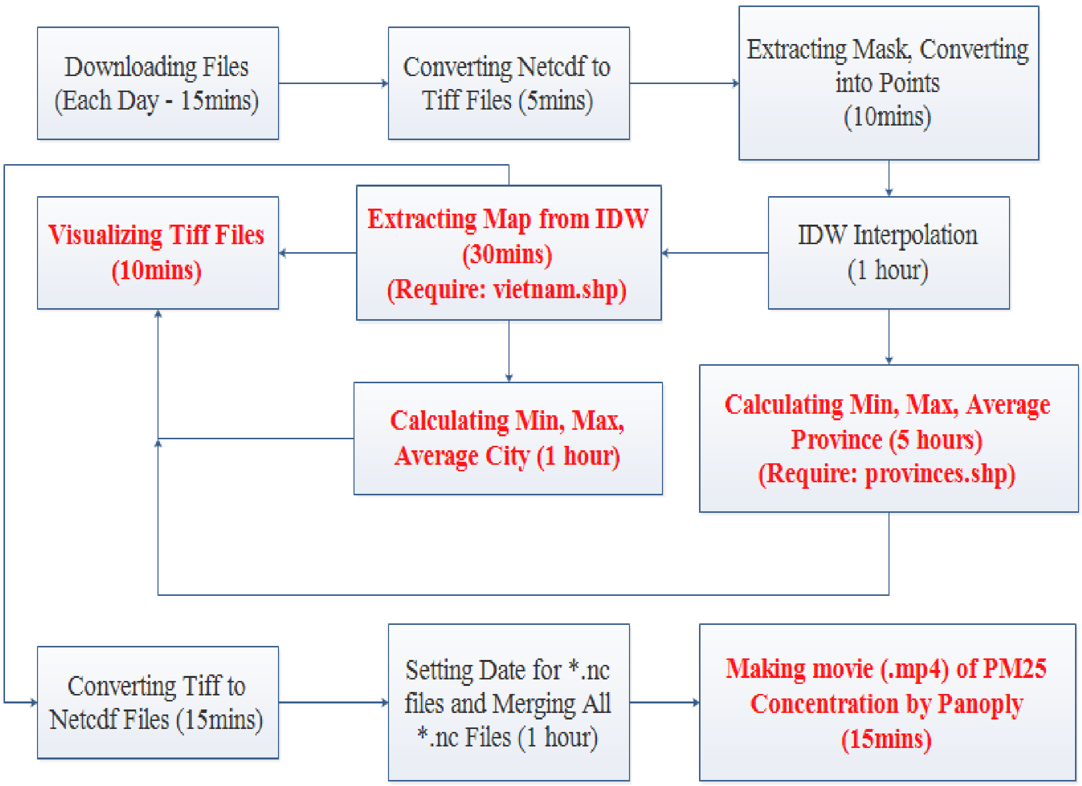

Figure 1. Method and processing steps.

Step 7 calculates the pollution level of the entire Vietnam with three quantities: minimum value, maximum value, and average value (Min, Max, Average); the results are exported as Excel files. Step 8 exports the necessary quantities for each province/city and islands (Con Dao, Truong Sa Islands, Hoang Sa Islands). After cutting and collaging, we will continue to change the colour to make it easier to see their pollution level (visualize GEOTiff File) (Step 9). Finally, to see the level of $PM_{2.5}$ pollution in Vietnam through each day of that month, we will take the .tif files from step 5 to convert them to NetCDF (.nc) files (Step 10) and use the tool cdo tool to set the minute, hour, day, month, year for each .nc file. All are merged into January.nc file. The book also uses the tool from Panoply (require: Java 11) to convert .nc files into a movie file (.mp4) of hourly $PM_{2.5}$ pollution values (Step 11) (Figure 1).

3. Results and discussion

3.1. Pollution distribution in January 2024

The average daily $PM_{2.5}$ concentration in January 2024 has a complex spatiotemporal distribution, but it is clear that the highest pollution concentration occurs in the North. From January 1 to January 2, the concentration decreased slightly, then increased sharply until January 5 and gradually decreased until January 7, then continued to increase and decrease unevenly until the peak on January 1 to January 30. The highest concentration reached 390.12 $\mu g/m^3$, and the lowest reached 4.16 $\mu g/m^3$. In most provinces in the Red River Delta, it is very high. In the two archipelagos of Hoang Sa and Truong Sa Islands, $PM_{2.5}$ pollution concentration is always at the allowable threshold ranging from 3.94-51.24 $\mu g/m^3$. Figure 2 shows the average daily $PM_{2.5}$ concentration variation in January 2024. Figure 3 shows the average daily distribution map of $PM_{2.5}$. Analysis results show that Hanoi and neighbouring provinces such as Bac Ninh, Vinh Phuc, and Phu Tho are most affected by pollution. On 4-5 January 2024, from Quang Binh to the Northern provinces, $PM_{2.5}$ concentrations reached high values. By 6 January 2024, the North and parts of the Southern provinces, such as Long An, An, Giang, Dong Thap, and Kien Giang, also had high concentrations. From 15-19 January 2024, Hanoi, surrounding provinces, Yen Bai, and Hoa Binh,... are greatly affected. On 23 January 2024, the entire North stretching to Quang Ngai and part of the Central Highlands and Southeast regions had high concentrations. From 24-31 January 2024, the scope of influence stretches across the entire northern region to Quang Ngai.

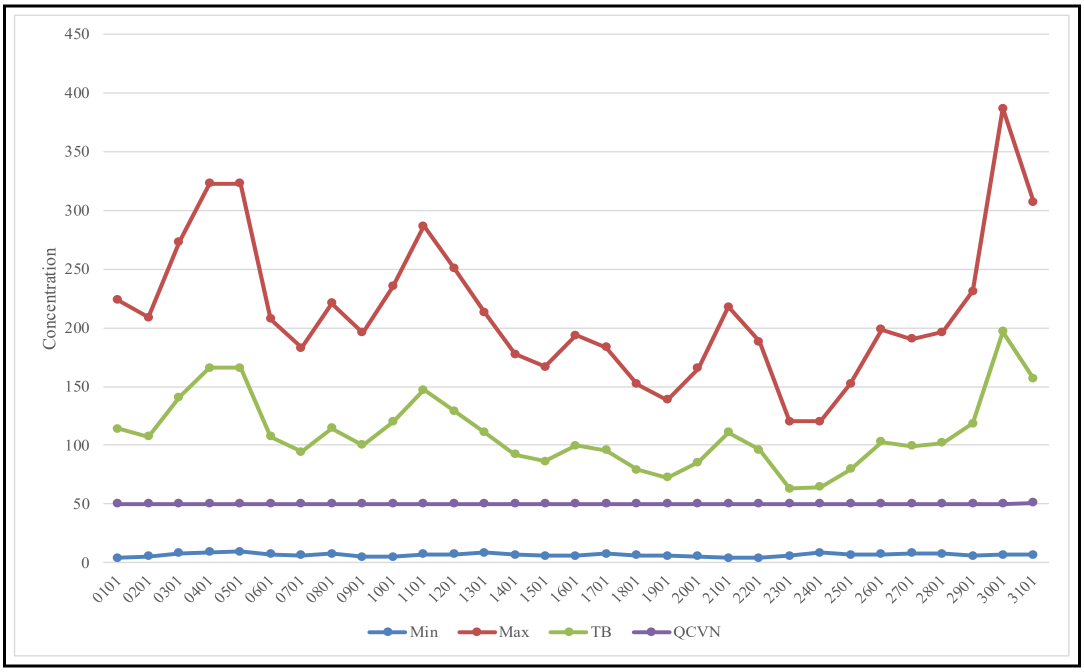

Figure 2. Average daily $PM_{2.5}$ ($\mu g/m^3$) concentration in January 2024.

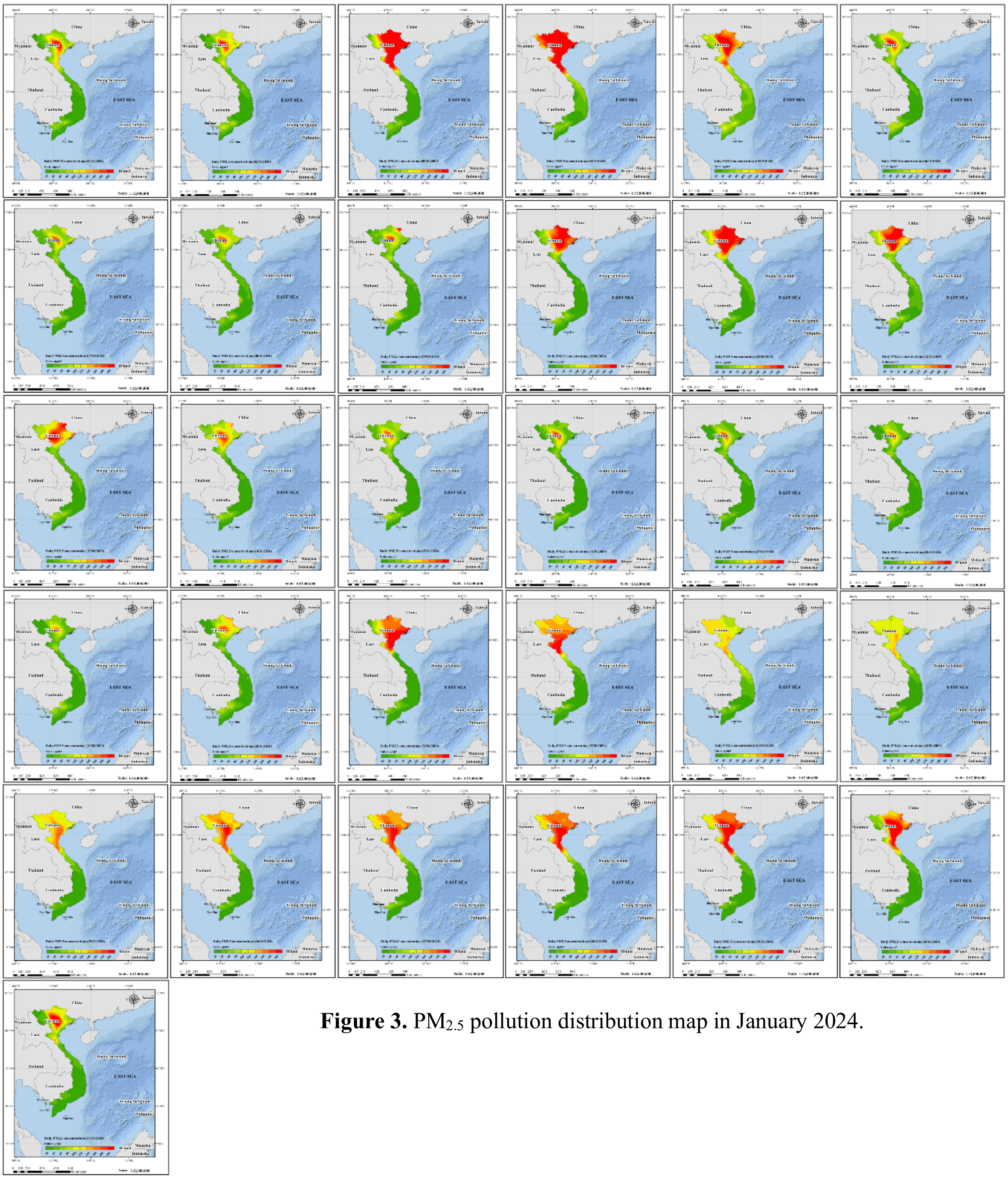

Figure 3. $PM_{2.5}$ pollution distribution map in January 2024.

3.2. Pollution distribution in February 2024

The average daily $PM_{2.5}$ concentration in February 2024 has a complex spatiotemporal distribution, and high pollution levels always occur in the country's North. From 1 February to 5 February, the concentration gradually decreased, then increased sharply until February 8 and progressively decreased unevenly over the days, after which the concentration increased or decreased steadily. With average monthly concentrations ranging from 5.02-151.75 μg/m^3. Figure 4 below shows the average $PM_{2.5}$ concentration variation of days in February 2024. The $PM_{2.5}$ concentration distribution map for each day is shown in Figure 5.

Hanoi capital and surrounding provinces still have alarming pollution levels (Figure 5). In the first three days of February 2024, most of the Red River Delta, the Northeast, part of the Northwest, and the provinces of Nghe An, Ha Tinh, and part of the South Central coastal region will be affected. of pollution. On 4 February 2024, provinces from Quang Nam to the North were affected by pollution. On 5-7 April 2024, the North Central region, Northeast, Northwest and Red River Delta, and part of the South Central coastal provinces will be affected. From 9-12 February 2024, provinces from Binh Dinh to the North will be highly affected. From 12-29 February 2024, the area of influence from central provinces such as Quang Tri, Quang Nam, Quang Ngai, and Binh Dinh extended to the North. In February 2024, the high-impact area has little impact on the Central Highlands, Southeast, and South.

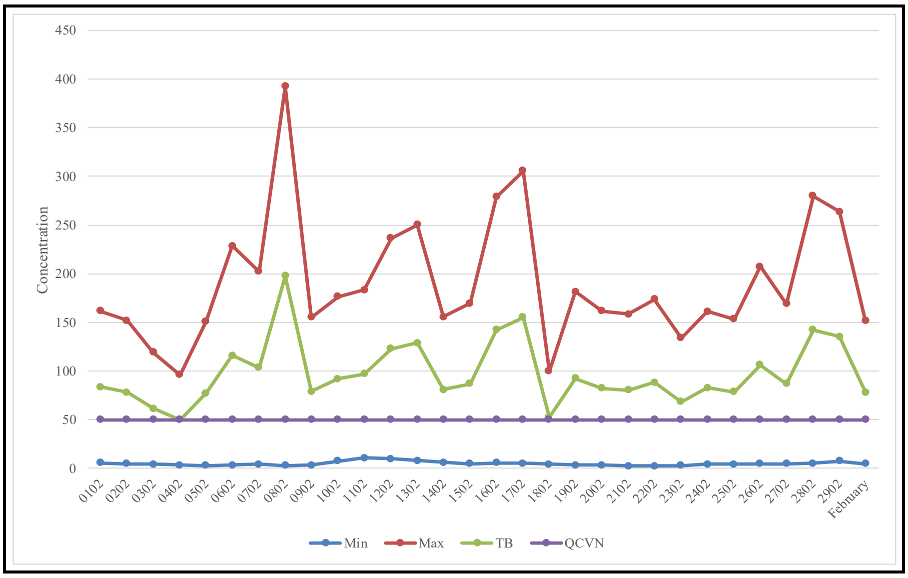

Figure 4. Average daily $PM_{2.5}$ ($\mu g/m^3$) concentration in February 2024.

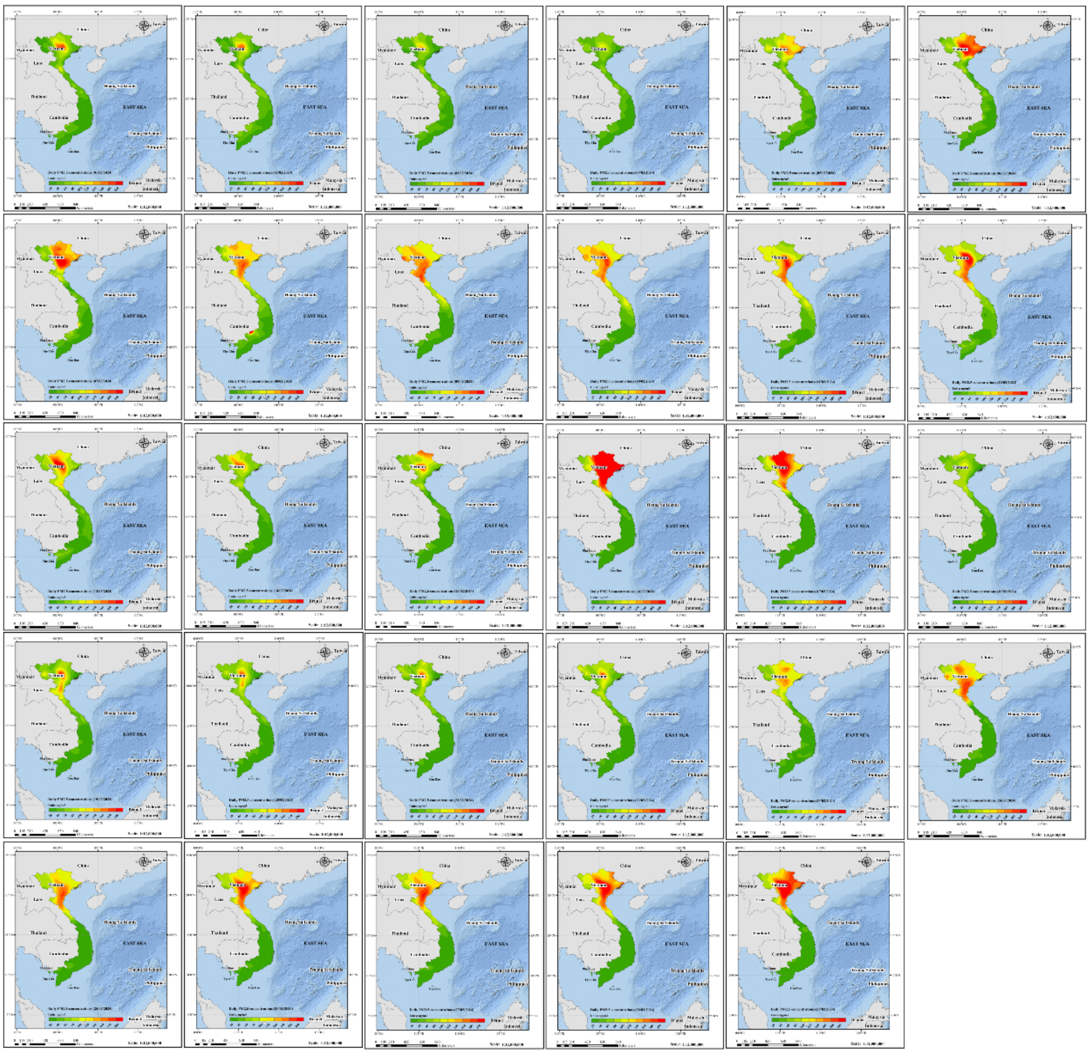

Figure 5. $PM_{2.5}$ pollution distribution map in February 2024.

3.3. Pollution distribution in March 2024

Like the previous two months, the average daily $PM_{2.5}$ concentration in March 2024 has a complex spatiotemporal distribution. The average concentration of this product ranges from 7.48-187.24 μg/m^3. Figure 6 shows the $PM_{2.5}$ pollution distribution map for the whole of Vietnam. Figure 7 shows the variation in average $PM_{2.5}$ concentration of days in March 2024. In the first two days of March 2024, the Red River Delta region, the Northeast, part of the Northwest and provinces such as Nghe An and Ha Tinh were severely affected by $PM_{2.5}$ pollution. On 3 March 2024, provinces from Quang Binh to the North, by 4 March 2024, most provinces from Binh Dinh to the North will be significantly affected. Especially on 5 March 2024, all of Vietnam will be affected. Hanoi, Hoa Binh, Yen Bai, and parts of the Northeast provinces, Phu Yen and Nghe An, are affected. From 9-12 March 2024, the area of influence will be from Nghe An-Ha Tinh, extending to the North. From 13-15 March, the area of influence covers the Mekong Delta, such as An Giang and Long An. In the remaining days of March, the northern region to Nghe An is most affected.

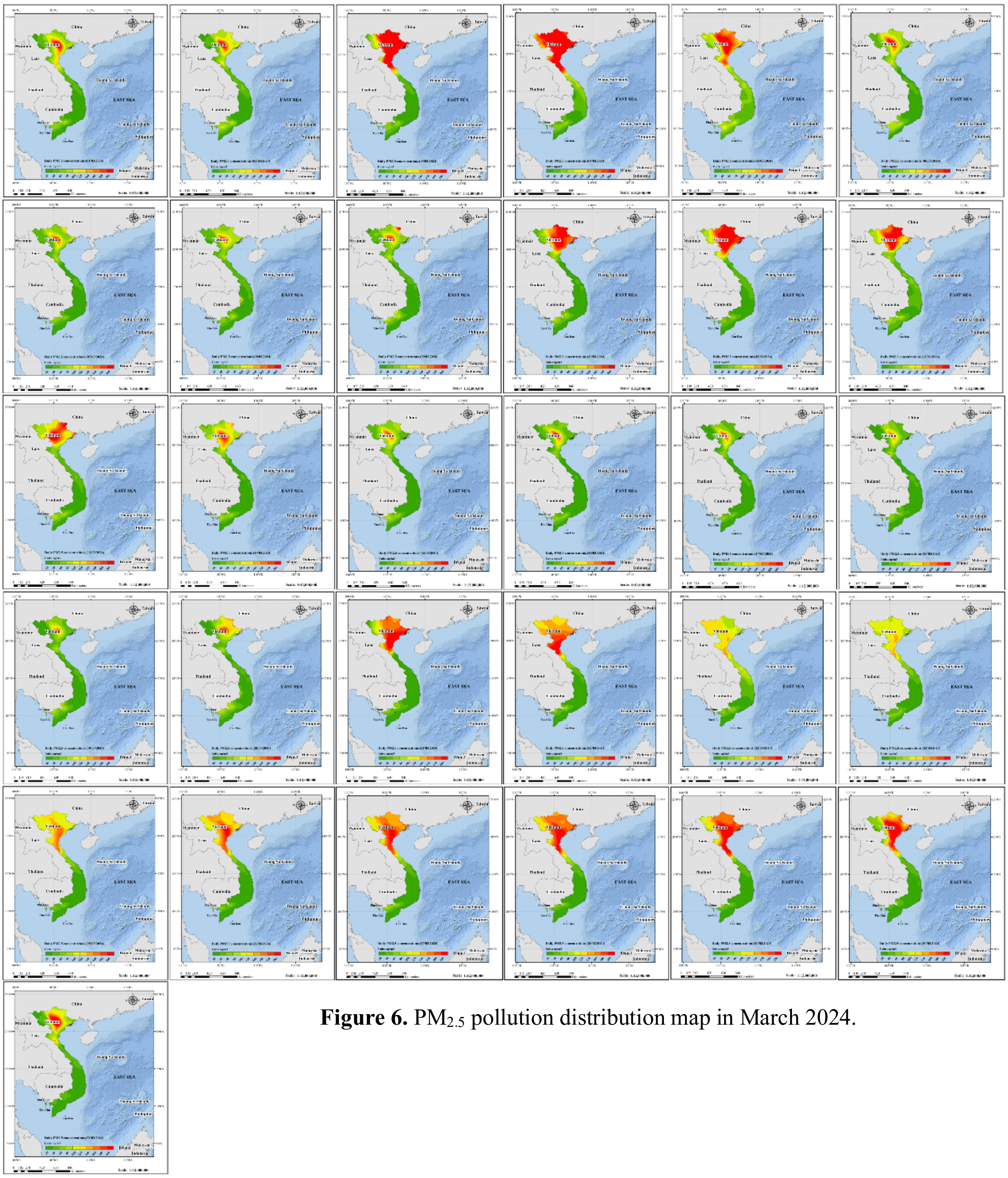

Figure 6. $PM_{2.5}$ pollution distribution map in March 2024.

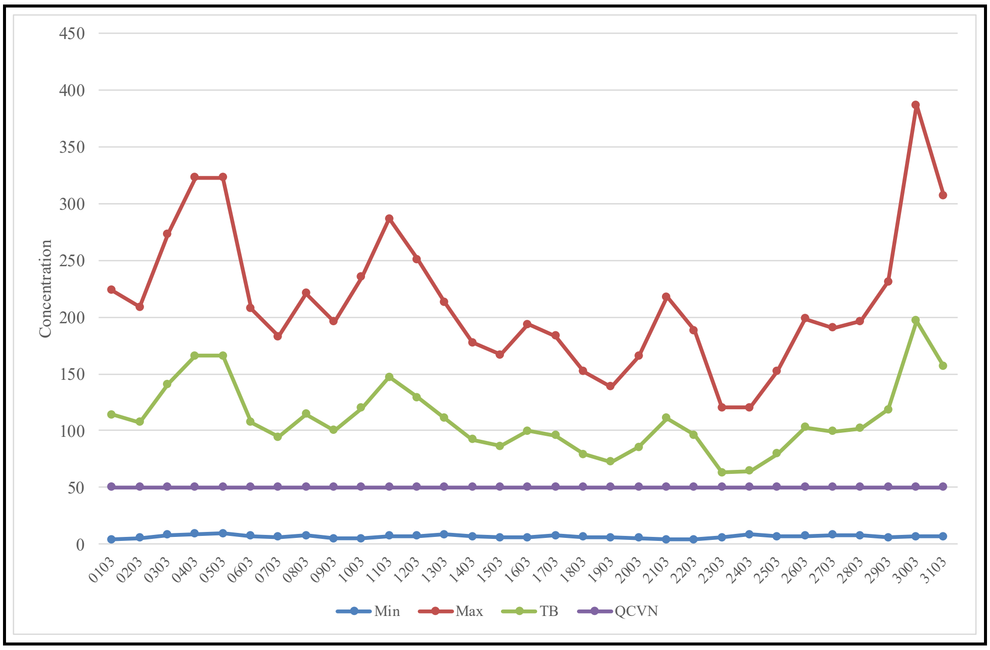

Figure 7. Average daily $PM_{2.5}$ ($\mu g/m^3$) concentration in March 2024.

3.4. Results of pollution distribution by region

ENAR software allows exporting tabular results of min/max concentrations and monthly averages for seven regions of the country, along with the country's two Islands of Hoang Sa and Truong Sa. The average results for January 2024 are shown in Table 1, Figure 8. It can be seen that the three Northern Delta regions, including Northwest, Northeast, and Red River Delta, all have much higher min and max concentrations compared to Vietnamese standard, followed by North Central, Southeast, Mekong Delta, and South Central Coast. The Central Highlands region, Hoang Sa, and Truong Sa Islands are still within allowed limits. Compared to January 2024, concentrations in February 2024 in areas improved (concentrations decreased significantly). In March 2024, the concentration increased compared to February, but it was generally smaller than January 2024.

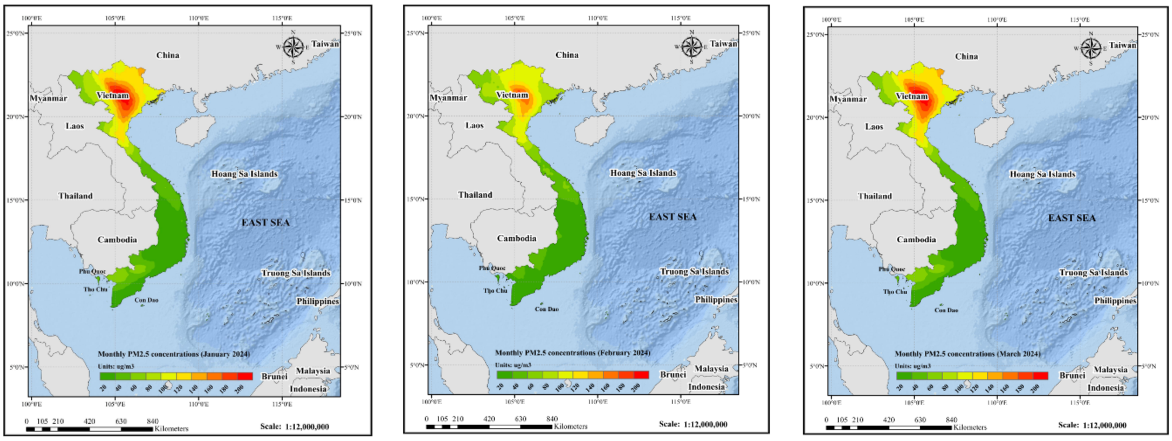

Figure 8. Average monthly $PM_{2.5}$ pollution distribution map from January to March 2024.

Table 1. Concentration by seven regions, Hoang Sa and Truong Sa Islands in January 2024.

Region	Concentration ($\mu g/m^3$)	
	Min	**Max**
Northwest	40.69	174.27
East Northern	87.37	187.29
Red river delta	72.56	186.07

Region	Concentration (μg/m^3)	
	Min	**Max**
Mekong Delta	8.79	54.83
South Central Coast	9.73	39.24
North Central	23.49	140.05
South East	9.42	56.01
Highlands	9.36	27.43
Hoang Sa	14.16	14.21
Truong sa	7.5	7.82

Table 2. Concentration by seven regions, Hoang Sa and Truong Sa Islands in February 2024.

Region	Concentration (μg/m^3)	
	Min	**Max**
Northwest	41.95	131.57
East Northern	65.72	149.25
Red river delta	63.94	151.78
Mekong Delta	6.2	29.22
South Central Coast	5.02	44.63
North Central	27.23	114.92
South East	6.5	36.05
Highlands	9.54	28.97
Hoang Sa	9.86	9.87
Truong sa	5.02	5.14

Table 3. Concentration by seven regions, Hoang Sa and Truong Sa Islands in March 2024.

Region	Concentration (μg/m^3)	
	Min	**Max**
Northwest	86.41	141.71
East Northern	65.51	160.29
Red river delta	60.90	164.68
Mekong Delta	6.56	26.25
South Central Coast	8.62	53.13
North Central	35.37	118.40
South East	7.15	25.73
Highlands	14.08	40.32
Hoang Sa	11.16	11.19
Truong sa	6.68	7.17

In the first three months of 2024, the Northeast region is always in the first position, with average monthly min/max concentrations ranging from 65.51-187.29 μm/m^3. This area has the highest exposure risk, often higher than allowed standards. Next is the Northwest region, with average monthly min/max concentrations ranging from 40.69-174.27 m/m^3 and very high exposure risk. On the territory of Vietnam, the Truong Sa and Hoang Sa islands have the lowest min/max level of 5.02-7.82 μm/m^3. Next is the Central Highlands region, which is still relatively "clean" with a min/max of 9.36-27.43 m/m^3 and the Mekong Delta, with a min/max of 6.2-54.83 μm/m^3. The Mekong Delta region still has times when it exceeds standards different from the Highlands, Hoang Sa, and Truong Sa Islands.

4. Conclusion

NASA's GEOS Composition Forecast System now provides near real-time estimates of the closest atmospheric composition. Five-day daily forecasts at high spatial resolution (0.25° latitude × 0.25° longitude up to the lower mesosphere) and high temporal frequency (hourly and 3-hourly) published entirely free of charge. For surface air quality, GEOS-CF simulates the stratosphere to troposphere transport. The results of running this model have been tested based on NASA's satellite image processing and monitoring system, so they are reliable. This study focuses on exploiting $PM_{2.5}$ concentration results output from GEOS-CF software. However, to exploit these results for Vietnam, it is necessary to process the results output from GEOS-CF automatically. The research has successfully built an ENAR automation module using the Python language, integrating many packages such as Arcpy, Arcgis scripting, netCDF4, pandas,... and software such as ArcGIS Pro, OSGeo4W, Cygwin, and Panoply. This tool allows the processing of GEOS-CF run results and exporting charts and maps to analyze the distribution of $PM_{2.5}$ pollution throughout the country.

The results of GEOS-CF validated were analyzed using continuously updating by NASA as satellite images, Balloons, and TOLNet Lidar. However, that does not mean that this result is reliable in Vietnam, but the authors hope to find colleagues and state agencies to provide data to further improve the result of this research. The authors will also continue to conduct further research to apply GEOS-CF to Vietnam. The next research directions include finding the relationship between $PM_{2.5}$ pollution levels at an altitude corresponding to a pressure of 985 hPa and ground-level pollution levels. Next is $PM_{2.5}$ pollution prediction based on deep learning algorithms.

Author contribution statement: Developing research ideas, drawing up a draft writing plan, writing and editing the manuscript: L.T.B.; processing data, GIS: U.K.L.; processing data, software: B.Q.P.

Acknowledgements: The authors would like to express their sincere gratitude to Dr K. E. Knowland from the Universities Space Research Association (USRA)/GESTAR, Columbia, MD, USA, NASA Goddard Space Flight Center (GSFC) and Global Modeling and Assimilation Office (GMAO) for valuable discussions. This research was funded by the Viet Nam National University, Ho Chi Minh City (VNU-HCM), grant No: B2023-20-23. We acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT) and Vietnam National University Ho Chi Minh City (VNU-HCM) for this study.

Competing interest statement: The authors declare no conflict of interest.

References

1. Bui, L.T.; Nguyen, N.T.H.; Nguyen, P.H. Chronic and acute health effects of - $PM_{2.5}$ exposure and the basis of pollution control targets. *Environ. Sci. Pollut. Res.* **2023**, *30(33)*, 1–23. doi: 10.1007/s11356-023-27936-9.
2. Nguyen, T.H.; Nagashima, T.; Van Doan, Q. Air quality modelling study on the controlling factors of fine particulate matter ($PM_{2.5}$) in Hanoi: A case study in December 2010. *Atmosphere* **2020**, *11(7)*, 733. doi: 10.3390/atmos11070733.
3. Hieu, V.; Quynh, L.X.; Ho, P.N.; Hens, L. Health Risk Assessment of Mobility-Related Air Pollution in Ha Noi, Vietnam. *J. Environ. Prot.* **2013**, *04(10)*, 1165–1172. doi: 10.4236/jep.2013.410133.
4. Di, Q.; Kloog, I.; Koutrakis, P.; Lyapustin, A.; Wang, Y.; Schwartz, J. Assessing PM2.5 Exposures with High Spatiotemporal Resolution across the Continental United States. *Environ. Sci. Technol.* **2016**, *50(9)*, 4712–4721. doi: 10.1021/acs.est.5b06121.
5. Lim, S.S.; et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **2012**, *380*, 2224–2260. doi: 10.1016/S0140-6736(12)61766-8.
6. Slama, R.; et al. Traffic-related atmospheric pollutants levels during pregnancy and offspring's term birth weight: A study relying on a land-use regression exposure model. *Environ. Health Perspect.* **2007**, *115(9)*, 1283–1292. doi: 10.1289/ehp.10047.

7. Halonen, J.I.; Lanki, T.; Yli-Tuomi, T.; Kulmala, M.; Tiittanen, P.; Pekkanen, J. Urban air pollution, and asthma and COPD hospital emergency room visits. *Thorax* **2008**, *63(7)*, 635–641. doi: 10.1136/thx.2007.091371.
8. Jia Y.; et al. Effect of Air Pollution on Heart Failure: Systematic Review and Meta-Analysis. *Environ. Health Perspect*. **2023**, *131(7)*, 76001. doi: 10.1289/EHP11506.
9. Dominici, F.; et al. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *Jama* **2006**, *295(10)*, 1127–1134. doi: 10.1001/jama.295.10.1127.
10. Peng, R.D.; et al. Emergency admissions for cardiovascular and respiratory diseases and the chemical composition of fine particle air pollution. *Environ. Health Perspect.* **2009**, *117(6)*, 957–963. doi: 10.1289/ehp.0800185.
11. Laden, F.; Schwartz, J.; Speizer, F.E.; Dockery, D.W. Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard six cities study. *Am. J. Respir. Crit. Care Med*. **2006**, *173(6)*, 667–672. doi: 10.1164/rccm.200503-443OC.
12. Pinto, J.P.; Lefohn, A.S.; Shadwick, D.S. Spatial variability of $PM_{2.5}$ in urban areas in the United States. *J. Air Waste Manag. Assoc.* **2004**, *54(4)*, 440–449. doi: 10.1080/10473289.2004.10470919.
13. Ho, B.Q.; Clappier, A.; François, G. Air pollution forecast for Ho Chi Minh City, Vietnam in 2015 and 2020. *Air Qual. Atmos. Heal.* **2011**, *4(2)*, 145–158. doi: 10.1007/s11869-010-0087-2.
14. Bui, L.T.; Nguyen, P.H.; My Nguyen, D.C. Linking air quality, health, and economic effect models for use in air pollution epidemiology studies with uncertain factors. *Atmos. Pollut. Res.* **2021**, *12(9)*, 101118. doi: 10.1016/j.apr.2021.101118.
15. Le, T.N.; Nguyen, C.M.D.; Nguyen, H.P.; Bui, T.L. Assessment of public health impacts associated with short-term $PM_{2.5}$ pollution exposure: A case study in Binh Duong province, Vietnam. *VN J. Hydrometeorol*. **2023**, *746*, 70–87. doi: 10.36335/vnjhm.2023(746).70-87.
16. Nguyen, G.T.H.; Shimadera, H.; Uranishi, K.; Matsuo, T.; Kondo, A. Numerical assessment of $PM_{2.5}$ and O_3 air quality in continental Southeast Asia: Impacts of future projected anthropogenic emission change and its impacts in combination with potential future climate change impacts. *Atmos. Environ*. **2020**, *226*, 117398. doi: 10.1016/j.atmosenv.2020.117398.
17. Knowland, K.E. Global modeling and assimilation office file specification for MERRA-2 climate statistics products, 2020.
18. Bey, I.; et al. Global modelling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *J. Geophys. Res. Atmos*. **2001**, *106(D19)*, 23073–23095. doi: https://doi.org/10.1029/2001JD000807.
19. Keller, C.A.; Long, M.S.; Yantosca, R.M.; Da Silva, A.M.; Pawson, S.; Jacob, D.J. "HEMCO v1.0: A versatile, ESMF-compliant component for calculating emissions in atmospheric models. *Geosci. Model Dev.* **2014**, *7(4)*, 1409–1417. doi: 10.5194/GMD-7-1409-2014.
20. Keller, C.A.; Knowland, K.E. Description of the NASA GEOS Composition Forecast Modeling System GEOS-CF v1 0.pdf. *J. Adv. Model. Earth Syst*. **2021**, *13(4)*, e2020MS002413. doi: 10.1029/2020MS002413.
21. Knowland, K.E.; et al. NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0: Stratospheric Composition. *J. Adv. Model. Earth Syst*. **2022**, *14(6)*, 1–28. doi: 10.1029/2021MS002852.
22. Eastham, S.D.; Weisenstein, D.K.; Barrett, S.R.H. Development and evaluation of the unified tropospheric-stratospheric chemistry extension (UCX) for the global

chemistry-transport model GEOS-Chem. *Atmos. Environ*. **2014**, 89, 52–63. doi: 10.1016/j.atmosenv.2014.02.001.
23. Bianz, H.; Prather, M.J. Fast-J2: Accurate simulation of stratospheric photolysis in global chemical models. *J. Atmos. Chem*. **2002**, *41(3)*, 281–296. doi: 10.1023/A:1014980619462.
24. Mao, J.; et al. Chemistry of hydrogen oxide radicals (HOx) in the Arctic troposphere in spring. *Atmos. Chem. Phys*. **2010**, *10(13)*, 5823–5838. doi: 10.5194/acp-10-5823-2010.
25. Sandu, A.; Sander, R. Technical note: Simulating chemical systems in Fortran90 and Matlab with the Kinetic PreProcessor KPP-2.1. *Atmos. Chem. Phys.* **2006**, *6(1)*, 187–195. doi: 10.5194/acp-6-187-2006.
26. Colarco, P.; Da Silva, A.; Chin, M.; Diehl, T. Online simulations of global aerosol distributions in the NASA GEOS-4 model and comparisons to satellite and ground-based aerosol optical depth. *J. Geophys. Res. Atmos.* **2010**, *115(D14)*, D14207. doi: 10.1029/2009JD012820.
27. Randles, C.A.; et al. The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation. *J. Clim*. **2017**, *30(17)*, 6823–6850. doi: 10.1175/JCLI-D-16-0609.1.
28. Janssens-Maenhout, G.; et al. HTAP-v2.2: A mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution. *Atmos. Chem. Phys*. **2015**, *15(19)*, 11411–11432. doi: 10.5194/acp-15-11411-2015.
29. Schultz, M.G.; et al. Global wildland fire emissions from 1960 to 2000. *Global Biogeochem*. *Cycles* **2008**, *22(2)*, 1–17. doi: 10.1029/2007GB003031.
30. Van der Gon, H.D.; Hendriks, C.; Kuenen, J.; Segers, A.; Visschedijk, A. TNO Report: Description of current temporal emission patterns and sensitivity of predicted AQ for temporal emission patterns. TNO, Princetonlaan 6, 3584 CB Utrecht, The Netherlands, 2011, pp. 1–22.
31. Bindle, L.; et al. Atmospheric chemistry model. Cambridge University Press, 2021, pp. 5977–5997.