

Responses to Review Comments

Dear Editor and Reviewers,

We thank you very much for the valuable suggestions and comments on our manuscript, which are very helpful to improve the quality of our manuscript. All your comments have been carefully addressed, and we have prepared a list of point-by-point responses below. You can also find our revisions in the change-tracked manuscript. Please note that the review comments are in **black**, our responses are in **blue**, and the text from the manuscript is in **black** (with revised text in **red**).

Regards,

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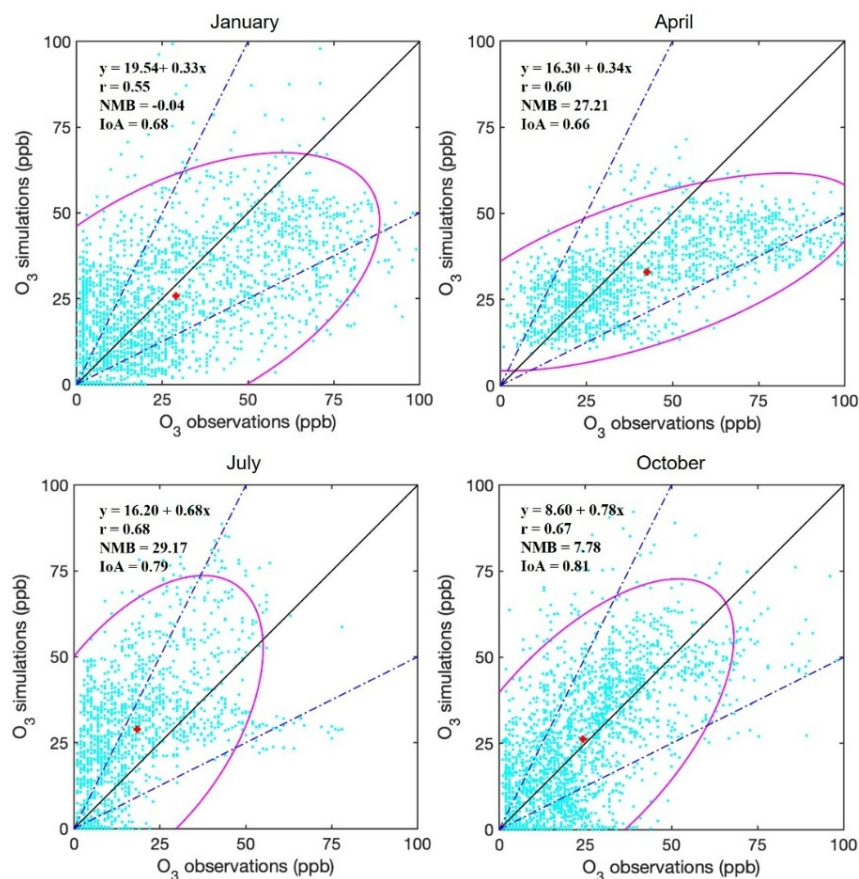
Reviewer #1:

This study analyzed the ozone sensitivity in Southeast Asia using the 3-D chemical transport model. The topic looks timely associated with the issue of recently high ozone enhancement in Asia. Whole research looks sincerely conducted, therefore this submitted manuscript is informative. I think that this work will be useful to the air quality community.

However, I have some questions about the quality of model results. If the quality of model is not guaranteed, we cannot use this work as the important scientific lesson. Please reply to my questions below. With authors' response, I will assess the meaning and value of results in this manuscript.

1. Please explain the meaning of Figure S10 more, which shows the surface ozone comparison between real observation data and authors' CMAQ model simulation. I am not clear if the model result is acceptable. Although correlation coefficients are from 0.5 to 0.6 (which may be not so bad), the variance (RMSE) of scatterplot looks too large to me. If this modeling result is reliable, please explain it compared with similar test results from previous references.

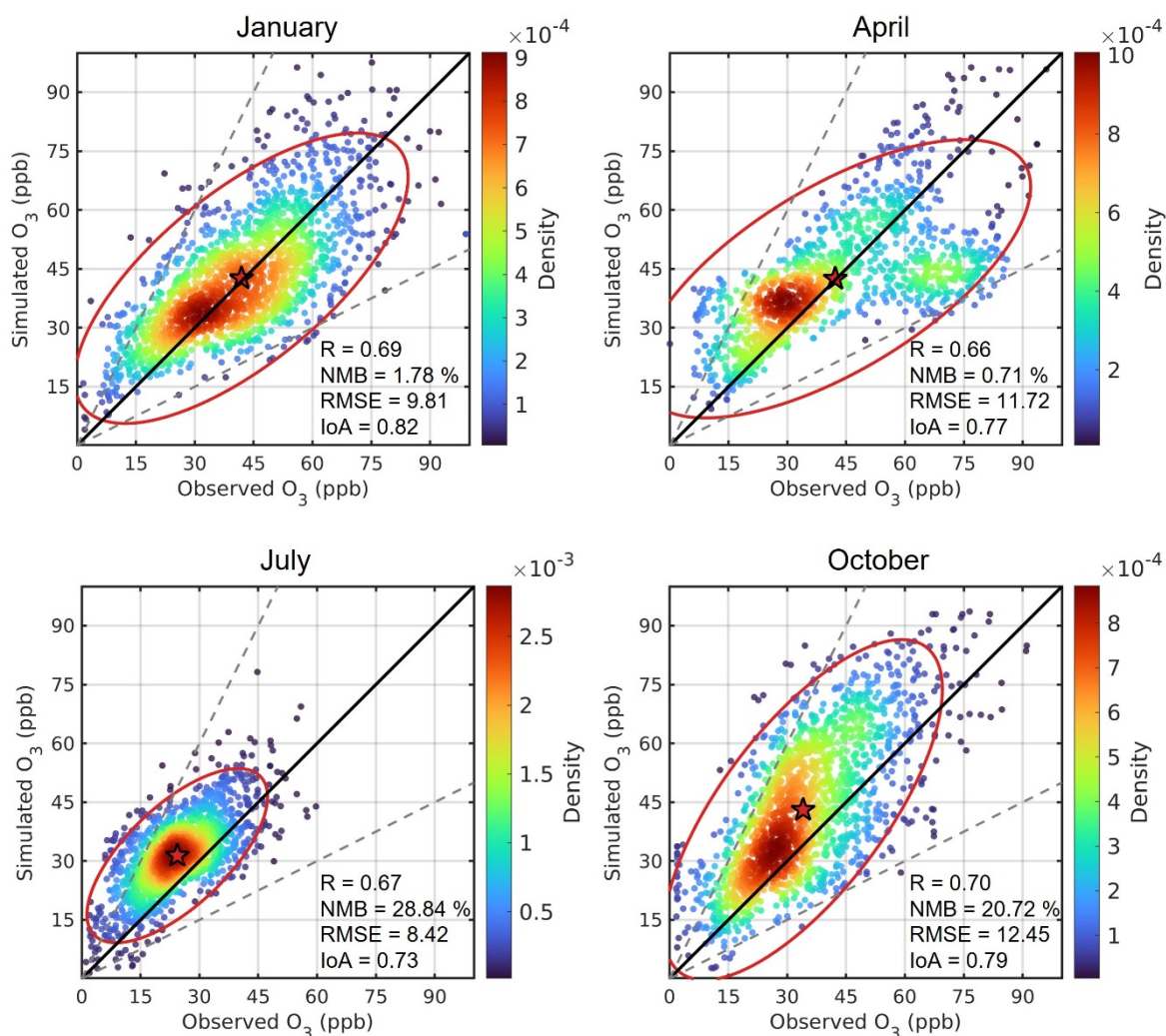
Response: We thank the referee for the valuable comment. Fig. S10 evaluated the CMAQ performance by comparing the simulated surface O₃ concentration with available ground-based observations across Southeast Asia. In the original manuscript, hourly observations from the EANET stations and MDA8 O₃ observations from the AQI platform were included in the same figure to increase the spatial coverage of the model evaluation. The correlation coefficients for the four monsoon seasons were 0.55, 0.60, 0.68, and 0.67, respectively, exceeding the benchmark criterion of $r > 0.5$. The corresponding RMSE values were 16.2, 16.4, 14.5, and 13.2 ppb for January, April, July, and October, respectively. Although there was no standardized RMSE threshold for regional O₃ simulations, the RMSE values were comparable with those reported in previous regional CMAQ studies. For instance, Eder et al. (2006) reported a domain-wide RMSE of 15.7 ppb for MDA8 O₃ over the northeastern United States using the Eta-CMAQ forecasting system. In Europe, Fink et al. (2023) reported the daily mean RMSE of approximately 15.9 ppb for the CMAQ O₃ simulation over the Mediterranean region. In China, Feng et al. (2024) reported the RMSE between CMAQ simulation and station observation, and found a large portion of stations had more than 35 $\mu\text{g m}^{-3}$ (17.8 ppb), especially in northern China. The previous studies indicated that the RMSE values in our simulation were within the commonly reported range for regional O₃ modeling applications.



Original Fig. S10. CMAQ model evaluation by comparing the O₃ simulation with the observation data from monitoring stations. The ellipses represent the 95% confidence interval of the scatter points, and the centroid crosses show the median value. The statistical indicators (r, NMB (%), and IoA) were calculated using all the comparison data from available stations. The 1:1 line denotes the perfect predictions, and the 2:1 and 0.5:1 lines represent the $\pm 50\%$ simulations, respectively.

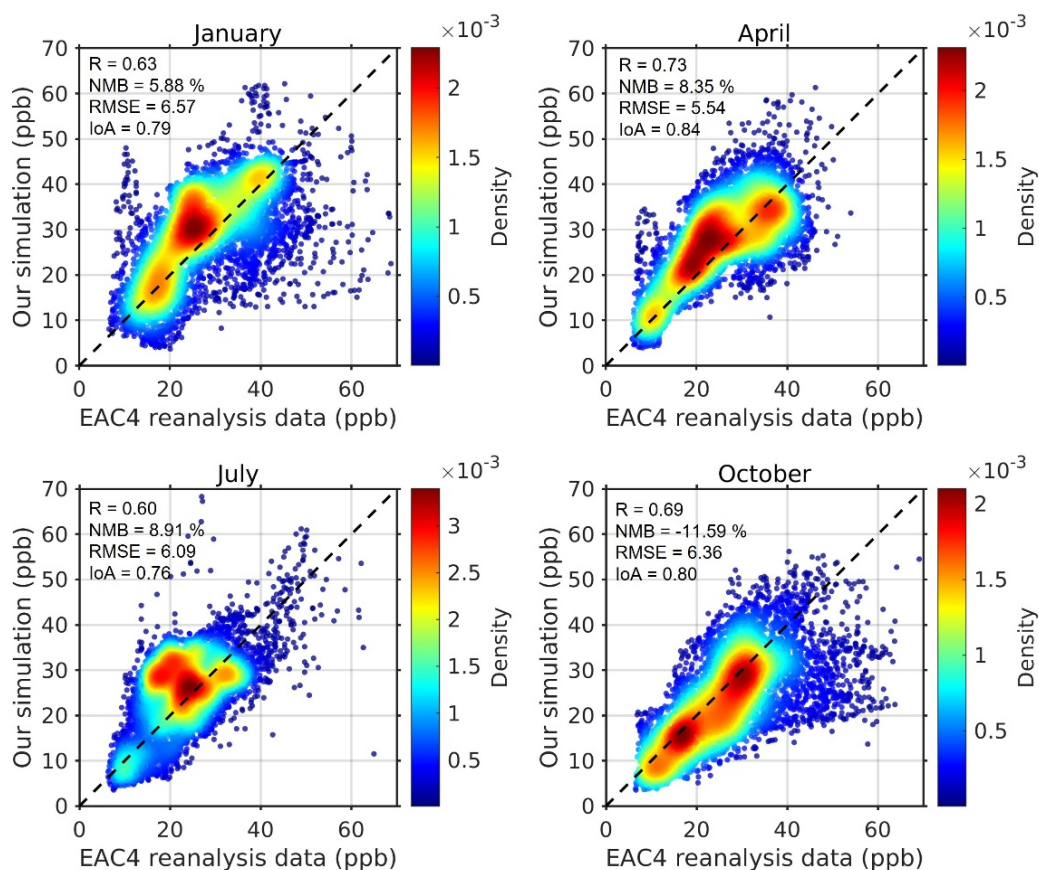
In the revised manuscript, we further included additional ground-based monitoring stations from Singapore, Malaysia, Thailand, and the OpenAQ dataset to improve the model evaluation. Together with the previous observation records from the EANET and AQI datasets, 67 stations were used in total, covering seven countries in Southeast Asia. The spatial distribution of O₃ concentration in all stations is shown in the revised Fig. S11. To keep a consistent comparison among different stations and datasets, the hourly CMAQ simulations and ground-based observations were aggregated into daily MDA8 O₃ concentration. Therefore, both the model simulations and observations were evaluated using the MDA8 O₃ metric. The revised Fig. S10 shows the overall comparison between the simulated and observed MDA8 O₃ levels during the

four monsoon seasons, with correlation coefficients of 0.69, 0.66, 0.67, and 0.70 and RMSE values of 9.8, 11.7, 8.4, and 12.4 ppb, respectively. The NMB and RMSE values for each station are shown in the revised Table S3, and the detailed descriptions of each station are provided in the revised Table S4. The evaluations provided a more comprehensive assessment of the CMAQ model performance in Southeast Asia.



Revised Fig. S10. CMAQ model evaluation by comparing the MDA8 O₃ simulation with the observation data from 67 monitoring stations in Southeast Asia for the four monsoon seasons. The ellipses represent the 95% confidence interval of the scatter points, and the centroid crosses show the median value. The statistical indicators (R, NMB (%), RMSE, and IoA) were calculated using all the comparison data from available stations. The 1:1 line denotes the perfect predictions, and the 2:1 and 0.5:1 lines represent the $\pm 50\%$ simulations, respectively.

The comparison between the simulation and the ground observation indicated that the performance of our CMAQ model was acceptable. However, there were still uncertainties such as model resolution, observation coverage, meteorological factors and emission inventories, resulting in the discrepancies between observation and our CMAQ simulation. For instance, the station observation data were point-based measurements, whereas the CMAQ simulations represented grid-averaged concentration at the resolution of 30 km. The differences could introduce uncertainties, especially in urban areas and coastal regions where O₃ concentration may vary substantially within a 30 km model grid. In addition, ground-based monitoring data were not available in Indonesia, Laos, Myanmar, and East Timor due to the limited observation coverage and data availability. We have elaborated the limitations in the Discussion in the revised manuscript. In addition to the ground-based observations, we further compared the CMAQ simulations with the monthly CAMS EAC4 reanalysis product, which provided a spatially continuous dataset for evaluating the regional O₃ distribution with 75 km resolution. The revised Figs. S12 and S13 show that the CMAQ simulation generally captured the spatial pattern and seasonal variation of surface O₃ over Southeast Asia, with correlation coefficients of 0.63, 0.73, 0.60, and 0.69 and RMSE values of 6.6, 5.5, 6.1, and 6.3 ppb for the four monsoon seasons, respectively. The comparison further supported the reliability of the simulated O₃ distribution in this study.



Revised Fig. S13. Evaluation between the CMAQ simulation and the CAMS EAC4 reanalysis data in the four monsoon seasons.

References:

- Eder, B., Kang, D., Mathur, R., Yu, S., & Schere, K. (2006). An operational evaluation of the Eta-CMAQ air quality forecast model. *Atmospheric Environment*, 40(26), 4894-4905.
- Feng, S., Jiang, F., Qian, T., Wang, N., Jia, M., Zheng, S., ... & Ju, W. (2024). Constraining non-methane VOC emissions with TROPOMI HCHO observations: impact on summertime ozone simulation in August 2022 in China. *Atmospheric Chemistry and Physics*, 24(13), 7481-7498.
- Fink, L., Karl, M., Matthias, V., Oppo, S., Kranenburg, R., Kuenen, J., ... & Majamäki, E. (2023). Potential impact of shipping on air pollution in the Mediterranean region-a multi model evaluation: comparison of photooxidants NO_2 and O_3 . *Atmospheric Chemistry and Physics*, 23(3), 1825-1862.

We revised the Results and Discussions sections to provide a more comprehensive comparison with the updated ground observation records and the global O₃ reanalysis data. The details can be found below:

Lines 187-193:

“...The spatial distribution of simulated ground-level O₃ was evaluated using observations from 67 stations across Southeast Asia. As shown in Fig. S10, most MDA8 O₃ simulations aligned within $\pm 50\%$ of the observations. The overall correlation (r) between the observed and simulated MDA8 O₃ across the four months was 0.68, exceeding the benchmark criterion of $r > 0.5$ (Yang & Zhao, 2023). The NMB, RMSE, and IoA were 13.26%, 10.60, and 0.78, respectively. The locations and observed O₃ concentration of the monitoring stations are shown in Fig. S11. Station-level evaluation results are presented in Table S3, while detailed information on each station is provided in Table S4, underscoring the reliability of the O₃ simulation in capturing the spatial variations across the region...”

Lines 491-498:

“...Our study also has several limitations. First, the relatively sparse monitoring network in Southeast Asia limited the evaluation of simulated surface O₃. In addition, ground-based monitoring data were not available in Indonesia, Laos, Myanmar, and East Timor due to the limited observation coverage and data availability. To complement the comparisons, global surface O₃ reanalysis data were used to assess the spatial consistency of the simulations. Future improvements in model evaluation would benefit from expanded ground-based monitoring networks and the integration of satellite-derived O₃ products. Second, the model resolution of 30 km may introduce the uncertainties when comparing the simulation and the ground observations, especially in urban areas and coastal regions where O₃ concentration may vary substantially within a model grid. Also, the 30 km resolution may not fully resolve sub-grid urban processes such as NO titration...”

Supplementary Figures and Tables:

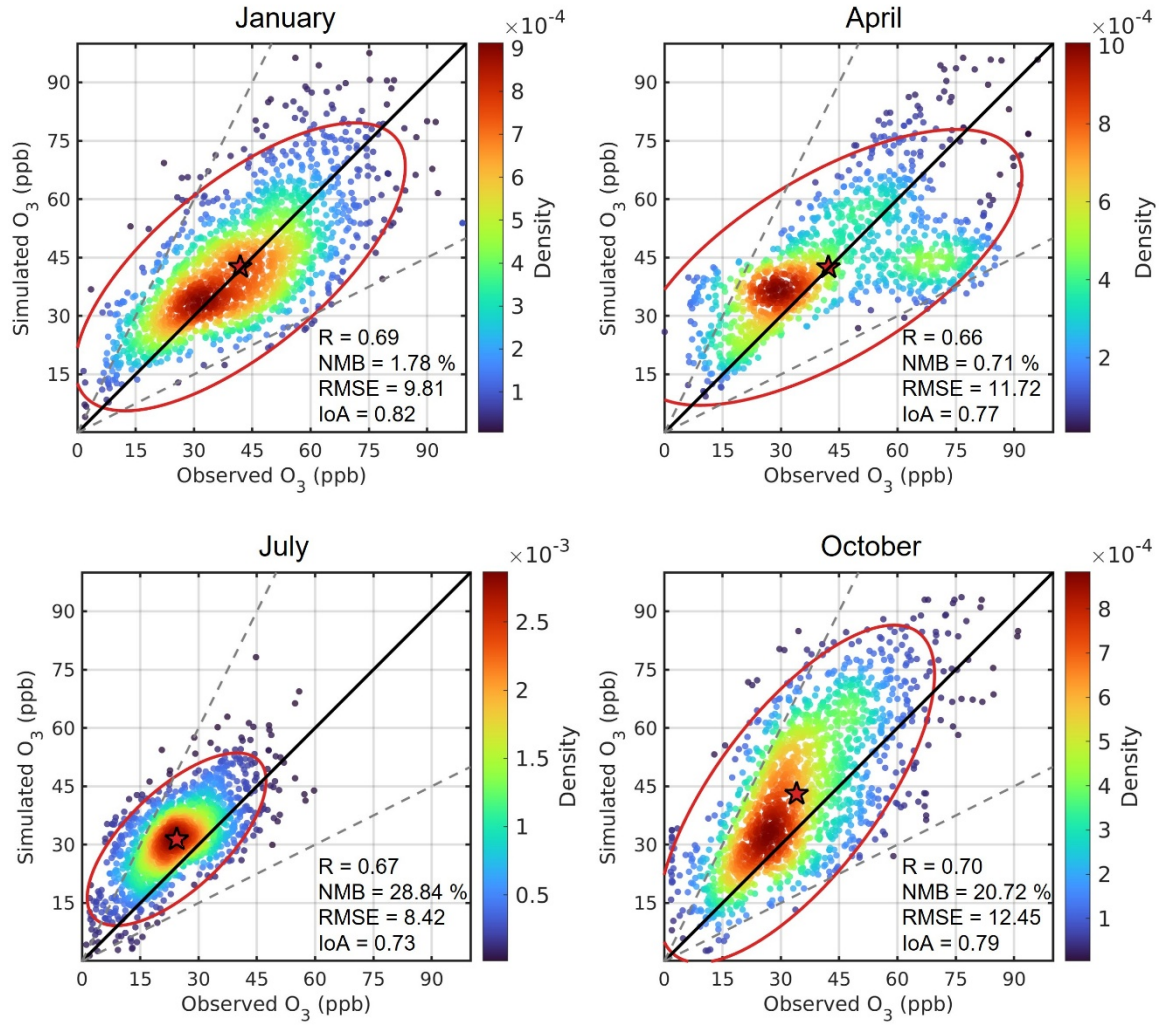


Fig. S10. CMAQ model evaluation by comparing the MDA8 O₃ simulation with the observation data from 67 monitoring stations in Southeast Asia for the four monsoon seasons. The ellipses represent the 95% confidence interval of the scatter points, and the centroid crosses show the median value. The statistical indicators (R, NMB (%), RMSE, and IoA) were calculated using all the comparison data from available stations. The 1:1 line denotes the perfect predictions, and the 2:1 and 0.5:1 lines represent the $\pm 50\%$ simulations, respectively.

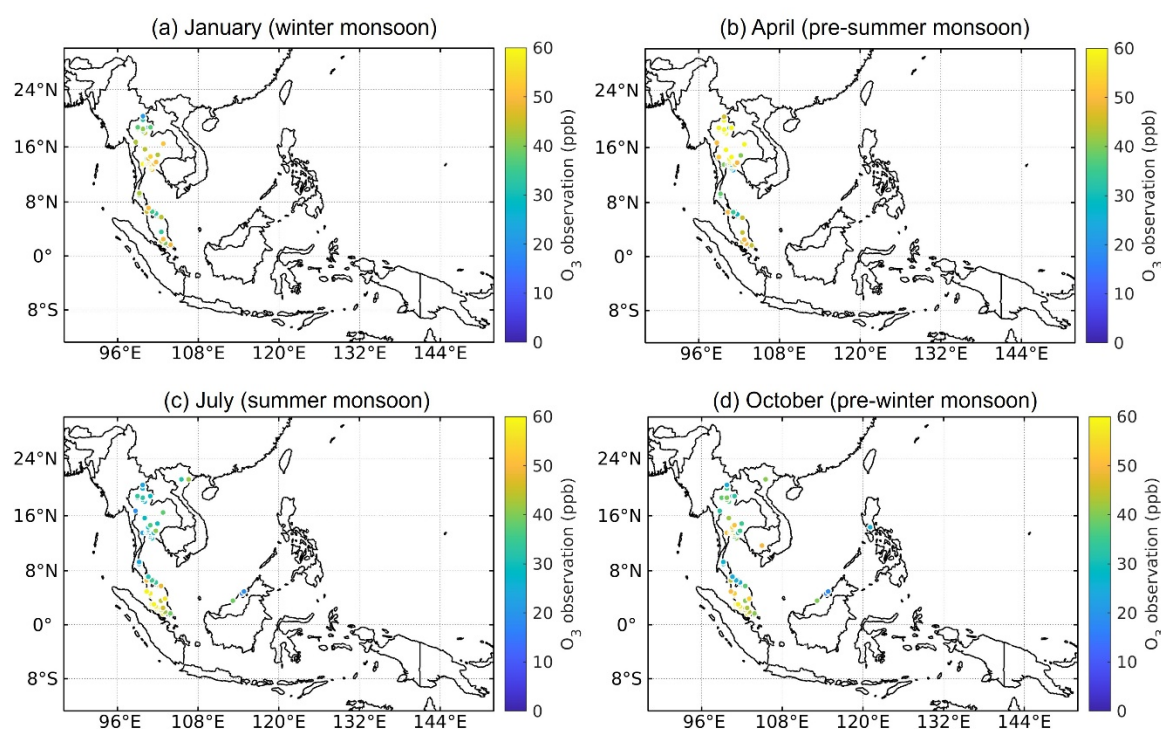


Fig. S11. MDA8 O₃ observations of 67 ground stations in the four months in Southeast Asia.

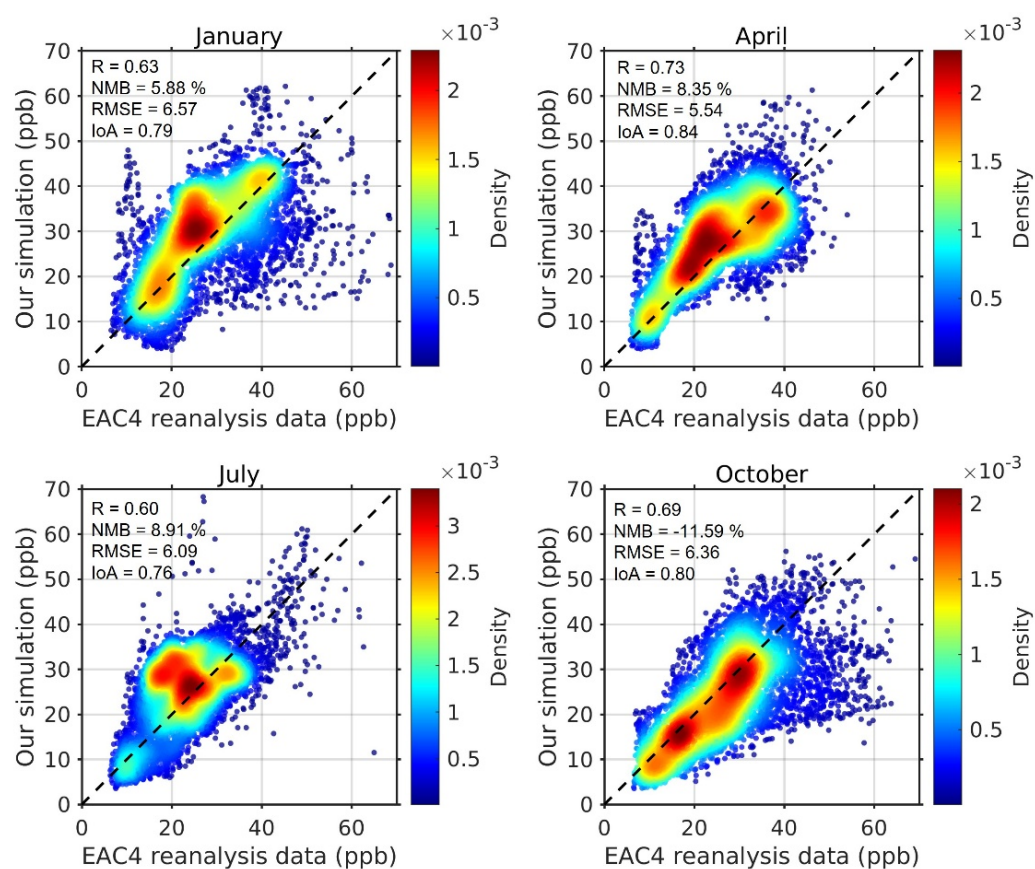


Fig. S13. Evaluation between the CMAQ simulation and the CAMS EAC4 reanalysis data in the four monsoon seasons.

Table S3. Evaluation of the CMAQ model simulation by comparing the MDA8 O₃ concentration levels with the ground-level measurements from 67 different stations in Southeast Asia.

Country	Station	January		April		July		October	
		NMB (%)	RMSE	NMB (%)	RMSE	NMB (%)	RMSE	NMB (%)	RMSE
Cambodia	EANET_S1	/	/	/	/	/	-3.02	5.39	/
	EANET_S2	-7.52	9.70	/	/	51.72	14.85	0.47	7.63
Thailand	EANET_S3	-10.38	8.62	/	/	/	/	23.81	10.03
	EANET_S4	/	/	-15.79	9.33	/	/	/	/
	EANET_S5	-19.71	7.39	-26.94	15.71	-0.23	5.66	/	/
	EANET_S6	/	/	-1.88	3.22	/	/	/	/
Brunei	AQI_S1	/	/	/	/	0.65	3.52	-1.48	3.58
	AQI_S2	/	/	/	/	8.35	3.27	-3.91	3.10
Philippines	AQI_S3	/	/	/	/	/	/	21.60	5.48
Vietnam	AQI_S4	/	/	/	/	-1.22	7.43	24.08	9.75
	AQI_S5	/	/	/	/	9.07	10.80	/	/
Thailand	AQI_S6	33.21	10.94	/	/	/	/	/	/
	AQI_S7	15.18	3.17	11.82	4.89	/	/	11.59	2.70
Malaysia	AQI_S8	/	/	/	/	-15.98	10.46	-23.68	13.19
	AQI_S9	/	/	/	/	-9.86	12.75	10.90	14.32
	AQI_S10	/	/	/	/	0.93	9.59	14.01	13.82
	AQI_S11	/	/	/	/	11.05	13.69	24.24	17.42
	AQI_S12	/	/	/	/	-12.83	14.27	5.54	11.46
	AQI_S13	/	/	/	/	-6.93	10.63	-14.30	9.83
	AQI_S14	/	/	/	/	25.85	15.96	5.10	11.05
	AQI_S15	/	/	/	/	1.34	9.57	15.38	15.16
	AQI_S16	/	/	/	/	11.53	13.98	21.92	17.23
	AQI_S17	/	/	/	/	-38.93	15.13	-36.40	15.34
	AQI_S18	/	/	/	/	-14.01	14.86	-9.86	10.78
	AQI_S19	/	/	/	/	4.39	10.76	9.47	10.70
	AQI_S20	/	/	/	/	-5.21	9.86	-3.11	9.84
	AQI_S21	/	/	/	/	-15.22	14.86	-0.52	11.82
Thailand	THA_S1	19.18	14.61	15.16	4.45	99.45	17.47	68.26	26.20
	THA_S2	11.10	12.68	18.03	5.41	41.75	10.63	33.44	15.79
	THA_S3	7.17	11.14	8.59	4.91	37.28	9.78	46.32	19.78
	THA_S4	5.61	7.63	2.53	2.27	24.36	7.40	25.34	14.72
	THA_S5	-0.94	12.55	4.71	2.85	32.15	7.38	24.09	12.32
	THA_S6	-1.33	10.16	35.72	8.48	17.22	5.68	10.44	8.19
	THA_S7	9.83	16.92	14.96	4.66	57.68	14.30	70.86	25.47
	THA_S8	15.99	17.01	4.19	2.50	40.34	12.01	50.24	20.35
	THA_S9	-20.95	9.54	-27.81	19.96	3.26	2.96	-10.50	8.25
	THA_S10	-9.28	9.01	1.87	3.33	7.51	5.25	2.58	7.25
	THA_S11	-1.15	8.24	1.94	1.87	45.85	10.40	33.20	8.56
	THA_S12	-14.67	10.71	/	/	23.01	8.69	38.08	9.68
	THA_S13	-8.23	9.35	-27.79	21.45	-3.70	4.17	/	/
	THA_S14	1.99	4.59	/	/	31.34	9.36	20.13	8.69
	THA_S15	-16.70	10.20	7.34	3.61	35.06	10.20	12.77	8.73
	THA_S16	14.95	8.74	1.48	1.01	-11.44	6.47	27.55	7.07
	THA_S17	-16.19	8.49	-37.71	26.69	8.36	6.91	-8.65	7.76

	THA_S18	-23.68	11.65	-35.21	22.18	0.87	5.64	0.49	1.17
	THA_S19	-29.23	14.77	-34.55	24.57	6.53	4.13	-7.43	7.45
	THA_S20	12.36	8.90	-20.19	9.41	34.15	8.09	5.51	5.65
	THA_S21	-20.94	10.88	-12.38	6.98	64.81	12.18	12.44	6.10
	THA_S22	-14.59	9.30	3.32	3.63	5.85	8.66	11.08	6.51
Malaysia	MYS_S1	64.89	12.73	-3.23	2.30	32.41	5.97	20.24	5.23
	MYS_S2	-0.61	2.85	0.80	1.32	-40.67	6.03	-29.33	5.87
	MYS_S3	42.96	6.13	3.68	1.39	8.28	2.97	13.84	3.00
	MYS_S4	0.51	2.42	0.72	0.79	23.55	6.71	32.47	6.27
	MYS_S5	11.08	5.10	-0.65	1.67	2.26	1.49	35.02	4.90
Singapore	SIN_S1	19.79	6.69	17.05	6.08	10.59	2.71	14.82	4.02
	SIN_S2	19.42	4.23	16.59	3.99	17.97	3.70	17.35	3.42
	SIN_S3	32.21	7.19	22.44	5.24	57.84	8.87	52.36	8.80
	SIN_S4	17.51	5.59	9.72	3.53	8.54	2.45	7.65	2.10
Thailand	OPENAQ_S1	8.70	4.84	-5.44	4.51	-3.17	4.92	21.77	5.88
	OPENAQ_S2	8.83	15.81	26.11	9.31	24.57	5.58	35.70	19.65
	OPENAQ_S3	-4.70	15.53	18.04	8.72	38.21	7.56	47.38	19.01
	OPENAQ_S4	-4.82	12.35	34.55	15.60	27.10	8.15	20.48	12.74
	OPENAQ_S5	-14.61	11.50	23.07	15.08	28.02	10.60	18.20	11.96
	OPENAQ_S6	-19.24	9.55	-43.21	33.84	9.86	2.77	-8.71	5.89
	OPENAQ_S7	-9.47	7.24	-27.10	16.71	3.62	2.24	-22.72	11.71
	OPENAQ_S8	-19.31	9.59	-36.96	27.00	3.40	2.50	-22.62	11.12
	OPENAQ_S9	1.58	5.10	-45.59	32.05	9.17	3.48	-18.01	8.22

Table S4. Descriptions of observation stations in Southeast Asia.

Country	Station	Location
Cambodia	EANET_S1	Phnom Penh
Thailand	EANET_S2	Bangkok
	EANET_S3	Samutprakarn
	EANET_S4	Kanchanaburi
	EANET_S5	Chiang Mai
	EANET_S6	Nakhon Ratchasima-Nai Mueang
Brunei	AQI_S1	Brunei Muara, Brunei
	AQI_S2	Pekan-Tutong, Brunei
Philippines	AQI_S3	Binan City
Vietnam	AQI_S4	Hanoi
	AQI_S5	Quang Ninh Phuong Nam
Thailand	AQI_S6	Ayutthaya Witthayalai School
	AQI_S7	Municipality Office
Malaysia	AQI_S8	Balok Baru
	AQI_S9	Bandaraya Melaka
	AQI_S10	Banting Selangor
	AQI_S11	Batu Muda
	AQI_S12	Batu Pahat
	AQI_S13	Jalan Tasek
	AQI_S14	Kg Air Putih
	AQI_S15	Nilai
	AQI_S16	Pelabuhan Kelang
	AQI_S17	Samalaju
	AQI_S18	Segamat
	AQI_S19	Seremban
	AQI_S20	SK Jalan Pegoh

	AQI_S21	Tangkak
Thailand	THA_S1	Bang Na, Khet Bang Na, Bangkok
	THA_S2	Bang Sao Thong, Bang Sao Thong, Samut Prakan
	THA_S3	Khlong Nueng, Khlong Luang, Pathum Thani
	THA_S4	Pratu Chai, Phra Nakhon Si Ayutthaya
	THA_S5	Na Mueang, Mueang, Ratchaburi
	THA_S6	Map Ta Phut, Meuang, Rayong
	THA_S7	Thung Sukhla, Si Racha, Chon buri
	THA_S8	Ban Suan, Mueang, Chon Buri
	THA_S9	Ban Dong, Mae Mo, Lampang
	THA_S10	Pak Nam Pho, Mueang, Nakhon Sawan
	THA_S11	Makham Tia, Mueang, Surat Thani
	THA_S12	Hat Yai, Songkhla
	THA_S13	Nai Mueang, Mueang, Khon Kaen
	THA_S14	Nai Mueang, Mueang, Nakhon Ratchasima
	THA_S15	Wang Yen, Plaeng Yao, Chachoengsao
	THA_S16	Bang Nak, Mueang, Narathiwat
	THA_S17	Nai Wiang, Mueang, Nan
	THA_S18	Ban Klang, Mueang, Lamphun
	THA_S19	Na Chak, Meuang, Phrae
	THA_S20	Wiang Phang Kham, Mae Sai, Chiang Rai
	THA_S21	MaePa, MaeSot, Tak
	THA_S22	Tha Tum, SiMahaPhot, Prachin Buri
Malaysia	MYS_S1	Batu Pahat, Johor
	MYS_S2	Kota Tinggi, Johor
	MYS_S3	Temer Loh, Pahang
	MYS_S4	Kangar, Perlis
	MYS_S5	Besut, Terengganu
Singapore	SIN_S1	Western Singapore
	SIN_S2	Eastern Singapore
	SIN_S3	Central Singapore
	SIN_S4	Northern Singapore
Thailand	OPENAQ_S1	Sateng, Mueang
	OPENAQ_S2	Samut Sakhon Wittayalai School
	OPENAQ_S3	Residence for Dept. of Mineral Resources
	OPENAQ_S4	Phaya Thai, Khet Phaya Thai
	OPENAQ_S5	Pak Phraio, Mueang
	OPENAQ_S6	Sop Pat, Mae Mo
	OPENAQ_S7	Mae Mo, Mae Mo
	OPENAQ_S8	Health Promotion Hospital Banthasri
	OPENAQ_S9	Natural Resources and Environment Office, Chiangrai

2. Is there any result about the evaluation of modeling CH₂O and NO₂? Since simulated ground-level CH₂O/NO₂ is used in this study (e.g., Figure S16), the validation of CMAQ CH₂O and NO₂ looks necessary related to the reliability to detect NO_x- or VOC-limited regions.

Response: We thank the referee for the important comment. To evaluate the simulations of CH₂O and NO₂, as well as the ground-level CH₂O/NO₂ ratios in Southeast Asia, we compared the CMAQ

results with available ground-based measurements and satellite data products. It should be noted that ground-based NO₂ observations were limited in Southeast Asia, and the available data were mainly obtained from several monitoring stations in Malaysia and Thailand. Therefore, we evaluated the simulated ground-level NO₂ using the available observations from 16 stations in total (Fig. S17a). As shown in Fig. S17b, the comparison of daily average NO₂ during the four monsoon seasons yielded an overall correlation coefficient of 0.61, an RMSE of 2.25 ppb, and an IoA of 0.73. These results indicated that the CMAQ simulation reasonably captured the variation of surface NO₂ over the available monitoring sites.

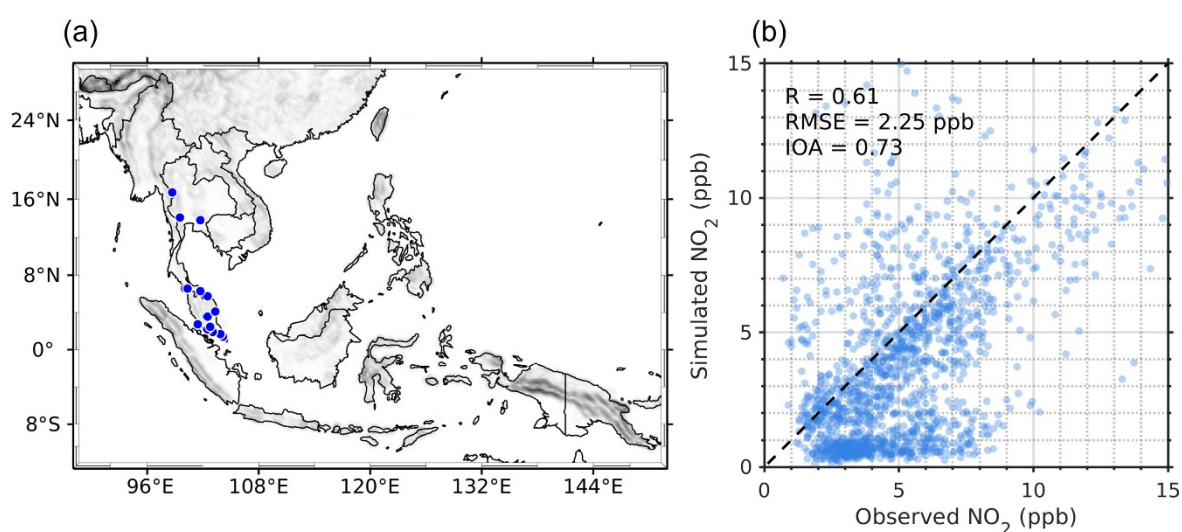


Fig. S17. (a) Observation stations of NO₂ in Southeast Asia. (b) CMAQ model evaluation of daily-averaged NO₂ with the observation data in the four monsoon seasons.

For CH₂O (formaldehyde), ground-based observations were not available in Southeast Asia. Therefore, we further evaluated the CMAQ-simulated CH₂O vertical column density covering all 26 model layers using the TROPOMI satellite data (https://data.gesdisc.earthdata.nasa.gov/data/S5P_TROPOMI_Level2/). As shown in Fig. S15, the CMAQ simulation presented the consistent spatial distribution with satellite-derived CH₂O columns, including the enhanced CH₂O levels over mainland Southeast Asia, Malaysia, Sumatra, and Java. The comparison showed an overall correlation coefficient of 0.77, an RMSE of 2.9×10^{-5} mol m⁻², and an IoA of 0.82 over the study domain, suggesting good agreement between the CMAQ simulation and the TROPOMI CH₂O retrievals.

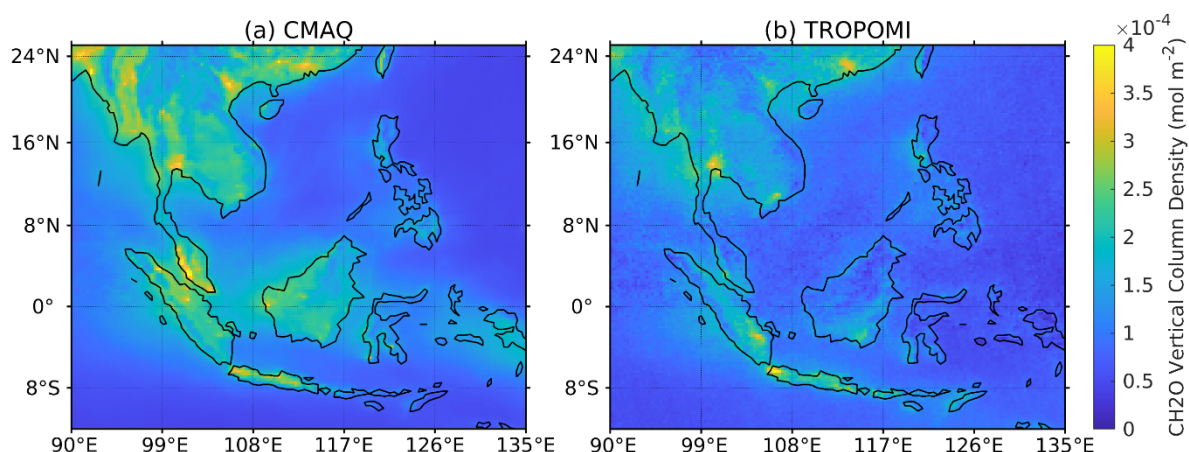


Fig. S18. Comparison of CH₂O vertical column density between (a) CMAQ simulation and (b) TROPOMI satellite retrievals in the four monsoon seasons in Southeast Asia.

In this manuscript, ground-level CH₂O/NO₂ ratios were used to identify the O₃ formation regimes during the four monsoon seasons. Therefore, to further evaluate the reliability of the O₃ formation regime classification, we not only assessed the CMAQ simulation of NO_x and CH₂O, but also compared our results with the CH₂O/NO₂ ratios derived from the TROPOMI satellite products. The thresholds for satellite column CH₂O/NO₂ ratios were set following previous studies in East Asia (Wang et al., 2021): regions with $0 < \text{CH}_2\text{O}/\text{NO}_2 < 2.3$ were classified as VOC-limited regimes, regions with $2.3 \leq \text{CH}_2\text{O}/\text{NO}_2 < 4.2$ were classified as transitional regimes, and regions with $\text{CH}_2\text{O}/\text{NO}_2 \geq 4.2$ were classified as NO_x-limited regimes. The TROPOMI-derived annual mean O₃ formation regimes during the four monsoon seasons are shown in Fig. S27 and showed a highly consistent spatial pattern with the CMAQ-based results (Fig. S26) over Southeast Asia. In particular, most regions in Southeast Asia were dominated by NO_x-limited conditions, while VOC-limited regimes mainly occurred in highly urbanized and industrialized areas, such as Singapore, Bangkok, coastal Vietnam, and parts of Java. Overall, the evaluations demonstrated that the CMAQ simulations reasonably reproduced both NO₂ and CH₂O distributions over Southeast Asia. The consistent O₃ formation regime patterns derived from CMAQ and TROPOMI further supported the reliability of using simulated ground-level CH₂O/NO₂ ratios to characterize O₃ sensitivity in this study.

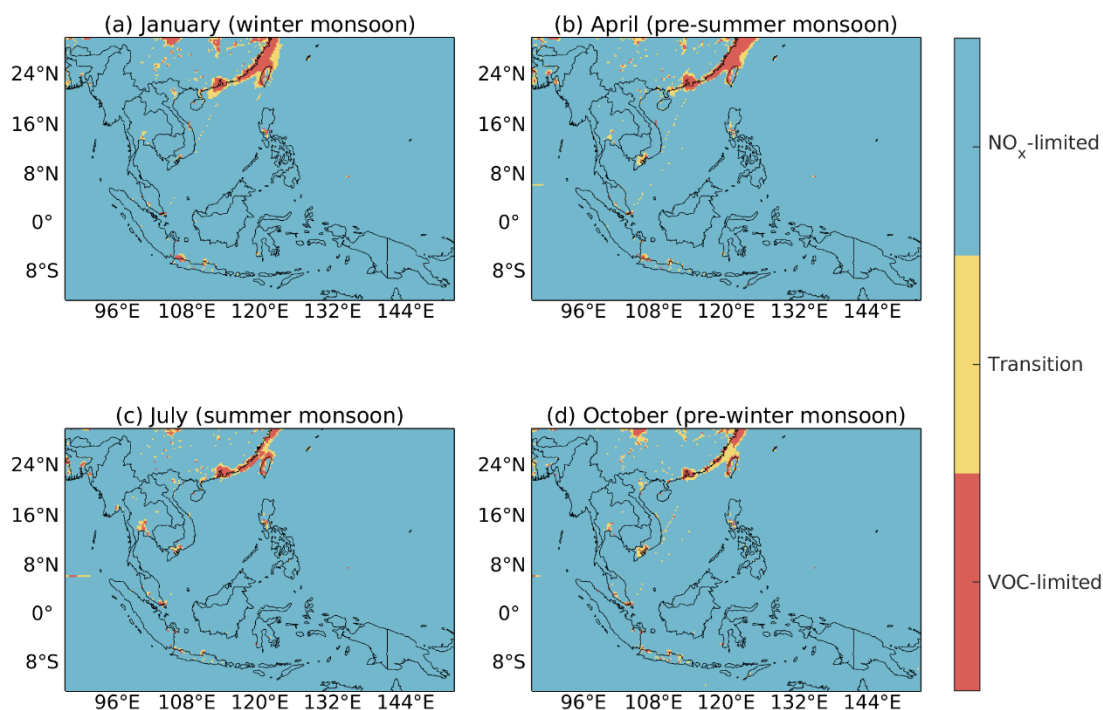


Fig. S26. Spatial distribution of the O_3 formation regimes over Southeast Asia during winter, pre-summer, summer, and pre-winter monsoon by the simulated ground-level CH_2O/NO_2 . The VOC-limited regime (<0.4), the transition regime ($0.4-0.7$), and the NO_x -limited regime (>0.7) are defined according to (Jin et al., 2017).

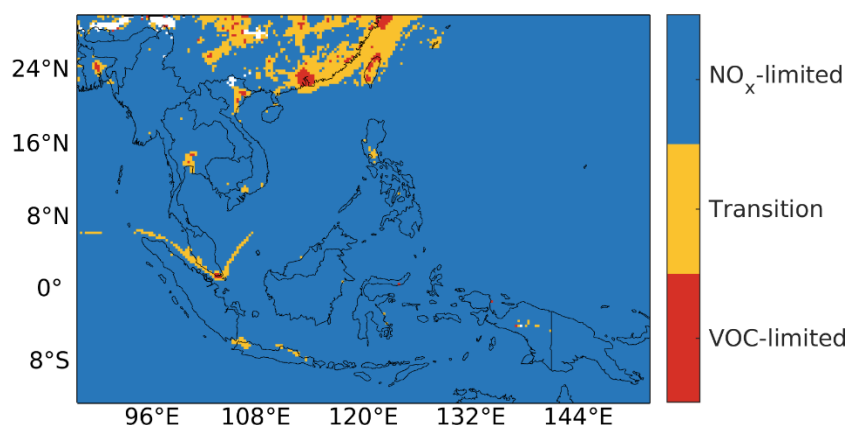


Fig. S27. Annual mean O_3 formation regimes over Southeast Asia by the TROPOMI satellite derived CH_2O/NO_2 . The VOC-limited regime (<2.3), the transition regime ($2.3-4.2$), and the NO_x -limited regime (>4.2) are defined, according to (Wang et al., 2021).

Reference:

Wang, W., van der A, R., Ding, J., van Weele, M., & Cheng, T. (2021). Spatial and temporal changes of the ozone sensitivity in China based on satellite and ground-based observations. *Atmospheric Chemistry and Physics*, 21(9), 7253-7269.

We have revised the Method and Result sections to evaluate the simulation of CH₂O, NO₂, and CH₂O/NO₂. The details can be found below:

Lines 181-184:

“...The simulated surface NO₂ concentration was evaluated against the available ground-based observations from Malaysia and Thailand. Also, the CMAQ-simulated CH₂O vertical column density covering all layers was evaluated against TROPOMI satellite products (https://data.gesdisc.earthdata.nasa.gov/data/S5P_TROPOMI_Level2/), and the model performance was assessed using R, RMSE, and IoA...”

Lines 204-210:

“...The evaluation of surface NO₂ concentration is presented in Fig. S17. The overall R between the observed and simulated daily mean NO₂ was 0.61, with an RMSE of 2.25 ppb and an IoA of 0.73, indicating that the model reasonably captured the spatial variation of surface NO₂ over the available monitoring sites. The CH₂O simulation showed consistent spatial patterns with TROPOMI satellite data (Fig. S18), indicating enhanced CH₂O levels over mainland Southeast Asia, Malaysia, Sumatra, and Java Island. The comparison yielded the overall R of 0.77, the RMSE of 2.9×10^{-5} mol m⁻², and the IoA of 0.82, suggesting good agreement between the CMAQ simulation and satellite-derived CH₂O columns...”

Supplementary Figures and Tables:

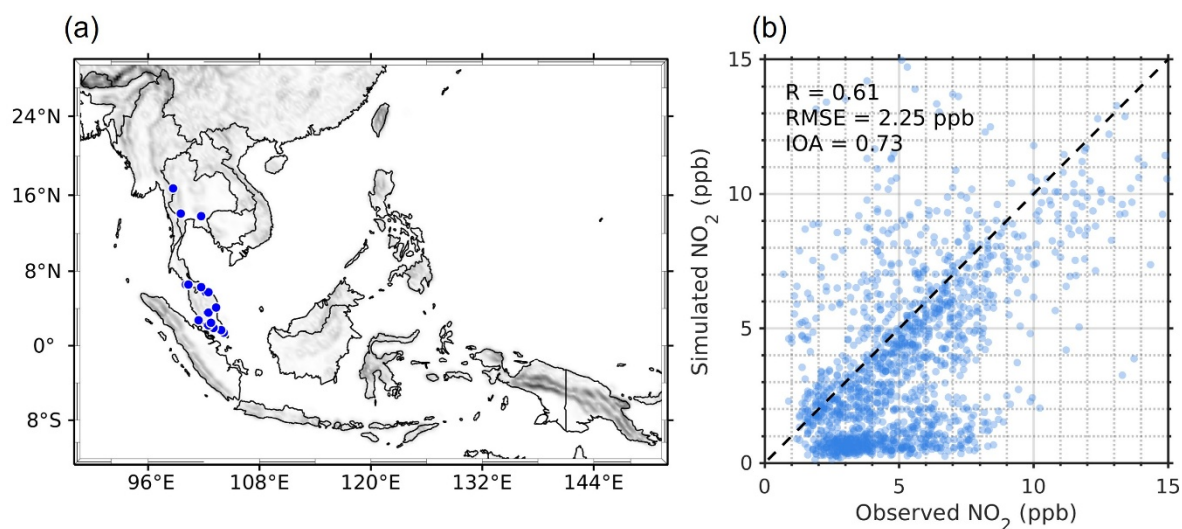


Fig. S17. (a) Observation stations of NO_2 in Southeast Asia. (b) CMAQ model evaluation of daily-averaged NO_2 with the observation data in the four monsoon seasons.

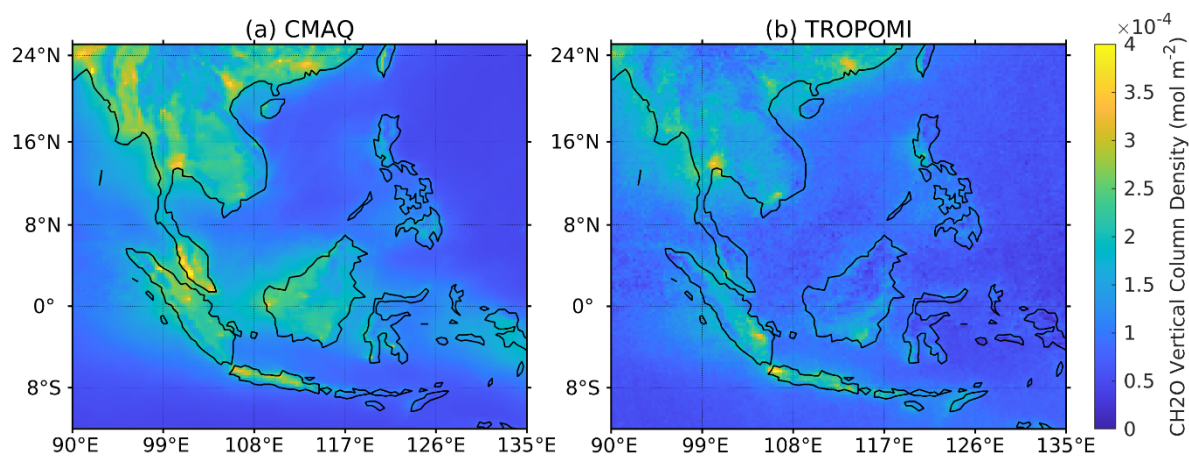


Fig. S18. Comparison of CH_2O vertical column density between (a) CMAQ simulation and (b) TROPOMI satellite retrievals in the four monsoon seasons in Southeast Asia.

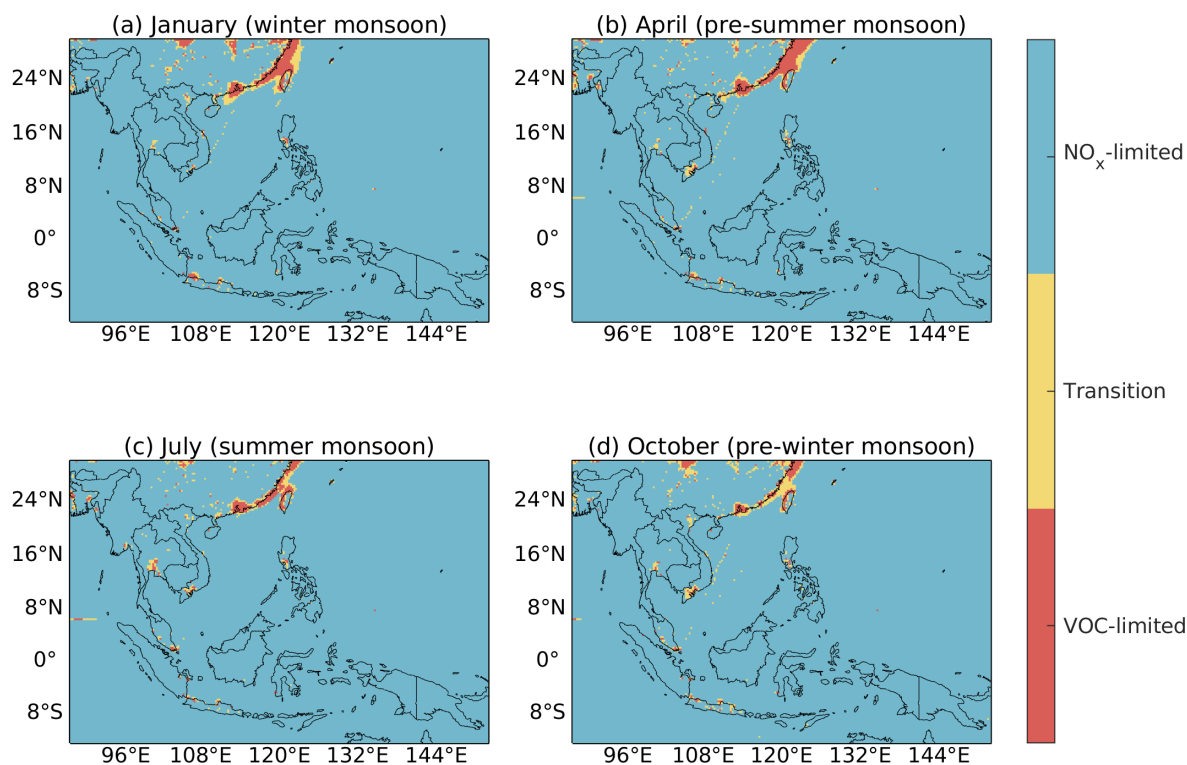


Fig. S26. Spatial distribution of the O_3 formation regimes over Southeast Asia during winter, pre-summer, summer, and pre-winter monsoon by the simulated ground-level CH_2O/NO_2 . The VOC-limited regime (<0.4), the transition regime ($0.4-0.7$), and the NO_x -limited regime (>0.7) are defined, according to (Jin et al., 2017). The simulated ground-level CH_2O/NO_2 was evaluated with the CH_2O/NO_2 ratios derived from the TROPOMI satellite products (Fig. S27), showing the highly consistent spatial patterns in Southeast Asia.

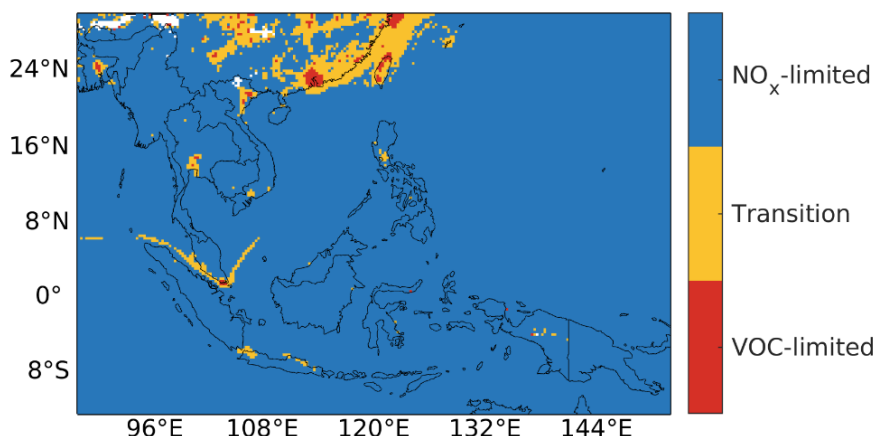


Fig. S27. Annual mean O₃ formation regimes over Southeast Asia by the TROPOMI satellite derived CH₂O/NO₂. The VOC-limited regime (<2.3), the transition regime (2.3-4.2), and the NO_x-limited regime (>4.2) are defined, according to (Wang et al., 2021).

3. Can we trust the CMAQ simulation results in the free troposphere? I am not sure the analysis quality of vertical distribution using CMAQ modeling data. Some clues should be suggested for guaranteeing the quality of free-tropospheric simulation (Also, please include the vertical layer height information name in Figure S19).

Response: Thanks for your important comment. To assess the reliability of the CMAQ simulation in the free troposphere, we further compared the vertical distribution of simulated O₃ with the CAMS EAC4 global reanalysis data at multiple pressure levels. As shown in the revised Figs. S14 and S15, the simulated O₃ vertical distributions were generally consistent with the reanalysis data, including the increasing O₃ concentration at higher layers and the large spatial variations over Southeast Asia. The quantitative comparison also showed reasonable agreement at most pressure levels (Fig. S16). The correlation coefficients (R) between CMAQ and CAMS EAC4 were 0.75, 0.79, 0.82, 0.81, 0.82, 0.76, and 0.72 at 1000, 950, 900, 850, 800, 700, and 600 hPa, respectively, with IoA values generally ranging from 0.73 to 0.82. The results indicated that CMAQ captured the major vertical and spatial variability of O₃ in the lower and middle troposphere. The comparison at 400 hPa showed relatively larger uncertainties with a correlation coefficient (R) of 0.60 and the RMSE of 15.8 ppb. The uncertainty was related to differences in vertical resolution and pressure-level matching between the CMAQ model layers and CAMS EAC4, the vertical profiles of emission inventories, and the boundary conditions used in the two modeling systems. The uncertainty was likely related to differences in vertical

resolution and pressure-level matching between the CMAQ model layers and CAMS EAC4, and the boundary conditions used in the two modeling systems. In particular, the corresponding CMAQ layer was Layer 24, with an average pressure of approximately 420 hPa, which did not exactly match the 400 hPa pressure level in the CAMS EAC4 dataset.

Overall, the comparison with CAMS EAC4 supported the reliability of the CMAQ simulation in representing the major vertical distribution characteristics of tropospheric O₃ over Southeast Asia, especially from the surface to the middle troposphere. In the revised Fig. S30, which corresponds to Fig. S19 in the original manuscript, we also added the pressure-level information to improve the presentation of the modelling results for each vertical layer. The vertical layer heights were also provided in Table S7:

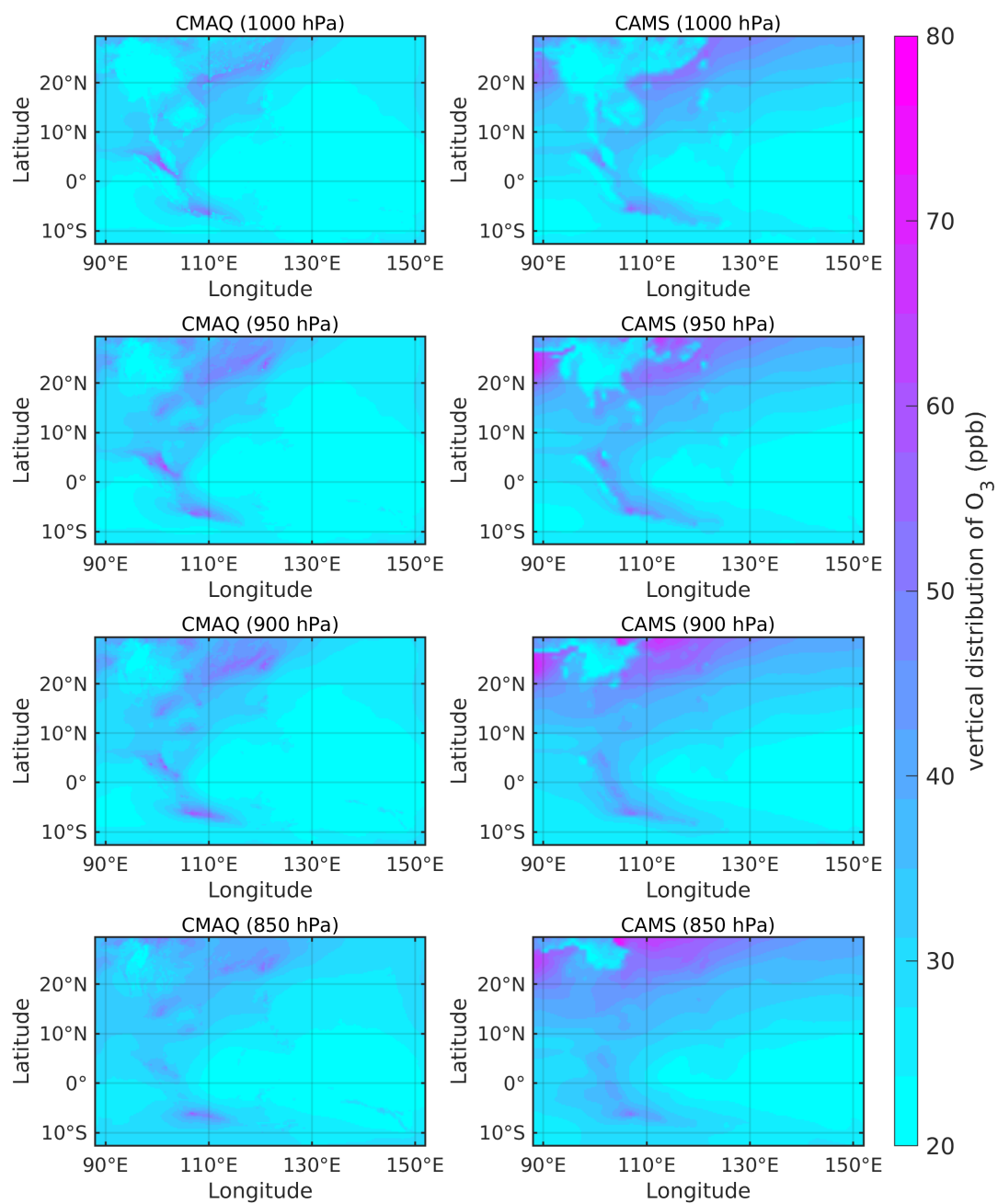


Fig. S14. Comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 1000, 950, 900, and 850 hPa, respectively.

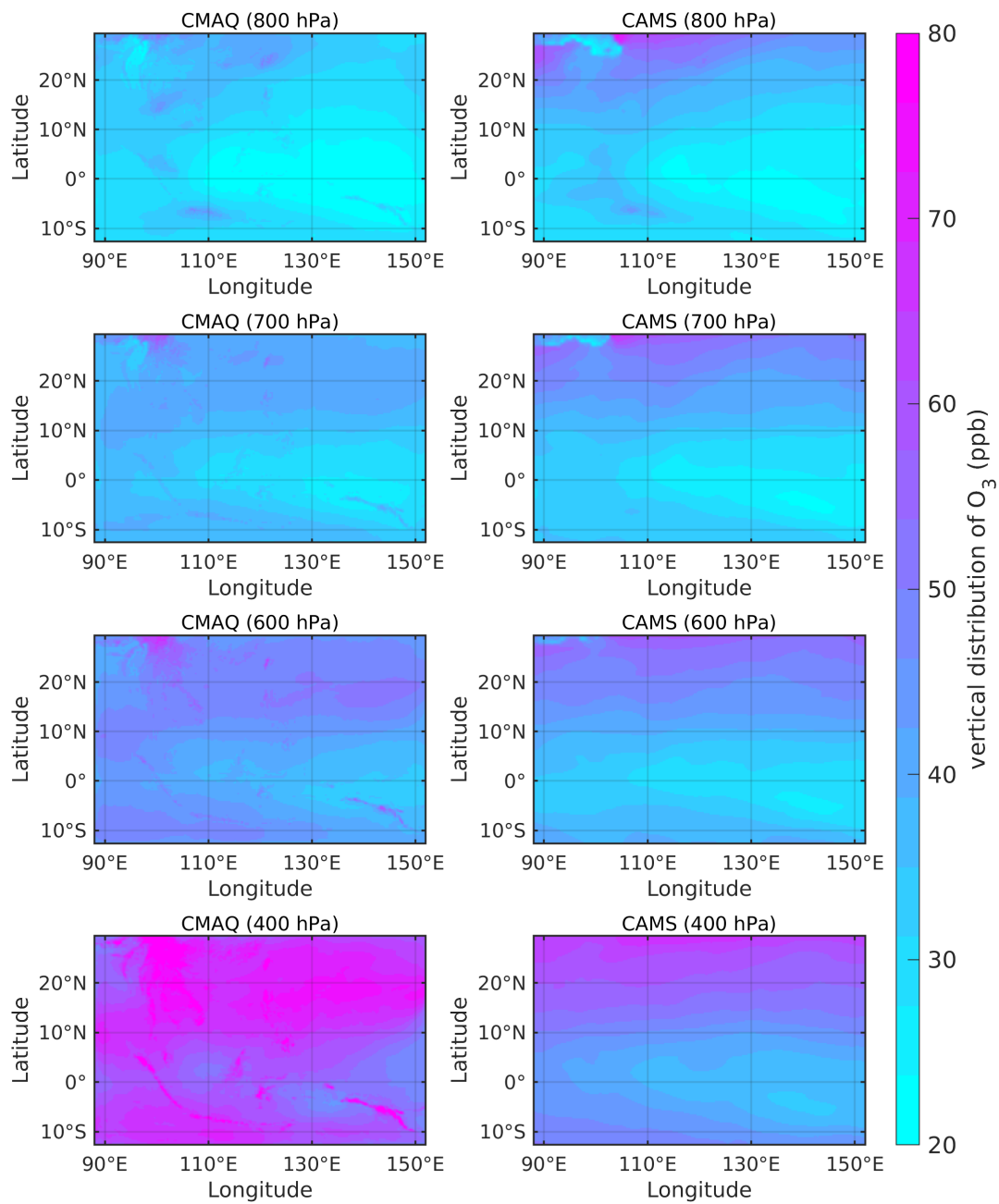


Fig. S15. Comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 800, 700, 600, and 400 hPa, respectively.

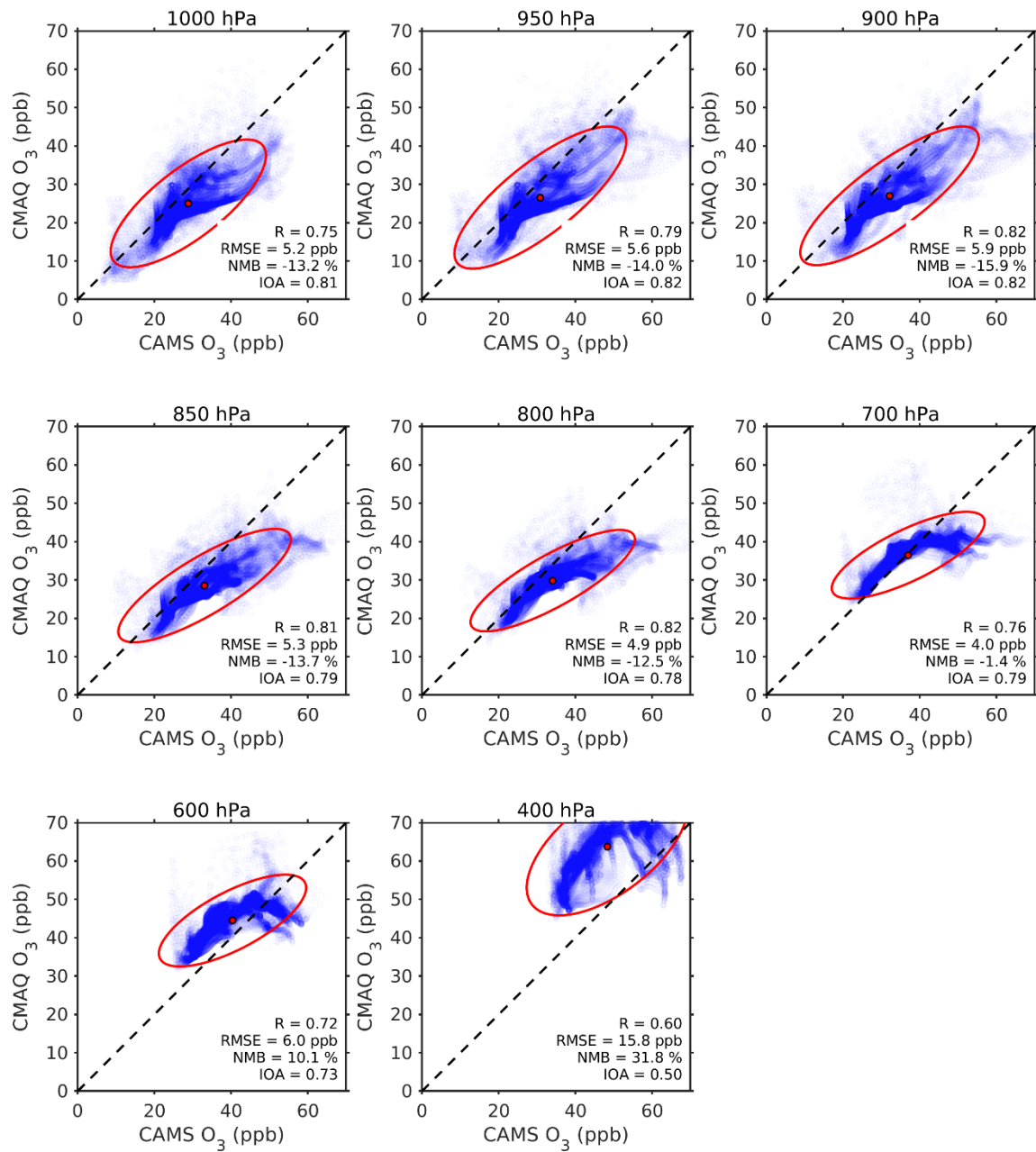


Fig. S16. Quantitative comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 1000, 950, 900, 850, 800, 700, 600, and 400 hPa, respectively.

Table S7. Averaged height (m) of each layer in the model simulation.

Layer	1	2	3	4
Height (m)	25	37	59	82
Layer	5	6	7	8
Height (m)	106	133	165	202
Layer	9	10	11	12
Height (m)	247	301	365	442
Layer	13	14	15	16
Height (m)	532	641	770	923
Layer	17	18	19	20
Height (m)	1107	1325	1585	1896
Layer	21	22	23	24
Height (m)	2634	3559	5406	9050
Layer	25	26		
Height (m)	14412	19584		

We revised the Method and Result sections to include evaluation of the vertical O₃ distributions with CAMS EAC4 reanalysis data, and added the average pressure-level information to Fig. S30. The details can be found below:

Lines 173-181:

“...Due to the limited availability and sparse spatial coverage of ground-based O₃ observations in Southeast Asia, we further assessed the surface CMAQ O₃ simulation using the CAMS ECMWF Atmospheric Composition Reanalysis 4 (EAC4) monthly reanalysis product, which combined multi-source observations with data assimilation and provided a spatially complete benchmark for evaluating large-scale O₃ patterns in data-sparse regions. In addition to the surface evaluation, we compared the vertical distribution of O₃ simulation with CAMS EAC4 at multiple pressure levels to assess the model performance in representing tropospheric O₃ structures. Model performance was rigorously evaluated using statistical assessments, including normalized mean bias (NMB), correlation coefficient (r), root mean square error (RMSE), and the index of agreement (IoA) between MDA8 O₃ observations and outputs from the CMAQ simulations (Kim et al., 2020). ... ”

Lines 201-204:

“...In addition, the scatter plots (Fig. S13) closely followed the 1:1 line, indicating that the simulations captured both the magnitude and spatial variability of surface O₃ in the reanalysis

data. Vertical layer comparisons between CMAQ simulation and the CAMS EAC4 reanalysis data further validated the reliability of the tropospheric O₃ simulation (Figs S14-S16). ...”

Supplementary Figures:

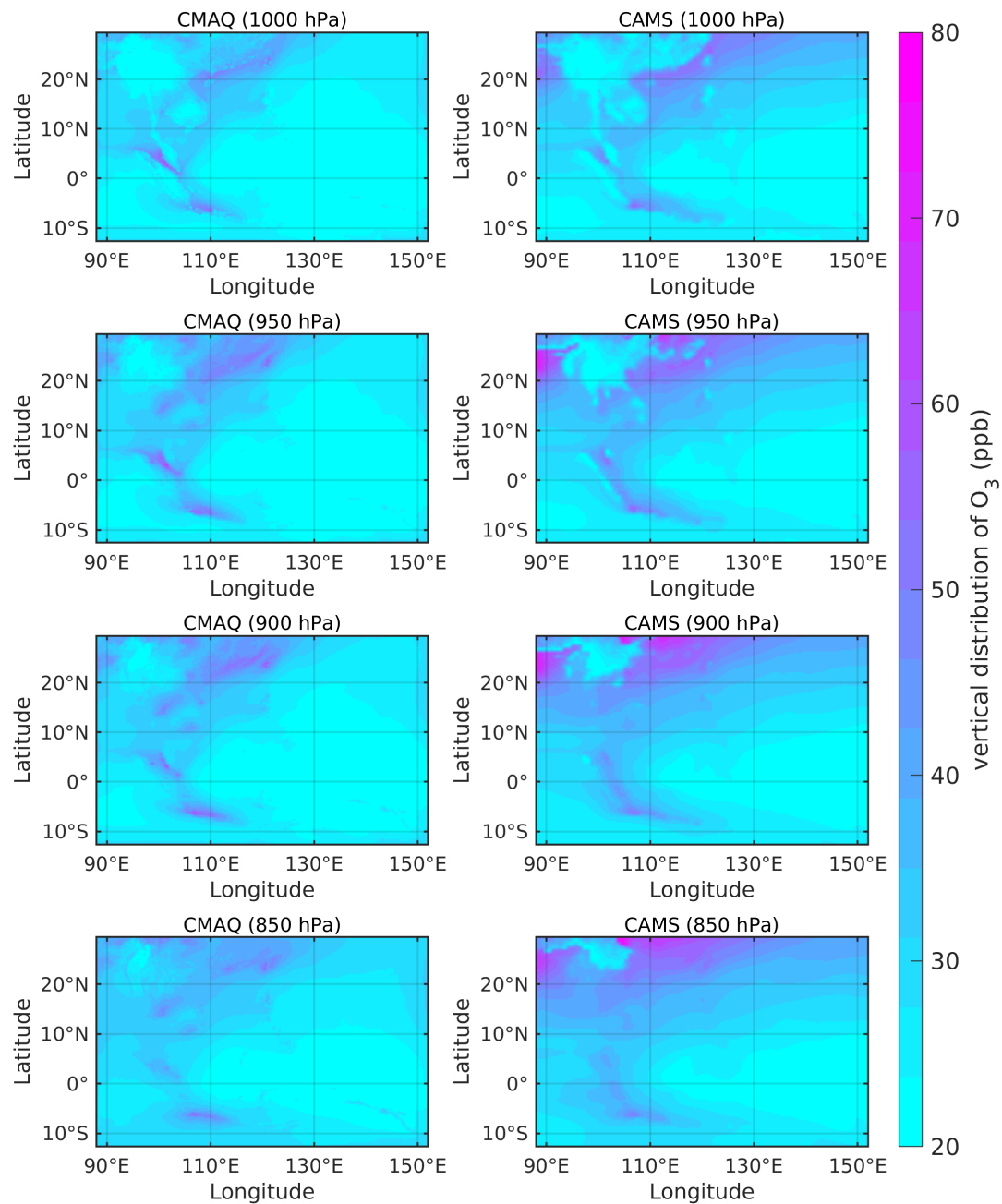


Fig. S14. Comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 1000, 950, 900, and 850 hPa, respectively.

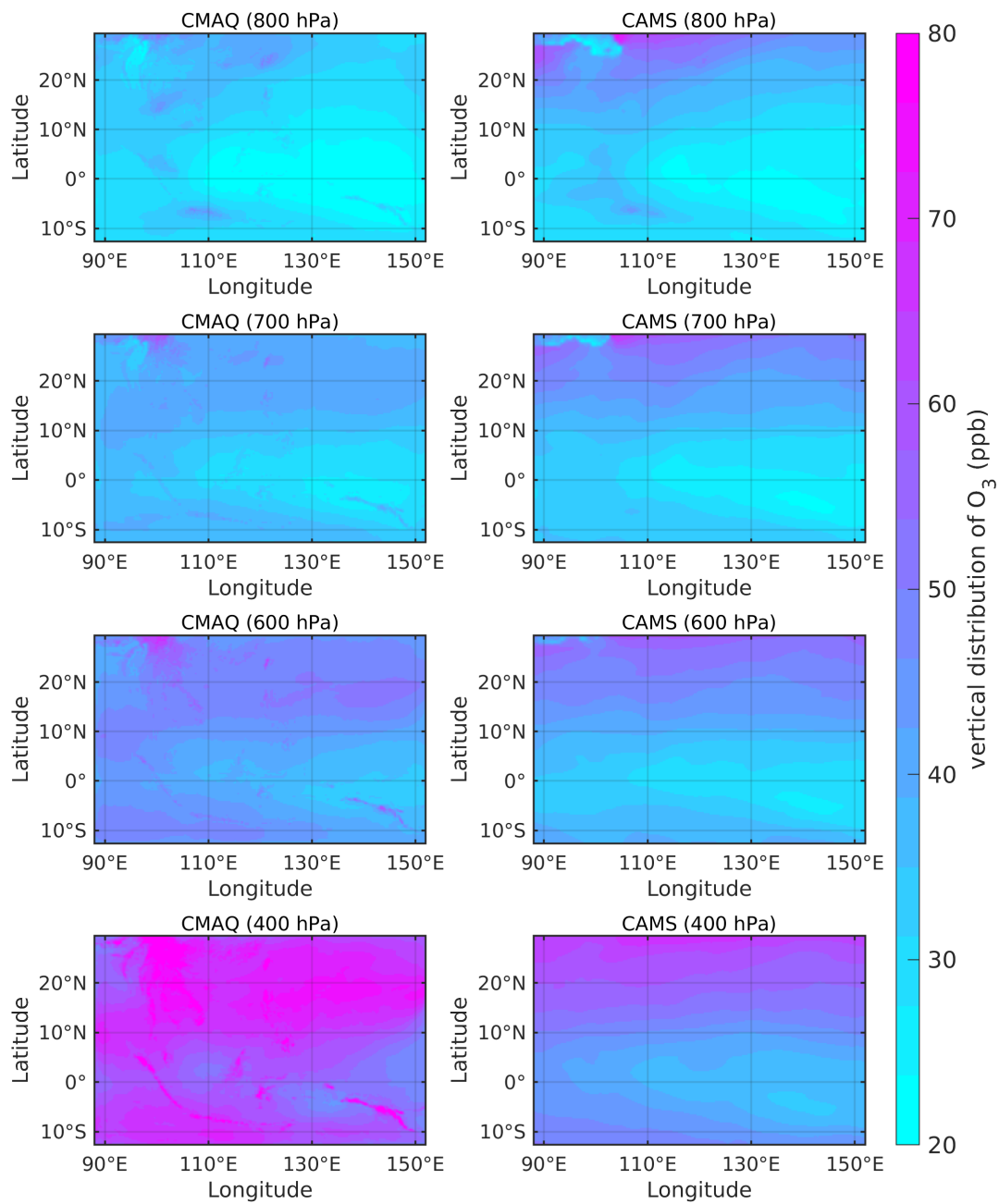


Fig. S15. Comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 800, 700, 600, and 400 hPa, respectively.

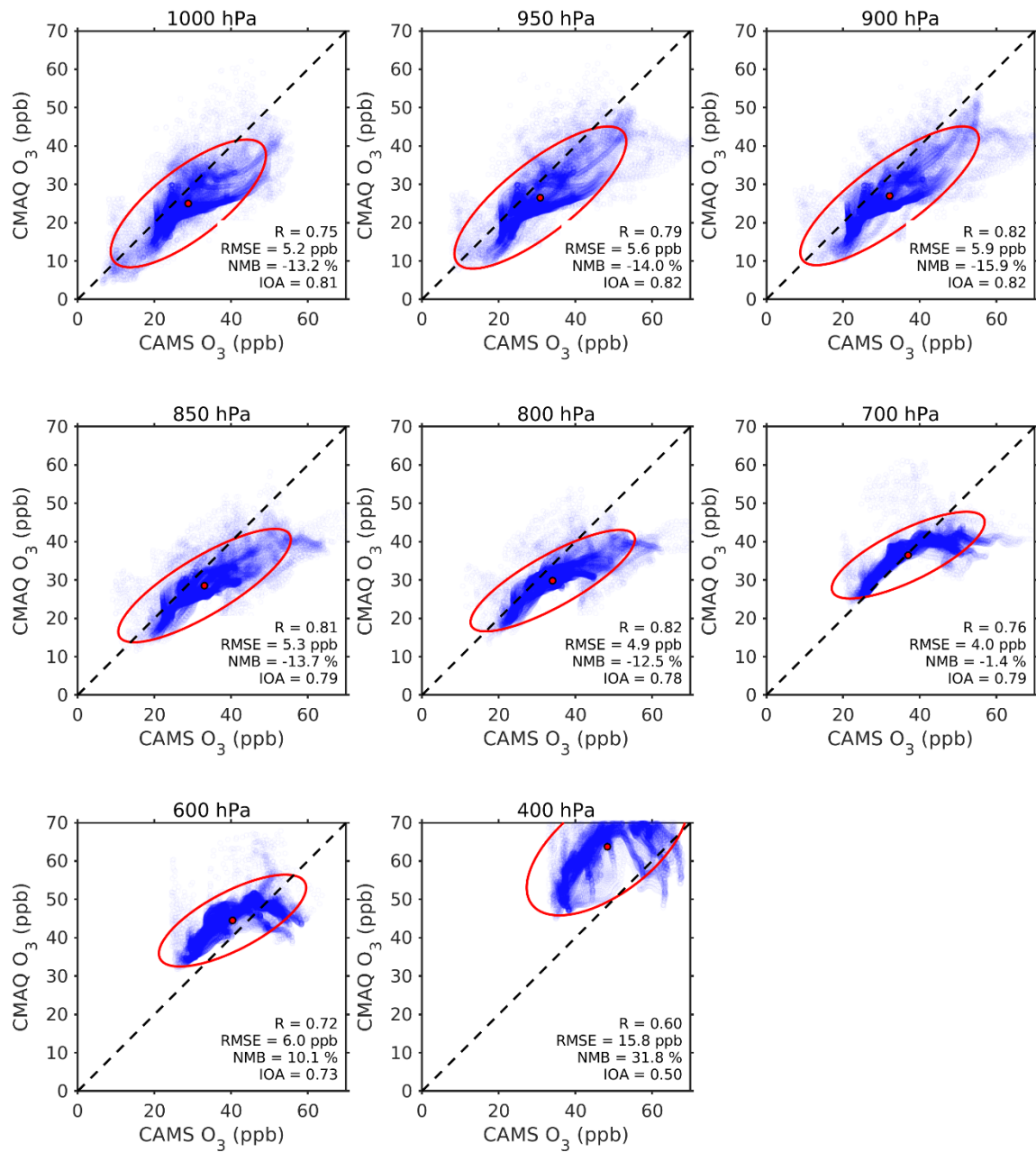


Fig. S16. Quantitative comparisons of O₃ concentration between CMAQ simulation and CAMS EAC4 reanalysis data at 1000, 950, 900, 850, 800, 700, 600, and 400 hPa, respectively.

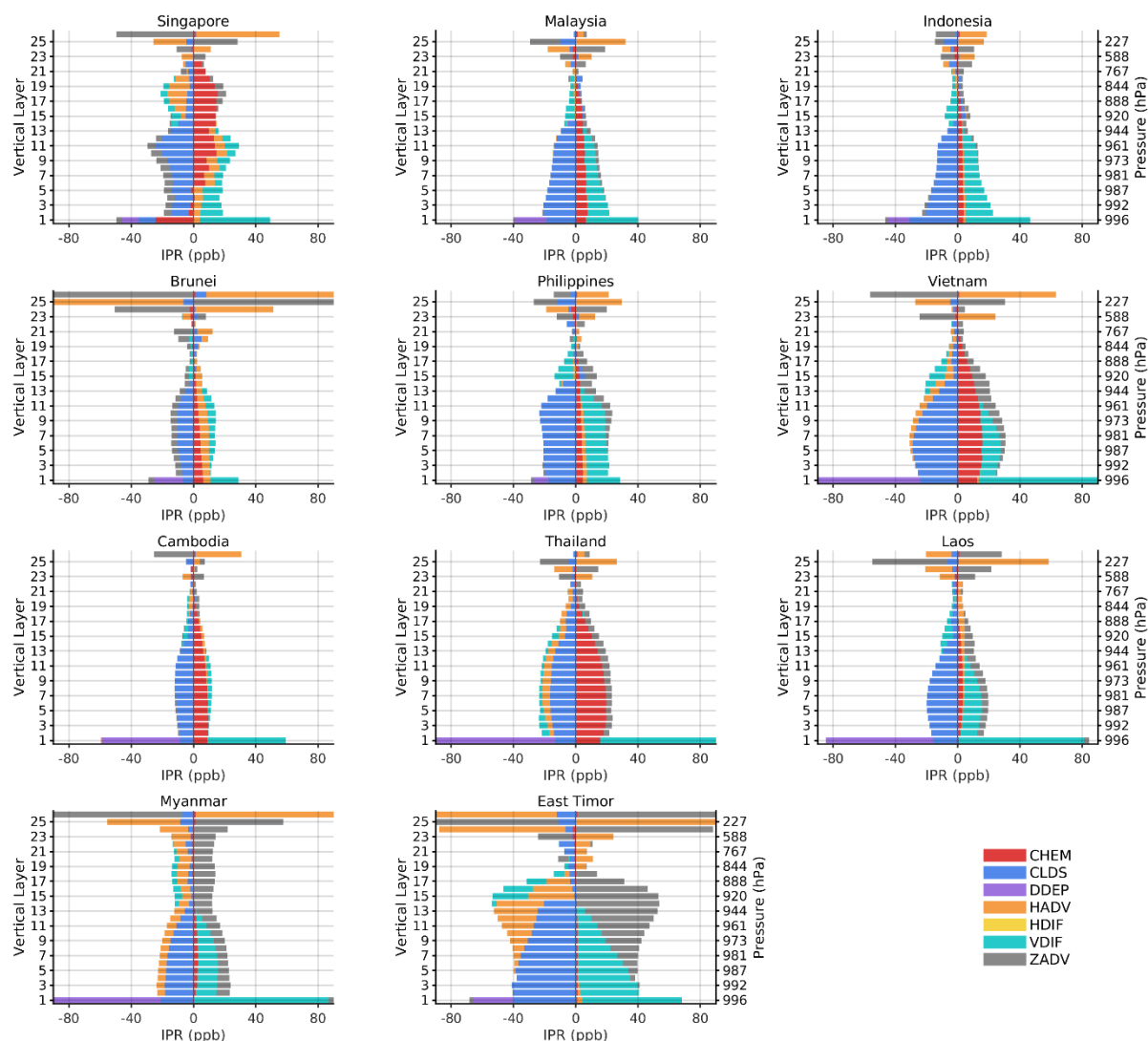


Fig. S30. The hourly averaged vertical distribution of the 26 layers from IPR analysis during the four monsoon seasons.

4. Authors showed the surface ozone distribution in Figures 1, S35 and S36. Based on these figures, the ozone production seems very high following the ship track. Is it right? In Figure S16, there are some yellow dots over the ocean, indicating the 'transition' region. Is it due to the high enhancement of NO_x production over the ship track? Can we say that the ship plume is very significant for ozone production and decision of chemical regimes (VOC or NO_x limited regime)? If yes, it is curious to me, because some previous studies show that the ozone level is higher over the sea (which is very rural area). When we compare the ozone level between the megacity and rural maritime area, ozone is usually lower in the megacity due to the ozone titration by high NO_x level. If NO_x emission from ship plumes matter, I guess that we can see the similar 'ozone titration' over the ship track, instead of ozone enhancement. Is it qualified for authors' CMAQ ozone simulation over the ocean?

Response: Thanks for your insightful comment. From our simulation results, elevated O_3 concentration and positive contributions from NO_x emissions were found along several major shipping routes in Southeast Asia, especially over the Malacca Strait, coastal Vietnam, the coastal areas around Java, and the Philippine Sea (Figs. 1, S65, and S66 in the revised Supplemental). It was due to the high enhancement of NO_x production over the shipping routes. Meanwhile, shipping NO_x reduced the surface CH_2O/NO_2 ratio in some maritime regions and shifted some grid cells from NO_x -limited regimes toward transitional or VOC-limited regimes (Fig. S26), indicating the influence of enhanced NO_x emissions in these areas.

To investigate the drivers of elevated surface O_3 along the shipping routes, we further plotted the spatial distribution of the physical and chemical processes related to O_3 formation, transport, and removal. As shown in Fig. S21, ground-level gas-phase chemistry over some shipping-influenced regions reduced O_3 , which was consistent with the transitional or VOC-limited regimes and indicated that shipping-related NO emissions consumed O_3 through NO titration. These results suggested that local titration was present near the surface.

However, local chemical loss was not the only process controlling the final O_3 concentration over the ocean. As shown in Figs. S22-S23, positive contributions from gas-phase chemistry were found in the upper layers (100 and 200 m, respectively) along most shipping routes. It was because the NO_x concentration was relatively lower in the upper layers, where the NO titration effect was substantially weakened. O_3 formed or accumulated in the upper layers could then be mixed downward through vertical diffusion and increase surface O_3 (Fig. S24). In addition, positive O_3 contributions were also observed around some shipping routes (Fig. S21), where NO_x was relatively lower, and the titration was weaker. The O_3 produced from lower- NO_x regions could also be transported into titration-influenced grids through horizontal advection. Moreover, as shown in Figs. 5 and 6, super-regional sources contributed substantially to O_3 in Southeast Asia, especially in January and July. The elevated O_3 over the Philippine Sea in January could also be partly associated with super-regional O_3 transport from the South China Sea. Therefore, the final O_3 increase along shipping routes represented the net effect of multiple processes. Local near-surface titration reduced O_3 in NO_x -saturated areas, while regional photochemical production, horizontal and vertical transport, and downward mixing increased O_3 . In our simulation, the positive effects from transport and mixing outweighed the local titration effect at the regional scale.

In addition, the special meteorological conditions contributed to the broadly NO_x -limited formation regimes in Southeast Asia. High air temperature, relative humidity and intensive sunlight enhanced the production rate of OH radical in the ocean and promoted the reaction between OH radicals and NO_2 . The consumption of NO_2 then contributed to the NO_x -limited and transitional regimes along many other shipping routes in the maritime Southeast Asia (Fang et al., 2025). To further support the reliability of the oceanic and coastal O_3 simulation, we compared the simulated O_3 with CAMS EAC4 reanalysis data. The comparison showed that CMAQ reasonably captured the elevated O_3 concentration along shipping routes, while CAMS EAC4 also showed higher O_3 concentration over the South China Sea and the Philippine Sea at a spatial resolution of 0.75° . Nevertheless, we acknowledge that the lack of direct marine O_3 observations and the 30 km model resolution introduced uncertainties in resolving ship-plume chemistry. We have therefore clarified in the revised manuscript that the shipping-related O_3 enhancement should be interpreted as a regional-scale effect resulting from multiple processes.

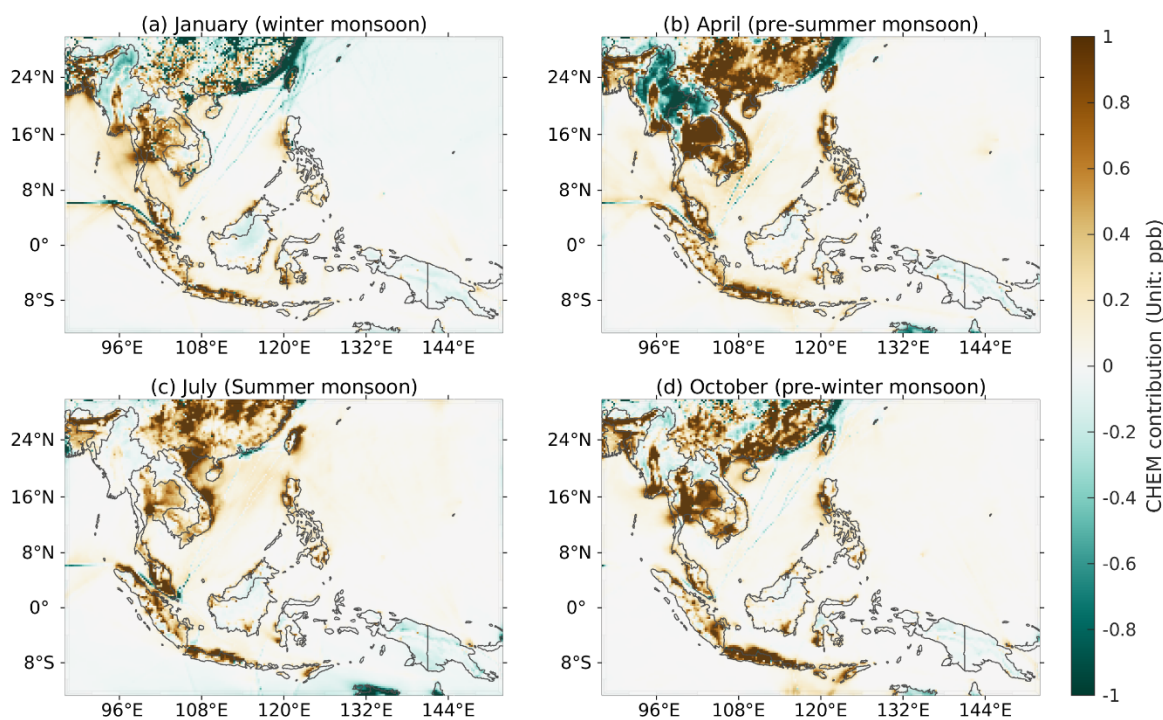


Fig. S21. Spatial distribution of gas-phase chemistry contribution to O_3 at surface level in Southeast Asia.

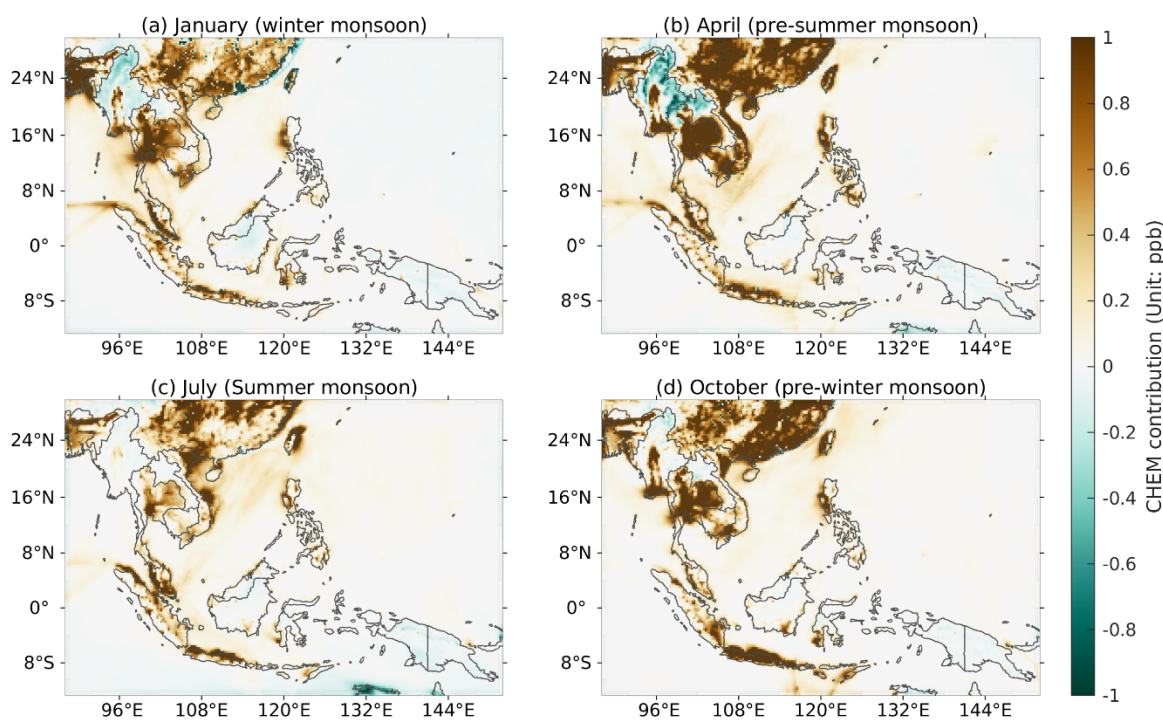


Fig. S22. Spatial distribution of gas-phase chemistry contribution to O_3 at 100 m height in Southeast Asia.

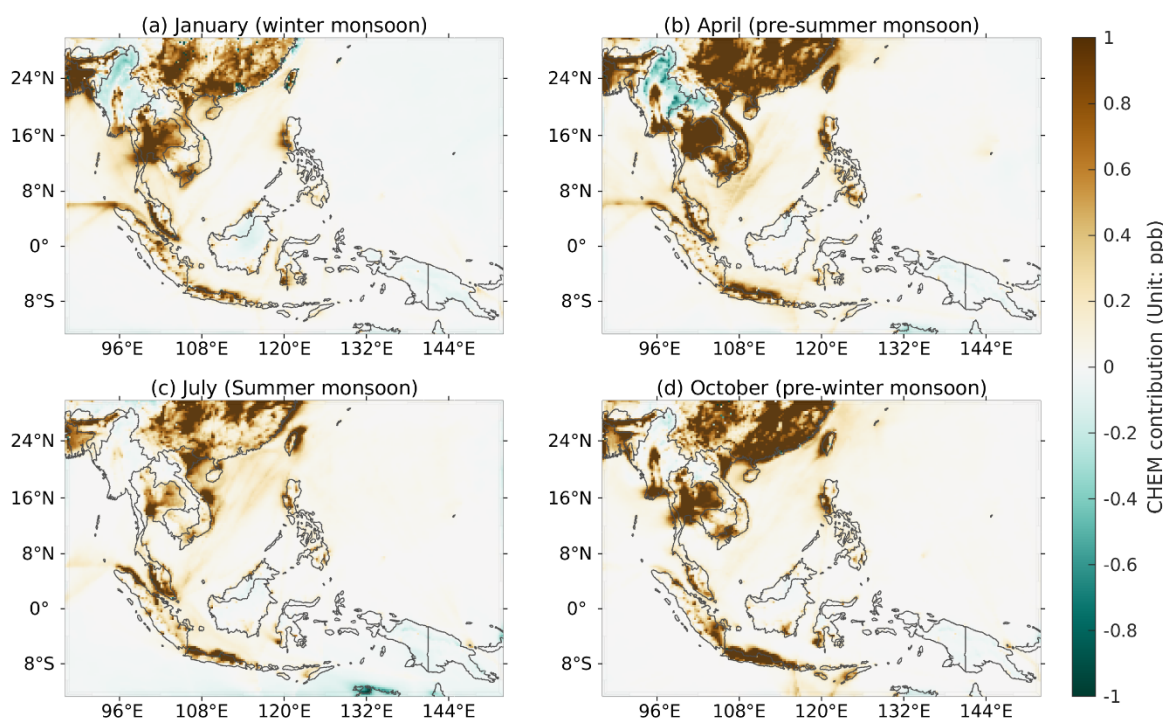


Fig. S23. Spatial distribution of gas-phase chemistry contribution to O_3 at 200 m height in Southeast Asia.

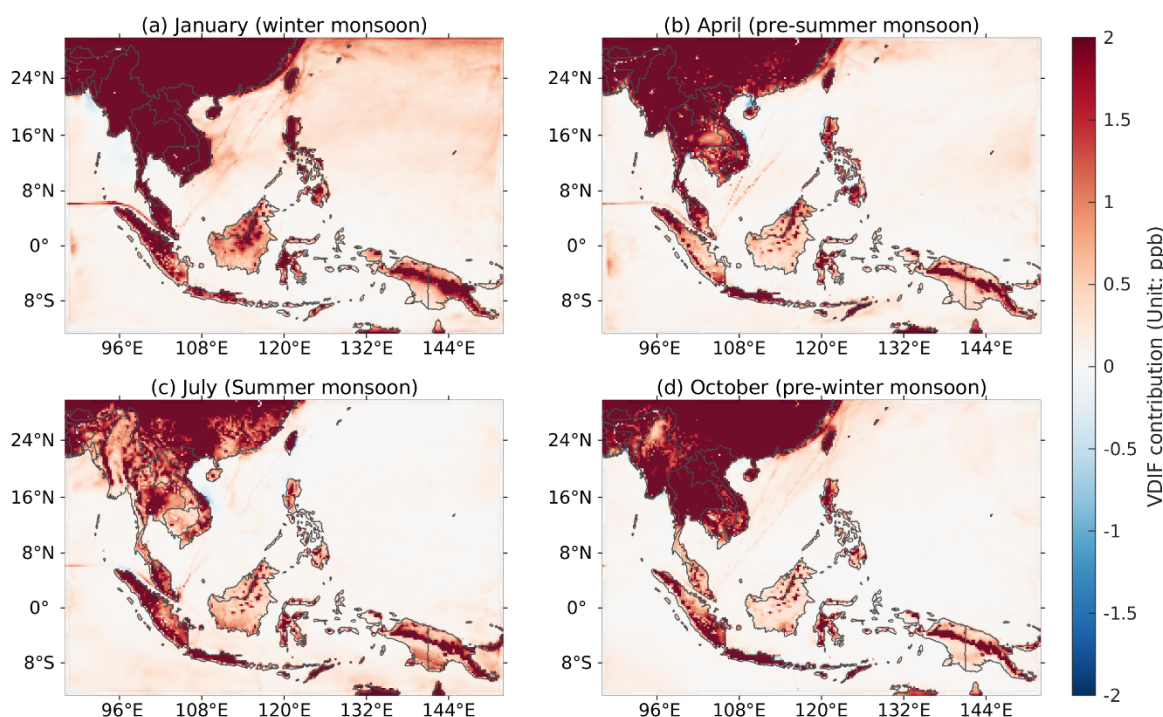


Fig. S24. Spatial distribution of vertical diffusion contribution to O_3 at surface level in Southeast Asia.

Reference:

Fang, T., Hu, J., Gu, Y., Sung, J. J., & Yim, S. H. L. (2025). Response of ozone to current and future emission scenarios and the resultant human health impact in Southeast Asia. *Environment International*, 197, 109333.

We have revised the Results section to explain the elevated O_3 levels along the shipping routes. The details can be found below:

Lines 215-224:

“...Elevated O_3 levels were found in major urban regions, including Singapore, the Malacca Strait, Jakarta, Bangkok, Hanoi, Ho Chi Minh City, and Manila. These regions were characterized by enhanced anthropogenic NO_x and VOC emissions (Figs. S19 and S20) from transportation, shipping, and industrial activities, which facilitated O_3 formation. Higher O_3 concentration was also found along several major shipping routes, reflecting the combined

influence of shipping NO_x emissions, regional photochemical production, and atmospheric transport. Although local NO titration may occur near shipping-influenced surface grids (Fig. S21), the O_3 formed in surrounding regions and upper layers (Figs. S22-S23) could be transported and mixed downward (Fig. S24), resulting in net O_3 enhancement over shipping routes. At the country level, Singapore exhibited the highest annual mean MDA8 O_3 concentration (62.4 ppb), followed by Vietnam (41.7 ppb), Thailand (40.5 ppb), Cambodia (35.2 ppb), Laos (33.3 ppb), the Philippines (32.2 ppb), Myanmar (30.1 ppb), Malaysia (29.1 ppb), East Timor (28.8 ppb), Indonesia (26.5 ppb), and Brunei (20.3 ppb). ...”

Supplementary Figures xx-xx:

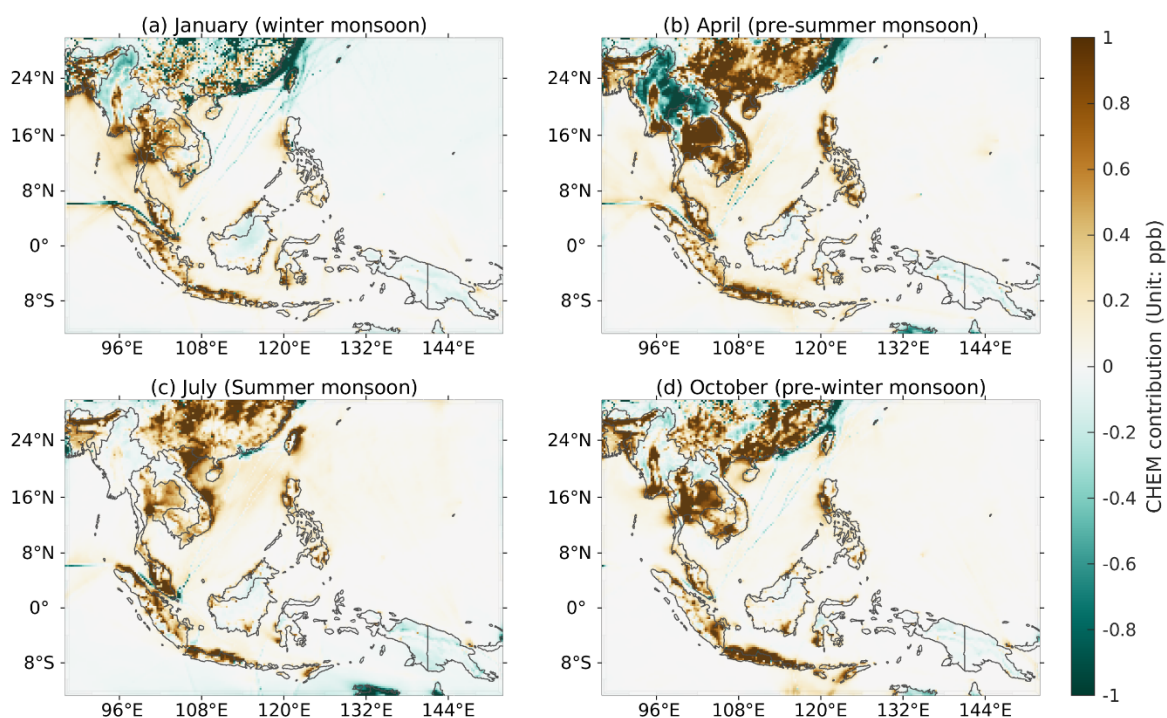


Fig. S22. Spatial distribution of gas-phase chemistry contribution to O_3 at surface level in Southeast Asia.

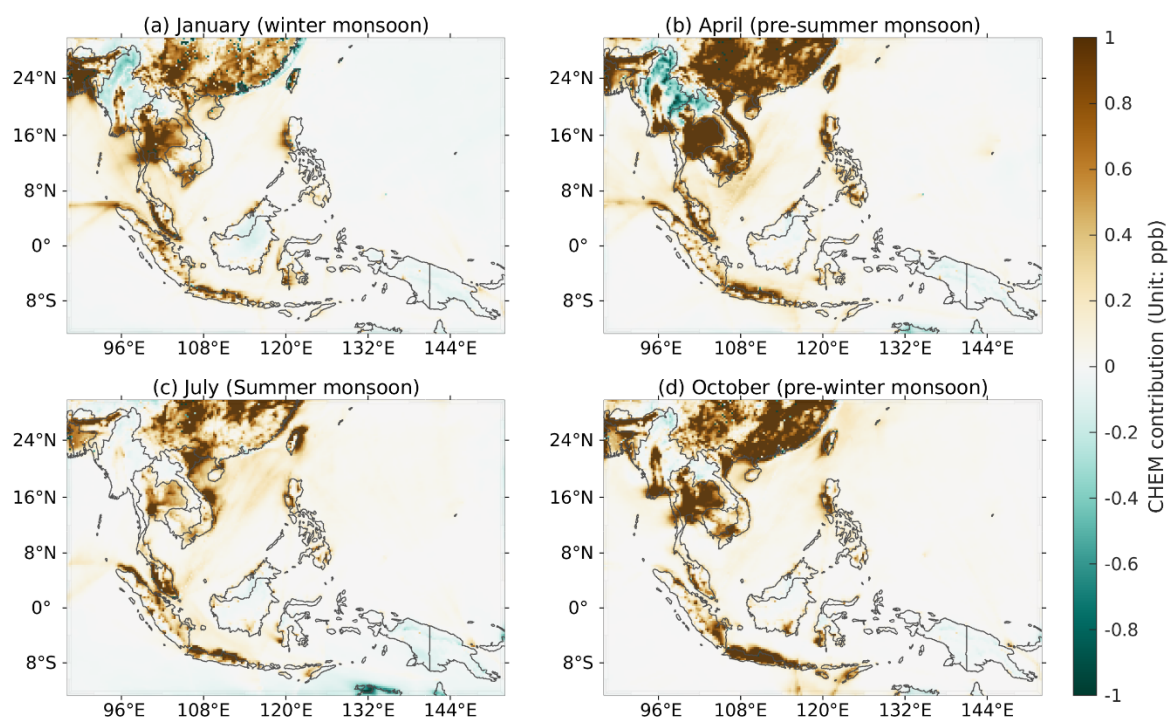


Fig. S23. Spatial distribution of gas-phase chemistry contribution to O_3 at 100 m height in Southeast Asia.

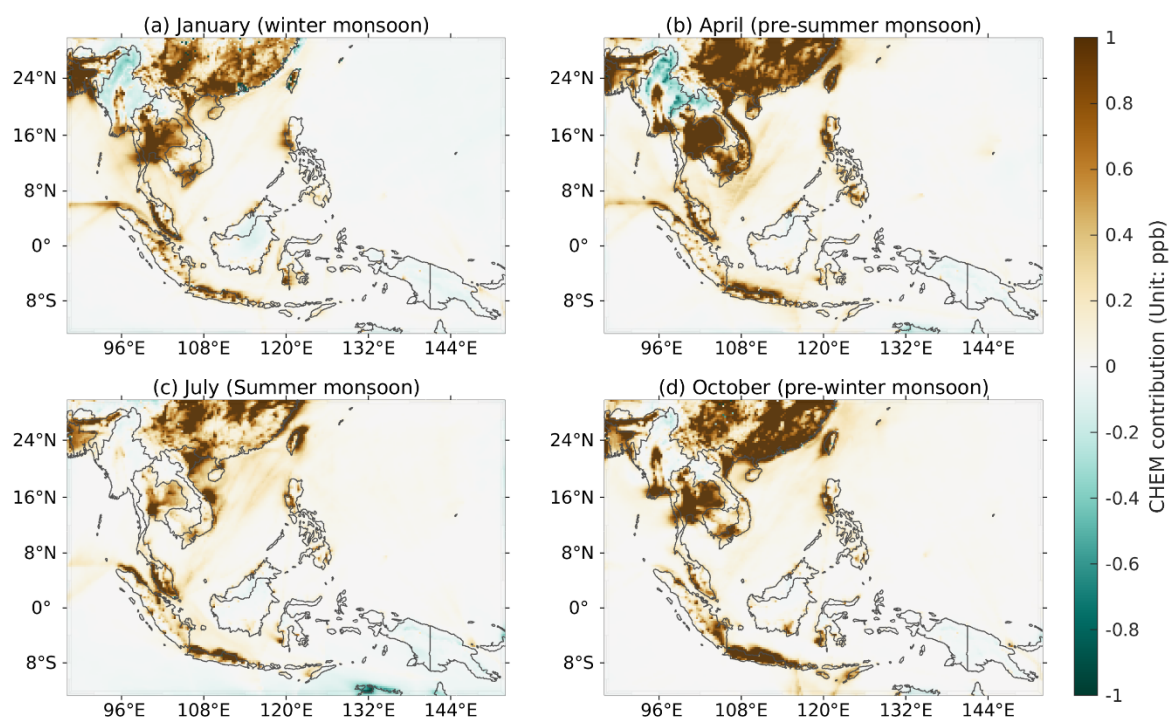


Fig. S24. Spatial distribution of gas-phase chemistry contribution to O_3 at 200 m height in Southeast Asia.

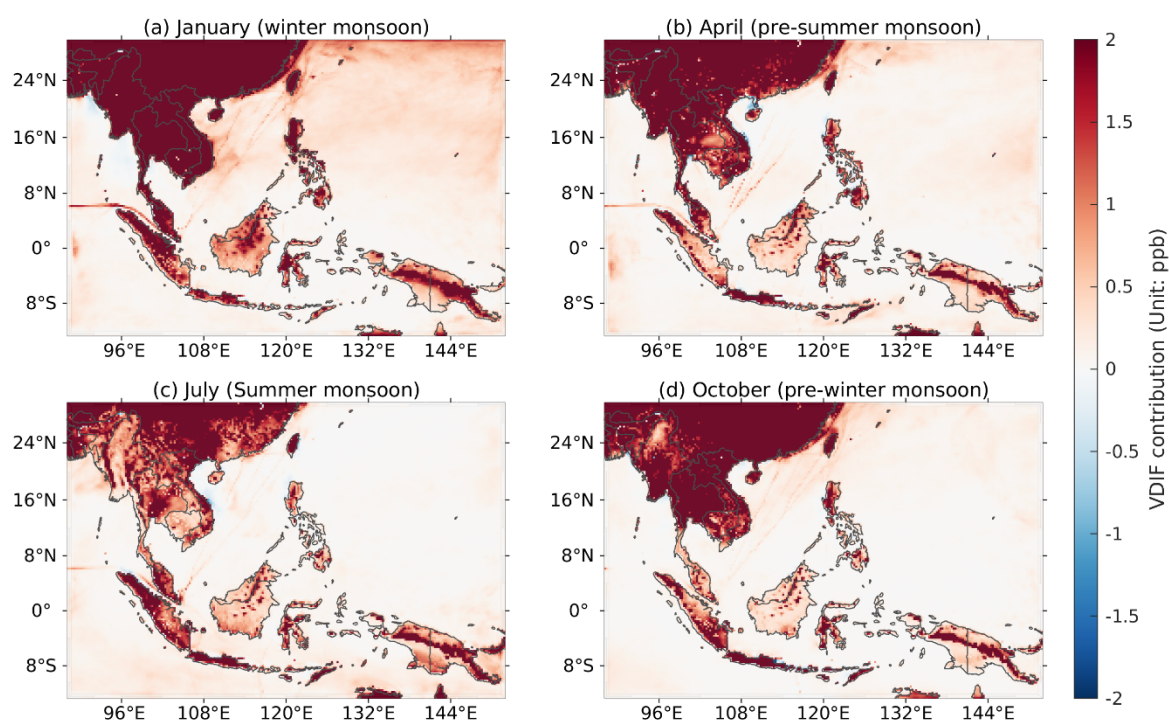


Fig. S25. Spatial distribution of vertical diffusion contribution to O_3 at surface level in Southeast Asia.

5. Please explain more in detail about the calculation of Integrated Process Rate (IPR) at the surface level. I am not very clear about its definition and the way to get this value in this study.

Response: Thanks for your important comment. The Integrated Process Rate (IPR) analysis is a diagnostic module in CMAQ that tracks the O₃ concentration change caused by each physical and chemical process during the model integration. For each model step, CMAQ calculated the accumulated O₃ concentration change associated with gas-phase chemistry (CHEM), cloud processes and aqueous chemistry (CLDS), dry deposition (DDEP), horizontal advection (HADV), horizontal diffusion (HDIF), vertical diffusion (VDIF), and vertical advection (ZADV) for each grid cell. Therefore, the IPR value does not represent the absolute O₃ concentration, but the contribution of each process to the change in O₃ concentration at each simulation step. Positive IPR value indicated that the corresponding process increased O₃ concentration, whereas a negative value indicated O₃ removal. For instance, as shown in Fig. 2, the gas-phase chemistry contributed negatively to the O₃ in Singapore, representing that O₃ titration at the surface level can generally reduce O₃ concentration in that area.

In this study, the surface-level IPR represents the process contributions in the first layer of the CMAQ model. For Fig. 2, the hourly IPR values were first averaged over all simulation days during the four representative monsoon periods and then spatially averaged over all model grids within each country. Therefore, each value represented the average hourly contribution of an individual atmospheric process to surface O₃ concentration in the corresponding country. The net O₃ process contribution, shown by the dotted line, was calculated as the sum of the seven process contributions. It should be noted that the IPR describes the O₃ change by different physical or chemical processes, but they do not identify the emission contributions. In this study, the IPR analysis was therefore used together with the CMAQ-adjoint model to provide a complementary assessment of the processes controlling O₃ formation, transport, and removal.

We have clarified the definition and calculation of the IPR values in the revised Method. The details can be found below:

Lines 134-144:

“...Process analysis in the CMAQ model is a diagnostic tool used to quantify the contributions of individual physical and chemical processes to changes in atmospheric O₃ concentration. This

study focused on the Integrated Process Rate (IPR) analysis. For each model simulation step, IPR recorded the accumulated change in O₃ concentration caused by gas-phase chemistry (CHEM), vertical diffusion (VDIF), horizontal diffusion (HDIF), horizontal advection (HADV), vertical advection (ZADV), cloud processes and aqueous chemistry (CLDS), and dry deposition (DDEP) for each grid cell. Positive IPR values indicated increases in O₃ concentration caused by the corresponding process, whereas negative values indicated O₃ removal. The surface-level IPR represented the process contributions in the first layer of the CMAQ model. The hourly values were averaged over the simulation periods and then spatially averaged over all model grids within each country. The net O₃ contribution was calculated as the sum of all physical and chemical processes. In this study, the IPR analysis quantified the physical and chemical processes controlling O₃ changes and was complementary to the CMAQ-adjoint analysis, which identified the contributions of precursor emission sources...”

6. In Figure 3 and 4, ozone sensitivity to NO_x and VOC is higher in the East of land area (It is very clear for the Philippines). Why does this happen? Is it because polluted plume is moving from land to ocean? If yes, I do not understand why polluted plume is moving to the east (seems affected by the westerly), because the tropical region (zero to ~30 northern latitude) is usually affected by the 'trade wind', which is generally northern easterly. If monsoon effect is stronger, then the wind pattern can be different from typical trade wind pattern. Could you explain more about this question?

Response: Thanks for your important comment. We agree that relatively high O₃ sensitivities were found to the east of several land regions in Figs. 3 and 4, particularly around the Philippines. However, we would like to clarify that the spatial distribution of adjoint sensitivity does not necessarily represent the movement of a polluted plume from land to ocean. Unlike forward sensitivity methods such as HDDM, which evaluate how changes in predefined emissions affect the O₃ concentration (Fang et al., 2025), the receptor-oriented adjoint model calculates the sensitivity of O₃ in a predefined receptor region to precursor emissions from each grid cell. The sensitivity at a given grid cell represents the response of O₃ in the receptor region to changes in precursor emissions from that grid cell. In this study, the receptor regions were defined as the total land areas of Southeast Asia and the 11 individual Southeast Asian countries. Therefore, high sensitivities over the ocean indicated that emissions from these marine or

coastal regions could be efficiently transported to the receptor regions and increase the O₃ concentration.

The wind patterns over Southeast Asia were strongly influenced by the seasonal monsoon circulation. During the winter monsoon, northeasterly winds prevailed over the Philippines (Fig. S9) and transported air masses from the South China Sea and western Pacific regions toward the Philippines. Therefore, the relatively high sensitivities in the eastern area of the Philippines indicated that emissions from these upwind marine regions could influence O₃ over the Philippines (Figs. 3 and 4). In contrast, during the summer monsoon, southwesterly winds transported air masses from the Indian Ocean toward the northeast and east (Fig. S9), and the enhanced sensitivities over the marine regions around Myanmar could reflect the influence of the emissions from those marine regions on O₃ in Southeast Asia (Figs. 3 and 4). We also calculated the relationships between adjoint sensitivities and wind directions. As mentioned in Section 3.3, approximately 73.6% of high-sensitivity grid cells were in the upwind regions relative to Southeast Asia (Fig. S34), indicating that the monsoon winds carried the pollution from the upwind areas to Southeast Asia and increased the regional O₃ concentration.

Therefore, the higher sensitivities in the east of the land regions were not caused by a persistent eastward movement of polluted plumes. Instead, they reflected the transport of pollutants from those higher-sensitivity areas toward Southeast Asian countries by the monsoon circulation.

Reference:

Fang, T., Hu, J., Gu, Y., Sung, J. J., & Yim, S. H. L. (2025). Response of ozone to current and future emission scenarios and the resultant human health impact in Southeast Asia. *Environment International*, 197, 109333.

We have clarified this interpretation in the Results section in the revised manuscript, and the details can be found below:

Lines 274-283:

“...The sensitivities around coastal and marine regions also exhibited clear seasonal variations that were closely associated with the regional monsoon circulation (Fig. S9a), indicating that

emissions from those areas could be efficiently transported to Southeast Asia and contribute to regional O₃ concentration during various monsoon circulations. For instance, during the winter monsoon, northeasterly winds transported air masses from the South China Sea and western Pacific toward the Philippines, resulting in relatively higher sensitivities over the eastern marine regions. During the summer monsoon, southwesterly winds transported air masses from the Indian Ocean toward Southeast Asia, leading to enhanced sensitivities over the upwind oceanic regions around Myanmar. The spatial distribution of O₃ sensitivity closely followed the prevailing wind directions, with approximately 73.6% of high-sensitivity grid cells located in climatological upwind regions relative to Southeast Asia (Fig. S34) ...”

7. Please include the axis name in Figure S7.

Response: Thanks for your important comment. We added the corresponding axis names and units to Fig. S7 in the revised Supplemental information to improve the clarity of the figure. Details can be found below:

Supplementary Figure:

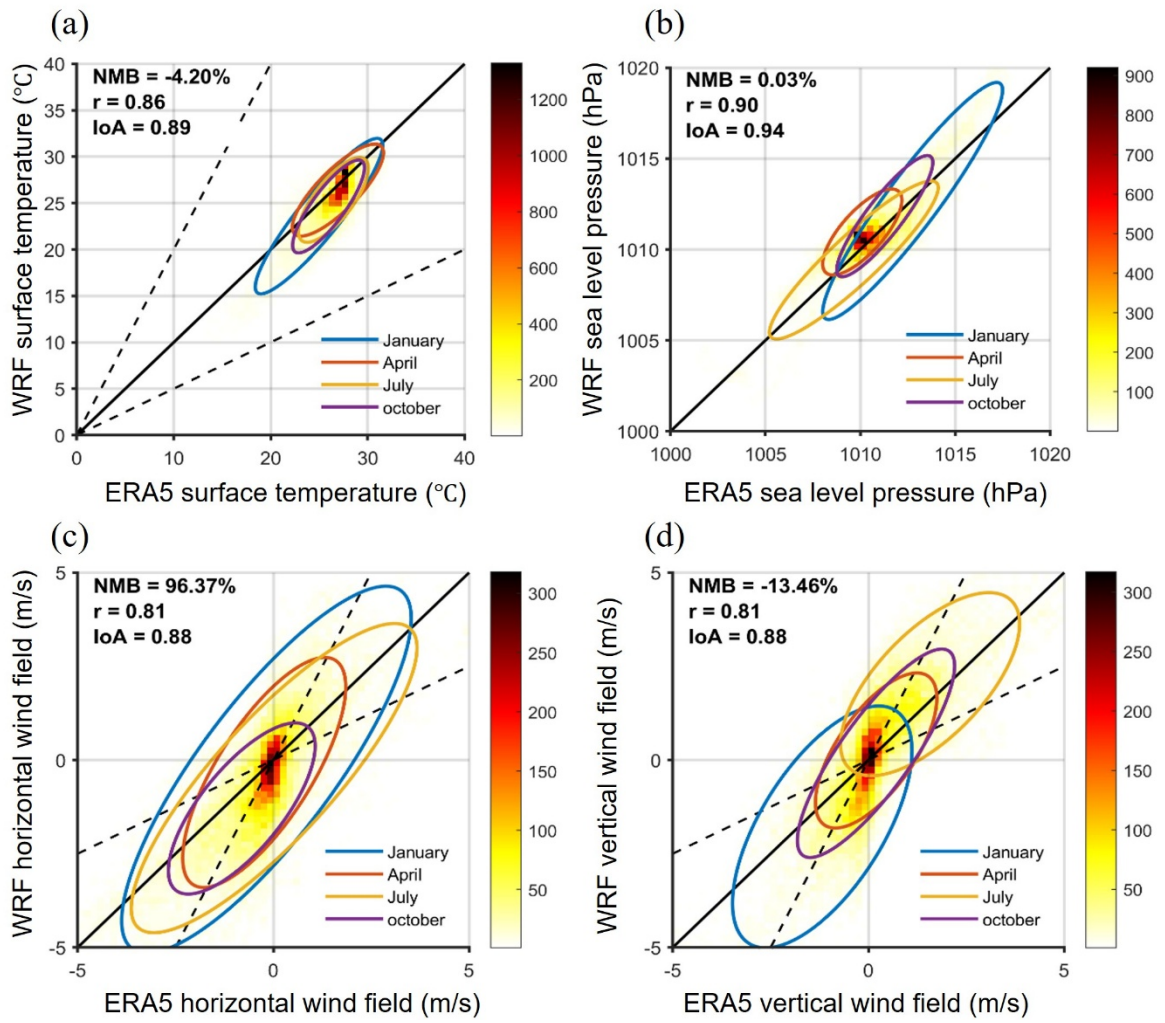


Fig. S7. Comparison between WRF simulation and the ERA5 reanalysis data for (a) surface temperature, (b) sea level pressure, (c) wind field horizontal direction, and (d) wind field vertical direction.

Reviewer #2:

This work evaluated the sensitivity of ambient O₃ to VOCs and NO_x and different sources in Southeast Asia. The manuscript is well-prepared and contributes to the field. Some suggestions are as follows:

1. Regarding the emission inventories, what are their target year and spatial resolution? Please provide the details. Are they consistent with the modelling year 2019?

Response: We thank the referee for the important comment. In our CMAQ simulation, the target year of the emission inventories was consistent with the modelling year of 2019. Anthropogenic emissions were obtained from the Copernicus Atmosphere Monitoring Service (CAMS) global emission inventory with the original spatial resolution of $0.1^\circ \times 0.1^\circ$. The CAMS emissions were mainly based on EDGAR v5.0 annual emissions, with sector- and country-specific temporal trends applied to extend the emissions to 2019. Monthly temporal profiles from CAMS-GLOB-TEMPO were further applied to represent the seasonal variations in anthropogenic emissions. In addition, biogenic VOC emissions were calculated using MEGAN v2.1 based on the 2019 meteorological conditions simulated by WRF and the corresponding land-cover and vegetation coverage. Therefore, the biogenic emissions were also consistent with the 2019 modelling year. The anthropogenic and biogenic emissions were spatially regridded to the $30 \text{ km} \times 30 \text{ km}$ and temporally allocated to hourly emissions, which were consistent with the spatial and temporal resolutions of the CMAQ model.

In the revised manuscript, we clarified the target year, original spatial resolution, and regridding of the anthropogenic and biogenic emission inventories. The details can be found below:

Lines 104-116:

“...To ensure model stability and produce reliable estimates, a two-day spin-up period (Czader et al., 2013; Zhang et al., 2014) was implemented for each monsoon season in our simulation.

Anthropogenic emissions over Southeast Asia were based primarily on the 2019 Copernicus Atmosphere Monitoring Service (CAMS) global emission inventory at the original spatial resolution of $0.1^\circ \times 0.1^\circ$. The inventory was mainly based on EDGAR v5.0 annual emissions, while sector- and country-specific temporal trends from the Community Emissions Data System (CEDS) v2.0 were applied to extend the emissions to 2019. Monthly temporal profiles

from CAMS-GLOB-TEMPO were further applied to represent the monthly temporal variations in anthropogenic emissions. Emissions were processed for nine source sectors, including transportation, shipping, industrial processes, residential, biomass burning, power generation, refineries, solvent and fugitive sources, and agriculture (Granier et al., 2019). Biogenic VOC emissions were estimated using MEGAN v2.1 based on the 2019 WRF meteorological conditions and the corresponding land-cover and vegetation information (Guenther et al., 2012). All emission data were spatially regridded to the 30 km × 30 km CMAQ domain and temporally allocated to hourly emissions. Therefore, both anthropogenic and biogenic emissions were consistent with the modeling year of 2019...”

2. Please mark the observations of monitoring stations in the maps for comparison.

Response: Thanks for your suggestion. In the revised manuscript, we added the monitoring observations to the maps for direct comparison with the simulation results. We further included additional ground-based monitoring stations from Singapore, Malaysia, Thailand, and the OpenAQ dataset to improve the model evaluation. Together with the previous observation records from the EANET and AQI datasets, 67 stations were used in total, covering seven countries in Southeast Asia. The revised maps are presented in Fig. S11.

The details can be found below:

Lines 187-193:

“...The spatial distribution of simulated ground-level O₃ was evaluated using observations from 67 stations across Southeast Asia. As shown in Fig. S10, most MDA8 O₃ simulations aligned within ±50% of the observations. The overall correlation (r) between the observed and simulated MDA8 O₃ across the four months was 0.68, exceeding the benchmark criterion of r > 0.5 (Yang & Zhao, 2023). The NMB, RMSE, and IoA were 13.26%, 10.60, and 0.78, respectively. The locations and observed O₃ concentration of the monitoring stations are shown in Fig. S11. Station-level evaluation results are presented in Table S3, while detailed information on each station is provided in Table S4, underscoring the reliability of the O₃ simulation in capturing the spatial variations across the region...”

Supplementary Figures:

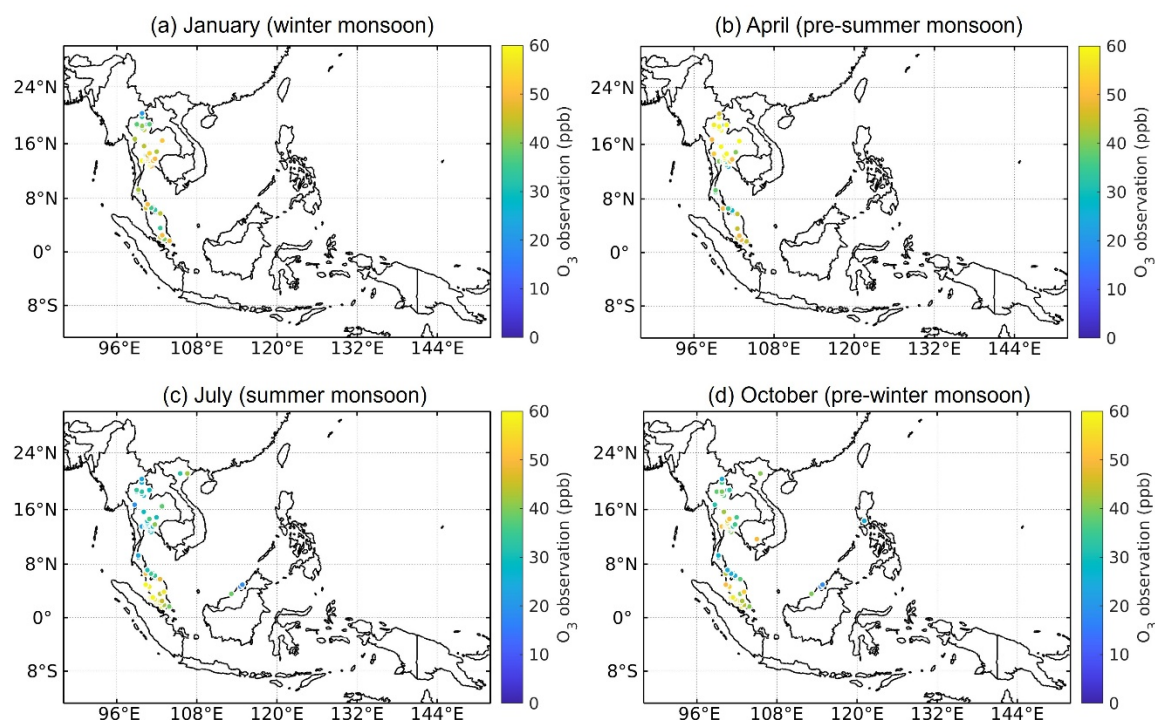


Fig. S11. MDA8 O₃ observations of 67 ground stations in the four months in Southeast Asia.

3. Figs 3 and 4, is it better to use one single scale bar for the four plots thus the comparisons among the four months would be clearer?

Response: Thanks for your suggestion. We agree that using a single scale bar would be better to compare the sensitivities of the four months. Therefore, we have revised Figs. 3 and 4 by applying a consistent color bar for the four monthly sensitivities.

The details can be found below:

Figures 3 and 4:

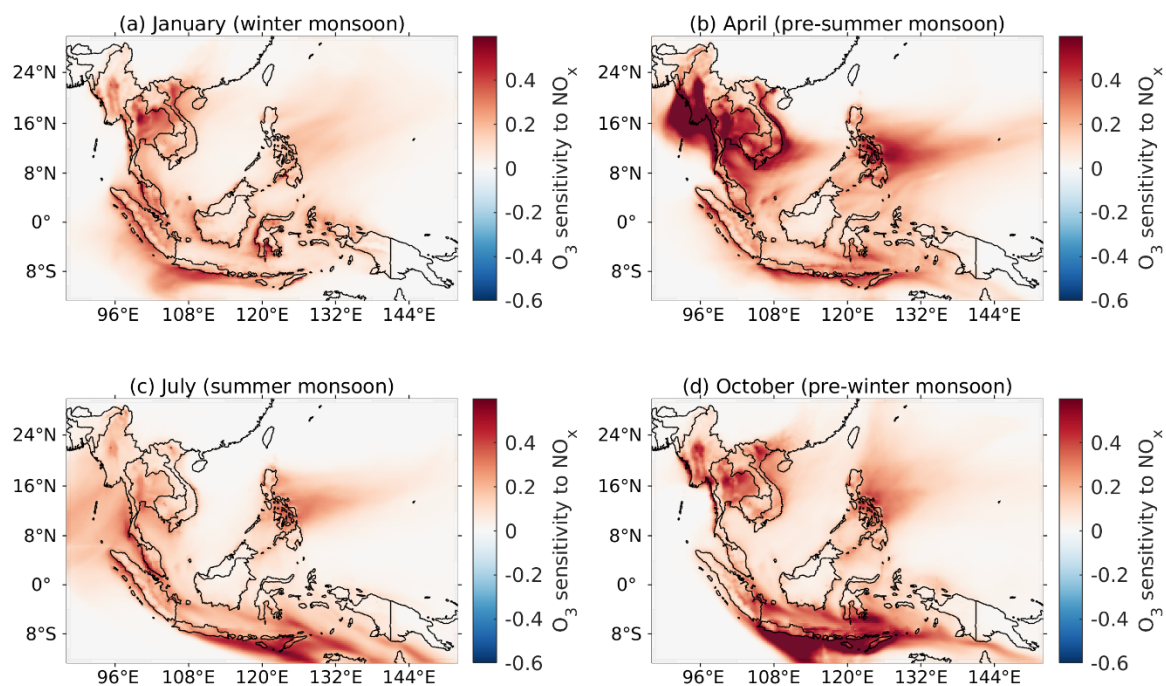


Figure 3: Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to NO_x emissions during the four monsoon seasons. Among them, the red color depicts positive sensitivity, while the blue color represents negative sensitivity. Unit: ppb/mol^{-s} .

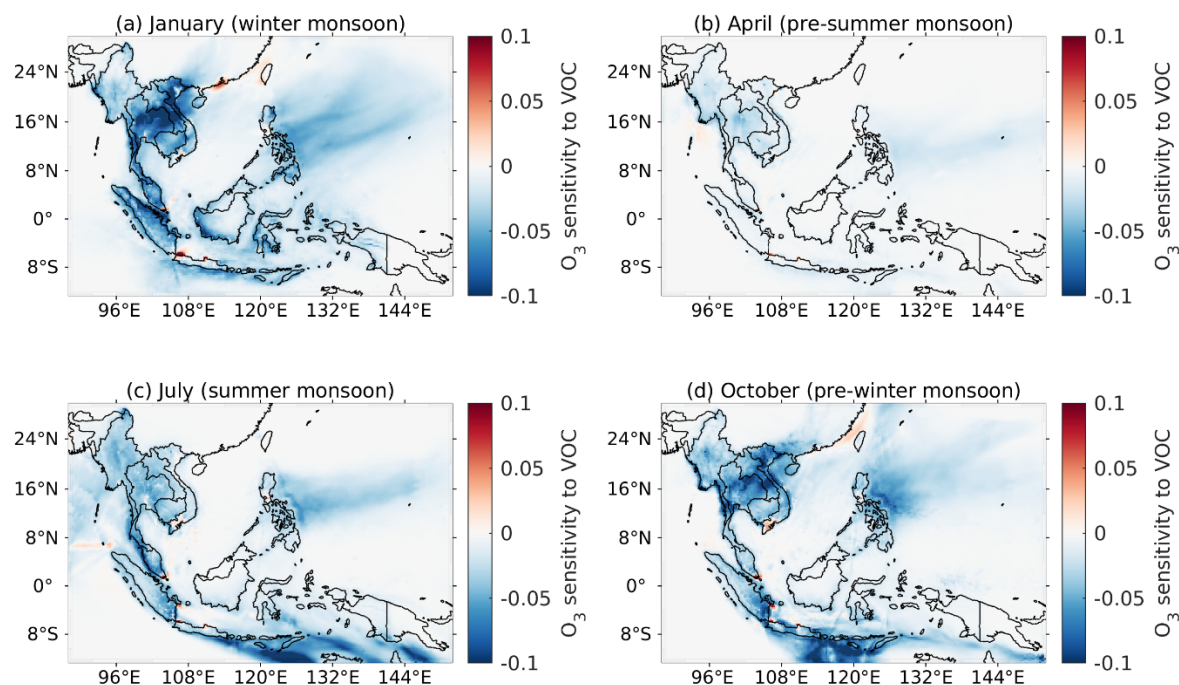


Figure 4: Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to VOC emissions during the four monsoon seasons. Among them, the red color depicts positive sensitivity, while the blue color represents negative sensitivity. Unit: ppb/mol^{-s} .

4. Discussion and conclusions. For ACP, please prepare a separate Conclusions section.

Response: Thanks for your valuable suggestion. In the revised manuscript, we separated the original “Discussion and conclusions” section into a Discussions section and a new Conclusions section. The Conclusions section summarized the major findings of the manuscript and their implications for O₃ mitigation in Southeast Asia. The details can be found below:

Lines 509-519:

“In this study, we applied the CMAQ-adjoint model with process analysis to investigate the sensitivity of surface O₃ to precursor emissions and quantify source contributions across Southeast Asia. The results showed that O₃ formation was predominantly NO_x-limited over most of the region, whereas VOC-limited or transitional regimes mainly occurred in highly urbanized and industrialized areas. Accordingly, O₃ generally showed positive sensitivities to NO_x emissions, while the responses to VOC emissions were broadly negative except urban regions. The process analysis further identified vertical diffusion, gas-phase chemistry, and horizontal advection as the major processes contributing to the surface O₃. In addition, regional and super-regional sources contributed substantially to O₃ across Southeast Asian countries. The findings suggested that effective control of O₃ in Southeast Asia requires coordinated regional NO_x reductions in the widespread NO_x-limited regions, while joint controls of VOC and NO_x emissions should be considered in VOC-limited urban areas. The strong transboundary influence also highlighted the urgent need for regional and international cooperation in controlling precursor emissions from major anthropogenic sectors such as transportation, industry and international shipping.”

5. The sensitivity of O₃ to VOCs. Can the results of major VOC species (Benzene, Isoprene etc.) be presented? Then the results would be more meaningful.

Response: We thank the referee for the valuable comment. To provide more detailed information about the sensitivity of O₃ to VOC species, we have added the O₃ sensitivity results to major VOC species in the four monsoon seasons, including isoprene, terpene, toluene, xylene, benzene and paraffinic carbon-bond lumped species (PAR). As shown in Figs. S35-S40, the O₃ sensitivities differed among VOC species, reflecting different oxidation and radical-propagation pathways. For instance, PAR was mainly from anthropogenic sources like transportation and industry, which generally showed positive sensitivities over urban regions and major shipping routes, due to the oxidation-related RO₂ radicals that promoted NO to NO₂ conversion. Negative PAR sensitivities over remote marine regions were associated with relatively lower

NO and enhanced radical termination, such as conversion from HO_2 to H_2O_2 . Isoprene mainly came from biogenic sources, and showed positive sensitivities mainly over urban centers and coastal areas, reflecting efficient reactions between isoprene-derived RO_2 radicals and anthropogenic NO_x . In contrast, terpene and aromatic species (i.e., toluene, xylene, and benzene) generally showed negative sensitivities, which could be related to terpene ozonolysis, OH consumption by aromatic species, and radical termination under low NO_x environment.

We have modified the manuscript to show the sensitivity of O_3 to major VOC species. The details can be found below:

Lines 307-320:

“...In contrast, regions characterized by VOC-limited chemical regimes (Fig. S26) exhibited positive sensitivities to VOC emissions, including coastal regions of China, the Malacca Strait, and major urban areas such as Bangkok, Singapore, Hanoi, and Jakarta. In these environments, O_3 formation was more determined by VOC availability, and VOC emissions enhanced photochemical O_3 production. The sensitivities of O_3 to the major VOC species were shown in Figs. S35-S40, including isoprene, terpene, toluene, xylene, benzene and paraffinic carbon-bond lumped species (PAR). The sensitivities differed among individual VOC species. For instance, PAR was mainly from anthropogenic sources like transportation and industry, which generally showed positive sensitivities over urban regions and major shipping routes, while negative sensitivities occurred over remote marine regions with relatively low NO levels. Isoprene mainly came from biogenic sources and presented positive sensitivities mainly over urban and coastal regions, due to the efficient reactions between isoprene-derived RO_2 radicals and anthropogenic NO emissions. In contrast, terpene and aromatic species (i.e., toluene, xylene, and benzene) generally showed negative sensitivities, suggesting that O_3 formation can be reduced by terpene ozonolysis, aromatic species related OH consumption, and radical termination under low NO_x environment. Overall, the magnitudes of O_3 sensitivity to VOC emissions (Fig. 4) were generally smaller than the sensitivity to NO_x emissions (Fig. 3), which is consistent with the widespread dominance of NO_x -limited regimes across Southeast Asia (Fig. S26) ...”

Supplementary Figures:

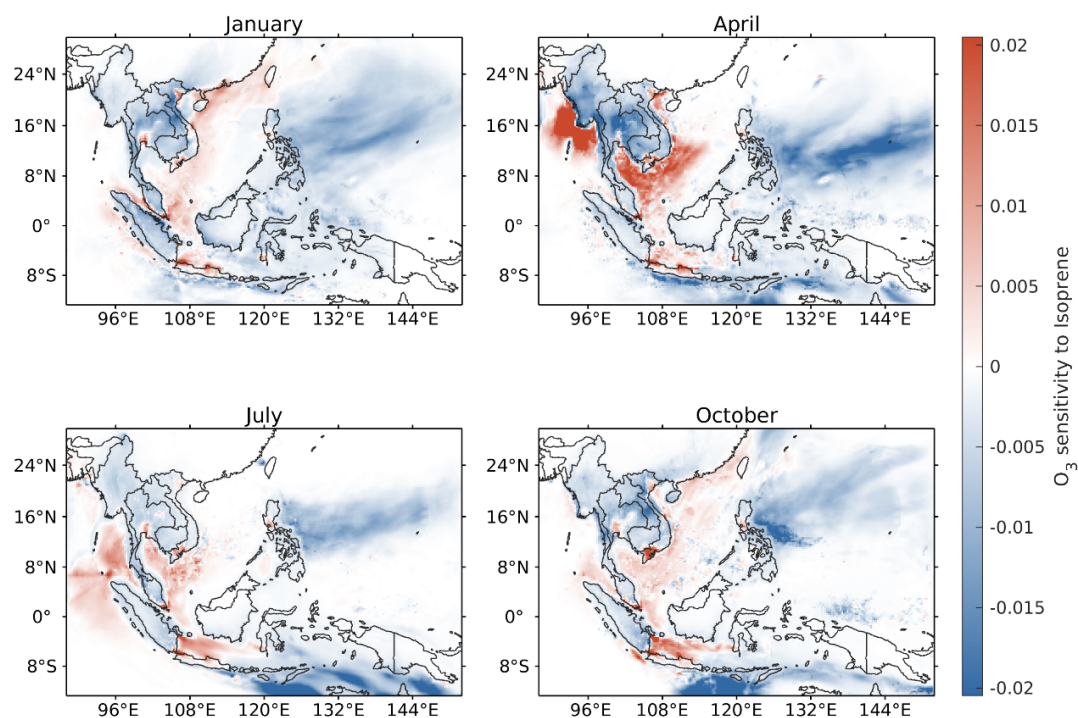


Fig. S35. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to isoprene emissions during the four monsoon seasons.

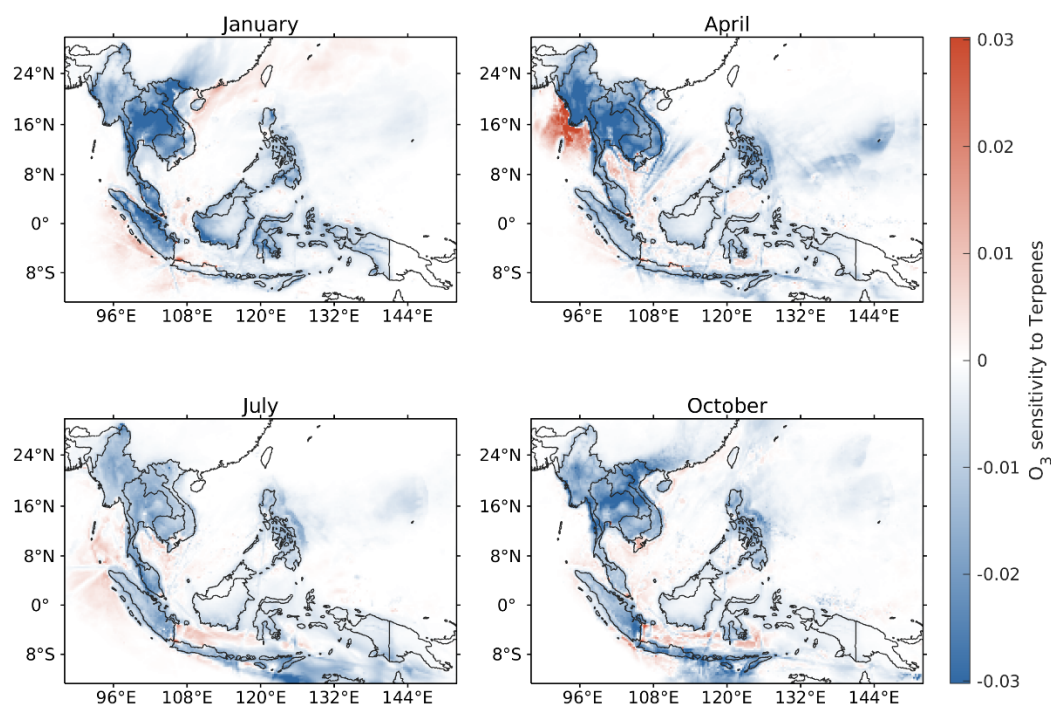


Fig. S36. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to terpene emissions during the four monsoon seasons.

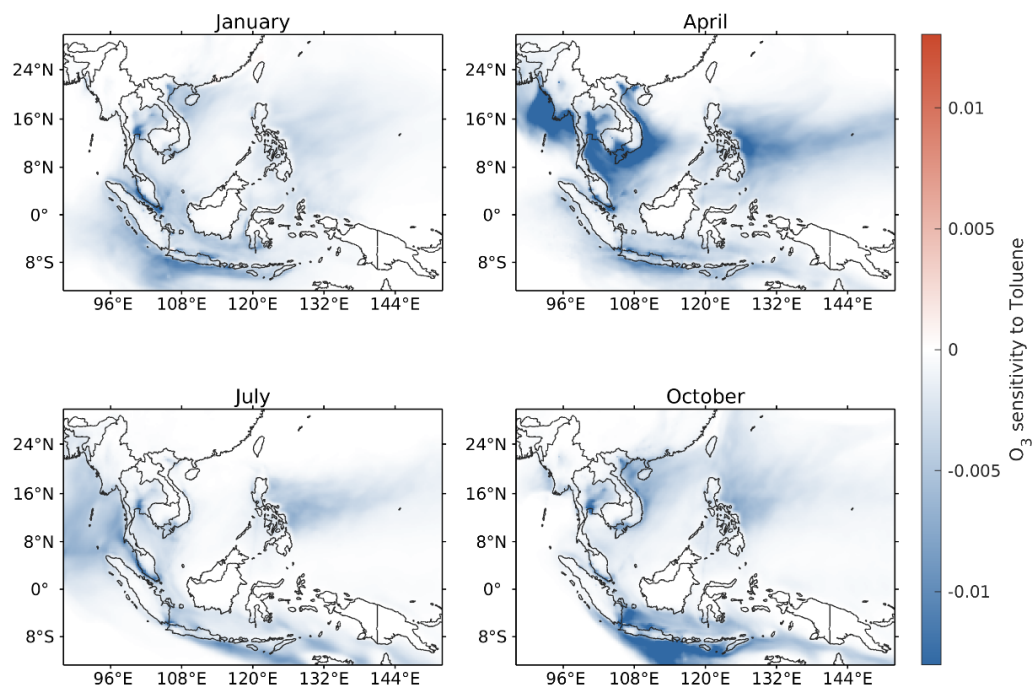


Fig. S37. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to toluene emissions during the four monsoon seasons.

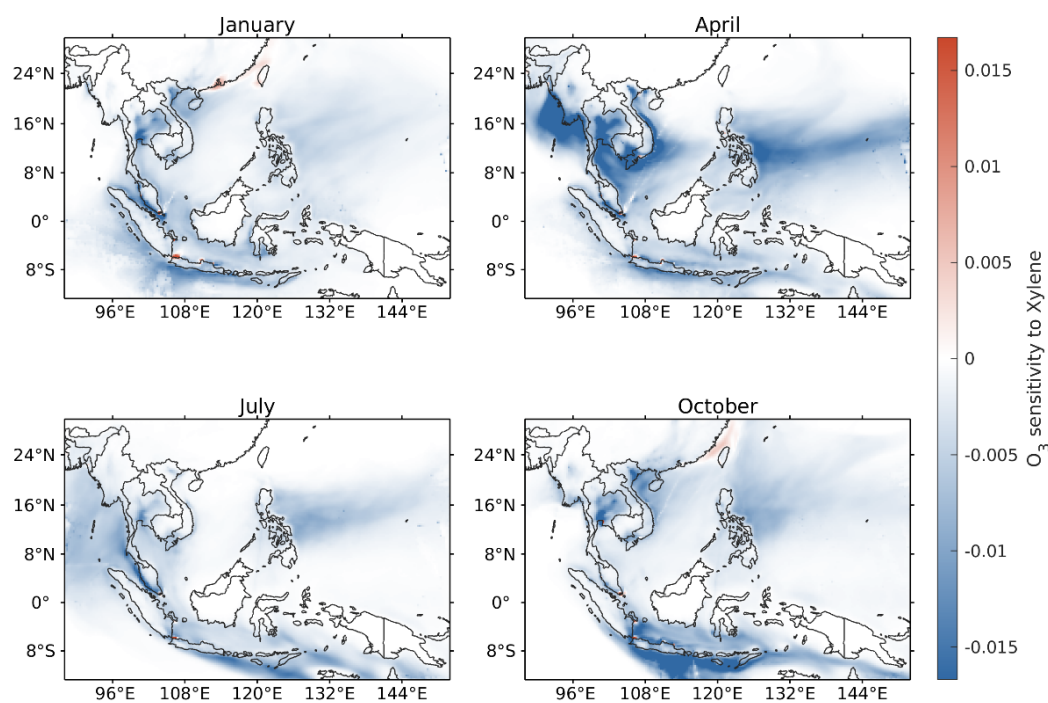


Fig. S38. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to xylene emissions during the four monsoon seasons.

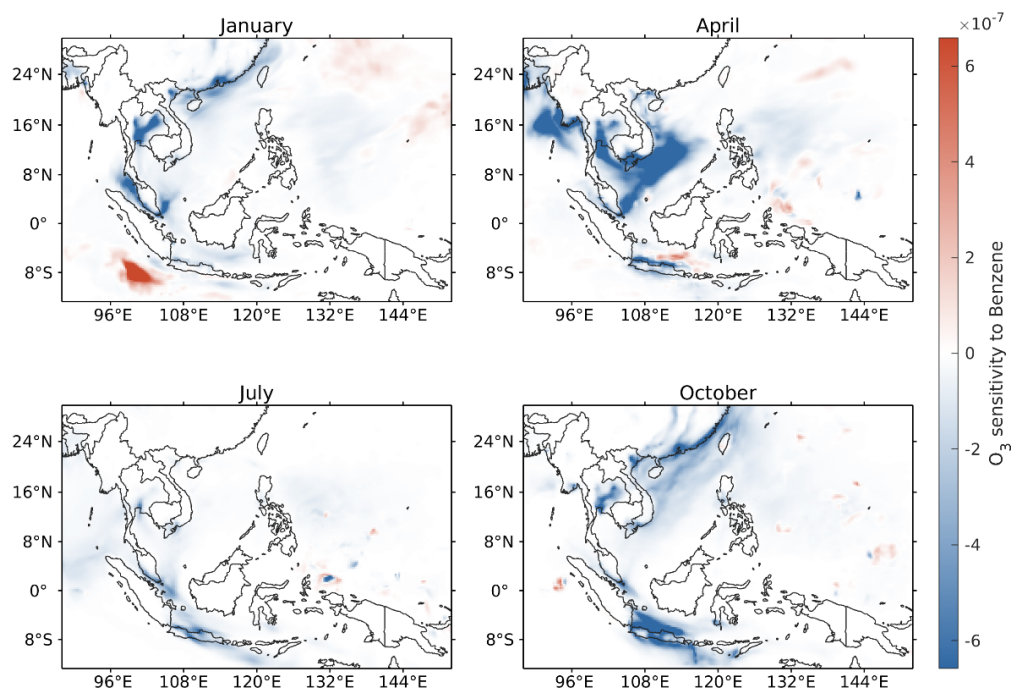


Fig. S39. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to benzene emissions during the four monsoon seasons.

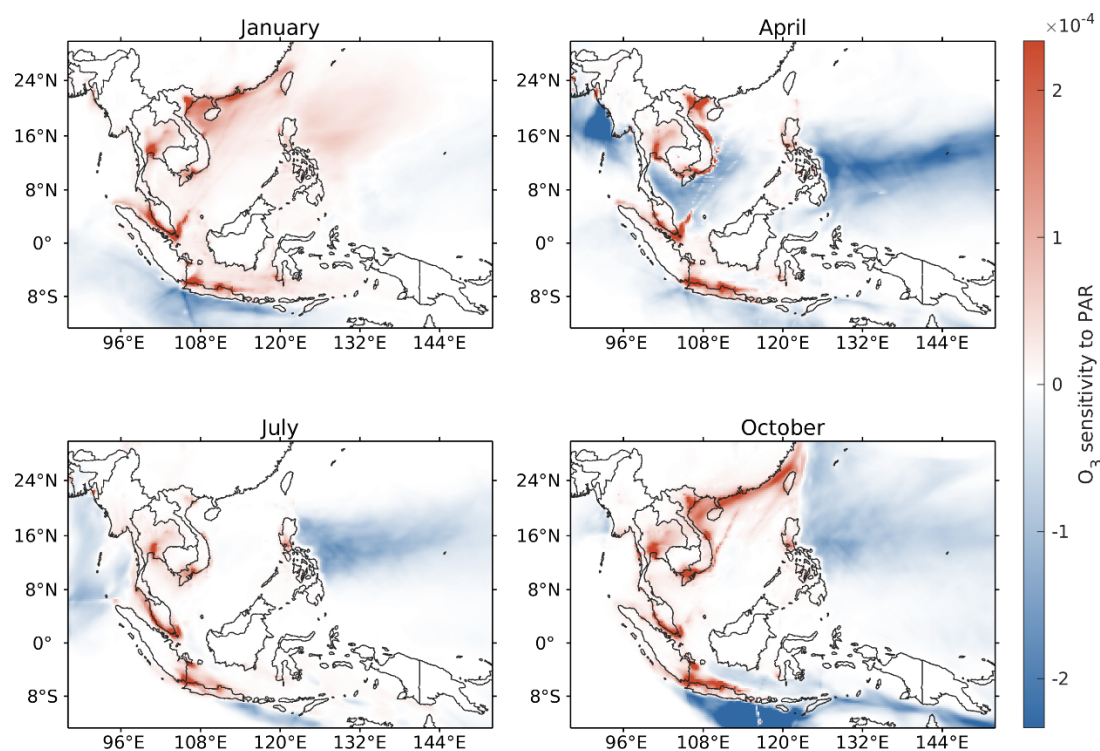


Fig. S40. Spatial distribution of the monthly mean sensitivity of O_3 in Southeast Asia to paraffinic carbon-bond lumped species (PAR) during the four monsoon seasons.

6. Please add the diurnal variability of source contributions, NO_x and VOCs sensitivity to O₃ in the different countries.

Response: We thank the referee for the valuable suggestion. We have added the diurnal variations in the O₃ sensitivities to NO_x and VOC emissions, as well as the source contributions, for each Southeast Asian country in the revised manuscript.

The NO_x sensitivities were calculated by averaging the grid-level sensitivities for each receptor country in Southeast Asia, showing significant diurnal variations (Fig. S52). Positive sensitivities generally increased from the early morning and reached the highest level between approximately 09:00 and 13:00 local time, reflecting enhanced photochemical O₃ production during the daytime. The minimum sensitivity occurred at around 19:00-21:00, indicating reduced O₃ production efficiency and enhanced O₃ titration. We also showed the sensitivities of VOC species in the four monsoon seasons. Unlike NO_x emissions, VOC sensitivity presented the larger spatial variations, therefore, we presented the spatial distribution of O₃ sensitivity to VOCs at 06:00, 12:00, 18:00, and 24:00 to reflect the diurnal variability in different Southeast Asian countries. As shown in Figs. S53-S63, relatively higher sensitivities occurred during the early morning (06:00) and nighttime (24:00) due to lower biogenic VOC emissions and weak OH and HO₂ radical production, particularly over urban and coastal regions with substantial NO_x emissions accumulated near the surface due to the shallow boundary layer. In contrast, negative sensitivities became more widespread during the daytime (12:00 and 18:00), and increased daytime biogenic VOC emissions resulted in more strongly NO_x-limited O₃ formation regimes and enhanced ozonolysis and radical termination, especially in rural Southeast Asia. Therefore, daytime VOC sensitivities were generally lower than the nighttime sensitivities in Southeast Asia.

We further added the diurnal variations in local, regional, and super-regional O₃ contributions for each Southeast Asian country. As shown in Fig. S68, local contributions showed enhanced positive contributions during the daytime in most Southeast Asian countries, and negative contributions during the nighttime, particularly in Singapore, due to the enhanced NO titration and weakened photochemical O₃ production. Nevertheless, the local and regional contributions remained positive during most nighttime hours in many countries, representing the net positive influence of nighttime emissions on the annual-average O₃ levels. Regional contributions were

relatively important in the afternoon and at night, reflecting the increased atmospheric transport. Super-regional contributions showed relatively weaker diurnal variations and remained high throughout the day, particularly in the Philippines, Myanmar, and East Timor. The results indicated substantial temporal variations of local, regional, and super-regional influences among Southeast Asian countries.

We have modified the manuscript to show diurnal variations of NO_x and VOC sensitivities and source contributions. The details can be found below:

Lines 326-337:

“...The negative sensitivities indicated that increasing NO_x emissions reduced net O₃ production, primarily because elevated NO concentration enhanced O₃ titration. The NO_x sensitivity showed diurnal variations across Southeast Asian countries (Fig. S52). Positive sensitivities generally increased from the early morning, reached the highest level between approximately 09:00 and 13:00 local time, and decreased rapidly in the late afternoon. The minimum sensitivities occurred around 19:00-21:00, reflecting reduced photochemical O₃ production and enhanced O₃ titration. In contrast, the sensitivities to VOC emissions exhibited positive values in the urban areas, indicating that VOC emissions in those urban regions contributed positively to O₃ concentration in the corresponding receptor countries. The VOC sensitivities showed large spatial variations among different species and regions (Figs. S53-S63). Higher sensitivities were generally evident at 06:00 and 24:00, whereas sensitivities became lower at 12:00 and 18:00. Since VOCs were dominated by biogenic emission sources, increased daytime biogenic VOC emissions and higher OH and HO₂ radicals resulted in more NO_x-limited O₃ formation regimes and enhanced O₃ consumption through ozonolysis and increased radical termination in rural areas, leading to the lower sensitivities during the daytime...”

Lines 383-392:

“.... The boundary contribution ranged from 0.37 ppb in Brunei to 14.7 ppb in East Timor, while transported super-regional emissions contributed between 3.5 ppb in East Timor and 10.9 ppb in the Philippines (Table S9), highlighting the substantial influence of super-regional sources on concentration and associated public health impacts in Southeast Asia. The diurnal distribution of source contributions reflected increased local contributions during the daytime

in most countries, while negative evening contributions occurred in Singapore, due to the enhanced NO titration and weakened photochemical O₃ production (Fig. S68). Nevertheless, local contributions remained positive during most nighttime hours, indicating the net positive influence of nighttime emissions on annual-mean O₃. Regional contributions became relatively more important in the afternoon and at night in several countries, reflecting the increased regional transport. Super-regional contributions showed weaker diurnal variations and remained high throughout the day, particularly in the Philippines, Myanmar, and East Timor...”

Supplementary Figures:

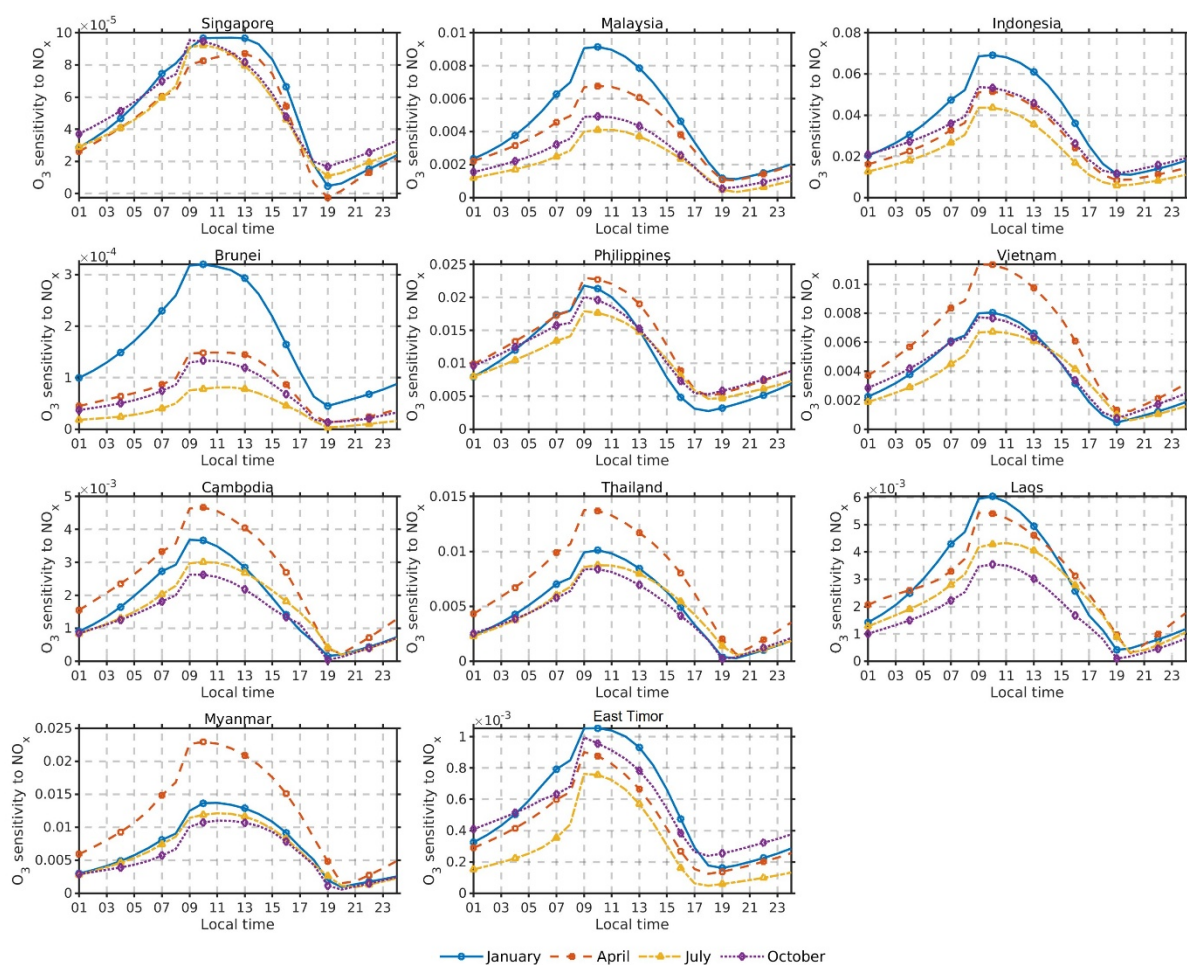


Fig. S52. Diurnal variability of the sensitivity O_3 to NO_x emissions in various countries in Southeast Asia.

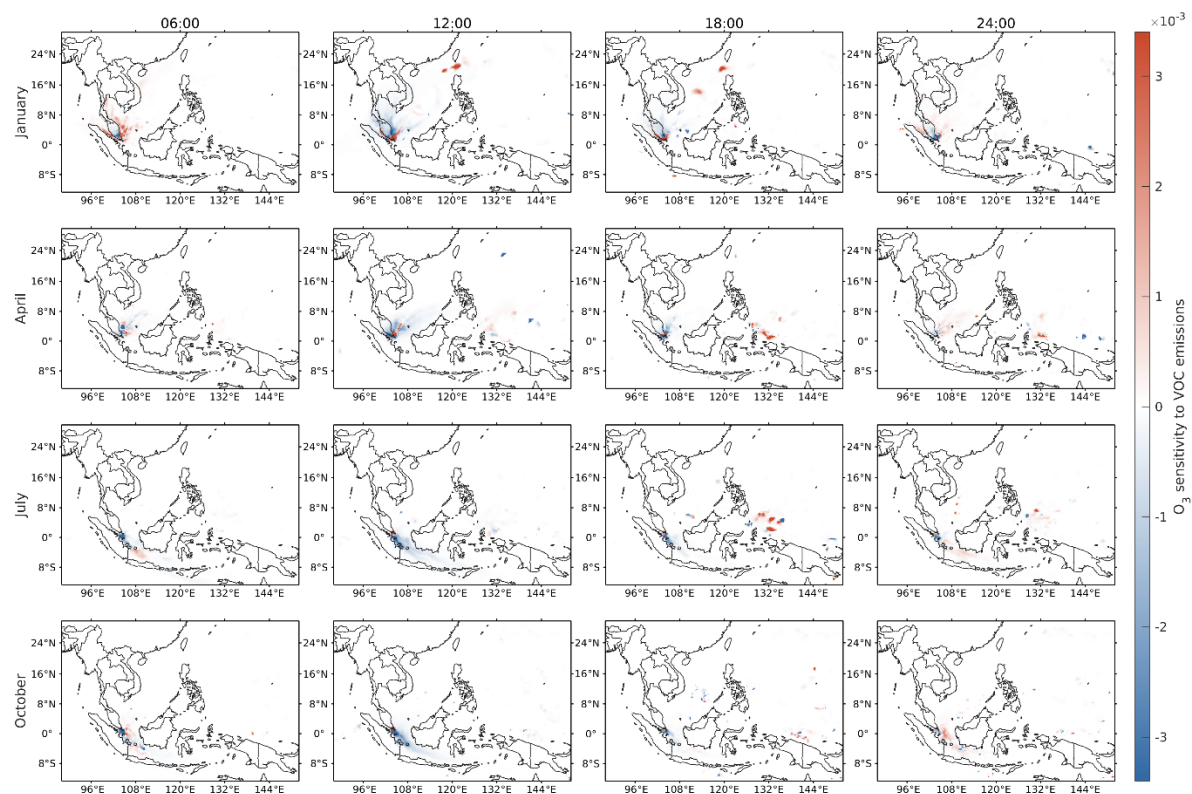


Fig. S53. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Singapore.

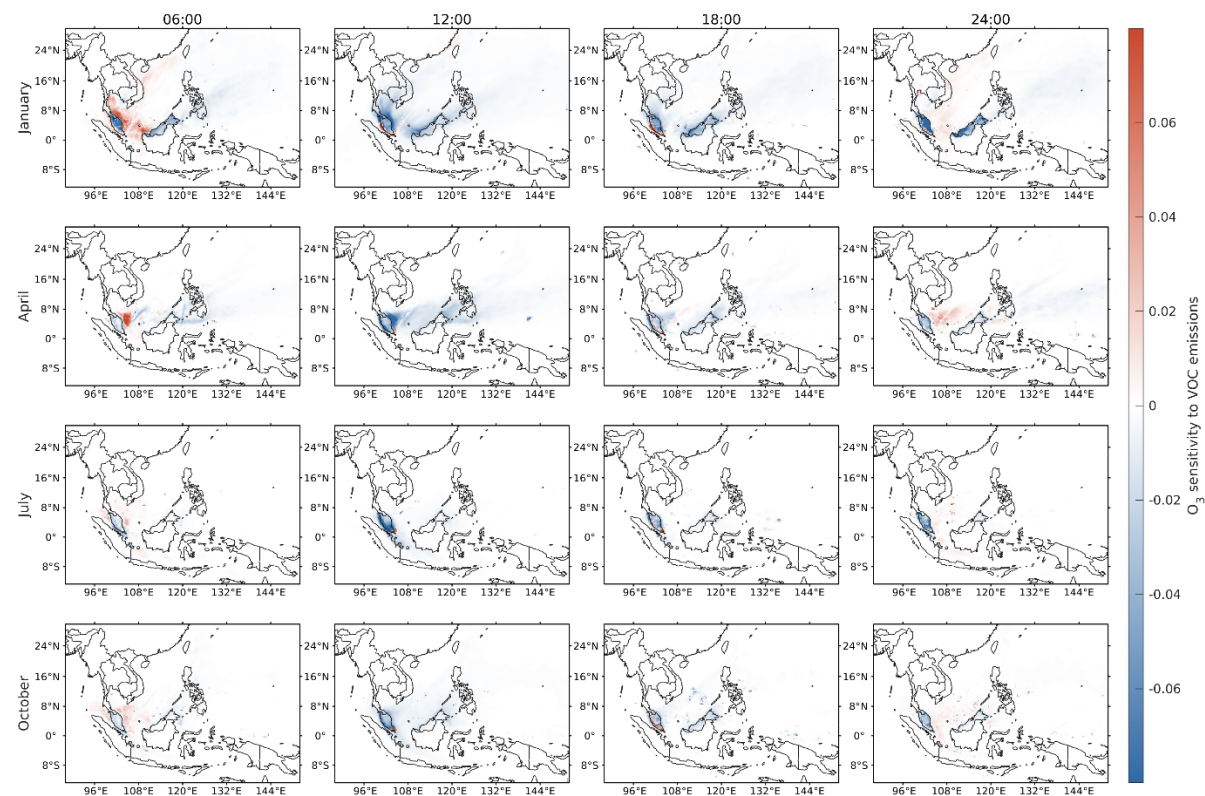


Fig. S54. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Malaysia.

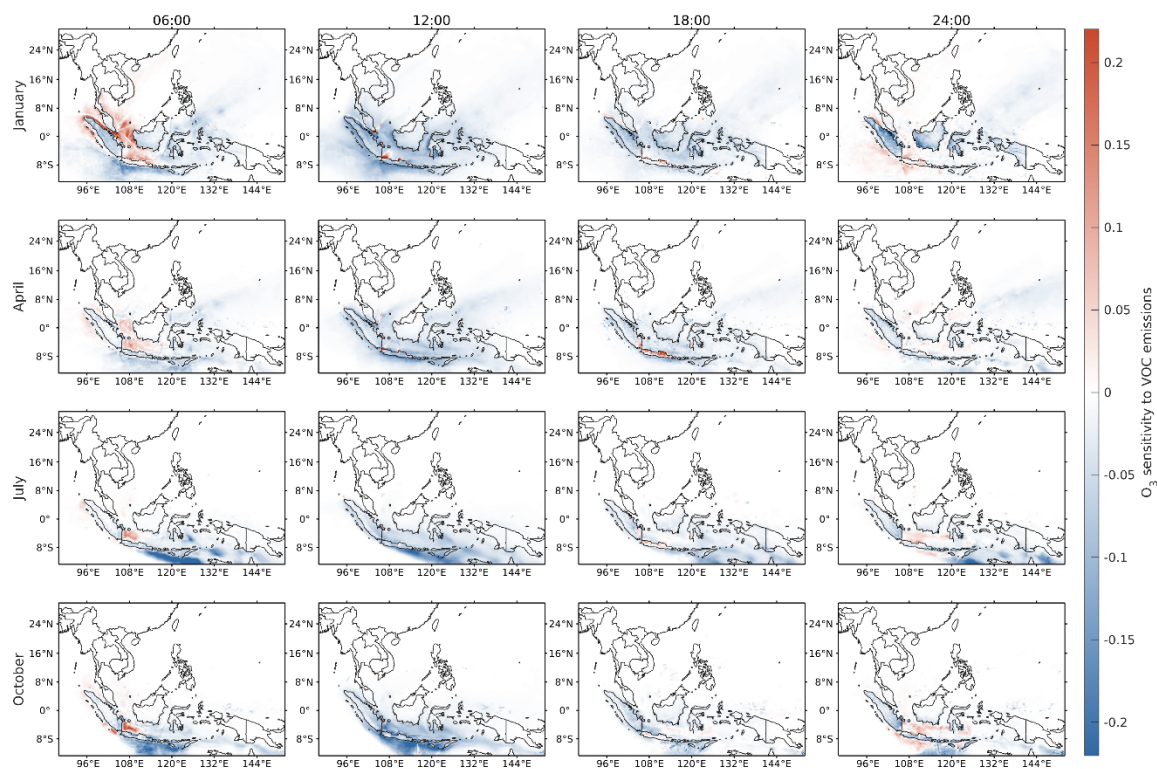


Fig. S55. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Indonesia.

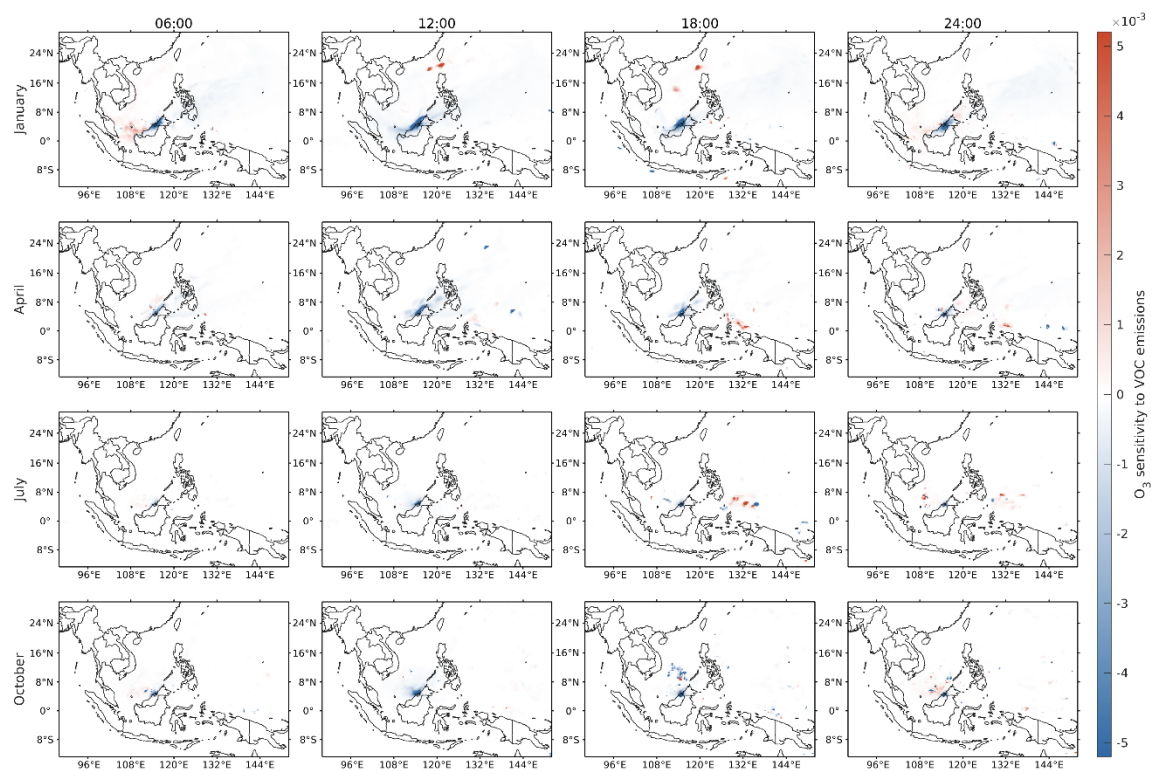


Fig. S56. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Brunei.

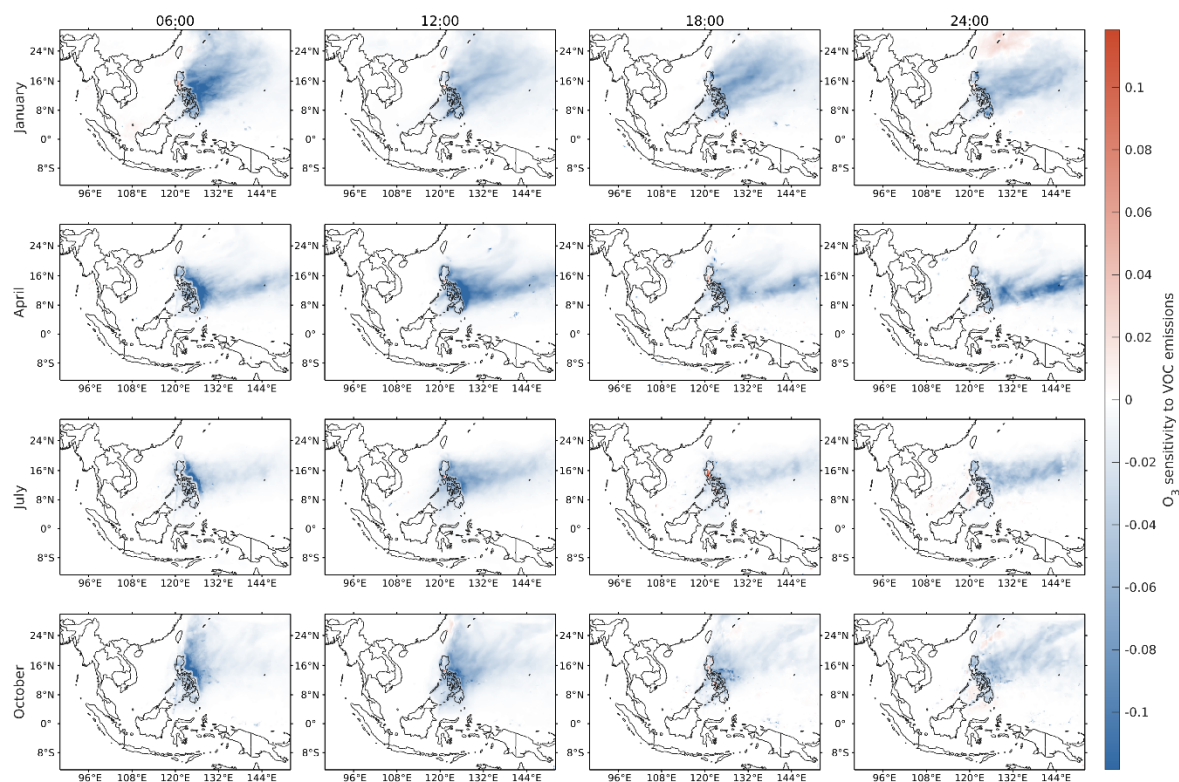


Fig. S57. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Philippines.

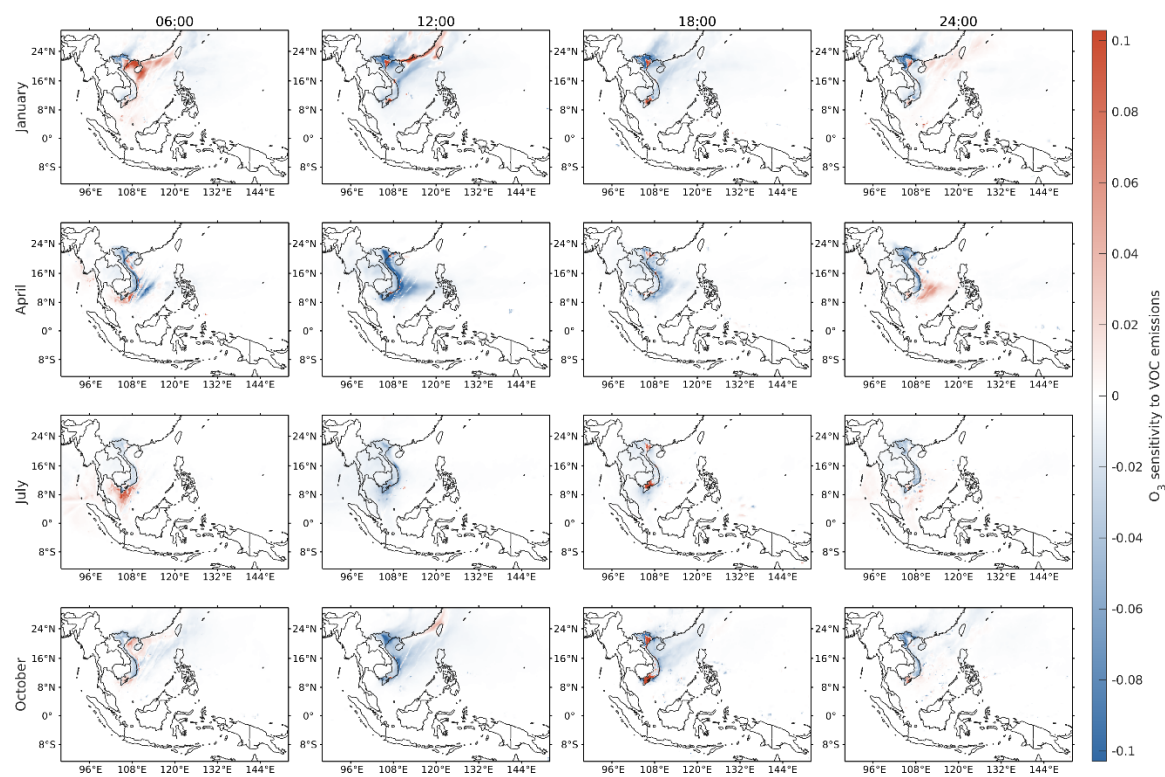


Fig. S58. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Vietnam.

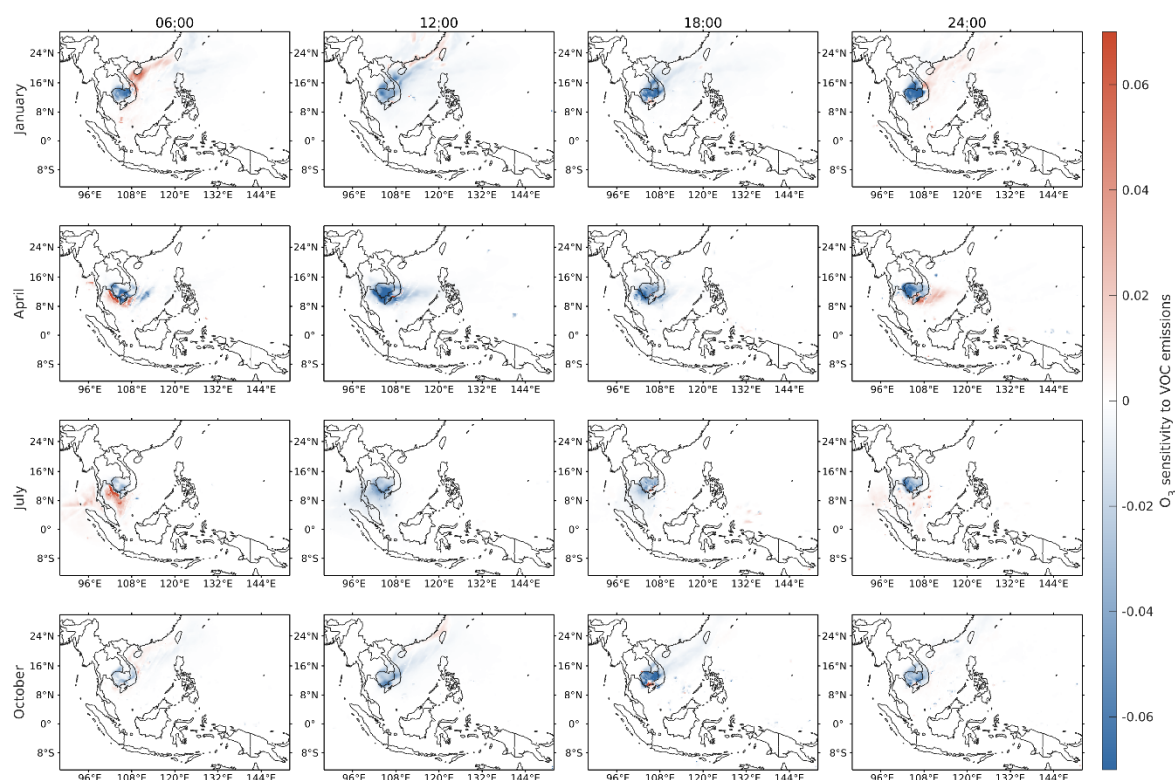


Fig. S59. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Cambodia.

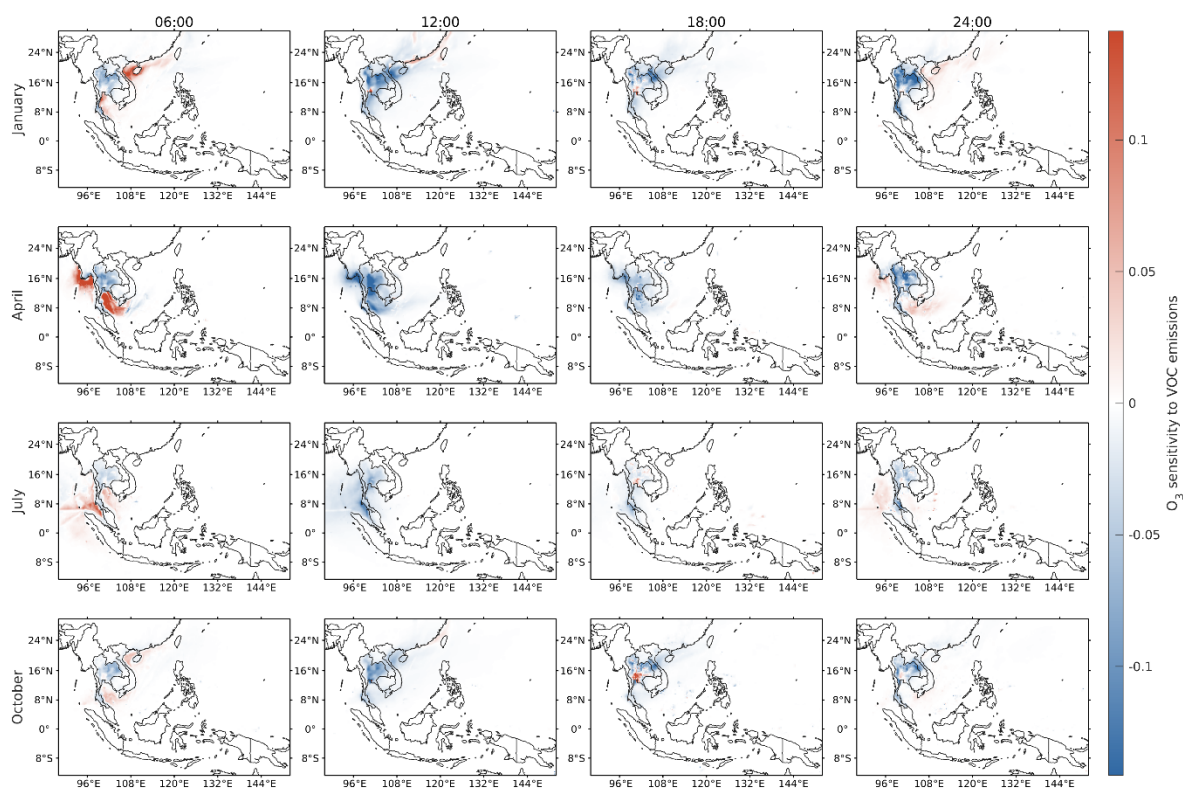


Fig. S60. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Thailand.

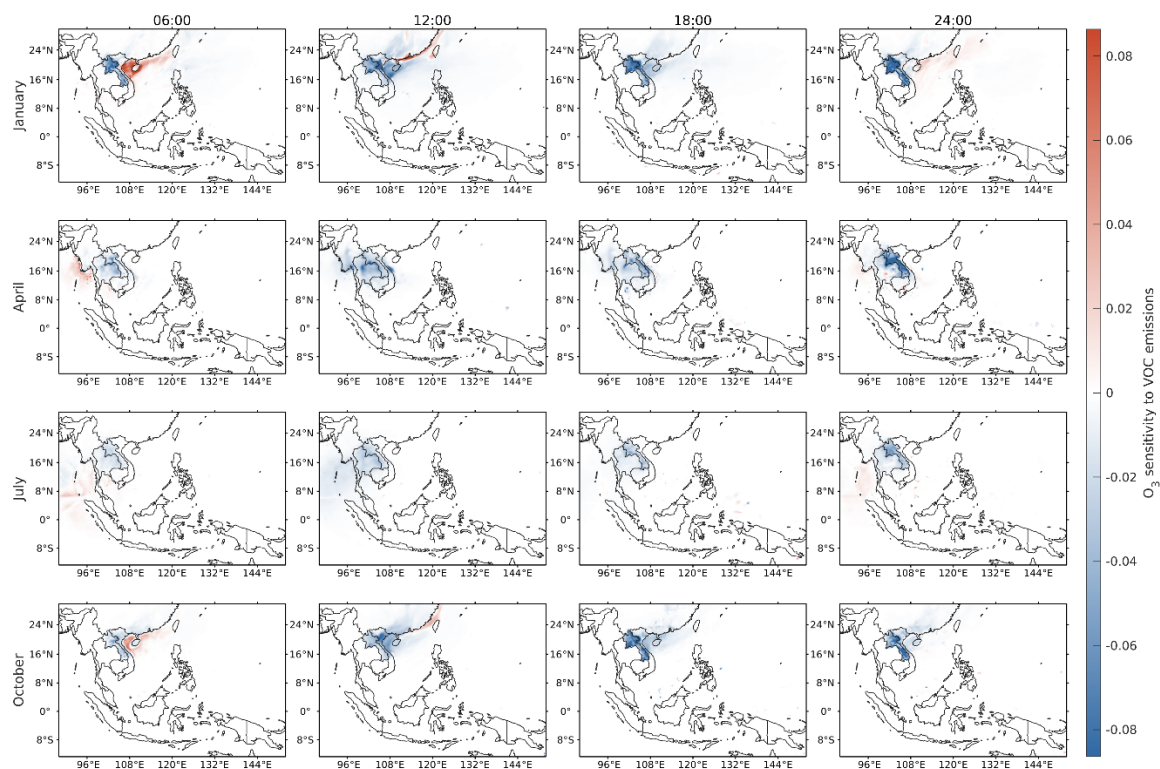


Fig. S61. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Laos.

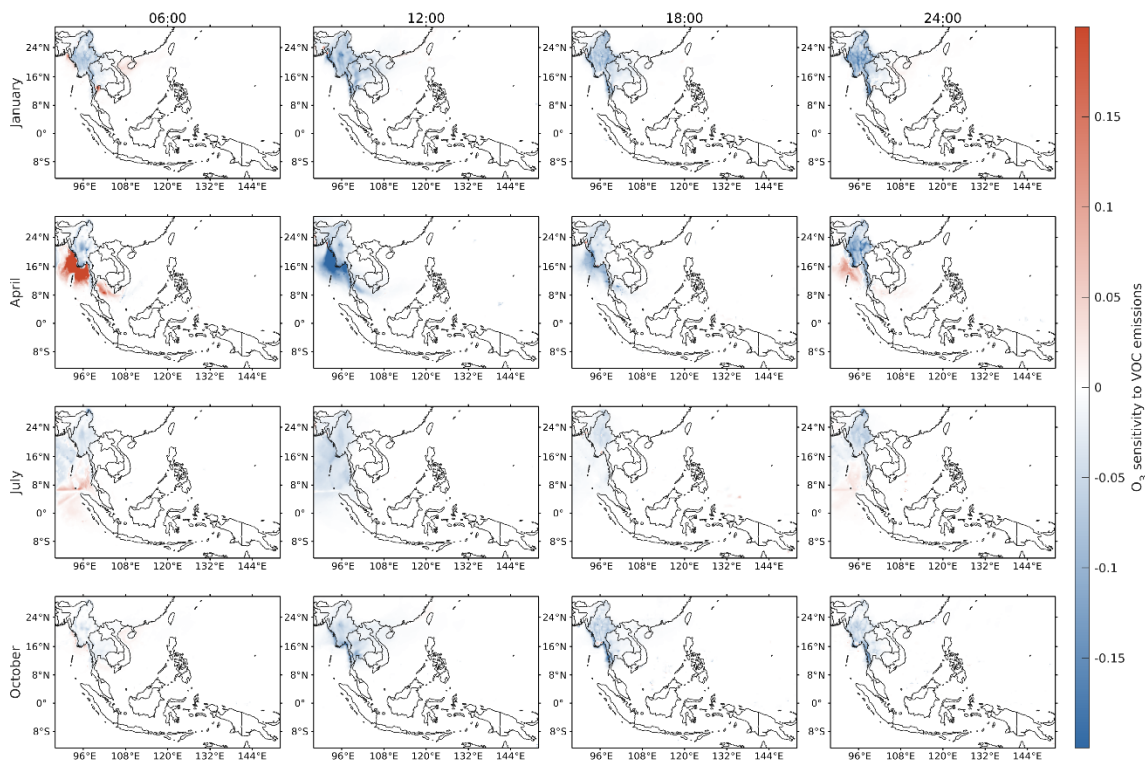


Fig. S62. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in Myanmar.

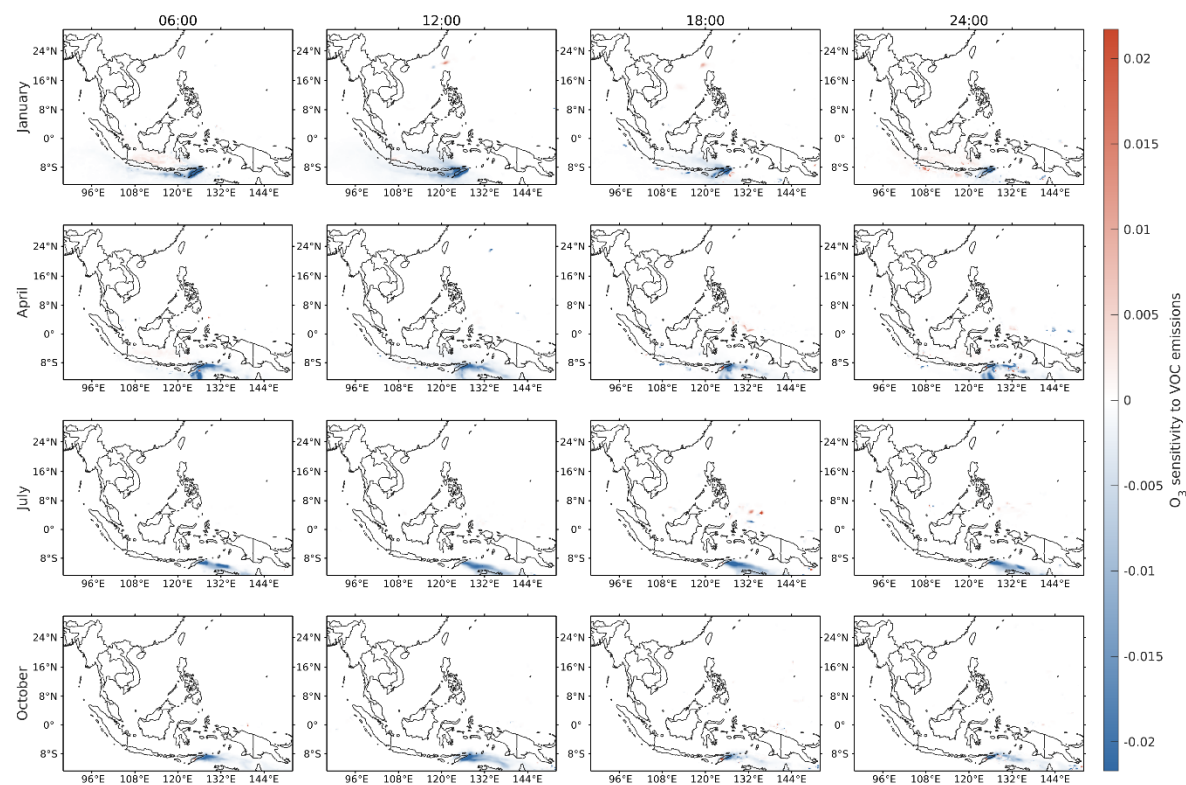


Fig. S63. Spatial distribution of the sensitivity of O_3 to VOC emissions at 6:00, 12:00, 18:00, and 24:00 in East Timor.

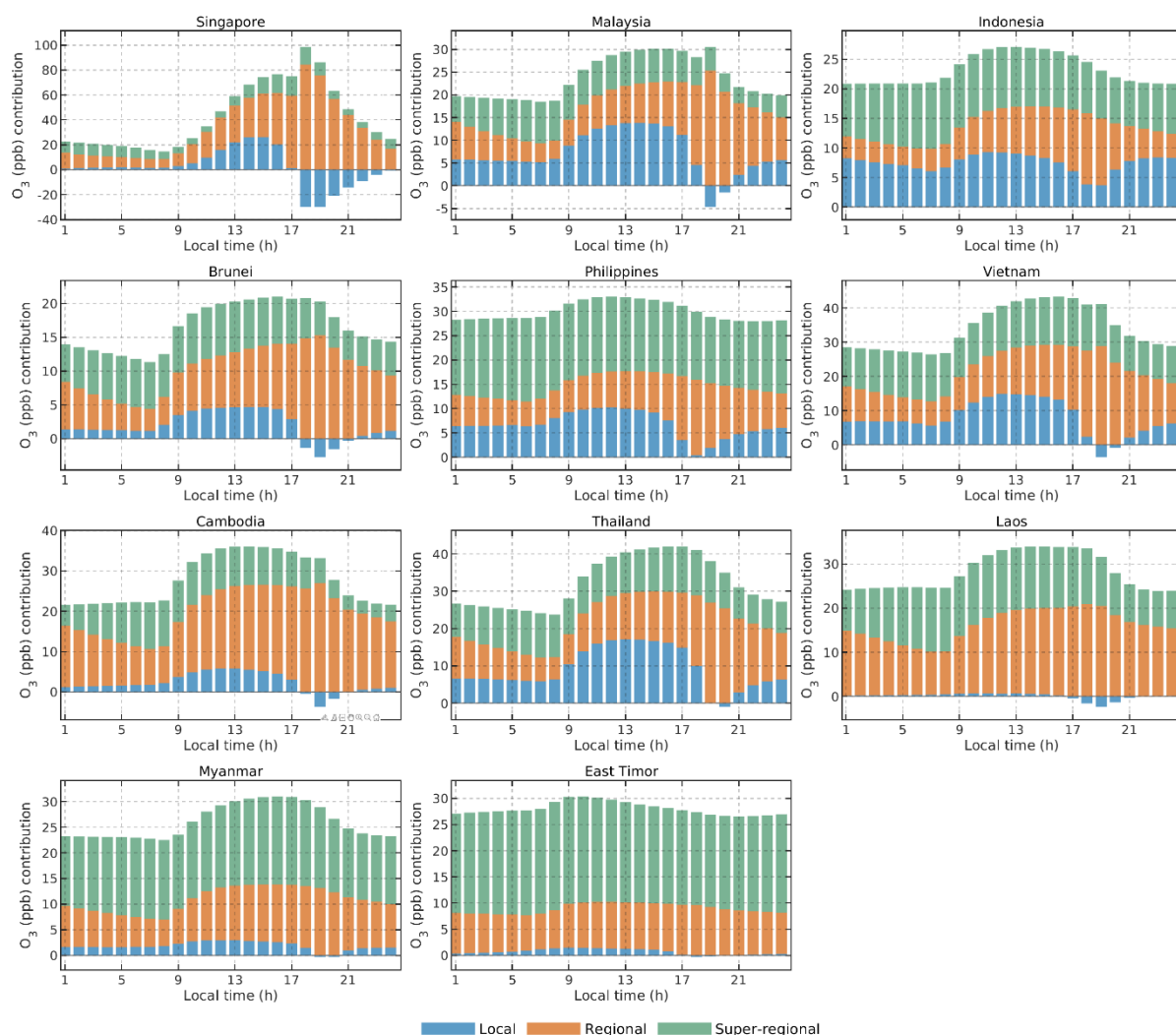


Fig. S36. Diurnal variability of local, regional and super-regional contributions in each Southeast Asian country.

7. S1 Gridded.

Response: We thank the referee for the comment. We assumed that this comment referred to adding latitude-longitude grid lines to Fig. S2, as Fig. S1 presents the overall study framework. Accordingly, we added grid lines to Fig. S2 to more clearly indicate the geographical location of Southeast Asia. The details can be found below:

Supplementary Figure:

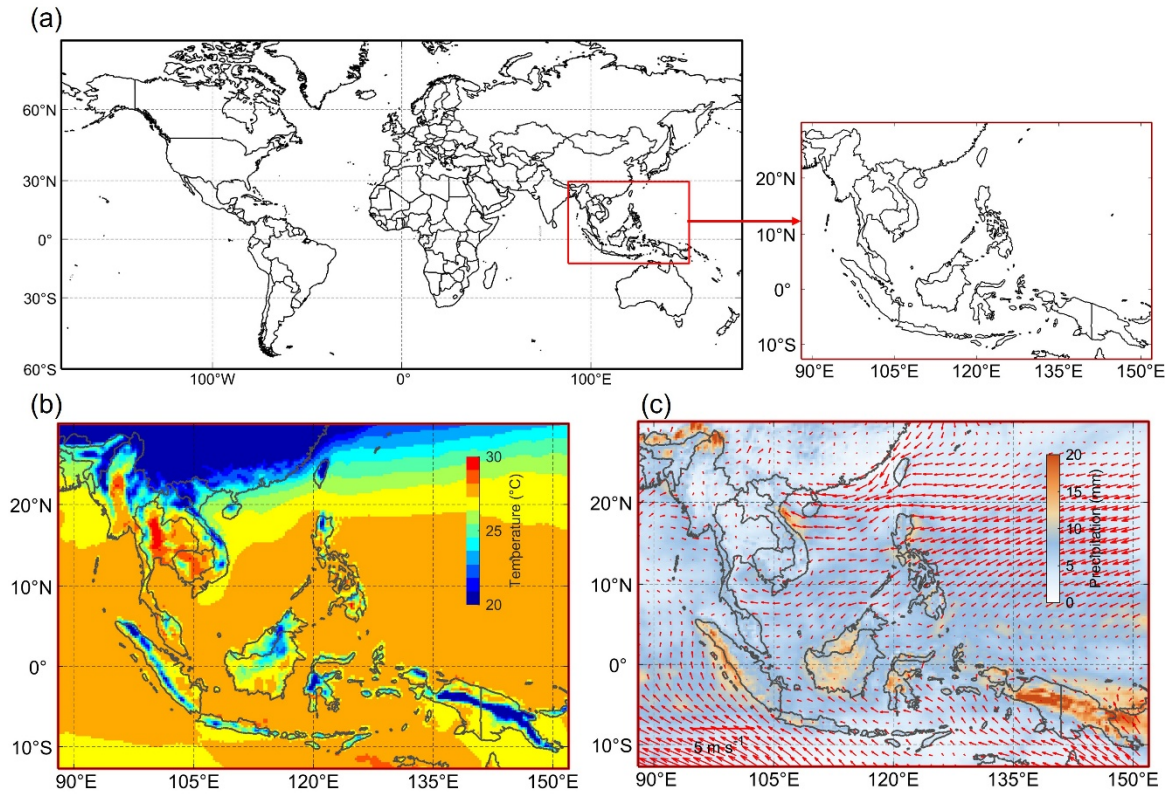


Fig. S2. Study domain and climatological characteristics of Southeast Asia. (a) The geographic location of the Southeast Asia study domain is highlighted on the global map, with country boundaries indicated. (b) Annual mean near-surface air temperature ($^{\circ}\text{C}$) over Southeast Asia. (c) Annual accumulated precipitation (mm) and mean near-surface wind fields (m s^{-1}) over Southeast Asia. SIN: Singapore, MYS: Malaysia, IDN: Indonesia, BRN: Brunei, PHL: Philippines, VNM: Vietnam, KHM: Cambodia, THA: Thailand, LAO: Laos, MMR: Myanmar, TLS: East Timor.

8. Figs S6, S8, and S11, please add a panel to show the difference between these two columns (simulations - reanalysis).

Response: We thank the referee for the helpful suggestion. We have added an additional panel to Figs. S6, S8, and S11 to show the differences between the simulations and reanalysis data. The revised figures provided a presentation of the spatial biases and improved the evaluation of the model performance. The details can be found below:

Supplementary Figures:

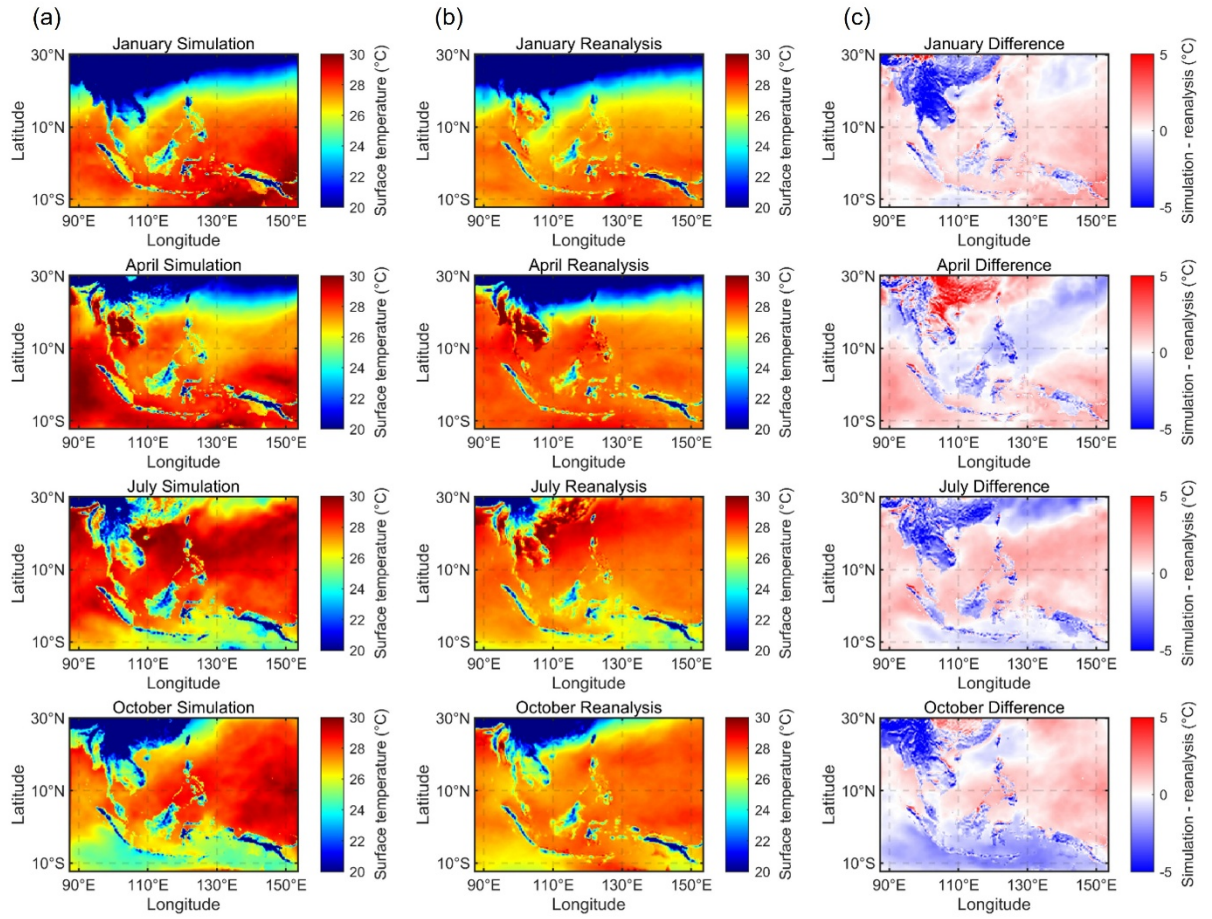


Fig. S6. Spatial comparison between the (a) simulated surface temperature, (b) the ERA5 reanalysis data (c) the differences between simulated and reanalysis data in the four monsoon seasons in Southeast Asia.

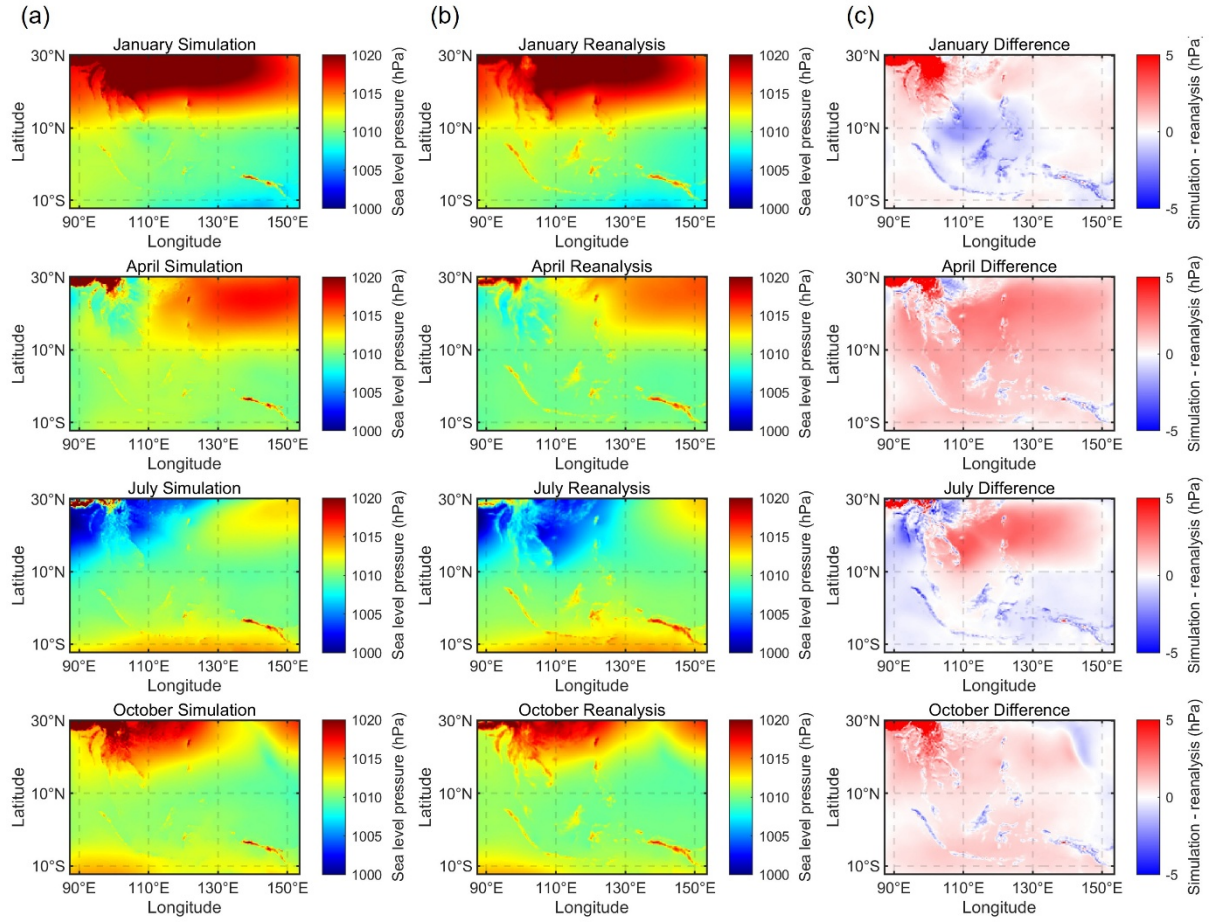


Fig. S8. Spatial comparison between the (a) simulated sea level pressure, the (b) ERA5 reanalysis data and (c) the differences between simulated and reanalysis data in the four monsoon seasons in Southeast Asia.

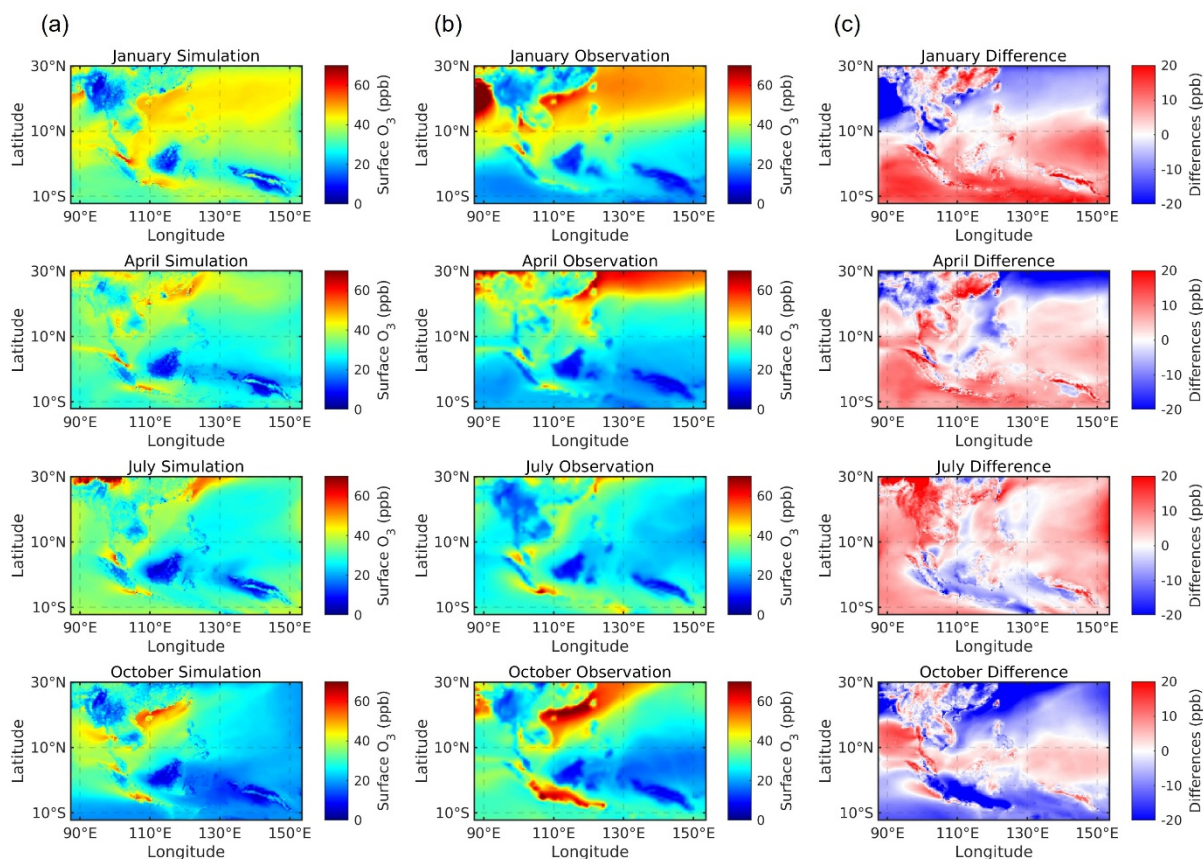


Fig. S12. Spatial comparison between (a) CMAQ simulation (b) the CAMS EAC4 reanalysis data (c) the differences between simulated and reanalysis data in the four monsoon seasons.

9. S10 the r ranged from 0.55 to 0.68. From my point of view, this does not indicate a nice performance of the models. Please explain whether this performance meets the common statistical standard.

Response: We thank the referee for the helpful suggestion. Fig. S10 evaluated the CMAQ performance by comparing the simulated surface O_3 concentration with available ground-based observations across Southeast Asia. In the original manuscript, hourly observations from the EANET stations and MDA8 O_3 observations from the AQI platform were included in the same figure to increase the spatial coverage of the model evaluation. The inconsistent temporal resolutions may have introduced additional uncertainty into the comparison between simulation and observation data. However, the correlation coefficients for the four monsoon seasons ranged from 0.55 to 0.68, which still exceeded the benchmark criterion of $r > 0.5$. The evaluation results were also comparable with the previous CMAQ simulation studies. For

instance, Albuquerque et al. (2018) reported O₃ correlation coefficients ranging from 0.56 to 0.67 across different monitoring sites, indicating that our comparison results were still within the commonly reported range in O₃ simulation studies.

In the revised manuscript, we further included additional ground-based monitoring stations from Singapore, Malaysia, Thailand, and the OpenAQ dataset to improve the model evaluation. Together with the previous observation records from the EANET and AQI datasets, 67 stations were used in total, covering seven countries in Southeast Asia. The spatial distribution of O₃ concentration in all stations is shown in the revised Fig. S11. To keep a consistent comparison among different stations and datasets, the hourly CMAQ simulations and ground-based observations were aggregated into daily MDA8 O₃ concentration. Therefore, both the model simulations and observations were evaluated using the MDA8 O₃ metric. The revised Fig. S10 shows the overall comparison between the simulated and observed MDA8 O₃ levels during the four monsoon seasons, with correlation coefficients of 0.69, 0.66, 0.67, and 0.70, which were comparable with those reported in the previous CMAQ simulation studies (Eder et al., 2004; Petetin et al., 2023). Also, we noticed that the correlation coefficient was insufficient to fully evaluate model performance. Therefore, we also assessed the simulation results using the normalized mean bias (NMB), root mean square error (RMSE), and index of agreement (IoA). The overall NMB, RMSE, and IoA were 13.26%, 10.60 ppb, and 0.78, respectively. The comparisons of NMB and RMSE from each station are shown in the revised Table S3, and the detailed descriptions of each station are provided in the revised Table S4. The evaluations provided a more comprehensive assessment of the CMAQ model performance in Southeast Asia.

The comparison between the simulation and the ground observation indicated that the performance of our CMAQ model was acceptable. However, there were still uncertainties such as model resolution, observation coverage, meteorological factors and emission inventories, resulting in the discrepancies between observation and our CMAQ simulation. For example, the station observation data were point-based measurements, whereas the CMAQ simulations represented grid-averaged concentration at the resolution of 30 km. The difference could introduce uncertainties, especially in urban areas and coastal regions where O₃ concentration may vary substantially within a 30 km model grid. In addition, ground-based monitoring data were not available in Indonesia, Laos, Myanmar, and East Timor due to the limited observation coverage and data availability. We have elaborated them in the Discussions in the revised manuscript. In addition to the ground-based observations, we further compared the CMAQ

simulations with the monthly CAMS EAC4 reanalysis product, which provided a spatially continuous dataset for evaluating the regional O₃ distribution with 75 km resolution. The revised Figs. S12 and S13 show that the CMAQ simulation generally captured the spatial pattern and seasonal variation of surface O₃ over Southeast Asia, with correlation coefficients of 0.63, 0.73, 0.60, and 0.69 and RMSE values of 6.6, 5.5, 6.1, and 6.3 ppb for the four monsoon seasons, respectively. This additional comparison further supported the reliability of the simulated O₃ distribution in this study.

References:

De Almeida Albuquerque, T. T., de Fátima Andrade, M., Ynoue, R. Y., Moreira, D. M., Andreão, W. L., Dos Santos, F. S., & Nascimento, E. G. S. (2018). WRF-SMOKE-CMAQ modeling system for air quality evaluation in São Paulo megacity with a 2008 experimental campaign data. *Environmental Science and Pollution Research*, 25(36), 36555-36569.

Eder, B., & Yu, S. (2006). A performance evaluation of the 2004 release of Models-3 CMAQ. *Atmospheric Environment*, 40(26), 4811-4824.

Petetin, H., Guevara, M., Garatachea, R., López, F., Oliveira, K., Enciso, S., ... & García-Pando, C. P. (2023). Assessing ozone abatement scenarios in the framework of the Spanish ozone mitigation plan. *Science of The Total Environment*, 902, 165380.

We have revised the Result and Discussion section to make a comprehensive comparison with the updated ground observation records and the global O₃ reanalysis data. The details can be found below:

Lines 187-193:

“...The spatial distribution of simulated ground-level O₃ was evaluated using observations from 67 stations across Southeast Asia. As shown in Fig. S10, most MDA8 O₃ simulations aligned within $\pm 50\%$ of the observations. The overall correlation (r) between the observed and simulated MDA8 O₃ across the four months was 0.68, exceeding the benchmark criterion of $r > 0.5$ (Yang & Zhao, 2023). The NMB, RMSE, and IoA were 13.26%, 10.60, and 0.78, respectively. The locations and observed O₃ concentration of the monitoring stations are shown in Fig. S11.

Station-level evaluation results are presented in Table S3, while detailed information on each station is provided in Table S4, underscoring the reliability of the O₃ simulation in capturing the spatial variations across the region...”

Lines 491-498:

“...Our study also has several limitations. First, the relatively sparse monitoring network in Southeast Asia limited the evaluation of simulated surface O₃. In addition, ground-based monitoring data were not available in Indonesia, Laos, Myanmar, and East Timor due to the limited observation coverage and data availability. To complement the comparisons, global surface O₃ reanalysis data were used to assess the spatial consistency of the simulations. Future improvements in model evaluation would benefit from expanded ground-based monitoring networks and the integration of satellite-derived O₃ products. Second, the model resolution of 30 km may introduce the uncertainties when comparing the simulation and the ground observations, especially in urban areas and coastal regions where O₃ concentration may vary substantially within a model grid. Also, the 30 km resolution may not fully resolve sub-grid urban processes such as NO titration...”

Supplementary Figures and Tables:

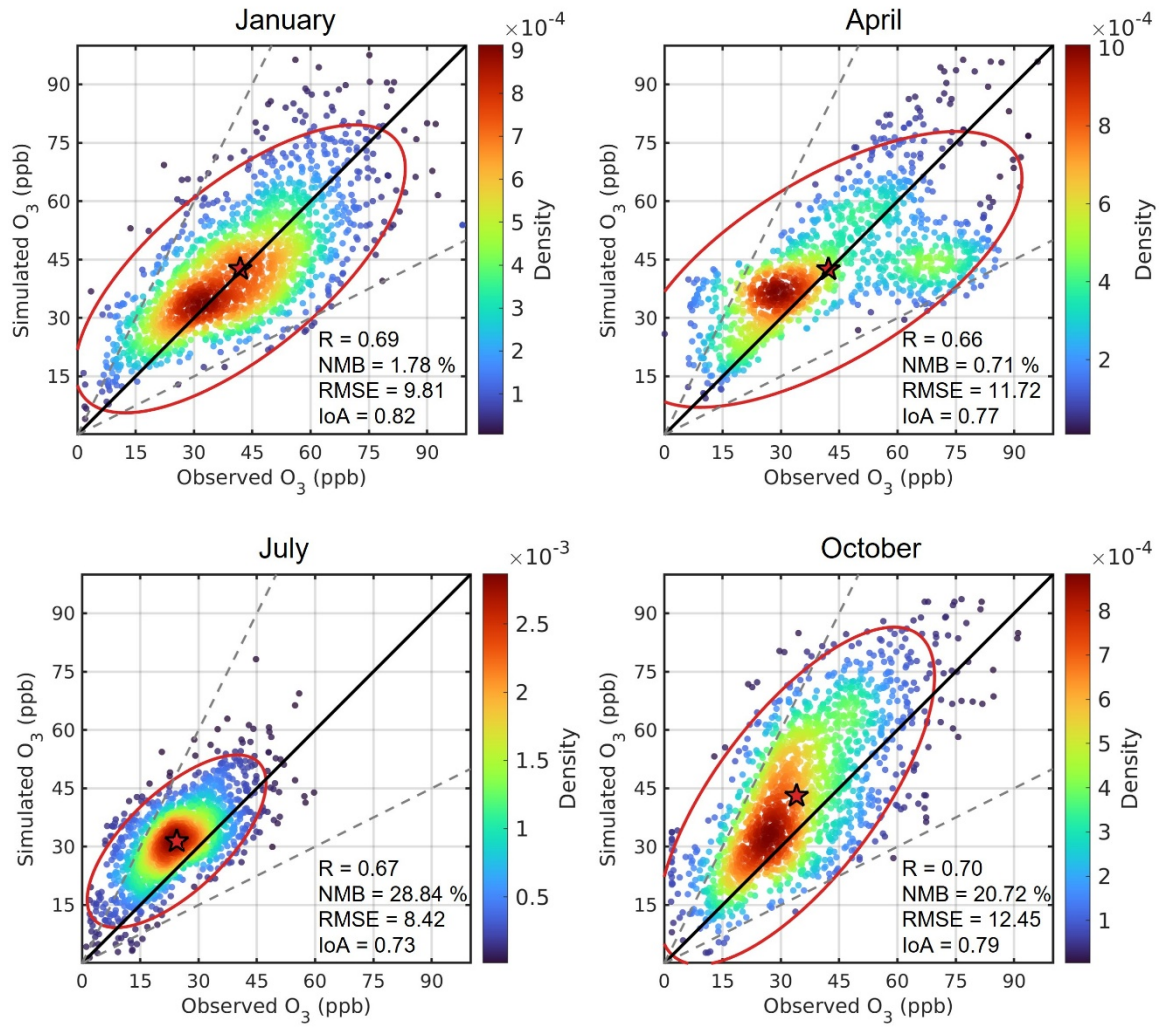


Fig. S10. CMAQ model evaluation by comparing the MDA8 O₃ simulation with the observation data from 67 monitoring stations in Southeast Asia for the four monsoon seasons. The ellipses represent the 95% confidence interval of the scatter points, and the centroid crosses show the median value. The statistical indicators (R, NMB (%), RMSE, and IoA) were calculated using all the comparison data from available stations. The 1:1 line denotes the perfect predictions, and the 2:1 and 0.5:1 lines represent the $\pm 50\%$ simulations, respectively.

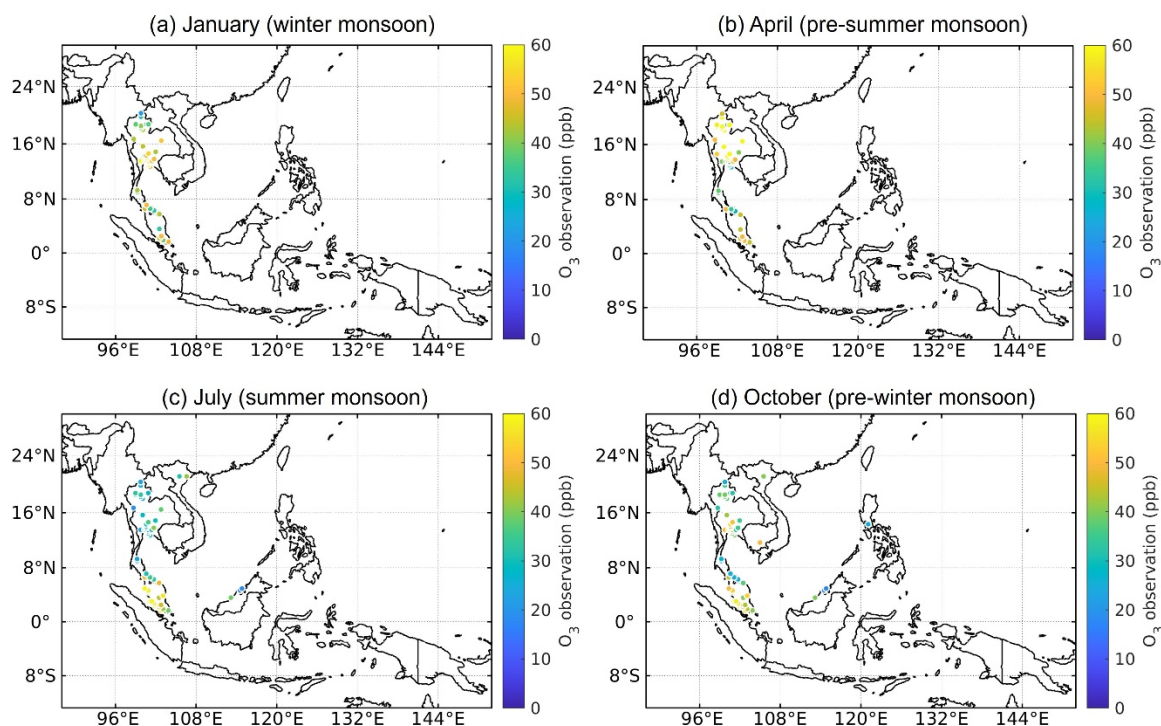


Fig. S11. MDA8 O₃ observations of 67 ground stations in the four months in Southeast Asia.

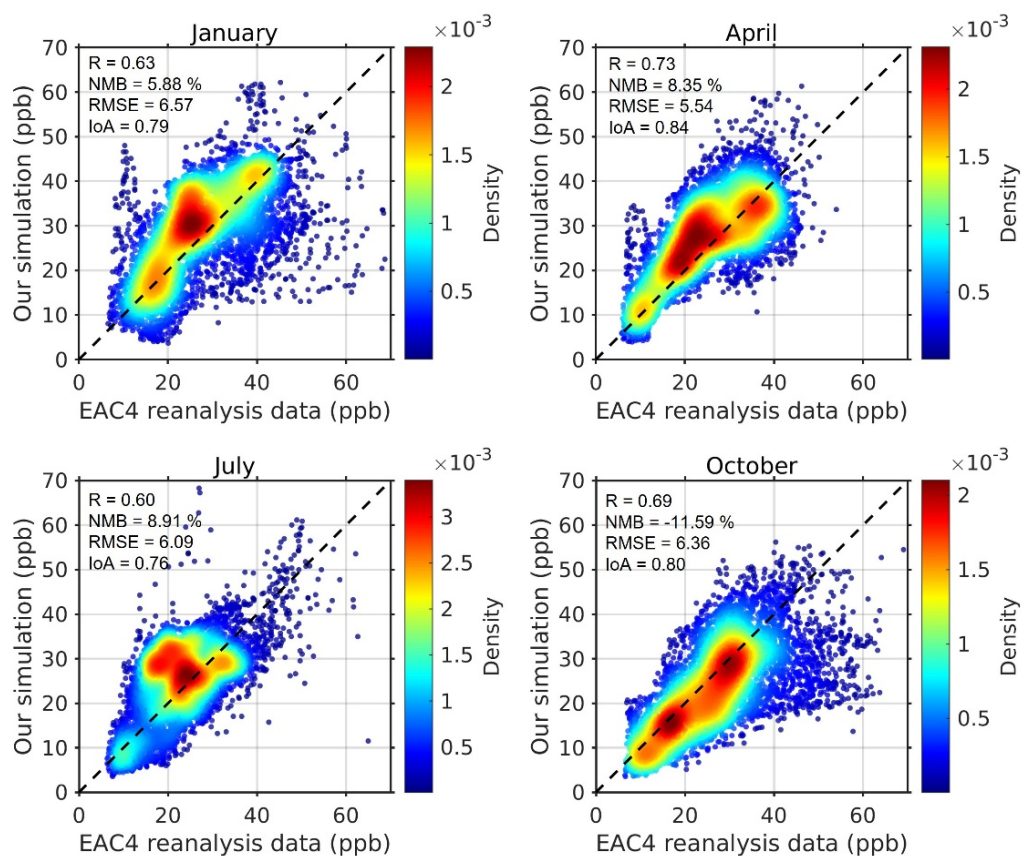


Fig. S13. Evaluation between the CMAQ simulation and the CAMS EAC4 reanalysis data in the four monsoon seasons.

Table S3. Evaluation of the CMAQ model simulation by comparing the MDA8 O₃ concentration levels with the ground-level measurements from 67 different stations in Southeast Asia.

Country	Station	January		April		July		October	
		NMB (%)	RMSE	NMB (%)	RMSE	NMB (%)	RMSE	NMB (%)	RMSE
Cambodia	EANET_S1	/	/	/	/	/	-3.02	5.39	/
	EANET_S2	-7.52	9.70	/	/	51.72	14.85	0.47	7.63
Thailand	EANET_S3	-10.38	8.62	/	/	/	/	23.81	10.03
	EANET_S4	/	/	-15.79	9.33	/	/	/	/
	EANET_S5	-19.71	7.39	-26.94	15.71	-0.23	5.66	/	/
	EANET_S6	/	/	-1.88	3.22	/	/	/	/
Brunei	AQI_S1	/	/	/	/	0.65	3.52	-1.48	3.58
	AQI_S2	/	/	/	/	8.35	3.27	-3.91	3.10
Philippines	AQI_S3	/	/	/	/	/	/	21.60	5.48
Vietnam	AQI_S4	/	/	/	/	-1.22	7.43	24.08	9.75
	AQI_S5	/	/	/	/	9.07	10.80	/	/
Thailand	AQI_S6	33.21	10.94	/	/	/	/	/	/
	AQI_S7	15.18	3.17	11.82	4.89	/	/	11.59	2.70
Malaysia	AQI_S8	/	/	/	/	-15.98	10.46	-23.68	13.19
	AQI_S9	/	/	/	/	-9.86	12.75	10.90	14.32
	AQI_S10	/	/	/	/	0.93	9.59	14.01	13.82
	AQI_S11	/	/	/	/	11.05	13.69	24.24	17.42
	AQI_S12	/	/	/	/	-12.83	14.27	5.54	11.46
	AQI_S13	/	/	/	/	-6.93	10.63	-14.30	9.83
	AQI_S14	/	/	/	/	25.85	15.96	5.10	11.05
	AQI_S15	/	/	/	/	1.34	9.57	15.38	15.16
	AQI_S16	/	/	/	/	11.53	13.98	21.92	17.23
	AQI_S17	/	/	/	/	-38.93	15.13	-36.40	15.34
	AQI_S18	/	/	/	/	-14.01	14.86	-9.86	10.78
	AQI_S19	/	/	/	/	4.39	10.76	9.47	10.70
	AQI_S20	/	/	/	/	-5.21	9.86	-3.11	9.84
	AQI_S21	/	/	/	/	-15.22	14.86	-0.52	11.82
Thailand	THA_S1	19.18	14.61	15.16	4.45	99.45	17.47	68.26	26.20
	THA_S2	11.10	12.68	18.03	5.41	41.75	10.63	33.44	15.79
	THA_S3	7.17	11.14	8.59	4.91	37.28	9.78	46.32	19.78
	THA_S4	5.61	7.63	2.53	2.27	24.36	7.40	25.34	14.72
	THA_S5	-0.94	12.55	4.71	2.85	32.15	7.38	24.09	12.32
	THA_S6	-1.33	10.16	35.72	8.48	17.22	5.68	10.44	8.19
	THA_S7	9.83	16.92	14.96	4.66	57.68	14.30	70.86	25.47
	THA_S8	15.99	17.01	4.19	2.50	40.34	12.01	50.24	20.35
	THA_S9	-20.95	9.54	-27.81	19.96	3.26	2.96	-10.50	8.25
	THA_S10	-9.28	9.01	1.87	3.33	7.51	5.25	2.58	7.25
	THA_S11	-1.15	8.24	1.94	1.87	45.85	10.40	33.20	8.56
	THA_S12	-14.67	10.71	/	/	23.01	8.69	38.08	9.68
	THA_S13	-8.23	9.35	-27.79	21.45	-3.70	4.17	/	/
	THA_S14	1.99	4.59	/	/	31.34	9.36	20.13	8.69
	THA_S15	-16.70	10.20	7.34	3.61	35.06	10.20	12.77	8.73
	THA_S16	14.95	8.74	1.48	1.01	-11.44	6.47	27.55	7.07
	THA_S17	-16.19	8.49	-37.71	26.69	8.36	6.91	-8.65	7.76
	THA_S18	-23.68	11.65	-35.21	22.18	0.87	5.64	0.49	1.17
	THA_S19	-29.23	14.77	-34.55	24.57	6.53	4.13	-7.43	7.45

	THA_S20	12.36	8.90	-20.19	9.41	34.15	8.09	5.51	5.65
	THA_S21	-20.94	10.88	-12.38	6.98	64.81	12.18	12.44	6.10
	THA_S22	-14.59	9.30	3.32	3.63	5.85	8.66	11.08	6.51
Malaysia	MYS_S1	64.89	12.73	-3.23	2.30	32.41	5.97	20.24	5.23
	MYS_S2	-0.61	2.85	0.80	1.32	-40.67	6.03	-29.33	5.87
	MYS_S3	42.96	6.13	3.68	1.39	8.28	2.97	13.84	3.00
	MYS_S4	0.51	2.42	0.72	0.79	23.55	6.71	32.47	6.27
	MYS_S5	11.08	5.10	-0.65	1.67	2.26	1.49	35.02	4.90
Singapore	SIN_S1	19.79	6.69	17.05	6.08	10.59	2.71	14.82	4.02
	SIN_S2	19.42	4.23	16.59	3.99	17.97	3.70	17.35	3.42
	SIN_S3	32.21	7.19	22.44	5.24	57.84	8.87	52.36	8.80
	SIN_S4	17.51	5.59	9.72	3.53	8.54	2.45	7.65	2.10
Thailand	OPENAQ_S1	8.70	4.84	-5.44	4.51	-3.17	4.92	21.77	5.88
	OPENAQ_S2	8.83	15.81	26.11	9.31	24.57	5.58	35.70	19.65
	OPENAQ_S3	-4.70	15.53	18.04	8.72	38.21	7.56	47.38	19.01
	OPENAQ_S4	-4.82	12.35	34.55	15.60	27.10	8.15	20.48	12.74
	OPENAQ_S5	-14.61	11.50	23.07	15.08	28.02	10.60	18.20	11.96
	OPENAQ_S6	-19.24	9.55	-43.21	33.84	9.86	2.77	-8.71	5.89
	OPENAQ_S7	-9.47	7.24	-27.10	16.71	3.62	2.24	-22.72	11.71
	OPENAQ_S8	-19.31	9.59	-36.96	27.00	3.40	2.50	-22.62	11.12
	OPENAQ_S9	1.58	5.10	-45.59	32.05	9.17	3.48	-18.01	8.22

Table S4. Descriptions of observation stations in Southeast Asia.

Country	Station	Location
Cambodia	EANET_S1	Phnom Penh
Thailand	EANET_S2	Bangkok
	EANET_S3	Samutprakarn
	EANET_S4	Kanchanaburi
	EANET_S5	Chiang Mai
	EANET_S6	Nakhon Ratchasima-Nai Mueang
Brunei	AQI_S1	Brunei Muara, Brunei
	AQI_S2	Pekan-Tutong, Brunei
Philippines	AQI_S3	Binan City
Vietnam	AQI_S4	Hanoi
	AQI_S5	Quang Ninh Phuong Nam
Thailand	AQI_S6	Ayutthaya Witthayalai School
	AQI_S7	Municipality Office
Malaysia	AQI_S8	Balok Baru
	AQI_S9	Bandaraya Melaka
	AQI_S10	Banting Selangor
	AQI_S11	Batu Muda
	AQI_S12	Batu Pahat
	AQI_S13	Jalan Tasek
	AQI_S14	Kg Air Putih
	AQI_S15	Nilai
	AQI_S16	Pelabuhan Kelang
	AQI_S17	Samalaju
	AQI_S18	Segamat
	AQI_S19	Seremban
	AQI_S20	SK Jalan Pegoh
	AQI_S21	Tangkak
Thailand	THA_S1	Bang Na, Khet Bang Na, Bangkok

	THA_S2	Bang Sao Thong, Bang Sao Thong, Samut Prakan
	THA_S3	Khlong Nueng, Khlong Luang, Pathum Thani
	THA_S4	Pratu Chai, Phra Nakhon Si Ayutthaya
	THA_S5	Na Mueang, Mueang, Ratchaburi
	THA_S6	Map Ta Phut, Meuang, Rayong
	THA_S7	Thung Sukhla, Si Racha, Chon buri
	THA_S8	Ban Suan, Mueang, Chon Buri
	THA_S9	Ban Dong, Mae Mo, Lampang
	THA_S10	Pak Nam Pho, Mueang, Nakhon Sawan
	THA_S11	Makham Tia, Mueang, Surat Thani
	THA_S12	Hat Yai, Songkhla
	THA_S13	Nai Mueang, Mueang, Khon Kaen
	THA_S14	Nai Mueang, Mueang, Nakhon Ratchasima
	THA_S15	Wang Yen, Plaeng Yao, Chachoengsao
	THA_S16	Bang Nak, Mueang, Narathiwat
	THA_S17	Nai Wiang, Mueang, Nan
	THA_S18	Ban Klang, Mueang, Lamphun
	THA_S19	Na Chak, Meuang, Phrae
	THA_S20	Wiang Phang Kham, Mae Sai, Chiang Rai
	THA_S21	MaePa, MaeSot, Tak
	THA_S22	Tha Tum, SiMahaPhot, Prachin Buri
Malaysia	MYS_S1	Batu Pahat, Johor
	MYS_S2	Kota Tinggi, Johor
	MYS_S3	Temer Loh, Pahang
	MYS_S4	Kangar, Perlis
	MYS_S5	Besut, Terengganu
Singapore	SIN_S1	Western Singapore
	SIN_S2	Eastern Singapore
	SIN_S3	Central Singapore
	SIN_S4	Northern Singapore
Thailand	OPENAQ_S1	Sateng, Mueang
	OPENAQ_S2	Samut Sakhon Wittayalai School
	OPENAQ_S3	Residence for Dept. of Mineral Resources
	OPENAQ_S4	Phaya Thai, Khet Phaya Thai
	OPENAQ_S5	Pak Phraio, Mueang
	OPENAQ_S6	Sop Pat, Mae Mo
	OPENAQ_S7	Mae Mo, Mae Mo
	OPENAQ_S8	Health Promotion Hospital Banthasri
	OPENAQ_S9	Natural Resources and Environment Office, Chiangrai

10. The discussion section is simple. More content (The vertical variability of 26 layers in Fig. S19, the impact of meteorology, differences among the four months, and implications of super-regional contributions etc.) should be added.

Response: Thanks for the valuable comment. In the revised manuscript, we have expanded the Discussion section to provide further interpretation of the major findings. First, we illustrated the meteorological conditions influenced not only surface O₃ levels but also the O₃ sensitivity to precursor emissions. Monsoon circulation changed the influential upwind source regions and transport pathways, while variations in solar radiation, surface temperature, cloud cover, and

precipitation affected the chemical lifetime and O₃ production efficiency. Second, we discussed the vertical variability of the physical and chemical processes across the model layers and explained how the interaction between near-surface O₃ loss, upper-layer photochemical production, vertical mixing, and horizontal advection influenced surface O₃. Third, we expanded the discussion of the super-regional contributions and the implications for O₃ mitigation. We highlighted that background O₃ could reduce the effectiveness of local emission controls and lead to elevated O₃ levels in countries with relatively low local emissions. We therefore further discussed the need for coordinated cross-regional emission management to reduce the super-regional contributions. The details can be found below:

Lines 428-440:

“...This study evaluated surface O₃ concentration and the sensitivities based on four monsoon seasons. The seasonal differences indicated that meteorological conditions not only influenced the O₃ concentration level but also affected the sensitivity between O₃ and precursor emissions. Monsoon circulation changed the upwind source regions and transport pathways, resulting in the elevated O₃ concentration during winter monsoon and relatively lower O₃ concentration during the summer monsoon. Meanwhile, variations in solar radiation, surface temperature, and cloud cover influenced the chemical lifetime and O₃ production efficiency. For instance, the stronger NO_x sensitivities during the pre-summer and pre-winter monsoon periods reflected the combined influence of increased biomass burning emissions and favourable photochemical conditions such as elevated surface temperature, reduced precipitation and relatively stagnant atmosphere. Under these conditions, local source made higher contribution to the regional O₃. In contrast, enhanced cloud cover and precipitation during the summer monsoon reduced photochemical activity and shortened the atmospheric lifetime of the precursors of O₃, decreasing the O₃ production efficiency and the local source contributions to regional O₃. The seasonal variations suggested that the effectiveness of emission controls should differ among monsoon periods and the O₃ mitigation strategies should therefore consider both seasonal chemical conditions and transport pathways...”

Lines 459-480:

“...The process analysis at the ground level identified vertical diffusion, gas-phase chemistry, and horizontal advection as the three dominant processes contributing to surface O₃ in Southeast Asia. However, vertical distributions across the 26 model layers further indicated that

surface O₃ was also largely influenced by the processes in the upper layers. In highly urbanized regions such as Singapore, strong NO titration reduced O₃ in the near-surface layers, while positive chemical production remained in the upper layers where NO titration was weaker and photochemical conditions were more favourable. O₃ generated or accumulated in the upper layers can be transported downward through large vertical diffusion, while O₃ and the precursors can also be transported horizontally to the downwind regions and contribute to the elevated O₃ concentration. The substantial O₃ transport was reflected by the relatively large contributions from horizontal advection in the upper layers, consistent with the source apportionment results showing that O₃ levels in Southeast Asian countries were largely determined by transboundary contributions. Specifically, the Philippines, Myanmar, and East Timor were particularly affected by super-regional pollution due to their proximity to the surrounding seas, whereas Singapore, Cambodia, and Laos experienced substantial regional influences associated with adjacency to the neighbouring countries with high precursor emissions. The predominance of transboundary O₃ indicated elevated background O₃ levels and substantial inequities in O₃ control effectiveness across Southeast Asian countries, as downwind receptors may experience high O₃ exposure despite relatively low emissions, thereby reducing the effectiveness of local mitigation efforts when the regional background remains high. Our findings underscored the need for a collaborative regional emission reduction framework to reduce O₃ pollution and improve public health across the region. In addition, regional emission controls should be complemented by broader international cooperation with surrounding regions due to the large super-regional contribution. Specifically, cross-regional emission management could be strengthened through coordinated monitoring, regional air quality forecasting, and joint NO_x mitigation during high-pollution seasons. In addition, stronger controls on international shipping emissions could help reduce the substantial maritime contribution to regional O₃. The measures are important for lowering regional and super-regional transboundary O₃ and improving the effectiveness of local emission control strategies...”