Response to reviewers on: Numerical simulation of nitrous oxide over Asia using regional climate-chemistry-ecology coupling model RegCM-Chem-YIBs

Xin Zeng et al.

We sincerely thank the reviewer for the valuable comments, which have played a crucial role in improving the quality of this article. We have carefully revised and responded to them one by one. In this document, we describe how we have addressed the reviewer's comments. Review comments in black, responses in blue and text added/modified in manuscript in red.

RC1: 'Comment on egusphere-2025-608', Anonymous Referee #1

General comments:

Original comment 1#: Descriptions on how the climate and land models are lacking, particularly N_2O processes in the ecosystem model. My understanding is the integrated model has no nitrogen processes, as N_2O fluxes from CAMS and EDGAR are used as inputs, rather from internal simulations.

Response: We appreciate the reviewer's accurate understanding and helpful comment. Indeed, in the current study, the RegCM-Chem-YIBs framework does not include internal nitrogen cycle processes or dynamic N_2O production mechanisms within the land surface model. The N_2O fluxes are externally prescribed based on the EDGAR and CAMS inventories, without contributions from in-situ biogeochemical simulations (e.g., soil nitrification and denitrification N_2O fluxes). The primary objective of this study is to evaluate how different external inventories affect the simulated spatial and seasonal distribution of N_2O under a consistent atmospheric transport framework. We have now clarified this model limitation explicitly in the revised manuscript (Lines 143-160), and we have also emphasized this as a key direction for

future model development in the Discussion section.

On the other hand, we have substantially revised the Introduction to improve its clarity, focus, and logical progression. We now begin by emphasizing the dual climate and ozone-depleting role of N_2O, establishing its relevance and urgency. We have removed general policy-related statements that were not directly aligned with the scientific focus of the paper. Through the literature, we found that a key gap in current modeling approaches: many frameworks treat the atmosphere as a passive boundary without explicitly simulating key atmospheric processes such as transport, mixing, and vertical redistribution of N_2O. Therefore, in order to assess the impact of surface emissions and atmospheric transport on the concentration of nitrous oxide (N_2O) in the troposphere, a three-dimensional global atmospheric chemical transport model (CTMs) is needed for research. We summarize recent advances in global-scale N_2O modeling and highlight that regional high-resolution simulations remain limited, especially over East Asia, a region with complex emission patterns and strong meteorological variability. Finally, we clearly stated the research objective: We used a chemically inert tropospheric tracer to separate and evaluate the impact of two inventories on N_2O concentration patterns in East Asia, driven by surface emissions and atmospheric transport, without considering internal biogeochemical processes of nitrous oxide. We also provided a detailed analysis of the seasonal variations and driving factors at six observation points in the region. These revisions improve the logical flow of the introduction and better position our study within the context of current scientific challenges. We believe the revised section more clearly conveys the rationale, novelty, and objectives of our work. We have now modified this part in the revised manuscript (Lines 34-126).

Revised version: (L143-149) In this study, we incorporate nitrous oxide (N_2O) as a new tracer species into the RegCM-Chem-YIBs modeling framework. This addition enables the simulation of N_2O concentration dynamics by considering external surface emissions and atmospheric transport processes. The model currently does not include stratospheric chemistry sinks of N_2O; hence, the simulated N_2O concentration is governed by its surface emissions and atmospheric redistribution. The surface N_2O emissions are prescribed from offline emission inventories (e.g., EDGAR and CAMS), which are read into the chemical module and mapped

to model grids at each timestep. These inventories do not currently include the online biogeochemical nitrogen cycle from the land surface model (e.g., nitrification/denitrification in CLM4.5), but can be optionally replaced or supplemented by interactive fluxes in future versions. The atmospheric transport of N_2O follows the same numerical treatment as other long-lived tracers (e.g., CO_2, CH_4) in RegCM-Chem (Shalaby et al., 2012). The atmospheric transport includes advection and diffusion. Advection is based on the three-dimensional wind fields (u, v, w) provided by the RegCM dynamical core. The vertical diffusion is dominated by the eddy diffusivity coefficient computed from the planetary boundary layer (PBL) scheme. The eddy diffusivity coefficient depends on atmospheric stability, surface roughness, and PBL height, consistent with the scheme used for other trace gases. Horizontal diffusion is applied for numerical stability, using constant or latitude-dependent eddy diffusivities. Using the enhanced model, we simulate N_2O concentrations over East, South, and Southeast Asia in 2020 and analyze their seasonal and spatial patterns under different emission scenarios.

(Lines 34-126) Nitrous oxide (N_2O) ranks as the third most prevalent greenhouse gas in the atmosphere, following carbon dioxide (CO_2) and methane (CH_4). With a global warming potential 273 times that of CO_2 and an atmospheric lifetime of 116 ± 9 years (Prather et al., 2015), N_2O contributes approximately 6% to the radiative forcing from long-lived greenhouse gases (WMO, 2023; NOAA, 2024). By 2022, the global average concentration of N_2O had reached 335.8±0.1 parts per billion (ppb), reflecting a 124% increase since the pre-industrial era. As a result, N_2O has become the largest contributor to the growth in effective radiative forcing among long-lived greenhouse gases since 1990 (WMO, 2023). In addition to its role as a potent greenhouse gas, N_2O is also a significant ozone-depleting substance (ODS). In the stratosphere, it undergoes photolysis to produce reactive nitrogen species (NOx), which catalyze ozone destruction (UNEP, 2013; Mcelroy and Mcconnell, 1971). In 2020, anthropogenic N_2O emissions, expressed in terms of CFC-11 equivalents, exceeded those of all CFCs by more than twofold, representing over 20% of the peak CFC emissions recorded in 1987 (Geneva, 2022). As such, N_2O is expected to remain the dominant ODS throughout the 21st century (Ravishankara et al., 2009). Despite its growing atmospheric burden, N_2O has received comparatively less attention than CO_2 and CH_4 in both observational and modeling

communities. In particular, there is still a lack of clarity regarding its spatial and temporal distribution in the free troposphere and lower stratosphere, as well as the relative importance of emission patterns and atmospheric transport in shaping these distributions.

As a greenhouse gas of significant global concern, accurately simulating the emission and concentration distribution of N_2O is essential for assessing the impacts of climate change and crafting effective emission reduction strategies (De Sisto et al., 2024; Zhou et al., 2020). From the site-specific models such as DNDC (Li et al., 1992), DAYCENT (Parton et al., 1996) to the dynamic global vegetation models (DGVMs; Cramer et al., 2001) like ORCHIDEE (Krinner et al., 2005), O-CN (Zaehle and Friend, 2010), CLM (Saikawa et al., 2013), TRIPLEX-GHG (Zhang et al., 2017) , IBIS (Ma et al., 2022) and LPJ-GUESS (Ma et al., 2025), the detailed process of nitrous oxide generation is added to the global model, allowing N_2O emissions to be truly coupled to climate, carbon cycle, water cycle, and human activities, so that their source-sink changes and climate feedbacks can be assessed at a global scale. In addition to process-based modeling, other commonly employed approaches include the emission factor (EF) method recommended by the IPCC (IPCC, 2019), which estimates emissions from agricultural and industrial activities based on nitrogen input and empirically derived coefficients. This method remains widely used in national greenhouse gas inventories. Atmospheric inverse modeling represents another major technique, using top-down constraints from ground-based or satellite observations to optimize emission estimates (Fischer, 2015; Patra et al., 2022; Stell et al., 2022). Together, these bottom-up and top-down methods have greatly contributed to global N_2O budget assessments. However, most of these modeling frameworks treat the atmosphere as a boundary or diagnostic layer, lacking an explicit simulation of key atmospheric processes such as transport, mixing, and vertical accumulation. Given its long atmospheric lifetime (Prather et al., 2015), inter-hemispheric gradients, and sensitivity to large-scale circulation, explicitly modeling N_2O transport is crucial for accurate concentration assessments.

To assess the impact of surface emissions and atmospheric transport on tropospheric nitrous oxide (N_2O) concentrations, researchers have developed multiple three-dimensional global atmospheric chemical transport models (CTMs). Within the TransCom-N_2O project framework, models from multiple institutions differ in spatial resolution, vertical layering, meteorological

forcing, and emission treatment, and have been widely employed to investigate the spatiotemporal distribution and transport mechanisms of N_2O (Thompson et al., 2014). The simulation based on GEOSCCM reconstructed the N_2O concentration and its isotope fluxes from 1980 to 2019, thereby revealing the contribution of anthropogenic emissions (Liang et al., 2022). Lickley et al. (2021) quantified the stratospheric influence on surface hemispheric differences in models and observations for N_2O. In addition, the influence of the Brewer-Dobson circulation on the transport and budget of N_2O in the stratosphere has also attracted attention (Minganti et al., 2022). Despite these advances, CTMs face persistent challenges. Most operate at relatively coarse spatial resolution (Chipperfield, 2006), limiting their ability to resolve regional and seasonal variations. Some models run in offline mode (Ishijima et al., 2010; Martin Heimann, 2003), relying on fixed meteorological inputs and thus unable to capture feedbacks between transport processes and emission changes. Furthermore, critical mechanisms such as stratospheric chemical reactions and stratosphere-troposphere exchange (STE) are often simplified or omitted. Therefore, enhancing the physical process characterization ability and spatial resolution of the model, as well as strengthening the coupling with observational data, are the key directions for future simulation of the evolution of N_2O concentration.

Regional climate-chemistry models, such as RegCM-Chem (Shalaby et al., 2012), provide the capability to resolve subcontinental-scale heterogeneity and capture dynamic meteorological drivers critical for simulating atmospheric constituents. However, their application to nitrous oxide (N_2O) remains limited and underexplored. While global inverse modeling studies have examined uncertainties associated with different inventories (Hong et al., 2017; Fischer et al., 2015), there is a notable lack of regional-scale evaluations on how discrepancies between inventories propagate through atmospheric transport to influence surface N_2O concentrations. This gap hampers our ability to accurately attribute observed concentration biases to either inventory errors or atmospheric process representations. Understanding the spatial and temporal variability of atmospheric N_2O at the regional scale is essential not only for assessing its climate forcing but also for its role in stratospheric ozone chemistry. East and South Asia, regions with substantial anthropogenic N_2O emissions driven by intensive fertilizer application

and livestock production (De Sisto et al., 2024; Zhang et al., 2022), remain poorly studied in terms of how local emissions and atmospheric transport interplay to control observed N_2O variability. Observational and satellite data indicate that surface emissions, vertical mixing, and stratosphere-troposphere exchange collectively shape regional N_2O distributions (Nevison et al., 2011; Thompson et al., 2013). Yet, current high-resolution regional models often underrepresent these key processes, particularly in monsoon-influenced areas characterized by strong seasonal dynamics and vertical coupling. Therefore, advancing regional climate-chemistry modeling frameworks is critical to disentangle local versus transported signals, reduce uncertainty in regional N_2O budgets, and improve source attribution accuracy. Addressing these challenges will enable more robust evaluations of emission inventories and atmospheric processes, ultimately supporting more effective mitigation strategies for this potent greenhouse gas.

Here, we introduce N_2O as a transported inert tracer into the RegCM-Chem-YIBs regional climate-chemistry-ecosystem model. The implementation includes horizontal advection, vertical mixing, and convection of N_2O in the atmosphere, without internal biogeochemical sources or sinks. Two widely used inventories CAMS and EDGAR are used as surface forcing to drive the model. Our objectives are to assess the spatial and seasonal variability of simulated N_2O concentrations over East, South, and Southeast Asia in 2020, evaluate the sensitivity of model outputs to the choice of inventory and explore the driving factors influencing the seasonal concentration of nitrous oxide. Unlike many process-based studies focusing on terrestrial emissions, our approach decouples surface flux generation from atmospheric redistribution, thereby enabling a clearer assessment of how inventory choices affect modeled N_2O distributions. This work serves as an initial step toward the inclusion of N_2O in regional climate-chemistry modeling systems, with implications for understanding the atmospheric transport of N_2O in high-emission regions. It also provides a framework that can be extended in future studies to incorporate biogenic fluxes and feedbacks with land surface processes. Section 2 provides a detailed overview of the methods and datasets used in this study, while the subsequent results and discussions are analyzed in detail in Sections 3 and 4. Our main conclusions and summaries can be found in Section 5.

Original comment 2#: The manuscript focuses on the seasonal fluctuations of N_2O concentrations and concludes that surface concentration is low when surface N_2O emissions are low. This is not supported by their figures. Moreover, the seasonal variations across all sites are not "pronounced" as claimed by the authors. The fluctuations are quite small, within about 1~2 ppb, which is minor relative to the N_2O concentration. A deep analysis on seasonal fluctuations of atmospheric N_2O concentrations can refer to the paper "The Modeled Seasonal Cycles of Surface N_2O Fluxes and Atmospheric N_2O".

Response: Thank you for these important comments. We agree that our original figures did not clearly support the statement regarding the seasonal co-variation between N_2O emissions and concentrations. To address this, we conducted a quantitative correlation analysis between monthly mean surface N_2O concentrations simulated by the model and the corresponding surface N_2O emissions across the study domain. Figure S5 exhibits the correlation between the CAMS emissions and the simulated concentration is higher ($R^2 = 0.84$, $p < 0.01$), while the correlation for EDGAR is slightly lower ($R^2 = 0.46$, $p < 0.01$). We explain it in lines 456-470 of the revised edition.

We added a new section 2.5 named "Extraction of Seasonal Signals in Surface N_2O Concentration and Driving Factors". According to the method of Sun et al. (2024), this section elaborates in detail on how we detrend and standardize the observational data and model simulation results, as well as the specific methods for extracting the seasonal influencing factors of surface nitrous oxide concentration from the existing data. The new section was in the revised manuscript (Lines 246-291). Although the seasonal fluctuation range of nitrous oxide concentration is relatively small compared to its concentration, after detrending and standardizing the ground nitrous oxide concentration data, we found that the six stations within the study area showed a relatively obvious seasonality, with amplitudes reaching 2.9-3.6. Figure 8 shows the seasonal fluctuations in nitrous oxide concentrations across the six stations and the seasonal variations in driving factors. Table S3 lists the amplitudes of these factors at these sites, which can demonstrate their seasonal intensity and relative contributions. Importantly, our results are consistent with previous modeling studies. For instance, Nevison et al. (2007)

showed that the modeled seasonal amplitude of surface N_2O generally represents only 0.1%–0.2% of the annual mean value. Similarly, the N_2O seasonal amplitude of multiple sites selected by Sun et al. (2024) also rarely exceeds 2.5 ppb. In our study, the amplitude of seasonal cycles at individual stations (1–2 ppb) falls well within this expected range.

Revised version:

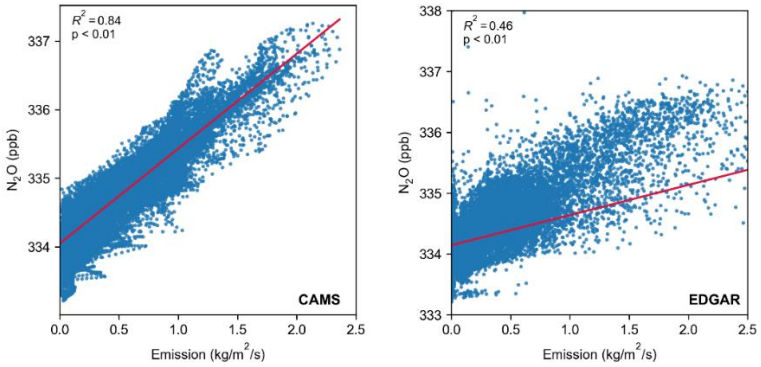

Figure S5. Spatial correlation of surface N_2O concentrations with emissions from CAMS and EDGAR inventories.

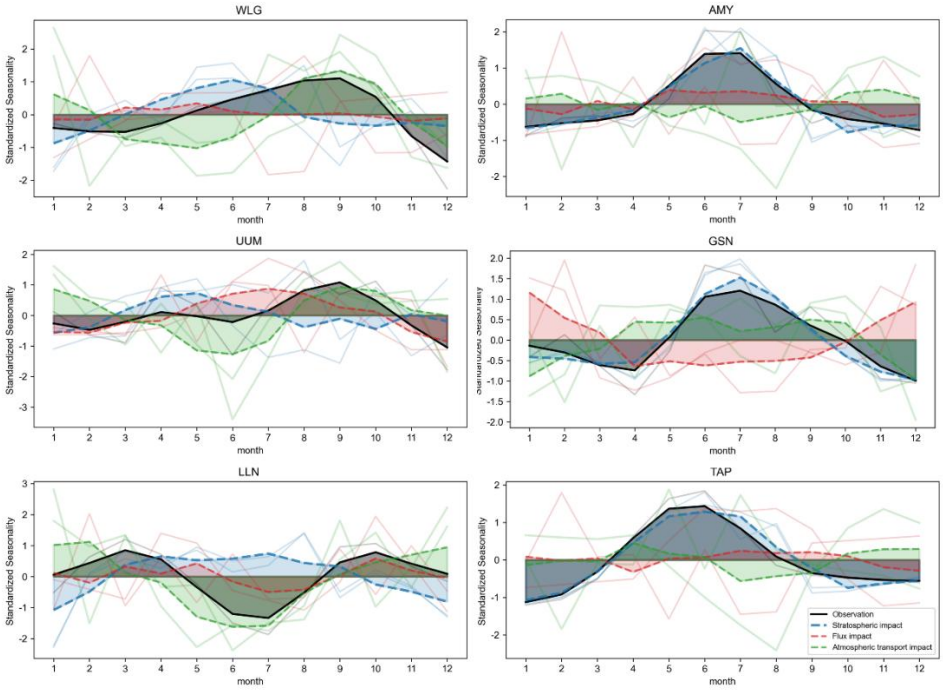

Figure 8. Seasonal patterns of surface N_2O concentrations and major driving factors at six sites in 2020.The black line represents the seasonal cycle of surface N_2O concentrations, while colored lines indicate the seasonal variations of influencing factors. Dashed red, blue, and green lines represent the smoothed average of the emissions contribution, stratospheric

contribution, and atmospheric transport contribution from the two emissions results, respectively. All variables are detrended and then normalized. For each factor, fine solid lines show the original data, and bold solid or dashed lines indicate the smoothed series. A shared legend is located in the lower-right corner of the TAP panel and applies to all six subplots.

Table S3. Amplitudes of seasonal cycles in surface N_2O concentrations and three major influencing processes: surface fluxes, atmospheric dynamics, and stratospheric contribution.

Site	observation	simulation	Flux impact	atmospheric transport impact	stratospheric impact
AMY	2.94	3.57	2.94	3.48	3.12
GSN	3.16	2.89	3.16	2.96	2.90
LLN	3.06	2.87	3.07	2.88	3.65
TAP	3.04	3.69	2.98	3.54	2.78
UUM	3.22	2.95	3.00	3.06	2.94
WLG	3.59	3.07	3.37	3.09	3.20

(L445-459): According to the grid-based correlation analysis results between the emission intensities from the two inventories (CAMS and EDGAR) and the simulated surface N_2O concentration field shown in Fig.S5, the results indicate that, within the study region, emission distribution is one of the primary drivers of the spatial variability in surface N_2O concentrations. The correlation between the CAMS emissions and the simulated concentration is higher (R^2 = 0.84, $p < 0.01$), while the correlation for EDGAR is slightly lower (R^2 = 0.46, $p < 0.01$). Despite the lower correlation, the EDGAR inventory remains valuable for large-scale assessments and policy-oriented studies, owing to its global consistency, regular data updates, and strong cross-regional applicability. It should be pointed out that although there is a strong spatial correlation, this does not imply a direct causal relationship between emission distributions and concentration patterns. Further comprehensive analyses incorporating transport processes and atmospheric dynamics are required. Importantly, the seasonality of surface N_2O concentrations exhibits pronounced spatial heterogeneity, particularly between land and ocean regions, where the dominant influencing factors differ significantly (Liao et al., 2004; Jiang et al., 2007; Sun et al., 2024). To better understand the region-specific drivers of this seasonality, we further investigated the seasonal patterns of N_2O at six ground-based observational sites across the study domain.

(L235-280): **2.5 Extraction of Seasonal Signals in Surface N_2O Concentration and Driving Factors**

To investigate the seasonal variations of surface N_2O concentrations and their key driving factors, we performed detrending and standardization of the monthly N_2O time series (Sun et al., 2024) from six observational stations, as well as associated environmental drivers, including surface emissions, stratospheric influence, and atmospheric transport parameters.

Detrending

Detrending aims to remove long-term monotonic trends from each time series to isolate intra-annual variability. For a given monthly series x_t, detrending was done using least-squares linear regression, and the residual was defined as the seasonal anomaly:

$$x_t' = x_t - (\alpha t + \beta) \quad (1)$$

where α and β are the slope and intercept of the linear fit to x_t, and x_t' is the detrended anomaly series. This procedure was applied to all relevant variables before seasonal comparison.

Standardization

To enable direct comparison of seasonal amplitudes and patterns among different variables which may have different units and variances, each detrended time series was further standardized using z-score normalization:

$$Z_t = (x_t' - \mu) / \sigma \quad (2)$$

where μ and σ are the mean and standard deviation of the detrended series x_t'. The resulting standardized time series Z_t has a mean of zero and unit variance, allowing direct comparison of seasonal fluctuations in N_2O and its drivers.

For the UUM site, observed surface N_2O concentrations were missing for November and December. These two values were gap-filled using linear interpolation to complete the seasonal cycle.

Decomposition of Seasonal Drivers

The seasonal variation in observed surface N_2O concentration ($\boldsymbol{S_{obs}}$) is known to be influenced by multiple processes (Nevison et al., 2011; Thompson et al., 2014), including:

- Surface emissions (EMI) from anthropogenic and natural sources
- Atmospheric transport (ATM) including advection and convection
- Stratospheric influence (STR) due to the stratosphere-troposphere exchange (STE) and chemical sinks in the stratosphere
- Model structural uncertainty and observation error ($\boldsymbol{\varepsilon}$)

We assume the seasonal signal of observed N_2O can be approximated as:

$$\boldsymbol{S_{obs} = S_{EMI} + S_{ATM} + S_{STR} + \varepsilon} \quad (3)$$

In our modeling system, RegCM-Chem-YIBs explicitly includes surface emissions and meteorology-driven transport, but stratospheric chemistry and STE are not. Thus, we approximate the stratospheric contribution (STR) to the seasonal cycle as the difference between observed and modeled N_2O at each site:

$$\boldsymbol{S_{STR} + \varepsilon \approx S_{obs} - S_{sim}} \quad (4)$$

where $\boldsymbol{S_{sim}}$ refers to the modeled N_2O concentration at the corresponding site. This residual implicitly includes the effects of STE, stratospheric sinks (e.g., photolysis, $O(^1D)$ reactions), and any model biases unrelated to emissions or transport and the observation error. For clarity, we refer to this residual as the stratospheric contribution (STC) in the following analysis.

The seasonality of surface emissions (EMI) is derived directly from the monthly gridded fluxes provided by the CAMS and EDGAR inventories. After regridding and matching to observation sites, the same detrending and standardization procedure was applied. The seasonal transport component (ATM) is then estimated by subtracting the flux-induced N_2O signal from the modeled total:

$$\boldsymbol{S_{ATM} = S_{sim} - S_{EMI}} \quad (5)$$

Original comment 3#: One advantage of regional climate models is that they can provide higher-resolution estimates of target variables. Yet there are no figures showing the model obtains N_2O concentrations with spatial details.

Response: We appreciate the reviewer's observation regarding the spatial resolution of the modeled N_2O concentration fields. Indeed, one of the key advantages of regional climate-chemistry models such as RegCM-Chem-YIBs is their ability to simulate atmospheric variables at fine spatial resolution (36 km × 36 km in our setup). However, in the original version, the figures based on simulations driven by CAMS reanalysis data (with a native resolution of 2.5° × 1.27°) appeared spatially coarse. This is because the input emissions and boundary conditions from CAMS, which are derived through global-scale top-down inversion, inherently limit the spatial variability of the resulting N_2O fields despite the high resolution of the dynamical core.

To better highlight the model's capacity to represent regional spatial detail, we have added new figures in the revised manuscript showing N_2O concentrations driven by the EDGAR inventory (resolution: 0.1° × 0.1°). These results clearly demonstrate enhanced spatial detail in surface N_2O distributions, especially over East Asia where emission heterogeneity is high. We believe this addition better supports the utility of the regional model and directly addresses the reviewer's concern. The revised figure is now shown in Figure 5.

Revised version:

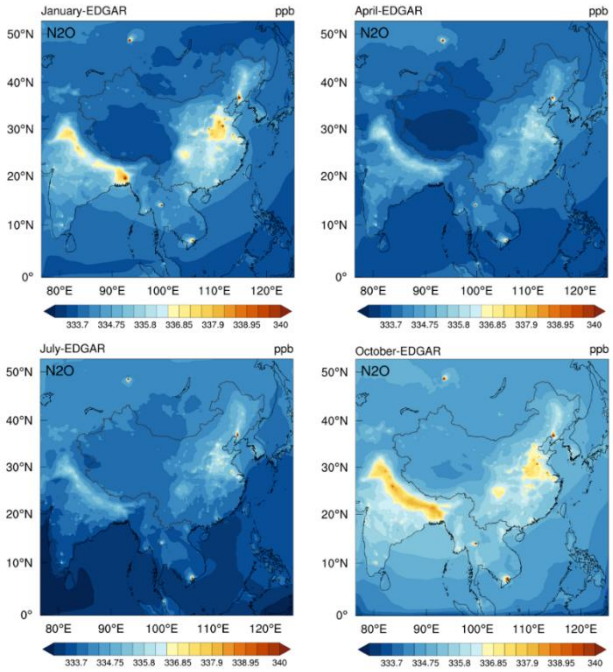

Figure 5. The distribution of the seasonal average ground-level N_2O concentration in 2020, as simulated by the EDGAR datasets.

Original comment 4#: The text is not well written. There are many statements explaining specific definitions or terms (e.g., Lines 109-112), which are not closely related to the topic of this manuscript.

Response: Thank you for comment. We fully agree that unnecessary definitions and explanations can detract from the clarity and focus of the manuscript. In the revised version, we have carefully reviewed the entire manuscript and removed or condensed background descriptions that are not directly relevant to the scientific objectives or methodology of this study. In addition, some necessary chapters and paragraphs have been added to broaden the depth of the article.

Specifically, we have revised Lines 109-112 to eliminate generic or widely known definitions. Our goal was to streamline the narrative and ensure that all included information directly supports the study's objectives and scope.

Additionally, we have improved the overall writing style for conciseness and scientific clarity.

Besides, we removed the overly general statements related to complex N_2O and atmosphere interactions and mitigation strategies, as these topics go beyond the scope of this study. We also revised the abstract and introduction to more accurately reflect the study objectives, emphasizing that this work serves as a necessary first step toward understanding the inventory driven uncertainties in N_2O simulations, prior to investigating interaction mechanisms or designing mitigation strategies. In addition, we explicitly clarified the study's scope in the introduction to avoid confusion about the intended contributions of the paper. We have made modifications to abstract in the revised manuscript (Lines 29-32, 118-124) to help readers better understand this work.

To study the seasonal variation of surface N_2O concentrations and the key drivers, we conducted detrending analysis and standardization on data of the six sites (Sun et al., 2024) and related environmental drivers (including surface emissions, stratospheric effects, and atmospheric transport parameters). We have added Section 2.5 to introduce the methods of detrending and standardization as well as the decomposition of factors affecting the seasonal signals of nitrous oxide on the ground. The modified parts are on lines 246-291 of the revised version.

We have divided the "results and discussions" in the original manuscript into two separate sections. For Section 3.4, we described in more detail the seasonality of nitrous oxide concentrations at the six sites in the study area and the contribution of its driving factors. After detrending and standardization, it was found that these sites all exhibited relatively obvious seasonal characteristics, and the contributions of each driving factor were not the same, varying from site to site. (Lines 456-511)

In the discussion section, we analyzed and compared the differences between the two inventories and the reasons for the similarities and differences between their simulation results and the observed and reanalyzed data. Then we discussed the reasons why the model of this study failed to reproduce the peak N_2O concentrations at the AMY, GSN and TAP sites in June. We also analyzed why the CAMS-driven simulations consistently produced higher N_2O concentrations than those driven by EDGAR at sites such as TAP, UUM, and WLG. In addition, the reasons why the regional average surface nitrous oxide concentration simulated by the model is low in summer and high in winter, which shows an inconsistent trend with the

observed values of these six observation stations, were also discussed. We analyzed three possible reasons that could explain this phenomenon, which are seasonal variation in the height of the atmospheric boundary layer, regional differentiated transport effects and the STE influence. Finally, we discussed the uncertainties of the article, including the uncertainties of observations, model uncertainties, and the uncertainties of the decomposition methods of seasonal drivers, and analyzed the limitations of the model. In future work, we plan to incorporate more detailed internal biogeochemical processes of N_2O into the model framework, particularly soil nitrification and denitrification. Moreover, evaluating the influence of multiple emission inventories in parallel will enhance the robustness of our conclusions. To better constrain the vertical budget and assess the role of stratosphere–troposphere exchange, we also aim to adopt a fully coupled chemistry-climate model that explicitly resolves STE processes. These improvements will enable more accurate attribution of N_2O variability and support more reliable scenario projections. (Lines 521-649)

We hope these revisions help strengthen the manuscript's focus and improve its readability for readers.

All the revisions have been incorporated into the revised manuscript, and we hope that the updated version now meets the requirements of the journal. We sincerely appreciate the reviewer's thoughtful comments and efforts, and we respectfully invite a re-evaluation of the manuscript.

The following are the newly added references:

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