We thank the reviewers for the constructive comments and helpful suggestions. We have revised the manuscript carefully according to those valuable suggestions. In the following, the detailed point by point responses to reviewers' comments are listed with our responses are shown in blue.

Response to Anonymous Referee # 1

Ref: EGUSPHERE-2025-6412

Title: Lifetimes and transport characteristics of different-sized aerosols in the Asian Tropopause Aerosol Layer: a climate model study

This manuscript investigates the lifetimes and transport characteristics of different-sized aerosol particles within the ATAL using idealized sensitivity experiments with the CESM. The study addresses the important question of aerosol persistence in the upper troposphere and lower stratosphere, a key factor for climate impact assessment. The topic is timely, and the experimental methodology is generally sound. However, inconsistent definitions of the ATAL region across figures undermine result comparability and require clarification. Several language issues also need correction. Overall, the manuscript provides valuable insights but requires minor revisions before it can be considered for publication.

Major comments:

1. The definition of the ATAL region appears inconsistent across the manuscript. In Figs. 2 and 8, the ATAL region is defined as 20–60° N, 20–150° E, while in Figs. 1 and 3, it is defined as 15–45° N, 0–160° E. Could the authors clarify whether a consistent regional definition was used throughout the analysis? If different definitions were adopted for different analyses, please explain the rationale behind these choices and specify the corresponding definitions clearly in the method section to avoid confusion in result interpretation.

Response: We thank the reviewer for pointing out this inconsistency. Since the discovery of the ATAL from satellite observations (Vernier et al., 2011), the definition of its spatial extent has varied slightly across published studies. In relevant previous studies, the meridional range of the ATAL is consistently selected as 15–45°N, while the zonal range varies substantially depending on research objectives, data sources and analytical methods. Here, we list some zonal ranges of the ATAL adopted in previous studies: 0–160°E (Zhang et al., 2020), 0–150°E (Raj et al., 2022), 5–105°E (He et al., 2021), 15–105°E (Vernier et al., 2011, 2015) and 30–105°E (Fairlie et al., 2019).

For Figs. 1 and 3, we adopted the ATAL region of 15–45°N, 0–160°E which is widely used in previous studies (e.g., Zhang et al., 2020). This full-scope definition covers all the different boundaries of the ATAL documented in previous studies for the purpose of validating our model performance in simulating the ATAL. For Figs. 2 and 8, we adopted an adjusted scope of 20–60°N, 20–150°E. These two figures focus on the quantitative assessment of the Asian summer monsoon anticyclone (ASMA) trapping effect on aerosols via the confinement duration, which is built directly on the

horizontal transport results of ATAL particles in Fig. 7. As Fig. 7 shows significant poleward transport of aerosols to mid-high latitudes beyond the core ATAL meridional range, we extended the analysis domain so that a more integrated picture of the transport pathway of particles can be captured.
Nevertheless, we recognize that we failed to elaborate on the rationale for these domain selections in the original manuscript, which may cause confusion for readers to interpretating the results. In the revised manuscript, we have clarified why different analysis domain is used in different figures and a detailed explanation of the domain selection rationale for Figs. 2 and 8 is added.

Some other comments:

1. Line 12: "a series of sensitivity experiments were conducted" → "a series of sensitivity experiments was conducted".

Response: Thanks for the reviewer's comments. We have revised it.

2. Line 120: "and MERRA-2 reanalysis data for summer 2000" → "and MERRA-2 reanalysis data for year 2000".

Response: Thanks for the suggestion. We have revised it.

3. Line 81: The summation subscript in Equation (1) has a typo: "$\sum_{t-0}^{t=2\ mo} C(t)$" should be revised to "$\sum_{t=0}^{t=2\ mo} C(t)$".

Response: Thanks for pointing out this. We have revised it.

4. Line 179: "We can note that the average mass concentration of the smallest NCl a2 particles..." uses colloquial expression that is not suitable for academic writing. It is recommended to revise to "Results show that" or directly describe the observed phenomenon.

Response: Thanks for the reviewer's comments! We have revised it.

5. Table 1: The unit "day" should be revised to the plural "days" in line with academic norms.

Response: Thanks for the suggestion. We have revised it.

6. Line 352: "Given that fact that aerosol mass concentration within the ATAL exhibits a persistent increasing trend..." → "Given the fact that…".

Response: Thanks for the reviewer's suggestion. We have revised it.

7. Line 354: "Estimates of the ATAL's radiative effects in previous studies have based on bulk aerosol properties" → "…have been based on…".

Response: Thanks for the comments. We have revised it.

Response to Anonymous Referee # 2

Ref: EGUSPHERE-2025-6412

Title: Lifetimes and transport characteristics of different-sized aerosols in the Asian Tropopause Aerosol Layer: a climate model study

Review of Dong et al. (2026) entitled "lifetimes and transport characteristics of different-sized aerosols in the Asian Tropopause Aerosol Layer: climate model study" The transport and lifetime of aerosols in the Upper Troposphere and Lower Stratosphere (UTLS) are keys to assessing their radiation, climate and chemical impacts. In this study, Dong et al. (2026) used the CESM2 dynamical model coupled with the MAM7 modal aerosol model to simulate idealized scenarios to investigate the aerosol lifetime and transport originated from the Asian Summer Monsoon (ASM) region. They conducted multiple simulations in which they artificially release Sodium Chlorine (NaCl) aerosols at several altitudes and locations. While the results presented in this study are not fully new and follow expectations based on already published work on the ASM, there are still values in conducting idealized cases to further summarize our general understanding even if it is rather simplified. As stated in the conclusion of this paper, the composition of the ATAL is far more complex than assuming NaCl but some transport characteristics especially near the tropopause are probably still valid. I also appreciate the coherent structure of this study which reads well. One could propose much complex experiments that could be a next step after this initial work. In summary, I recommend the publication of this after some revisions which I propose below:

I have two major comments about the simplified approach the authors have taken:

1. How does convection affect the aerosol lifetime in these simulations and how could this be differentiated from sedimentation? Could you find metrics to study this using existing simulations?

Response: We thank the reviewer for this good question. Convection influences aerosol lifetime through several intertwined pathways. 1. Vertical redistribution of aerosols out of the boundary layer which is on a relatively short timescale. Strong convective updrafts can rapidly pump aerosols from the boundary layer—the primary "removal zone"—into the free and upper troposphere; 2. Modulation of aerosols' wet removal time. By governing when and where aerosols enter (activate) and leave (resuspend) clouds, convection effectively regulates the height and efficiency of wet scavenging (Ghan et al., 2001; Pant et al., 2026); 3. Modulation of aerosols' dry deposition time. Convection can transform aerosols' microphysical properties in ways that ultimately accelerate their removal via sedimentation and dry deposition.

In our model simulations, these processes are represented by separate parameterization schemes. Vertical transport of interstitial aerosols by deep convection uses updraft and downdraft mass fluxes from the Zhang–McFarlane scheme, and is currently computed separately from wet removal (Collins et al. 2004). Cloud-borne aerosols associated with stratiform clouds are assumed not to interact

with convective clouds. Shallow convective transport is treated analogously with mass fluxes from the shallow convection scheme. Turbulent transport of aerosols is given a special explicit treatment to strengthen coupling with aerosol activation in stratiform clouds. Although these parameterizations capture the first-order effects, they do not explicitly resolve the full microphysical coupling within convective clouds.

Sedimentation is a continuous, size-dependent gravitational settling process that acts at all levels, whereas convection is an intermittent, sub-grid-scale transport that redistributes aerosols vertically and alters their size distribution. In principle, one can separate their contributions in the model's process-level tendency budgets: the aerosol mass tendency at each level is the sum of advection (including convective transport), turbulent mixing, sedimentation, wet scavenging, and sources/sinks. By saving the instantaneous tendencies from the convective transport and sedimentation modules, one can quantify their direct contributions to the vertical flux of aerosol mass.

However, this direct separation captures only the direct transport effect, not the indirect microphysical pathway (e.g., convective processing changing particle size and thereby modifying the sedimentation rate). The latter is an emergent consequence of the coupled system and cannot be cleanly isolated by tendency diagnostics alone.

It should be pointed out that the current model configuration does not explicitly resolve convective dynamics and associated cloud microphysics; these are represented through sub-grid parameterizations with inherent assumptions (e.g., convective transport is calculated separately from wet removal, and cloud-borne stratiform aerosols do not interact with convective clouds). As a result, the indirect pathway—whereby convection modifies particle size and subsequently alters sedimentation—emerges from a sequence of parameterized steps that were not fully coupled. A fully explicit separation requires convection-permitting simulations with online aerosol–cloud interactions, which is beyond the capacity of the current global modeling configuration.

In summary, convection affects lifetime through vertical redistribution, cloud processing, and wet removal time. Sedimentation acts as a continuous size-dependent sink. Using existing simulations, the parameterized and partially decoupled nature of convective transport prevents a strict quantitative separation of its effect from sedimentation. The above points are clarified in the revised paper.

2. Would the same experiments repeated with organics, sulfate and or Ammonium nitrate particles differ?

Response: There is no doubt that the same experiments with organics, sulfate, or ammonium nitrate give rise to different results in aerosol burden, spatial distribution, and lifetime. Chemically, NaCl remains inert throughout transport, whereas organics undergo oxidation and aging, sulfate governs particle acidity and heterogeneous chemistry, and ammonium nitrate partitions between the gas and particle phases in response to ambient temperature, which would cause partial evaporation of the particles in the warm upper troposphere. Radiative effects would also differ: sea salt is a purely scattering aerosol, but organic aerosols often contain absorbing components

such as black and brown carbon, implying that using NaCl as a proxy would overestimate the single-scattering albedo and bias the direct radiative effect. Furthermore, fine particles such as sulfate and aged organics have longer atmospheric residence times than coarse sea salt, which would increase their background concentrations in the upper troposphere and lower stratosphere. However, the primary objective of this study is not to reproduce the full chemical and radiative lifecycle of realistic ATAL aerosols, but to isolate how atmospheric dynamics—convective injection, large-scale circulation, and gravitational settling—differentially affect the transport and confinement of particles as a function of size. To achieve this, we deliberately selected sea salt particles as chemically inert and radiatively inactive tracers, disabled their direct radiative effect, and systematically varied only the particle size, release location, and release height across 27 independent experiments. Introducing reactive or absorbing species would couple physical transport with chemical sources, sinks, and radiative feedbacks, making it difficult to disentangle the pure dynamical controls that are the focus of this work. Therefore, while the reviewer's point is indeed important and the differences among aerosol species are physically meaningful, addressing those differences lies beyond the scope of the specific question we set out to answer. For the purpose of establishing a clean, size-resolved dynamical transport baseline, the simplified use of inert sea salt particles is an ideal experimental design. We have now clarified this rationale and acknowledged the limitations in the revised manuscript.

In addition, I propose other modifications:

1. Section 2.2 line 80-85: The aerosol lifetime equation is a little confusing since the authors include a global aerosol mass term C and a loss rate term D. I do not think it makes sense to include total mass and loss in the same equation. Please provide further explanations about this equation.

Response: Thanks for the reviewer's comments. We have revised it.

We appreciate the reviewer's insightful comment regarding the potential conceptual confusion introduced by Eq. (1).

$$\tau_{2\,mo} = \frac{\sum_{t=0}^{t=2\,mo} C(t)}{\sum_{t=0}^{t=2\,mo} D(t)}\ , \qquad (1)$$

We clarify that the simultaneous inclusion of *C(t)* (global aerosol mass burden) and *D(t)* (sink term) in the same equation is mathematically and physically consistent, originating from the discrete integral form of the mass balance equation.

In any given domain, the species mass balance may be described as

$$\frac{dC(t)}{dt} = \mathrm{S(t)} - \frac{C(t)}{\tau(t)}$$

where *C(t)* is the species abundance at time *t*, *S(t)* is the source rate, and *τ(t)* is the removal timescale (Croft et al., 2014).

To address the reviewer's concerns about dimensional coherence, we explicitly provide the intermediate derivation steps as follows:

In the case of an emission pulse (either instantaneous or over a short period) followed by a removal period considerably longer than the pulse, the mean lifetime can be

similarly defined using the integral form of the original differential mass balance equation and assuming *S(t)*=0 for the time period of integration (Croft et al., 2014), we have:

$$\frac{dC(t)}{dt} = -\frac{C(t)}{\tau(t)}$$

Since the absolute aerosol mass loss rate (sink term) is defined as $D(t) = \frac{C(t)}{\tau(t)}$, the equation can be simply rewritten as:

$$\frac{dC(t)}{dt} = -D(t)$$

By integrating both sides over a specific period (e.g., 2 months) under the assumption of a time-invariant removal timescale, the mean lifetime can be calculated via the ratio of the total mass inventory over time to the total cumulative loss over the same period:

$$\tau_{2\,mo} = \frac{\sum_{t=0}^{t=2\,mo} C(t)dt}{\sum_{t=0}^{t=2\,mo} D(t)\,dt}$$

In numerical modeling, where a finite timestep Δt is used, this continuous integral is discretized as:

$$\tau_{2\,mo} = \frac{\sum_{t=0}^{t=2\,mo} C(t) \cdot \Delta t}{\sum_{t=0}^{t=2\,mo} D(t) \cdot \Delta t}$$

As the timestep Δt is constant throughout the integration period, it mathematically cancels out in both the numerator and the denominator, ultimately yielding the simplified form presented in Eq. (1):

$$\tau_{2\,mo} = \frac{\sum_{t=0}^{t=2\,mo} C(t)}{\sum_{t=0}^{t=2\,mo} D(t)}$$

Rather than an arbitrary inclusion, the numerator $\sum_{t=0}^{t=2\,mo} C(t)$ represents the time-integrated species mass burden, which measures the cumulative presence of the species in the atmosphere over time. Meanwhile, the denominator $\sum_{t=0}^{t=2\,mo} D(t)$ represents the total accumulated mass loss during the same period. The ratio of these two terms yields the mass-weighted average removal timescale, which is physically equivalent to the mean lifetime. For a system predominantly in the decay phase following a pulse emission, this ratio accurately approximates the steady-state lifetime.

We acknowledge that the absence of the Δt notation in the printed equation may lead to dimensional confusion at first glance. We hope this detailed explanation resolves the concerns regarding the physical soundness of Eq. (1).

2. L94: I believe that this line is overstated since previous simulations of the ATAL using the same model had a hard time and overestimated dust concentration. Could you please comment on that?

Response: We thank the reviewer for this comment. We agree that the original

statement on L94 was overstated, and we have revised it accordingly in the manuscript. Previous simulations with the same model indeed showed a tendency to overestimate dust concentrations, and we fully acknowledge this known bias. However, as demonstrated by Bossolasco (2021), comparisons of simulated CO with MLS and ACE-FTS observations indicate that, apart from a possible underestimation of CO emissions, the CAM5-MAM7 configuration is able to reproduce the position and spatial extent of the Asian monsoon anticyclone with reasonable fidelity. For the purpose of our study—which focuses on the size-dependent physical transport of passive tracers rather than on achieving a precise reproduction of absolute aerosol concentrations—the model's capacity to capture the large-scale dynamical structure of the anticyclone is sufficient. We have toned down the original claim in the revised manuscript and added some text to acknowledge the model's limitations regarding dust simulation. We appreciate the reviewer's careful reading and valuable suggestion.

3. L116: IPCC itself is not a database for emissions. Please clarify exactly which ones you are using?

Response: We thank the reviewer for pointing out this error. The original statement on L116 was indeed inaccurate: we incorrectly referred to the emission source simply as the "IPCC data set," whereas the anthropogenic emissions used in the CAM5-MAM7 configuration are taken from the IPCC AR5 emission data set. We have corrected this mistake in the revised manuscript. According to the official CESM CAM5 documentation, anthropogenic emissions of primary aerosol species and precursor gases—specifically OC, BC, and SO_2—are from the Lamarque et al. (2010) IPCC AR5 emission data set. We appreciate the reviewer's careful reading and apologize for the confusion caused by this oversight.

4. L105: The MAM7 microphysical processes described in this paragraph are very interesting but having a schematic would help the reader to understand.

Response: Thanks for this helpful suggestion. Following the reviewer's advice, we have added a schematic diagram adapted from Liu et al. (2012) as a supplementary figure (see bellow) in the revised manuscript to better illustrate the MAM7 microphysical processes described in this paragraph. This figure clearly shows the inter-modal mass transfer pathways in the MAM7 framework, wherein only the Aitken mode and the primary carbon mode transfer mass to the accumulation mode, while no mass transfer occurs between other modes. We believe this visual aid helps readers more easily grasp the size-resolved aerosol processing that is central to our experimental setup.

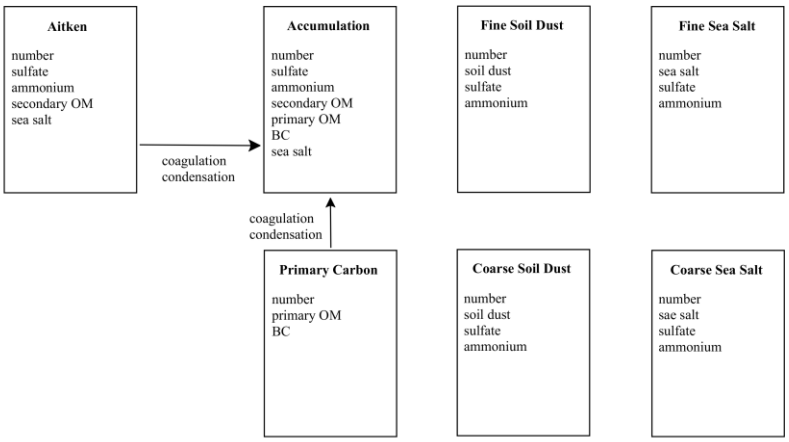

Figure S1: Predicted species for the component of each aerosol mode in MAM7. (Liu et al., 2012)

5. The term NCl is used across the paper but I believe the authors are referring to NaCl.

Response: The term "NCl" is the abbreviation used for sea salt in the CESM model output, while its actual chemical composition is indeed NaCl. To maintain consistency with the model's internal naming convention and our experimental configuration, we retained the abbreviation "NCl" throughout the manuscript. However, we fully agree that this may cause confusion for readers, and we have now added an explicit clarification in the revised text stating that NCl denotes sea salt (NaCl) as represented in the model.

6. Fig. 3 is very interesting and additional information could be added to understand the interactions between NaCl and cirrus cloud near the tropopause.

Response: We thank the reviewer for this interesting suggestion. As shown in Fig. 3, for the intermediate-sized a4 particles released at 16–17 km, the mass concentration contours in the first ten days run partly parallel to the tropopause, hinting at some temporary residence near the tropopause. Sea salt particles can indeed interact with cirrus clouds near the tropopause primarily as cloud condensation nuclei, influencing cloud lifetime and ice crystal size; upon cloud dissipation, the particles are released back into the free atmosphere, which could slightly prolong their atmospheric residence. However, since cirrus clouds themselves typically persist for only a few hours, this effect on the overall transport and lifetime of aerosols is rather limited. We have added some text address this issue in the revised manuscript.

Response to Hongwei Sun

Ref: EGUSPHERE-2025-6412

Title: Lifetimes and transport characteristics of different-sized aerosols in the Asian Tropopause Aerosol Layer: a climate model study

The manuscript uses CESM model to simulate the transport and lifetime of passive sea salt aerosol in the Asian tropopause aerosol layer. Several sensitive tests with different aerosol size, injection regions, and injection altitudes have been considered in the manuscript, which could help increase our understanding of how the trapping effect of the Asian summer monsoon circulation influence the particle transport. It's good to see that the manuscript shows some interesting findings. However, several caveats need to be addressed or clarified before the manuscript can be considered for publication, as outlined below.

Major comments:

1. This study focus on the passive particle transport, the most straightforward way should be directly adding a passive aerosol in CESM, which can only interact with transport and gravity settling. However, this study takes sea salt as the passive aerosol, with "their radiative and chemical effects being disabled in the model" (Line 370). But more clarification is needed for doing so:

(1) Should sea salt be NaCl, rather than NCl?

(2) Line 132: For sea salt, are there aerosol microphysical growth (e.g., coagulation, condensation)?

(3) Sea salt aerosols are hygroscopic, which means water vapor influences the sea salt aerosol size and concentration. Have the authors turn off this influence in CESM?

(4) Would sea salt aerosols serve as CCN to interact with clouds in CESM? If so, the authors may need to turn off this aerosol-cloud interactions, which can influence the loss rate of sea salt aerosols.

(5) Are there sea salt emissions in CESM? What is the background sea salt aerosol size/concentration, in addition to the NCl injection in the Asian tropopause aerosol layer?

(6) Line 138: what is a1 particles? Define their size.

Response: We thank the reviewer for these detailed and constructive comments regarding our experimental design.

(1) It is correct that sea salt is chemically NaCl. In CESM, sea salt is internally abbreviated as "NCl", and to maintain consistency with the model's internal nomenclature and our injection configuration, we have adopted this abbreviation throughout the manuscript. We recognize that this may cause confusion, and in the revised manuscript we have explicitly stated that NCl denotes sodium chloride (NaCl) to avoid any ambiguity.

(2) As described in Line 134 and Sect. 2.3, NCl a2 particles do experience microphysical growth after release. Through liquid-phase chemical processes and coagulation, they can grow continuously until they reach the size range characteristic of a1 (accumulation mode) particles. This modal transfer is explicitly simulated in

MAM7 via coagulation and condensation processes, and we have ensured that the description in the manuscript clearly reflects this behavior.

(3) In our experimental setup, we did not disable the hygroscopic growth of sea salt aerosols. Our rationale is fourfold:

First, the actual impact of hygroscopic growth in the UTLS is very limited: the deliquescence relative humidity of NaCl is around 75%, while the UTLS environment is extremely cold and dry, with relative humidity typically well below this threshold. Only in the vicinity of deep convective towers or cirrus clouds may the relative humidity transiently exceed the deliquescence point. Thus, most of the time the injected NaCl particles exist as dry crystals, and hygroscopic effects on size and settling velocity are negligible.

Second, retaining hygroscopicity avoids artificially underestimating particle size and settling velocity in the rare high-humidity scenarios; suppressing this growth would systematically bias the simulated lifetimes toward longer values.

Third, keeping hygroscopicity maintains consistency with other physical processes in the model, such as CCN activation and wet scavenging, which rely on the ambient (wet) particle size.

Fourth, from a methodological standpoint, we deliberately avoided making excessive non-standard modifications to the MAM7 aerosol module. We have already disabled radiative and chemical effects so that NaCl behaves as a near-passive tracer in the free atmosphere, while retaining physical properties directly relevant to transport and removal—including hygroscopicity. We believe this configuration better balances physical realism and the idealized nature of our transport experiment.

(4) Yes, in our setup sea salt aerosols can serve as CCN and participate in cloud-related processes, including cloud formation and precipitation. We chose not to deactivate this aerosol–cloud interaction for two main reasons.

First, because our injection occurs primarily in the UTLS region, where water vapor abundance is much lower than in the mid- and lower troposphere, cloud interactions are largely limited to cirrus near the tropopause, apart from localized convective clouds. In CAM5–MAM7, cirrus is simulated via parameterization schemes, and their typical lifetime is on the order of hours. After cloud dissipation, the aerosol particles acting as CCN are released back into the free atmosphere, so the net effect on the large-scale transport and residence time that we focus on is relatively limited.

Second, completely disabling the CCN activity of sea salt would also effectively switch off wet scavenging by clouds, a process that is particularly significant in the frequent deep convection during the Asian summer monsoon. Suppressing wet removal while retaining convective updraft transport would lead to an unrealistic accumulation of aerosols at upper levels.

Considering these factors, we decided to retain the ability of sea salt particles to act as CCN and interact with clouds.

(5) We thank the reviewer for this question. CESM includes a default sea salt emission scheme following Mårtensson et al. (2003) for particles with geometric diameter $< 2.8\ \mu m$ and Monahan et al. (1986) for larger particles, with the flux dependent on wind speed and water temperature as detailed in the model description.

The resulting background sea salt aerosol concentration is reflected in Fig. 4: prior to the particle injection, the mass concentration of NCl a2 in the stratosphere is approximately 2.8×10^{-12} kg kg^{-1}, and that of NCl a4 is about 7×10^{-12} kg kg^{-1}. These background levels are very low compared to the injected amounts, ensuring that the injected signal dominates our analysis.

(6) We apologize for the lack of clarity. The a1 particles refer to the accumulation mode aerosols as defined in Lines 95–97 of the manuscript, with a size range of 0.056–0.26 µm. We have verified that this definition is explicitly provided in the text to avoid any confusion.

2. I may need help to understand the lifetime calculation that the authors used here. It seems all the calculation is based on the two-month-mean time series of aerosol mass concentration (Line 81-85):

(1) How does the author calculate the C(t), the global aerosol mass burden, based on the two-month-mean time series of aerosol mass concentration? Is the global aerosol mass burden the total column aerosol mass burden or the mass burden in the upper troposphere lower stratosphere (UTLS)? If UTLS, defining based on 200-50 hPa (Line 283) may not accurate as we know the tropopause height is very different between tropics and higher latitudes.

(2) How does the author calculate the D(t) denoting the aerosol mass loss rate during a timestep Δt, which represents the total mass removed by deposition processes during that interval (Line 84)?

(3) If I understand correctly, based on the lifetime calculation equation (Line 83), the author should get a time series of the 2-month mean aerosol lifetime based on the two-month-mean time series of aerosol mass concentration. If so, I would like to see this time series of the 2-month mean aerosol lifetime.

(4) There is a typo in Equation (1): "t-0" should be "t=0" in the numerator.

Response: We thank the reviewer for these detailed questions and insightful comments. We address each point in turn below:

(1) The mass burden $C(t)$ used in the lifetime calculation refers specifically to the aerosol mass integrated within the UTLS region, not the global total column burden. We define the UTLS as the 200–50 hPa layer. We agree that a fixed pressure range may not represent the tropopause at all latitudes. However, the bulk of the aerosol transport in our analysis occurs over low and mid-latitudes (see Fig. 7), where the subtropical tropopause lies near 10–12 km (~250–200 hPa) and the tropical tropopause near 17–18 km (~100–70 hPa). In this context, the 200–50 hPa range provides a reasonable and consistent enclosure of the UTLS, and this definition has also been used in previous studies (e.g., Niemeier and Schmidt, 2017; Bossolasco et al., 2021).

(2) The mass loss rate $D(t)$ is obtained by taking the difference in $C(t)$ between two consecutive model output time steps. This difference represents the total mass of aerosol removed from the UTLS domain by deposition processes (dry and wet) during that interval.

(3) It is correct that the equation yields a time series of the two-month mean lifetime.

We chose a two-month averaging window because, as shown in Fig. 4, the UTLS mass burdens of a2 and a4 particles reach a quasi-steady state after approximately two months. As requested, we now provide the non-smoothed time series of $\tau_{2\mathrm{mo}}$ for all release cases in a new supplementary figure. This figure presents the lifetime evolution for particles of all three size modes released from the South Asia, ASMA, and East Asia injection points at three different altitude levels.

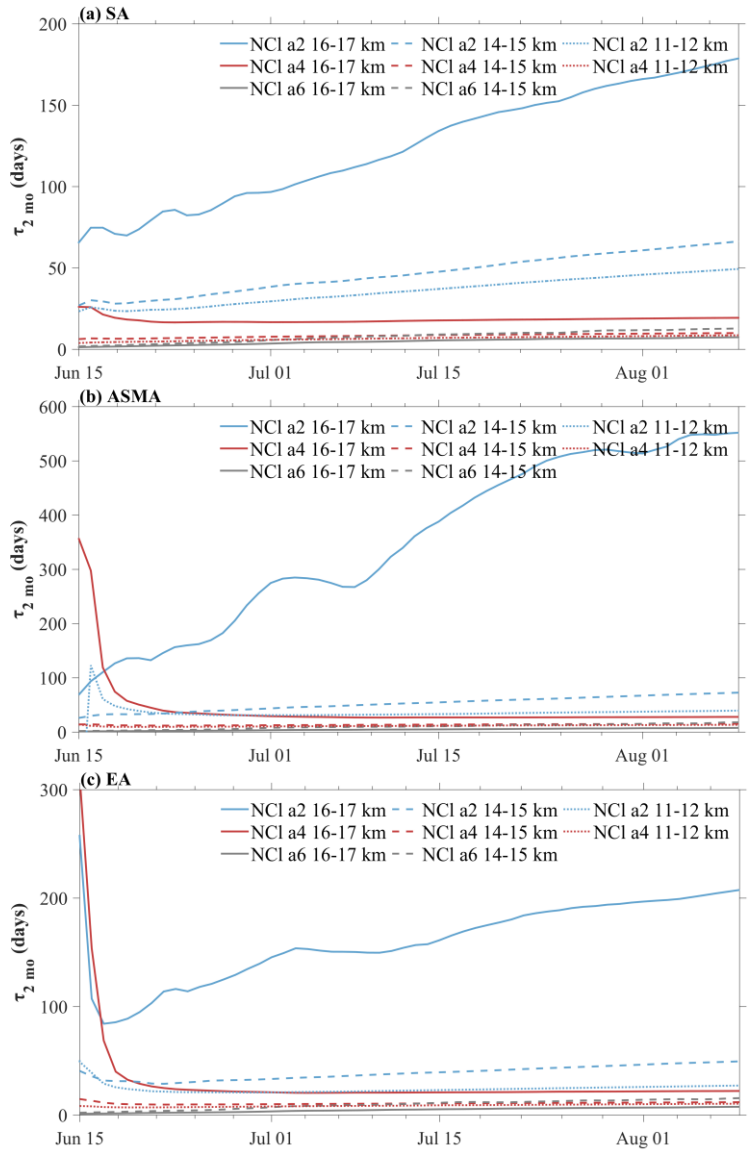

Figure 1: The simulated time series of the $\tau_{2\ \mathrm{mo}}$ of (a) SA injection point (b) ASMA injection point and (c) EA injection point released at different locations (red for a2 particles, blue for a4 particles, gray for a6 particles). Line styles denote release altitude: thick solid line for 16-17 km, dashed line for 14-15 km, and chain-dotted line for 11–12 km (unit: days).

(4) The typo is corrected. Thanks.

3. One important question worth checking/clarifying is if the ASM anticyclone is mainly good at trap the aerosols in the upper troposphere (near and below tropopause), or the ASM anticyclone is also good at allowing aerosols to transport upward and cross the tropopause (from the upper troposphere to the lower stratosphere). I think

the author touch this point somewhere in the manuscript, but may worth a more detailed discussion.

Response: This is a question. We agree that the dual role of the Asian summer monsoon anticyclone deserves a more detailed discussion than we originally provided. The anticyclone indeed acts both as an efficient trap that confines aerosols in the upper troposphere and near the tropopause, and as a critical pathway that facilitates their upward transport across the tropopause into the lower stratosphere. The trapping effect is primarily driven by the closed streamlines of the anticyclone, which isolate pollutants delivered by deep convection and inhibit lateral mixing with cleaner extraneous air, thereby maintaining enhanced aerosol and trace-gas concentrations within the upper troposphere–lower stratosphere region (Bian et al., 2020). However, this confinement is not permanent: trapped air gradually escapes to the stratosphere via two principal routes. The dominant route is slow diabatic uplift across isentropic surfaces over the southern flank of the anticyclone, which directly injects a substantial fraction of the air mass into the stratosphere, while a secondary route involves isentropic eddy shedding toward midlatitudes (Bian et al., 2020). The existence of the ATAL serves as direct observational evidence of successful cross-tropopause transport (Yu et al., 2017; Ma et al., 2019; Zhang et al., 2020). Thus, the anticyclone functions simultaneously as an effective reservoir in the upper troposphere and as a pump for cross-tropopause entry, representing two sequential steps in the complete transport pathway from Asian surface emissions to the global stratosphere. In the revised manuscript, we have expanded the relevant discussion to clarify this dual role.

Minor comments:

Line 223-229: this paragraph's explanation is dependent on the injection regions, as mentioned in the next paragraph. If injections happen in the EA and SA regions at 16-17 km, the lifetime is also short.

Response: We fully agree that the atmospheric lifetime and retention characteristics of aerosols are sensitively depend on injection regions, a point that we have examined in detail from multiple perspectives in the manuscript. The paragraph in Lines 223–229 is intended as a concise summary of the results grouped by injection height, as presented in Fig. 5a. At the same time, as can be seen from Fig. 4, even aerosols released over the EA region at 14–15 km retain substantially higher mass in the stratosphere than those injected over the ASMA at 11–12 km, suggesting that the injection height is a primary control. Taking NCl a2 particles as an example, when they are injected at the 16–17 km level over the EA, SA, and ASMA regions, their lifetimes are 207.6, 178.8, and 552.0 days, respectively. While the lifetimes over EA and SA are indeed considerably shorter than that over the ASMA at the same altitude, but still markedly longer than those released over the ASMA regions at 14–15 km. This indicates that injection height remains the dominant factor governing lifetime in this context, and the regional differences are explicitly addressed in the following paragraph. In the revised manuscript, the complete set of calculated lifetimes for all experiments has been included as a supplementary table.

Table S1: The $\tau_{2\ mo}$ calculated from the time series of the average mass concentration of NCl a2, a4 and a6 particles within the 200−50 hPa range for different release altitudes and different release locations. (unit: days).

Release sites	Release height	$\tau_{2\ mo}$(days)		
		NCl a2	NCl a4	NCl a6
ASMA	16−17 km	552.0159	28.0516	7.7835
	14−15 km	72.8006	15.4760	18.0015
	11−12 km	39.6531	13.4948	/
SA	16−17 km	178.7538	19.3742	19.3742
	14−15 km	66.3175	10.0047	12.8270
	11−12 km	49.3869	8.6786	/
EA	16−17 km	207.5658	22.2742	7.6751
	14−15 km	49.5613	11.9457	15.6592
	11−12 km	27.2507	10.5382	/

Figure 5 needs clarification: does Figure 5a show injection for all three regions? Does Figure 5b show injection at all injection altitude? But Line 234 mentions injection at 16-17 km, which may indicate Figure 5b only shows results for injection at 16-17 km? This can be related to my last comment.

Response: Figure 5a presents results for injections over all three regions, and Fig. 5b presents results for all injection altitudes. Line 234 mentions the 16–17 km case simply to highlight a noteworthy feature: for NCl a2 particles released at this altitude, the $\tau_{2\ mo}$ value over the ASM anticyclone hinterland is more than double that over the SA and EA regions, reaching 552 days. This example was included to highlight the regional dependence at high altitudes and as a target to the subsequent discussion on how injection location influences aerosol lifetime and transport characteristics. It was not intended to imply that Fig. 5b is restricted to the 16–17 km injection case. To avoid any potential misunderstanding, we have clarified this point in the revised manuscript, and the complete set of calculated lifetimes for all experiments has been included as a supplementary table.

Figure 6:

(1) add “probability density distributions” to the figure caption.

(2) Explain what is Day 10 to Day 120 in the figure caption.

(3) I think x axis should be using aerosol concentration, which may make more sense than using probability density, especially if you want to compare the left and right columns.

Response: We thank the reviewer for the constructive suggestions on Fig. 6.
(1, 2) We have changed the figure caption to "Mean vertical probability density distributions of NCl a2 particles after release at different locations, where solid lines represent releases at 16-17 km, dashed lines denote releases at 14-15 km. The lines in blue, red, and gray denote the ASM anticyclone hinterland release site, SA release site, and EA release site, respectively. The orange (16-17 km) and gray (14-15 km) bars indicate the initial release height. The day numbers on the top of each panel represent the days after release."
(3) Regarding the choice of the x-axis, we appreciate the reviewer's suggestion. However, because different experimental setups lead to substantial differences in aerosol mass concentration in the UTLS region (as shown in Fig. 4), directly using aerosol concentration would introduce redundant information arising from these mass differences. Since the primary aim of Fig. 6 is to examine how the injection settings influence the vertical distribution pattern of aerosols, we adopted probability density to normalize the results across experiments, thereby enabling a clearer and more focused comparison of the vertical structures. We have added a brief justification for this choice in the revised manuscript.

Figure 7:
(1) why use probability, instead of the particle number concentration, which can also show the change of total particle number between the two columns.
(2) Would be good to add boxes (like Figure 2) to indicate the injection regions.
(3) This is total column or only some vertical levels (UTLS)?
Figure 7 only shows the injection at 14-15 km, results from injection at 16-17 km may also be worth showing, at least in the supporting information.
Response: (1) Regarding the use of probability instead of particle number concentration, the rationale is the same as discussed for Fig. 6. Since different injection configurations lead to pronounced differences in the total aerosol mass residing in the UTLS, directly using particle number concentration would introduce redundant information arising from these mass differences, which are already thoroughly examined in Fig. 4. The primary purpose of Fig. 7 is to reveal how the horizontal distribution patterns differ among experiments, and normalizing the results to probability density allows for a cleaner comparison of the spatial structures by removing the confounding effect of total particle number. We have clarified this reasoning in the revised manuscript.
(2) We appreciate the suggestion to add boxes indicating the injection regions. We have now added injection location boxes to Fig. 7, following the style used in Fig. 2, so that the source regions can be readily identified.
(3) We confirm that Fig. 7 presents the total column distribution, and we have clarified this in the figure caption. Regarding the request to show results for the 16–17 km injection, we examined these outputs and found that the horizontal transport patterns are qualitatively consistent with those at 14–15 km, with the primary difference being higher stratospheric retention as already discussed in other analyses. To maintain conciseness in the main text, we have kept only the 14–15 km case in Fig.

7, but the complete results for the 16–17 km injection have been included in the supplementary information.

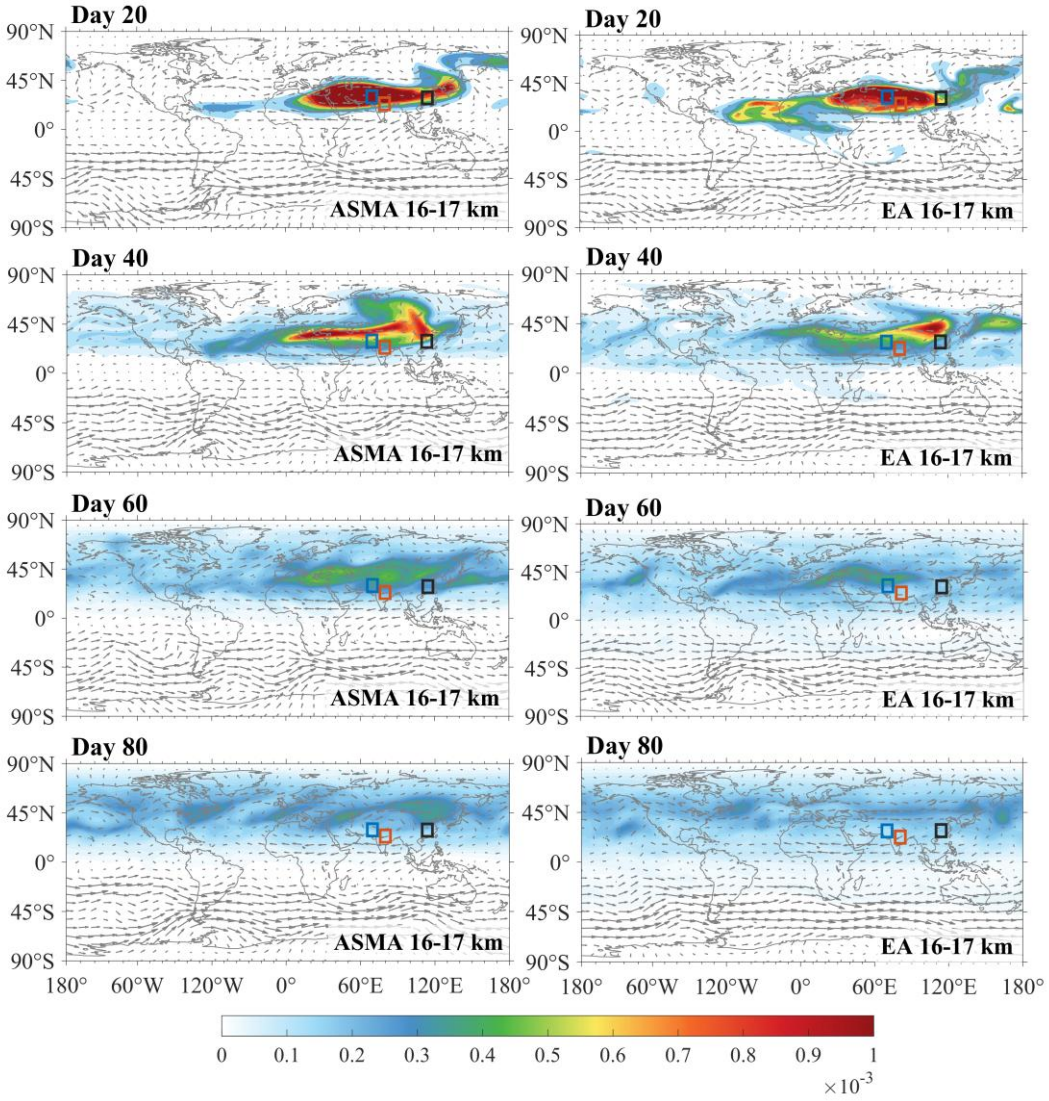

Figure S2: Mean probability distribution functions of NCl a2 particles released at the ASM anticyclone hinterland (left) and EA (right) release site at 16-17 km, overlaid with horizontal wind vectors (gray arrows).

Figure 8:

(1) one issue in this paper is using both pressure level and height level, which may make readers have difficulty to compare. I can see that the authors have made an effort to clarify this, but I may be a bit picky and would encourage the authors to improve it further.

(2) The red line in Figure 8c shows very low decay, any physical explanation?

(3) The ratio (in the subplots) in the end will reach a steady state of 20%, which confused me. If you look at the lines in the main plot, shouldn't the steady-state ratio in the subplot be around 50%?

Response: We thank the reviewer for the detailed suggestions on Fig. 8.

(1) We agree that using both pressure and altitude levels may cause confusion for readers. In our experimental setup, the external emission source in CESM must be

specified in geometric altitude (km), so all particle injections were released at prescribed altitude levels. However, the model's default diagnostic output uses pressure as the vertical coordinate. To avoid introducing unnecessary errors through coordinate transformations, we retained the pressure-based vertical coordinate for all analyses of model output. We have added clarifying remarks at points in the manuscript where the dual use of coordinates could cause ambiguity.
(2) As for the very slow decay of the red line in Fig. 8c, the underlying physical explanation was discussed in the original manuscript (Lines 315–323). During the Asian summer monsoon, the region over South Asia has been repeatedly identified by previous studies as an effective pathway for the upward transport of tropospheric air into the UTLS (Bian et al., 2020). Consequently, particles released over this region are continuously replenished into the UTLS by persistent deep convection, which sustains their mass concentration within the ATAL and leads to the notably slow decay seen in the figure.
(3) The main panel of Fig. 8 shows the time series of mass concentration within the ATAL region (20–60° N, 20–150° E) and the North American (NA) region (20–60° N, 20–150° W). After sufficient transport and mixing, the concentrations in these two regions converge to similar values, as the main panel indicates. The subplots, however, display the fraction of the total aerosol mass over the entire Northern Hemisphere that resides within the ATAL region. Because the ATAL and NA regions together represent only a small portion of the Northern Hemisphere, and their mass concentrations become comparable at steady state, the fraction within the ATAL stabilizes at a value well below 50%—approximately 20% according to our simulations—reflecting the areal weighting among the regions.

Line 285-286: In addition to the particle entering the ASM anticyclone center. Would the ratio also reflect the number of particle got scavenged/removed (due to the loss/deposition rate) after injection but before reaching North America?
Response: We thank the reviewer for this insightful comment. The ratio shown in the subplots is defined as the total mass of NCl a2 particles within the ATAL region divided by the total mass over the entire Northern Hemisphere. If particles are scavenged or removed by dry and wet deposition and thus leave the ATAL domain, their mass is no longer counted. Consequently, this ratio does not directly reflect the number of particles scavenged or removed after injection but before reaching North America. However, since dry and wet deposition processes operate continuously throughout the transport pathway, their influence is inherently embedded in the temporal evolution of the ratio. Nevertheless, it is not possible to isolate the contribution of deposition from this ratio alone.

Table 1: why the duration of anticyclonic confinement at 11-12 injection altitude is much larger for injections in SA than injections in ASMA?
Response: The longer duration of anticyclonic confinement at the 11–12 km injection altitude for the SA release site compared to the ASMA release site is discussed in the manuscript (Lines 319–325): "In the SA release site experiment, the high value of the

mass proportion in the ATAL region relative to the Northern Hemisphere total is maintained for a longer time, significantly differing from the other sites. This indicates that a greater proportion of NCl a2 particles in this experiment are transported upward into the anticyclone center compared to the others, allowing them to reside longer within the ATAL region and experience a longer trapping effect by the ASM anticyclone, up to 70 days. This result is consistent with Fig. 4, demonstrating that during the ASM period, the region over SA (the Indian subcontinent) serves as an effective pathway for transporting aerosol particles from lower altitudes to the upper troposphere and even into the stratosphere"

Line 315: Can the authors explain why "The proportion of NCl a2 particles entering the ASM anticyclone center is largest when particles are released at SA and smallest when particles are released at EA"? This may be related to my last comment.
Response: The reason that the proportion of NCl a2 particles entering the ASM anticyclone center is largest for the SA release and smallest for the EA release stems from their distinct geographical positions relative to the anticyclone circulation and the associated transport pathways. As discussed in the manuscript (Lines 272–276), the EA release site is located near the edge of the ASM anticyclone, where the atmospheric circulation is less enclosed. When released at the height of 14–15 km, aerosol particles released at this site disperse more rapidly and extensively outward, with a significant fraction even reaching the Southern Hemisphere UTLS region, thereby reducing the proportion that enters and remains within the anticyclone core. In contrast, the SA release site lies over the Indian subcontinent, a region that has been repeatedly identified as an efficient conduit for upward transport of tropospheric air into the UTLS during the Asian summer monsoon (Lines 319–325). Consequently, a larger fraction of particles released over SA is lifted directly into the anticyclone center, where they are more effectively trapped and can reside for extended periods. These contrasting behaviors are also consistent with the horizontal distribution patterns shown in Fig. 7 and the mass evolution in Fig. 4.

Line 331: reside stably within the "stratosphere", or within the "UTLS"?
Response: Thanks for the comments. We have revised "within the stratosphere" → "within the UTLS region".

Line 342: change "minimal diffusion" to "minimal horizontal diffusion".
Response: We have revised it.

Line 358: remove "that fact".
Response: Corrected.

Finally, based on my own research experience, I would suggest including a discussion at the end of the manuscript noting that "further studies using a Lagrangian trajectory tracking model [Sun et al., 2023; 2024] may provide a more detailed understanding of the trapping effect of the ASM circulation. In such models, each injected particle can

be treated as tagged, allowing greater flexibility to evaluate different injection locations and times, and to better characterize the three-dimensional structure of the ASM anticyclone region regarding particle transport and lifetime." For example, as shown in Figure 1 of Sun et al. (2023), each particle's lifetime can be linked to its specific injection location.

Sun, H., Bourguet, S., Luan, L. et al. Stratospheric transport and tropospheric sink of solar geoengineering aerosol: a Lagrangian analysis. npj Clim Atmos Sci 7, 115 (2024). https://doi.org/10.1038/s41612-024-00664-8

Sun, H., Bourguet, S., Eastham, S., & Keith, D. (2023). Optimizing injection locations relaxes altitude-lifetime trade-off for stratospheric aerosol injection. Geophysical Research Letters, 50, e2023GL105371. https://doi.org/10.1029/2023GL105371

Response: We thank the reviewer for this constructive suggestion. Following the reviewer's recommendation, we have added a discussion at the end of the revised manuscript pointing out that further studies employing a Lagrangian trajectory tracking model, such as those developed by Sun et al. (2023, 2024), may provide a more detailed understanding of the trapping effect of the ASM circulation.

References

Bian, J., Li, D., Bai, Z., Li, Q., Lyu, D., Zhou, X.: Transport of Asian surface pollutants to the global stratosphere from the Tibetan Plateau region during the Asian summer monsoon, Nat. Sci. Rev., 7(3): 516–533, https://www.sciengine.com/doi/10.1093/nsr/nwaa005, 2020.

Bossolasco, A., Jegou, F., Sellitto, P., Berthet, G., Kloss, C., and Legras, B.: Global modeling studies of composition and decadal trends of the Asian Tropopause Aerosol Layer, Atmos. Chem. Phys., 21, 2745–2764, https://doi.org/10.5194/acp-21-2745-2021, 2021.

Collins, W., Rasch, P., Boville, B., Hack, J., McCaa, J., Williamson, D., & Kiehl, J. (2004). Description of the NCAR Community Atmosphere Model (CAM 3.0). NCAR Technical Note, TN-464+STR.

Croft, B., Pierce, J. R., and Martin, R. V.: Interpreting aerosol lifetimes using the GEOS-Chem model and constraints from radionuclide measurements, Atmos. Chem. Phys., 14, 4313–4325, https://doi.org/10.5194/acp-14-4313-2014, 2014

Ghan, S. J., Easter, R. C., Chapman, E. G., Abdul-Razzak, H., Zhang, Y., Leung, L. R., Laulainen, N. S., Saylor, R. D., and Zaveri, R. A.: A physically based estimate of radiative forcing by anthropogenic sulfate aerosol, J. Geophys. Res., 106, 5279–5293, https://doi.org/10.1029/2000JD900503, 2001.

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017–7039, https://doi.org/10.5194/acp-10-7017-2010, 2010.

Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., Lamarque, J.-F., Gettelman, A., Morrison, H., Vitt, F., Conley, A., Park, S., Neale, R., Hannay, C., Ekman, A. M. L., Hess, P., Mahowald, N., Collins, W., Iacono, M. J., Bretherton, C. S., Flanner, M. G., and Mitchell, D.: Toward a minimal representation of aerosols in climate models: description and evaluation in the Community Atmosphere Model CAM5, Geosci. Model Dev., 5, 709–739, https://doi.org/10.5194/gmd-5-709-2012, 2012.

Ma, S., Zhang, X., Gao, C., Tong, D. Q., Xiu, A., Wu, G., Cao, X., Huang, L., Zhao, H., Zhang, S., Ibarra-Espinosa, S., Wang, X., Li, X., and Dan, M.: Multimodel simulations of a springtime dust storm over northeastern China: implications of an evaluation of four commonly used air quality models (CMAQ v5.2.1, CAMx v6.50, CHIMERE v2017r4, and WRF-Chem v3.9.1), Geosci. Model Dev., 12, 4603–4625, https://doi.org/10.5194/gmd-12-4603-2019, 2019.

Mårtensson, E. M., Nilsson, E. D., de Leeuw, G., Cohen, L. H., and Hansson, H.-C.: Laboratory simulations and parameterization of the primary marine aerosol production, J. Geophys. Res., 108(D9), 4297, doi:10.1029/2002JD002263, 2003.

Monahan, E. C., Spiel, D. E., and Davidson, K. L.: A model of marine aerosol generation via whitecaps and wave disruption, in Oceanic Whitecaps, edited by E. C.

Monahan and G. M. Niocaill, Oceanographic Sciences Library, vol. 2, pp. 167–174, Springer, https://doi.org/10.1007/978-94-009-4668-2_16, 1986.
Niemeier, U. and Schmidt, H.: Changing transport processes in the stratosphere by radiative heating of sulfate aerosols, Atmos. Chem. Phys., 17, 14871–14886, https://doi.org/10.5194/acp-17-14871-2017, 2017.
Pant, C. S., Waman, D., Patade, S., Deshmukh, A., Singh, N., Phillips, V., and Bansemer, A.: A modified stratiform cloud microphysics parameterization: evaluation using the Community Atmosphere Model version 6 single-column model, Atmos. Chem. Phys., 26, 7407–7433, https://doi.org/10.5194/acp-26-7407-2026, 2026.
Sun, H., Bourguet, S., Eastham, S., and Keith, D.: Optimizing injection locations relaxes altitude-lifetime trade-off for stratospheric aerosol injection, Geophys. Res. Lett., 50, e2023GL105371, https://doi.org/10.1029/2023GL105371, 2023.
Sun, H., Bourguet, S., Luan, L., Eastham, S., and Keith, D.: Stratospheric transport and tropospheric sink of solar geoengineering aerosol: a Lagrangian analysis, npj Clim. Atmos. Sci., 7, 115, https://doi.org/10.1038/s41612-024-00664-8, 2024.
Yu, P., Rosenlof, K. H., Liu, S., Telg, H., Thornberry, T. D., Rollins, A. W., Portmann, R. W., Bai, Z., Ray, E. A., Duan, Y., Pan, L. L., Toon, O. B., Bian, J., and Gao, R. S.: Efficient transport of tropospheric aerosol into the stratosphere via the Asian summer monsoon anticyclone, Proc. Natl. Acad. Sci. U.S.A., 114, 6972–6977, https://doi.org/10.1073/pnas.1701170114, 2017.
Zhang, J., Wu, X., Bian, J., Xia, X., Bai, Z., Liu, Y., Cai, Z., Huo, J., and Lyu, D.: Aerosol variations in the upper troposphere and lower stratosphere over the Tibetan Plateau, Environ. Res. Lett., 15, 094068, https://doi.org/10.1088/1748-9326/ab9b43, 2020.