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Optimizing Injection Locations Relaxes Altitude-Lifetime Trade-Off for Stratospheric Aerosol Injection

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Key Points:

- Injection longitudes influence particle lifetime because of zonal asymmetry of poleward winds, especially in the lower stratosphere
- Optimizing injection latitude and longitude can increase stratospheric lifetime of injected particles without increasing injection altitude
- Injection strategies can be developed to maintain an interhemispheric balance of particle lifetime without compromising total lifetime

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Stratospheric Aerosol Injection (SAI) aims to offset some climate hazards by injecting aerosols into the stratosphere to reflect solar radiation. The lifetime of injected particles influences SAI's radiative efficacy—the ratio of radiative forcing to particle mass flux. We employ a Lagrangian trajectory model with particle sedimentation to simulate how background circulations influence the transport of passive particles (without microphysical growth) in the stratosphere and quantify sensitivities of particle lifetime to injection locations. At 20 km, optimizing injection locations can increase particle lifetime by >40%. Injection strategies can be constrained to maintain an interhemispheric balance of particle lifetime without significantly decreasing total lifetime. Generally, increasing injection altitude increases particle lifetime while also increasing costs and environmental impacts of deployment aircraft. Optimizing injection latitude and longitude can relax this altitude-lifetime trade-off by increasing lifetime without needing to increase altitude, which warrants further testing in global climate models with aerosol microphysics.

Plain Language Summary Stratospheric Aerosol Injection (SAI) aims to reduce climate change by increasing the amount of aerosols in the stratosphere. These additional aerosols can reflect additional sunlight to partially offset the energy imbalance caused by greenhouse gases. The lifetime of injected particles in the stratosphere is one of the important factors that can influence the cooling effects of SAI, as particles that stay longer in the stratosphere can reflect more sunlight over their lifetime. We use observed stratospheric winds to simulate the transport of injected particles and then calculate the particle's lifetime in the stratosphere, aiming to understand how lifetime is related to the location and season at which the particles are injected. For particles injected at 20 km altitude, we can increase particle lifetime by >40% by optimally choosing injection locations. Increasing injection altitude can increase particle lifetime while also increasing the costs and environmental impacts of deployment aircraft. Our results suggest that optimizing injection latitude and longitude to increase lifetime can relax the trade-off between altitude and lifetime by increasing particle lifetime without needing to increase injection altitude.

1. Introduction

Stratospheric Aerosol Injection (SAI) is the deliberate introduction of aerosols or aerosol precursors into the stratosphere to reflect incoming shortwave radiation, which could reduce net radiative forcing and climate change. The climatic changes caused by SAI scale approximately linearly with the average radiative forcing, though climate response is also dependent on the spatial pattern of radiative forcing. The economic and environmental costs of SAI deployment along with the environmental impacts of descending particles (Eastham et al., 2018) scale approximately linearly with the mass flux of injected material. SAI radiative efficacy, the ratio of radiative forcing to the flux of injected material, is thus important in determining the ratio of climate response to policy-relevant costs and environmental risks. The radiative efficacy is largely influenced by the lifetime of injected particles and the particle size distribution (Kleinschmitt et al., 2018; Niemeier et al., 2011; Weisenstein et al., 2022). Understanding the dependence of particle lifetime on injection strategies is a useful step in understanding how to optimize injection strategies to achieve a given climate outcome with less side effects.

Since the climatic impacts of SAI are sensitive to injection strategies (Jones et al., 2017; Laakso et al., 2022; Robock et al., 2008; Vattioni et al., 2019; Visioni et al., 2019), researchers have proposed varying injection

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strategies to meet specific goals (Keith & MacMartin, 2015; MacMartin et al., 2017), such as adopting four injection points at different latitudes to achieve multiple simultaneous surface temperature objectives (Kravitz et al., 2017). Previous injection strategies (Dai et al., 2018; Tilmes et al., 2017; Visioni et al., 2019) have considered various injection altitudes, latitudes, and seasonal timing, but most studies have assumed the injection at either a single longitude or a ring covering all longitudes. Here, we examine how particle lifetime depends on the location (including longitude, which hasn't been studied before) and season of injection, so to optimize injection strategies that can increase the particle lifetime in the stratosphere.

Moreover, many climate modeling studies have proposed SAI injections at or above 20 km altitude (English et al., 2012; Kleinschmitt et al., 2018; Tilmes et al., 2017; Zhao et al., 2021). But such injection altitudes are challenging and require expensive aircraft for deployment (McClellan et al., 2012; Moriyama et al., 2016; Smith & Wagner, 2018). This would require high fuel consumption per unit of delivered aerosol and cause large environmental impacts, such as the depletion of stratospheric ozone due to aviation NOx emissions (Eastham et al., 2022; Fritz et al., 2022). We, therefore, choose particle lifetime in the stratosphere as a policy-relevant objective function, aiming to understand how much an optimal choice of injection locations (including latitude and longitude) can increase particle lifetime without increasing injection altitude, relaxing the altitude-lifetime trade-off.

We use a Lagrangian trajectory model, LAGRANTO (Sprenger & Wernli, 2015), modified to incorporate particle sedimentation. The disadvantage of our model is that it does not include aerosol or chemical processes and it cannot directly compute the radiative efficacy, nor can it capture the atmospheric response to SAI. The advantage of the model is twofold. First, it is computationally efficient allowing us to explore a wide range of injection locations independently, which helps us to quantitively analyze the degree to which selecting injection latitude or longitude can increase particle lifetime in the stratosphere. Second, the use of high-resolution wind fields from ERA5 data (see Section 2) and lack of numerical diffusion provide a higher-fidelity simulation of particle transport in the stratosphere.

This modeling approach is complementary to fully coupled global climate model (GCM) simulations. It can suggest strategies for optimizing particle lifetime that can guide future studies using GCMs that have fully coupled chemical, aerosol, and radiative processes but that may provide a less accurate representation of particle transport. A multiscale plume-in-grid model (Sun et al., 2022), which is a global Eulerian Model (e.g., GCMs, chemical transport models (CTMs)) coupled with a Lagrangian plume model, will be able to leverage the advantages from both global Eulerian models (e.g., the atmospheric response to SAI) and Lagrangian plume model (e.g., lack of numerical diffusion).

2. Methods and Data

The input wind field for the LAGRANTO model is from 3-hourly ERA5 data (Hersbach et al., 2020), with $1° \times 1°$ horizontal resolution and 137 vertical model levels (Bourguet & Linz, 2022). We modified LAGRANTO to account for the sedimentation (Draxler & Hess, 1997; Van der Hoven, 1968) of injected particles. All injected particles have the same spherical shape with a radius of 0.2 μm, which enables a good scattering efficiency (Dykema et al., 2016; Pierce et al., 2010). Particle density is set to 1.8 g/cm^3 (i.e., the density of sulfate aerosol). Figure S1 and Table S1 in Supporting Information S1 show the sensitivity of particle lifetime to different particle radii (i.e., 0.05, 0.2, 0.376 μm). Particle lifetime decreases as the radius is increased from 0.05 to 0.376 μm.

We inject passive particles once every 3 days from the fixed injection points for 10 years (2000–2009), and each injected particle is simulated in LAGRANTO for 10 years. There are seven injection altitudes ($N_z = 7$): 16 km (100 hPa), 18 km (75 hPa), 19 km (65 hPa), 20 km (55 hPa), 21 km (47 hPa), 22 km (40 hPa), 24 km (30 hPa). The injection points in the horizontal direction form a mesh ranging from 30° N to 30° S with a 3° interval in latitude (number of injection latitudes: $N_y = 21$), and from $-180°$ to 180° with a 15° interval in longitude (number of injection longitudes $N_x = 24$). Therefore, the injection rate is 504 (i.e., $N_x \times N_y$) particles every 3 days for each injection altitude. As shown in Figure S2 and Text S1 in Supporting Information S1, it takes more time for the number of injected particles to reach a steady state in the stratosphere if the injection altitude is higher, and at the steady state, there are more particles (i.e., larger particle burden) in the stratosphere for the higher altitude injections. We calculate the stratospheric lifetime of each particle as the period between when the particle is injected into the stratosphere and when it reaches the tropopause (See Text S2 in Supporting Information S1 for details). In this study, the tropopause height, which is defined as the lower height of thermal lapse rate tropopause

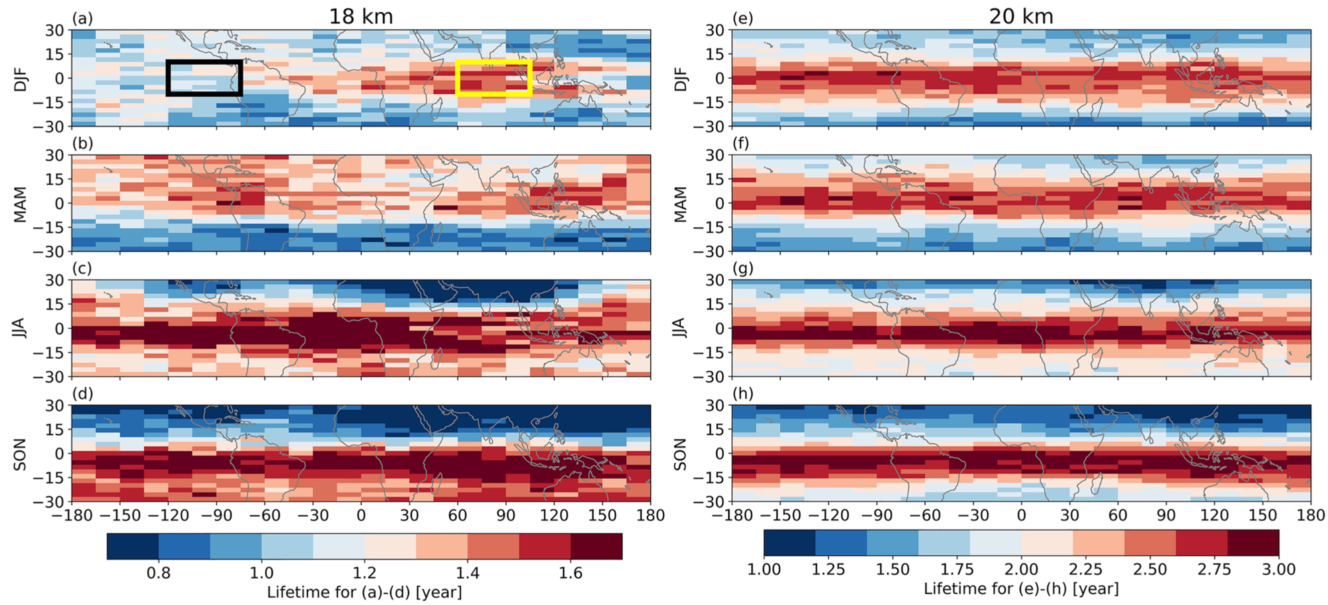

Figure 1. Particle lifetime distribution as a function of initial injection longitudes and latitudes.

(WMO, 1957) and dynamical tropopause (based on thresholds of 3.5 potential vorticity units in the extratropics and 380 K of potential temperature in the tropics), is derived from ERA5 data (Hoffmann & Spang, 2022).

3. Results

3.1. Particle Lifetime's Sensitivity to Injection Locations

Figure 1 maps the particle lifetime based on the injection locations at 18 and 20 km by season (DJF, MAM, JJA, and SON). The lifetime distribution from other injection altitudes (i.e., 16, 19, 21, 22, and 24 km) can be found in Figure S3 in Supporting Information S1. Figure 1 shows that the particle lifetime distribution is not uniform. There is seasonal variability in particle lifetime, as well as a dependence of particle lifetime on injection longitude and latitude, especially at a lower injection altitude. Particles injected at 20 km generally have a longer lifetime in the stratosphere than those injected at 18 km because particles injected at a higher altitude are more likely to be advected by the deep branch of Brewer-Dobson Circulation (BDC) and have a longer lifetime in the stratosphere. Particles injected at lower altitudes are more likely to be entrained in the shallow branch of BDC, causing particles to transport from the lower tropical stratosphere to the midlatitude or polar tropopause in a shorter time (Tilmes et al., 2017; Visioni et al., 2018).

This shows the mean particle lifetime over all injections from 2000 to 2009. The left (right) column is for injection at 18 km (20 km), with each row showing a different season. The black and yellow boxes in subplot (a) indicate two selected injection areas used in Figure 3.

Particles injected closer to the equator generally have longer lifetimes, as is shown by the zonal mean lifetimes in Figure 2a. The particles initialized near the equator will be brought deep into the stratosphere by BDC's upwelling flow, while particles injected away from the equator can exit to the troposphere following isentropic mixing to midlatitudes (A. Plumb, 1996). Figure 2a also shows a seasonal cycle: particles injected in the winter hemisphere, DJF in North Hemisphere (NH) or JJA in South Hemisphere (SH), generally have a longer lifetime than those injected in the summer hemisphere (JJA in NH or DJF in SH), which is consistent with the fact that the BDC is stronger in the winter hemisphere (Rosenlof, 1995). Additionally, Figure 2a shows a smaller maximum lifetime in DJF relative to JJA, as marked by the red and black arrows. This is because the tropical tropopause height is higher in DJF than in JJA (Figure 2b), so particles injected at a fixed height in the lower tropical stratosphere in DJF are closer to the tropical tropopause than those injected in JJA and are therefore more likely to be transported from the stratosphere to the troposphere. Figure S4 in Supporting Information S1 shows that this difference of zonal mean maximum lifetime between DJF and JJA injections becomes smaller when the injection altitude increases, with the difference vanishing for injection altitudes reaching 22 km.

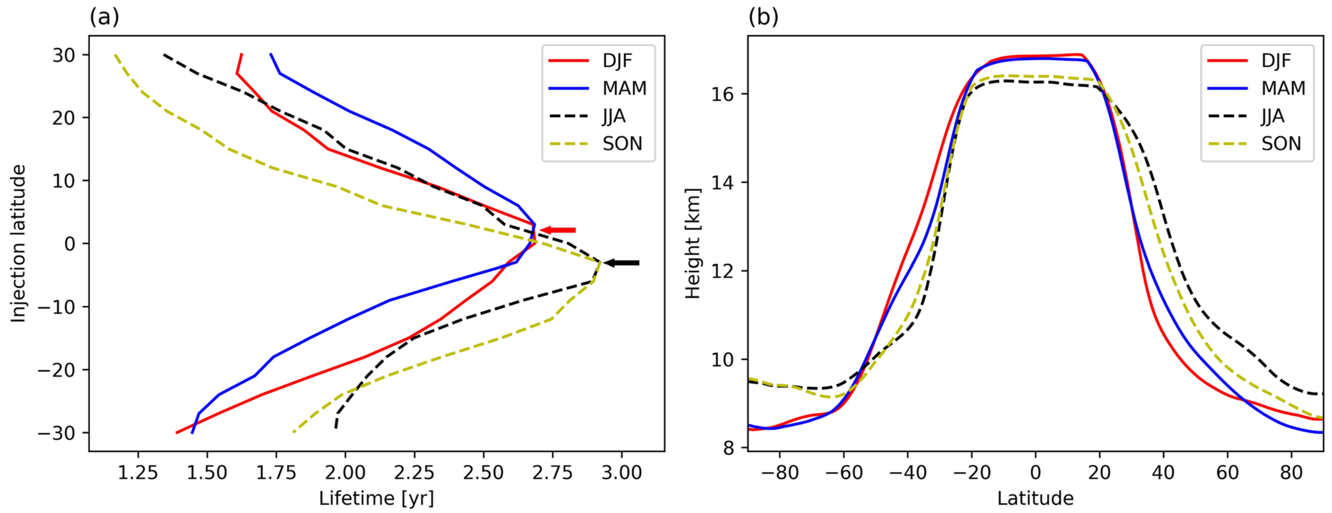

Figure 2. (a) Zonal mean particle lifetime versus injection latitude at 20 km in four seasons, corresponding to the right column of Figure 1. The red (black) arrow marks the maximum lifetime of the red (black) line. (b) The zonal mean of tropopause height in four seasons.

For the first time, we analyze the sensitivity of particle lifetime to injection longitude. We find that particles injected at different longitudes can have different lifetimes in the stratosphere, especially for injection altitudes lower than 20 km. Figure 3a shows the monthly mean particle lifetime averaged over the two selected injection areas (marked by the yellow and black boxes in Figure 1a), which have the same injection altitude and latitudes but different injection longitudes. The particles injected in the yellow box have a mean lifetime of 1.33 years, while those injected in the black box only have a mean lifetime of 1.08 years.

We explain the difference in particle lifetime between the two injection longitudes by using the poleward wind, where positive (negative) poleward wind speed equals positive (negative) meridional wind speed in the NH or negative (positive) meridional wind speed in the SH. Figure 3b shows the monthly mean poleward wind speed averaged over the two selected injection areas. The mean poleward wind speed from the yellow box is −0.38 m/s, which transports injected particles equatorward in the tropical pipe, where they can have a longer lifetime in the stratosphere. By contrast, the mean poleward wind speed from the black box is 0.55 m/s, which transports injected particles poleward out of the tropical pipe, where the injected particles can quickly reach the tropopause. Figure S5 in Supporting Information S1 shows an example of the transport of particles injected at two different longitudes, which clearly shows how the poleward wind influences particle transport and lifetime in the stratosphere.

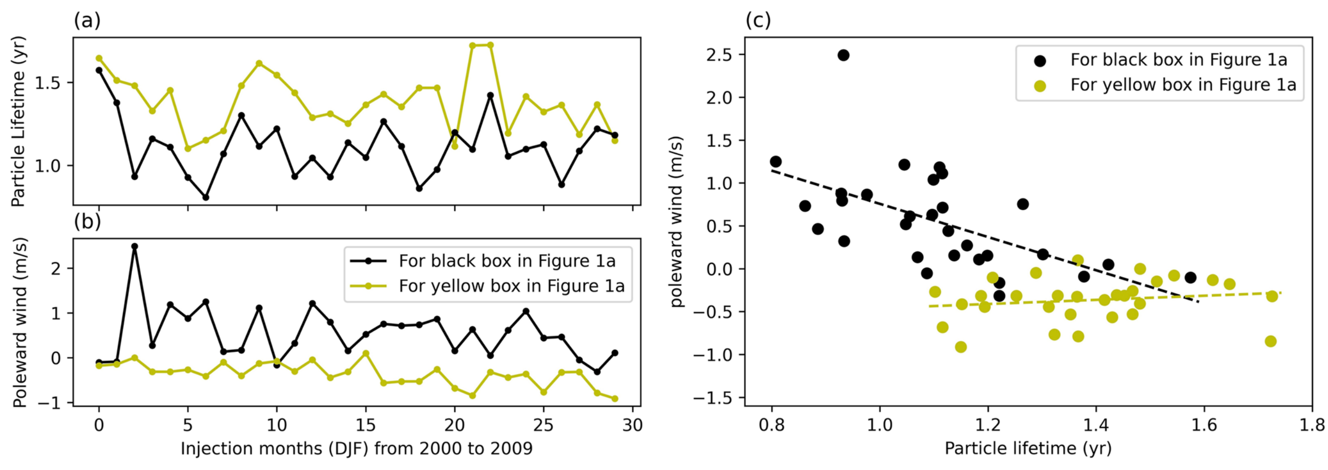

Figure 3. Time series of (a) particle lifetime and (b) poleward wind speed averaged over the two selected injection areas (yellow and black boxes in Figure 1a) at 18 km in all injection months (DJF) from 2000 to 2009. (c) Scatterplot of the values (particle lifetime vs. poleward wind) presented as time series in (a) and (b). The black (yellow) dashed line is the linear fit for the black (yellow) dots in (c).

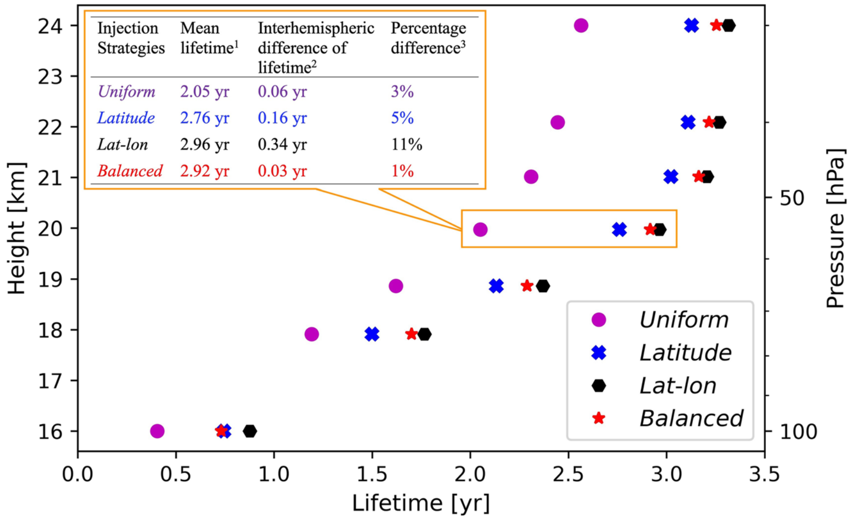

Figure 4. Mean stratospheric lifetime of particles injected at different injection altitudes for different injection strategies. The table in the orange box shows three metrics that evaluate particle lifetime from the four injection strategies at 20 km. [1]Mean lifetime represents the mean lifetime of particles from all injection locations ($N_x \times N_y$) and injection time (2000–2009). [2]Interhemispheric difference of lifetime represents the difference of the mean particle lifetime between NH and SH. [3]Percentage difference represents the interhemispheric difference of lifetime divided by the mean lifetime.

Moreover, the black dots in Figure 3c show that positive poleward wind speed values in the initial injection locations have a negative relationship with the particle lifetime (correlation coefficient of −0.57). This means that injected particles are more likely to have a smaller lifetime if the positive poleward wind is larger. Negative poleward wind speed values do not have a clear correlation with the particle lifetime (yellow dots in Figure 3c), which means that any negative poleward wind will help to trap injected particles in the tropical pipe, regardless of magnitude.

3.2. Exploring Injection Strategies to Increase Particle Lifetime

We design injection strategies by selecting combinations of injection latitudes and longitudes to increase particle lifetime subject to various constraints. For each altitude, we examine uniform injection in the tropics as a reference along with three other improved injection strategies. Instead of using fixed injection locations in the whole injection period, our three improved injection strategies (i.e., *Latitude*, *Lat-lon*, and *Balanced*) have injection locations that vary with season to maximize particle lifetime. Figure S6 in Supporting Information S1 gives a detailed example of how to inject particles in the following four injection strategies.

1. *Uniform*: particles are uniformly injected in the tropical area using all injection points ($N_x \times N_y$) as described in Section 2.
2. *Latitude*: particles are injected uniformly across all longitudes (N_x) at one selected latitude for each season to maximize particle lifetime.
3. *Lat-lon*: particles are injected at a single point for each season to maximize particle lifetime.
4. *Balanced*: particles are injected from one or several points each season, chosen to maximize particle lifetime subject to an interhemispheric balance constraint (i.e., the difference of particle lifetime between the NH and SH should be less than 1%). This is achieved by a Linear Programming (LP) solver described in Text S3 in Supporting Information S1.

Figure 4 shows that particle lifetime increases with increasing injection altitude for all injection strategies, but the benefit of additional altitude decreases with height. By applying a bilinear regression (Muggeo, 2003) to the vertical profile of particle lifetime in each injection scenario (shown in Figure S7 in Supporting Information S1), we can see there is an elbow point at around 20.5 km in each injection strategy. For example, the *Uniform* injection strategy shows that the vertical increasing rate of particle lifetime is 0.41 years/km under 20.5 km, while only 0.09 years/km above 20.5 km. Moreover, we find that the three improved injection strategies have a larger rate of increase in lifetime with height (more than 0.50 years/km) than the *Uniform* strategy (0.41 years/km) at injection altitudes under 20.5 km. Whereas, above 20.5 km the lifetime benefits of increased injection altitude are smaller for improved strategies (compared to the *Uniform* strategy), as the rate in improved strategies (less than 0.05 years/km) becomes smaller than that in the *Uniform* strategy (0.09 years/km). This means that below (above) 20.5 km the improved injection strategies have a larger (smaller) lifetime benefit of additional altitude than the *Uniform* strategy.

Figure 4 also shows that the mean particle lifetime can increase by 0.7 years by only selecting injection latitude (*Latitude* strategy) at 20 km, compared to the uniform injection in all tropical areas (*Uniform* strategy). The increase of lifetime becomes even larger (0.9 years) when we select both injection latitude and longitude (*Lat-lon* vs. *Uniform* strategies), which is consistent with our previous findings (Figure 3a) that selecting injection longitude can increase particle lifetime in the stratosphere. This increase of lifetime caused by selecting latitude and longitude indicates that the aircraft can fly at a lower altitude to achieve a similar stratospheric particle lifetime (akin to particle burden) as a uniform injection at a higher altitude. For example, particles injected at 18.5 km in strategy *Lat-lon* could have a similar mean particle lifetime to those injected at 20 km in strategy *Uniform* (see Figure 4), which means selecting injection latitude and longitude can allow aircraft to fly 1.5 km lower while maintaining the same particle lifetime target.

Even though we can increase the mean particle lifetime by selecting injection longitude and latitude, doing so may also increase the imbalance of particle lifetime between the NH and SH. Taking the 20 km injection altitude as an example (see orange box in Figure 4), the percentage difference of particle lifetime between the NH and SH is 3% in strategy *Uniform*, but 11% in strategy *Lat-lon*. Climate responses to SAI vary with the interhemispheric balance, such as the ITCZ shift that may occur when the SAI injection happens only in one hemisphere (Haywood et al., 2013; Smyth et al., 2017). Thus, we adopted a Linear Program (LP) solver (described in Text S3 in Supporting Information S1) to design a *Balanced* strategy, which can maximize the mean particle lifetime subject to the interhemispheric balance of particle lifetime. Figure 4 shows that the mean particle lifetime from strategy *Balanced* (red dots) is slightly smaller than that from strategy *Lat-lon* (black dots), but the *Balanced* constrains the percentage difference of particle lifetime between the NH and SH to be less than 1%, compared to 11% from the *Lat-lon* strategy (See Figure 4). This indicates that we can achieve the interhemispheric balance of particle lifetime without a large sacrifice to the mean particle lifetime in the stratosphere. Moreover, this method can be used to develop strategies subject to other constraints or physical objectives (e.g., spatial control of particle lifetime distribution between equatorial and poleward regions).

In this study, the three improved injection strategies select injection locations in annually-repeating seasonal cycles, so injection locations do not vary with year. Thus, the improved injection strategies could not respond to interannual variability in the circulation. An alternative approach, at least in principle, is selecting injection locations based on a forecast model, which can adapt to interannual variability from various internal (e.g., ENSO, QBO) and external (e.g., volcano eruption, solar variability) forcing. Figure S8 in Supporting Information S1 indicates that selecting injection latitude and longitude by this alternative approach (including interannual variabilities) could further increase the particle lifetime by more than 15%, compared to selecting injection latitude and longitude in a seasonal cycle.

4. Conclusions and Discussion

We conclude our results from two perspectives: the physics of atmospheric transport and the application to SAI.

From the physical perspective, we explore how background circulations influence particle transport and lifetime in the stratosphere. There is a seasonal cycle in particle lifetime (Figure 2a), with particles injected in the winter hemisphere (DJF in NH or JJA in SH) generally having a longer lifetime than those injected in the summer hemisphere (JJA in NH or DJF in SH), which is consistent with the fact that the BDC is stronger in the winter hemisphere. The maximum value of zonal mean particle lifetime at 20 km in DJF is approximately 0.2 years smaller than that in JJA (marked by the red and black arrows in Figure 2a). Given the fact that tropical tropopause height is higher in DJF than in JJA (Figure 2b), particles injected in the lower tropical stratosphere in DJF could be closer to the tropopause and then are more likely to be exchanged between the stratosphere and troposphere. Due to the zonal asymmetry of poleward wind in the lower tropical stratosphere, particles injected at the same altitude and latitude, but at different longitudes will undergo different rates of poleward transport resulting in different particle lifetimes in the stratosphere. The poleward wind at injection locations can be a useful predictor of the particle lifetime in the stratosphere.

From the SAI application perspective, this study uses four injection strategies to quantify the sensitivity of particle lifetime to injection locations, including the novel question of how injection longitude affects particle lifetime. It is already well established that increasing the altitude of injection will increase the lifetime (Kleinschmitt et al., 2018; Niemeier et al., 2011; Tilmes et al., 2017), but this incurs a tradeoff due to the relationship between deployment altitude and deployment cost (McClellan et al., 2012; Moriyama et al., 2016; Smith & Wagner, 2018). Our results show that—for particle lifetime—this tradeoff can be relaxed through the careful selection of the injection longitude and latitude, given an "optimized" (*Lat-lon* strategy) injection at 18.5 km achieving a similar mean lifetime as an "unoptimized" (*Uniform* strategy) injection at 20 km.

Though we have shown that optimizing injection locations can increase particle lifetime, there are limits. The simulation in this study is simplified (e.g., neglecting aerosol microphysical growth) to focus on the one-way influence from the atmospheric circulations to the particle transport and lifetime in the stratosphere, the atmospheric responses (like stratospheric heating) to the injected aerosol are not considered here. But this limit may be not significant in some situations, such as (a) the simulation of early SAI with a small injection rate, like a small injection of SO_2 (i.e., 1 Tg S yr^{-1}) that can cause -0.8 W/m^2 global mean net SW flux at surface and less than 1 K of temperature increase in the lower tropical stratosphere (Heckendorn et al., 2009), or (b) the simulation of SAI with solid aerosol (other than sulfate aerosols) injections, which may avoid stratospheric heating (Keith et al., 2016).

Results from our analysis can suggest strategies that can be tested with GCMs to evaluate the sensitivity of SAI's radiative efficacy and climatic impacts to injection longitude, which should include not only the physical dynamics (discussed in this study) but also aerosol microphysics, chemical reactions, radiative effects, etc. What's more, this study focuses on injections in the tropical stratosphere to explore the physical mechanism of how injection longitude influences particle transport and lifetime for SAI. It will also be important to evaluate injection longitude's influence on SAI in the extra-tropical area since radiative forcing applied further poleward may cause a larger change of global mean temperature (Forster et al., 2000; Kaur et al., 2023) and deliberately choosing the injection latitudes (including high latitude) can help to modify the SAI's climatic impacts (Lee et al., 2021; MacMartin et al., 2017).

Data Availability Statement

The ERA5 data can be accessed from https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5. LAGRANTO model results are openly available from https://doi.org/10.7910/DVN/UKIBWE.

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References

Bourguet, S., & Linz, M. (2022). The impact of improved spatial and temporal resolution of reanalysis data on Lagrangian studies of the tropical tropopause layer. *Atmospheric Chemistry and Physics*, *22*(20), 13325–13339. https://doi.org/10.5194/acp-22-13325-2022

Dai, Z., Weisenstein, D. K., & Keith, D. W. (2018). Tailoring meridional and seasonal radiative forcing by sulfate aerosol solar geoengineering. *Geophysical Research Letters*, *45*(2), 1030–1039. https://doi.org/10.1002/2017GL076472

de Forster, P. F., Blackburn, M., Glover, R., & Shine, K. P. (2000). An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. *Climate Dynamics*, *16*(10), 833–849. https://doi.org/10.1007/s003820000083

Draxler, R., & Hess, G. (1997). Description of the HYSPLIT_4 model-ling system. *NOAA Technical Memorandum ERL AOML*, *224*.

Dykema, J. A., Keith, D. W., & Keutsch, F. N. (2016). Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophysical Research Letters*, *43*(14), 7758–7766. https://doi.org/10.1002/2016GL069258

Eastham, S. D., Fritz, T., Sanz-Morère, I., Prashanth, P., Allroggen, F., Prinn, R. G., et al. (2022). Impacts of a near-future supersonic aircraft fleet on atmospheric composition and climate. *Environmental Sciences: Atmosphere*, *2*(3), 388–403. https://doi.org/10.1039/D1EA00081K

Eastham, S. D., Weisenstein, D. K., Keith, D. W., & Barrett, S. R. H. (2018). Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmospheric Environment*, *187*, 424–434. https://doi.org/10.1016/j.atmosenv.2018.05.047

English, J. M., Toon, O. B., & Mills, M. J. (2012). Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering. *Atmospheric Chemistry and Physics*, *12*(10), 4775–4793. https://doi.org/10.5194/acp-12-4775-2012

Fritz, T. M., Dedoussi, I. C., Eastham, S. D., Speth, R. L., Henze, D. K., & Barrett, S. R. H. (2022). Identifying the ozone-neutral aircraft cruise altitude. *Atmospheric Environment*, *276*, 119057. https://doi.org/10.1016/j.atmosenv.2022.119057

Haywood, J. M., Jones, A., Bellouin, N., & Stephenson, D. (2013). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, *3*(7), 660–665. https://doi.org/10.1038/nclimate1857

Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., et al. (2009). The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environmental Research Letters*, *4*(4), 045108. https://doi.org/10.1088/1748-9326/4/4/045108

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hoffmann, L., & Spang, R. (2022). An assessment of tropopause characteristics of the ERA5 and ERA-Interim meteorological reanalyses. *Atmospheric Chemistry and Physics*, *22*(6), 4019–4046. https://doi.org/10.5194/acp-22-4019-2022

Jones, A. C., Haywood, J. M., Dunstone, N., Emanuel, K., Hawcroft, M. K., Hodges, K. I., & Jones, A. (2017). Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nature Communications*, *8*(1), 1382. https://doi.org/10.1038/s41467-017-01606-0

Kaur, H., Bala, G., & Sheshadri, A. (2023). *Why is climate sensitivity to polar radiative forcings larger than to tropical radiative forcings*. EGU General Assembly 2023. EGU23-17500. https://doi.org/10.5194/egusphere-egu23-17500

Keith, D. W., & MacMartin, D. G. (2015). A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change*, *5*(3), 201–206. https://doi.org/10.1038/nclimate2493

Keith, D. W., Weisenstein, D. K., Dykema, J. A., & Keutsch, F. N. (2016). Stratospheric solar geoengineering without ozone loss. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(52), 14910–14914. https://doi.org/10.1073/pnas.1615572113

Kleinschmitt, C., Boucher, O., & Platt, U. (2018). Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO2 injection studied with the LMDZ-S3A model. *Atmospheric Chemistry and Physics*, *18*(4), 2769–2786. https://doi.org/10.5194/acp-18-2769-2018

Kravitz, B., MacMartin, D. G., Mills, M. J., Richter, J. H., Tilmes, S., Lamarque, J.-F., et al. (2017). First simulations of designing stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12616–12634. https://doi.org/10.1002/2017JD026874

Laakso, A., Niemeier, U., Visioni, D., Tilmes, S., & Kokkola, H. (2022). Dependency of the impacts of geoengineering on the stratospheric sulfur injection strategy – Part 1: Intercomparison of modal and sectional aerosol modules. *Atmospheric Chemistry and Physics*, *22*(1), 93–118. https://doi.org/10.5194/acp-22-93-2022

Lee, W. R., MacMartin, D. G., Visioni, D., & Kravitz, B. (2021). High-latitude stratospheric aerosol geoengineering can Be more effective if injection is limited to spring. *Geophysical Research Letters*, *48*(9), e2021GL092696. https://doi.org/10.1029/2021GL092696

MacMartin, D. G., Kravitz, B., Tilmes, S., Richter, J. H., Mills, M. J., Lamarque, J.-F., et al. (2017). The climate response to stratospheric aerosol geoengineering can be tailored using multiple injection locations. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12574–12590. https://doi.org/10.1002/2017JD026868

McClellan, J., Keith, D. W., & Apt, J. (2012). Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters*, *7*(3), 034019. https://doi.org/10.1088/1748-9326/7/3/034019

Moriyama, R., Sugiyama, M., Kurosawa, A., Masuda, K., Tsuzuki, K., & Ishimoto, Y. (2016). The cost of stratospheric climate engineering revisited. *Mitigation and Adaptation Strategies for Global Change*, *22*(8), 1207–1228. https://doi.org/10.1007/s11027-016-9723-y

Muggeo, V. M. R. (2003). Estimating regression models with unknown break-points. *Statistics in Medicine*, *22*(19), 3055–3071. https://doi.org/10.1002/sim.1545

Niemeier, U., Schmidt, H., & Timmreck, C. (2011). The dependency of geoengineered sulfate aerosol on the emission strategy. *Atmospheric Science Letters*, *12*(2), 189–194. https://doi.org/10.1002/asl.304

Pierce, J. R., Weisenstein, D. K., Heckendorn, P., Peter, T., & Keith, D. W. (2010). Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. *Geophysical Research Letters*, *37*(18), L18805. https://doi.org/10.1029/2010GL043975

Plumb, R. A. (1996). A "tropical pipe" model of stratospheric transport. *Journal of Geophysical Research*, *101*(D2), 3957–3972. https://doi.org/10.1029/95JD03002

Robock, A., Oman, L., & Stenchikov, G. L. (2008). Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *Journal of Geophysical Research*, *113*(D16), D16101. https://doi.org/10.1029/2008JD010050

Rosenlof, K. H. (1995). Seasonal cycle of the residual mean meridional circulation in the stratosphere. *Journal of Geophysical Research*, *100*(D3), 5173–5191. https://doi.org/10.1029/94JD03122

Smith, W., & Wagner, G. (2018). Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environmental Research Letters*, *13*(12), 124001. https://doi.org/10.1088/1748-9326/aae98d

Smyth, J. E., Russotto, R. D., & Storelvmo, T. (2017). Thermodynamic and dynamic responses of the hydrological cycle to solar dimming. *Atmospheric Chemistry and Physics*, *17*(10), 6439–6453. https://doi.org/10.5194/acp-17-6439-2017

Sprenger, M., & Wernli, H. (2015). The LAGRANTO Lagrangian analysis tool – Version 2.0. *Geoscientific Model Development*, *8*(8), 2569–2586. https://doi.org/10.5194/gmd-8-2569-2015

Sun, H., Eastham, S., & Keith, D. (2022). Developing a plume-in-grid model for plume evolution in the stratosphere. *Journal of Advances in Modeling Earth Systems*, *14*(4), e2021MS002816. https://doi.org/10.1029/2021MS002816

Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Vitt, F., et al. (2017). Sensitivity of aerosol distribution and climate response to stratospheric SO_2 injection locations. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12591–12615. https://doi.org/10.1002/2017JD026888

Van der Hoven, I. (1968). Deposition of particles and gases In D. Slade (Ed.), *Meteorology and atomic energy* (p. 445), *TID-24190*, NTIS.

Vattioni, S., Weisenstein, D., Keith, D., Feinberg, A., Peter, T., & Stenke, A. (2019). Exploring accumulation-mode H_2SO_4 versus SO_2 stratospheric sulfate geoengineering in a sectional aerosol–chemistry–climate model. *Atmospheric Chemistry and Physics*, *19*(7), 4877–4897. https://doi.org/10.5194/acp-19-4877-2019

Visioni, D., MacMartin, D. G., Kravitz, B., Tilmes, S., Mills, M. J., Richter, J. H., & Boudreau, M. P. (2019). Seasonal injection strategies for stratospheric aerosol geoengineering. *Geophysical Research Letters*, *46*(13), 7790–7799. https://doi.org/10.1029/2019GL083680

Visioni, D., Pitari, G., Tuccella, P., & Curci, G. (2018). Sulfur deposition changes under sulfate geoengineering conditions: Quasi-biennial oscillation effects on the transport and lifetime of stratospheric aerosols. *Atmospheric Chemistry and Physics*, *18*(4), 2787–2808. https://doi.org/10.5194/acp-18-2787-2018

Weisenstein, D. K., Visioni, D., Franke, H., Niemeier, U., Vattioni, S., Chiodo, G., et al. (2022). An interactive stratospheric aerosol model intercomparison of solar geoengineering by stratospheric injection of SO2 or accumulation-mode sulfuric acid aerosols. *Atmospheric Chemistry and Physics*, *22*(5), 2955–2973. https://doi.org/10.5194/acp-22-2955-2022

WMO. (1957). Meteorology - a three-dimensional science: Second session of the commission for aerology. *World Meteorological Organization Bulletin*, *IV*(4), 134–138.

Zhao, M., Cao, L., Bala, G., & Duan, L. (2021). Climate response to latitudinal and altitudinal distribution of stratospheric sulfate aerosols. *Journal of Geophysical Research: Atmospheres*, *126*(24), e2021JD035379. https://doi.org/10.1029/2021JD035379