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Supporting Information for

Optimal Choice of Injection Locations Reduces Altitude-lifetime Trade-off for Stratospheric Solar Geoengineering

Hongwei Sun[1], Stephen Bourguet[2], Sebastian Eastham[3, 4], and David Keith[1]

[1] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, United States

[2] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, United States

[3] Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

[4] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

Contents of this file

Text S1 to S3

- Text S1. Time series of the number of particles staying in the stratosphere from each injection altitude.
- Text S2. Kernel density distribution of seasonally particle lifetime for each injection altitude.
- Text S3. Linear Programming (LP) solver for the *Balanced* injection strategy.

Figures S1 to S8

- Figure S1. Mean stratospheric lifetime of particles injected at different injection altitudes for different particle radii (i.e., 0.05, 0.2, 0.376 um) under the *Uniform* strategy.
- Figure S2. (a) Time series of the number of particles staying in the stratosphere from each injection altitude. τ is the mean particle lifetime in the stratosphere. Each injection altitude has the same injection rate (see Method section). (b) Kernel density distribution of seasonally particle lifetime (from $N_x \times N_y = 504$ horizontal injection locations, see Method section) for each injection altitude.
- Figure S3. Particle lifetime distribution as a function of initial injection longitudes and latitudes. This shows the mean particle lifetime over all injections from 2000 to 2009 at 16, 19, 21, 22, 24 km (like Figure 1).
- Figure S4. Zonal mean particle lifetime vs. injection latitude at 18, 20, and 22 km in four seasons (like Figure 2a).

- Figure S5. An example of the transport of particles injected at different longitude (marked by red and yellow boxes in Figure 1a) at 18 km on Jan 1st, 2003.
- Figure S6. An example of the injection percent for different injection strategies based on the particle lifetime distribution (Figure 1a) at 18 km (injection altitude) in DJF (injection time).
- Figure S7. (a) Mean stratospheric lifetime of particles injected at different injection altitudes for different injection strategies (same as Figure 4). The dashed lines represent the bilinear regression fit for the data points. (b) Vertical increasing rate of particle lifetime.
- Figure S8. Mean stratospheric lifetime of particles injected at different injection altitudes for different injection strategies for (a) the annual-repeating seasonal cycle (the selected location only changes with different seasons, same as Figure 4) and (b) including interannual variabilities (the selected location changes with both seasons and years).

Table S1

- Table S1. Three metrics from different injection strategies for particles with different radii (i.e., 0.05, 0.2, 0.376 um) injected at 20 km in 2000.

Text S1. Time series of the number of particles staying in the stratosphere from each injection altitude.

As shown in Figure S2.a, the number of particles in the stratosphere increases until a steady state is achieved when particles are injected at a constant rate in the tropics from 2000-2009. It takes more time for the number of particles to reach a steady state 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, confirming prior results that that particle lifetime increases with increasing injection altitude. After the injections stop in 2010, the total number of particles in the stratosphere decreases since particles could reach the tropopause and exit the stratosphere. The decreasing trend follows the exponential decay function $N(t) = N(0) \cdot e^{-\tau t}$, where t is the number of days after injection stops on Jan 1, 2010, N is the number of particles in the stratosphere, τ is the mean particle lifetime in the stratosphere (shown in Figure S2.a).

Text S2. Kernel density distribution of seasonally particle lifetime for each injection altitude.

In global climate models, particle lifetime is indirectly calculated by using injection rate to divide the steady-state particle number. In contrast, we directly calculate each particle's lifetime in the stratosphere with the Lagrangian trajectory model by tracking the time lapse from its injection to exit at the tropopause. The maximum particle lifetime is 10 years, which means that the injected particle has not reached the tropopause in the whole 10-year simulation. This is not necessarily meaningful for any individual trajectory, but the distribution of lifetimes for a large number of trajectories can inform us of how particles are transported in the stratosphere. Figure S2.b shows the kernel density distribution of particles' stratospheric lifetime for different injection altitudes. We can also see that particles injected at a higher altitude tend to have a longer lifetime in the stratosphere. The particle lifetime distribution from the lower stratospheric injection (<20 km) is more concentrated, while particles injected higher in the stratosphere (≥20 km) have a larger value range of stratospheric lifetimes. We also notice that there are overlapping areas between different lines, which suggests that choosing injection locations and time at a lower altitude can achieve a similar particle lifetime to the uniform injection at a higher altitude. For example, 20% of the area under the purple line (19 km) has a particle lifetime larger than 2.0 years, which is the mean particle lifetime from the uniform injection at 20 km.

Text S3. Linear Programming (LP) solver for the *Balanced* injection strategy.

As shown in Figure 1, for a given injection altitude and season, the particle injected at location (i, j) will have a lifetime $L(i,j)$ in the stratosphere, where i=1, 2, …, Nx represents the index of injection longitude, j=1, 2, …, Ny represents the index of injection latitude. This lifetime $L(i,j)$ can be divided into two parts: the particle's lifetime in the NH ($L\_NH(i,j)$) and in the SH ($L\_SH(i,j)$). Thus:

$$L(i,j) = L\_NH(i,j) + L\_SH(i,j) \qquad (1)$$

If we let $P(i,j)$ refer to the injection percent at location (i, j) for each injection altitude and season. The sum of injection percent from all injection locations should be 100% for each injection altitude and season:

$$\sum_{iy=1}^{Ny} \sum_{ix=1}^{Nx} P(x,y) = 100\% \qquad (2)$$

The total particle lifetime for each injection altitude and season, which we want to maximize, is:

$$L_{total} = \sum_{j=1}^{Ny} \sum_{i=1}^{Nx} L(i,j) \times P(i,j) \qquad (3)$$

Similarly, the particle lifetime in NH and SH are:

$$L_{NH} = \sum_{j=1}^{Ny} \sum_{i=1}^{Nx} L\_NH(i,j) \times P(i,j) \qquad (4)$$

$$L_{SH} = \sum_{j}^{Ny} \sum_{i}^{Nx} L\_SH(i,j) \times P(i,j) \qquad (5)$$

The percentage difference of particle lifetime between NH and SH is defined as:

$$PD = \frac{|L_{NH} - L_{SH}|}{L_{total}} \times 100\% \qquad (6)$$

PD has a value range between [0,100%]. $PD = 0$ means the particle lifetime in the NH is the same as that in the SH, which represents the perfect interhemispheric balance of particle lifetime. $PD = 100\%$ means all particles always stay in one hemisphere, which shows a most interhemispheric imbalance of particle lifetime. In this study, we assume the interhemispheric balance of particle lifetime between NH and SH when: $PD < 1\%$.

In summary, the LP solver can calculate the injection percent $P(i,j)$ to maximize the total particle lifetime (L_{total}) subject to the interhemispheric balance of the particle lifetime ($PD < 1\%$). Figure S6 shows an example of the distribution of injection percent calculated by the LP solver.

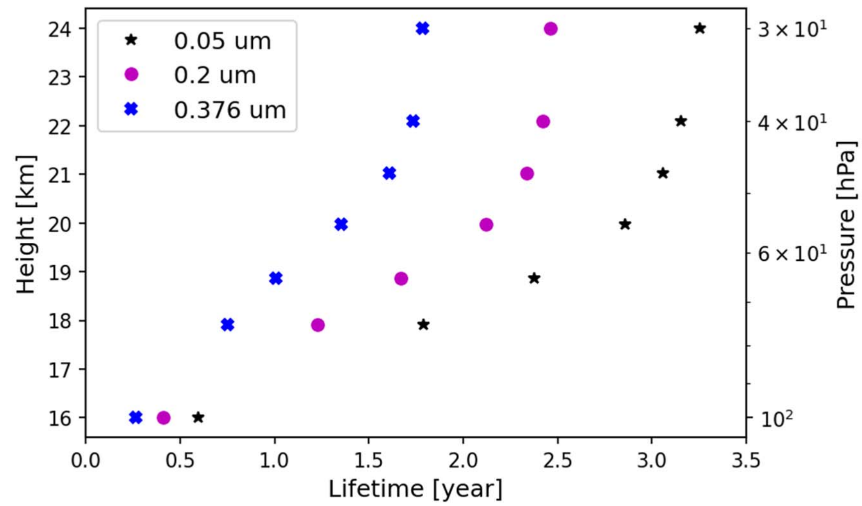

Figure S1. Mean stratospheric lifetime of particles injected at different injection altitudes for different particle radii (i.e., 0.05, 0.2, 0.376 um) under the Uniform strategy.

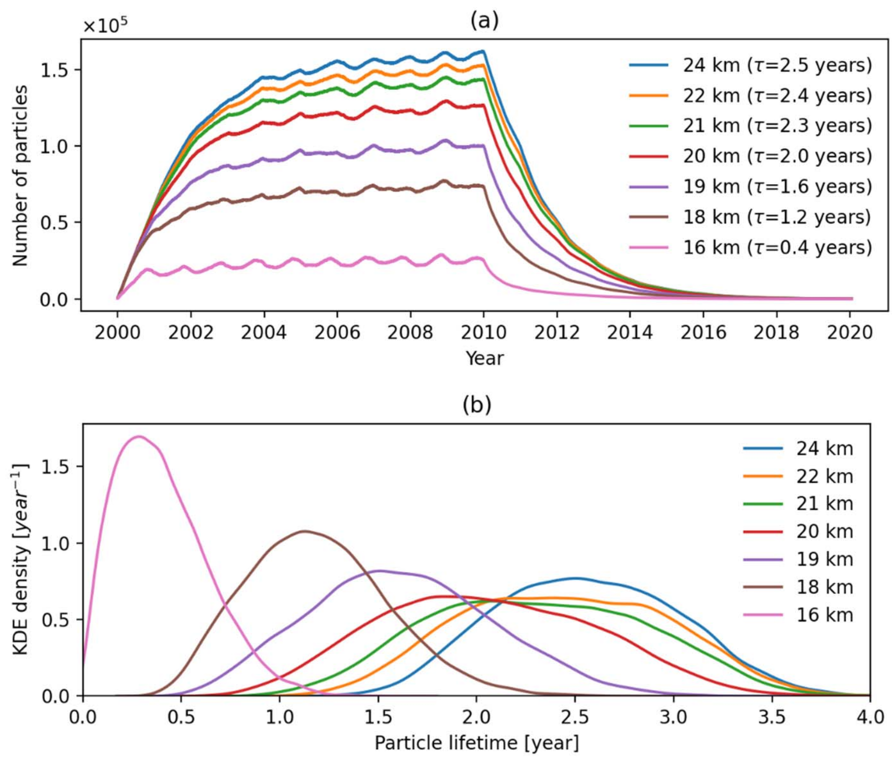

Figure S2. (a) Time series of the number of particles staying in the stratosphere from each injection altitude. τ is the mean particle lifetime in the stratosphere. Each injection altitude has the same injection rate (see Method section). (b) KDE (kernel density estimation) density distribution of seasonally particle lifetime (from $N_x \times N_y = 504$ horizontal injection locations, see Method section) for each injection altitude.

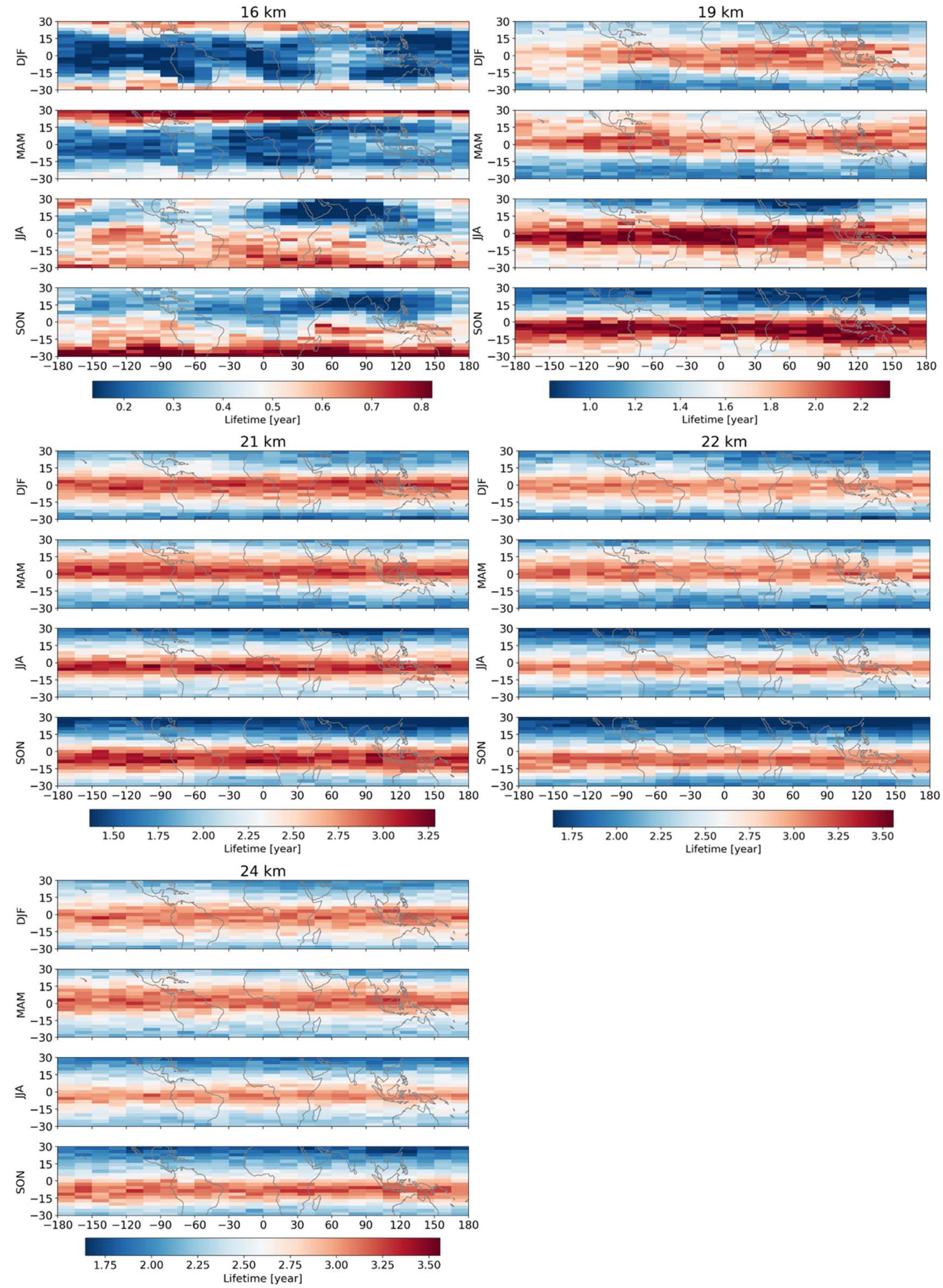

Figure S3. Particle lifetime distribution as a function of initial injection longitudes and latitudes. This shows the mean particle lifetime over all injections from 2000 to 2009 at 16, 19, 21, 22, 24 km (like Figure 1).

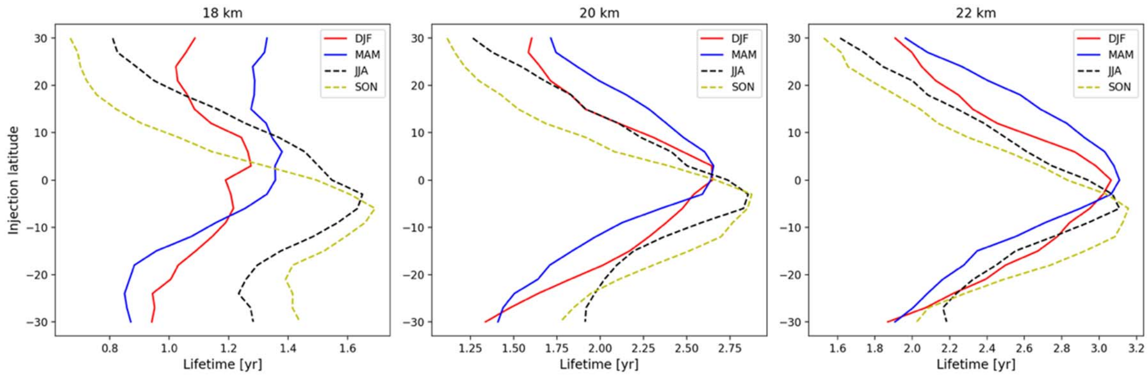

Figure S4. Zonal mean particle lifetime vs. injection latitude at 18, 20, and 22 km in four seasons (like Figure 2a).

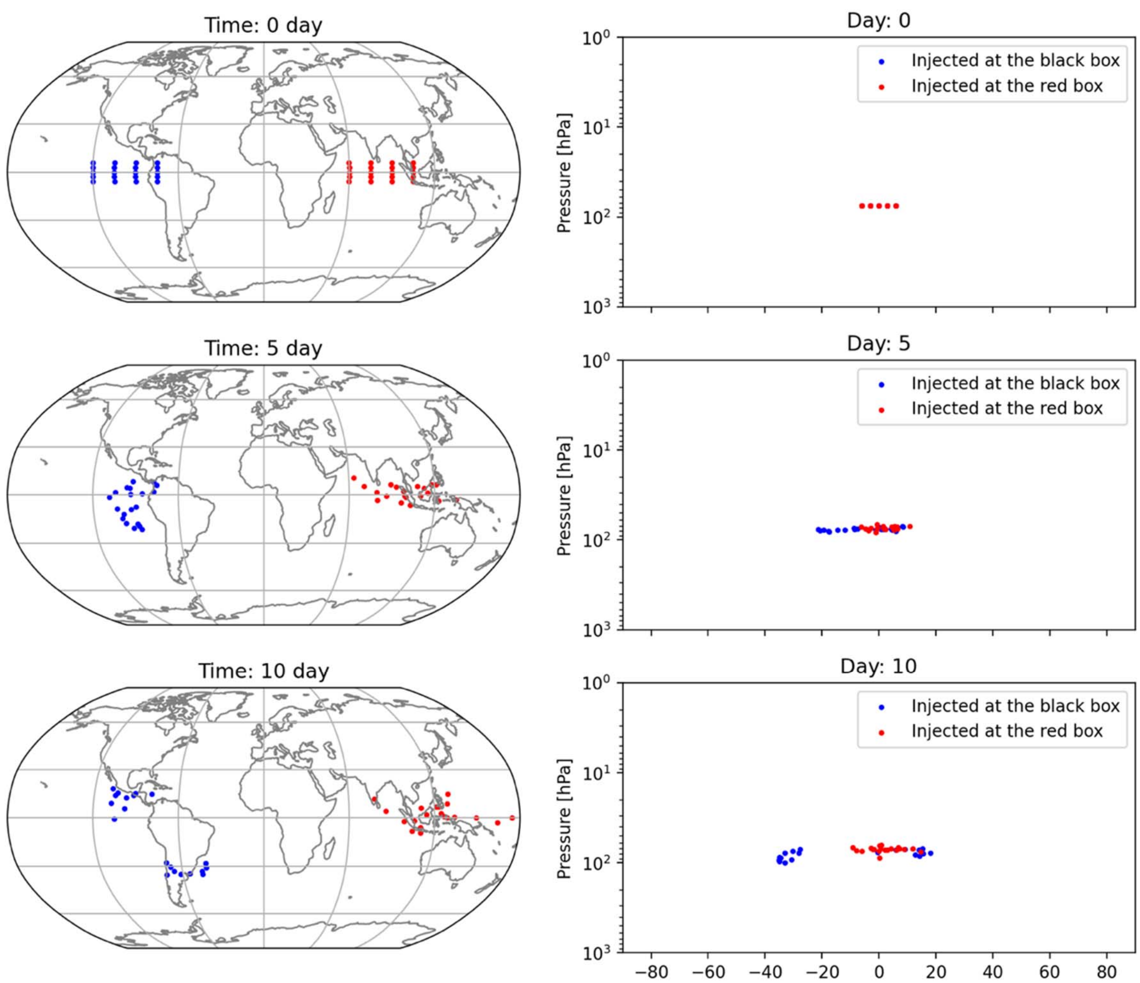

Figure S5. An example of the transport of particles injected at different longitude at 18 km on Jan 1st, 2003.

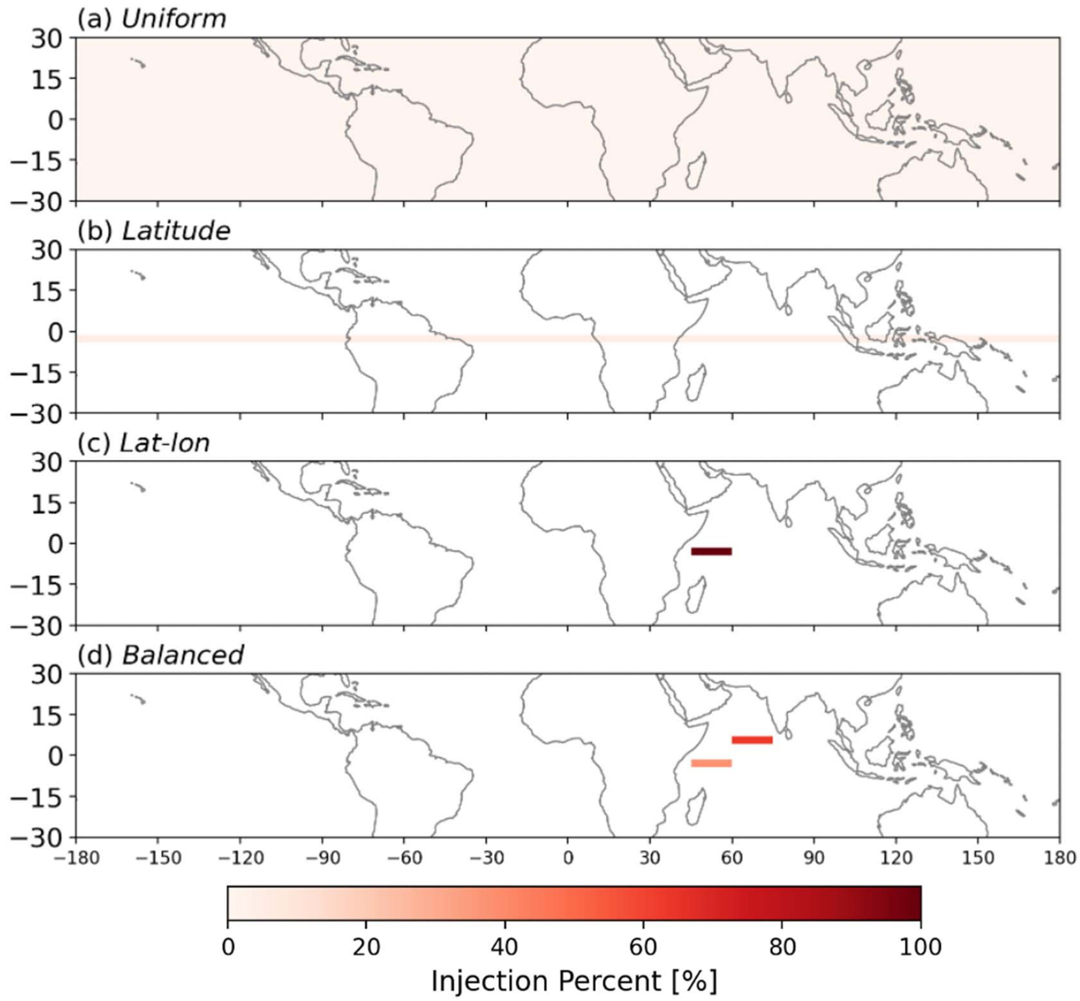

Figure S6. An example of the injection percent for different injection strategies based on the particle lifetime distribution (Figure 1a) at 18 km (injection altitude) in DJF (injection time).

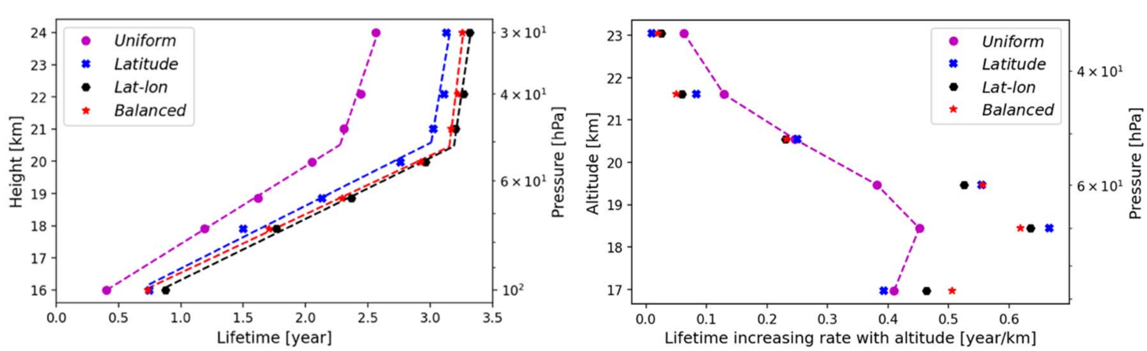

Figure S7. (a) Mean stratospheric lifetime of particles injected at different injection altitudes for different injection strategies (same as Figure 4). The dashed lines represent the bilinear regression fit for the data points. (b) Vertical increasing rate of particle lifetime.

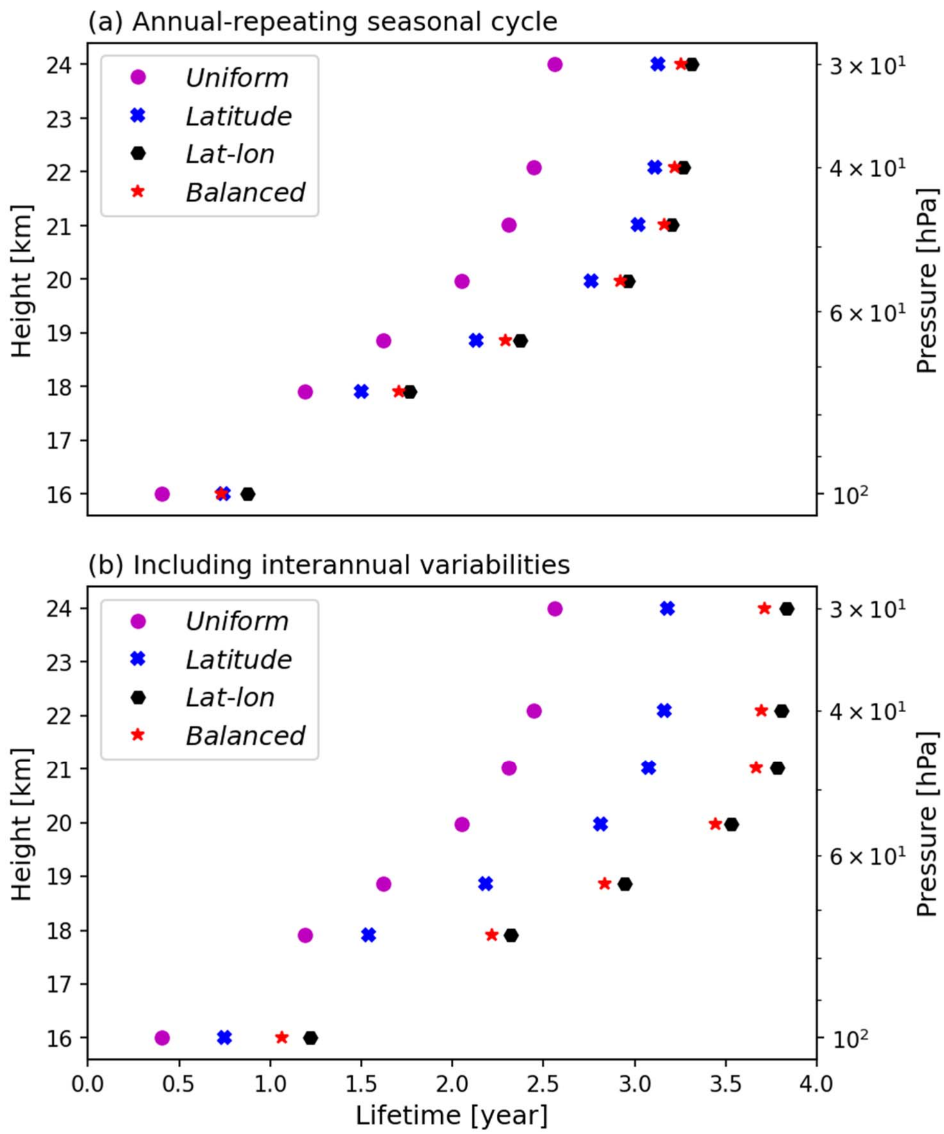

Figure S8. Mean stratospheric lifetime of particles injected at different injection altitudes for different injection strategies for (a) the annual-repeating seasonal cycle (the selected location only changes with different seasons, same as Figure 4) and (b) including interannual variabilities (the selected location changes with both seasons and years.

Table S1. Three metrics from different injection strategies for particles with different radii (i.e., 0.05, 0.2, 0.376 um) injected at 20 km in 2000.

Radius	Injection Strategies	Mean Lifetime[1]	Interhemispheric Difference of Lifetime[2]	Percentage Difference[3]
0.05 um	*Uniform*	2.85 years	0.12 years	4%
	Latitude	3.85 years	0.75 years	19%
	Lat-lon	4.68 years	1.20 years	26%
	Balanced	4.61 years	0.04 years	1%
0.2 um	*Uniform*	2.12 years	0.10 years	5%
	Latitude	2.89 year	0.51 years	18%
	Lat-lon	3.58 years	0.98 years	27%
	Balanced	3.50 years	0.04 years	1%
0.376 um	*Uniform*	1.35 years	0.02 years	1%
	Latitude	1.83 years	0.55 years	30%
	Lat-lon	2.30 years	0.55 years	24%
	Balanced	2.23 years	0.03 years	1%

Note:

[1] Mean lifetime: the mean lifetime of particles from all injection locations and injection time at 20 km.

[2] Interhemispheric difference of lifetime: the difference of the mean particle lifetime between NH and SH.

[3] Percentage difference: interhemispheric difference of lifetime divided by the mean lifetime.