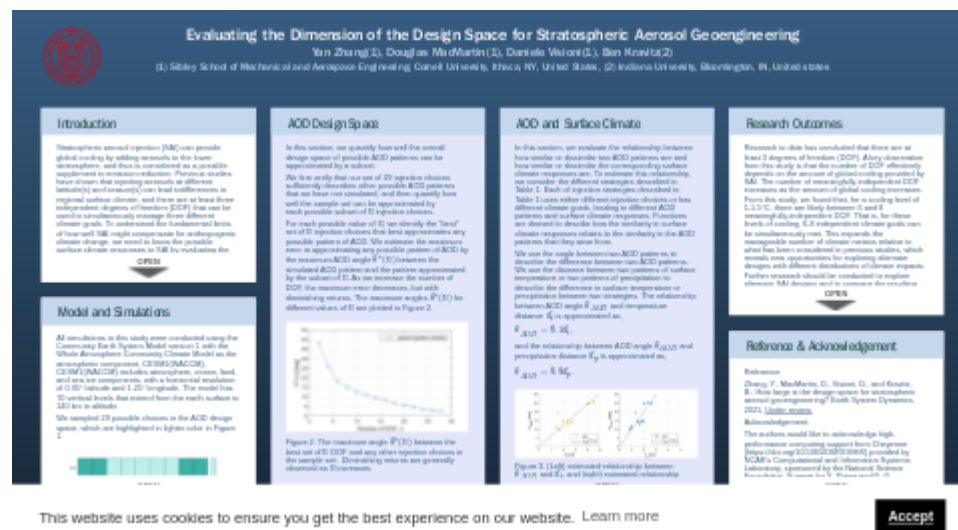


# Evaluating the Dimension of the Design Space for Stratospheric Aerosol Geoengineering



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## INTRODUCTION

Stratospheric aerosol injection (SAI) can provide global cooling by adding aerosols to the lower stratosphere, and thus is considered as a possible supplement to emission reduction. Previous studies have shown that injecting aerosols at different latitude(s) and season(s) can lead to differences in regional surface climate, and there are at least three independent degrees of freedom (DOF) that can be used to simultaneously manage three different climate goals. To understand the fundamental limits of how well SAI might compensate for anthropogenic climate change, we need to know the possible surface climate responses to SAI by evaluating the SAI design space. This research work quantifies the number of meaningfully-independent DOF of the SAI design space.

This number of meaningfully-independent DOF depends on both the climate metrics that we care about and the amount of cooling. From the available simulation data of different SAI strategies, we observe that between surface air temperature and precipitation, surface air temperature dominates the change of surface climate. The number of injection choices that produce detectably different surface temperature is more than the number of injection choices that produce detectably different precipitation. At low levels of cooling, only a small set of injection choices yield detectably different surface climate responses. As more cooling is needed, more injection choices produce detectably different surface climate. For a cooling level of 1-1.5°C, we find that there are likely between 6 and 8 DOFs.

# MODEL AND SIMULATIONS

All simulations in this study were conducted using the Community Earth System Model version 1 with the Whole Atmosphere Community Climate Model as the atmospheric component, CESM1(WACCM). CESM1(WACCM) includes atmosphere, ocean, land, and sea ice components, with a horizontal resolution of 0.95° latitude and 1.25° longitude. The model has 70 vertical levels that extend from the earth surface to 140 km in altitude.

We sampled 29 possible choices in the aerosol optical depth (AOD) design space, which are highlighted in lighter color in Figure 1.

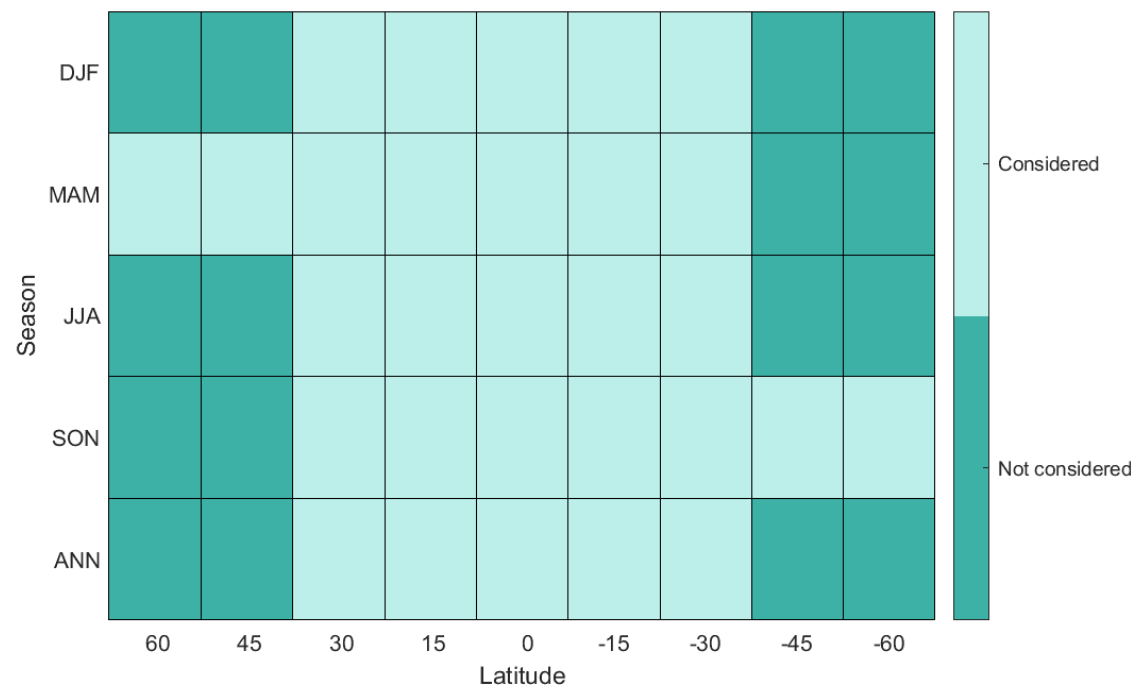


Figure 1. The 29 injection choices included in the sample set.

We also used existing simulations for 5 different stratospheric injection strategies to relate how similar or dissimilar AOD patterns are to how similar or dissimilar the resulting surface climate responses are.

Table 1. Injection design of the 5 existing SAI simulations analyzed in this study.

Name of simulation	Injection latitude	Injection season	Number of ensemble members	Objectives	Reference
GLENS	30° N, 15° N, 15° S, 30° S	annually-constant	21	T0, T1, T2	Tilmes et al. (2018)
iSpring	30°N, 15° N, 15° S, 30° S	MAM at 30° N and 15° N; SON at 15° S and 30° S	3	T0, T1, T2	Visioni et al. (2020c)
iAutumn	30° N, 15° N, 15° S, 30° S	SON at 30° N and 15° N; MAM at 15° S and 30° S	3	T0, T1, T2	Visioni et al. (2020c)
Equatorial (EQ)	Equator	annually-constant	3	T0	Kravitz et al. (2019)
PREC (1 <sup>st</sup> simulation in Lee et al., 2020a)	30° N, 15° N, 15° S, 30° S	annually-constant	1	T0, ITCZ, SSI	Lee et al. (2020a)

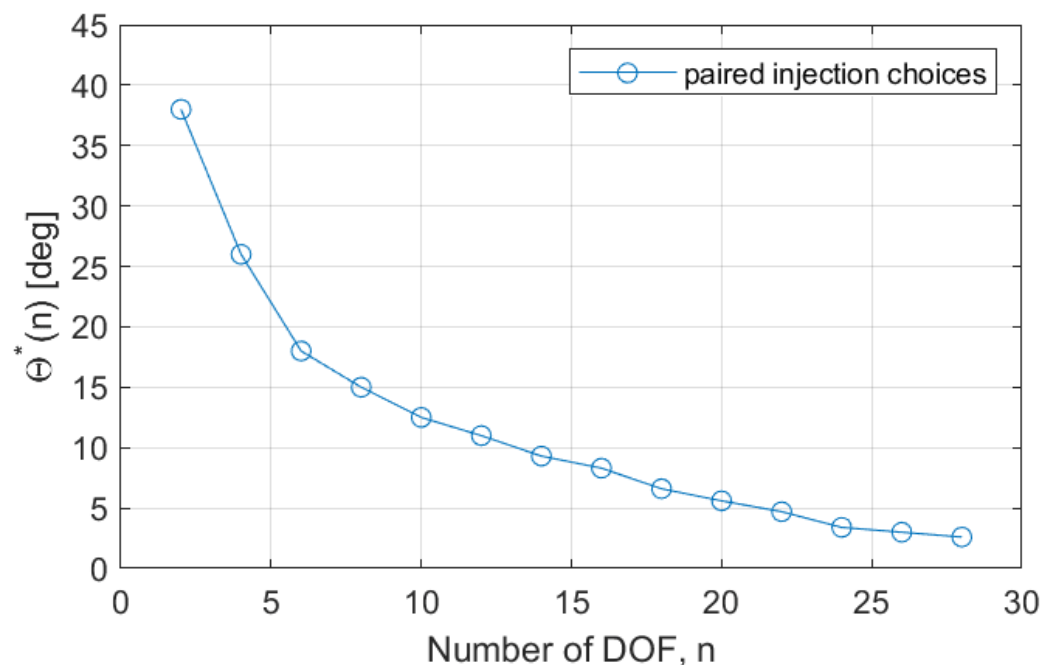
## AOD DESIGN SPACE

In this section, we quantify how well the overall design space of possible AOD patterns can be approximated by a subset.

We first verify that our set of 29 injection choices sufficiently describes other possible AOD patterns that we have not simulated, and then quantify how well the sample set can be approximated by each possible subset of  $n$  injection choices.

For each possible value of  $n$ , we identify the "best" set of  $n$  injection choices that best approximates any possible pattern of AOD. We estimate the maximum error in approximating any possible pattern of AOD by the maximum AOD angle  $\theta^*(n)$  between the simulated AOD pattern and the pattern approximated by the subset of  $n$ . As we increase the number of DOF, the maximum error decreases, but with diminishing returns. The maximum angles  $\theta^*(n)$  for different values of  $n$  are plotted in Figure 2.

Figure 2. The maximum angle  $\theta^*(n)$  between the best set of  $n$  DOF and any other injection choices in the sample set. Diminishing returns are generally observed as  $n$  increases.



## AOD AND SURFACE CLIMATE

In this section, we evaluate the relationship between how similar or dissimilar two AOD patterns are and how similar or dissimilar the corresponding surface climate responses are. To estimate this relationship, we consider the different strategies described in Table 1. Each of injection strategies described in Table 1 uses either different injection choices or has different climate goals, leading to different AOD patterns and surface climate responses. Functions are derived to describe how the similarity in surface climate responses relates to the similarity in the AOD patterns that they arise from.

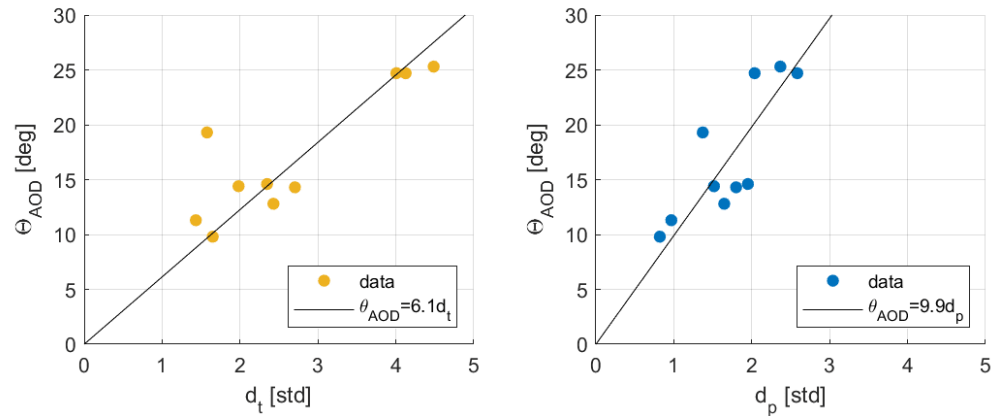
We use the angle between two AOD patterns to describe the difference between two AOD patterns. We use the distance between two patterns of surface temperature or two patterns of precipitation to describe the difference in surface temperature or precipitation between two strategies. The relationship between AOD angle  $\theta_{AOD}$  and temperature distance  $d_t$  is approximated as,

$$\theta_{AOD} = 6.1d_t,$$

and the relationship between AOD angle  $\theta_{AOD}$  and precipitation distance  $d_p$  is approximated as,

$$\theta_{AOD} = 9.9d_p.$$

Figure 3. (Left) estimated relationship between  $\theta_{AOD}$  and  $d_t$ , and (right) estimated relationship between  $\theta_{AOD}$  and  $d_p$ .



Given that all five SAI strategies were simulated to provide a global cooling of 4°C, we derive the equation for estimating how different the AOD patterns have to be in order to result in detectably different surface climate. The detailed derivations can be found in Zhang et al., 2021.

Whether the surface climates are detectably different depends on the amount of global cooling. For a particular level of global cooling, the minimum angle between the AOD patterns of two SAI strategies with detectably different surface temperature is estimated as,

$$\theta_a^t = 24/\Delta T_t,$$

and the minimum angle between the AOD patterns of two SAI strategies with detectably different precipitation is estimated as,

$$\theta_a^p = 40/\Delta T_p,$$

where  $\Delta T_t$  and  $\Delta T_p$  are the considered level of global cooling.

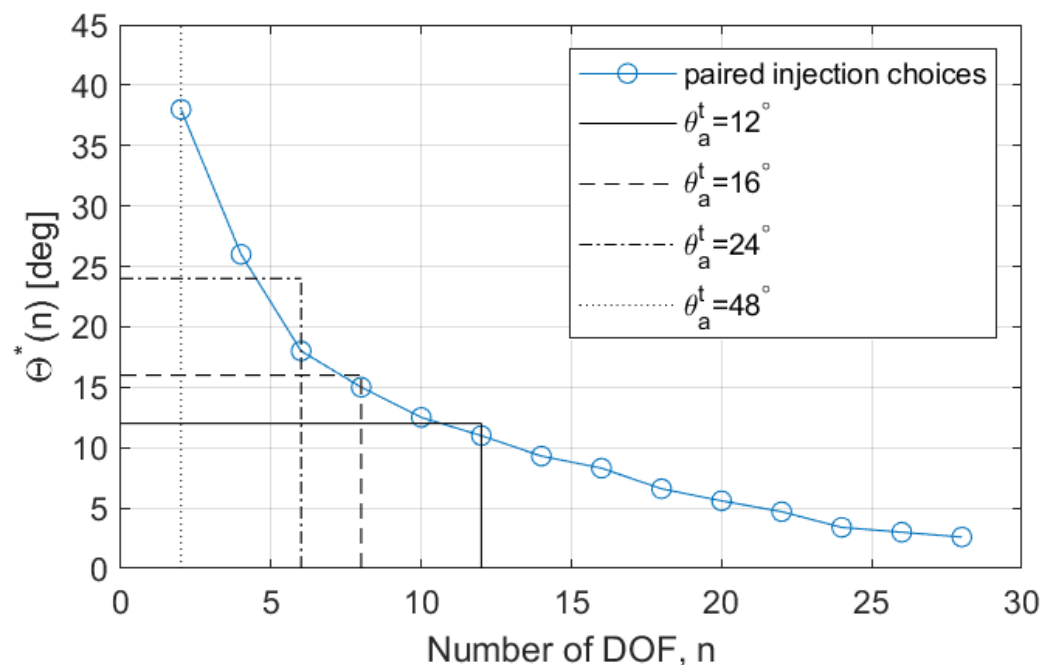
## RESEARCH OUTCOMES

Research to date has concluded that there are at least 3 degrees of freedom (DOF). A key observation from this study is that the number of DOF effectively depends on the amount of global cooling provided by SAI. The number of meaningfully-independent DOF increases as the amount of global cooling increases. From this study, we found that, for a cooling level of 1-1.5°C, there are likely between 6 and 8 meaningfully-independent DOF. That is, for these levels of cooling, 6-8 independent climate goals can be simultaneously met. This expands the manageable number of climate metrics relative to what has been considered in previous studies, which reveals new opportunities for exploring alternate designs with different distributions of climate impacts. Further research should be conducted to explore alternate SAI designs and to compare the resulting climate responses and associated trade-offs.

Table 2. The minimum number of DOF of the SAI design space for four targeted levels of cooling. At each level of cooling,  $\theta_a^t$  is the maximum angle that can be formed between two AOD patterns that yield undetectably different temperature responses.  $\theta^*(n)$  is the maximum angle between any possible AOD pattern and the design space of  $n$  DOFs, and must be smaller than  $\theta_a^t$ .

Targeted level of cooling [ $^{\circ}\text{C}$ ]	Cut-off angle $\theta_a^t$	Minimum number of DOF, $n$	$\theta^*(n)$
0.5	$48^{\circ}$	2	$38^{\circ}$
1	$24^{\circ}$	6	$18^{\circ}$
1.5	$16^{\circ}$	8	$15^{\circ}$
2	$12^{\circ}$	12	$11^{\circ}$

Figure 4. The minimum number of DOF corresponding to the worst-case error in approximating AOD patterns.  $\theta_a^t = 24^{\circ}$  corresponds to the minimum AOD angle between two detectable SAI strategies, at a cooling level of 1°C.  $\theta_a^t = 16^{\circ}$  corresponds to the minimum AOD angle between two detectable SAI strategies, at a cooling level of 1.5°C.



## REFERENCE & ACKNOWLEDGEMENT

### Reference:

Zhang, Y., MacMartin, D., Visioni, D., and Kravitz, B.: How large is the design space for stratospheric aerosol geoengineering? *Earth System Dynamics*, 2021, [Under review](#).

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## ABSTRACT

Stratospheric aerosol injection (SAI) can provide global cooling by adding aerosols to the lower stratosphere, and thus is considered as a possible supplement to emission reduction. Previous studies have shown that injecting aerosols at different latitude(s) and season(s) can lead to differences in regional surface climate, and there are at least three independent degrees of freedom (DOF) that can be used to simultaneously manage three different climate goals. To understand the fundamental limits of how well SAI might compensate for anthropogenic climate change, we need to know the possible surface climate responses to SAI by evaluating the SAI design space. This research work quantifies the number of meaningfully-independent DOFs of the SAI design space. This number of meaningfully-independent DOF depends on both the climate metrics that we care about and the amount of cooling. From the available simulation data of different SAI strategies, we observe that between surface air temperature and precipitation, surface air temperature dominates the change of surface climate. The number of injection choices that produce detectably different surface temperature is more than the number of injection choices that produce detectably different precipitation. At low levels of cooling, only a small set of injection choices yield detectably different surface climate responses. As more cooling is needed, more injection choices produce detectably different surface climate. For a cooling level of 1-2°C, we find that there are likely between 6 and 12 DOFs. This reveals new opportunities for exploring alternate SAI designs with different distributions of climate impacts and evaluating the underlying trade-offs between different climate goals.

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