

Replies to comments by reviewer 3

Comment: This manuscript presents a timely and fundamentally important study that connects the currently very active topic of stratospheric aerosol injection (SAI) to a concrete and practical problem in the satellite observation community: how heavy stratospheric aerosol loading affects solar occultation measurements and the retrievability of aerosol extinction profiles.

I find the overall research idea excellent. The study successfully links geoengineering scenarios to real observational limitations and demonstrates how SAI-induced aerosol loading can directly influence satellite measurements, retrieval sensitivity, and wavelength selection. In this sense, the manuscript represents a strong and valuable fundamental study that fits very well within the scope of Atmospheric Measurement Techniques. I also appreciate the use of established models (MAECHAM5-HAM and SCIATRAN) and the clear focus on the “zero transmission problem”, which is highly relevant not only for hypothetical SAI deployments but also for major volcanic eruptions.

I largely agree with Referee 1 that, while the core idea and modelling framework are strong, the current version of the paper would benefit substantially from deeper analysis and more extensive discussion. Strengthening these aspects would significantly enhance the paper’s impact, particularly for readers seeking a clearer and more quantitative understanding of the sensitivity and magnitude of SAI impacts on solar occultation measurements. Below I outline my two main suggestions, which I hope will help to improve the manuscript.

Reply: We thank the reviewer for his/her constructive and helpful comments. We tried to answer every comment in an appropriate way.

Comment: Major Comment:

1. The main analysis focuses on a continuous SO_2 injection rate of 30 Tg S yr^{-1} , with only a brief mention of results for 10 Tg S yr^{-1} . While I understand the motivation to examine an extreme, upper-end SAI scenario, the applicability of the conclusions would be strengthened by either expanding the discussion of intermediate or lower emission rates, or by more clearly justifying why 10 and 30 Tg S yr^{-1} were selected as representative cases.

Reply: Thank you for the comment. We chose 30 Tg S yr^{-1} , as a deliberately high, upper-end SAI scenario to probe the zero-transmission problem under conditions where radiative forcing effects are most pronounced. This allows us to assess whether and how zero transmission would emerge in a hypothetical large-scale deployment. While ambitious, this injection rate has been discussed in SAI modelling studies [e.g, 1, 2]. We acknowledge that 30 Tg S yr^{-1} is at the high end of proposed scenarios, however, the upper limit in the context of possible SAI applications depends, for instance, on the the specific goal, such as specific radiative forcing effects.

The 10 Tg S yr^{-1} case was selected as a Pinatubo-like reference (the 1991 eruption injected approximately 20 Tg SO_2), while acknowledging that volcanic eruptions represent impulsive rather than continuous injections such as the SAI injections performed here. This lower rate allows us to examine whether and to what extent the zero-transmission problem occurs at more moderate injection levels and to determine the minimum wavelength required for the latitude range of the injection.

The results showed that a wavelength of at least 1543 nm would be necessary in the latitude range of the injection, which is not the case for the 30 Tg S yr⁻¹ scenario. We believe that this is a valuable addition and, in line with the focus of the study, we decided to mention the latitude range of the injection because this is where aerosol loading is highest (for the month analysed here) and the zero-transmission effect is most pronounced, making it the region of greatest concern for this problem.

[1] Laakso, A., Niemeier, U., Visionsi, D., Tilmes, S., and Kokkola, H.: Dependency of the impacts of geoengineering on the stratospheric sulfur injection strategy – Part 1: Intercomparison of modal and sectional aerosol modules, *Atmos. Chem. Phys.*, 22, 93–118, <https://doi.org/10.5194/acp-22-93-2022>, 2022.

[2] Niemeier, U. and Timmreck, C.: What is the limit of climate engineering by stratospheric injection of SO₂?, *Atmos. Chem. Phys.*, 15, 9129–9141, <https://doi.org/10.5194/acp-15-9129-2015>, 2015.

We added the following to the introduction:

”This injection rate is analysed as a deliberately high, upper-end SAI scenario to probe the zero-transmission problem under conditions where radiative forcing effects are most pronounced. Although it appears to be a comparatively high emission rate, the upper limit in the context of possible SAI applications depends, for instance, on the specific goal, such as specific radiative forcing effects.”

We added the following to the discussion:

”The injection rate of 30 Tg S yr⁻¹ was selected as a deliberately high, upper-end SAI scenario to probe the zero-transmission problem under conditions where radiative forcing effects are most pronounced. This enables an assessment of whether and how zero transmission may emerge in a hypothetical large-scale deployment. While ambitious, injection rates of this magnitude have been discussed in previous SAI modelling studies (e.g., Niemeier and Timmreck, 2015; Laakso et al., 2022). The injection rate lies at the upper end of proposed scenarios, however, potential upper limits in SAI applications depend on the specific objectives, for instance the targeted radiative forcing.”

As well as:

”The 10 Tg S yr⁻¹ injection was selected as a Pinatubo-like reference (the 1991 eruption injected approximately 20 Tg SO₂), while emphasising that volcanic eruptions represent impulsive rather than continuous injections. This lower rate allows examining whether and to what extent the zero-transmission problem occurs at more moderate injection rates and to determine the minimum wavelength required for the latitude range of the injection, since this latitude range is where aerosol loading is highest (for the month analysed here) and the possible zero-transmission effect is most pronounced, making it the region of greatest concern for this problem.”

Comment: In addition, I encourage the authors to clarify whether the relationship between required wavelength and emission strength is approx. linear, or whether it exhibits threshold behaviour (i.e. abrupt transitions where a given wavelength rapidly becomes unusable). Even a qualitative or semi-quantitative sensitivity discussion would greatly enhance the broader relevance of the results.

Reply: Thank you for pointing this out. Based on the injection scenarios of 10 and 30 Tg S yr⁻¹, we can qualitatively evaluate the scaling behaviour. The results show that longer wavelengths are required at higher injection rates due to higher aerosol loading, resulting in higher aerosol optical depth and lower transmission from the perspective of the satellite solar occultation instrument (depending on the wavelength). Therefore, it is a monotonic relationship, where higher injection rates require longer wavelengths. Based on the data we assume a sub-linear relationship between required wavelength and the injection rate (factor 3 increase in injection rate yields $\approx 23\%$ increase in threshold wavelength for 5° N).

We added the following to the discussion:

”The relationship between injection rate and wavelength threshold appears monotonic: Higher injection rates increase aerosol loading and aerosol optical depth, requiring longer wavelengths to maintain measurable transmission for satellite solar occultation measurements. Comparing the two scenarios, a threefold increase in injection rate (10 to 30 Tg S yr⁻¹) corresponds to approximately 23 % increase in the minimum wavelength threshold at 5° N (from 1543 to 1900 nm), suggesting sub-linear scaling. While a complete characterization would require additional intermediate injection scenarios, the results suggest that the zero-transmission problem intensifies with increasing injection rate.”

Comment: 2. I concur with Referee 1 that the manuscript currently lacks sufficient depth in its analysis and discussion. The Results and Discussion section reads as a rapid presentation of figures, with limited interpretation of the underlying physical mechanisms or broader implications.

I encourage the authors to expand the discussion to address questions such as: Why do certain wavelengths fail or succeed at specific latitudes and altitudes? How do aerosol vertical structure and steady-state aerosol loading jointly control retrieval sensitivity? What do these results imply for instrument design, wavelength selection strategies, and the interpretation of real occultation data under extreme aerosol conditions?

Addressing these points would substantially strengthen the manuscript and allow readers to fully appreciate the insights gained from this study.

Reply: We followed the reviewer’s suggestion and added additional statements and discussions to various parts of the manuscript:

l. 180 (after Fig. 2): ”The lack of good agreement can be attributed to the high AOD (0.45 at 550 nm) near the latitude of the injection, resulting in high aerosol extinction and low transmission from the perspective of the satellite solar occultation instrument.”

l. 190: ”Consistent with expectations and the averaging kernels (panel (b) of Fig. 2) the minimum transmission values of $\approx 10^{-14}$ fall below the detection threshold where measurement noise dominates the signal, preventing the retrieval algorithm from extracting meaningful information about the vertical profile of aerosol extinction coefficients.”

l. 198 (after Fig. 4): ”The improved retrieval performance reflects the principle that aerosol extinction decreases with increasing wavelength, confirming the generally accepted idea that, in the case of very high emissions, the appropriate approach is to use longer wavelengths for aerosol measurements.”

l. 207: "The transmission at the minimum still remains on the order of about $10^{-6} - 10^{-5}$, while the transmission values at the other tangent heights stay within ranges that allow useful measurement information to be retrieved from these heights, leading to the improved retrieval performance."

l. 214: "The reduced aerosol loading at these latitudes allows shorter wavelengths to maintain sufficient transmission from the perspective of the solar occultation instrument for the aerosol extinction profile retrieval."

l. 244: "The results presented above reveal a relationship between latitude, AOD, vertical structure, and minimum retrieval wavelength. Thereby, three factors jointly control retrieval feasibility:

First, the AOD determines the overall attenuation of the signal. With high AOD, the extinction of the solar signal is so strong that no meaningful retrieval is possible at the corresponding altitudes. This is accompanied by correspondingly low transmissions from the satellite solar occultation instrument's perspective. The latter two points depend also on the wavelength and latitude.

Second, the vertical profile of the aerosol extinction coefficients, which modulates the retrieval sensitivity. For the latitudes near the Equator, aerosol extinction coefficients peak near 19 km (e.g, Fig. 4, for 5° N), creating a localized transmission minimum that can fall below detection limits at shorter wavelengths. At higher latitudes, aerosol extinction coefficients peak over a broader altitude range (e.g, Fig. 8 for 45° N and S), reducing peak extinction values and allowing information to be retrieved from a larger altitude range of the vertical profile.

Third, the steady-state nature of continuous injection differs fundamentally from volcanic eruptions, since continuous injections result in a much lower sulfate injection per time compared to a volcanic eruption with the same injected amount."

l. 276: "These findings, considering the assumptions made, can have direct implications for solar occultation instrument design. Instruments intended to detect and monitor SAI deployments above a certain size or major volcanic eruptions (or both in the hypothetical case of SAI deployments and a simultaneous volcanic eruption) should incorporate channels extending to at least 1900 nm to ensure coverage for the latitudes with high aerosol loading. The current SAGE III/ISS maximum aerosol wavelength of 1543 nm would be marginally insufficient for retrievals within $\approx \pm 15^\circ$ of a 30 Tg S yr^{-1} continuous tropical injection, though adequate for mid-to-high latitudes and lower injection rates (as demonstrated by the 10 Tg S yr^{-1} results at 5° N)."

In response to the comments made by Reviewer 1, we have made further additions to the manuscript. We kindly ask you to take this into account. A complete list of all changes would be too lengthy to be included here.

Comment: Minor comments

1. While aerosol deposition and sedimentation are included in MAECHAM5-HAM, this is only mentioned briefly. A short statement clarifying how aerosol removal balances continuous injection in the quasi-steady-state regime would improve transparency.

Reply: We added the following to the MAECHAM5-HAM section: "In the quasi-steady-state phase, the stratospheric sulphur burden stabilises at approximately 20.6 Tg S for the 30 Tg S yr^{-1} injection scenario, indicating that $\approx 10 \text{ Tg S yr}^{-1}$ is continuously removed through sedimentation and deposition processes, balancing the injection rate."

Comment: 2. The use of Ångström extrapolation to derive extinction at additional wavelengths is reasonable, but a brief comment on its validity under very high aerosol loadings (and large particle sizes) would be helpful.

Reply: We thank the reviewer for this important comment.

For the visible spectral range (500–550 nm \rightarrow 520 nm) the calculated Ångström exponent α is very small and slightly negative throughout the 10–27 km altitude range (≈ -0.12 to -1.07). These values indicate that the aerosol extinction is nearly flat in this narrow spectral range ($\Delta\lambda = 20$ nm). Consequently, the interpolation to 520 nm results in a change in extinction that is negligible compared to the original 500 nm. In other words, the Ångström method introduces no significant error in this case. For longer wavelengths in the infrared, the calculated Ångström exponents are significantly larger, e.g.: 1050–1585 nm \rightarrow 1543 nm: $\alpha \approx 1.2$ – 1.97 , 1585–1888 nm \rightarrow 1800 nm: $\alpha \approx 2.1$ – 5.4 (higher values due to very low extinction coefficients (≈ 10 – 14 km)), 1888–2250 nm \rightarrow 1900 nm: $\alpha \approx 3$ – 6 (higher values due to very low extinction coefficients (≈ 10 – 14 km)). Therefore, even under conditions of elevated aerosol loading, the method provides a reasonable approximation for the wavelengths considered here. The explanations refer to a latitude of 5°N .

In summary, the Ångström method is valid for the current study.

We added the following to Sect. 2.2.1:

”For a latitude of 5°N and the visible spectral range (500 – 550 nm \rightarrow 520 nm), the calculated α were small and slightly negative throughout the altitude range (≈ -0.12 to -1.07), indicating nearly wavelength-independent extinction in this narrow spectral interval ($\Delta\lambda = 20$ nm). Consequently, the interpolation introduces a negligible change in extinction. In the near-infrared range, α increases to values between approximately 1.2 and 6 (higher values due to very low extinction coefficients (≈ 10 – 14 km)). These values confirm that the Ångström parameterisation provides a reasonable approximation for the spectral regions considered in this study.”

Comment: 3. Although SAGE III/ISS provides an important reference, a brief clarification of how instrument-specific assumptions (e.g. field of view, tangent height spacing) influence the results would improve transferability to other occultation sensors.

Reply: Thank you for the comment. In our study, we did not assume a specific instrument configuration but adopted values representative of a typical satellite solar occultation system, such as SAGE III/ISS. Pointing uncertainty was explicitly included via a ± 100 m tangent height perturbation, as this represents one of the dominant error sources. Within the range of typical occultation sensor configurations, variations in FOV and tangent spacing primarily affect vertical smoothing characteristics rather than the magnitude of aerosol extinction uncertainty. The resulting error characteristics are therefore transferable to other occultation sensors with comparable vertical resolution and pointing performance.

We added the following to Sect. 2.2.1:

”Vertical field of view, and sampling assumptions represent a typical satellite solar occultation instrument and the resulting error characteristics are likely transferable to other occultation sensors with comparable vertical resolution and pointing performance, provided that a similar retrieval approach is applied.”