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A5 3 That's a lot of sulphates

J. Taylor, E. Greathead, J.Rai

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

This short study utilises the concept of Stratospheric Aerosol Injection (SAI), which mimics the cooling effects of volcanic eruptions, to estimate the total mass of atmospheric sulphate aerosols required to cause the extinction of all life forms inhabiting the planet, by blocking solar radiation from penetrating the stratosphere. By considering the mean free path of solar photons in the stratosphere it was found that an aerosol number density of approximately 3.54×10^{20} m^{-3} was necessary to prevent light reaching the Earth's surface. It was subsequently determined that this equates to a total mass of $\approx 5.92\times\ 10^{14}$ kg

Introduction

Stratospheric Aerosol Injection (SAI) is one of the newer proposed methods of solar geoengineering to reduce the effects of climate change, aiming to mimic the cooling effects of volcanic eruptions [1]. It involves the manual enrichment of the Earth's stratosphere with sulphate aerosols (mainly SO_2), these are microscopic fine particles which have the capability to scatter and absorb solar radiation, as well as reflect it back out into space. This reflection of light in turn reduces the total solar flux incident on the Earth's surface, cooling the planet as a result.

While this has many potential uses in reducing the global average temperature enough to offset the effects of climate change by modulating the Earth's radiative budget, in this study we instead chose investigate a theoretical value for the total mass of SO_2 aerosols that would need to be 'injected' into the stratosphere to block out all solar radiation to inhibit natural processes essential for life.

In order to reduce the complexity of the calculations, for now we assume that all solar radiation will be blocked, as this will guarantee extinction of all life, with the potential of a more complex model being employed in future papers.

Calculations and Discussion

To begin, in order to simplify the model we are choosing to ignore the effects of the Earth's albedo, however this is a potential addition for future papers. We made the assumption that the stratosphere has uniform aerosol density and that all the aerosols are roughly the same size, so that the probability of a photon being reflected, P_r, will be the same across the entire stratospheric region.

To calculate this probability, we consider a small infinitesimal chunk of the stratosphere of area, A, and thickness δS. In this small region the probability is given by $P_r = \sigma/A$, where σ is the area of the aerosol cross section and all other variables are as previously stated. From this it can be deduced that the portion of radiation reflected by one molecule, δI, is given by δI$= -\sigma/A\times I$, hence for a system of N molecules δI= $-\sigma/A \times IN$. It can also be said that N= $nA\delta S$, where n is the number density of aerosols in the region and all other variables are as previously stated. This expression for N can then be substituted into the equation developed for δI to produce the following:

$$\delta I = -\frac{\sigma}{A} In A \delta S = -n\sigma\delta S I \tag{1}$$

Equation (1) can then be considered in differential form:

$$dI = -I d\tau \tag{2}$$

where I is as previously defined and τ is the optical path depth of the photons. Comparing (1) and (2) it is evident that $d\tau = n\sigma dS$. Integrating this element from 0 to δS (the thickness of the stratospheric chunk being considered), allows us to say that $n\sigma\delta S = \tau$. Using also the relationship between optical depth and mean free path of $\tau = \delta S/l_{mfp}$ where l_{mfp} is the mean free path of solar photons traveling through the stratosphere, we can deduce that:

$$l_{mfp} = \frac{1}{n\sigma} \tag{3}$$

All variables are as previously stated. The stratosphere extends from 10 km to 50 km above the planets surface [2], meaning that the mean free path required to prevent radiation from reaching the Earth's surface is 40 km. Additionally assuming that each aerosol can be modelled as a sphere with a radius of ≈ 150 pm [3], the cross sectional area of each SO_2 molecule is ≈ 7.1 $\times 10^{-20}$ m^2. Furthermore, through re-arranging equation (3) and substituting in the known values, it can be determined that the number density of aerosols is n ≈ 3.54 × 10^{14} m^{-3}.

With the number density now known, to extend this across the entire stratosphere and find the total number of sulphate aerosols needed, the total stratospheric volume must be calculated. This can be approximated by computing the spherical volume of the Earth up to the troposphere [2] and subtracting this from the volume extended up to the edge of the stratosphere, providing a total stratospheric volume of ≈ 2.06 × 10^{19} m^3. Now multiplying the number density by the stratospheric volume we find that a total of ≈ 7.29 × 10^{33} evenly distributed aerosols is necessary for a mass extinction to occur. Assuming the mass of SO_2 to be approx. 1.67 × 10^{-25} kg, the total mass of aerosols required is ≈ 1.22 Gg.

The calculated value of ≈ 1.22 Gg is an underestimate of the total mass required, this is mainly due to the assumptions we have made about the distribution of these molecules in the stratosphere. In reality, when comparing SAI to the volcanic eruptions it is mimicking, a specific eruption (dependent on the classification [4]) will produce substantial cooling effects in either the northern or southern hemisphere due to the self-coagulative effects of all of the molecules being released at the same place in a short time span [5].

Conclusion

The model we have used indicates that a total mass of order 10^9 SO_2 aerosols would be necessary to block enough solar radiation from penetrating the atmosphere in order to bring a halt to all processes fundamental to life on Earth.

References

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