Brief Report

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Brief Report

A Proposal of Geoengineering Method as Global Warming Countermeasure: Stratospheric O_3 Increase to Reduce Earth's Surface Temperature

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Abstract: A method of geoengineering/solar radiation management is proposed as global warming countermeasure. The idea is to decrease surface temperature by increasing stratospheric ozone. One-dimensional (vertical) radiative-convective equilibrium temperature calculations show that surface temperature can be lowered by increasing the amount of ozone in the stratosphere. It was the increase in altitude above about 25 km that reduced surface temperatures. The method of increasing the amount of ozone (O_3 injection), the rate of decrease of surface temperature after the ozone increase, and the rate of decrease of ozone concentration by photochemical reaction and diffusion/transport after the ozone increase are discussed.

Keywords: geoengineering; global warming countermeasure; stratospheric O_3

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1. Introduction

The current status of global warming is quite serious. The global average temperature has reached a warming of 1.1 °C in 2011-2020 in comparison to 1850-1900. Anthropogenic climate change is already affecting many extreme weather and climate events in all regions of the world. This is causing extensive adverse effects on nature and people, and associated losses and damages. Global greenhouse gas emissions in 2030, as suggested by Nationally Determined Contributions (NDCs) published by October 2021, indicate that warming is likely to exceed 1.5 °C during the 21st century, making it even more difficult to limit warming below 2 °C.

Global CO_2 net emissions zero will need to be achieved by early 2050 for a 1.5 °C limit, and by early 2070 for a 2 °C limit [1]. The situation is so severe that it cannot be met only by promoting renewable energy as an alternative to fossil fuels. Geoengineering has been considered as another method of global warming countermeasures. A typical example of geoengineering/solar radiation management (SRM) is the application of sulfate aerosols in the stratosphere [2]. Although this method can reliably lower temperatures, it has been shown to have negative side effects such as increased air pollution and ozone depletion [3]. In this report, I propose another method, which might have the potential to reduce the shortcomings although many issues need further consideration as will be described later. The method is to increase the amount of stratospheric O_3 and decrease earth's surface temperature. First, I show that the surface temperature can be lowered by increasing the amount of O_3 in the stratosphere using one-dimensional (vertical) radiative-convective equilibrium temperature calculations. Then, I discuss the problems that need to be considered with respect to this method.

2. Calculation Methods

「The Climate Laboratory」[4] and「Colaboratory」(Google) were used for one-dimensional (vertical) radiative-convective equilibrium temperature calculations [5] and other calculations. The RRTMG (Rapid Radiative Transfer Model) which is used in many current GCMs was employed in the radiative-convective equilibrium temperature calculations. The calculations process looks for lapse rates exceeding a fixed threshold and performs an instantaneous adjustment that mixes temperatures while conserving energy. The convergence judgment conditions typically applied were $<10^{-2}$ K although it showed less than 10^{-3} K in most calculations. As reference exhibitting reliability of the calculations, it is noted that a doubling of CO_2 showed an increase of 1.30 °C in the surface temperature without feedback. Therein, the Planck feedback was -3.3 $Wm^{-2}K^{-1}$ and the water vapour feedback was +1.86 $Wm^{-2}K^{-1}$, which were both similar to those of the complex GCM models [6].

3. Results and Discussion

3.1. Change in Surface Temperature with Change (Increase) of O_3 Amount

One-dimensional (vertical) radiative-convective equilibrium temperature calculations were performed by changing (increasing) the amount of O_3 with respect to vertical distribution. (albedo = 0.25, adj_lapse_rate = 6.5 (°C/km)) The calculations were made keeping constant relative humidity for the amount of H_2O. The results obtained are shown in Figure 1 and Tables 1 and 2. Tables 1 and 2 show the amounts of temperature change from the standard condition.

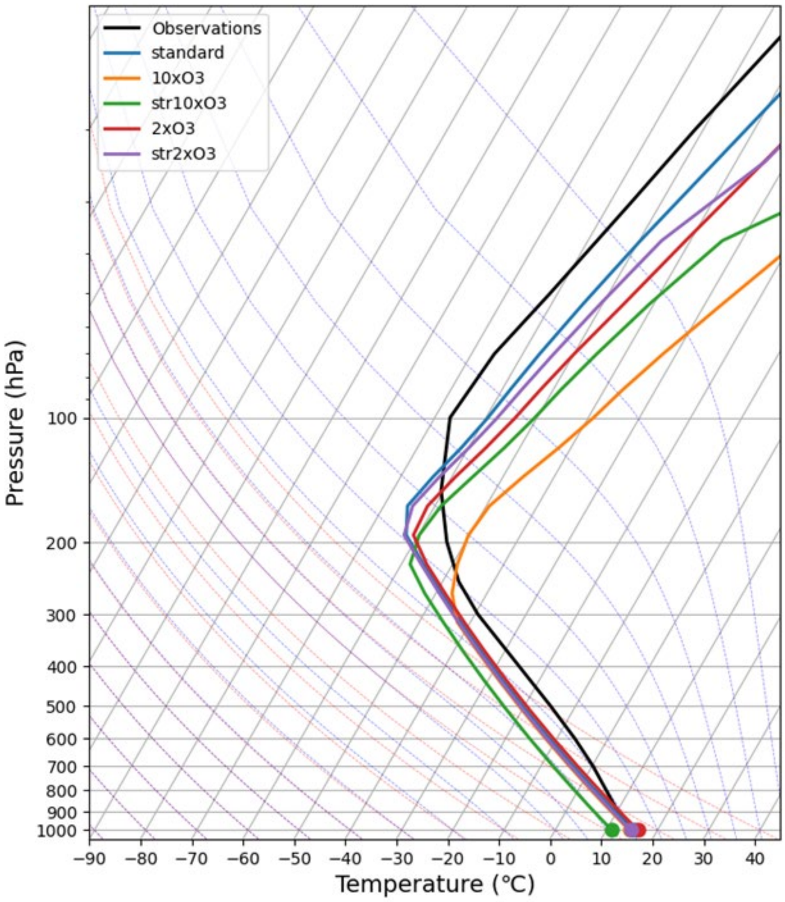

Figure 1. Altitude-temperature curve change with O_3 amount (observation, standard condition, 2x O_3, 2x stratospheric O_3, 10x O_3, 10x stratospheric O_3).

Table 1. Surface temperature change with O3 amount.

	standard	2x O_3	2x str.O_3	10x O_3	10x str.O_3
change amount(K)	288.45 K	0.87	-0.56	-0.84	-4.24

Table 2. Surface temperature change with O_3 amount (10x at one point altitude level only).

altitude (hPa)	3.5	7.4	14	23.9	37.2	53.1	70	85.4	100.5

change amount(K)	-1.63	-1.20	-0.92	-0.09	0.70	1.10	1.03	0.87	0.94
altitude (hPa)	118.3	139.1	163.7	192.5	226.5	266.5	313.5	368.8	433.9
change amount(K)	1.02	1.13	1.28	1.36	1.22	0.99	0.86	0.82	0.79
altitude (hPa)	510.5	600.5	696.8	787.7	867.1	929.6	970.6	992.6	
change amount(K)	0.75	0.66	0.50	0.31	0.17	0.07	0.03	-0.18	

Altitude level:

[3.54, 7.39, 13.97, 23.94, 37.23, 53.11, 70.06, 85.44, 100.51, 118.25, 139.11, 163.66, 192.54, 226.51, 266.48, 313.50, 368.82, 433.90, 510.46, 600.52, 696.80, 787.70, 867.16, 929.65, 970.56, 992.56 (hPa)]

O_3 amount in standard condition:

[7.53e-6, 8.52e-6, 7.87e-6, 5.60e-6, 3.46e-6, 2.03e-6, 1.13e-6, 7.30e-7, 5.27e-7, 3.84e-7, 2.82e-7, 2.12e-7, 1.63e-7, 1.18e-7, 8.24e-8, 6.26e-8, 5.34e-8, 4.73e-8, 4.24e-8, 3.91e-8, 3.56e-8, 3.12e-8, 2.73e-8, 2.47e-8, 2.30e-8, 2.22e-8]

H_2O amount in standard condition:

[2.16e-06, 2.15e-06, 2.15e-06, 2.13e-06, 2.12e-06, 2.11e-06, 2.09e-06, 2.11e-06, 2.42e-06,
3.13e-06, 5.01e-06, 9.61e-06, 2.09e-05, 4.79e-05, 1.05e-04, 2.12e-04, 3.94e-04, 7.11e-04,
1.34e-03, 2.05e-03, 3.17e-03, 4.97e-03, 6.62e-03, 8.38e-03, 9.39e-03, 9.65e-03]

Other absorbing species amounts:

CO_2 0.000348, CH_4 1.65e-06, N_2O 3.06e-07, O_2 0.21, CFC11 0.0, CFC12 0.0, CFC22 0.0, CCL_4 0.0

When stratospheric O_3 is increased, the increase in stratospheric O_3 acts to absorb shortwave radiation better, increasing stratospheric temperatures and decreasing surface temperatures. On the other hand, an increase in tropospheric O_3 increases surface temperatures. These degrees are greater by a factor of 10 than by a factor of 2. Table 2 shows the case where the amount of O_3 is increased by a factor of 10 for each altitude level only. The altitude boundary at which an increase in O_3 lowers or raises surface temperatures is about 25 km. The calculations performed for three different ozone distributions (26 km, 22 km, and 19 km maximum altitudes) reported that surface temperatures increased with decreasing maximum altitude [7]. The results presented here are consistent with this report. It was found from these data that an increase in O_3 in the stratosphere (above 25 km altitude) decreases surface temperatures.

3.2. As for Stratospheric O_3 Increase

Next, concerning the method to increase the amount of O_3 in the stratosphere, a typical method is to inject O_3 directly into the stratosphere. After injection, O_3 diffuses/transports and its concentration changes/decreases. Since the O_3 concentration exceeds the natural (steady-state) O_3 concentration, the O_3 concentration will decrease also due to photochemical reactions. First, without considering diffusion/transport, the O_3 concentration change due to photochemical reactions will be discussed.

Ozone production and destruction in the stratosphere can be explained by the Chapman model.

$O_2 + h\nu$(240nm 以下) $\rightarrow$ $O + O$ (J_1) -- ①
$O + O_2 + M \rightarrow O_3 + M$ (k_1) -- ②
$O_3 + h\nu$(320nm 以下) $\rightarrow$ $O + O_2$ (J_2) -- ③
$O + O_3 \rightarrow 2O_2$ (k_2) -- ④

Thus, the rate of change of each quantity is as follows.

$d\ nO = 2*J_1*nO_2 + J_2*nO_3 - k_1*nO*nO_2*n_{air} - k_2*nO*nO_3$ -- ⑤
$d\ n0_2 = J_2*nO_3 + 2*k_2*nO*nO_3 - J_1*nO_2 - k_1*nO*nO_2*n_{air}$ -- ⑥
$d\ n0_3 = k_1*nO*nO_2*n_{air} - J_2*nO_3 - k_2*nO*nO_3$ -- ⑦

(nO: oxygen atom density, nO_2: oxygen molecule density, nO_3: ozone molecule density, n_{air}: air density)

For example, I consider an injection of O_3 (10 times the amount of the natural state) into a region at an altitude of 30 km. There are literature reports on the calculation of stratospheric ozone with the values shown in Table 3 [8,9]. Let me consider this as an example.

Table 3. Example of each value in Chapman model (Tokyo, 3 pm on Aug.20, zenith angle 46.7°).

Altitude (km)	Temperature (K)	Dissociation constant(s^{-1})		Rate constant (cm^6s^{-1}) (cm^3s^{-1})		Air density (cm^{-3})	O_2 density (cm^{-3})	O_3 density (cm^{-3})
		J_1	J_2	k_1	k_2	n_{air}	nO_2	nO_3
30	234	2.576e-12	1.601e-4	1.019e-33	1.147e-15	2.749e17	5.759e16	3.610e12

Assuming that the oxygen atom density nO is in a steady state, using equation ⑤ = 0 and the values in Table 3, nO is about 1e7. Using 10 times the value in Table 3 (3.610e13) as the initial value for nO_3, values in Table 3 for nO_2 and n_{air}, and 1e7 as the initial value for nO, and evolving (5) through (7) in time, the respective densities were calculated. The result obtained is shown in Figure 2.

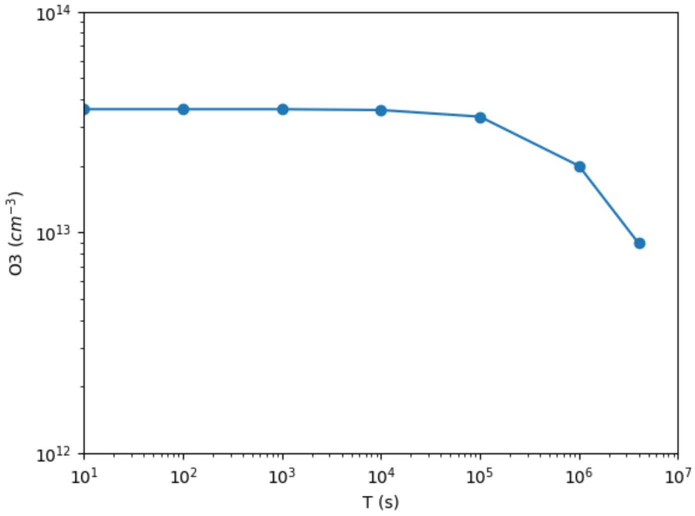

Figure 2. Change in O_3 concentration after O_3 injection.

The O_3 level remained almost unchanged until about 10^4 s, at which point it began to decrease, reaching 2.00e13 at 10^6 s (≈10^1 days). The O concentration changed with the O_3 one. It is considered that it takes about 10^2 days for the O_3 concentration to reach around the original O_3 concentration (3.610e12). This calculation assumes constant solar radiation and other weather conditions. If the time without solar radiation is taken into account, the rate of decrease of O_3 becomes smaller. It is suggested here that in terms of the photochemical reaction factor, the concentration of injected O_3 remains high for about 10^1 to 10^2 days. The data is consistent with the general fact that O_3 produced in the low-latitude stratosphere is transported to the mid- and high-latitudes. In reality, the rate of decrease is larger than in Figure 2 because the increase in O_3 causes stratospheric temperature to rise.

3.3. Rate of Surface Temperature Decrease by Stratospheric O_3 Increase

I examined how fast the surface temperature subsequently decreased with increasing stratospheric O_3. For example, Figure 3 shows the calculated results of the time course of the surface temperature when the O_3 density is increased by a factor of 10 only at an altitude of 30 km. The initial values of the surface temperature and the temperature at each altitude were set to the equilibrium temperature under the standard conditions. In this calculation, the amount of H_2O was fixed at the value of the standard conditions.

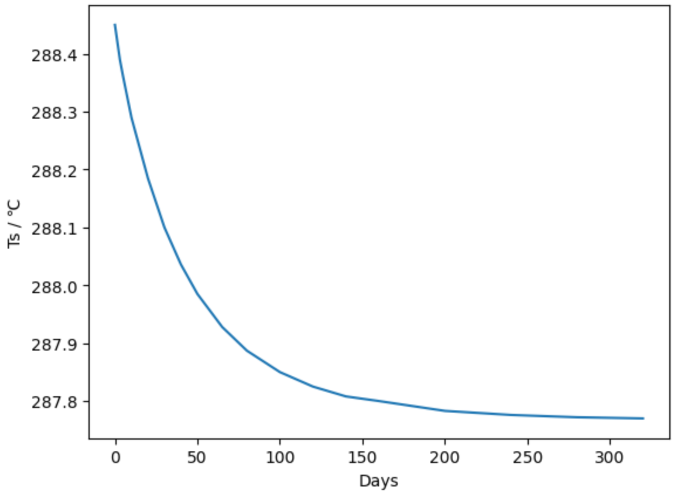

Figure 3. Surface temperature time course after O_3 increase.

It is seen that the surface temperature decreases by 0.35K (50%) at 30 days, 0.60K (90%) at 100 days, and 0.68K at equilibrium.

3.4. Injected O_3 Diffusion/Transport and Remarks

I discuss the diffusion/transport of O_3 which is injected. The way of spread/concentration change of O_3 after injection will depend on the location, the season/time, etc. of injection. For example, considering 30 km above Japan, the main driving force for transport is considered to be the east-west wind (typically several m/s to a dozen of m/s) [10], and it is inferred that the transport is mainly in the east-west direction. The winds in the north-south direction are typically < a few m/s [11] and are smaller than those in the east-west direction. Certainly, the vertical diffusion/transport has only a small influence, as the eddy diffusion coefficient is about 10^4 cm^2/s. Considering that the easterly wind speed is several m/s to a dozen of m/s, i.e., ~1000 km/day, the factor of concentration change due to diffusion/transport is presumed to be dominant rather than concentration change (decrease) due to (photo)chemical reaction as described in the previous chapter.

If the O_3 transport speed (wind speed of the east-west wind) is large, such as 1000 km/day, it may be difficult to perform the intended O_3 application. However, there are periods having < a few m/s among a year, for example, it is small in May every year. Considering the fact that it takes about one month for the surface temperature to decrease after an increase in O_3, it may be possible to plan for injection during this period to suppress high temperatures in summer.

Finally, I describe some of the issues involved in the application of the present method. The surface temperature calculations in this report are one-dimensional (vertical) radiative-convective equilibrium temperature calculations, i.e., they are simulation results for a single (average) location on the earth. More sophisticated computational (climate) models are needed. Based on detailed meteorological data for each region of the earth, advanced computational (climate) models must be engaged on a region-by-region and global basis. Although I employed a simple Chapman model above, it is also necessary to consider more detailed atmospheric chemical reaction processes; how the injected O_3 traces reaction paths with the atmosphere. In addition, stratospheric temperatures will increase, and the influences of this on the climate must also be investigated. The injected O_3 will decrease in concentration and return to its natural concentration through chemical reactions and diffusion/transport, but depending on the scale and method of application, it may enter the troposphere. The O_3 reaching the troposphere will cause an increase in surface temperature. Countermeasures need to be taken to address this issue. It is known that there are natural ozone exchange processes between the troposphere and the stratosphere such as stratosphere-troposphere exchange (STE) and deep convective storms. Although these are processes which occur at specific regions of the earth, close investigations about these processes will be required and instructive for the present study.

The O_3 injection location/area and amount/method should be determined after considering and predicting O_3 diffusion/transport according to the degree of surface temperature reduction, timing and duration, and size of the surface area which are designed. This may be very difficult with the current forecasting and observation technology. In all aspects, predicting the diffusion/transport process of O_3 to be injected is an essential primary task. Consideration of the cost of implementation is also necessary.

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