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The Role of Atmospheric Nuclear Explosions on the Stagnation of Global Warming in the  
Mid 20th Century

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## **ABSTRACT**

*This study suggests that the cause of the stagnation in global warming in the mid 20th century was the atmospheric nuclear explosions detonated between 1945 and 1980. The estimated GST drop due to fine dust from the actual atmospheric nuclear explosions based on the published simulation results by other researchers (a single column model and Atmosphere-Ocean General Circulation Model) has served to explain the stagnation in global warming. Atmospheric nuclear explosions can be regarded as full-scale in situ tests for nuclear winter. The non-negligible amount of GST drop from the actual atmospheric explosions suggests that nuclear winter is not just a theory but has actually occurred, albeit on a small scale. The accuracy of the simulations of GST by IPCC would also be improved significantly by introducing the influence of fine dust from the actual atmospheric nuclear explosions into their climate models; thus, global warming behavior could be more accurately predicted.*

Keywords: Atmospheric nuclear explosions; Global-mean surface temperature, Global warming

## 1. Introduction

The global mean surface temperature (GST) has been rising for more than one hundred years (Fig. 1, the black line). This is, of course, the phenomenon known today as global warming. The rise in GST seems to begin in 1917 although the radiative forcing due to greenhouse gasses (GHG) continues to increase at least from 1880 (Fig. 5 in Hansen et al., 2007). The absence of warming prior to 1917 may be explained by the negative radiative forcing of stratospheric aerosols due to large eruptions as those of Krakatau (1883) (Winchester, 2003), Santa Maria (1902) and Novarupta (1912), all with a VEI (volcanic explosivity index) rating of 6, and by the relatively inactive sun around 1900 (Fig. 1).

The rise in GST appears to have stagnated in the mid 20th century (Fig. 1, the black line), despite the fact that the atmospheric concentration of CO<sub>2</sub> (e.g. Fig. 2.3 in Topic 2, IPCC, 2007, p. 4) or, more directly, the radiative forcing by all GHG (Fig. 5 in Hansen et al., 2007) continued to increase. This stagnation cannot be explained by reduced solar activity because the sun was very active between 1954 and 1965 (Fig. 1). During the stagnation period, there were the eruptions of Bezymianny in 1956 and Mt. Agung in 1963, both with VEI ratings of 5 (note that VEI is a logarithmic scale). These may have contributed to the stagnation, however, they are unlikely to have been the main cause because the both eruptions occurred after the stagnation began and their VEIs were smaller than the three giant eruptions around 1900.

The stagnation in global warming in the mid 20th century has not been simulated well even by the most advanced climate models (e.g. Hansen et al., 2007) which considered various additional effects of radiative forcing beyond insolation and volcanic activities. The objective of this paper is not to precisely simulate GST while considering new details of radiative forcing but to suggest the possibility that the atmospheric nuclear explosions known as the Trinity test, Little Boy, Fat Man and the subsequent nuclear weapons tests caused the stagnation in global warming.

Statistics concerning the atmospheric nuclear explosions and previous research on the effects of atmospheric nuclear explosions on global climate are described in section 2. The possible causes of the stagnation in global warming are discussed in section 3. An estimation of the decline in GST produced due to the actual atmospheric nuclear explosions is attempted in section 4 based on the simulation results of other researchers. A method to mitigate global warming by injecting fine limestone powder into the lower stratosphere as an application of the GST drop caused by atmospheric nuclear explosions is proposed in section 5. Concluding remarks are given in section 6.

## **2. Background**

Atmospheric nuclear explosions began with the Trinity test in 1945. The explosions of Little Boy at Hiroshima and Fat Man at Nagasaki followed in the same year. The total yield of the 441 atmospheric nuclear explosions before the PTBT (Partial Test Ban Treaty) in 1963 prohibited atmospheric nuclear weapons tests reached 409 MT (Table 1 in UNSCEAR, 2000, pp. 195-204). Most nuclear weapons tests were moved underground after the PTBT. However, China began testing, and France continued testing, after the PTBT. Sixty-three atmospheric tests with 31 MT total yield were carried out by both countries after the PTBT. The last bomb being detonated in the atmosphere at Lop Nor by China in 1980. The total yield of the 504 atmospheric nuclear explosions between 1945 and 1980 was 440 MT.

Arakawa (1954) may have been the first who pointed to the possible relationship between climate change and the nuclear weapons tests. He suggested the possibility that the severely cold summer in 1954 in northern Japan was due to the hydrogen bomb tests by the United States over the Bikini Atoll between February and May of that year (p. 132 of Arakawa, 1954). Arakawa also pointed out the possibility that the haze at a higher altitude may have been

caused by abnormal polarization due to the small particles (diameter 0.8-1.0  $\mu\text{m}$ ) injected into the stratosphere by those hydrogen bomb tests (p.130 of Arakawa, 1954). However, he did not propose any mechanism for the severely cold summer. Arakawa et al. (1955) discussed the past temperature drops caused by eruptions and, by analogy, explained the mechanism of the temperature drop in 1954 summer as a product of extraordinary blocking highs and ridges over Central Europe, the western part of the Okhotsk Sea and the northwestern part of the North American Continent produced by the hydrogen bomb tests (p. 242 of Arakawa et al., 1955). It should be noted that the temperature drop caused by the attenuation of insolation by sulfate aerosols from giant eruptions was not yet widely accepted at that time (Dörries, 2006).

H. E. Landsberg, the director of the Office of Climatology of the U.S. Weather Bureau at that time, also pointed out in 1958 that "Conceivably one could throw enough dust into the stratosphere by nuclear explosions to intercept an appreciable amount of the solar radiation. This might, again conceivably, cause some changes of the general circulation. The effect would pass off in a few years -a short time as climatic spans go. Also, the effect would be general over the globe, with unpredictable effects as far as small land segments are concerned. It could hardly be called control" (Landsberg, 1958, p. 756).

Turco et al. carried out one of the early quantitative simulations of the effects of imaginary nuclear wars on the global climate. This work can be found in such articles as Turco et al. (1983), Turco et al. (1984), Ehrlich et al. (1984) and others. TTAPS will be used hereafter to designate these articles if there is no need to distinguish them specifically; these publications showed similar results for different cases, with only slightly different explanations. The simulation results are widely known as the famous "nuclear winter" and predicted a change in average surface air temperature over continental land areas in the Northern Hemisphere. These calculations used a single-column model with 60 vertical levels. The model top was 38 km and the length of simulation was 300 days. These calculations injected sub-micrometer dust consisted of siliceous minerals and glass as a result of surface and near-surface nuclear

explosions into the stratosphere and, to a lesser degree, the troposphere. Size of the dust was assumed to be log-normal distribution with mode radius  $r_m$  of  $0.25 \mu\text{m}$  and  $\sigma = 2$  with a power-law tails at large sizes of  $r^{-0.4}$  where  $r$  is the radius. The log-normal and power-law distributions were connected at a radius of  $1 \mu\text{m}$ . Index of refraction at visible wavelengths was assumed to be  $1.50 - 0.001i$ . They also injected sub-micrometer smoke into the troposphere to simulate the city and wild fires that would result from atmospheric nuclear explosions. Size distribution and index of refraction were assumed to be  $r_m = 0.1 (\mu\text{m})$  for urban fires and  $0.05 \mu\text{m}$  for wildfires both with  $\sigma = 2$ , and  $1.75 - 0.30i$ , respectively. Details on explosion altitude was not given in their references but surface burst percentage was assumed to be between 0 and 100% depending on the scenarios. The simulated temperature drop in Turco et al. (1983) resulting from the 65 Mt sub-micrometer dust produced by a 3,000-MT "general counterforce attack", not accounting for the sub-micrometer smoke, was 7K (case 11 in Fig. 1, p. 1286 in Turco et al., 1983) and lasted for more than 300 days (the full length of the simulation). On the other hand, the temperature drop for just a 100-MT "city attack", without sub-micrometer dust but with 150 Mt sub-micrometer smoke, was, remarkably, 32K and lasted for the rather short duration of only 100 days (case 14 in Fig. 1, p. 1286 in Turco et al., 1983).

The mechanism of the surface air temperature drop from nuclear war, which is not the same but similar to that activated by giant eruptions, is explained as follows. In atmospheric nuclear explosions at or near the ground, earth, dust, and other debris from the earth's surface are taken up into the fireball, then condensed onto particles of appreciable size. These contaminated particles range in diameter from less than  $1 \mu\text{m}$  to several millimeters (section 9.50 in Glasstone & Dalan, 1977). The sub-micrometer dust contained in the contaminated particles is called "fine dust" in the remainder of this paper. The top and bottom heights  $H_T$  and  $H_B$  (km) of the nuclear cloud produced by the surface explosion from a nuclear bomb with yield  $M$  (MT) are represented by the following equations (Turco et al. 1983), resulting in the fact that most fine dust is injected to the stratosphere for nuclear bombs whose yield is

more than 1 MT (Fig. 2).

$$H_T = 23M^{0.2} \quad (1)$$

$$H_B = 13M^{0.2} \quad (2)$$

The ratio of fine dust amount injected to the stratosphere, of course, also depends on the height of the tropopause, and also on the altitude of the detonations. Flammable materials are ignited by the nuclear fireball (Turco et al., 1983, p. 1284). Many of these fires would be promptly snuffed out by the passage of the spherical blast wave, but a large number of second fires would be started (Turco et al., 1984, p. 25). The fires generate smoke which contains sub-micrometer fractions (later called "soot" for convenience). The fine dust and soot reduce insolation and cause the surface air temperature drop.

The contributions of such surface and near surface bursts on the sea used mainly by France (Mururoa etc.) and the US (Bikini etc.) for the GST drop would be much less than those of surface and near-surface bursts on land because the particles entering the atmosphere from sea water surface consist mainly of sea salts and water drops (section 9.53 in Glasstone & Dalan, 1977). The particles from explosions at such high altitude ( $> 50$  km) for anti-ballistic missiles and anti-satellite weapons as the US (Johnston Island etc.) and the Soviet Union (Kapustin Yar) consist only of radioactive residue of the weapon and the deployment rocket, with particle diameters ranging from 0.01 to 20  $\mu\text{m}$  (section 9.48 in Glasstone & Dalan, 1977). These residues may significantly affect the global circuit (Markson, 2007) but may not cause large GST drop by reducing insolation. For example, Starfish Prime with 1.4 MT nuclear yield which exploded at 400 km above the Pacific Ocean in July 9, 1962 was launched by Thor missile which weighed 49.6 t at launch. The Starfish Prime itself should not be heavier than several tons. On the other hand, the surface explosion of a nuclear bomb with 1.4 MT nuclear yield will be assumed to cause fine dust of 26000 t as later described in section 4. The mass of the missile and the nuclear bomb is not negligible and further investigation is required but much smaller than the mass of fine dust by surface and near-surface nuclear explosions.

In the case of nuclear weapons tests, fires are not expected to occur, and soot is not usually generated. The fine dust from atmospheric nuclear weapon tests within the troposphere soon falls to the ground within a one month half-removal time (UNSCEAR, 2000, p. 162, Fig. III). On the other hand, the fine dust that reaches a height near the tropopause rapidly spreads with the jet streams, although mainly in the same hemisphere. The fine dust that reaches the stratosphere stays there for months to years (UNSCEAR, 2000, p. 162, Fig. III), with a half-removal time ranging from 3 months (from the lower polar stratosphere to the troposphere) to 3.5 years (from the upper equatorial stratosphere to the troposphere). For nuclear wars, the soot is generated and may behave in a similar way to fine dust. The largest difference between the volcanic eruptions and the atmospheric nuclear explosions in the global cooling context is that the main attenuation material of insolation for the eruptions is sulfate aerosol; for atmospheric nuclear explosions, the main materials of attenuation are the fine dust and soot.

TTAPS ignored the influence of the actual atmospheric nuclear explosions on global climate and mentioned only imaginary nuclear wars. However, the results for scenarios F and G on p. 28 of Turco et al. (1984) are for fine dust without soot. These results, therefore, can be regarded as an effective simulation of an atmospheric nuclear weapons test. This is why scenarios F and G of Turco et al. (1984) were used for scaling as shown below, although these results could be regarded as tentative conclusions (p. 119 of Dörries, 2006). Many studies of nuclear winter were carried out after TTAPS, as summarized by Robock et al. (2007), but none of these mentioned the influence of the actual atmospheric nuclear explosions on the global climate.

Kondratyev (1988) pointed out the possibility that NO<sub>2</sub> produced by nuclear fireballs in the hydrogen bomb tests in 1958, 1961 and 1962 by the Soviet Union affected the global climate. This finding should not be ignored; however, it is rather difficult to verify these findings

because most of the references in the book by Kondratyev (1988) are inaccessible.

Hishida (2001 in Japanese) has also pointed out the possibility of the influence of atmospheric nuclear explosions on the global climate. He examined the bombings in World War II in Europe as well as the atmospheric nuclear explosions afterward and stated that fine dust and soot from these events may be the main causes of the regime shift in GST and SST (surface sea temperature) between 1940 and 1975. However, he did not carry out any quantitative calculation of the temperature change produced by the fine dust and soot from the bombings or by the atmospheric nuclear explosions.

Robock et al. (2007) represents the most recent study on nuclear winter. These authors used an AOGCM (Atmosphere-Ocean General Circulation Model) with a horizontal resolution of  $4^\circ \times 5^\circ$  and with 23 vertical levels. The model top was 80 km and the length of simulation was 10 years with 8 runs. They put 5 Mt, 50 Mt and 150 Mt of black carbon into the upper troposphere as typical mixture of black soot that would result from nuclear war. A total of 150 Mt of black carbon corresponds to a 5000-MT-yield nuclear war. For 50 Mt and 150 Mt cases, the black carbon had mass extinction coefficient of  $5.5 \text{ m}^2/\text{g}$ , single scattering albedo of 0.64 and mass absorption coefficient of  $2.0 \text{ m}^2/\text{g}$ . They injected the black carbon into the upper troposphere (300-150 mbar) over a one-week period starting on 15 May spread over all grid boxes over the 48 United States and over Russia. For 5 Mt case, the black carbon had mass extinction coefficient of  $9.0 \text{ m}^2/\text{g}$ , single scattering albedo of 0.31 and mass absorption coefficient of  $6.21 \text{ m}^2/\text{g}$ . They injected the black carbon into one model box at  $30^\circ\text{N}$ ,  $70^\circ\text{E}$  (Pakistan) in the upper troposphere (300-150 mbar) and the higher layers in lower latitudes during a 1-day period. The maximum GST drops of the 5 Mt, 50 Mt and 150 Mt cases were approximately 1.4K, 4.0K and 8.5K, respectively, and lasted more than the 10-year length of the simulation. The results provided by Robock et al. (2007) will be used for the scaling of Little Boy and Fat Man because Robock et al. (2007) used the latest AOGCM and their results are more reliable for the case of an explosion with soot than TTAPS.

Thompson (2008, p.647) estimated GST drop by Little Boy and Fat Man to be less than 0.03K based on Robock et al. (2007). He did not mention on effects by other atmospheric nuclear explosions. Fujii (2010) suggested that the stagnation in global warming between 1945 and 1976 can be explained by the effects of the actual atmospheric nuclear explosions. He derived simple equations representing relationship between nuclear yield and GST drop based on TTAPS and Robock et al. (2007) for soot dominated case and fine dust dominated case. He assumed that the slopes of the equations for fine dust and soot were the same without any verification. He estimated GST drop by substituting not each explosions but total yield or average annual yield without considering type of tests (surface, water, rocket, etc.), nuclear cloud height or fireball size. The observed stagnation of 0.5K was within the estimated GST drop range of 0.07K–0.8K. It should be said that his estimation on GST drop was very rough and more detailed investigation is required.

### **3. Possible causes of stagnation in global warming in the mid 20th century**

Thompson et al. (2008) suggested that changes in the methods used to measure SSTs, a shift from engine room temperature measurements (US ships) to uninsulated bucket measurements (UK ships), caused a 0.5-K SST drop and the SST drop resulted in 0.3-K GST drop since 1945. In the present study, an attempt was made to add 0.3K to the temperature data since 1945 as a correction for the changes in the measurement method (Fig. 1, the blue line). The stagnation in global warming in the mid 20th century can still be observed although with a smaller GST anomaly of shorter duration than in the original GST (Fig. 1, the black line).

Schlesinger & Ramankutty (1994) noted the rapid rise in GST between about 1908 and 1946, and the subsequent reversal of this warming until about 1965 which did not appear in their simulation considering greenhouse gases (GHG) and anthropogenic sulfate aerosols (ASA).

They concluded that the oscillation of surface temperature in the North Atlantic (AMO, Atlantic Multidecadal Oscillation) and North American regions, which had a 65-70 year period, dominated the GHG+ASA-induced warming, thereby obscuring the latter and interfering with its detection. The AMO is, however, in this author's opinion, not the cause but the effect of some radiative forcings. The cause is what should be looked for. Andronova & Schlesinger (2000, p. 2138) called the stagnation in global warming "1944-1976, a period of observed global cooling" and also suggested AMO as one of the possible causes.

Hansen et al. (2007) showed their simulation results concerning the GST for 1880–2003 with the GISS modelE. They considered the radiative forcings of well-mixed greenhouse gases, stratospheric H<sub>2</sub>O, ozone, land use, snow albedo, solar irradiance, stratospheric aerosols, tropospheric aerosol direct effect and aerosol indirect effect. Their 5-run mean simulated GST (Fig. 6 in their paper), however, does not show the stagnation in global warming in the mid 20th century but continues to increase until the 0.2-K GST drop due to the Mt. Agung eruption in 1963 (with a VEI rating of 5). This account would indicate that the above radiative forcings may not be the main cause of the stagnation in global warming. The prediction in Hansen et al. (2007), however, seems fair for the period after the Mt. Agung eruption in 1963, as shown in Fig. 6 in their paper, including a 0.2-K GST drop caused by the El Chichón eruption in 1982 and a 0.3-K GST drop caused by Mt. Pinatubo in 1991, an eruption which emitted 15–19 Mt SO<sub>2</sub> aerosol (Ward, 2009, p. 3190) and induced a negative radiative forcing of 2.7 W/m<sup>2</sup> (Minnis et al., 1993, p. 1412).

Hansen et al. (2007) admitted that the peak warmth near 1940 (it was not "near 1940" but clearly at 1944 in the original GST or at 1953 in the corrected GST, as shown in Fig. 1) was not produced by their models. They stated that it might be fruitless to search for an additional forcing to produce the peak warmth. Instead, they suggested natural oscillations and soot blown to the Arctic from industrial activity at the outset of World War II as possible causes. It was already stated above that AMO, one of the natural oscillations, was not the cause but

instead a result. For another example of the natural oscillations, ENSO (El Niño-Southern Oscillation) may not be the main cause of the stagnation in global warming because the stagnation can still be observed in SST from which the effect of ENSO was removed (Fig. 1 in p. 1959 of Compo & Sardeshmukh, 2010). It should be also pointed out that the effect of soot from industrial activity at the outset of World War II is negligible because even the such raids in the end of the World War II in 1945 as Dresden, Nuremberg, Tokyo, Essen, Nagoya, Dortmund, Osaka, Hiroshima and Nagasaki, which should have generated much more soot than the outset of World War II, on GST is estimated to be negligible in the next section.

As one of the attempts, the annual yield of the actual atmospheric nuclear explosions was added to Fig. 1. The period of the atmospheric nuclear explosions almost coincides with the period of the stagnation in global warming in the mid 20th century. Assuming that a linear global warming trend from 1880 to 2009 (Fig. 1, the green broken line), the GST anomaly (the difference between the broken blue and green lines in Fig. 1) is predicted as a function with a GST drop of 0.2K (Fig. 3). This intuitive prediction may seem exaggerated; however, a total yield of 440 MT, equivalent to the total yield of all atmospheric nuclear explosions, can induce nuclear winter in the simulation provided by either TTAPS or Robock et al. (2007). The actual atmospheric nuclear explosions should have influenced the global climate by a mechanism similar to nuclear winter even though they were carried out over a period of 36 years and did not produce soot from cities (except for Little Boy and Fat Man, both in 1945). However, GST anomaly is not simulated with climate models in this paper. Instead, in the next section, GST drop produced by the fine dust and soot from the actual atmospheric nuclear explosions is estimated based on the results of the above simulation results of TTAPS and Robock et al. (2007).

There may be mechanisms for GST drop other than the simple mechanism of insolation attenuation caused by fine dust and soot from atmospheric nuclear explosions acting as a blocking highs and ridges suggested by Arakawa et al. (1955). However, the mechanism was

suggested to merely explain the local and temporary air temperature drop and there has been no attempts were made to relate them to the stagnation of global warming. Kondratyev (1988) has suggested a great contribution of NO<sub>2</sub> from hydrogen bombs. The mechanism is not denied but the mechanism of GST drop by attenuation of insolation by fine dust and soot seems more widely accepted.

#### **4. Estimation of GST drop by the fine dust and soot from the actual atmospheric nuclear explosions**

The following GST drop-time function (Fig. 4) was assumed to roughly approximate the GST anomaly plots (Figure 2 in Robock et al., 2007),

$$\Delta T = -A_{\max} \sin \left[ \pi \exp \left( - \frac{t \ln 2}{\Delta t} \right) \right] \quad (3)$$

where  $\Delta T$ ,  $A_{\max}$ ,  $t$  and  $\Delta t$  are GST anomaly (K), maximum GST drop (K), elapsed time (y) and constant (y), respectively. This function shows a peak of GST drop,  $-A_{\max}$ , at  $t = \Delta t$ . GST drop gradually decreases with time.  $\Delta T$  becomes  $-A_{\max}/2$  at  $t = 2.59\Delta t$  or  $e$ -folding time is  $3.06\Delta t$ .

The atmospheric nuclear tests did not generate soot from cities. There are no such results in Robock et al. (2007). Scenarios F and G in the table on p. 28 of Turco et al. (1984) are the only available models which produced GST drop plots due to the effects of only fine dust. Scenario F/G is named "General counterforce attack"/"Hard-target counterforce attack" with total yield of 3000/5000 MT, surface burst percentage of 70/100%, no urban or industrial targets, yield of each warhead 1-10/5-10 MT, total number of explosions of 2150/700, no soot, 55/650 Mt fine dust with optical depth of 0.8/10.

The GST drop duration was approximately 3 months for soot-dominated cases (in which soot was injected into the troposphere) and more than 10 months for fine dust-dominated cases (in which fine dust was injected mainly into the stratosphere) for TTAPS. Soot was injected to the

upper troposphere, heated by absorption of shortwave radiation and lofted into the upper stratosphere in Robock et al. (2007). GST drop duration was more than 10 years with  $e$ -folding time of 4.6 years. One of the reasons for this difference is the climate model. TTAPS used the single column model, and they showed only the average surface air temperature over continental land areas in the Northern Hemisphere. This means that the model extent is limited and the limited extent causes overestimation of peak GST drop and underestimation of GST duration. On the other hand, Robock et al. (2007) used AOGCM and showed the GST drop. The duration of the GST drop revealed by TTAPS may have been underestimated; the duration of GST drop by Robock et al. (2007) seems to be more reliable.

Considering the ambiguity of the peak value and duration of GST drop in the results by TTAPS, the direct approximation of GST drop plots by Eq. (3) was not carried out but CGD (cumulative GST drop in Ky, Fig. 4) was defined as the integral of GST drop (K) with respect to time (y) and was graphically measured for the simulated GST drop plots on p. 17 in Ehrlich et al. (1984). The simulated GST drop plots were approximated so that the approximated equation by Eq. (3) had the same CGD. The relationship between the mass of fine dust  $M_D$  in Mt and the CGD for GST drop plots in Turco et al. (Fig. 5) can be represented as

$$\text{CGD} = 0.222M_D^{0.777} . \quad (4)$$

The quantity of data in Fig. 5 is at a minimum for determining Eq. (4) and the accuracy of the above equation should be investigated in the future. The relationship between the amount of fine dust and the yield of surface bursts  $M_{\text{Surface}}$  (MT) in Turco et al. (1984) is

$$M_D = 0.01858M_{\text{Surface}} , \quad (5)$$

as shown in Fig. 6 (scenario G was excluded from the derivation of Eq. (5) because the scenario assumed 100% surface burst mainly for hardened silos with 8 times the fine dust per surface explosion yield). The relationship between the CGD and  $M_{\text{Surface}}$  is therefore

$$\text{CGD} = 0.0600M_{\text{Surface}}^{0.777} . \quad (6)$$

On the other hand, CGD for Eq. (3) is

$$\text{CGD} = A_{\max} \int_0^{\infty} \sin \left[ \pi \exp \left( -\frac{t \ln 2}{\Delta t} \right) \right] dt. \quad (7)$$

Replacing

$$\pi \exp \left( -\frac{t \ln 2}{\Delta t} \right) = x, \quad (8)$$

$$\text{CGD} = A_{\max} \int_{\pi}^0 \sin x \frac{dt}{d \left[ \pi \exp \left( -\frac{t \ln 2}{\Delta t} \right) \right]} dx = \frac{A_{\max} \Delta t}{\ln 2} \int_0^{\pi} \frac{\sin x}{x} dx. \quad (9)$$

The integral is known as sine integral and using the solution

$$\int_0^z \frac{\sin x}{x} dx = z - \frac{z^3}{3 \cdot 3!} + \frac{z^5}{5 \cdot 5!} - \frac{z^7}{7 \cdot 7!} + \dots, \quad (10)$$

CGD is obtained as

$$\text{CGD} = \frac{A_{\max} \Delta t}{\ln 2} \left( \pi - \frac{\pi^3}{3 \cdot 3!} + \frac{\pi^5}{5 \cdot 5!} - \frac{\pi^7}{7 \cdot 7!} + \dots \right) = 2.67 A_{\max} \Delta t \quad (11)$$

Nuclear weapons tests on water, in the stratosphere and at high atmosphere were removed from the calculation because they produced smaller amount of fine dust as already stated in section 2 and 330 explosions which were categorized into "Surface", "Land surface", "Tower", "Balloon", "Air", "Air drop", "Air burst" on land with total yield of 265 MT were selected for calculation from Table 1 in UNSCEAR, 2000, pp. 195-204. Test types are as reported to UNSCEAR by the country and there are no detailed explanations in UNSCEAR (2000).

Nuclear yield of other test types than "Surface" and "Land surface" should be reduced according to radius of fireball and altitude of explosions because fine dust is generated by fireball contacting to the ground. Let's assume a fireball with the maximum radius  $R_M$  (m) by a nuclear explosion at height  $H$  (m) from the ground surface. Ignoring the interaction between fireball and the ground surface and taking  $y$ -axis downward from the center of explosion (Fig. 7a), the volume  $V_B$  ( $\text{m}^3$ ) of the fireball below ground surface is

$$V_B = \int_H^{R_M} \pi(R_M^2 - y^2) dy = \pi \left[ R_M^2 y - \frac{y^3}{3} \right]_H^{R_M} = \pi \left[ R_M^2 (R_M - H) - \frac{R_M^3 - H^3}{3} \right]. \quad (12)$$

The ratio of  $V_B$  to the entire volume of fireball  $V_F$  ( $m^3$ ) is

$$R_V = \frac{V_B}{V_F} = \frac{\pi \left[ R_M^2 (R_M - H) - \frac{R_M^3 - H^3}{3} \right]}{\frac{4}{3} \pi R_M^3} = \frac{3}{4} \left[ 1 - \frac{H}{R_M} - \frac{1}{3} + \frac{1}{3} \left( \frac{H}{R_M} \right)^3 \right]. \quad (13)$$

$$= \frac{3}{4} \left[ \frac{2}{3} - \frac{H}{R_M} + \frac{1}{3} \left( \frac{H}{R_M} \right)^3 \right] = \frac{1}{2} - \frac{3}{4} \frac{H}{R_M} + \frac{1}{4} \left( \frac{H}{R_M} \right)^3$$

Of course,

$$R_V = 0, \text{ if } H > R_M \quad (14)$$

This function represents decrease in  $R_V$  with increase in  $H/R_M$  as shown in Fig. 7b. The maximum radius of fireball is represented by

$$R_M = 1060M^{0.4} \quad (15)$$

where  $M$  is the nuclear yield in (MT) (section 2.127 in Glasstone & Dallan, 1977).

Considering that  $R_V$  is 0.5 for surface explosions, nuclear yield  $M$  was corrected as

$$M_{\text{Surface}} = 2R_V M \quad (16)$$

for approx. half nuclear weapons tests which were categorized as "Tower", "Balloon", "Air", "Air drop", "Air burst" on land and whose altitude was given in Table 1 in UNSCEAR (2000). The average  $2R_V$  of 0.106 from the above tests was used for other tests whose altitude was not given in Table 1 in UNSCEAR (2000).

Scenarios F and G assumed warheads whose yield was more than 1 MT. The bottom of nuclear cloud reaches the stratosphere in the cases. Nuclear weapons tests however include explosions less than 1 MT yield and the bottom of nuclear cloud from those small explosions do not reach the stratosphere. Nuclear yield  $M$  was therefore further corrected according to the nuclear cloud height as

$$M_{\text{Surface}} = 2R_{\text{Strato}} R_V M \quad (17)$$

$$R_{\text{Strato}} = 0, \text{ if } H_S > H_T \quad (18)$$

$$R_{\text{Strato}} = \frac{H_T - H_S}{H_T - H_B}, \text{ if } H_T > H_S > H_B \quad (19)$$

$$R_{\text{Strato}} = 1, \text{ if } H_B > H_S \quad (20)$$

where  $H_T$  and  $H_B$  (km) are the top and bottom heights of nuclear cloud and given by Eqs. (1) and (2).  $H_S$  (km) is the height of the tropopause and was assumed to be 11 km.  $R_{\text{Strato}}$  begins to increase from nuclear yield of 0.025 MT and reach 1 at 0.433 MT as shown in Fig. 8. The dependency of  $R_{\text{Strato}}$  on tropopause or explosion altitude was ignored in this paper. It should be noted however that  $R_{\text{Strato}}$  increases but  $R_V$  decreases with explosion altitude, namely, they offset each other. For example, effects of explosions at a higher altitude than fireball radius were not included in the GST drop calculation because  $R_V$  is zero. As a result, effects of  $R_{\text{Strato}}$  correction are not significant as described later (Fig. 9b).

Only Little Boy and Fat Man generated soot from Hiroshima and Nagasaki. The CGD produced by the combat use of the two bombs was estimated based on the GST drop plots (Figure 2 in Robock et al., 2007). The plots were not directly approximated by Eq. (3) but via CGD as fine dust cases. The relationship between the mass of soot  $M_{\text{Soot}}$  in Mt and the CGD that was graphically measured for Fig. 2 in Robock et al. (2007) is

$$\text{CGD} = 3.40M_{\text{Soot}}^{0.568} \quad (21)$$

(Fig. 5). The amount of soot was assumed in Robock et al. (2007) as

$$M_{\text{Soot}} = 0.03M \quad (22)$$

where  $M$  is the nuclear yield in MT. Substituting Eq. (22) into Eq. (21), the following equation is obtained.

$$\text{CGD} = 0.464M^{0.568} \quad (23)$$

Roughly speaking, the CGD from a soot-inducing nuclear explosion (e.g., a city attack) is approximately one order larger than the CGD from the same yield of a fine dust-inducing surface nuclear explosion (e.g., a surface nuclear weapons test) as shown in Fig. 5. This was mainly due to the difference in size distributions and optical properties of fine dust and soot (already described in section 2).

Removing nuclear weapons tests at higher altitude than the maximum fireball radius and those less than 0.025 MT whose fine dust does not reach the stratosphere, 2 combat use, 4 explosions with total yield of 0.765 MT at "surface" and "land surface" on land and 104 explosions by "air", "air drop", "airburst", "balloon" and "tower" on land with total yield of 262 MT, average  $2R_V$  of 0.106 and average  $R_{\text{Strato}}$  of 0.76 were used for the calculation (Table 1). Calculation procedure is as follows:

- (1) For combat use cases, CGD was calculated by substituting  $M$  into Eq. (23).
- (2) For surface nuclear weapons tests,  $H_T$  and  $H_B$  were calculated by substituting  $M$  into Eqs. (1) and (2).  $R_{\text{Strato}}$  was calculated by substituting  $H_T$  and  $H_B$  into one of Eqs. (18) to (20).  $M_{\text{Surface}}$  was calculated by substituting  $M$ ,  $R_{\text{Strato}}$  and  $R_V$  of 0.5 into Eq. (17). CGD was calculated by substituting  $M_{\text{surface}}$  into Eq. (6).
- (3) For nuclear explosion tests in air,  $R_M$  was calculated by substituting  $M$  into Eq. (15).  $R_V$  was calculated by substituting  $R_M$  and  $H$  into Eq. (13) or  $2R_V$  of 0.106 was assigned to explosions whose altitude was not given in Table 1 in UNSCEAR (2000).  $H_T$  and  $H_B$  were calculated by substituting  $M$  into Eqs. (1) and (2).  $R_{\text{Strato}}$  was calculated by substituting  $H_T$  and  $H_B$  into one of Eqs. (18) to (20).  $M_{\text{Surface}}$  was calculated by substituting  $M$ ,  $R_{\text{Strato}}$  and  $R_V$  into Eq. (17) and then CGD was calculated by substituting  $M_{\text{Surface}}$  into Eq. (6).
- (4) The peak GST drop  $A_{\text{max}}$  was calculated for each explosion by substituting CGD and  $\Delta t$  into Eq. (11).
- (5) GST drop-time function by each explosion was calculated substituting  $A_{\text{max}}$  and  $\Delta t$  into Eq. (3).
- (6) GST drop-time functions for 110 explosions were superposed considering the explosion year.

The calculated GST drop for the 110 actual atmospheric nuclear explosions, assuming  $\Delta t$  to be 3 years based on Figure 2 in Robock et al. (2007) is shown in Fig. 9a (base case) with

results assuming  $\Delta t = 2$  and 4 (y) for references. In the base case, the GST drop gradually increases and reaches the peak in 1965, several years after a significant amount of atmospheric nuclear weapons tests were carried out just before the PTBT in 1963, mainly due to the large hydrogen bombs by the Soviet Union. The GST drop decreases after the peak and becomes almost negligible in 1980. There is not a significant difference between the three cases but the values of peak GST drop decreases and duration of GST drop becomes longer with increase in  $\Delta t$ . Effect of correction for  $R_{\text{Strato}}$  is not significant (Fig. 9b) because most GST drop is due to large explosions whose  $R_{\text{Strato}}$  is 1, namely, nuclear yield is more than 0.433 MT and  $H_B$  is beyond the tropopause.

The GST drop caused by the 110 selected atmospheric nuclear explosions (base case) was removed from the GST data, which was already corrected based on Thompson et al. (2008), to estimate GST behavior without the effects of the actual atmospheric nuclear explosions. The re-corrected GST (Fig. 1, the red line) continues to rise at an almost constant rate of approx. 0.016K/y from 1917 to 1965 and then slightly decreases until 1976. The slight decrease can be explained by the low solar activity between 1965 and 1976 (Fig. 1). A detailed investigation of these figures should be undertaken in the future. However, it would be very important if GST behavior could be explained simply by the effects of the known radiative forcings after removing the effects of the actual atmospheric nuclear explosions and correcting for the change in the measuring method of SST. These results suggest that a detailed GCM study which included the effects of fine dust from nuclear weapons testing might be able to reproduce the GST stagnation.

For all of the cases in Fig. 9a, the calculated effects of Little Boy (0.015 MT) and Fat Man (0.021 MT) were negligible. This is because their yields were very small, despite the fact that they generated soot. The total mass of conventional explosives for the raids at the end of World War II in 1945 at Dresden (>2 kt, Feb. 13-14), Nuremberg (2 kt, Feb. 20, 1.8 kt, Feb. 21), Tokyo (1.65 kt, Mar. 9), Essen (4.74 kt, Mar. 11), Nagoya (1.8 kt, Mar. 11), Dortmund

(4.9 kt, Mar. 12) and Osaka (1.73 kt, Mar. 13) was 19 kt (= 0.019 Mt, p. 73 in Mark, 1976) and is comparable to the yield of Little Boy or Fat Man, which caused severe but local and short term-climate disturbances, including air temperature drop and precipitation. The effects of Little Boy or Fat Man on GST were, however, calculated as negligible. These raids with conventional explosives may have induced similar local short-term climate disturbances. However, the effects of these raids on GST is also negligible.

## **5. Injection of fine limestone powder into the lower stratosphere to mitigate global warming**

According to the IPCC's AR4 (2007), predicted GST rise of 2.3K by 2050 since 2000 with 0% reduction of anthropogenic CO<sub>2</sub> emissions will be corrected to 1.7K with a 50% reduction in anthropogenic CO<sub>2</sub> emissions. Accompanying world economic loss is predicted to be more than 5.5% (IPCC's AR4, 2007). The reduction of anthropogenic CO<sub>2</sub> emission may sometimes induce a reduction of the R/P (reserves to production ratio) of energy resources. For example, introducing oxygen combustion technique for CCS (carbon dioxide capture and storage) results in decreasing efficiency of coal power plants by 7-10% for oxygen production and CO<sub>2</sub> compression (p. 1004 of Wall et al., 2009). Introducing Light Water Reactors worldwide as one of the attempts to reduce anthropogenic CO<sub>2</sub> emissions apparently produces a significant reduction of R/P for uranium, which is only 124 years (Source: OECD/NEA-IAEA URANIUM2009).

Considering the fact that giant eruptions have actually induced a GST drop and considering the possibility that atmospheric nuclear explosions induced a GST drop, some geoengineering proposals (Lenton & Vaughan, 2009), including injection of sulfate aerosol into the stratosphere (Crutzen, 2006, Jones et al., 2010), seem effective. There are, however, concerns that sulfate aerosols would induce environmental problems such as acid rain and

photochemical oxidants. Chang & Shih (1991) proposed to seed particles of Welsbach materials (e.g. thorium oxide and other oxides of metal) whose diameter was in the range of 10 to 100  $\mu\text{m}$  to the stratosphere by seeding aircrafts. Thorium oxide is however radioactive. Thorium oxide and other oxides of metal are very likely to cause environmental problems. Fly ash, mainly consists of silicon dioxide and calcium dioxide, would be very effective for reducing insolation because of its dark color. However, fly ash is known to cause severe health problems, if inhaled, such as silicosis, asthma etc. On the other hand, limestone is harmless to human beings. Fine limestone powder, however, is described in MSDS as "Any physical condition normally aggravated by dust, such as eye, nose, and throat inflammation, and asthma, could be aggravated by Calcium Carbonate dust." and "Respirable level 5  $\text{mg}/\text{m}^3$ ". Assuming 6.4 Mt/y, which will be later proposed to obtain 0.6K GST drop, is uniformly distributed in troposphere and average tropopause height is 11 km, concentration would be  $1.14 \times 10^{-3} \text{ mg}/\text{m}^3$ . Concentration would be  $0.42 \text{ mg}/\text{m}^3$ , which is still less than the respirable level, even assuming that the powder for one year falls from stratosphere to troposphere in a day. Moreover, solubility of calcium carbonate is  $4.70 \times 10^{-4} \text{ mol}/\text{l}$  at  $P_{\text{CO}_2}$  is  $3.5 \times 10^{-4} \text{ atm}$ . Proposing 6.4 Mt/y is  $6.35 \times 10^{10} \text{ mol}/\text{y}$ . World average rain precipitation is 880 mm/y. Multiplying by the earth's surface area  $5.1 \times 10^8 \text{ km}^2$ , we obtain world average precipitation volume of  $4.49 \times 10^{17} \text{ l}^3/\text{y}$ . This rain can contain calcium carbonate of  $2.11 \times 10^{14} \text{ mol}/\text{y}$ , namely, the injected limestone powder will be dissolved into rain, even not acid, as soon as it falls to troposphere. Rather, liming to improve the environment is widely carried out. For example, in Sweden, several thousand lakes and streams have been limed repeatedly to mitigate acidification (Guhren et al., 2006). Thus the possibility of injecting fine limestone powder into the lower stratosphere to mitigate global warming was investigated as follows.

A very simple estimation of the GST drop from the injection of fine limestone powder is given below as a first step of my proposal. This estimation is partly based on the procedure shown in the Appendix of Robinson (1985). Let's assume a spherical limestone particle with diameter  $d$  (m), the volume of a particle  $V$  ( $\text{m}^3$ ) and sectional area  $A$  ( $\text{m}^2$ ) are

$$V = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 \quad (24)$$

$$A = \frac{\pi d^2}{4} . \quad (25)$$

The mass of the particle  $m$  (kg) is

$$m = \rho V , \quad (26)$$

where  $\rho$  is the density in kg/m<sup>3</sup>. Letting  $M_L$ ,  $A_E$ ,  $t_i$  and  $t_s$  be the injection rate of limestone powder (kg/y), the surface area of the earth (m<sup>2</sup>), injection period (y) and average duration of limestone powder in the stratosphere (y), respectively, and assuming that  $t_i \geq t_s$  (Fig. 10), the amount  $n$  (m<sup>-2</sup>) of limestone powder per unit surface area of the earth on the plateau in Fig. 10 is

$$n = t_s \frac{M_L}{mA_E} . \quad (27)$$

The ratio  $R$  (-) of the sectional area of limestone powder to the earth's surface area is

$$R = nA . \quad (28)$$

Reflected insolation by the limestone powder  $\Delta W$  (J) is

$$\Delta W = \mu RW , \quad (29)$$

where  $\mu$  is the reflectivity of the visible light (-), and  $W$  is the insolation (J). Stefan-Boltzmann law represents radiated heat flux  $q$  (W/m<sup>2</sup>) from an object whose absolute temperature is  $T$  (K) as

$$q = \sigma \varepsilon T^4 \quad (30)$$

where  $\sigma$  is Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ) and  $\varepsilon$  is emissivity (-). Namely, the fourth power of the absolute temperature of an object is proportional to heat flux. Assuming that the powder does not absorb energy, the small GST drop  $\Delta T$  (K) can be roughly estimated based on the Stefan-Boltzmann law as

$$\Delta T = \frac{\Delta W}{4W} T , \quad (31)$$

where  $T$  is average GST in K. Substituting Eqs. (24) to (29) into Eq. (31), GST drop can be represented as

$$\Delta T = \frac{3}{8} \frac{\mu t_s M_L T}{\rho d A_E}. \quad (32)$$

It is important that GST drop is inversely proportional to diameter of the powder. Finally, the injection rate (kg/y) required for the desired GST drop is represented as

$$M_L = \frac{8}{3} \frac{\Delta T}{T} \frac{\rho d A_E}{\mu t_s}. \quad (33)$$

The values shown in Table 2 were used in the calculation. Average GST, density of calcium carbonate and surface area of the earth are known values. Diameter of limestone, average duration and GST drop are assumption and reflectivity are after the reference. Substituting for the values shown in Table 2 into Eq. (33), a very rough estimation is obtained that a 0.4-6.4-Mt/y injection of fine limestone powder (depending on its reflectivity and  $t_s$ ) into the lower stratosphere would be required to obtain and maintain a 0.6-K GST drop from  $t_s$  to  $t_i$  after injection begins. This injection rate is 8% to 128% the simulated results shown in Fig. 3 on p. 6002 of Jones et al. (2010), where the author proposes a 5-Mt/y SO<sub>2</sub> injection for 20 years for a 0.6-K or 0.4-K GST drop calculated with HadGEM2 or ModelE.

The upper 6.4 Mt/y will be used in the following conservative cost estimation. This value is just 0.19% the world's limestone production (3,440 Mt in 1999, source: Taiheiyo Cement Corporation Web Site, <http://www.taiheiyo-cement.co.jp/rd/research/3cemcon/313.html> in Japanese). The price of 6.4 Mt of crushed limestone would be around 36 MUSD (source: HighBeam Business Web Site, <http://business.highbeam.com/industry-reports/mining/crushed-broken-limestone>) but fine limestone powder is more expensive due to grinding cost and would cost around 1.7 GUSD (Nishiyama, 2009, an engineer at Japanese limestone mining company, personal communication). Let us assume that transport planes are used to inject fine limestone powder into the lower stratosphere because missiles are too expensive, and their fragments might cause environmental problems. Transport planes usually do not fly in the lower stratosphere because more fuel is required, but they have the capacity to reach that layer. The Antonov

An-124 (a Russian transport plane), for example, can carry a 230-t payload so that 28000 flights a year or 76 flights a day would be required to inject fine limestone powder at a rate of 6.4 Mt/y. Assuming the cost to be 10 kUSD per flight, the yearly cost would be 280 MUSD. According to IPCC's AR4, cost to mitigate global warming by 0.6K is more than 5.5% GDP for 50 years as stated above. The world GDP in 2009 is 57.8 TUSD (source: International Monetary Fund Web Site, <http://www.imf.org/external/pubs/ft/weo/2010/02/weodata/weorept.aspx?pr.x=37&pr.y=15&sy=2009&ey=2009&scsm=1&ssd=1&sort=country&ds=.&br=1&c=001%2C998&s=NGDPD&grp=1&a=1>) and 5.5% is 3180 GUSD or 64 GUSD/y. A total yearly cost of 2.0 GUSD for injection is just 1/32 the cost for reduction of anthropogenic CO<sub>2</sub> emissions. It should be pointed out that the greenhouse effect of the CO<sub>2</sub> in the 6.4 Mt limestone powder is negligible compared with the 29 Gt world CO<sub>2</sub> emission (2007). The neutralization of acid rain would also be expected. Deliberate consideration would, of course, be required before execution of the injection of fine limestone powder because it may affect temperature stratification, cloud distributions, stratospheric water load (Solomon et al., 2009), aqueous chemistry etc.

## 6. Concluding remarks

This study suggests that the cause of the stagnation in global warming in the mid 20th century was the atmospheric nuclear explosions detonated between 1945 and 1980, especially the large hydrogen bomb tests. The estimated GST drop due to the fine dust from the actual atmospheric nuclear explosions based on the published simulation results (TTAPS and Robock et al., 2007) has served to explain the stagnation in global warming.

The necessity of "possible natural analogues and data from observations that follow nuclear tests during the late 1950s and early 1960s" to estimate the possible climatic impact of major post-nuclear disturbances of the gaseous and aerosol composition of the atmosphere has

already been pointed out by Kondratyev (1988, p. 13). Atmospheric nuclear explosions can be regarded as full-scale in situ tests for nuclear winter, albeit with smaller yields. The non-negligible amount of the GST drop from the actual atmospheric explosions suggests that nuclear winter is not just a theory but has actually occurred. In other words, it can be said that ignoring the effects of the actual atmospheric nuclear explosions on GST is equivalent to denying the possibility of the occurrence of nuclear winter. The accuracy of the simulations of GST by IPCC may also be significantly improved by introducing the influence of fine dust from the actual atmospheric nuclear explosions into their climate models; thus, global warming behavior could be much more accurately predicted.

A method to mitigate global warming by injecting fine limestone powder into the lower stratosphere was proposed. Many factors still need to be investigated. However, the method could be implemented at a much smaller cost than the current attempts to reduce anthropogenic CO<sub>2</sub> emissions. The fine limestone powder injection could also mitigate acid rain and would be much better for human health than other methods that use sulfate aerosols or oxides of metal.

This study is rather primitive and there are many things left for further investigation. The possibility is acknowledged that there are different mechanisms to explain the GST drop produced by atmospheric nuclear explosions. These could consist of either complicated climate phenomenon induced by the atmospheric nuclear explosions (Arakawa et al., 1955) or NO<sub>2</sub> from the hydrogen bomb explosions (Kondratyev, 1988).

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