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VARIATION IN ATMOSPHERIC TURBIDITY IN THE AREA AROUND JAPAN

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Abstract

Atmospheric turbidity coefficients were calculated at five sites in Japan (from 1978 to 1995 at Nemuro; from 1980 to 1995 at Sapporo, Shionomisaki and Tosashimizu; and from 1970 to 1995 at Ishigakijima). The turbidity coefficients were 0.03-0.30 at Nemuro, 0.05-0.40 at Sapporo, 0.05-0.45 at Shionomisaki, 0.03-0.40 at Tosashimizu, and 0.03-0.35 at Ishigakijima. There were maxima in 1982-1984 and 1991-1993 due to the volcanic eruptions of Mt.El Chichon in 1982 and Mt.Pinatubo in 1991. The effect of the big volcanic eruptions on atmospheric turbidity lasted two years. Excepting the volcanic eruptions, the turbidity coefficients in rural areas of Japan increased from 1954 through 1989. The aerosol increase seems to derive from increasing human activity in east Asia. Assuming that the global turbidity coefficient has increased by 0.028 in 35 years, the global mean surface temperature is estimated to have decreased by 0.41 ℃.

KEYWORDS: *atmospheric turbidity coefficient, albedo effect of aerosols on climate, air pollution,human activity, Mt.El Chichon eruption, Mt.Pinatubo eruption*

1. Introduction

Increasing concentrations of greenhouse gases such as carbon dioxide and methane have increased the global mean surface temperature by 0.45 ±0.15 ℃ in the last 100 years. Increases in natural and anthropogenic atmospheric aerosols may affect the climate, although the effect is opposite in sign (IPCC, 1992). Atmospheric aerosols affect the global climate by scattering and absorbing solar radiation, the albedo or direct effect of aerosols (Rasool and Schneider, 1971; Yamamoto and Tanaka,1972; Coakley *et al.*, 1983; Potter and Cess, 1984; Charlson *et al.*, 1992). The albedo effect depends on both the optical thickness and absorption properties of aerosols, the size distribution and complex index of refraction. The optical thickness is an

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integrated extinction coefficient affected by the total aerosol content of an air column, and is associated with the turbidity coefficient.

Toon and Pollack (1976) proposed a global average model of the optical thickness as a function of latitude, but used limited data in the derivation of the model. It is necessary to obtain more data on the optical thickness of aerosols in various parts of the world to estimate the climatic effect.

If the global optical thickness is increasing, climatic effects will be serious. Peterson *et al.*(1981) analyzed 8,500 observations of atmospheric turbidity over Central North Carolina, U.S.A. from 1969 to 1975. They concluded that there was a distinct summer increase through 1976, but no change in the winter. Szymber and Sellers (1985) analyzed the Linke turbidity factor at Tucson, Arizona, U.S.A. from 1956 to 1983, and showed extreme perturbations from 1964 to 1966 due to the volcanic eruption of Mt.Agung on Bali in 1963 and from 1982 to 1983 due to Mt.El Chichon in Mexico in 1982. But, they found no long-term upward or downward trends in turbidity. More research on recent secular variations in the optical thickness of aerosols or atmospheric turbidity was required.

Yamamoto *et al.*(1968) used the turbidity coefficient β as $\tau_M(\lambda) = \beta/\lambda$, where $\tau_M(\lambda)$ is the optical thickness due to Mie scattering by aerosols at wavelength λ, and reported the hemisphere distribution of turbidity coefficient as estimated from direct solar radiation measurements. Arao and Yamamoto (1981) calculated secular variations in the turbidity coefficients over Japan from 1950s to 1979.

The study here calculated the turbidity coefficients at 5 meteorological stations in Japan: from 1978 to 1995 at Nemuro; from 1980 to 1995 at Sapporo, Shionomisaki and Tosashimizu; and from 1970 to 1995 at Ishigakijima. Combining these results with those by Arao and Yamamoto (1981), the secular variation in turbidity coefficients in the area around Japan from 1954 to 1995 was discussed.

2. Turbidity Coefficient

The turbidity coefficient was calculated according to Yamamoto *et al.*(1968). With the observed intensity of solar radiation I_{OBS} and that reduced to the mean distance between the sun and the earth I_M, then

$$\begin{aligned} I_M &= (R/R_0)^2 I_{OBS} \\ &= \int I_0(\lambda) T_R(m,\lambda) T_M(m,\lambda) T_G(m,\lambda) d\lambda, \end{aligned} \tag{1}$$

where R and R_0 are the instantaneous and averaged distances between the sun and the earth; $I_0(\lambda)$ is the solar radiation energy in the wavelengths between λ and $\lambda + d\lambda$ outside the atmosphere; $T_R(m,\lambda)$ is a transmission functions due to Rayleigh scattering by air molecules, $T_M(m,\lambda)$ and $T_G(m,\lambda)$ are Mie scattering by aerosols and absorption by gases such as water vapor, ozone, and carbon dioxide. The parameter m, air mass, is given by $m = secZ$, where Z is the zenith angle of the sun.

The transmission function due to aerosols is given by

$$T_M(m,\lambda) = exp[-\tau_M(\lambda) \cdot m], \tag{2}$$

where τ_M is the optical thickness due to Mie scattering by aerosols. The size distribution of aerosols was assumed to be a Junge distribution given by

$$n(r) = \begin{cases} C \times 10^4, & \text{for } 0.03 \leq r < 0.1\mu m \\ Cr^{-4}, & \text{for } 0.1 \leq r \leq 10\mu m \end{cases} \tag{3}$$

where C is a constant and $n(r)dr$ is the number of aerosol particles with radii between r and $r + dr$, included in the whole air column. The optical thickness τ_M is then given by

$$\tau_M(\lambda) = \beta/\lambda, \tag{4}$$

where

$$\beta = 2\pi^2 C \int Q(\alpha, m^*)\alpha^{-2} d\alpha \tag{5}$$

and

$$\alpha = 2\pi r/\lambda. \tag{6}$$

In Eq.(5), $Q(\alpha, m^*)$ is an efficiency factor for extinction of the Mie scattering, and m^* is the complex refractive index of aerosols.

The transmission function due to absorption by atmospheric gases is given by

$$T_G(m, \lambda) = T_{O_3}(m, \lambda) \cdot T_{H_2O}(mw, \lambda, Pe_{H_2O}) \cdot T_{CO_2}(mu, \lambda, Pe_{CO_2}) \tag{7}$$

where T_{O_3} is the transmission due to ozone, and $T_{H_2O}(mw, \lambda, Pe_{H_2O})$ and $T_{CO_2}(mu, \lambda, Pe_{CO_2})$ are the mean transmission functions due to water vapor and carbon dioxide in the near infrared bands. The parameters w and u are water vapor and carbon dioxide amounts in the whole air column, and Pe is the effective pressure parameter.

In a dustfree atmosphere ($\beta = 0$), the intensity of solar radiation I_{DF} penetrating the atmosphere is given by

$$I_{DF} = \int I_0(\lambda) T_R(m, \lambda) T_G(m, \lambda) d\lambda. \tag{8}$$

We can calculate the intensity I_{DF} as a function of the air mass m and amount of water in the air mass mw.

In the actual atmosphere, we consider the transmission function due to aerosols $T_M(m, mw, m\beta)$, which is averaged over the whole spectral region, as

$$T_M(m, mw, m\beta) = I_M/I_{DF}. \tag{9}$$

The calculated intensity I_{DF} and observed value I_M allows a determination of the value of $T_M(m, mw, m\beta)$.

The purpose is to determine the value of β from three given parameters m, mw, and T_M. In a conversion factor $\gamma(m, mw, m\beta)$,

$$\gamma(m, mw, m\beta) = T_M(1, mw, m\beta)/T_M(m, mw, m\beta), \tag{10}$$

with values assigned to m, mw, and $m\beta$, both $T_M(1, mw, m\beta)$ and $T_M(m, mw, m\beta)$ can be calculated, and γ expressed in a chart as a function of m and $T_M(m, mw, m\beta)$. Using the values of m and $T_M(m, mw, m\beta)$ determined in Eq.(9), γ is obtained from the chart, and Eq.(10) allows an evaluation of $T_M(1, mw, m\beta)$.

Since $T_M(1, mw, m\beta)$ is a function of two parameters mw and $m\beta$, we can determine β from a chart as a function of mw and $T_M(1, mw, m\beta)$.

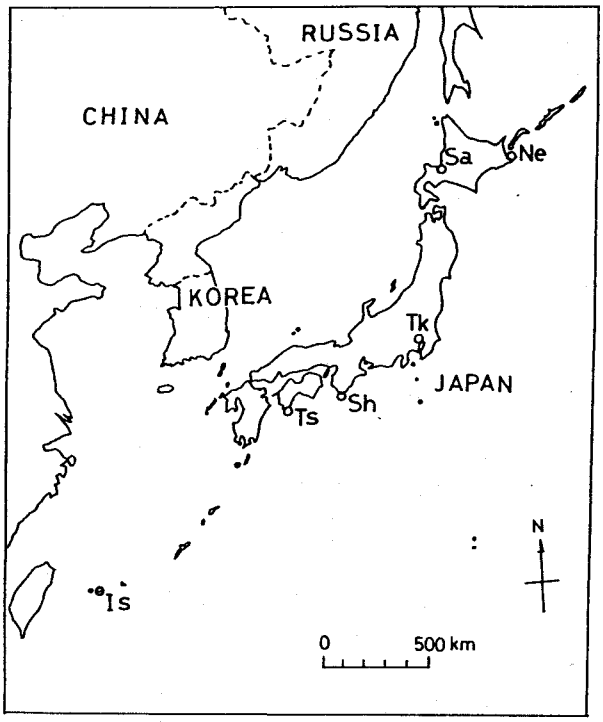

Figure 1. Map of the area around Japan. Sa: Sapporo, Ne: Nemuro, Tk: Tokyo Sh: Shionomisaki, Ts: Tosashimizu, Is: Ishigakijima

3. Estimating Turbidity Coefficients

The turbidity coefficients β at 5 meteorological stations in Japan (Nemuro, Sapporo, Shionomisaki, Tosashimizu and Ishigakijima) were estimated. Figure 1 is a map of Japan and the surrounding area. Arao and Yamamoto (1981) calculated β values at Nemuro from 1953 to 1979, and at Sapporo from 1955 to 1979, at Shionomisaki from 1953 to 1979, and at Tosashimizu from 1951 to 1979. We calculated β at Nemuro from 1978 to 1995, and at Sapporo, Shionomisaki and Tosashimizu from 1980 to 1995. At Ishigakijima, the calculations are from 1970 to 1995, with only limited data from 1970 to 1983. The 1995 values were for July at all 5 locations.

The estimates need data for water vapor amounts w in the whole air column in addition to direct solar radiation I_M. The empirical formula of Yamamoto *et al.*(1971) was adopted for calculating w, giving the relation of w to the surface vapor pressure e. The turbidity coefficients above the 5 stations were calculated with data of direct solar radiation, surface temperature, and relative humidity.

Figures 2-6 show the calculated turbidity coefficients β, at Nemuro, Sapporo, Shinomisaki, Tosashimizu, and Ishigakijima. The direct solar radiation can only be measured on clear days, and the number of β in a month was 3 to 10.

At Nemuro (Fig.2) the turbidity coefficients β were 0.03 to 0.35. They increased in spring and summer, and decreased in autumn and winter. From 1982 to 1984 and from 1991 to 1993 the values were 0.10 and 0.20 higher, caused by the eruption of Mt.El Chichon, Mexico in

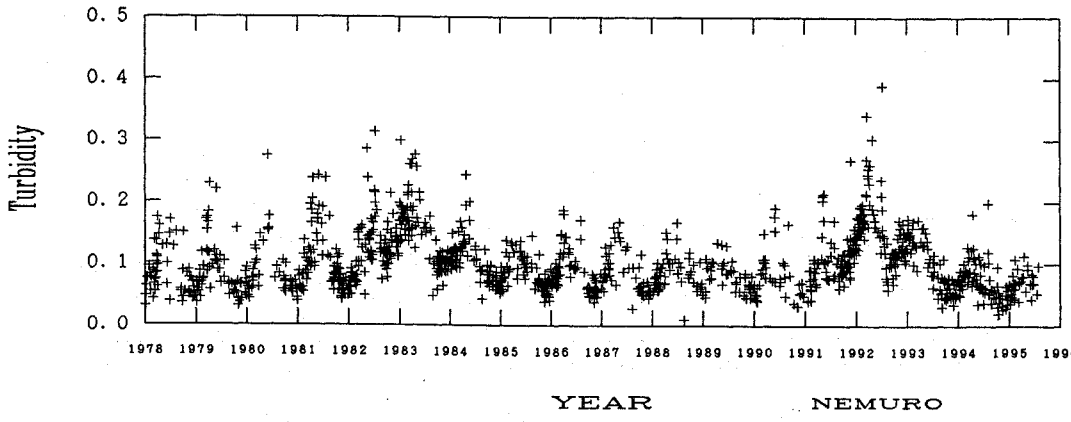

Figure 2. Atmospheric turbidity coefficients at Nemuro.

March and April, 1982 and Mt.Pinatubo, Philippines in June, 1991. The eruptions emitted much gaseous sulfur dioxide into the stratosphere, which was converted to sulfuric acid particles through photochemical reaction by solar irradiation. In the stratosphere there are no removal processes like rainout or washout for these particles, and due to gas to particle conversion they are too small to fall easily. The particles, thus, suspended in the stratosphere scatter the solar radiation, which reduced the direct solar radiation penetrated to the earth's surface (Mass and Portman, 1989; McCormick *et al.*, 1995).

At Sapporo (Fig.3) the turbidity coefficients were 0.05 to 0.40, higher than at Nemuro. They increased in spring and summer, and decreased in autumn and winter. In March and April soil particles are blown up from the dry ground after the thawing of snow, and the value of β increased in spring, up to 0.40.

At Shionomisaki (Fig.4) the turbidity coefficients were 0.05 to 0.45. There was more turbidity coefficient data at Shionomisaki than at Sapporo, with a stronger concentration around 0.10 to 0.15.

At Tosashimizu (Fig.5) the turbidity coefficients were 0.03 to 0.40. They increased in spring and summer, and decreased in autumn and winter. There was a strong increase from 1991 to 1994 due to the Mt.Pinatubo eruption.

In Fig.6 at Ishigakijima, there was little data of direct solar radiation before 1984 . The data after 1984 did not show as strong seasonal variations as those at Nemuro and Shionomisaki. Ishigakijima is an island in the western Pacific and the coefficient very much in spring, due to long range transport of Yellow sand from continental China.

4. Increases of Atmospheric Turbidity due to Volcanic Eruptions

To estimate the effect of volcanic eruptions on atmospheric turbidity, we investigated the secular variation in the turbidity coefficients β at Nemuro. As there is only little data, 3 to 10 coefficients in a month, a three-month moving average atmospheric turbidity coefficient denoted as β_{rm} was used. Then, the value of β_{rm} of each month before the eruption was subtracted from that in the respective month after the eruption. The difference was considered

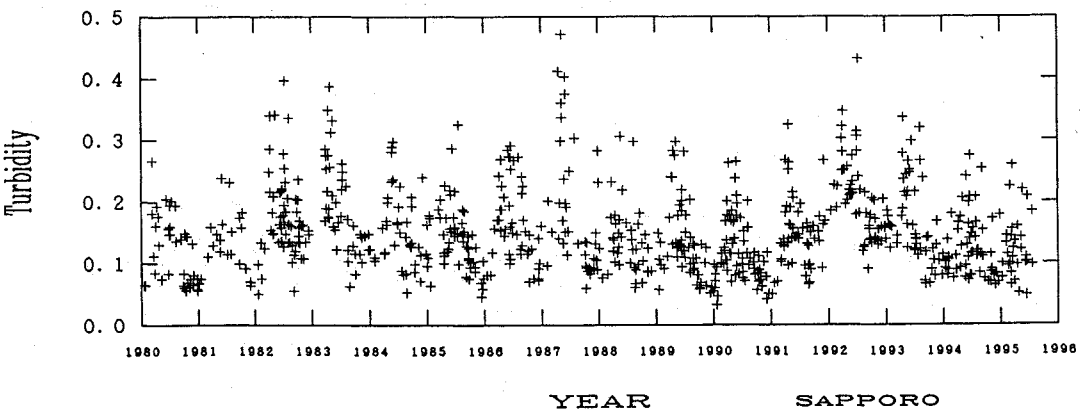

Figure 3. Atmospheric turbidity coefficients at Sapporo.

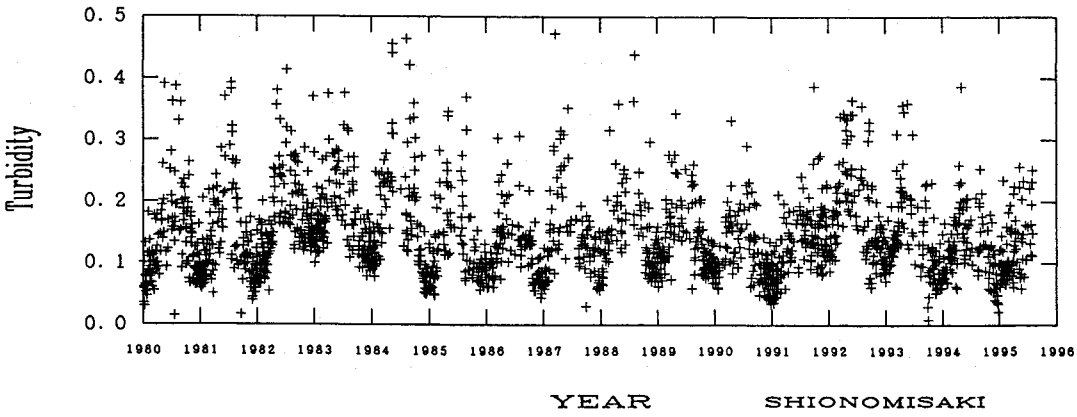

Figure 4. Atmospheric turbidity coefficients at Shionomisaki.

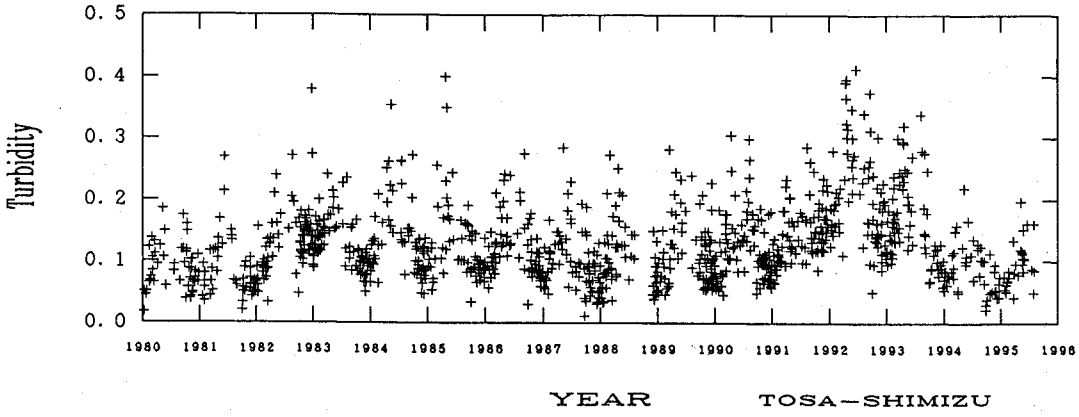

Figure 5. Atmospheric turbidity coefficients at Tosashimizu.

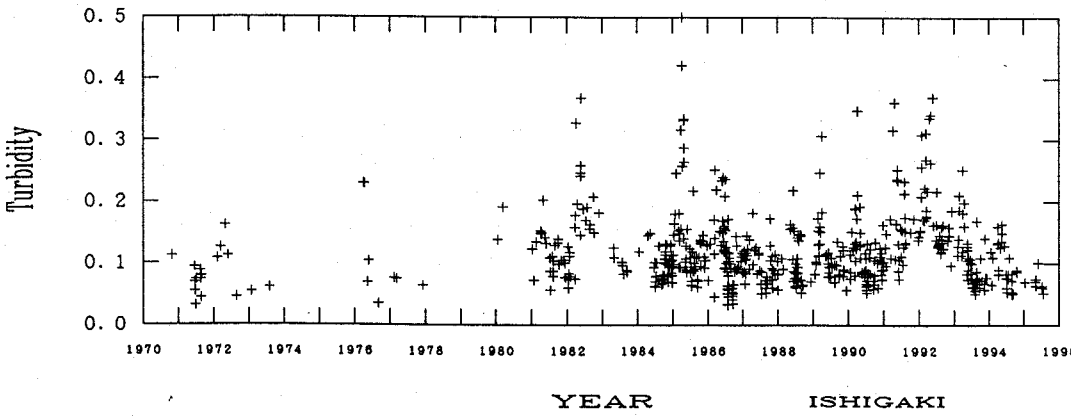

Figure 6. Atmospheric turbidity coefficients at Ishigakijima.

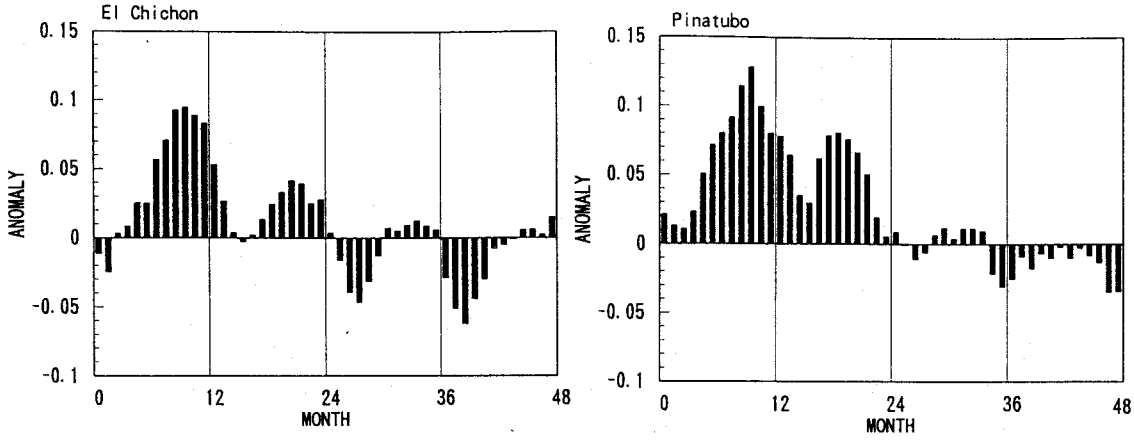

Figure 7. Anomaly in the three-month moving average turbidity coefficient at Nemuro after the eruptions of Mt.El Chichon and Mt.Pinatubo.

the anomaly in the turbidity coefficient. Figure 7 shows the anomaly in each month after the eruption of Mt.El Chichon in April 1982 and Mt.Pinatubo in June 1991.

For 1982 through 1985 the anomaly due to Mt.El Chichon was positive for 2 years and the maximum anomaly of 0.10 occurred 10 months after the eruption. In 1991 through 1995 the anomaly due to the Mt.Pinatubo eruption was also positive for 2 years, and the maximum anomaly of 0.13 occurred 10 months after the eruption. It was concluded that the effect of large volcanic eruptions on atmospheric turbidity lasts for about 2 years, and that the effect due to Mt.Pinatubo was larger than that due to Mt.El Chichon.

5. Secular Variations in Atmospheric Turbidity in the Area around Japan

Arao and Yamamoto (1981) estimated secular variations in atmospheric turbidity in the area around Japan from 1950s to 1979. Combining these results with this study, the variation from 1950s through 1995 at the five meteorological stations was analyzed. The annual mean values varied so much that it was difficult to establish long-term trends, and to minimize short-term fluctuations, we calculated three-year moving average atmospheric turbidity coefficients, which are shown in Fig.8.

The three-year moving average turbidity coefficient at Sapporo increased in the late 1960s, early 1980s, and early 1990s. At the other stations (Nemuro, Shionomisaki, Tosashimizu and Ishigakijima), the turbidity coefficients increased in the mid 1960s, early 1980s, and early 1990s. At Sapporo, the increase in the late 1960s was caused by severe urban air pollution due to coal combustion for domestic heating. Changing to kerosene improved the air quality in the 1970s, and the turbidity decreased. The increase at the three other stations (Nemuro, Shionomisaki and Tosashimizu) in the mid 1960s was caused by the volcanic eruption of Mt.Agung in Bali in 1963 as well as the transport of particulate air pollutants from urban areas with severe air pollution in Japan.

Figure 9 shows annual average concentrations of sulfur dioxide (SO_2) and suspended particulate matter (SPM, aerosol less than 10 μm in diameter) averaged for 15 air pollution monitoring stations in Japan (Japan Environmental Protection Agency, 1994). Sulfur dioxide concentrations were about 0.06 ppm in the mid 1960s and decreased gradually after 1968. Concentration of SPM also decreased gradually, showing an improvement in air quality in Japan after the end of the 1960s.

In the early 1980s and early 1990s, the turbidities at all 5 locations increased rapidly due to the volcanic eruptions of Mt.El Chichon in 1982 and Mt.Pinatubo in 1991 as stated above.

Generally, the turbidities from 1950s to 1995 at Nemuro, Shionomisaki, and Tosashimizu gradual increase, even excepting the effect of the volcanic eruptions in 1963, 1982, and 1991. At Nemuro the three-year moving average turbidity coefficient increased from 0.054 in 1954 to 0.082 in 1989. At Shionomisaki and Tosashimizu the turbidity coefficients increased from 0.07 in the mid 1950s to 0.13 and 0.11 in the late 1980s. Thus, atmospheric turbidity in rural areas of Japan increased by 0.03 to 0.06 over these 35 years. The increase was caused by increased emissions of pollutants in Japan with the economic growth of the 1960s, and the increasing long range transport of pollutants emitted from China with its recent industrialization. In China, annual emissions of sulfur dioxide increased from 10,175,000 tons in 1975 to 19,989,000 tons in 1987.

6. Estimating the Albedo Effect on Climate

As stated above, turbidity coefficients, proportional to the total atmospheric aerosols in the whole air column, have increased in the last 35 years in rural areas of Japan. If the atmospheric aerosols increase globally, they may cause global cooling due to scattering of the solar radiation back to space. We, then, estimated the albedo effect of aerosols on climate. The global mean atmospheric turbidity was assumed to that measured in Nemuro in this study, 0.054 in 1954 and 0.082 in 1989. From Eq.(4) the respective optical thicknesses at 0.5μm wavelength were 0.108 and 0.164.

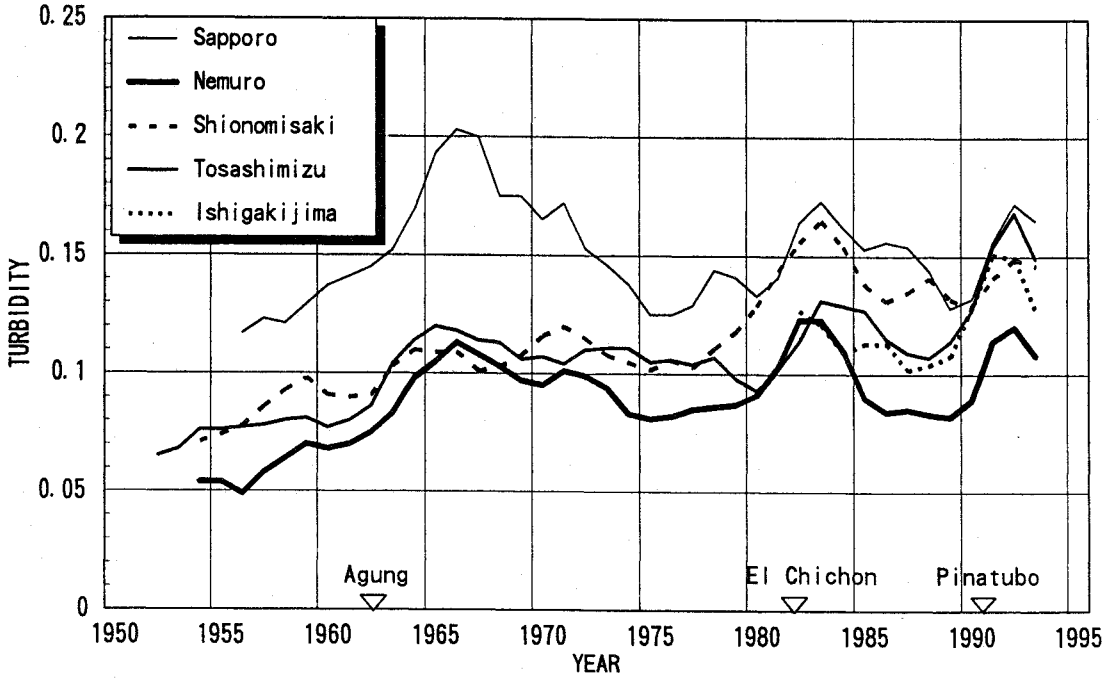

Figure 8. Three-year moving average turbidity coefficients in Japan.

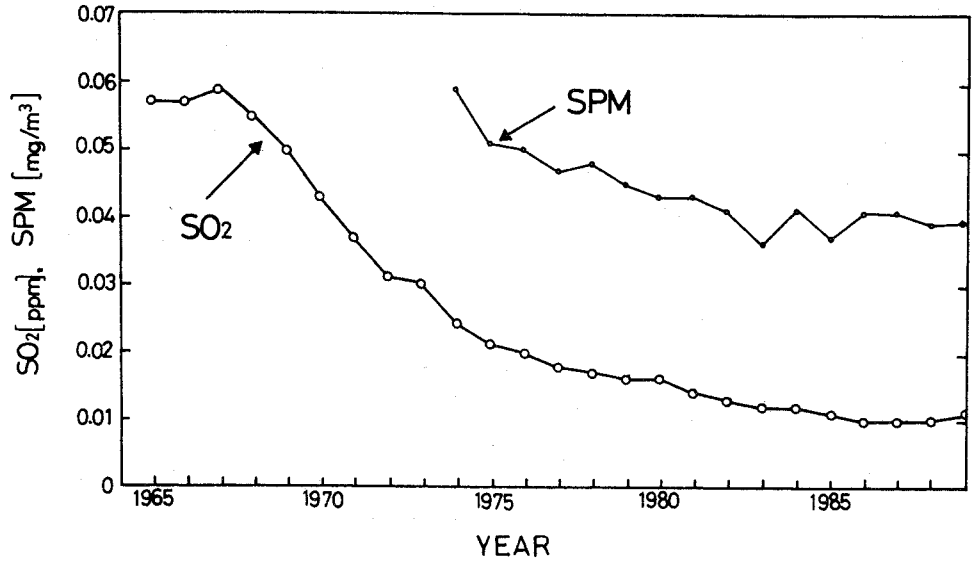

Figure 9. Annual average concentrations of sulfur dioxide (SO_2) and suspended particulate matter (SPM) averaged over 15 air pollution monitoring stations in Japan.(Japan EPM, 1994).

The atmosphere consists of three layers: stratosphere, free troposphere, and the atmospheric boundary layer. According to Toon and Pollack (1976), the optical thickness at 0.55μm wavelength in the stratosphere and the free troposphere is 0.008 and 0.05. Then, assuming that the global mean optical thickness of the stratosphere and the free troposphere at 0.50μm wavelength were also 0.008 and 0.05, the optical thickness of the atmospheric boundary layer was 0.050 in 1954 and 0.106 in 1989.

The complex refractive index of aerosols in the stratosphere was assumed to be $1.45\text{-}10^{-7}i$ as sulfuric acid particles (Palmer and Williams, 1975) and in the free troposphere $1.55\text{-}0.01i$ according to aircraft observations by Asano (1989). Adopting log-normal size distributions of the geometric number mean diameter of 0.11μm, we calculated the single scattering albedo and the phase function of the stratospheric aerosols and the free tropospheric aerosols. For the boundary layer aerosols we assumed that the aerosols had the same components as those measured at the foot of Mt.Niseko, 80 km southwest of Sapporo, Hokkaido. Then,the single scattering albedo and phase function of the global mean boundary layer aerosols were calculated based on the chemical characterization of aerosols in Ohta *et al.*(1996). The calculated single scattering albedo was 0.931 in the boundary layer.

The planetary albedo A_0, the albedo at the top of the atmosphere with no cloud (clear atmosphere), was obtained by solving the equation of radiative transfer with delta-P_3 approximation, which is an improved P_3 approximation method (Ohta and Tanaka, 1984) based on delta-function approximation of the phase function by Wiscombe (1977). For the surface albedo As we adopted 0.15 and 0.05 for as land and sea, respectively.

A simple global energy balance climate model was used to estimate the climatic effect of the global boundary layer aerosol increase. For the earth-atmosphere system, the energy balance equation is given by

$$\pi Re^2 \cdot S(1-A) = 4\pi Re^2 \cdot L \tag{11}$$

where Re is the radius of the earth, S the solar constant, A the global albedo of the real atmosphere, and L the global average outgoing longwave flux from the top of the atmosphere. The global albedo A is

$$A = n_c A_c + (1-n_c)A_0 \tag{12}$$

where n_c is the global average cloud amount and A_c the global average cloud albedo. Based on the estimates by Robinson (1966) and Budyko (1969), we adopted n_c=0.5 and A_c=0.5. According to Budyko (1969), L is expressed empirically as a function of Ts, the global average temperature near the surface, as

$$L = a + bTs - (a_1 + b_1 Ts)n_c \tag{13}$$

where a, b, a_1, and b_1 are numerical constants. If L is expressed in kcal cm^{-2} month^{-1}, then a=14.0, b=0.14, a_1=3.0 and b_1=0.10.

The global average surface temperature was calculated with Eqs.(11)-(13) for global mean turbidity coefficients of 0.054 and 0.082. One was calculated for the land surface ($A_0 = 0.15$) and one for the sea surface ($A_0 = 0.05$), summed up and weighted by 0.3 for land and by 0.7 for the sea from the surface area ratio. The temperature difference between a global mean turbidity coefficient of 0.082 and one of 0.054 was -0.41 ℃. This shows that a global increase in atmospheric turbidity by 0.028 over 35 years may cause a global cooling of 0.41 ℃ in the surface atmosphere.

The global increase of atmospheric aerosol assumptions were based on an analysis of variations in atmospheric turbidity coefficients at Nemuro, a rural area of Japan, and may be an overestimate. However, the 0.41 ℃ cooling is of the same order as the global warming of 0.45 ± 0.15 ℃ in these 100 years. This shows the need for considering the aerosol effect on climatic change.

The albedo effect of aerosols depends strongly on the absorptivity (the complex index of refraction) of aerosols as well as the optical thickness. Further, atmospheric aerosols affect the global climate indirectly by an enhancement of shortwave albedo of clouds due to increased concentrations of cloud droplets caused by increased cloud condensation nuclei such as sulfate aerosols (Coakley *et al.*,1987; Leaitch *et al.*,1992; Twohy *et al.*,1995).

In conclusion, the results here stress the importance to establish the global distribution and variation in optical thickness, absorption properties, and chemical species of aerosols in different regions of the world for a more accurate forecast of climatic changes.

7. Conclusion

Atmospheric turbidity coefficients were calculated according to Yamamoto *et al.*(1968), at Nemuro from 1978 to 1995; at Sapporo, Shionomisaki and Tosashimizu from 1980 to 1995; and at Ishigakijima from 1970 to 1995 . The calculated turbidity coefficients were 0.03-0.30 at Nemuro, 0.05-0.40 at Sapporo, 0.05-0.45 at Shionomisaki, 0.03-0.40 at Tosashimizu, and 0.03-0.35 at Ishigakijima. There were maxima in 1982-1984 and 1991-1993 due to volcanic eruptions of Mt.El Chichon and Mt.Pinatubo. The effect on atmospheric turbidity of the volcanic eruptions lasted for about two years, and the effect due to the Mt.Pinatubo eruption was larger than that due to Mt.El Chichon.

To minimize the effect of short-term fluctuations a three-year moving average atmospheric turbidity coefficient was calculated. Combining the results here with those of Arao and Yamamoto (1981) the variation in the coefficients from 1950s through 1994 at the above five sites were analyzed. At Sapporo there was an increase in the late 1960s due to urban air pollution by coal combustion for domestic heating. At the other four sites, there were increases in the mid 1960s due to the volcanic eruption of Mt.Agung in 1963 and transport of pollutants from urban areas with severe air pollution in Japan. In the first half of the 1980s and 1990s, all five sites show increases due to the volcanic eruptions of Mt.El Chichon in 1982 and Mt.Pinatubo in 1991.

Excepting the effect of volcanic eruptions, turbidity coefficients in rural areas of Japan increased from 1954 to 1989. The increase seems to derive from increasing human activity in east Asia.

The albedo effect of aerosols on climate was estimated with a simple global energy balance climate model. Assuming a global average turbidity coefficient increase by 0.028 over the 35 years based on the analysis at Nemuro, the global mean surface temperature is estimated to have decreased by 0.41 ℃.

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