ATMOSPHERIC AEROSOL OPTICAL THICKNESS AFTER THE MT. EL CHICHON ERUPTION FROM OBSERVATIONS IN MEXICO CITY AND VANCOUVER

I. Galindo, K.Ya. Kondrat'ev, and G. Zenteno

Center of Sciences about Earth at Colima University, Mexico
Center for Ecological Safety of the Russian Academy of Sciences, St. Petersburg
Received April 6, 1995

Measurements of direct solar radiation in polluted atmosphere over Mexico City are used to infer the growth of aerosol optical depth (AOD) due to volcanic aerosol and large volcanic ash particles emerged there between March 28 and April 4, 1982, as a result of El Chichon eruption (17.5°N, 93.3°W, Mexico). These measurements, as well as those conducted in Vancouver (Canada), showed that the initial episode of AOD growth took place in the period between April and July 1982 in both places, being more pronounced in the former. AOD value has fallen down to its usual background level only by February 1993. Secondary AOD maxima have, however, occurred during April–July 1983 period in Mexico and between October 1982 and September 1983 in Vancouver. From results obtained it is concluded that the initial AOD increase in April–July 1982, observed both in Vancouver and Mexico, was mainly due to shortliving volcanic ash particles residing near the ground surface, whereas the secondary AOD maxima were associated with the formation of stratospheric volcanic aerosol.

1. INTRODUCTION

The atmospheric aerosol is very important in natural and anthropogenic changes of the global climate, primarily because of its impact on both short-wave and long-wave radiation transfer and, thereby, on radiation balance of the underlying surface, atmosphere, and atmosphere–surface system and thus on the climate itself.[1–10] Sulfate aerosols play an important role in these process. In the troposphere sulfates arise from gas-phase reactions in industrial emissions of sulfur gas, while in the stratosphere sulfates, being also the product of gas-phase reactions, appear after explosive volcanic eruptions.

Langner and Rodhe[11] have estimated yields from various sulfate sources in the Northern hemisphere to be approximately (in Gigatons of sulfur per year): 64 (industry); 6.9 (the World Ocean); 5.8 (volcanos). From these figures, it seems to be a very difficult task to separate pure "volcanic" signal from the entire climate change. Among the parameters describing fundamental aerosol properties (such as particle size, shape, microstructure, number density, complex refractive index, etc.), most important to climate is atmospheric aerosol optical depth (AOD). It should be emphasized that the assumption on purely scattering aerosol that has recently become very popular in estimating the effect of aerosol on climate calls for the necessity to remind how important is the account for complex nature of the aerosol refractive index and, as a result, its contribution to the radiation absorption.[1,4] That is why in this paper we mainly discuss measurements of direct solar radiation (DSR) carried out in Mexico and Vancouver in 1982–1983 to monitor AOD changes due to El Chichon eruption (17.5°N, 93.3°W).

2. EL CHICHON ERUPTIONS

The first of the series of eruptions of El Chichon volcano, located at Chiapas State (SW Mexico) was on 28 March, 1982. Later, between late March and early April of 1982, three more strong eruptions of this volcano have happened, all near the Eastern edge of the Mexican neovolcanic belt (at the present volcanic arc Chiapas). Over several ages in the past El Chichon exhibited only solfataric activity. Since the Chiapas is located the joint of three Tectonic plates, American, Cocos, and Caribbean, it was believed that the volcanic activity is mainly the result of Cocos plate sinking toward below south-east Mexico domain.

The period after El Chichon eruption was a good opportunity to collect much more information about the volcanic effect on climate than had been accumulated before, owing to the availability of thus extensive measurements this time.[9] In particular, it has been the first opportunity to observe the dynamics of the global field, of such trace gases as HCl and OH and to detect their growth after the eruption. Such an increase has probably caused a corresponding decrease in O_3, NO,

0235-6880/96/03 227-04 $02.00

and NO_2 content. Dispersion of the sulfur gas releases has first been tracked from satellite observations, while the combination of remote sensing data and data of *in situ* measurements enabled detailed analysis of gas-phase reactions of SO_2 transformation into sulfuric acid drops.

The observations analyzed show that there are at least three reasons for the unusual scale of the eruptive aerosol cloud: 1) high sulfur concentration in volcanic releases, 2) latitude of volcano, and 3) season of the eruption. The eruption can be classified as moderately powerful. After the final accident on April 4 the released gaseous species were transported up to the altitudes above 25 km, while the amount of released sulfur gas evidently exceeded the maximum observed over the last 100 years,[9] namely 3.3 Mt as measured by TOMS spaceborne spectrometer.

The initial product of the first eruption were tefra particles, mixed with crystalline components and it was accompanied by strong emissions of alkaline silicon species (relative to abundant pyroclastic substance after the second and the third eruptions). Initially the tefra consisted mainly of juvenile species and litoid fractions. First eruptions emitted large amount of ash, moderate amount of pumice, and small amounts of litoid. During the first period, till April 2, a large amount of light-grey ash was emitted, that covered vast territory north-east of the volcano. The ash layer depth was 0.5 m 15 km away from the volcano, decreasing to 0.2 m at 75 km distance. In the Vilia-Ermosa city (the state of Tabasco), the layer was about 0.1 m thick.

The second phase consisted of two powerful eruptions (April 3 at 19:00 LT and April 4 at 05:36 LT), that were accompanied by releases of light brown ash, composed mostly of tefra, whose bulk progressed east of the volcano. By April 4 the rate of ash deposition reached 0.33 g m^{-2} s^{-1} near Teapa, where this had the effect of twilight with visibility less than 5 m. By 12:30 LT the ash deposition diminished to 0.05 g m^{-2} s^{-1}. These days the volcano valleys were filled with pyroclastic streams of hot ash and big pumice stones. The thickness of tefra layer, as measured on April 5 near Palenku (125 km east of the volcano), was over 0.4 m.

Chemical analysis of 30 tefra samples, gathered at different locations on April 3 to April 7, has shown that:

1) between March 28 and April 2 there occurred emissions of light-grey substance reach in silicon, which later was covered with tefra of high litic content;

2) found was tefra reach in iron, magnesium, and calcium oxides.

According to Matson and Robock estimates,[12] the stratospheric eruptive cloud from El Chichon eruption was the most powerful one over past century, and the consequence for the near-ground layer was over 5°C drop of local air temperature, which then expected to drop by 0.5°C during 1984–1985.

The unique, integrated ground-based, balloon-borne, airborne, and satellite data acquired after the El Chichon eruption has provided an important verification for the model of gas-phase transformation of eruptive sulfuric gas to stratospheric sulfuric-acid aerosol, as well as for numerical simulation of transport, gravitational sedimentation of volcanic aerosol and its effect on the radiation regime and climate.

The eruptive cloud had made its first complete revolution around the Earth during 21 days at mean velocity of 22 m/s (Ref. 12). From data of lidar sensing at Hawaiian Islands, over which the thickest part of the cloud has passed on April 9, the relative (with respect to Rayleigh scattering) backscattering coefficient exceeded 200, the value never observed before, with the most intense backscattering occurred at 26 km altitude. The structure of the eruptive cloud had vertical stratification. Two months after the eruption a relatively uniform global distribution of volcanic aerosol established at 20 km, at the altitude of minimum aerosol concentration. The availability of simultaneous AOD measurements at such distant sites as Mexico and Vancouver has enabled an analysis of the volcanic aerosol evolution.

3. AEROSOL OPTICAL DEPTH (AOD) DETERMINATION

We calculate AOD, a characteristic of direct solar radiation attenuation by the aerosol in the entire atmosphere layer, using the following formula[14–16]

$$\tau_a = 1/\{m'\ln[I/(T_0T_r - a_w)I_0]\}, \quad (1)$$

where $\tau_=$ is AOD, m' is the air mass corrected for the observed atmospheric pressure, I is the direct solar radiance (mJ·m^{-2} h^{-1}), $T_0(T_r)$ is the transmission allowing for the ozone absorption (Rayleigh scattering), a_w is the relative absorption by the water vapor, I_0 is the extraterrestrial solar irradiance.

Atmospheric mass is calculated, after Kasten,[17] as

$$m = 1/[\cos\theta + 0.15(93.885 - \theta)^{-1.253}], \quad (2)$$

where θ is solar zenith angle in degrees. Value of m' is

$$m' = mp/101.3, \quad (3)$$

where p is the atmospheric pressure in kPa. According to Ref. 18 the transmission due to absorption by ozone is given by

$$T_0 = 1.0 - a_{vis} - a_{uv}, \quad (4)$$

$$a_{vis} = 0.002118x/(1.0 + 0.0042x + 0.00000323x^2), \quad (5)$$

$$a_{uv} = 0.1082x/(1.0 + 13.86x)^{0.805} + 0.00658x/[1.0 + (10.36x)^3]. \quad (6)$$

The ozone column density is assumed to be 3.5 mm (Ref. 19). Thus,

$$x = 3.5\ m'. \quad (7)$$

According to Ref. 18, the relative absorption by water vapor is

$$a_w = 2.9w'/[(1.0 + 141.5w')^{0.635} + 5.925w'], \quad (8)$$

where

$$w' = mn(p/1013.25)^{0.75} . \quad (9)$$

According to Ref. 20, the water vapor column density

$$w = 0.1\exp(2.2572 + 0.05454\, T_d), \quad (10)$$

where T_d is the dew point temperature determined by the empirical relation[21]

$$T_d = 1.0/[T - \log(RH - 2.0)/2352.6], \quad (11)$$

where T is the air temperature, RH is the relative humidity in per cent.

Since the atmospheric pressure changes only a little during a year, the following approximations apply

$$a_{vis} = 0.002\ 0279x + 0.000\ 23211, \quad (12)$$

$$a_{uv} = 0.000\ 70438x + 0.014\ 1164. \quad (13)$$

The water vapor column density can be given by

$$w = 0.493RH/[T_d\exp(26.23 - 5416/T_d)]. \quad (14)$$

Finally, for the transmission due to Rayleigh scattering we have[14]

$$T_r = 0.98552 - 0.10345m' + 0.1073m'^2 + 0.00198m'^3 + \\ + 0.00011m'^4 - 0.000002m'^5. \quad (15)$$

As to the functional dependence, we have $\tau_= = \tau_=(I, m, p, T_d)$. As estimates show, the calculation provide in contrast to the technique from Ref. 16, the accuracy better than 0.74%.

4. DATA OF OBSERVATIONS

Hourly values of direct solar radiation are from observations between 10:00 and 14:00 LT at actinometry observatory of Mexico National University by means of Linke-Foisner actinometer. These measurements are being carried out there since 1957. Data in Fig. 1 (curve *2*) are five-year average annual behavior of the background AOD prior to El Chichon eruption (1977–1981) (triangles and circles are minimum and maximum AOD values). The maximum February–March and April–May AOD values are mostly explained by meteorological conditions.[12]

The 1982–1983 increase in AOD (Fig. 1, curve *2*) might be related to two eruptions, namely: 1) Niamarnagira eruption in Zaire (1.25°S, 29.12°E), the most likely source of "mysteriousB volcanic cloud[9] caused an AOD increase in January–March 1982, and 2) a few eruptions of El Chichon volcano during March 28 to April 4, 1982, whose consequence was AOD increase throughout the Northern hemisphere. AOD peaked in April–July 1982 and then gradually decreased to the minimum values by February 1982.

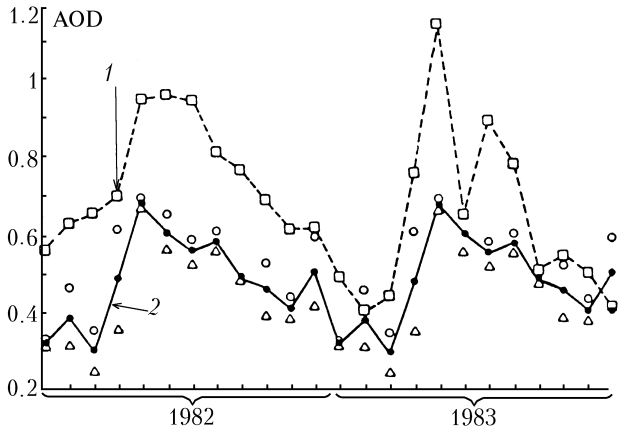

FIG. 1. Change in aerosol optical depth as inferred from observations in Mexico City during 1982–1983 (curve 1) and monthly mean AOD averaged over five years preceding El Chichon eruption (curve 2).

From observations by Hay and Darby,[16] a substantial growth of AOD due to the eruption in Vancouver (Fig. 2) started in April 1982, peaked by May–June, and then decreased till September; again AOD increased to May 1983 and fell off down to background level only by the end of 1983.

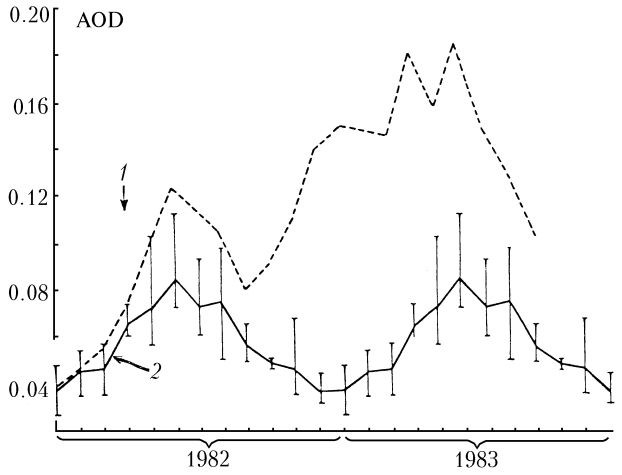

FIG. 2. Change in the aerosol optical depth from observations in Vancouver (curve 1) and monthly mean AOD averaged over five years preceding El Chichon eruption (curve 2), after Ref. 16.

As is seen from the above data, both in Mexico and Vancouver there was rapid and fairly short-term AOD growth after the eruption which can be attributed to the effect of big particles, mainly of ash and pumice,[23] rather than eruptive stratospheric sulfuric-acid aerosol. Secondary maxima, however, have appeared to be dissimilar: that in Vancouver lasted much longer. At both sites, the development of secondary maxima should be related to the effect of stratospheric eruptive aerosol of later formation. This

is supported by observations after Fuego and Colima eruptions which showed correlation between growing turbidity level and intensifying twilight phenomena.

Volcano-induced decrease of direct solar radiation was as much as 30% in Mexico and 33% in Vancouver. Comparable decrease was recorded even in Fairbanks (Alaska), particularly in 1982–1983 winter (i.e. 9 months after the eruption). From this it is concluded that the optical properties of the eruptive cloud were characterized by a strong backscattering.

5. CONCLUSIONS

The above results allow the following main conclusions to be drawn.

1. From April till July 1982, both in Mexico and Vancouver, there was a considerable growth of atmospheric optical depth caused by El Chichon eruption, with a dominant contribution to the increase coming from short-lived volcanic ash particles. The subsequent AOD decrease was observed till September 1982 in Vancouver and till February 1983 in Mexico.

2. Secondary AOD maxima, occurred from October 1982 till September 1983 in Vancouver and from April till July 1983 in Mexico, developed as a result of formation of stratospheric eruptive sulfur acid aerosol, which was supported by the intensified typically posteruptive twilight phenomena.

3. Annual AOD behavior in Mexico was dominated by the quasi two-year oscillation of the stratospheric wind featured by the presence of maximum in Easterly wind in the 10°S–10°N belt.

4. Stratospheric aerosol layer from El Chichon eruption has played an important role in determining the value of direct solar radiation at the surface level which reduced (about 9 months after the eruption, i.e. at the time of maximum effect of the volcano) by 38% in Alaska, 33% in Vancouver, and 30% in Mexico. Obviously, the volcanic effect on reduction of solar radiation enhanced with latitude.

REFERENCES

1. K.Ya. Kondrat'ev, ed., *Aerosols and Climate* (Gidrometeoizdat, Leningrad, 1991), 542 pp.
2. K.Ya. Kondrat'ev, *Volcanos and Climate*, Itogi Nauki i Tekhniki: Meteorol. i Klimatol., Vol. 13 (VINITI, Moscow, 1995), 204 pp.
3. K.Ya. Kondrat'ev, *Global Climate* (Nauka, St. Petersburg, 1992), 350 pp.
4. K.Ya. Kondrat'ev and L.S. Ivlev, Dokl. Ros. Akad. Nauk **34**, No. 1, 98–99 (1995).
5. K.Ya. Kondrat'ev, *Climate Shocks: Natural and Anthropogenic* (Jon Wiley & Sons, New York, 1988), 296 pp.
6. I. Galindo, Ciencia **45**, 21–27 (1992).
7. S.G. Jennings, ed., *Aerosol Effects on Climate* (The Univ. of Arizona Press, Tucson and London, 1993), 304 pp.
8. K.Ya. Kondrat'ev and A.P. Cracknell, *Observing Global Climate Change* (Taylor & Francis, London, 1996) (to be published).
9. K.Ya. Kondrat'ev and I. Galindo, *Volcanic Activity and Climate* (A. Deepak Publ., Hampton, 1996) (to be published).
10. R.E. Newell, in: *1985 Yearbook of Science and Technology* (McGraw Hill, New York, 1994), pp. 206–225.
11. J. Langner and M. Rodhe, J. Atmos. Chem. **13**, 225–263 (1991).
12. M. Matson and A. Robock, Geofis. Int. **23**, 117–127 (1984).
13. J.J. DeLuisi, E.G. Dutton, K.L. Coulson, T.E. Defoor, and B.G. Mendonca, J. Geophys. Res. **C88**, 6769–6772 (1983).
14. J.A.Davis and J.E. Hay, in: *Proc. First Canadian Solar Radiation Data Workshop*, Toronto (1978), pp. 32–58.
15. J. Freund, Atmosphere–Ocean **21**, 158–167 (1983).
16. J.E. Hay, R. Darby, Atmosphere–Ocean **22**, No. 3, 354–368 (1984).
17. F. Kasten, Arch. Meteorol. Geophys. Bioclimatol. **B14**, 206 –233 (1966).
18. A.A. Lacis and J.E. Hansen, J. Atmos. Sci. **31**, 118–133 (1974).
19. R.A. MacClatchey, J.E. Selby, J.S. Garing, R.W. Fenn, and F.E. Volz, Environm. Res. Pap. No. 354, Air Force Cambridge Lab. (1971), 85 pp.
20. T.K. Won, in: *Canadian Prairie Area Third Conf.*, Canadian Solar Energy Soc., Inc. Edmonton, ALTA (1977), 23 pp.
21. A. Estrada and J. Arroyo, personal communication, 1988.
22. M. Iqbal, *Introduction to Solar Radiation* (Academic Press, Toronto, 1983), 390 pp.
23. E.M. Patterson, C.O. Pollard, and I. Galindo, Geophys. Res. Lett. **10**, 317–320 (1983).
24. I. Galindo, in: *Aerosols and Their Climatic Effects*, ed. by H.E. Gerber and A. Deepak (A. Deepak Publ., Hampton, 1984), pp. 245 –259.
25. I. Galindo, Geofis. Int. (1995) (to be published).