Journal of Volcanology and Geothermal Research, 11(1981) 67—80
Elsevier Scientific Publishing Company, Amsterdam — Printed in Belgium

A LATITUDINALLY DEPENDENT VOLCANIC DUST VEIL INDEX, AND ITS EFFECT ON CLIMATE SIMULATIONS

ALAN ROBOCK

Department of Meteorology, University of Maryland, College Park, Md. 20742 (U.S.A.)

(Received March 5, 1980; revised and accepted December 11, 1980)

ABSTRACT

Robock, A., 1981. A latitudinally dependent volcanic dust veil index, and its effect on climate simulations. J. Volcanol. Geotherm. Res., 11: 67—80.

A latitudinally dependent annual average volcanic dust veil index is developed based on indices of Lamb and Mitchell. This index is then used to force a climate model to determine if an improved volcanic index could improve the correlations previously found when forcing the model with hemispherically averaged dust. It does not. This suggests that natural variability may also be an important cause of climate change during the past 400 years.

INTRODUCTION

Volcanic dust has often been discussed as a cause of climatic change. Theoretical studies of the radiative effects (Pollack et al., 1976), comparisons of eruption dates with climatological data (Mitchell, 1961; Oliver, 1976; Mass and Schneider, 1977; Taylor et al., 1980) and numerical modeling experiments (Hunt, 1977; Hansen et al., 1978, Robock, 1978, 1979a) have all indicated that volcanoes may be important. When a large volcano erupts it ejects large amounts of dust and gases into the stratosphere. The dust particles slowly settle out, with the large particles settling faster. (As the particles descend into the troposphere, they are rapidly washed out and rained out and are no longer important.) The gases react to form aerosols which also slowly settle out. At the same time these particles are being transported by the stratospheric winds. Thus, the volcanic dust veil slowly spreads away from the location of the eruption as it dissipates. The exact character of the veil depends on many factors, including the height of the eruption column, the height of the tropopause, the amount, composition and size distribution of the erupted particles, the amount and composition of the gases, and the strength, direction and turbulence of the stratospheric winds. Due to the time scales involved, however, the result is that the dust is spread into a latitudinal band which slowly diffuses away from the latitude of the eruption as the dust settles out. Dust will be used in this paper to refer to both particulates from ash and aerosols formed from gases.

Previous modeling studies (Robock, 1978, 1979a) have obtained high correlations between model outputs and climatic data when forcing a climate model with a Northern Hemisphere (NH) average dust veil from Lamb (1970) or Mitchell (1970). When comparing the output to the data, the highest correlations were found with hemispheric average quantities, and correlations with temperature records in smaller latitude bands were not as high. This paper reports the results of an experiment to try to improve these results by creating a latitudinally dependent volcanic dust veil index, using the data of Lamb and Mitchell, and forcing the model with this more detailed dust veil index in hopes of improving the latitude-dependent results by providing more accurate latitude-dependent forcing.

The next section of the paper describes the calculation of the index. Next, the climate model used for the calculations is briefly reviewed. The following section describes the past temperature data with which the model results are compared. Finally, the results of the calculations are presented, together with conclusions.

LATITUDINALLY DEPENDENT VOLCANIC DUST VEIL INDEX

Previous compilations of volcanic dust

The most comprehensive compilation of climatically significant volcanic eruptions is the one by Lamb (1970). In addition to a list of all the volcanic eruptions since 1500 with an estimate of their magnitude, he provides a NH average volcanic dust veil index (DVI) calculated using simple assumptions about the spread and decay of the dust. This NH DVI was used in Robock (1978, 1979a) to force a climate model to test the effects of volcanic dust on climate change. Mitchell (1970) computed his own NH DVI from data supplied him by Lamb for the period since 1850 and this index was also used in Robock (1978, 1979a). The DVI's from Lamb and Mitchell are shown in Fig.1, with the amplitudes of the Mitchell index adjusted so that the two indices agree for the eruption of Gunung Agung in Bali in 1963. Hirschboeck (1980) has also compiled a comprehensive list of volcanic eruptions including those of no climatological significance, but she did not include some major eruptions cited by Lamb, and did not sufficiently evaluate the magnitude of the eruptions. Therefore, this index was not used in volcanic dust climate simulations.

A problem with using Lamb's DVI to force a climate model is that the DVI was calculated partially based on an *a priori* assumption that volcanic dust causes a cooling at the earth's surface. Lamb used three methods for estimating the DVI from an individual volcano. He then calculated a mean DVI, weighting each individual estimate according to his opinion of its accuracy. All of the estimates were not available from all volcanoes, depending on how much information was recorded and survived. One estimate depended on estimates of the actual volume of dust ejected into the stratosphere and

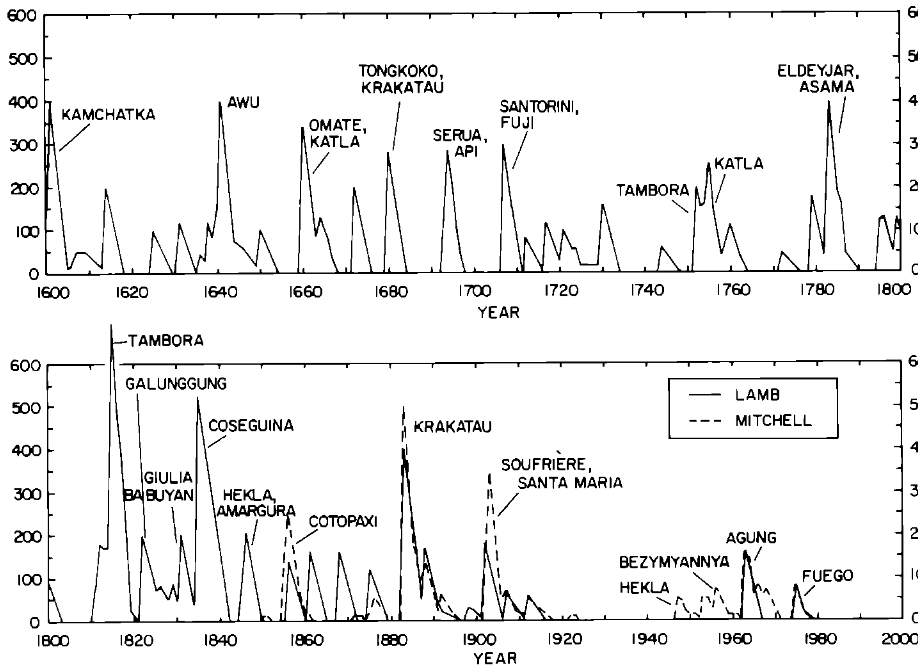


Fig.1. Northern Hemisphere average volcanic dust veil index from Lamb (1970) and Mitchell (1970).

was considered the least reliable. Another estimate depended on estimates of the amount of depletion of solar radiation reaching the ground, based on actual measurements in modern times, and visual descriptions of sunsets and other optical phenomena in earlier times. The third estimation technique, weighted equally with the radiation one, was making the DVI proportional to temperature drops in an early estimate of average surface air temperature over the Northern Hemisphere by Köppen (1873, 1914). Thus, temperature drops after volcanoes were built into the DVI. Although Köppen's curves may not have represented hemispheric averages well (Groveman and Landsberg, 1979a), the DVI was tied to the available temperature curves.

Lamb (1970) recognized this problem and so produced two NH average DVI values [appendix II, tables 7 (a) and 7 (b)]. In table 7 (a) he eliminated DVI for those eruptions for which evidence was based *solely* on temperature drops. Thus, the index presented in table 7 (a) still includes estimates of DVI based *partially* on temperature drops. It is not independent of the temperature curve, as would appear from a careless reading of the table caption. Table 7 (b) includes estimates for the period 1700—1899 based solely on temperatures.

An additional problem with using Lamb's NH DVI is that he arbitrarily excluded from his index volcanoes with DVI less than 100. This resulted in Agung being the only volcano included in the index in the past sixty years. Mitchell (1970), on the other hand, included other volcanoes such as Hekla, Mt. Spurr and Bezymyannaya during the 1940s and 1950s in his NH DVI Experiments in Robock (1978) showed that Mitchell's DVI produced a better NH average simulation for the last 100 years than did Lamb's.

New latitude-dependent volcanic dust index

Because of the above problems, experiments were conducted to answer the question: Can improvements in the method of estimating and averaging volcanic DVI's based on Lamb's compilation improve the results when used as input to a numerical climate simulation? First, values of DVI for each individual volcano (d.v.i./E_{max} in appendix I of Lamb, 1970) were modified to remove the influence of temperature. [Because Lamb included a factor (E_{max}) to account for the latitudinal spread of dust in his d.v.i. estimates, it was necessary to divide by this quantity to get the actual size of each eruption at its source.] Values were recalculated based only on estimates of radiation deficits and volumes of dust injected into the stratosphere. Next, a model (described below) was used to calculate the spread in latitude and decay in time of the dust injected from each volcano. The result from this model was then a latitude—time array of volcanic dust loading. Finally, these data were averaged for each hemisphere, area-weighting the latitude bands, to give a hemispheric annual average DVI. Experiments were then conducted forcing the climate model with both hemispherically averaged and latitudinally dependent volcanic dust and the results were compared to observed temperature data.

As mentioned above, the basic sources for a new latitudinally dependent volcanic dust veil index were the compilations of Lamb (1970) and Mitchell (1970), which gave locations and magnitudes of past volcanic eruptions. Lamb's values of d.v.i./E_{max} from his appendix I were categorized into annual average totals for 10° latitude bands for the whole earth. For the period 1850—present a second compilation of the same type was constructed from the data of Mitchell. Mitchell classified the eruptions according to severity classes 1—4 which corresponded to ranges of volume of volcanic dust loading. Values of d.v.i./E_{max} were calculated using Lamb's equation (3) (p.472) which directly relates the index to volume of dust, but this resulted in values too low for Krakatau in 1883 which was arbitrarily assigned a value of 1000 by Lamb. Therefore, to make Mitchell's estimate correspond to those of Lamb, his severity class of 1 (Krakatau) was assigned an index of 1000, class 2 an index of 100, class 3 an index of 10 and class 4 an index of 1.

Because some of Lamb's index values were calculated with an *a priori* temperature dependence, the values were adjusted to exclude this evidence. This resulted in removing some eruptions which were based solely on temperature drops and adjusting values for other eruptions so that the index was based only on radiation or dust evidence. The largest adjustments were for Tambora in 1815 and Cosiguina in 1835. For Tambora particularly, the large index calculated by Lamb was based on the large temperature drop for the 1812—1818 period, but there were large eruptions in every one of the four years preceding Tambora which probably contributed significantly to this temperature drop. The final array of index values had a maximum of 1000 for any volcano.

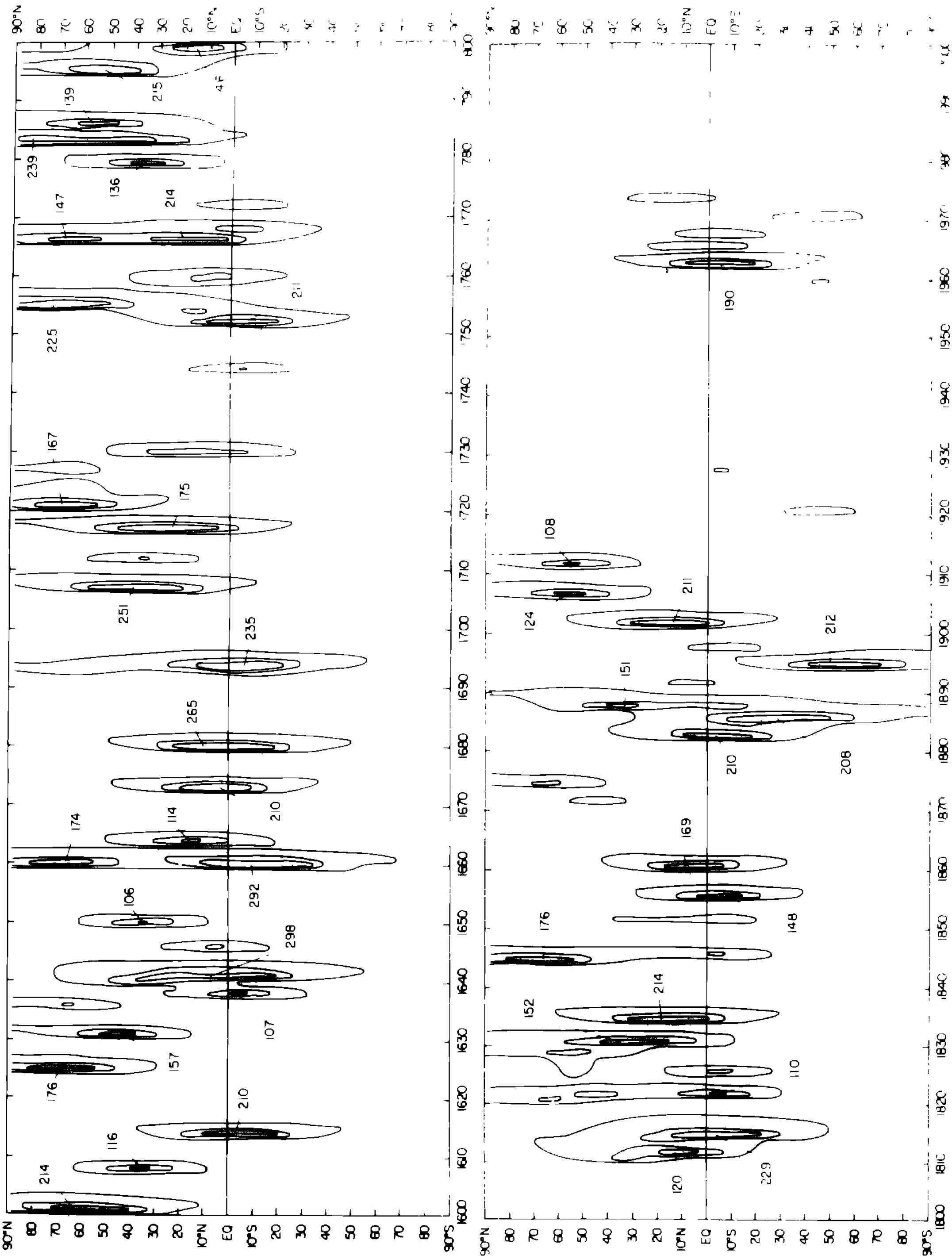
The above procedure produced a latitude band—year array of sources of volcanic dust. In order to use these data to force a climate model it was necessary to model the spread in latitude and decay in time of the dust to produce a simulation of the actual latitude—year distribution of the dust. A simple Gaussian model of these processes was parameterized from the detailed model calculations of Cadle et al. (1976). While this resulted in ignoring some of the details of the actual processes, such as the seasonal cycle of the stratospheric dynamics and the variation of tropopause height in time and space, it was considered consistent with the quality of the source data.

By considering (for the simulation of the Agung and Fuego eruptions by Cadle et al., 1976), the rate of spread of volcanic dust (their figs.1 and 4) and the decay in time of the total concentration (their fig.3), the relative concentration of dust was expressed as:

$$C = \exp\left[\frac{y^2}{-1.76t^{1.146}} - 0.0017t\right]$$

where y is the distance from the eruption in degrees of latitude and t is the time from the eruption in days. Tables were constructed of C for each 10° latitude band for eruptions in each other latitude band for 15-day intervals. The annual average concentration for each latitude band was then calculated and these tables were used for the reconstruction. Finally, the value of d.v.i./E_{max} for each eruption was multiplied by the value of C from the tables appropriate for each latitude band for its distance and time from the eruption and the contribution at each latitude band for each year from each volcano was totaled. The resulting latitude—time distribution of volcanic dust is shown in Fig.2. The major eruptions can be identified by the centers of concentration at the appropriate latitude and year. Regions of enhanced concentration due to several eruptions close in time and space can also be identified, particularly in the 1810s and 1880s.

Northern Hemispheric average concentrations were also calculated by area-weighting the values in Fig.2 and these results are shown in Fig.3. The amplitude of the index was arbitrarily adjusted so that the amplitudes for Agung were the same as in the earlier compilations shown in Fig.1. It can be seen that the curves in Fig.1 and 3 are similar, the differences being due to the adjustments of the source data to exclude temperature effects, and the more accurate method of calculating the NH average.



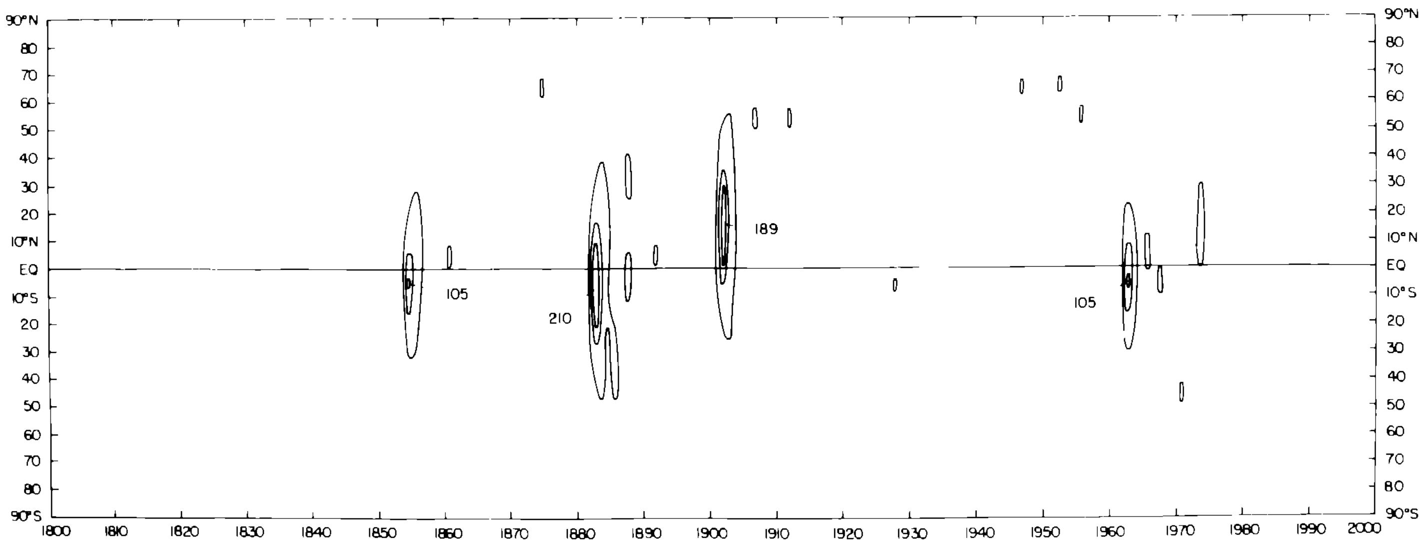


Fig.2 Latitudinal distribution of volcanic dust veil index. The top two portions were calculated from adjusted data of Lamb (1970). The bottom portion was calculated from data of Mitchell (1970). The contours are at index values of 20, 60 and 100; the maximum value at the center is also plotted.

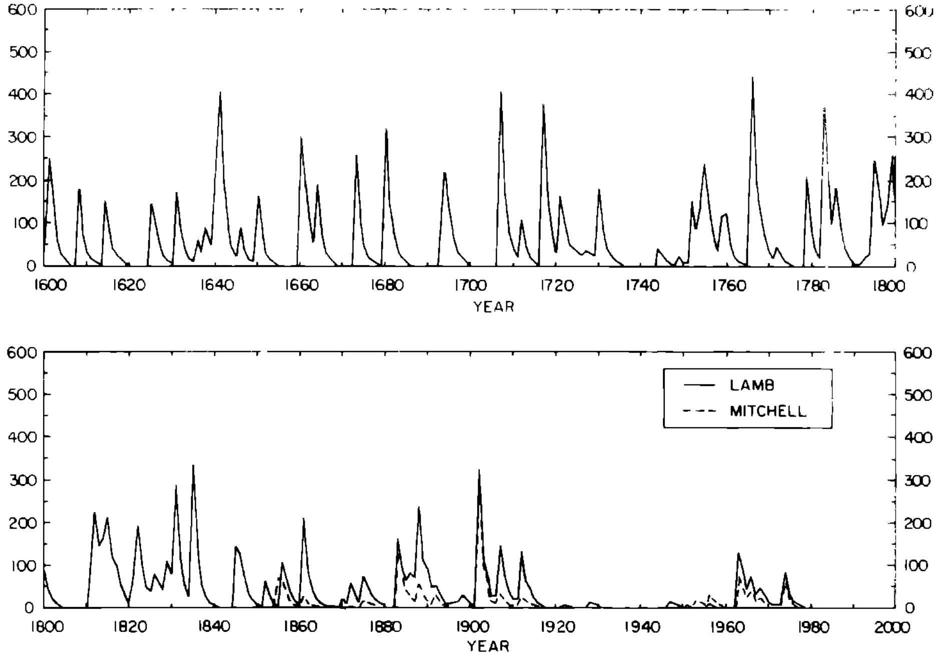


Fig.3. Northern Hemisphere average volcanic dust veil index calculated from Fig.2 and adjusted so that the value for Agung corresponds to that in Fig.1.

RESULTS

Experimental procedure

An energy-balance climate model, described in the next section, was forced by five different volcanic indices and the results of the simulations were compared to the observed surface temperature changes, described in the following section, for the period 1621—1975. The first run was the same as the one reported by Robock (1978), forcing with the old Lamb NH index to 1850 and the old Mitchell NH index since 1850 (Fig.1). The second run, also with NH average forcing imposed at all latitudes globally, used the new Lamb index to 1850 and the new Mitchell index since 1850 (Fig.3). The third run used latitudinally dependent annual average forcing (Fig.2) with Lamb's data before 1850 and Mitchell's since. The fourth run also used latitudinally dependent forcing (Fig.2), but used that based on Lamb for the entire simulation. Finally, Harshvardhan (1979) has shown that the effects of volcanic dust depend on latitude and season due to the solar zenith angle and albedo dependencies of the radiative perturbation. The last run used the same forcing as the third run, but the annual average forcing from the dust was modified by the relative seasonal and latitudinal weights as shown by Harshvardhan (1979, fig.10).

The first run was calibrated as in Schneider and Mass (1975), with a dust veil index of 160 corresponding to solar constant reduction of 0.5%. The magnitude of the forcing of all the other runs was adjusted so that the resulting simulations produced NH average temperature fluctuations of comparable magnitudes. Therefore, only the relative interannual fluctuations and not the actual amplitudes should be considered when comparing the simulations with the observation and with each other.

Climate model

The climate model used in these simulations is based on that of Sellers (1973, 1974). It is identical to the one used in Robock (1979a). The basic energy-balance equation solved in the model for surface air temperature over land and water separately for each 10° latitude band with a 15-day time step is:

$$c\,\frac{\partial T}{\partial t} = Q\,(1-\alpha) - I - \mathrm{div}\,(F)$$

where T is temperature, t is time, c is the thermal inertia, Q is the incoming solar radiation, α is the planetary albedo, I is the outgoing infrared radiation and F is the horizontal energy transport by atmospheric and oceanic motions. For a discussion of changes made to the model and a detailed description of its performance see Robock (1977, 1979b).

Past temperature data

Several compilations of past surface temperature data were compared to the results of the volcanic dust simulations. Mitchell (1961) presented 5-year averages of surface temperature for various latitude band combinations for the past 100 years. Budyko (1969) presented annual average NH temperatures for 1881—1960 and these were updated by Asakura (Natl. Acad. Sci., 1975). Graphs of the temperature data of Mitchell and Budyko are presented in Robock (1978). The correlation coefficient between Mitchell's 5-year average 0—80°N data and 5-year averages of Budyko's data is 0.93 (Robock, 1978). Thus, correlations as high as this value, which is a comparison of two sets of observations of the same quantity, should be considered as close as one could expect for correlations between either set of observations and the model simulations. Borzenkova et al. (1976), updating the work of Budyko (1969), presented annual average NH temperature from 1881 to 1975. Before this period, a dense enough network of stations did not exist to obtain a representative hemispheric temperature by spatial averaging. Many individual instrumental station records, as well as proxy records do exist, however, and these were used by Groveman and Landsberg (1979a, b) to reconstruct the annual average NH average surface temperature starting in 1579. They used the technique of multiple linear regression using these individual series based on their correlations with the record of Borzenkova et al. The data from Groveman and Landsberg are presented in Fig.4 as 10-year averages, although annual averages were used for calculations of the correlations with model results.

While these temperature records are the best available at present, they all suffer from problems such as not adequately representing the ocean areas, measurement errors and urbanization. The early part of the Groveman and Landsberg reconstruction, in particular, is based on only a few proxy records. Thus, correlations and conclusions in this paper are subject to revision when future improved reconstructions are used. The revisions will not necessarily make the results worse.

Discussion of the simulations

Ten-year averages of the first three simulation runs are plotted with the observations of Groveman and Landsberg (1979a, b) in Fig.4. All the simulations appear to well reproduce the climate except for the early 19th century, and none appears to do particularly better than any other. This is also seen in Table I, where correlations of annual averages of the simulations with the above data as well as the compilations of Mitchell (1961) and Budyko (1969) for the past century are shown. For the past 400 years, none of the forcings did better than any others, and all produced significant correlations. For the past 100 years, the new Mitchell NH average forcing produces slightly poorer results than the old one, although the old one did not contain temperature dependencies for this period. Using latitude-dependent forcing improved the results slightly, but not to the level of the old NH average forcing. Using Lamb latitude-dependent forcing made only small differences, and weighting the forcing according to Harshvardhan (1979) made almost no difference.

CONCLUSIONS

The experiment described above was designed to test whether an improved latitude-dependent volcanic dust veil index when used to force a climate model could result in better latitude-dependent or hemispheric average

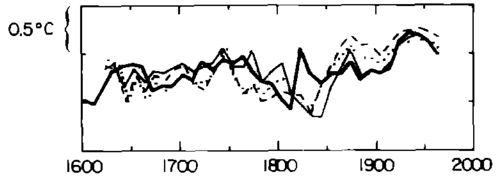


Fig.4. Ten-year average of observations and model simulations of Northern Hemisphere average surface temperatures. Observations (thick solid line) are from Groveman and Landsberg (1979a, b). Simulation runs, as listed in Table I, are MO (NH) (thin solid line), MN (NH) (dashed line), MN (LAT) (dotted line).

TABLE I

Correlation coefficients between model simulation runs and temperature data sets

Temperature data set	Averaging period (years)	Period of record	Model simulation run				
			MO (NH)	MN (NH)	MN (LAT)	LN (LAT)	MN-H (LAT)
Mitchell							
0—80°N W	5	1870—1959	0.86	0.77	0.83	0.85	0.83
0—80°N A	5	1870—1969	0.81	0.75	0.77	0.81	0.77
0—60°N W	5	1870—1959	0.73	0.62	0.71	0.73	0.71
0—60°N A	5	1870—1959	0.80	0.71	0.74	0.75	0.74
0—60°S W	5	1880—1959	0.81	0.63	0.81	0.78	0.82
0—60°S A	5	1880—1959	0.81	0.71	0.82	0.76	0.82
40—70°N W	5	1845—1959	0.68	0.56	0.63	0.71	0.60
40—70°N A	5	1845—1959	0.60	0.47	0.51	0.60	0.47
30S—30°N A	5	1880—1959	0.77	0.62	0.75	0.68	0.75
Budyko-Asakura							
NH	1	1881—1968	0.82	0.77	0.81	0.73	0.81
NH	5	1881—1968	0.97	0.90	0.93	0.90	0.94
Groveman and Landsberg							
NH	1	1621—1975	0.41	0.44	0.41	0.41	0.40

The temperature data came from Mitchell (1961), Budyko (1969), Asakura (Natl. Acad. Sci., 1975), and Groveman and Landsberg (1979a). The numbers under Mitchell refer to latitude bands, W to winter average, A to annual average and NH to Northern Hemisphere average. The averaging periods refer to both the temperature data and the simulation results. The sources of volcanic dust forcing for the model simulation runs are M (Lamb, 1970, up to 1850 and Mitchell, 1970, since 1850), L (Lamb, 1970, for the entire time period), O (old dust spread model; data taken from original papers as in Fig.1), N (new dust spread model as described in this paper), NH (NH average, Fig.3 for MN), LAT (latitude-dependent dust, as in Fig.2), and -H (modified by results of Harshvardhan, 1979).

simulations of surface temperature for the past 400 years. It did not. Thus, the limitations of the theory of volcanically caused climatic change, the volcanic eruption chronology and magnitude estimates of Lamb and Mitchell, the model to spread the volcanic dust, the climate model and/or the past temperature compilations are demonstrated. In the following I will speculate on which of the aspects of the problem seem to be the most serious, and discuss studies currently under way to remedy them.

Volcanic dust veils seem well established as a cause of climate change over the past 400 years. The studies in this paper, as well as the theoretical, observational and modeling studies discussed in the introduction, all show this relation. While volcanoes appear to be an important cause of climate change during this period, this does not mean to imply that other forcings were not acting at the same time. In particular, the first part of the 19th century shows the most rapid warming of the entire period, following the largest volcanic eruption of the period. It is easy to speculate on possible causes. Although solar variations as a function of sunspot number do not explain climate variations during this period (Robock, 1978, 1979a), an anomalous increase in the solar constant of a fraction of 1% could have caused the warming. Anthropogenic activities were probably not of sufficient amplitude to have had any effect during this period, since their effects probably have not been observed even today.

Natural internal variations of the climate system, sometimes called autovariation or almost-intransitivity, may have caused the warming in the early 19th century. They may also explain the discrepancies during the rest of the time period between the calculated curves and the observations. In fact, the results of the experiments in this paper may be explained by natural variability. The random forcing introduced by baroclinic instability causes the climate to vary without any external forcing. The naturally variable atmospheric heat transports prevent the system from reaching a steady equilibrium. In fact, such an equilibrium may not exist (Lorenz, 1976). The experiments in Robock (1978, 1979a) show that this may be an important cause of climate change on these time scales. If the changes introduced by the different volcanic forcings in this paper are not larger than the natural changes in the system, they could not produce a better simulation. Thus, if we accept the hypothesis of volcanic dust and natural variability both being important causes of climate change, we may have reached the limit of our ability to simulate the past climate on these time scales.

The proper method for introducing volcanic eruptions into a climate model is currently being studied. The relative time-dependent effects of eruptions at different latitudes and at different times during the seasonal cycle were not included in the present experiment and may be important. In addition, the climate model used in this experiment can simulate the seasonal cycle well, but ignores a part of the climate system that is probably important on these long time scales, namely the deep ocean. Deep ocean circulations could, in the real world, introduce long period forcings which have not been considered above. These may be random or periodic, depending on the ocean model used, or the assumed circulation. Future studies, in order to be complete, will have to include the ocean as an explicit internal portion of the climate system or to explicitly consider it as an external forcing. The natural variability experiments reported in Robock (1978, 1979a) included heat storage in the ocean surface layers, but did not explicitly consider the deep ocean.

The volcanic source function, and the model of the spread and decay of the dust in the atmosphere could be improved, but as mentioned above, this may not improve the simulation results. S. Self (pers. comm., 1979) is attempting to construct a better volcanic dust index using geological evidence which he expects to be more accurate than the qualitative observations used by Lamb. More accurate reconstructions of past temperature will also help to clarify the issue in the future.

All the volcanic simulations agreed well with the observations, but an improved volcanic dust veil index did not improve the simulations. It is suggested that the most likely explanation for this is that the climatic fluctuations are being caused not only by volcanic dust, but by random internal forcing as well. The differences between the different external forcings imposed by the different volcanic indices are not as large as the difference between the actual climate and that part of the actual climate being caused by volcanic dust, and therefore the correlations between the simulation runs with volcanic dust and the observations are not improved. This applies both to the latitudinal variation of climate during the past 100 years and to the Northern Hemisphere average temperature during the past 400 years. It is also possible, however, that results from an improved climate model incorporating deep oceans, an improved volcanic index based on geological evidence or an improved temperature reconstruction could modify the above results.

ACKNOWLEDGEMENTS

I would like to thank Alan Krol and Tom Kucsera for assistance in calculating the latitudinally dependent volcanic dust index. I thank Claire Villanti for drafting the figures and Suzanne McGregor for typing the manuscript. This research was supported by NASA grant NSG-5209 and by NSF grant ATM-7918215.

REFERENCES

Borzenkova, I. I., Vinnikov, K. Ya., Spirina, L. D. and Stekhnovskiy, D. I., 1976. Change in air temperature in the Northern Hemisphere during the period 1881—1975. Meteorol. Hydrol., No. 7: 34—45. (27—35 in Russian)

Budyko, M. I., 1969. The effect of solar radiation variations on the climate of the earth. Tellus, 21: 611—619.

Cadle, R. D., Kiang, C. S. and Louis, J.-F., 1976. The global-scale dispersion of the eruption clouds from major volcanic eruptions. J. Geophys. Res., 81: 3125—3132

Groveman, B. S. and Landsberg, H. E., 1979a. Reconstruction of Northern Hemisphere temperature: 1579—1880. Publication No. 79—181. Meteorology Program, University of Maryland, College Park, Md., 46 pp.

Groveman, B. S. and Landsberg, H. E., 1979b. Simulated Northern Hemisphere temperature departure 1579—1880. Geophys. Res. Lett., 6: 767—769.

Hansen, J. E., Wei-Chyung Wang and Lacis, A. A., 1978. Mount Agung eruption provides a test of a global climatic perturbation. Science, 199: 1065—1068.

Harshvardhan, 1979. Perturbation of the zonal radiation balance by a stratospheric aerosol layer. J. Atmos. Sci., 36: 1274—1285.

Hirschboeck, K. K., 1980. A new worldwide chronology of volcanic eruptions (with a summary of historical ash-producing activity and some implications for climatic trends of the last one hundred years). Palaeogeogr., Palaeoclimatol., Palaeoecol., 29: 223—241.

Hunt, B.G., 1977. A simulation of the possible consequences of a volcanic eruption on the general circulation of the atmosphere. Mon. Weather Rev., 105: 247—260.

Köppen, W., 1873. Über mehrjährige Perioden der Witterung, insbesondere über die 11-jährige Periode der Temperatur. Z. Meteorol., Vienna 8: 241—248; 257—267.

Köppen, W., 1914. Lufttemperaturen, Sonnenflecke und Vulkanausbrüche. Meteorol Z. Braunschweig, 31: 305—328.

Lamb, H. H., 1970. Volcanic dust in the atmosphere: with a chronology and assessment of its meteorological significance. Trans. R. Philos. Soc. Lond., A266: 425—533.

Lorenz, E. N., 1976. Nondeterministic theories of climatic change. Quaternary Res., 6: 495—506.

Mass, C. and Schneider, S. H., 1977. Statistical evidence on the influence of sunspots and volcanic dust on long-term temperature records. J. Atmos. Sci., 34: 1995—2004.

Mitchell, J. M., Jr., 1961. Recent secular changes of global temperature. Ann. N.Y. Acad. Sci., 95: 235—250.

Mitchell, J. M., Jr., 1970. A preliminary evaluation of atmospheric pollution as a cause of the global temperature fluctuation of the past century. In: S. F. Singer (Editor), Global Effects of Environmental Pollution. D. Reidel, Dordrecht, pp. 139—155.

National Academy of Sciences, 1975. Understanding Climatic Change: A Program for Action. Report of the Panel on Climatic Variation to the U.S. Committee for GARP, Natl. Acad. Sci., Washington, 239 pp.

Oliver, R. C., 1976. On the response of hemispheric mean temperature to stratospheric dust: an empirical approach. J. Appl. Meteorol., 15: 933—950.

Pollack, J. B., Toon, O. B., Sagan, C., Summers, A., Baldwin, B. and Van Camp, W., 1976. Volcanic explosions and climatic change: a theoretical assessment. J. Geophys. Res., 81: 1071—1083.

Robock, A., 1977. Climate Predictability and Simulation with a Global Climate Model. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 219 pp.

Robock, A., 1978. Internally and externally caused climate change, J. Atmos. Sci., 35: 1111—1122.

Robock, A., 1979a. The "Little Ice Age": Northern Hemisphere average observations and model calculations. Science, 206: 1402—1404.

Robock, A., 1979b. The performance of a seasonal global climatic model. In: W. L. Gates (Editor), Report of the JOC Study Conference on Climate Models: Performance, Intercomparison and Sensitivity Studies, GARP Publication Series. WMO/ICSU, Geneva, pp. 766—802.

Schneider, S. H. and Mass, C., 1975. Volcanic dust, sunspots and temperature trends. Science, 190: 741—746.

Sellers, W. D., 1973. A new global climatic model. J. Appl. Meteorol., 12: 241—254.

Sellers, W. D., 1974. A reassessment of the effect of CO_2 variations on a simple global climatic model. J. Appl. Meteorol., 13: 831—833.

Taylor, B. L., Tsvi Gal-Chen and Schneider, S. H., 1980. Volcanic eruptions and long-term temperature records: an empirical search for cause and effect. Q. J. R. Meteorol. Soc., 106: 175—199.