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Volcanic Effects on Climate

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ABSTRACT

Volcanic eruptions which inject large amounts of sulfur-rich gas into the stratosphere produce dust veils which last several years and cool the earth's surface. At the same time, these dust veils absorb enough solar radiation to warm the stratosphere. Since these temperature changes at the earth's surface and in the stratosphere are both in the opposite direction of hypothesized effects from greenhouse gases, they act to delay and mask the detection of greenhouse effects on the climate system.

Tantalizing recent research results have suggested regional effects of volcanic eruptions, including effects on ENSO. In addition, a large portion of the global climate change of the past 100 years may be due to the effects of volcanoes, but a definitive answer is not yet clear. While effects of several years have been demonstrated with both data studies and numerical models, long-term effects, while found in climate model calculations, await confirmation with more realistic models. Extremely large explosive prehistoric eruptions may have produced severe weather and climate effects, sometimes called a "volcanic winter."

Complete understanding of the above effects of volcanoes is hampered by inadequacies of data sets on volcanic dust veils and on climate change. Space observations can play an increasingly important role in an observing program in the future. The effects of volcanoes have not adequately been separated from ENSO events, and climate modeling of the effects of volcanoes is in its infancy. Specific suggestions are made for future work to improve our knowledge of this important component of our climate system.

1. Introduction

Since 1784, when Benjamin Franklin suggested that the Hecla eruption in Iceland in 1783 might have been responsible for the abnormally cold winter of 1783-4 (Franklin, 1784), emissions from volcanoes have been implicated as a possible cause of weather and climate variations. Although conventional wisdom (Ramanathan, 1988; Self and Rampino, 1988) holds that the effects of volcanoes on climate have not yet been demonstrated, much work has already shown that volcanoes can be important causes of hemispheric temperature changes for several years following large eruptions and even on a 100-year time scale, when their cumulative effects are taken into account. It has also been suggested that they can influence atmospheric circulation, and interact with the El Niño/Southern Oscillation (ENSO) in complex ways, perhaps even causing ENSOs. Because the climatic signal of volcanic eruptions is of approximately the same amplitude as that of ENSO, and because there have been so few large eruptions in the past century, it has been difficult to separate the volcanic signal from that of other simultaneous climatic variations. Large prehistoric eruptions, such as those of Toba, must have had severe climatic consequences, and such eruptions will occur in the future. In order to improve our understand of the effects of volcanoes on climate, more research is necessary.

2. Data on Volcanic Eruptions

It has become clear in the last decade (*e.g.*, Rampino and Self, 1984) that the effect of a volcano on climate is most directly related to the sulfur content of emissions that reach into the stratosphere, and not to the explosivity of the eruption. These sulfur gases convert to small sulfate particles, which persist for several years in the stratosphere and efficiently scatter the incoming sunlight, reducing the direct and total solar radiation reaching the ground.

In order to investigate the effects of volcanic eruptions on climate, it would be desirable to have a volcanic index that is proportional to the physical effect of the volcanic dust veil on climate, namely the net radiation deficit. If the index is incomplete in its geographical or temporal coverage, if it assumes that surface air temperature drops after an eruption and uses this information to create the index, or if it is a measure of some property of volcanic eruptions other than its long-term stratospheric dust loading, it will be unsuitable for this type of study. All volcanic indices produced so far suffer from one or more of these problems. Yet if the various deficiencies of each index are kept in mind, they can be used cautiously, which has not been the case in many instances, as discussed in the next section.

The first extensive modern compilation of past volcanic eruptions is the classic study of Lamb (1970), updated by Lamb (1977, 1983). Lamb created a volcanic Dust Veil Index (DVI), specifically designed for analyzing the effects of volcanoes on "surface weather, on lower and upper atmospheric temperatures, and on the large-scale wind circulation." (Lamb, 1970, p. 470) The methods used to create the DVI are described by Lamb (1970), and in more detail by Kelly and Sear (1982), and include historical reports of eruptions, optical phenomena, radiation measurements (for the period 1883 onward), temperature information, and estimates of the volume of ejecta.

The formula for the DVI includes a term Emax, which gives an estimate of the fraction of the globe covered by the dust veil. In order to compare the amount of material emitted from volcanoes, it is convenient to present DVI = d.v.i./Emax, as was done in Table 1. Although the DVI for the Mt. St. Helens eruption of 1980 was 500, and DVI for El Chichón of 1982 was 800, Emax for Mt. St. Helens was 0.3, while Emax for El Chichón was 1. Therefore, Lamb's (1983) estimate of the relative climatic effect of the two volcanoes was different by a factor of more than 5.

Lamb's DVI has been often criticized (*e.g.*, Bradley, 1988) as having used climatic information in its derivation, thereby resulting in circular reasoning if the DVI is used as an index to compare to temperature changes. In fact, for only a few eruptions between 1763 and 1882 was the Northern Hemisphere (NH) averaged DVI calculated based solely on temperature information. Robock (1981a) created a modified version of Lamb's DVI which excluded temperature information. When used to force a climate model, the results did not differ significantly from those using Lamb's original DVI, demonstrating that this is not a serious problem.

Mitchell (1970) also produced a time series of volcanic eruptions for the period 1850-1968 using data from Lamb. As discussed by Robock (1978, 1981a), the Mitchell volcanic compilation for the NH is more detailed than Lamb's, because Lamb excluded all volcanoes with DVI < 100 in producing his NH annual average DVI (Table 7(a), p. 526). Thus Mitchell's volcanic series has proven to be very useful as a climatic volcanic index.

More recently, a comprehensive survey of past volcanic eruptions (Simkin *et al.*, 1981) produced the Volcanic Explosivity Index (VEI) (Newhall and Self, 1982) which gives a geologically-based measure of the power of the volcanic explosion. Unfortunately, this index has been used in many studies (see next section) as an index of the climatological impact of volcanoes without any modification. A careful reading of Newhall and Self (1982), however, will find the following quotes: "We have restricted ourselves to consideration of volcanological data (no atmospheric data). . ." and "Since the abundance of sulfate aerosol is important in climate problems, VEI's must be combined with a compositional factor before use in such studies." In their table 1 they list criteria for estimating the VEI in "decreasing order of reliability," and the very last criterion out of 11 is "stratospheric injection." For VEI of 3, this is listed as "possible," for 4 "definite," and for 5 and larger "significant." If one attempts to work backwards, and use a geologically determined VEI to give a measure of stratospheric injection, serious errors can result. Not only is this the least reliable criterion for assigning a VEI, but it was never intended as a description of the eruption which had a VEI assigned from more reliable evidence.

Eruptions with a high VEI may also have a large stratospheric impact, such as Tambora (1815, VEI = 7) or Krakatau (1883, VEI = 6), but 3 recent examples demonstrate the danger in using the VEI for climate studies. Mt. St. Helens in 1980 had a high VEI of 5, and while it had a large local temperature impact (Robock and Mass, 1982; Mass and Robock, 1982), it had a negligible stratospheric impact (Robock, 1981b). Agung in 1963 and El Chichón in 1982, on the other hand, had a very large stratospheric impact (Robock, 1983a) but a smaller VEI of 4. Several studies (discussed below) have been done using the VEI as an index for the climatic effect of volcanoes, and then excluded Mt. St. Helens as a special case. This example raises the question of the possibility of other special cases in the past for which we do not have the additional information as in this case.

Schönwiese (1988) has even created a Smithsonian Volcanic Index (SVI) which takes 10 to the VEI power, and includes volcanoes with VEI of 3 and greater. This is clearly not justified.

As mentioned by Newhall and Self (1982), by combining information about the typical type of eruption that each volcano produces with the VEI, it may be possible to produce a "climatic VEI," but it will probably be necessary to include additional information to produce a good index of the climatic impact of past eruptions.

Ice core analysis (*e.g.*, Lyons *et al.*, 1988) can give the chemistry and particle content of well-dated layers, which can give a measure of the important volcanic parameters. Xu (1988) has actually used the Acidity Index of Hammer *et al.* (1980) as a volcanic index for comparison to climatic data. Unfortunately, small local eruptions can give as large a signal as distant large eruptions. By comparing the acidity and particle records from Greenland, Antarctic, and tropical ice cores, it may be possible to produce a global or hemispheric record from signals that appear simultaneously in all 3 regions or in the tropics and one of the high latitude cores.

Radiation measurements of the transmission of the direct solar beam give indications of the atmospheric turbidity. By combining measurements from many locations to eliminate local influences, Pollack *et al.* (1976), Pivovarova (1977), and Bryson and Goodman (1980) presented time series of radiation, interpreted as the volcanic loading of the atmosphere. Xu (1985) created a volcanic index based on radiation data. and Mass and Portman (1988) also give other sources of actinometric data. Because each of these data sets is incomplete spatially and temporally, and because local influences may not have been completely eliminated, by themselves they are not sufficient as a measure of volcanic influence on the atmosphere. By combining all the available radiation information, however, they would be a valuable input to a volcanic index.

Another source of information comes from lunar brightness during eclipses (Keen, 1983). In addition, lidar measurements (*e.g.*, McCormick and Osborn, 1986), balloon sampling (*e.g.*, Hoffmann and Rosen, 1984a,b), and aircraft sampling (*e.g.*, Sedlacek *et al.*, 1983) can all now give detailed measurements of the stratospheric aerosol concentration. Satellite data from the SAM II (*e.g.*, McCormick and Brandl, 1986) and SAGE measurements (*e.g.*, McCormick, 1987) also give measures of stratospheric aerosols. An instrument designed for measuring ozone, TOMS on Nimbus 7, can also pick up the signal of sulfur dioxide from volcanic eruptions, and in fact has been used by Krueger (personal communication) to identify the source of the "mystery cloud" of early 1982 as the Nyamuragira eruption of 26 December 1981 in eastern Zaire.

Until a good climatic-volcanic index is developed, all previous studies using inadequate indices must be evaluated cautiously. Since DVI, VEI and acidity index are correlated (Schönwiese, 1988), the results presented below are in partial agreement even if based on different indices. An objective, quantitative measure of the effects of volcanoes on climate, however, will require a better volcanic index.

3. Volcanic Effects on Temperature

There have been many studies in the past attempting to link climatic changes with large volcanic eruptions. (Lamb (1970) even took temperature drops as indications of the size of volcanic eruptions, in a few cases without any other evidence, when creating his volcanic index.) These studies range from case studies of a single large eruption or a few eruptions, to comparisons of time series of temperature to the timing of eruptions, to superposed epoch analyses combining the signals of many eruptions. The different studies distinguish themselves from each other by their choices of volcanoes (or volcanic indices), temperature data sets (usually air at the surface, but also upper air and sea surface), time resolution, analysis technique (especially whether climatic data are normalized by their standard deviation for monthly data), and treatment of ENSO signal. In this section the effects of the 1815 eruption of Tambora are discussed, and then analyses of more recent eruptions are compared.

A. Tambora – Cause of the "Year Without a Summer?"

The book by Stommel and Stommel (1983), which is subtitled, "The Story of 1816, The Year Without a Summer," presents the fascinating story of the severe weather disruptions in New England and Western Europe, which also resulted in 1816 being called, "Eighteen Hundred and Froze-to-Death" and "Poverty Year" (Humphreys, 1940). Stommel and Stommel's book includes the stories of the record price of grain in London, Mary Shelley writing Frankenstein influenced by the terrible summer weather on the shores of Lake Geneva, and the killing summer frosts in the United States and Canada (Robock, 1984c). They conclude that the case cannot be proven that the great eruption of Tambora in 1815 was responsible for the extreme weather of the next year because evidence was only available from a small region of the globe (eastern North America and Western Europe).

Recent studies, however, present new evidence of climate effects both in China and India in 1816, although Kondo (1988) found no evidence of effects in Japan. Hameed *et al.* (1989) found evidence in Chinese documents of abnormally cold weather from the winter of 1815-16 through the summer of 1817, manifesting itself in crop failures and snow in June, 1816. Sigurdsson and Carey (1988) point out the bad harvests in India in 1816 that led to a famine which was followed by a serious cholera outbreak. In the next 2 decades the cholera spread as the greatest pandemic of the century to Europe and Asia.

One aspect of the 1816 events that is not widely recognized is that their were significant volcanic eruptions in each of the 4 years preceding Tambora (Sabrina in 1811, Soufriere and Awu in 1812, Vesuvius in 1813, and Mayon in 1814), so that any effects felt in 1816 were the cumulative effect of 5 years of enhanced stratospheric aerosol loading. Stothers (1984) and Rampino and Self (1982), who presented a detailed geological description of the Tambora eruption, found a NH temperature depression of approximately 0.7°C in 1816 from a limited network of stations. Humphreys (1940) similarly found a depression of about 1.0°C in 1816. Both studies and Groveman and Landsberg (1979) all found that the NH temperature was cool for several years before 1816, and then rose rapidly, by more than 1°C, during the next 10 years. The antecedent cooling can be easily explained by the effects of the preceding volcanoes, but the subsequent strong warming is more difficult to understand. How good were the temperature records? Was this a response to a dust-free atmosphere? Were internal oscillations becoming dominant? Was there strong tropical ocean forcing of the climate system during this period? If so, was it made stronger by the volcanoes? Quinn *et al.* (1987) report no ENSO events from 1814 to 1828, but their record may be incomplete.

Thus, the case of the volcanic eruptions of 1811-1815 and the severe weather of 1816 is strongly suggestive of the large potential short-term effect of volcanoes on climate. One individual case cannot prove the relationship, however, since other causes of interannual variability were undoubtedly playing a part simultaneously, but with unknown amplitude. Next, studies which combine the effects of several eruptions (although none with as large a stratospheric impact as Tambora) and study the effects on temperature with the improved data network of the past 100 years are presented.

B. Comparative Studies

Humphreys (1940), Yamamoto *et al.* (1975), Angell and Korshover (1985), Kondo (1988), Angell (1988), and Xu (1988) all present time series of volcanic eruptions and climate change and comment on the correspondence. Robock (1990) contains a table comparing all these studies and the volcanoes used in each one. In each case the evidence is suggestive of a cause and effect, with varying degrees of agreement. All use surface air temperatures, except Kondo also used reports of crop failures and famines in Japan, Xu used reports of cold summers in China, and Angell also used sea surface and upper air temperatures.

Although visually comparing time series can suggest agreements, the superposed epoch technique, discussed next, can objectively filter out other effects and give a quantitative measure of the volcanic effect. Of course, if some other cause of climate variation is correlated with volcanic eruptions, the superposed epoch technique will not remove it. This seems to be the case with ENSOs, and Angell (1988) showed that, by removing a signal correlated with SSTs in the tropical Pacific with a 6-month lag, the volcanic signal is made clearer. This argument still may suffer from circular reasoning, since the SST is also part of the signal being measured.

C. Superposed Epoch Analyses

In superposed epoch analysis, a key date is identified for each volcanic eruption, the resulting temperature data are superposed on each other, and then the average is used to measure the signal of volcanic eruptions. This has been done for data-averaging periods on time scales ranging from 5 years (Mitchell, 1961) to 1 year (Mass and Schneider, 1977; Schönwiese, 1988) to 1 season (Taylor *et al.*, 1980; Angell and Korshover, 1985; Lough and Fritts, 1987) to 1 month (Self *et al.*, 1981; Kelly and Sear, 1984; Sear *et al.*, 1987; Bradley, 1988; Mass and Portman, 1989).

When a 1 month averaging period is used, the months are counted starting with the month of the eruption, so that if two volcanoes occurred in different years, say one in April and one in August, then the effects after three months would be an average of July and November data. Thus, if there is a seasonal component to the response of the climate system, it cannot be identified with this technique. Recognizing that climate variability is larger in the winter, in order to avoid averaging large and small variations together, Kelly and Sear (1984), Sear *et al.* (1987), and Bradley (1988) have all looked at normalized monthly surface air temperatures, with the temperature anomalies divided by the standard deviation of temperature for that month. However, this analysis technique gives less weight to winter temperature fluctuations and also works to obscure the seasonal cycle of temperature response.

Mass and Portmann (1989) have removed an ENSO signal, in a manner similar to Angell (1988), and find a definite volcanic signal.

D. Seasonal Cycle Analysis

It has been shown by Robock (1983b) that the sea ice/thermal inertia feedback is responsible for the amplification of climate response in high latitudes and in winter for equilibrium climate simulations with an energy-balance climate model. This also explains the results Manabe and Stouffer (1980) obtained with a GCM. For transient experiments with volcanic eruptions (Robock, 1981b, 1984a; discussed below) and for nuclear winter forcing (Robock, 1984b; Vogelmann *et al.*, 1988) it has also been shown with an energy-balance model that the sea ice/thermal inertia feedback causes an amplification of the seasonal cycle when the climate system cools, resulting in more cooling in the polar regions in the winter. Yamamoto *et al.* (1975) also found winter polar enhancement of the volcanic cooling for several eruptions.

Since volcanic eruptions are thought to result in cooling of the climate system for a few years, Robock (1985) has presented a preliminary analysis in which the amplitude of the seasonal cycle in high latitudes is examined by doing an analysis of surface temperature that compares all months from different years. This analysis also solves another problem of previous studies, namely that large volcanic eruptions can sometimes occur close to each other in time, and a superposed epoch analysis must make the assumption that the year or years before the key date (date of the eruption) represent a normal climate. Since the climate system is constantly fluctuating, this analysis examines the overall level of volcanic forcing and compares it to the corresponding response of the climate system.

Robock (1985) presented a volcanically-weighted temperature variation, but it seems more straight-forward to simply present the correlation coefficient between temperature variations and a volcanic index. It is expected that if such an analysis were done with the ENSO signal removed from an improved temperature data set, such as the global set from the University of East Anglia, (Jones *et al.*, 1988), with an improved volcanic index, that it will be possible to establish a typical volcanic signal in a more definitive manner than before.

E. Stratospheric Effects

Even though the data record is shorter, large warming beyond the level of the quasi-biennial oscillation has been measured in the stratosphere following the Agung and El Chichón eruptions (*e.g.*, Labitzke *et al.*, 1983, Parker and Brownscombe, 1983; Angell and Korshover, 1983; Quiroz, 1983, 1984; Fujita, 1985; Wendler and Kodama, 1986). This is in the opposite direction of anticipated effects from greenhouse cases which will be "virtually certain" to cause large stratospheric cooling (National Research Council, 1987). Thus these large stratospheric effects of volcanoes, while only lasting a few years, will have to be dealt with when modeling or interpreting climatic data in attempts to identify a greenhouse signal.

5. Climate Model Calculations

A. Energy-Balance Models

Energy-balance climate model calculations by Schneider and Mass (1975); Oliver (1976); Robock (1978, 1979, 1981b, 1984a); Gilliland (1982); and Gilliland and Schneider (1984) have all shown cooling effects due to volcanic eruptions for several years. As mentioned above, Robock (1984a) demonstrated the winter polar enhancement of cooling due to the sea ice/thermal inertia feedback, the same pattern seen in the observations (Fig. 1).

Robock (1978, 1979, 1981b) demonstrated a long-term effect of volcanic eruptions with the warming of the 1920s and 1930s resulting from the lack of significant eruptions. Oerlemans (1988) coupled an energy-balance climate model with a glacier model and found that about half of the observed long-term behavior of glaciers for the past 100 years can be explained by volcanoes and half by greenhouse gases. (Porter (1981) had previously found a relationship between glacier advances and volcanoes for the past 100 years.) The models used for these calculations had only a 75-m mixed layer ocean, and these longer time scales of the climate system may depend on deep ocean circulation (Hansen *et al.*, 1985). Experiments with coupled atmospheric and oceanic GCMs will be necessary to confirm this result.

B. Radiative-Convective Models

Hansen *et al.* (1978) and Vupputuri and Blanchet (1984) have used radiative-convective models to calculate the vertical distribution of the climatic effect of the Agung and El Chichón eruptions, respectively. They both found cooling at the surface and warming in the stratosphere, which corresponds to the observations mentioned above.

C. Zonally-Averaged Model

MacCracken and Luther (1984) used a zonally-averaged dynamic climate model to calculate the vertical and latitudinal response to the El Chichón eruption. They found cooling at the surface in agreement with the energy-balance calculations of Robock (1984a), but in addition found intriguing precipitation and circulation anomalies caused by a shift in the ITCZ, which they suggested may be related to El Nino generation.

D. General Circulation Model (GCM) Simulations

Hunt (1977) presented the first GCM calculation of the effects of a volcano on climate, but it was done with a crude model and did not examine seasonal effects. Hansen *et al.* (1988) recently performed time-dependent simulations of climate from 1960 through 2050 with a GCM at the NASA Goddard Institute for Space Sciences (GISS). In three different simulations with different amounts of greenhouse gases, the effects of a total of 12 large and 9 small volcanoes were shown to cause cooling for several years. Although Hansen *et al.* present hemispheric, annual average results of these simulations, showing cooling from the volcanoes, the seasonal and latitudinal signal of the volcanoes has not been analyzed in their output. In addition, the simple ocean model used precluded the precise determination of long-time scale effects.

It is obvious that only with GCM studies of the effects of volcanic eruptions will the subtle interactions of the climate system, including possible ENSO or monsoon relationships, and the geographical distribution of effects be determined. Currently ongoing experiments include those of Graf (1989) at the Max Planck Institute in Hamburg and of Hansen, McCormick and Pollack (Hansen *et al.*, 1988) at GISS in New York.

5. Relationship to ENSO

On 4 April 1982, the El Chichón volcano in Mexico erupted, putting more aerosols into the stratosphere than any other volcano in this century, with the possible exception of Agung in 1963 (Robock, 1983). Although climate model calculations (Robock, 1984a; Hansen *et al.*, 1988) suggested a large drop in hemispheric average surface air temperatures for several years following the eruption, 1983 was in fact one of the warmest years on record (Hansen and Lebedeff, 1988). It is believed that this was due to the unprecedented ENSO of 1982.

This is only the most dramatic example of the combination of ENSO and volcanic signals in the climate system. Even if the effects are completely independent physically, they complicate the interpretation of either. Therefore, both modeling and data analysis studies (such as Angell, 1988) are necessary to separate and understand the climate responses to this combination of externally and internally-caused variations.

It has even been suggested that the El Chichón eruption produced the 1982-83 ENSO (*e.g.*, Hirono, 1988). This idea merits further investigation.

6. Recommendations: Volcanoes and Climate

The following projects should receive high priority in future research:

1. **An index of volcanic aerosols should be produced that is related to the climatic effect of volcanoes, not their explosivity.** It would start with the Dust Veil Index and Volcanic Explosivity Index, and then modify them with information obtained from ice cores, radiation measurements, surveys of the sulfur content of volcanic emissions, descriptive reports of eruptions and of optical effects, and modern information from lidars and satellite measurements.

2. **Comprehensive analysis of past temperature, pressure and precipitation data should be performed, searching for the volcanic signal while accounting for the internal climate variations related to ENSO.**

3. **General circulation model simulations of volcanic eruptions should be carried out.** These would produce the signal of a volcanic eruption that

would be compared to that found in the analysis above. Simultaneous forcings by tropical sea surface temperature anomalies and volcanoes should also be used to attempt to understand whether the climatic response is related or independent. The 1982-83 El Chichón-ENSO would be a good case to study. The case of an extremely large eruption should also be studied.

4. **The global aerosol monitoring effort should be continued, with special consideration to allow comprehensive observations of future volcanic eruptions.** A combination of spacecraft, airplanes, balloons and ground-based observations will allow complete coverage of the background aerosol distribution and perturbations due to volcanoes and other causes, such as dust storms and smoke.

REFERENCES

Angell, J. K., 1988: Impact of El Niño on the delineation of tropospheric cooling due to volcanic eruptions. *J. Geophys. Res.*, **93**, 3697-3704.

Angell, J. K., and J. Korshover, 1983: Comparison of stratospheric warmings following Agung and El Chichón, *Mon. Wea. Rev.*, **111**, 2129-2135.

Angell, J. K., and J. Korshover, 1985: Surface temperature changes following the six major volcanic episodes between 1780 and 1980. *J. Clim. Appl. Meteor.*, **24**, 937-951.

Angione, Ronald J. and G. de Vaucouleurs, 1986: Twenty years of atmospheric extinction at McDonald Observatory. *Pub. Astron. Soc. Pac.*, **98**, 1201-1207.

Asaturov, M. L., M. I. Budyko, K. Ya. Vinnikov, P. Ya. Groisman, A. S. Kabanov, I. L. Karol, M. P. Kolomeev, Z. I. Pivovarova, E. V. Rozanov, and S. S. Khmelevtsov, 1986: *Volcanics, Stratospheric Aerosol and Earth's Climate.* (Gidrometeoizdat, Leningrad), 256 pp. (in Russian)

Bradley, Raymond S., 1988: The explosive volcanic eruption signal in Northern Hemisphere continental temperature records. *Climatic Change*, **12**, 221-243.

Bryson, R. A. and B. M. Goodman, 1980: Volcanic activity and climatic changes. *Science*, **207**, 1041-1044.

Ellsaesser, Hugh W., 1983: Isolating the climatogenic effects of volcanoes. UCRL-89161, (Lawrence Livermore National Laboratory, Livermore, CA), 29 pp.

Franklin, B., 1784: Meteorological imaginations and conjectures. *Manchester Literary and Philosophical Society Memoirs and Proceedings*, **2**, 122 or 375.

Fujita, Toshio, 1985: The abnormal temperature rises in the lower stratosphere after the 1982 eruptions of the volcano El Chichón, Mexico. *Papers in Meteor. and Geophys.*, **36**, No. 2, 47-60.

Gilliland, R. L., 1982: Solar, volcanic and CO_2 forcing of recent climatic changes. *Clim. Change*, **4**, 111-131.

Gilliland, R. L. and S. H. Schneider, 1984: Volcanic, CO_2 and solar forcing of Northern and Southern Hemisphere surface temperatures. *Nature*, **310**, 38-41.

Graf, Hans-F., 1989: Forced cooling of the polar T21 atmosphere and tropical climate variability. Report No. 45, Max-Planck-Institut für Meteorologie, 25 pp.

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

Hameed, Sultan, P.-Y. Zhang, and W.-C. Wang, 1989: Climate in China after the Tambora Eruption of 1815. *CDIAC Communications*, Winter 1989, 6-8.

Hammer, C. U., H. B. Clausen, and W. Dansgaard, 1980: Greenland Ice Sheet evidence of post-glacial volcanism and its climatic impact. *Nature*, **288**, 230-235.

Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, and G. Russell. 1988: Global climate changes as forecast by the GISS 3-D model. *J. Geophys. Res.*, **93**, 9341-9364.

Hansen, James and Sergej Lebedeff, 1988: Global surface air temperatures: update through 1987. *Geophys. Res. Let.*, **15**, 323-326.

Hansen, J., G. Russell, A. Lacis, I. Fung and D. Rind, 1985: Climate response times: dependence on climate sensitivity and ocean mixing. *Science*, **229**, 857-859.

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

Hirono, M., 1988: On the trigger of El Niño Southern Oscillation by the forcing of early El Chichón volcanic aerosols. *J. Geophys. Res.*, **93**, in press.

Hofmann, D. J., and J. M. Rosen, 1984a: Balloonborne particle counter observations of the El Chichón aerosol layers in the 0.01 - 1.8 um radius range. *Geofísica Internacional*, **23**, 143-153.

Hofmann, D. J., and J. M. Rosen, 1984b: Measurement of the sulfuric acid weight percent in the stratospheric aerosol from the El Chichón eruption. *Geofísica Internacional*, **23**, 309-310.

Humphreys, W. J., 1940: *Physics of the Air.* (Dover, New York), 676 pp.

Hunt, B. G., 1977: A simulation of the possible consequences of a volcanic eruption on the general circulation of the atmosphere. *Monthly Weather Review*, **105**, 247-260.

Jones, P. D., 1988: Hemispheric surface air temperature variations: recent trends and an update to 1987. *J. Climate*, **1**, 654-660.

Keen, R. A., 1983: Volcanic aerosols and lunar eclipses. *Science*, **222**, 1011-1013.

Kelly, P. M. and C. B. Sear, 1982: The formulation of Lamb's dust veil index. In *Atmospheric Effects and Potential Climatic Impact of the 1980 Eruptions of Mount St. Helens*, Adarsh Deepak, Ed., NASA Conference Publication 2240, (NASA, Washington, DC), pp. 293-298.

Kelly, P. M. and C. B. Sear, 1984: Climatic impact of explosive volcanic eruptions. *Nature*, **311**, 740-743.

Kondo, Junsei, 1988: Volcanic eruptions, cool summers, and famines in the Northeastern part of Japan. *J. Climate*, **1**, 775-788.

Kontratyev, K. Ya., 1988: Volcanoes and Climate, WCP-54, WMO/TD - No. 166, (World Meteorological Organization, Geneva), 103 pp.

Labitzke, K., B. Naujokat, and M. P. McCormick, 1983: Temperature effects on the stratosphere of the April 4, 1982 eruption of El Chichón, Mexico.

Geophys. Res. Lett., **10**, 24-26.

Lamb, H. H., 1970: Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Phil. Trans. Roy. Soc. London*, **A266**, 424-533.

Lamb, H. H., 1977: Supplementary volcanic dust veil index assessments. *Climate Monitor*, **6**, 57-67.

Lamb, H. H., 1983: Update of the chronology of assessments of the volcanic dust veil index. *Climate Monitor*, **12**, 79-90.

Lough, J. M. and H. C. Fritts, 1987: An assessment of the possible effects of volcanic eruptions on North American climate using tree-ring data, 1602 to 1900 A.D. *Climatic Change*, **10**, 219-239.

Lyons, W. B., P. A. Mayewski, M. J. Spencer and M. S. Twickler, 1988: A Northern Hemisphere volcanic chemistry (1869-1984) and climatic implications using a South Greenland ice core. Submitted to *J. Geophys. Res.*

MacCracken, M. C. and F. M. Luther, 1984: Preliminary estimate of the radiative and climatic effects of the El Chichón eruption. *Geofísica Internacional*, **23**, 385-401.

Manabe, S., and R. J. Stouffer, 1980: Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *J. Geophys. Res.*, **85**, 5529-5554.

Mass, Clifford F., and David A. Portman, 1989: Major volcanic eruptions and climate: a critical evaluation. *J. Climate*, **2**, 566-593.

Mass, Clifford and Alan Robock, 1982: The short-term influence of the Mount St. Helens volcanic eruption on surface temperature in the Northwest United States. *Mon. Wea. Rev.*, **110**, 614-622.

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

McCormick, M. Patrick, 1987: SAGE Aerosol Measurements, Volume III-January 1, 1981, to November 18, 1981. NASA Reference Publication 1173. 269 pp.

McCormick, M. Patrick, and M. T. Osborn, 1986: Airborne Lidar Measurements of the El Chichón Stratospheric Aerosols, May 1983. NASA Reference Publication 1172. 87 pp.

McCormick, M. Patrick, and David Brandl, 1986: SAM II Measurements of the Polar Stratospheric Aerosol, Volume VIII-April 1982 to October 1982. NASA Reference Publication 1165. 74 pp.

Mitchell, J. M., Jr., 1961: Recent secular changes of the 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 *Global*

Effects of Environmental Pollution, S. F. Singer (ed.), (Reidel, Dordrecht), 139-155.

National Research Council. 1987: *Current Issues in Atmospheric Change.* National Academy Press, Washington, D.C. 39 pp.

Newhall, C. G. and S. Self, 1982: The volcanic explosivity index (VEI) – an estimate of explosive magnitude for historical volcanism. *J. Geophys. Res.*, **87**, 1231-1238.

Oerlemans, Johannes, 1988: Simulation of historic glacier variations with a simple climate-glacier model. *J. Glaciology*, **34**, 333-341.

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

Parker, D. E., and J. K. L. Brownscombe, 1983: Stratospheric warming following the El Chichón volcanic eruption, *Nature*, **301**, 406-408.

Pivovarova, Z. I., 1977: Utilization of surface radiation data for studying atmospheric transparency. *Meteorology and Hydrology*, No. 9, 24-31. [in Russian]

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

Porter, Stephen C., 1981: Recent glacier variations and volcanic eruptions. *Nature*, **291**, 139-142.

Quinn, William H., Victor T. Neal, and Santiago E. Antunez de Mayolo, 1987: El Niño occurrences over the past four and a half centuries. *J. Geophys. Res.*, **92**, 14449-14461.

Quiroz, R. S., 1983: The isolation of stratospheric temperature change due to the El Chichón volcanic eruption from nonvolcanic signals. *J. Geophys. Res.*, **88**, 6773-6780.

Quiroz, R. S., 1984: Influence of the El Chichón eruption on the stratosphere after summer 1982. *Geofísica Internacional*, **23**, 363-372.

Ramanathan, V., 1988: The greenhouse theory of climate change: a test by an inadvertant global experiment. *Science*, **240**, 293-299.

Rampino, M. R. and S. Self, 1982: Historic eruptions of Tambora (1815), Krakatoa (1883) and Agung (1963), their stratospheric aerosols and climatic impact. *Quat. Res.*, 18, 127-163.

Rampino, M. R. and S. Self, 1984: Sulphur-rich volcanic eruptions and stratospheric aerosols. *Nature*, **310**, 677-679.

Robock, Alan, 1978: Internally and externally caused climate change. *J. Atmos. Sci.*, **35**, 1111-1122.

Robock, Alan, 1979: The "Little Ice Age": Northern Hemisphere average observations and model calculations. *Science*, **206**, 1402-1404.

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

Robock, Alan, 1981b: The Mount St. Helens volcanic eruption of 18 May 1980: minimal climatic effect. *Science*, **212**, 1383-1384.

Robock, Alan, 1983a: The dust cloud of the century. *Nature*, **301**, 373-374.

Robock, Alan, 1983b: Ice and snow feedbacks and the latitudinal and seasonal distribution of climate sensitivity. *J. Atmos. Sci.*, **40**, 986-997.

Robock, Alan, 1984a: Climate model simulations of the effects of the El Chichón eruption. *Geofísica Internacional*, **23**, 403-414.

Robock, Alan, 1984b: Snow and ice feedbacks prolong effects of nuclear winter. *Nature*, **310**, 667-670.

Robock, Alan, 1984c: Review of *Volcano Weather. Nat. Wea. Dig.*, **9**, 5-6.

Robock, Alan, 1985: Detection of volcanic, CO_2 and ENSO signals in surface air temperature. *Adv. Space Res.*, **5**, No. 6, 53-56.

Robock, Alan, 1990: The volcanic contribution to climate change of the past 100 years. in *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations*, Michael E. Schlesinger, Ed., (Elsevier), in press.

Robock, Alan and Clifford Mass, 1982: The Mount St. Helens volcanic eruption of 18 May 1980: large short-term surface temperature effects. *Science*, **216**, 628-630.

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

Schönwiese, Christian-D., 1988: Volcanic activity parameters and volcanism-climate relationships within recent centuries. *Atmósfera*, **1**, 141-156.

Sear, C. B., P. M. Kelly, P. D. Jones and C. M. Goodess, 1987: Global surface-temperature responses to major volcanic eruptions. *Nature*, **330**, 365-367.

Sedlacek, W. A., E. J. Mroz, A. L. Lazrus, and B. W. Gandrud, 1983: A decade of stratospheric sulfate measurements compared with observations of volcanic eruptions. *J. Geophys. Res.*, **88**, 3741-3776.

Self, Stephen and Michael R. Rampino, 1988: The relationship between volcanic eruptions and climate change: still a conundrum? *Eos*, **69**, 74-75, 85-86.

Self, S., M. R. Rampino and J. J. Barbera, 1981: The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures. *J. Volcanol. Geotherm. Res.*, **11**, 41-60.

Sigurdsson, Haraldur and Steven Carey, 1988: The far reach of Tambora. *Natural History*, No. 6, 66-73.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall and J. H. Latter, 1981: *Volcanoes of the World.* (Hutchinson Ross, Stroudsburg, PA), 240 pp.

Stommel, Henry, and Elizabeth Stommel, 1983: *Volcano Weather.* (Seven Seas Press, Newport, RI), 177 pp.

Stothers, Richard B., 1984: The great Tambora eruption in 1815 and its aftermath. *Science*, **224**, 1191-1198.

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

Toon, Owen B., 1982: Volcanoes and climate. In *Atmospheric Effects and Potential Climatic Impact of the 1980 Eruptions of Mount St. Helens*, Adarsh Deepak, Ed., NASA Conference Publication 2240, (NASA, Washington, DC), pp. 15-36.

Toon, Owen B. and James B. Pollack, 1980: Atmospheric aerosols and climate. *American Scientist*, **68**, 268-278.

Vogelmann, A. M., A. Robock and R. G. Ellingson, 1988: Effects of dirty snow in nuclear winter simulations. *J. Geophys. Res.*, **93**, 5319-5332.

Vupputuri, R. K. R. and J. P. Blanchet, 1984: The possible effects of El Chichón eruption on atmospheric thermal and chemical structure and surface climate. *Geofísica Internacional*, 23, 433-447.

Wendler, G. and Y. Kodama, 1986: Some remarks on the stratospheric temperature for Fairbanks, Alaska, after the El Chichón eruption. *Atmosphere-Ocean*, **24**, 346-352.

Xu, Qun, 1985: The assessment of volcanic dust veil index of Northern temperate zone in the recent 100 years. *Acta Geophysica Sinica*, 28, 558-568.

Xu, Qun, 1988: The abnormally cold summers of central China and their relation to volcanic eruptions. in *Aerosols and Climate*, Peter Hobbs and M. Patrick McCormick, Eds., (Deepak, Hampton, VA), 223-232.

Yamamoto, Ryozaburo, Tatsuya Iwashima, and Makoto Hoshiai, 1975: Change of the surface air temperature averaged over the Northern Hemisphere and large volcanic eruptions during the year 1951-1972. *J. Meteor. Soc. Japan*, **53**, 482-486.

THE STUDY OF ATMOSPHERIC VOLCANIC EMISSIONS

by

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It is an oddity that in examination of climate records the two most readily identifiable causes of 1 - 2 year fluctuations in global surface temperatures are volcanic eruptions and El Nino Southern Oscillations. Yet there has been little regard paid to volcanoes in the face of impending climate change due to increases in the atmospheric abundances of greenhouse gases. Another oddity connected with volcanoes is that society's interest in them waxes with the occurrence of a large explosive eruption in which hundreds or thousands of lives are lost and rapidly wanes afterwards. This behavior, perhaps all too human, leaves peoples and their governments in a state of perpetual unpreparedness to deal with the cataclysms which sooner or later occur. It is understandable that society will not support costs to remain prepared for years at a time while other problems and programs clamor for financial resources. Understanding of volcanic phenomena and the associated emissions of chemical substances that effect the environment and climate will permit rational planning with regard to societal concerns and will likely provide scientists with important clues about the nature of climate changes.

Science has long recognized that volcanic emissions of volatile substances have played a vital role in determining the composition of the earth's crust, the oceans and the atmosphere. Furthermore, their role continues to have such influence. Much of the influence is being exerted in extensive submarine releases of magma which occur out of sight and in regions not readily accessible for scientific study. Consequently, atmospheric emissions represent the best subjects for scientific scrutiny of volatile volcanic materials, the processes that affect them and their effect on the surface environment.

The key quantities of interest in the studies of volcanic emissions are the fluxes of individual components. Sulfur compounds are most important because they are the most abundant of the reactive substances in volcanic plumes and it is through their oxidation to sulfate particulate material that it may influence climate by changing the global albedo directly or through the formation of clouds. Berresheim and Jaeschke,1983 estimated the volcanic flux of sulfur compounds to have a lower limit of 12 Tg/yr. The NATO Workshop (Galloway et al, 1985) assessment estimated a factor of 2 uncertainty in the total global natural S-emissions of 80 Tg/yr. Thus it can be appreciated that in years with large explosive eruptions, the volcanic contribution to the total can be a substantial fraction of the total.

Friend, 1989 reviewed the global fluxes of chlorine and fluorine and suggests that emission from volcanoes could comprise the major part of atmospheric F flux. Symonds et al, 1985 estimated 0.06 - 6.0 Tg/yr. If the true flux is greater than about 1 Tg/yr, volcanic sources would dominate over sea salt aerosols, blowing soil dust and anthropogenic sources. By contrast, volcanoes contribute relatively little to the global fluxes of chlorine; sea salt aerosols being the dominant source. Nonetheless, Cl emissions from large explosive volcanoes may be of significance in perturbing stratospheric ozone chemistry.

The studies performed in the early 1980's by the group of scientists assembled in Project RAVE (Research on Atmospheric Volcanic Emissions) in combining airborne sampling of volcanic plumes with ground-based studies of the same materials provided insights concerning the gaseous and trace element compositions of volcanic plumes and their emission rates. Since only a few plumes (5) could be studied, the combined results of RAVE and all other volcanic flux studies do not provide the basis for making accurate estimates of the global fluxes of volcanic materials through the atmosphere. (See Galloway et al, 1985.) The experience gained by the RAVE investigators makes it possible to consider undertaking a new study of volcanic emissions aimed toward the ends outlined above. It is suggested to assemble a group of potential principle investigators to consider writing a proposal for a such a study involving aircraft sampling of plumes of active volcanoes and subproposals for individual participation in the program. The investigators would be atmospheric chemists and physicists who have established airborne measurement capabilities for the important volcanic effluents and volcanologists who are experts in the phenomenology and chemistry of active volcanoes.

List of substances which could be studied.

Sulfur compounds: SO_2, H_2S, CS_2, OCS, particulate SO_4^{2-}.
Halogen compounds: HCl, HF, particulate Cl^- and F^-.
Nitrogen compounds: NO, NH_3, particulate NO_3^- and NH_4^+.
Trace elements: Particulate As, Sb, Se, Al, Fe, Ca, and others.
Radioactive elements: Rn and its progeny.

Measurements to permit flux estimates and spatial distribution of material in plumes: SO_2 column density (COSPEC), particulate vertical profile (LIDAR), inertial navigational derived parameters of position and wind speed.

REFERENCES

Friend, J.P., Natural chlorine and fluorine in the atmosphere, water, and precipitation, WMO, Global Ozone Research and Monitoring Project - Report No. 20: "Scientific Assessment of Stratospheric Ozone: 1989", Vol. II, Appendix: AFEAS Report, 1989.

Galloway, J.N., R.J. Charlson, M.O. Andreae and H. Rodhe, eds., "The Biogeochemical Cycling of Sulfur and Nitrogen in the Remote Atmosphere", NATO ASI Series, Series C: Mathematical and Physical Sciences Vol. 159, D. Reidel Publishing Co., Boston, 1985.

Symonds, R.B., W.I. Rose and M.H. Reed, Contribution of Cl- and F-bearing gases to the atmosphere by volcanoes, *Nature, 344,* 415-418, 1988.

EOS AND AEROSOLS

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PARAMETERS

1.) τ (optical depth)

- spatial variability
- vertical structure
- temporal variability

2.) δ (asymmetry factor)

3.) ΔA_p (impact on planetary albedo)

$$A_p = \frac{1}{S_o} \int_0^1 I_R(\mu)\, d\mu$$

APPROACHES

Type	EOS Instrument	Predecessor
1. Limb scanning	SAGE II	SAM, SAGE
2. Nadir imaging	MODIS	AVHRR
3. Polarization	EOSP	Venus polar.
4. Multiangle imaging	MISR	(none)
5. Laser sounding	LAWS	(none)

COMBINATION APPROACH

- o vertical structure: SAGE, LAWS
- o horizontal structure: MISR, LAWS, MODIS
- o total optical depth: MISR, MODIS, LAWS, EOSP
- o size, δ: MISR, SAGE, EOSP
- o albedo impact: MISR, MODIS

other related measurements:

- o cloud discrimination (HIRIS)
- o albedo, fluxes (ERB)

O Polarization

- \+ very sensitive to aerosol properties

- -- very sensitive to everything (land surface)
- -- rather poor spatial resolution

O Laser sounding

- \+ direct measurement of backscatter vs. height

- -- uncertain conversion of backscatter to τ
- -- untested

O Multiangle imaging

- \+ global coverage of τ at high resolution
- \+ separates aerosol and surface reflectivity
- \+ direct measurement of $I_R(\mu)$

- -- very limited vertical resolution
- -- untested

O Limb scanning

- \+ direct measure of τ
- \+ indirect measure of size (τ (λ))
- \+ direct measure of $\Delta\tau$ (z)

- -- long path-integrated measurement (~200 km)
- -- limited tropospheric information
- -- possible confusion with cirrus

O Nadir imaging

+ global coverage of τ at high resolution

-- inferred τ subject to error due to
  - o ground reflectivity
  - o cloud contamination

Appendix H

PARTICIPANTS

Dr. Thomas Ackerman	Penn State University
Dr. Alfred T. Anderson	University of Chicago
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Dr. Ming-Ying Wei	NASA/HQ
Dr. William Zoller	University of Washington

Appendix I

WORKSHOP ON
VOLCANO CLIMATE INTERACTIONS
CENTER OF ADULT EDUCATION, UNIVERSITY OF MARYLAND
COLLEGE PARK, MARYLAND

18 - 19 NOVEMBER 1990

AGENDA

DAY 1 - Room No. 0105

08:00	Registration	
09:00	Welcoming Remarks	M. Baltuck
09:10	Agenda and Objectives	L. Walter
09:30	*Coffee Break*	
09:45	**VOLCANO PALEOCLIMATE**	M. Rampino
10:15	Informal Presentations/Discussion	
11:45	*Lunch*	
12:30	**PETROLOGY/TECTONICS**	H. Sigurdsson
13:00	Informal Presentations/Discussion	
14:30	*Break*	
14:45	**CLOUD DISSIPATION**	S. Thompson
15:15	Informal Presentations/Discussion	
18:30	*Reception (Chesapeake Room)*	
19:15	*Dinner*	
20:00	General Discussion	

DAY 2 - Room No. 0105

08:30	**VOLCANO MICROPHYSICS/ ATMOSPHERIC CHEMISTRY**	R. Turco
09:00	Informal Presentations Discussion	
10:30	*Coffee Break*	
10:45	**RADIATION/CLIMATE MODELLING**	A. Robock
11:15	Informal Presentations/Discussion	
12:45	*Lunch*	
13:30	REVIEW, SUMMARY, AND PLANS	All
15:30	Adjourn	