THE EXPLOSIVE VOLCANIC ERUPTION SIGNAL IN NORTHERN HEMISPHERE CONTINENTAL TEMPERATURE RECORDS

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Abstract. Several catalogs of explosive volcanic eruptions are reviewed and their limitations assessed. A new, homogeneous set of high quality gridded temperature data for continental regions of the northern hemisphere is then examined in relation to the timing of major explosive eruptions. Several of the largest eruptions are associated with significant drops in summer and fall temperatures, whereas pronounced negative anomalies in winter and spring temperatures are generally unrelated to volcanic activity. The effect of explosive eruptions on temperature decreases latitudinally away from the location of the eruption. High latitude eruptions have the greatest impact on high and mid latitudes; low latitude eruptions mainly influence low and mid latitudes. Temperature depressions following major eruptions are very abrupt but short-lived (1 to 3 months) decreasing in magnitude over the course of the subsequent 1 to 3 years. Generally any signal is indistinguishable from noise after 12 months but a small recurrent drop in temperature is evident about 12 to 24 months after the initial anomaly. Considering all known eruptions which injected material into the stratosphere over the last 100 years (except the 5 largest eruptions) a significant temperature depression is observed over the continents only in the month immediately following the eruption. There is no evidence that large eruptions over the last 100 years have had a significant effect on low frequency temperature changes.

1. Introduction

The effects of explosive vulcanism on the earth's surface temperature have been investigated on numerous occasions (e.g. Lamb, 1970; Budyko, 1969, 1974; Mitchell, 1961, 1970; Spirina, 1971; Yamamoto *et al.*, 1975; Oliver, 1976; Mass and Schneider, 1977; Taylor *et al.*, 1980; Self *et al.*, 1981; Kelly and Sear, 1984, Angell and Korshover, 1985). However, in spite of this attention, there is still considerable uncertainty about the magnitude and statistical significance of any effects, as well as their geographical distribution and duration (e.g. Ellsaesser, 1983; Parker, 1985). Part of the problem stems from the inadequacies of the basic data on both explosive eruptions and (to a lesser extent) global temperature. In this paper I review the various indices and catalogs of explosive eruptions, and the temperature data sets available for analysis. I then examine: (a) the seasonal response to volcanic forcing; (b) the effects that major eruptions at different latitudes have on temperature over the northern hemisphere continents as a whole and on land areas in different latitude zones and (c) the effects of a

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larger sample of smaller volcanic eruptions on temperatures over the northern hemisphere continents.

2. Data

2.1. *Temperature Data*

The numerous problems associated with obtaining a high quality (i.e. homogeneous) set of long-term temperature data for an extensive area of the globe have been discussed by Bradley and Jones (1985). In all previous studies of the effects of explosive volcanic eruptions on temperature, a limited set of station data was selected (generally from World Weather Records) and were not tested for homogeneity. Only Kelly and Sear (1984) used a very large network of station data representative of the continental land masses as a whole. However, the data they used was also not tested for homogeneity. To be confident that a change in temperature is a true climatic signal and not an artifact of poor data quality it is important that only homogeneous data are examined. Consequently, in this study, the basic temperature data set (described in Bradley *et al.*, 1985) was first screened for homogeneity. Only good quality data were then used in an interpolation scheme to produce a gridded set of monthly temperature anomalies (from a 1951–70 reference period) for northern hemisphere continental regions (Jones *et al.*, 1985, 1986). The anomaly data, on a 10° longitude × 5° latitude grid, were cosine-weighted and averaged to produce time series of hemispheric and zonal mean temperatures (Figure 1). Three approximately equal area zones were selected (0–20° N, 20–45° N, and 45–85° N). It must be emphasized that these are not true hemispheric or zonal averages but are, in fact, land-based or continental chronologies. Furthermore, the geographical coverage of data used to construct these series has varied through time (see Figure 7 in Jones *et al.*, 1986). This explains why the variance is higher in the early part of each record. At the time of optimum data availability (in the 1950s) the gridded set contains 57% of the maximum number of points for the northern hemisphere, decreasing to 30% in 1891 and only 8% in 1851.

2.2. *Indices of Explosive Volcanic Eruptions*

Data on the occurrence and magnitude of climatically significant explosive eruptions is poor. There are four principal chronologies of explosive eruptions which have been published. These are: a Dust Veil Index (DVI) (Lamb, 1970); a Volcanic Explosivity Index (VEI) (Simkin *et al.*, 1981; Newhall and Self, 1982); an estimate of atmospheric optical depth (Pollack *et al.*, 1976) and a record of electrolytic conductivity or excess sulfate in ice cores (Hammer, 1977; Hammer *et al.*, 1980; Legrand and Delmas, 1987). Here we discuss the derivation of these

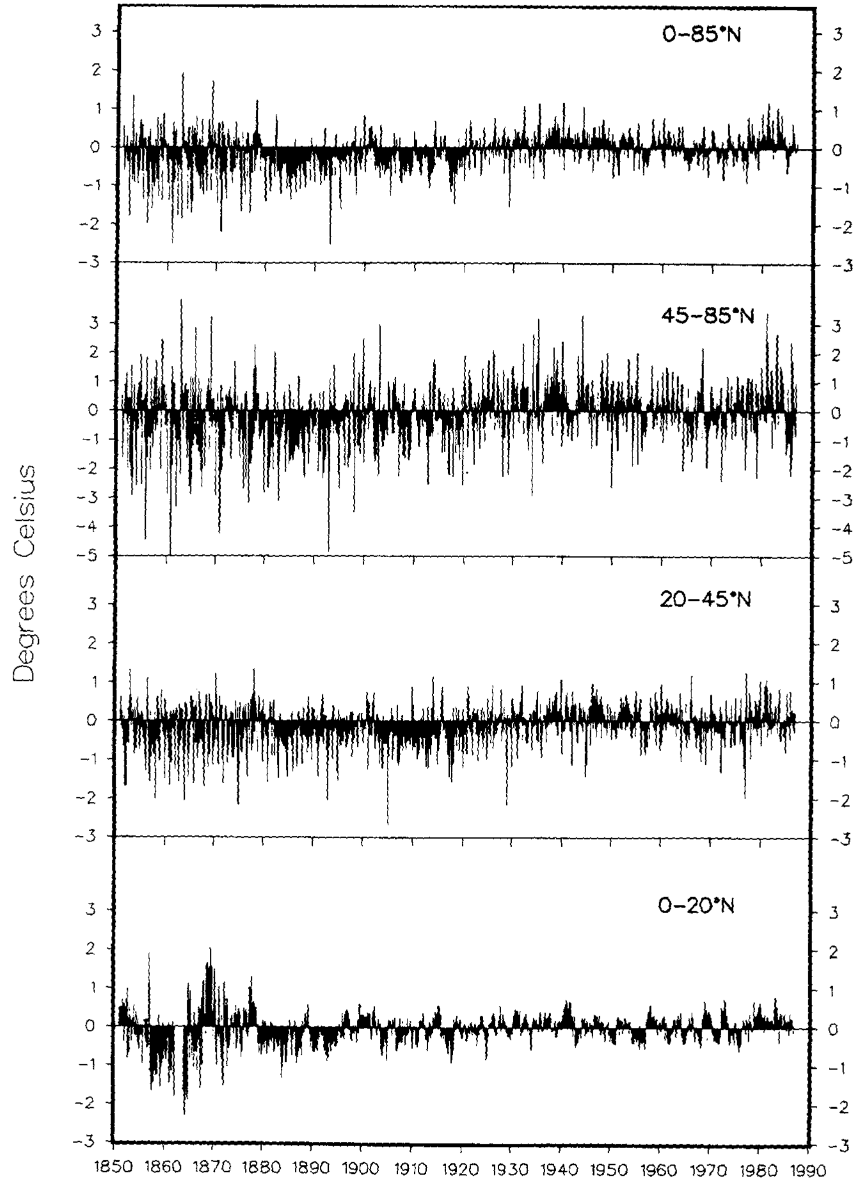

Fig. 1. Monthly temperature anomalies for the northern hemisphere land areas and for 3 latitude zones (based on data from Bradley *et al.*, 1985 and Jones *et al.*, 1985). All values are expressed as anomalies from the 1951–70 reference period.

indices and their limitations; it will be apparent that none are ideal for climatic purposes.

Almost all previous studies of climatic effects have relied on Lamb's Dust Veil Index (DVI) chronology (Lamb, 1970). Unfortunately, the DVI assigned to individual eruptions is quite subjective and very dependent on observations and effects in mid latitudes. Lamb based the DVI on either geological estimates of eruption magnitude or on one of three formulae:

$$\mathrm{DVI} = 0.97R.E.t \quad \text{or} \quad 52.5T.E.t \quad \text{or} \quad 4.4q.E.t$$

where R is the greatest depletion of direct radiation as registered by monthly averages in mid latitudes of the hemisphere concerned

T is the estimated lowering of average temperature (in °C) over the mid latitude zone of the hemisphere affected 'for the year most affected'

q is the estimated total volume (in km^3) of solid matter dispersed as dust in the atmosphere

and t is the total time in months between the eruption and last observation of the dust veil or its effect on monthly radiation or temperature values in mid latitudes

The value of E ranges from 0.3 to 1.0, depending on the maximum extent attained by a dust veil.

The different multipliers used in each formula were derived empirically from a consideration of R, T, and q for the 1883 eruption of Krakatau, so that the final DVI derived by each method would equal 1000 for this event.

Note that values of R, T, and t all depend on observations in mid latitudes. In this study, we are interested in the impact of explosive eruptions at different latitudes, so an index based largely on mid latitude effects is not appropriate. Furthermore, the derivation of the DVI using T (and an estimate of t based on temperature lowering) may lead to circular reasoning in any climatic analysis of the DVI. Lamb was cogniscent of this problem and in 13 cases (since 1850) he based DVI estimates either partly or wholly on radiation data. However, the records he used are all short (average length 15 years) cover different time periods and contain inhomogeneities (Pollack *et al.*, 1976). The data are mostly from urban sites (not mountain observatories as claimed) and no low or high latitude records (<30° or >50° N) were included. From 1932 to 1954, only two Japanese radiation records were used. The radiation data are thus far from ideal.

When Lamb was unable to estimate a DVI based on any of the three formulae, geological estimates of eruption magnitude were used (based on Sapper, 1927). Eruptions were assigned a DVI equal to the average DVI for eruptions of similar size. These averages were obtained largely by subjective assessment or by observations of negative temperature anomalies, thought to be the result of the preceding eruption. Most of the DVI values assigned to eruptions before 1900 were derived in this manner.

An alternative method of classifying explosive volcanic eruptions is that proposed by Newhall and Self (1982). They rank eruptions using only volcanological criteria to assess, where possible, the magnitude, intensity, dispersive power and destructiveness of an event. Each eruption is ranked from 1 to 8 (8 being the largest) and a chronology of volcanic events spanning the last 8000 years has been constructed (Simkin *et al.*, 1981). The classification clearly identi-

TABLE I: Major Explosive Eruptions, 1851–1981 (after Simkin *et al.*, 1981)

Location	Elev. (m)	Lat.	Long.	Date	VEI
A) Major High Latitude Eruptions (>45° N)					
Alaid, Kurile Is.	2339	50.8	155.50E	04 1981	4
Mt. St. Helens, W. U.S.	2549	46.2	122.18W	05 1980	5
Bezymianny, Kamchatka	2800	56.1	160.72E	02 1979	4
Augustine, Alaska	1227	59.4	153.42W	01 1976	4
Plosky Tolbachik	3085	55.9	160.47E	07 1975	4
Sheveluch, Kamchatka	3395	56.8	161.58E	11 1964	4
Bezymianny, Kamchatka	2800	56.1	160.72E	03 1956	5
Spurr, Alaska	3374	61.3	152.25W	07 1953	4
Hekla, Iceland	1491	61.0	17.70W	03 1947	4
Sarychev, Kurile Is.	1497	48.1	153.20E	11 1946	4
Kliuchevskoi, Kamchatka	4850	56.2	160.78E	01 1945	4
Raikoke, Kurile Is.	0551	48.3	153.25E	02 1924	4
Katla, Iceland	1363	63.6	19.03W	10 1918	4
Katmai, Alaska	0841	58.3	155.16W	06 1912	6
Ksudach, Kamchatka	1079	51.8	157.52E	03 1907	5
Thordarhyna, Iceland	1659	64.3	17.60W	05 1903	4
Augustine, Alaska	0127	59.4	153.42W	10 1883	4
Askja, Iceland	1510	65.0	16.75W	03 1875	5
Grimsvotn, Iceland	1719	64.4	17.33W	01 1873	4
Sinarka, Kurile Is.	0934	48.9	154.18E	? 1872	4
Sheveluch, Kamchatka	3395	56.8	161.58E	02 1854	5
B) Major Mid-Latitude Eruptions (20–45° N)					
Tiatia, Kurile Is.	1822	44.35	146.25E	07 1973	4
Komaga-take, Japan	1140	42.07	140.68E	06 1929	4
Sakura-jima, Japan	1118	31.58	130.67E	01 1914	4
Tarumai, Japan	1024	42.68	141.38E	03 1909	4
Suwanose-jima, Japan	0799	29.53	129.72E	10 1889	4
Bandai, Japan	1819	37.60	140.08E	07 1888	4
Nasu, Japan	1917	37.12	139.97E	07 1881	4
Suwanose-jima, Japan	0799	29.53	129.72E	? 1877	4
Komaga-take, Japan	1140	42.07	140.68E	09 1856	4
Usu, Japan	0725	42.53	140.83E	04 1853	4
C) Major Low Latitude Eruptions, (8° S to 20° N)*					
Mt. Pagan, Mariana Is.	0570	18.3	145.80E	05 1981	4
Fuego, Guatemala	3763	14.5	90.88W	10 1974	4
Fernandina, Galapagos	1495	–00.4	91.55W	06 1968	4
Lengai, E. Africa	2886	–02.8	35.90E	08 1966	4
Awu, Indonesia	1320	03.7	125.50E	08 1966	4
Kelut, Indonesia	1731	–07.9	112.31E	04 1966	4
Taal, Philippines	0400	14.0	121.00E	09 1965	4
Agung, Indonesia	3142	–08.3	115.51E	03 1963	4
Bagana, Solomon Is.	1702	–06.1	155.19E	02 1952	4
Rabaul, New Britain	0229	–04.3	152.20E	05 1937	4
Manam, New Guinea	1725	–04.1	145.06E	08 1919	4
Tungurahua, Ecuador	5016	–01.5	78.45W	04 1918	4
Agrigan, Mariana Is.	0965	18.8	145.67E	04 1917	4
Colima, Mexico	4100	19.4	103.72W	01 1913	4?
Taal, Philippines	0400	14.0	121.00E	01 1911	4

(Table I – *continued*)

Location	Elev. (m)	Lat.	Long.	Date	VEI
Santa Maria, Guatemala	3772	14.8	91.55W	10 1902	6
Soufriere, West Indies	1178	13.3	61.18W	05 1902	4
Pelee, West Indies	1397	14.8	61.17W	05 1902	4
Dona Juana, Colombia	4250	01.5	76.93W	11 1899	4
Tungurahua, Ecuador	5016	-01.5	78.45W	01 1886	4
Krakatau, Indonesia	0813	-06.1	105.42E	08 1883	6
Cotopaxi, Ecuador	5897	-00.7	78.43W	06 1877	4
Purace, Columbia	4600	02.4	76.38W	10 1869	4

* Minus latitude = °S.

fies those events which are thought to have injected material into the stratosphere; such eruptions are assigned a Volcanic Explosivity Index (VEI) of 4 or more (Table I). These eruptions produced at least 10^8 m^3 of ejecta and had column heights of 10–25 km+. They are described as Plinian or Ultra Plinian (explosive) eruptions. The classification does not assess the composition of the eruption plume (i.e. if mainly siliceous or sulphurous) since such data are only available for a very small number of eruptions (Devine *et al.*, 1984; Rampino and Self, 1984a). The index does not rely on any assessment of temperature depression, atmospheric effects or reduction in radiation receipts, and is not weighted by climatic observations in mid-latitudes (as with the DVI or optical depth record) or high latitudes (as with the ice core record). It is thus a climatically independent estimate of explosivity.

Variations in the electrolytic conductivity of Greenland ice cores were first shown to be related to the deposition of acidic snow following large explosive eruptions by Hammer (1977) and Hammer *et al.* (1980). More detailed chemical studies have enabled the amount of volcanic H_2SO_4 deposited in polar snow to be calculated (Delmas *et al.*, 1985; Legrand and Delmas, 1987). Similarities in electrolytic conductivity profiles from the Crête ice core (~71° N) and Lamb's D.V.I. suggest that the chemical composition of ice cores can provide an index of volcanic explosivity. Indeed, Legrand and Delmas (1987) recently proposed that a Glaciological Volcanic Index (GVI) be developed from ice core measurements in Greenland and Antarctica. Several problems face such a development. Firstly, the ice core records are primarily from high latitudes and are thus strongly biased towards high latitude eruptions, particularly (in the case of Greenland ice cores) those of Icelandic volcanoes (Hammer, 1984). Secondly, they mainly record sulfur-rich eruptions, though high chloride or nitrate levels in some cores may identify other important eruptions (e.g. in the Mount Logan ice core; Holdsworth, 1985). Thirdly the eruption signal may differ markedly from one ice core to another and important events, such as Katmai, may not appear in some ice core records at all (cf. Mayewski *et al.*'s (1986) 'excess sulfate' record from near Dye-3, Greenland, ~65° N, with that of Hammer

(1977) from Crête, Greenland, ~71° N). This simply reflects the fact that the spatial distribution of acidic snowfall varies after volcanic eruptions and hence the record of deposition will vary from one ice coring site to another. None of these problems seem to be insuperable: ice cores from lower latitudes (e.g. the Quelccaya Ice Cap in Peru; Thompson *et al.*, 1986) will help resolve latitudinal effects on the dispersal of volcanic material. The collection of many short cores from a wide area of the larger ice sheets will enable a better assessment of the spatial pattern of acid deposition to be made. More detailed chemical studies thus hold the promise of a significant improvement in our understanding of volcanic explosivity through time. However, at present there is no G.V.I. for eruptions, and published conductivity or sulfate ice core profiles do not differ substantially from the D.V.I. and V.E.I. indices for the last 100 years.

Ideally, the optimum index of volcanically-induced turbidity would be a time series of direct and/or diffuse radiation receipts at a set of well-distributed, high altitude sites. Such data do not exist. Nevertheless, Lamb (1970) attempted to construct a composite record of direct radiation from the late 19th century, as discussed above. Subsequently, Pollack *et al.* (1976) constructed a record of atmospheric optical depth using essentially the same basic data, though with some adjustments for changes in measurement techniques. This can not be considered as a definitive, long-term homogeneous optical depth record. It is based on 14 separate station records, mostly from mid-latitudes, with a mean record length of 15 years, each covering different periods. The records are adjusted to a common reference period (though how this is accomplished in the case of non-overlapping records is not clear) and then combined. No data are presented for the period 1922–1962 because Lamb's D.V.I. lists no significant eruption in this interval. However, Soviet analysts (e.g. Pivovarova, 1977) have argued for many years that the post-1940s cooling of the northern hemisphere is paralleled by a decline in direct radiation, as recorded in Soviet actinometric data. At this stage, a reliable optical depth does not exist although it is possible that such an index could be constructed from carefully screened radiation data.

Clearly, there is no single index of volcanic explosivity which is ideal for climatic studies. Every index has its own limitations. Furthermore, in all catalogs, it is likely that some eruptions have been missed and others misclassified. In the late 19th and early 20th centuries, many remote eruptions probably went unobserved and unrecorded (Newhall and Self, 1982; Legrand and Delmas, 1987). Even in recent years, observations of injections of material into the stratosphere are incomplete. Sampling of aerosols in the stratosphere during the 1970s revealed several occurrences of high sulfate levels, almost certainly from unrecorded volcanic eruptions mostly at high latitudes (Sedlacek *et al.*, 1983). In 1982, elevated sulfate levels from an unknown volcanic eruption were also recorded by high altitude aircraft and balloons (Mroz *et al.*, 1983).

In summary, we are in the unsatisfactory position of having to assess the climatic effect of large explosive eruptions with an incomplete knowledge of the forcing factor which we wish to investigate. Fortunately, for most of the biggest eruptions of the last 100 years, there is little disagreement between the various catalogs discussed above so it is possible to examine these cases, at least, with some confidence.

In this study I examine the high quality temperature data set of Jones *et al.* (1985) and use the Volcanic Explosivity Index of Simkin *et al.* (1981) as a record of explosive eruptions. In spite of the limitations of each of these data sets, I consider them to be the best currently available for this analysis. In particular, since the intention here is to examine the impact of explosive eruptions at different latitudes, indices which are based on data weighted towards a particular latitude band are not appropriate. In the future, it is possible that the chronology of explosive eruptions (specifically their impact on stratospheric sulfuric acid loading and atmospheric optical depth) can be improved (Legrand and Delmas, 1987; Keen, 1983) but it is unlikely that major improvements in the land-based temperature set can be achieved.

According to Simkin *et al.* (1981), from 1851 to 1981 there were at least 55 magnitude 4 or greater eruptions in the Northern Hemisphere and in the zone from 8° S to the Equator (Table I). The near-equatorial zone of southern hemisphere eruptions has been included in view of the well-documented transport of volcanic debris in the stratosphere into the Northern Hemisphere following eruptions of Mt. Agung (8° S) in 1963 and Krakatau (6° S) in 1883 (Symons, 1888; Wexler, 1951; Dyer and Hicks, 1968; Cadle *et al.*, 1976). Historically, eruptions have occurred in two main zones – in low latitudes (8° S–20° N) and in high latitudes (>45° N). Only 10 eruptions with a VEI $\geqslant 4$ occurred in mid-latitudes (Table I). Explosive eruptions were reported in all months except December; 60% of all the eruptions occurred in the first half of the year. This is relevant in terms of the seasonal response to explosive eruptions, as discussed further below.

3. Time Series of Seasonal Temperature Anomalies, 1851–1984

As a first step in determining if statistically significant temperature anomalies are associated with explosive volcanic eruptions, time series of seasonal temperature anomalies were prepared for the northern hemisphere as a whole (0–85° N) and for the three latitudinal zones (0–20° N, 20–45° N, and 45–85° N). Examination of time series for each season indicates that very pronounced negative anomalies occur occasionally, sometimes in only one season, sometimes in several consecutive seasons of the same year. A comparison of these anomalies with the dates of major explosive eruptions (Table I) shows that in almost all cases Spring (M, A, M) and Winter (D, J, F) anomalies are unrelated temporally to these events. However, this is not true of the Summer (J, J, A) and Fall (S, O, N) temperature extremes (cf. Taylor *et al.*, 1980). Figure 2 shows anomalies (from the 1951–70 reference period) for these two seasons. A 21 year unweighted running mean* was superimposed on the data and estimates of the 5% and 1% confidence levels (based on a 1 tail test) were plotted as dashed lines. These have been calculated as follows:

$$x - 1.73\ \sigma\ (5\%\ \text{level}) \quad \text{and} \quad x - 2.53\ \sigma\ (1\%\ \text{level})$$

where x is the mid-point value of a 21 year running mean and σ is the standard deviation of the same 21 values. This approach takes into account the low frequency change in temperature and estimates the significance of individual anomalies with respect to the 'local' mean and 'local' variability which is clearly greater in the early part of the record. A one-tail test of significance is appropriate as all studies of the effects of stratospheric aerosols point to an expected drop in large-scale surface temperature (e.g. Harshvardhan and Cess, 1976; Pollack *et al.*, 1976; Toon and Pollack *et al.*, 1976; Toon and Pollack, 1980).

From Figure 2, it is clear that several major volcanic events (VEI > 4) have had pronounced but short-lived effects on seasonal surface temperature averaged over northern hemisphere continental land areas. In Summer months (June, July, August) for example, statistically significant falls in temperature occurred in 1884 (after the August 1883 eruption of Krakatau) in 1907 (following the March eruption of Ksudach) and 1956 (following the March eruption of Bezymianny). Pronounced, but less significant anomalies also occurred in 1903 (following Santa Maria, October 1902) and 1912 (following Katmai, June 1912). Anomalies in 1862 and 1867 do not appear to be related to any known major eruptions. In Fall months (Sept., Oct., Nov.) major anomalies occurred in 1912 (Katmai; significant at >99% level), 1956 (Bezymianny) and 1976 (>99% level). The 1976 signal is of interest because a pronounced negative anomaly was also recorded for Spring and Summer months of the same year. Two VEI 4 eruptions in Kamchatka (in July 1975) and Alaska (in January 1976) (Table I) may be the cause of these temperature depressions. Extremely low Fall temperatures in 1856 and 1864 are not related to any known major eruptions.

Analysis of time series for each latitude zone sheds further light on the nature of these anomalies. Once again, only large negative anomalies in Summer and Fall seasons are consistently related to volcanic events (Figures 3 and 4). The magnitude and statistical significance of the anomalies varies latitudinally. The 1912 Katmai anomaly is pronounced in mid and high latitudes, particularly in Fall months, but not apparent at all in low latitudes. This presumably reflects the restricted latitudinal dispersal of the high latitude dust (cf. Lamb, 1970). However, by contrast, the 1956 eruption cloud from Bezymianny (similar

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* A 21 year running mean was selected to characterise the low frequency nature of each time series. Running means were extended to the ends of each record by replacing 'missing' points with the mean of whatever valid points were in the 21 year sample. As standard deviations were based on these 21 year averages, the value of σ is reduced towards the beginning and end of each record. Consequently, the statistical significance in the first and last 10 years of each diagram is progressively overestimated towards each limit.

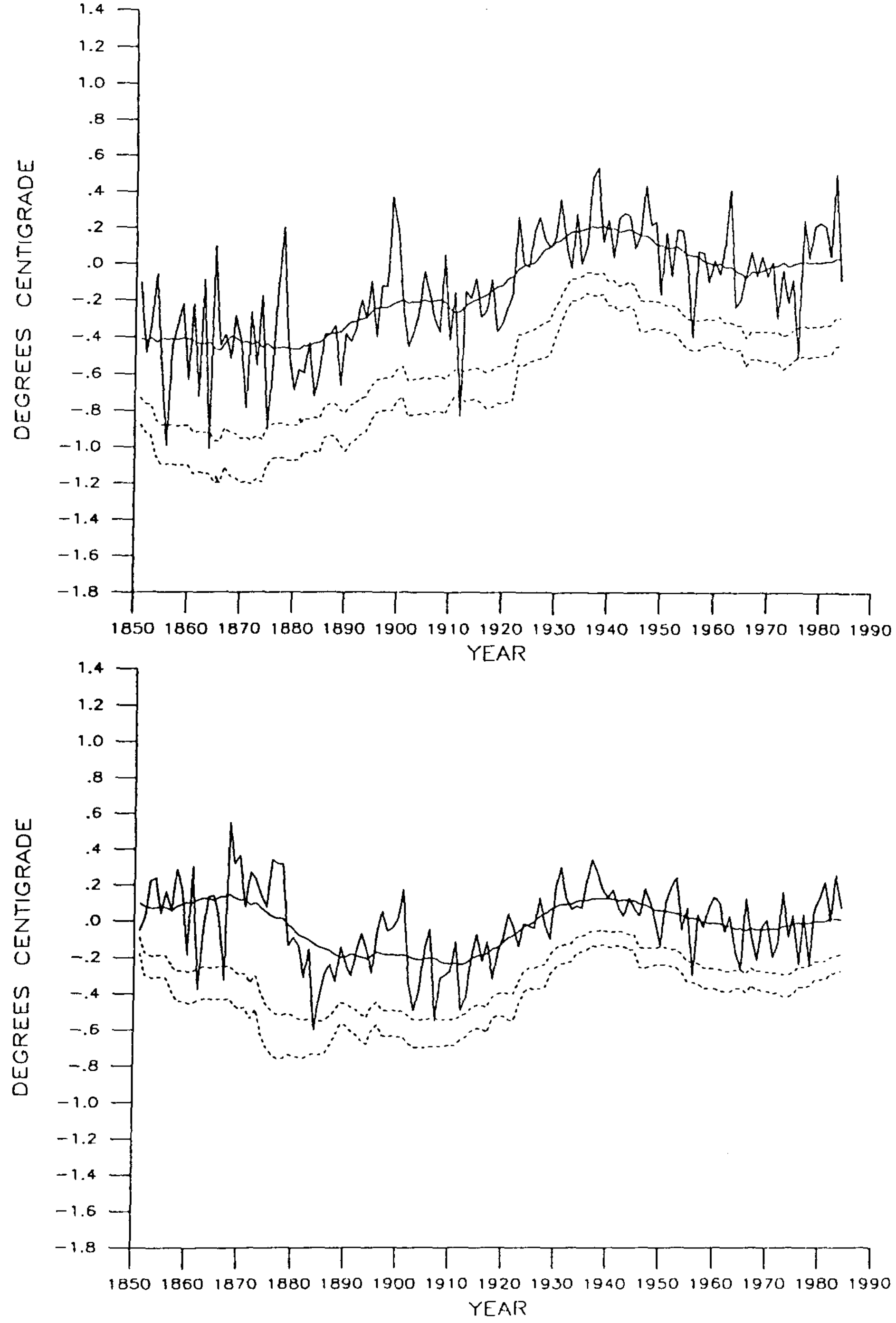

Fig. 2. Summer (June, July, August) (bottom) and Fall (September, October, November) (top) mean temperature anomalies for northern hemisphere land areas, expressed as anomalies from 1951–70 means. A 21 year running mean is superimposed on the yearly averages; dashed lines show the 5% and 1% (1 tail) confidence intervals, with respect to the 21 year running mean values.

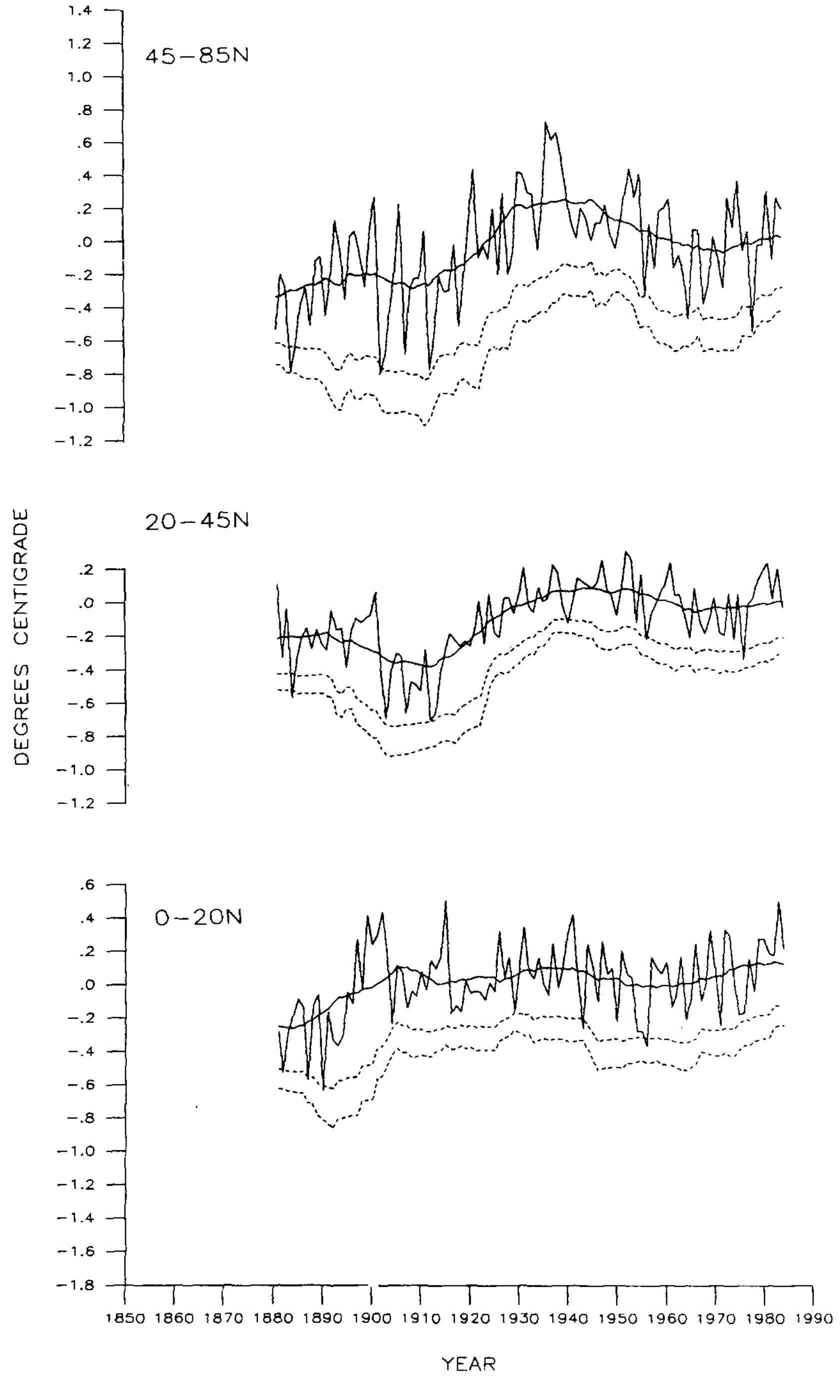

Fig. 3. Summer (June, July, August) temperature anomalies for 3 latitude zones. Running means and confidence intervals as in Figure 2.

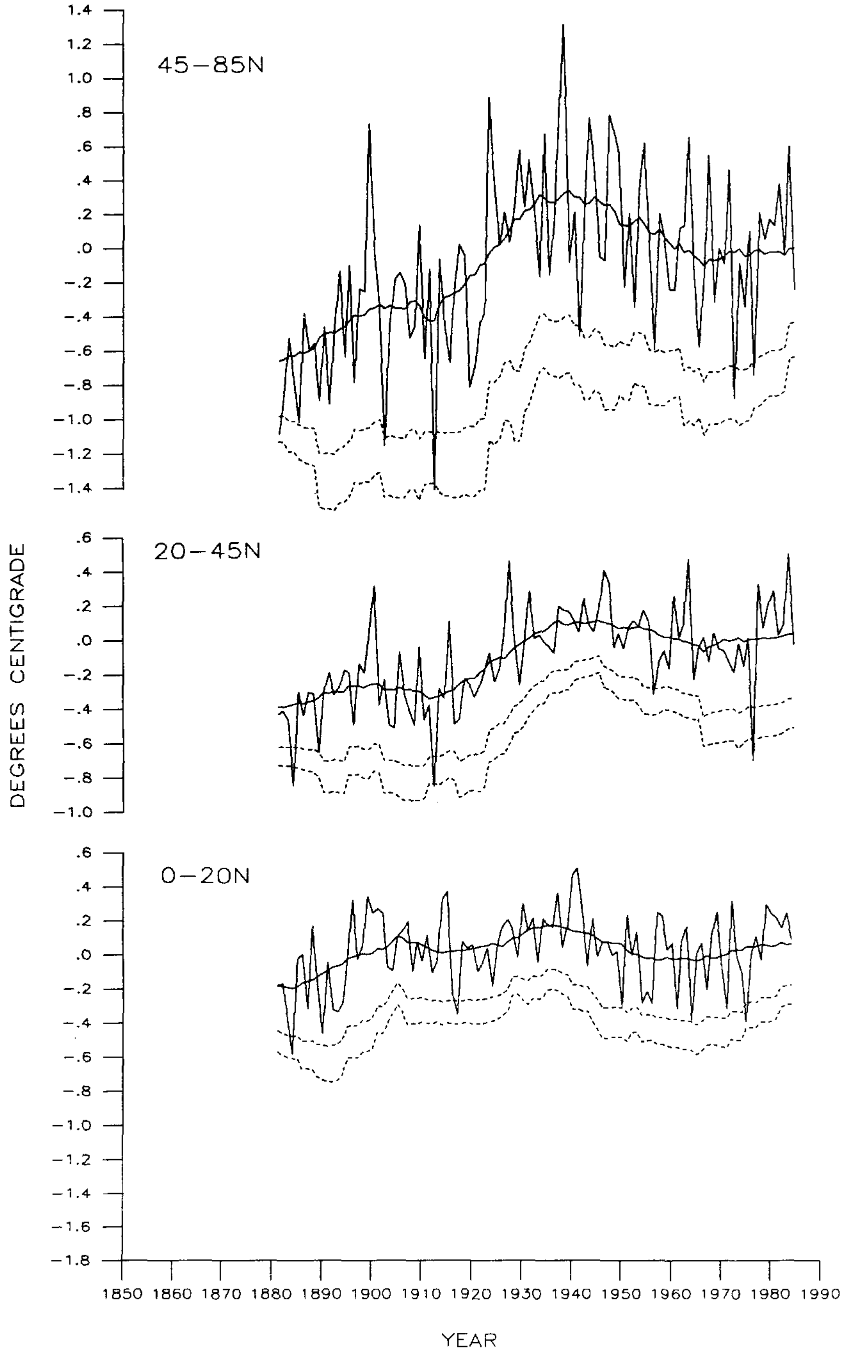

Fig. 4. Fall (September, October, November) temperature anomalies for 3 latitude zones. Running means and confidence intervals as in Figure 2.

latitude to Katmai) appears to have had an impact in all latitude bands, though in low latitudes a prolonged Summer and Fall anomaly began earlier (in 1954) perhaps indicating some other (coincidental) factor affecting that region.

Low-latitude eruptions, such as the circum-Caribbean events of 1902 had an impact at high latitudes in the Summer and Fall of 1902 and in mid-latitudes in 1903 (possibly enhanced by a large eruption in Iceland in May, 1903). However, no Summer anomaly is apparent at all in low latitudes until 1904. The Krakatau eruption of August 1883 had a significant effect on mid- and high-latitudes but was not statistically significant at low latitudes where the eruption took place. Finally, the 1976 anomalies in middle and high latitudes suggest that the significance of the eruptions of Plosky Tolbachik (Kamchatka) in July 1975 or (more probably) Mt. Augustine, Alaska in January 1976 may have been underestimated.

The reasons why anomalies related to major volcanic eruptions are principally found in Summer and Fall months are not obvious. For the Northern Hemisphere as a whole, the only other statistically significant seasonal anomalies which could be related to volcanic events were pronounced temperature depressions in the Spring months of 1956 and 1976. In Winter months, out of 20 statistically significant negative anomalies in 3 latitude zones, only the anomalously cool Winter of 1883–84 in low latitudes could be reasonably linked to a major eruption. It may be relevant that most major eruptions have occurred in late Spring so that subsequent effects on surface temperature, which are clearly short-lived, will be maximized in Summer and Fall months (cf. Kelly and Sear, 1984). This is discussed further below. It may also be relevant that the period of the year when surface temperatures most closely follow (seasonal) changes in solar radiation receipts is late Summer and Fall i.e. this is the period of maximum sensitivity to perturbations of solar radiation (Kukla, 1975). Consequently, any reduction in solar radiation at the surface, due to optical depth changes resulting from a major eruption, would likely have the greatest impact on surface temperature during that period.

4. Superposed Epoch Analysis

To investigate the mean response of zonal and hemispheric temperature to major eruptions at different latitudes, superposed epoch analysis has been employed (Panofsky and Brier, 1965). The method is designed to reduce noise in a data set which may be subject to many diverse forcing factors and to indicate the mean response following specific events. Basically, key dates are selected and data before and after these dates are averaged. In the analysis carried out here, 36 months before and after each key date were selected. Problems may arise if the key date occurs in the midst of a period when a strong upward or downward trend is occurring. Compositing of monthly temperature data (which has a higher variance in Winter than in Summer months) may also be a problem if the

TABLE II: Standard deviations of monthly anomalies from 1951–70 reference period. Analysis based on 1881–1980 period (°C)

	J	F	M	A	M	J	J	A	S	O	N	D
0–20° N	0.33	0.36	0.32	0.29	0.26	0.26	0.24	0.25	0.22	0.22	0.27	0.33
20–45° N	0.55	0.63	0.39	0.34	0.31	0.26	0.25	0.24	0.28	0.32	0.40	0.46
45–85° N	1.18	1.04	0.91	0.63	0.47	0.39	0.34	0.41	0.43	0.68	0.82	0.91
0–85° N	0.56	0.52	0.39	0.31	0.27	0.23	0.21	0.23	0.24	0.34	0.39	0.43

data are not first standardized. To eliminate such problems, in this analysis, the monthly (hemispheric and zonal) anomaly data were standardized by the standard deviation of the respective monthly means for 1881–1980 (i.e. $x^1 = x/\sigma$). These are given in Table II. The standardized units were then used in each superposed epoch analysis. The procedure thus follows that of Kelly and Sear (1984). To obtain an estimate of temperature change after a key date relative to prevailing conditions, the 36 month period prior to the key date was used as a reference (rather than a 12 month period, as used by Kelly and Sear). Thus, the mean of months x_{i-36} to x_{i-1} (where i is the eruption month) were subtracted from all values x_{i-36} to x_{i+36}. In the superposed epoch analysis only temperature data from the period 1880–1984 were used to avoid the limited set of data before this period. Consequently, only eruptions between 1883 and 1981 were selected to ensure that data from 3 years prior to and 3 years subsequent to, major eruptions fell within the prescribed interval of 1880–1984.

Estimates of statistical significance were made by Monte Carlo simulations (cf. Kelly and Sear, 1984) using 400 randomly selected sets of dates (the significance level varying with the number of cases in each set). In the analysis of a very small number of events, the estimates of statistical significance levels for each month are quite variable, even when the number of simulations is doubled. In these cases a band equal to the mean of estimates ($\pm 1\sigma$) has been constructed; the precise 5% significance level falls within this band which thus provides a general estimate of the significance of mean temperature anomalies.

4.1. *Effects of the Largest Eruptions* (*VEI* = 5 *or* 6)

In this analysis only the dates of the 5 largest eruptions (1883–1981) within the zone 8° S–90° N were selected. These were: Krakatau (Aug., 1883) Santa Maria (Oct., 1902) Ksudach (March, 1907) Katmai (June, 1912) and Bezymianny (March, 1956)*. Note that 3 of these were at high latitudes and 2 at low latitudes.

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* Although the eruption of Mount St. Helens in May 1980 was rated by Simkin *et al.* (1981) as a magnitude 5 eruption it was not included in this analysis. This was because the force of this explosive event was primarily directed laterally, not vertically, so in terms of stratospheric input of siliceous material I considered it to be more comparable with less powerful (VEI = 4) eruptions

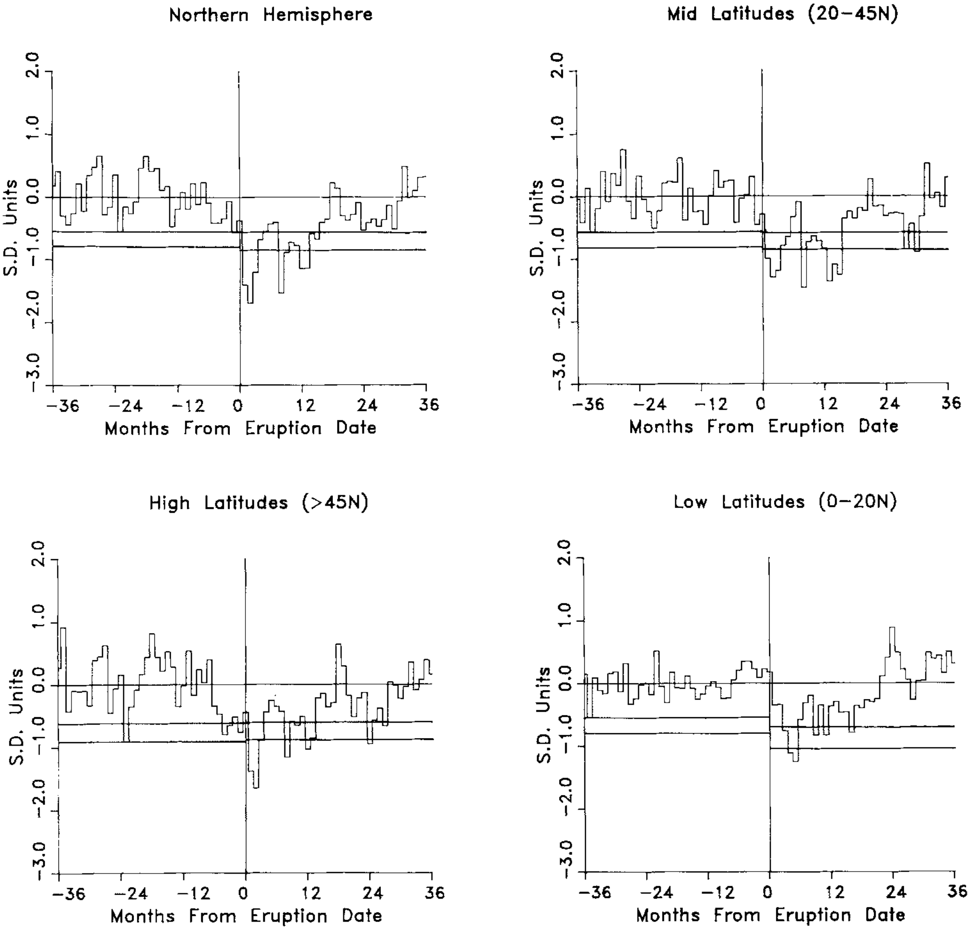

Fig. 5. Superposed epoch analysis of the 5 largest explosive eruptions (VEI = 5 or 6) since 1880 for the northern hemisphere and for 3 latitude zones. The eruptions were: Krakatau (Aug., 1883) Santa Maria (Oct., 1902) Ksudach (March, 1907) Katmai (June, 1912) and Bezymianny (March, 1956). Estimate of 5% (1 tail) significance level shown is based on 400 simulations, using 5 randomly selected dates per case. Band width of significance level is calculated as $\{x_i/36\}^{+1}$ and $\{x_i/37\}^{+1}$. Significance levels were calculated separately for the preceding 36 months as these were used as a reference period for the analysis (see text).

Figure 5 shows the results of a superposed epoch analysis of these 5 eruptions in terms of their effects on the northern hemisphere land areas as a whole (cf. Kelly and Sear, 1984) and on land areas within each latitudinal zone. At high latitudes, there is a statistically significant drop in temperature in the 3 months

(cf. Anon, 1981). However, it has been pointed out, in review, that Mount Saint Helens did in fact vent considerable gaseous material to the stratosphere and logically should have been included in the analysis with the other VEI 5 eruptions. I accept this criticism; nevertheless, the eruption had minimal climatic impact (Robock, 1981; Newell, 1982).

following the eruptions with a gradual reduction in the magnitude of the anomaly over the following 27 months. However, significant anomalies recur at intervals of approximately 12 and 24 months after the initial temperature depression. The maximum effect (of ~0.4 °C; Table II) occurs in the summer and fall months immediately following the event, and this effect is then repeated at a lower magnitude in the same seasons of the following two years. Between these periods, temperatures were not significantly depressed.

In mid-latitudes, temperatures were lowered in a similar manner with maximum depression in the *second* summer after the eruptions. The extreme is actually eight months following the eruption but this results from exceptional temperature depressions following the eruptions of the two low latitude eruptions which occurred in August and October so that the '8th month signal' is

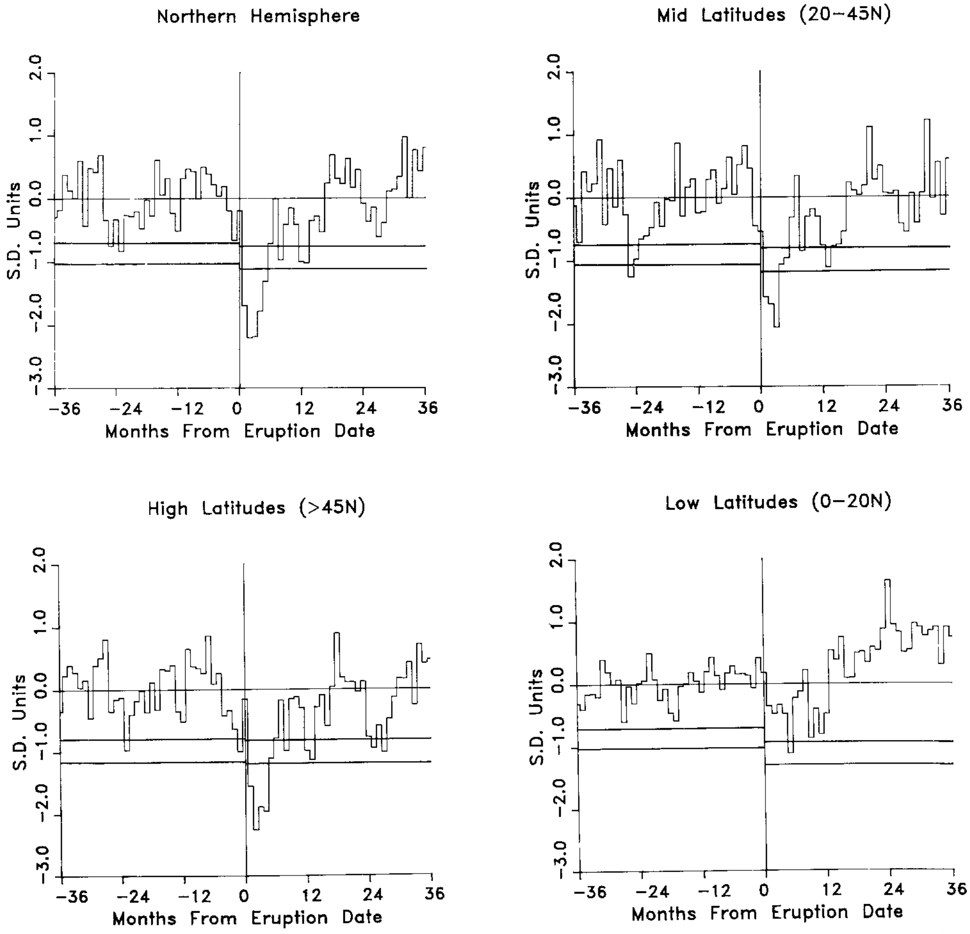

Fig. 6. Superposed epoch analysis of the three largest (VEI = 5 or 6) high latitude eruptions of the last 100 years, for the northern hemisphere and for 3 latitude zones. The eruptions were: Ksudach (March, 1907) Katmai (June, 1912) and Bezymianny (March, 1956). 5% (1 tail) significance levels shown are based on 400 simulations using 3 randomly selected dates per case (see Figure 5).

actually also a 'summer signal' related to these eruptions (see below). At low latitudes the maximum effect of the major eruptions is, on average, 5 months after the events. This is presumably related, in part, to the delay in dispersal of the eruption cloud from high to low latitudes in 3 of the 5 cases.

For the northern hemisphere land area record as a whole, a pronounced drop in temperature for 3 months following the eruptions is observed, with a similar depression 8–13 months later. In all zones, and over the hemisphere as a whole, temperatures gradually recover from the initial drop within 2–3 years of the eruptions. However, this recovery is indistinguishable from noise after about 15 months.

To examine the effects of large high and low latitude eruptions in more detail, the two sets of 3 major high and 2 major low latitude events were separated and

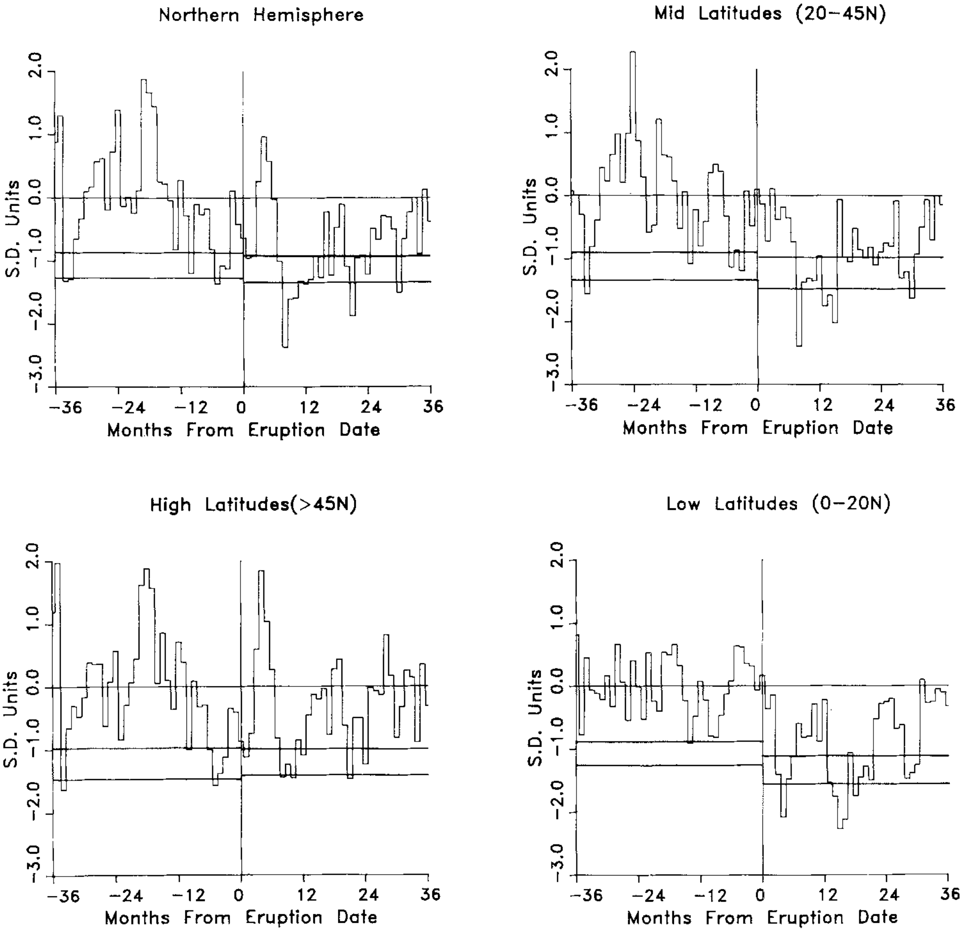

Fig. 7. Superposed epoch analysis of the 2 largest (VEI = 5 or 6) low latitude eruptions of the last 100 years, for the northern hemisphere and for 3 latitude zones. The eruptions were: Krakatau (Aug., 1883) and Santa Maria (Oct., 1902). 5% (1 tail) significance level shown is based on 400 simulations using 2 randomly selected dates per case (see Figure 5).

the superposed epoch analysis repeated (Figures 6 and 7). Bearing in mind the limited sample size, the results indicate that the high latitude eruptions had a significant impact on hemispheric temperatures for 1–5 months after the events (on average a drop of 0.5 °C, from May–September) and again, to a smaller extent, a year later (Figure 6). This mainly reflects the impact on mid to high latitudes. Temperatures were depressed for 12–15 months after these eruptions but this depression can not be distinguished from noise after 6 months. At low latitudes, the only month with a statistically significant temperature depression is 5 months after the events (September, on average).

The effect of the 2 major low latitude eruptions is somewhat more complex (Figure 7). At low latitudes, a significant cooling occurs 3–5 months after the events (December–March in these cases) and again 13–21 and 28–30 months later. In general, temperatures remained depressed for 2–3 years following the eruptions. It is possible that the apparently warmer period 7–12 months after the events was influenced by an El Nino episode in 1902–3. In general, such episodes result in very pronounced warming over low latitude land areas (Bradley *et al.*, 1987). However, with only two volcanic events in the sample, it is very difficult to separate any volcanic signal at low latitudes from any (opposing) El Nino signal.

At mid-latitudes, cooling occurred 8–15 months and 28–30 months after the low latitude eruptions with temperatures generally lowered for 2 years following the initial onset of cooling. At high latitudes, the maximum signals were 8–10, 21 and 24 months after the event. For the hemisphere as a whole, cooling was very pronounced 8–10 months after the events (i.e. the following summer) thereafter declining in significance through the subsequent winter months. Secondary peaks occurred 21 and 30 months after the eruptions (i.e. June and March, on average, in years 2 and 3 following the eruptions).

4.2. *Effects of Eruptions with a Volcanic Explosivity Index of* 4

Newhall and Self (1982) define eruptions with a VEI of 4 or above as having 'definite' stratospheric input. Using the catalog of Simkin *et al.* (1981) and its revision and update (Simkin, 1985; pers. comm.) 44 eruptions with a VEI of 4 or more affected the zone 8° S to 90° N between 1883 and 1981. A superposed epoch analyis was carried out on only those (38) events in which the VEI was equal to 4 (i.e. excluding the largest events). For the northern hemisphere as a whole, a statistically significant temperature anomaly was recorded but only in the month immediately following these eruptions (-0.25σ; significant at $>5\%$ level using a 1 tail test). However, when the data were divided into 3 latitudinal zones and the analysis repeated for each zone, no statistically significant drop was detectable in any of the individual zones alone. When the VEI = 4 eruptions were divided into 3 groups (of 19 low, 6 middle and 13 high latitude eruptions, as in Table I) and the analysis was repeated, there was no statistically significant temperature decline in any zone, or over the northern hemisphere as a whole.

5. Discussion

The major impact of explosive volcanic activity on continental surface temperature occurs in Summer and Fall months, at the most ecologically sensitive time of year (Bray, 1971). It also occurs at the time of year when the influence on glacier mass balance is likely to be most significant (Bradley and England, 1978; Porter, 1981). This seasonal effect is not just because many of the biggest eruptions occur in Spring; following the 2 biggest low latitude eruptions of the last 100 years (which occurred in the Fall) temperatures over northern hemisphere land areas reached lowest levels the following summer. With the biggest high latitude eruptions (which occurred in Spring) the effect was maximized in the following summer and fall months, then 'disappeared' during winter months, to reappear the next Spring/Summer. It could be argued that this apparent resonance is merely a reflection of the larger standard deviation of winter months compared to summer months, so that a similar magnitude temperature depression would be amplified in summer months by the standardization procedure employed. However, re-analysis without standardization indicates that this is not so; the 'resonance effect' is real.

It appears that there is a greater sensitivity to volcanic aerosol forcing in summer and fall months (cf. Kukla, 1975) but the reasons for this are unclear. There is some evidence that stratospheric aerosols in polar regions may evaporate and condense seasonally, in response to seasonal changes in stratospheric temperature, but these changes appear to occur early in the year (Rosen and Hofmann, 1983; Hofmann and Rosen, 1985). Elsewhere stratospheric temperatures are fairly constant throughout the year so this is unlikely to be a factor of widespread importance. There is also evidence that depletion of direct radiation in the 'summer half year' is greater than in the 'winter half year' after at least some major 20th century eruptions (Pivovarova, 1977) but more detailed analysis of the radiation data is needed to understand the reasons for this. Recent modelling studies by Harvey and Schneider (1986) show a maximum temperature depression over land areas in summer months (following a 2% decrease in solar constant on January 1) and a recurrent, smaller amplitude anomaly the following summer. This response is related to seasonally varying oceanic mixing (mixed layer depth) which modulates the seasonal temperature change over land. Oceanic mixing may thus play an important role in the seasonality of the temperature anomalies observed.

There is no evidence in the period analysed that even the largest eruptions had any long-term effect (>3 years) on temperature. This implies that large explosive eruptions, at infrequent time intervals, have little impact on the low frequency signal in zonal and hemispherically averaged data. This is contrary to the conclusions of Budyko (1969, 1974) who interprets long-term changes in direct radiation (principally due to volcanic aerosol loading) as a major factor influencing low frequency temperature change, particularly over the past 50 years.

Because the mean maximum response to explosive eruptions is so abrupt and short-lived (particularly for eruptions with a VEI of 4) it seems unlikely that sulfate aerosols *alone* are the critical factor in the immediate (1 month) temperature depression, contrary to the conclusions of Rampino and Self (1982, 1984a). Fine ash, which is largely removed within a few months, may be at least as important a factor in the primary abrupt temperature depression (cf. Rampino and Self, 1984b). However, sulfate aerosols, which may take several months to reach maximum density following an eruption, are likely to be responsible for the more prolonged, (but diminishing) effects observed in subsequent years.

6. Conclusions

(1) Very large, but historically rare, explosive eruptions (VEI 5 or 6) have a very pronounced, short-lived impact on continental surface temperature. The effect is generally maximized in the 2–3 months following the eruption, diminishing thereafter for up to 2–3 years. Summer and Fall months experience the greatest temperature depression whereas Winters often show little or no effect. Over northern hemisphere land areas as a whole, initial temperature depression averages ~0.4 °C (Figure 6; Table II). There is evidence for a small secondary peak in the magnitude of anomalies about one year after the first peak response and a smaller third peak about a year later.

(2) The latitude of an eruption is an important factor in determining the extent of its influence on temperature. High latitude eruptions have their biggest effect at high and mid latitudes whereas low latitude eruptions mainly affect low and mid latitudes. Consequently, mid latitudes are particularly vulnerable to both low and high latitude explosive eruptions.

(3) Explosive eruptions of VEI magnitude 4 have a detectable effect on temperatures over northern hemisphere land areas only in the month immediately following an eruption. However, the effect is small (0.25σ) equivalent to a depression of only 0.05 to 0.1 °C depending on the season.

(4) The effects of major explosive eruptions on lowering land area surface temperature during the past 100 years are abrupt and short-lived. For there to be significant volcanic effects on low frequency temperature changes, explosive eruptions of the magnitude studied here would have to recur at short intervals (<3 years) and there is no evidence that this has happened over the last 100 years.

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References

Angell, J. K. and Korshover, J.: 1985, 'Surface Temperature Changes Following the Six Major Volcanic Episodes between 1780 and 1980', *J. Climate and Appl. Met.* **24**, 937–951.

Anon: 1981, 'Mount Saint Helens and the Climate', *Earthquake Information Bulletin* **13**, 5.

Bradley, R. S., Diaz, H. F., Kiladis, G., and Eischeid, J. K.: 1987, 'ENSO Signal in Continental Temperature and Precipitation Records', *Nature*.

Bradley, R. S. and England, J.: 1978, 'Influence of Volcanic Dust on Glacier Mass Balance at High Latitudes', *Nature* **271**, 736–738.

Bradley, R. S. and Jones, P. D.: 1985, 'Data Bases for Isolating the Effects of the Increasing Carbon Dioxide Concentration', in M. C. MacCracken and F. M. Luther (eds.), *Detecting the Climatic Effects of Increasing Carbon Dioxide*. U.S. Dept. of Energy, Washington D.C., pp. 29–53.

Bradley, R. S., Kelly, P. M., Jones, P. D., Diaz, H. F., and Goodess, C. M.: 1985, 'A Climatic Data Bank for the Northern Hemisphere Land Areas, 1851–1980', *Technical Report TR017*, U.S. Dept. of Energy Carbon Dioxide Research Division, Washington D.C., 335 pp.

Bray, J. R.: 1971, 'Vegetational Distribution, Tree Growth and Crop Success in Relation to Recent Climatic Change', *Adv. in Ecol. Res.* **7**, 177–233.

Budyko, M. I.: 1969, 'The Effect of Solar Radiation Variations on the Climate', *Tellus* **21**, 611–619.

Budyko, M. I.: 1974, *Climate & Life*, Academic Press, 508 pp.

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.

Delmas, R. J., Legrand, M., Aristarain, A. J., and Zanolini, F.: 1985, 'Volcanic Deposits in Antarctic Snow and Ice', *J. Geophysical Research* **90**, D7, 12901–12920.

Devine, J. D., Sigurdsson, H., Davis, A. N., and Self, S.: 1984, 'Estimates of Sulfur and Chlorine Yield to the Atmosphere from Volcanic Eruptions and Potential Climatic Effects', *J. Geophys. Res.* **89**, B7, 6309–6325.

Dyer, A. J. and Hicks, B. B.: 1968, 'Global Spread of Volcanic Dust from the Bali Eruption of 1963', *Q. J. Roy. Met. Soc.* **94**, 545–554.

Ellsaesser, H. W.: 1983, 'Isolating the Climatogenic Effects of Volcanoes', *Rep. UCRL-89161,* Lawrence Livermore Lab., Livermore, California.

Hammer, C. U.: 1977, 'Past Volcanism Revealed by Greenland Ice Sheet Impurities', *Nature* **270**, 482–486.

Hammer, C. U.: 1984, 'Traces of Icelandic Eruptions in the Greenland Ice Sheet', *Jokull* **34**, 51–65.

Hammer, C. U., Clausen, H. B., and Dansgaard, W.: 1980, 'Greenland Ice Sheet Evidence of Post-Glacial Volcanism and its Climatic Impact', *Nature* **288**, 230–255.

Harshvardhan and Cess, R. D. : 1976, 'Stratospheric Aerosols: Effect upon Atmospheric Temperature and Global Climate', *Tellus* **28**, 1–10.

Harvey, L. D. D. and Schneider, S. H.: 1985, 'Transient Climate Response to External Forcing on 10^0–10^4 Year Time Scales 2. Sensitivity Experiments with a Seasonal, Hemispherically Averaged, Coupled Atmospheric, Land and Ocean Energy Balance Model', *J. Geophysical Res.* **90**, D1, 2207–2222.

Hofmann, D. J. and Rosen, J. M.: 1985, 'Antarctic Observations of Stratospheric Aerosol and High Altitude Condensation Nuclei Following El Chichon Eruption', *Geophysical Res. Letters* **12**, 13–16.

Holdsworth, G.: 1985, 'Acid Content of Snow from a Mid-Tropospheric Sampling Site on Mount Logan, Yukon Territory, Canada', *Annals of Glaciology* 7, 153–160.

Jones, P. D., Wigley, T. M. L., and Kelly, P. M.: 1982, 'Variations in Surface Air Temperatures: Part 1. Northern Hemisphere, 1881–1980', *Monthly Weather Review* **110**, 59–72.

Jones, P. D., Raper, S. C. B., Santer, B., Cherry, B. S. G., Goodess, C., Kelly, P. M., Wigley, T. M. L., Bradley, R. S., and Diaz, H. F., 1985: 'A Grid Point Surface Air Temperature Data Set for the Northern Hemisphere', *Technical Report TR022*, U.S. Dept. of Energy Carbon Dioxide Research Division, Washington D. C., 251 pp.

Jones, P. D., Raper, S. C. B., Bradley, R. S., Diaz, H. F., Kelly, P. M., and Wigley, T. M. L.: 1986, 'Northern Hemisphere Surface Air Temperature Variations, 1851–1984', *J. Climate & Appl. Met.* **25**, 161–179.

Keen, R. A.: 1983, 'Volcanic Aerosols and Lunar Eclipses', *Science* **222**, 1011–1013.

Kelly, P. M. and Sear, C. B.: 1984, 'Climatic Impact of Explosive Volcanic Eruptions', *Nature* **311**, 740–743.

Kukla, G.: 1975, 'Missing Link between Milankovitch and Climate', *Nature* **253**, 600–603.

Lamb, H. H.: 1970, 'Volcanic Dust in the Atmosphere; with a Chronology and Assessment of its Meteorological Significance', *Phil. Trans. Roy. Soc. London* **A266**, 425–533.

Legrand, M. and Delmas, R. J.: 1987, 'A 220-Year Continuous Record of Volcanic H_2SO_4 in the Antarctic Ice Sheet', *Nature* **327**, 671–676.

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.

Mayewski, P. A., Lyons, W. B., Spencer, M. J., Twickler, M., Dansgaard, W., Koci, B., Davidson, C. I., and Honrath, R. E.: 1986, 'Sulfate and Nitrate Concentrations from a South Greenland Ice Core', *Science* **232**, 975–977.

Mitchell, J. M., Jr.: 1961, 'Recent Secular Change 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 Global Temperature Fluctuations of the Past Century', in S. F. Singer (ed.), *Global Effects of Environmental Pollution* D. Reidel Publ. Co., Dordrecht, pp. 139–155.

Mroz, E. J., Mason, A. S., and Sedlacek, W. A.: 1983, 'Stratospheric Sulfate from El Chichon and the Mystery Volcano', *Geophys. Res. Letters* **10**, 873–876.

Newell, R. E.: 1982, *Mount Saint Helens Eruptions of 1980: Atmospheric Effects and Potential Climatic Impact*, NASA Special Publication No. SP-458, 119 pp.

Newhall, C. G. and Self, S.: 1982, 'The Volcanic Explosivity Index (VEI): An Estimate of Explosive Magnitude for Historical Volcanism', *J. Geophys. Res.* **87**, C2, 1231–1238.

Oliver, R. C.: 1976, 'On the Response of Hemispheric Mean Temperature to Stratospheric Dust: An Empirical Approach, *J. of Appl. Met.* **15**, 933–950.

Panofsky, H. A. and Brier, G. W.: 1965, *Some Applications of Statistics to Meteorology*, Penn. State Univ., University Park, Pennsylvania.

Parker, D. E.: 1985, 'Climatic Impact of Explosive Volcanic Eruptions', *Met. Mag.* **114**, 149–161.

Pivovarova, Z. I.: 1977, 'Utilization of Surface Radiation Data for Studying Atmospheric Transparency', *Meteorologia i Gidrologia*, **9**, 24–31.

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.

Porter, S. C.: 1981, 'Recent Glacier Variations and Volcanic Eruptions', *Nature* **291**, 139–142.

Rampino, M. and Self, S.: 1982, 'Historic Eruptions of Tambora (1815), Krakatau (1883) and Agung (1963), their Stratospheric Aerosols and Climatic Impact', *Quat. Res.* **18**, 127–143.

Rampino, M. and Self, S.: 1984a, 'Sulfur-rich Volcanic Eruptions and Stratospheric Aerosols', *Nature* **310**, 677–679.

Rampino, M. R. and Self, S.: 1984b, 'The Atmospheric Effects of El Chichon', *Scientific American* **250**, 34–43.

Robock, A.: 1981, 'The Mount Saint Helens Volcanic Eruption of May 18, 1980: Minimal Climatic Effect', *Science* **212**, 1383–1384.

Rosen, J. M. and Hofmann, D. J.: 1983, 'Unusual Behavior in the Condensation Nuclei Concentration at 30 km', *J. Geophysical Res.* **88**, 3725–3731.

Sedlacek, A. W., Mroz, E. J., Lazrus, A. L., and Gandrud, B. W.: 1983, 'A Decade of Stratospheric Sulfate Measurements Compared with Observations of Volcanic Eruptions', *J. Geophys. Res.* **88**, 3741.

Self, S., Rampino, M., and Barbera, J. J.: 1981, 'The Possible Effects of Large 19th and 20th Century Volcanic Eruptions on Zonal and Hemispheric Surface Temperatures', *J. Volcanol. & Geothermal Res.* **11**, 41–60.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J. H.: 1981, *Volcanoes of the World*, Hutchinson Ross, Stroudsberg, Penn., 233 pp.

Spirina, L. P.: 1971, 'On the Effect of Volcanic Dust on the Temperature Regime of the Northern Hemisphere', *Meteorol. i Gidrol.*, No. 10, 38–43.

Symons, G. J. (ed.): 1888, *The Eruption of Krakatoa and Subsequent Phenomena*, Rept. of the Krakatoa Committee of the Royal Society, London, Harrison and Trubner.

Taylor, B. L., Gal-Chen, T., and Schneider, S. H.: 1980, 'Volcanic Eruptions and Long-term Temperature Records: An Empirical Search for Cause and Effect', *Q. J. Roy. Met. Soc.*, **106**, 175–199.

Thompson, L. G., Mosley-Thompson, E., Dansgaard, W., and Grootes, P. M.: 1986, 'The Little Ice Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap', *Science* **234**, 361–364.

Toon, O. B. and Pollack, J. B.: 1980, 'Atmospheric Aerosols and Climate', *American Scientist* **68**, 268–278.

Wexler, H.: 1951, 'Spread of the Krakatoa Volcanic Dust as Related to the High-level Circulation', *Bull. Amer. Met. Soc.* **32**, 48–53.

Yamamoto, R., Iwashima, T., and Hoshiai, M.: 1975, 'Change of the Surface Air Temperature Averaged over the Northern Hemisphere and Large Volcanic Eruptions During the Years 1951–1972', *J. Met. Soc. Japan* **53**, 482–485.

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