Atmósfera (1988), **1**, pp. 141-156

Volcanic activity parameters and volcanism-climate relationships within the recent centuries

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(Manuscript received October 30, 1987; accepted March 10, 1988)

RESUMEN

Los productos arrojados por el vulcanismo incluyendo las conversiones de gas a partícula, forman capas de aerosoles atmosféricos que influyen sobre los procesos de radiación y en consecuencia el clima. Por esto las mayores erupciones explosivas son de interés predominante. Estas causan calentamientos estratosféricos mientras que la capa límite atmosférica cercana a la superficie sufre enfriamiento. Con el propósito de estudiar estos efectos vistos a través de las variaciones de temperatura ocurridas durante siglos recientes (la estratosfera desde 1958), se ha definido un índice nuevo de actividad volcánica "SVI" basado en la cronología de volcanes de la institución Smithsoniana. Este parámetro se compara con parámetros similares y se usa para realizar el análisis del forzamiento volcánico sobre la estratosfera y la troposfera. En el análisis estadístico se utilizan técnicas de correlación, de coherencia móvil e "integrada" y se consideran datos con filtros pasa bajo de uno y de 10 años (low-pass). Las series de tiempo de la temperatura del aire corresponden al Hemisferio Norte, a la media del Artico así como a las estaciones Filadelfia (USA) y Hohenpeissenberg (RFA). En términos generales las relaciones vulcanismo clima, son más pronunciadas para intervalos grandes de tiempo que para eventos particulares. Finalmente se lleva a cabo un análisis de señal móvil en el que sólo en algunos casos las señales volcánicas en el clima y las razones señal, ruido, exceden el nivel de confidencia de 95%.

ABSTRACT

The ejecta of volcanism, including gas-to-particle conversions, form atmospheric aerosol layers which influence the radiation processes and in consequence the climate. Thereby, the major explosive eruptions are of predominant interest. They cause stratospheric warmings whereas the atmospheric boundary layer near surface is cooled. In order to study these effects, focussed on air temperature variations within the recent centuries (stratosphere only since 1958) a new volcanic activity index "SVI" is defined based on the Smithsonian volcano chronology. This parameter is compared with other similar parameters and used for an stratosphere-troposphere analysis of volcanic forcing. A long-term statistical analysis uses correlation and coherence techniques "integrated" and moving with time, considering the annual and 10 yr low-pass filtered data. The air temperature time series refer to the Northern Hemisphere and Arctic mean as well as to the stations Philadelphia (USA) and Hohenpeissenberg (FRG). In general, the long-term volcanism-climate relationships may be more pronounced than singular events. Finally, a moving signal analysis is performed where the volcanic signals in climate and the signal-to-noise ratios exceed the 95% confidence level in some cases.

1. Introduction

The mechanism of volcanic activity is not only a matter of discussion in the field of geology, geophysics and mineralogy but also of great interest in climatology. Newhall and Self (1982) who have interpreted the most comprehensive volcano chronology based on historical and geological sources (Simkin *et al.*, 1981, 1985) recommend, similar to other authors, to focus the attention to the major explosive eruptions for the purpose of a climatological analysis. These major eruptions in contrast to minor ones, inject the volcanic material (particles and gases) into the stratosphere (predominantly 20 - 50 km) where the rock particles have a residence time of a few months but the sulfuric acid aerosols formed by gas-to-particle conversions remain approximately 1 - 5 yr (Hammer *et al.,* 1981; Rampino and Self, 1984; Jäger *et al.*, 1984).

The volcanogenic aerosol layers scatter the solar irradiation and only a reduced part of the multi-scattered irradiation can reach the Earth's surface. This was clearly recorded, for example, after the

El Chichón eruption (Mexico, 1982) where the atmospheric transmission dropped from 92% to 79% at Mauna Loa Observatory (Newell and Hsiung, 1984). Simultaneously, LIDAR measurements of the stratospheric integrated particulate backscattering indicated an approximately 7 -fold increase at station Garmisch-Partenkirchen (FRG). This increase, however, may be due to several volcanic eruptions (additionally Gareloi, St. Helens and Manam just before the El Chichón eruption, Galunggung nearly at the same time, all in 1983 and recorded by Simkin *et al.*, 1985). One more important feature of these LIDAR measurements (Jäger *et al.*, 1984; Reiter and Jäger, 1986) is the long-term increase of the stratospheric backscattering since 1977 culminating in 1982-1983 (see also Schönwiese, 1988).

The absorption of solar irradiation by the volcanogenic stratospheric aerosol layers may lead to a warming of these layers whereas the decrease of the atmospheric transmission should lead to a cooling of the atmospheric boundary layer near the surface. (Weak volcanic eruptions, if only affecting the troposphere, may lead to a warming of the atmospheric boundary layer.) Moreover, the climate response to explosive volcanic activity should be large-scale in space because the stratospheric sulfuric acid aerosols, due to their long residence time, undergo a wide-spread mixing (and are transported in direction to the stratospheric polar low; McCormick *et al.*, 1978). Any analysis of volcanism-climate relationships must account for these features in time and space.

The temperature response of the atmosphere to volcanic forcing was discussed in a number of deterministic studies (see e.g., Oliver, 1976; Pollack *et al.*, 1976; Bryson and Goodman, 1980). A case study of Toon and Pollack (1980) concerning the Agung eruption (1963) was able to simulate both a pronounced stratospheric warming and a relatively weak cooling of the atmospheric boundary layer, in fair coincidence with physical expectations and the observations (see also Hansen *et al.*, 1981). Some empirical studies considering particularly the temperature response in the atmosphere near the ground include time series analysis covering the recent centuries (Miles and Gildersleeves, 1978; Schöwiese, 1983, 1984), case studies (Sear and Kelly, 1982; Mitchell, 1982; Robock, 1983) and the superposed epoch method (Angell and Korshover, 1985), just to mention a few of these papers. Stratospheric warmings following the major volcanic eruptions have been described and interpreted by Labitzke and Naujokat (1983) and by Labitzke *et al.* (1986a, 1986b) for the last 20 years.

Handler (1986) has supposed that tropical explosive volcanoes could cause a warming of the sea surface temperatures and he assumes a connection with the ENSO (El Niño, southern oscillation) events. This is in contrast to Newell and Hsiung (1984) who argue that the El Chichón eruption has been balanced, to a certain extent, by the 1983 ENSO event as far as the temperature response near the ground is concerned. A statistical analysis of volcanism-precipitation relationships performed by Cress (1987) was not very successful. These findings confirm that hypotheses concerning the volcanic forcing of other climatic elements than air temperature are very problematic.

This paper is focussed on the air temperature during the recent centuries for which continuous instrumentally-based direct measurements are available. The large-scale feature of volcanic forcing is taken into account by using mean Northern Hemisphere and mean arctic temperature data (near surface) 1851-1985 provided by Jones (1985a, 1985b). The records of two stations, Hohenpeissenberg (FRG, mountain station) and Philadelphia (USA) for 1981-1985, are also considered (all data are annual averages). Mean Northern Hemisphere data for the stratosphere are available since 1965 (Labitzke *et al.*, 1986a) or since 1958 (Angell and Korshover, 1984) the latter data being very uncertain in the interval 1968/69 (not used here) and before 1964 (for a detailed discussion see Labitzke *et al.*, 1986b). A reconstruction of the mean Northern Hemisphere temperatures near the surface back to 1579 (Groveman and Landsberg, 1979) is again very uncertain (see discussion Schönwiese, 1984, 1987b) so that data before 1750 are not used.

2. Volcanic activity parameters

Lamb (1970, 1983) was the first who tried to evaluate a parameter time series which quantifies the volcanic particle loading of the stratosphere within the recent centuries. His "dust veil index" DVI in terms of mean annual data, available for the Northern Hemisphere since 1500 (data since 1750, Fig. 1) and for the Southern Hemisphere since 1890, is based on empirical regression equations using alternatively the observations of the direct solar irradiation (decreased by known volcanic eruptions) or the assessed volume of the volcanic ejecta or (5% of the northern hemisphere data) observed temperature drops which may be hypothetically forced by volcanism. These data have been frequently used in climate analysis. Despite of Lamb's intensive and careful work, however, this DVI time series is inhomogeneous (due to the different regression equations) and not strictly independent from the temperature response which will be analysed. Moreover, within the interval 1916-1962 the DVI data are zero which seems to be unrealistic when compared with the Smithsonian volcano chronology (Simkin *et al.*, 1981).

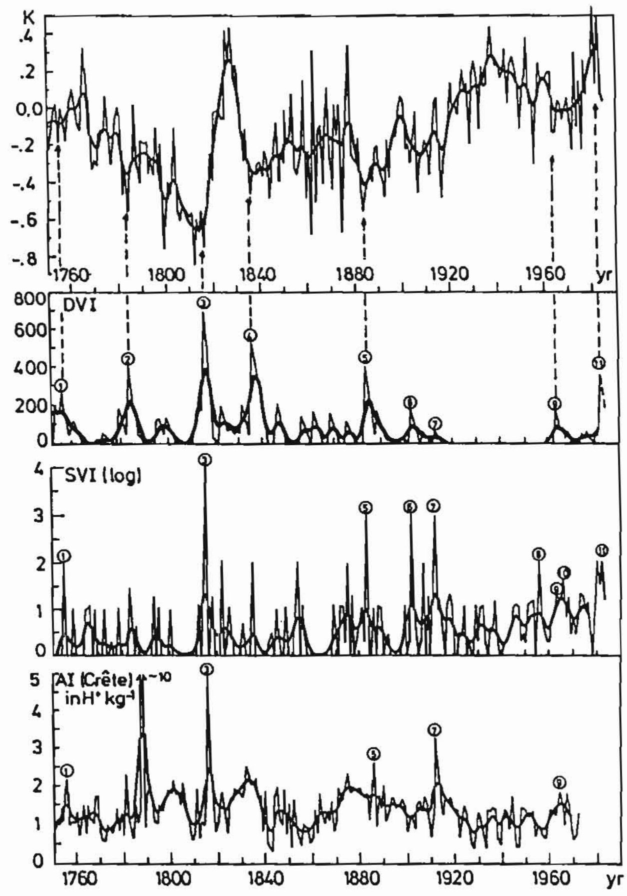

Fig. 1. Mean Northern Hemisphere annual air temperature variations TNH 1750-1985 (deviations from the 1880-1979 average, data from Groveman and Landsberg, 1979, since 1851 from Jones, 1985), thin line, and 10 yr Gaussian low-pass filtered data, heavy line; lower plots corresponding data of the volcanic activity parameters DVI 1750-1983 (annual data from Lamb, 1970, 1983), SVI 1750-1983 (Smithsonian volcanic index as presented in this paper, logarithmic scale) and AI 1750-1972 (acidity index based on ice core measurements at station Crête, central Greenland, annual data from Hammer *et al.*, 1980, 1981).

It is very helpful, therefore, that in addition to DVI, alternative series are available based on ice core measurements. In this paper the Crête (central Greenland) measurements are used specifying the acidity (H^+ ion concentration) of the ice core samples and reflecting, therefore, to a certain extent, the acid volcanogenic material deposited in the polar ice. This Crête "acidity index" AI series was provided by Hammer *et al.* (1980, 1981) also in terms of annual data (553-1972, Fig. 1). These data, however, are regional and not necessarily representative for the mean Northern Hemisphere. This is clearly indicated in case of the Laki (Iceland) eruption in 1783 which is extremely outstanding in the AI series but comparably small in the DVI series and Simkin's *et al.* (1981) chronology. Moreover, the AI series does not strictly discern between eruptions which have affected the stratosphere and those which have not. Finally, the H^+ ion concentration may be influenced by non-volcanic environmental effects.

These shortcomings of DVI and AI favour the evaluation of a third volcanic activity parameter based on the Smithsonian volcano chronology (Simkin *et al.*, 1981, 1985; Hirschboeck, 1980). This chronology classifies all volcanic eruptions known from historical or geological sources with respect to both their column height and the volume of their ejecta in terms of the "volcanic explosivity index" VEI = 0, 1, ..., 8. Newhall and Self (1982) describe details and state that "the set of eruptions which needs to be considered for volcano-climate studies is probably the set with VEI $\geqq$ 3, from 1755 to the present". VEI = 3 means a column height of 3 - 15 km so that the stratosphere may or may not be affected. Evidently, this poses a problem if this recommendation is followed. Moreover, there exists an increasing trend of the VEI $\leqq$ 3 observations in the 20th century probably not correlated with the real volcanic activity.

Despite these difficulties, Bissolli (1985) and Schönwiese (1986) tried to evaluate an annual volcanic activity parameter based on the VEI $\geqq$ 3 eruptions which includes the major ones (maximum Tambora 1815, VEI = 7) but also frequent minor eruptions (VEI = 3) with the exception of those which did certainly not affect the stratosphere (as far as known from Simkin *et al.*, 1981). In respect to the volume of the mass m ejected by the volcanoes Smikin's *et al.* (1981) chronology uses the relation

$$m = 10^{VEI+4.5}$$

or

$$m \sim 10^{VEI} \tag{1}$$

($VEI = 3 \rightarrow m = 10^7 - 10^8 \mathrm{m}^3$; $VEI = 4 \rightarrow m = 10^8 - 10^9 \mathrm{m}^3$; etc.). In consequence, the "Smithsonian volcanic index"

$$SVI = \sum_{i=1}^{n} 10^{VEI} \tag{2}$$

was defined which summarizes the VEI $\geqq$ 3 eruptions for each year (n eruptions per particular year) weighted by the volume of the assessed ejecta. Because some tropical eruptions on the Southern Hemisphere (e.g., Krakatau 1883) have also influenced the Northern Hemisphere climate, all eruptions 10^oS to 90^oN were included (nearly the same results were obtained if also the volcanoes 10^oS to 23 $1/2^o$ S were considered (Bissolli, 1985).

In Fig. 1 the annual and 10 yr low-pass filtered data of the DVI, SVI and AI (Crête parameter) time series are compared (the temperature record will be discussed later) covering the interval 1750 - 1983 (AI until 1972; data before 1750 are more uncertain, see Schönwiese, 1986). Table 1 specifies some statistical properties of these time series (unfiltered data) and Table 2 compares the VEI > 4 (since 1960 including VEI = 4) volcanoes with the annual parameter values. Some major volcanic eruptions are denoted by numbers in Figure 1 and Table 2 which may be helpful for intercomparisons.

parameter	time interval	m	s	sk	r_a	r(DVI)	r(SVI)	r(AI)
DVI	1500-1980	56.9	93.6	2.6	+.67	1	+.33	+.16
	1781-1980	65.6	106.8	2.7	+.69	1	+.45	+.21*
SVI	1500-1980	35.2	464.8	20.6	.00	+.33	1	+.22
	1781-1980	73.7	716.3	13.4	-.01	+.45	1	+.30*
AI	1500-1972	1.56	.69	4.5	+.30	+.16	+.22	1
	1781-1972	1.44	.83	6.0	+.16	+.21*	+.30*	1

*) time lag 1 year (DVI or SVI, respectively, leading)

Table 1. Some statistical properties of the volcanic activity parameters DVI, SVI and AI Crête, annual Northern Hemisphere data (definitions see text); m: arithmetic mean, s: standard deviation, sk: moment coefficient of skewness, r_a: autocorrelation coefficients (time lag 1 yr), r: correlation coefficients of the parameters (confidence level 95% exceeded).

	volcano	coordinates	elevation	year (month)	VEI	SVI	DVI	AI
1	Katla	63.6 N 19.0 W	1363 m	1755(10)	5	100	255	2.17(1756)
3	Tambora	8.3 S 118.0 E	2851 m	1815(4)	7	10 001	695	4.95(1816)
	Galunggung	7.3 S 108.1 E	2168 m	1822(10)	5?	112	200	?
4	Cosiguina	13.0 N 87.6 W	859 m	1835(6)	5	101	525	2.18(1836)
	Sheveluch	56.8 N 161.6 E	3395 m	1854(2)	5	102	0	1.03(1856)
	Askja	65.0 N 16.8 W	1510 m	1875(3)	5	101	120	2.31
5	Krakatau	6.1 S 105.4 E	300 m	1883(8)	6	1012	400	2.60(1886)
6	Santa Maria	14.8 N 91.6 W	2700 m	1902(10)	6	1032	180	1.63(1905)
	Ksudach	51.8 N 157.5 W	1079 m	1907(3)	5	102	60	1.74
7	Novarupta (Katmai)	58.3N 155.2W	2285 m	1912(6)	6	1001	60	3.25
8	Bezymianny	56.1 N 160.7 E	2800 m	1956(3)	5	103	0	1.42(1960)?
9	Agung	8.3 S 115.5 E	3142 m	1963(3)	4	20	160	1.85(1964)
	Sheveluch	56.8 N 161.8 E	3395 m	1964(11)	4	17	(120)	1.63(1965)??
	Taal	14.0 N 121.0 E	300 m	1965(9)	4	18	(80)	?
	Kelut	7.9 S 112.3 E	1731 m	1966(4)	4			
10	Oldoinyo Lengai	2.8 S 35.9 E	2880 m	1966(8)	4	43	80	1.80(1967)
	Awu	3.7 N 125.5 E	1320 m	1966(8)	4			
	Fernandina	0.4 S 91.6 E	1495 m	1968(6)	4	19	60	?
	Tiatla	44.4 N 146.3 E	1822 m	1973(7)	4	22	25	
	Fuego	14.5 N 90.9 W	3763 m	1974(10)	4	20	50	
	Plasky Tolbachik	55.9N 160.5E	3085 m	1975(7)	4	12	(40)	
	Augustine	59.4 N 153.4 W	1227 m	1976(1)	4	14	65	
	Bezimianny	56.1 N 160.7 W	2800 m	1979(2)	4	12	(20)*	
	St. Helens	46.2 N 122.2 W	1920 m	1980(5)	5	112	50	
	Alaid	50.8 N 155.5 E	2339 m	1981(4)	4	25	(40)*	
	Pagan	18.1 N 145.8 E	570 m	1981(5)				
11	El Chichon	17.3 N 93.2 W	1350 m	1982(3,4)	4(5)	17(107)	365	
	Una Una	0.2 S 121.6 E	508 m	1983(7)	4	(17)		

Table 2. Chronological list of explosive volcanic eruptions VEI > 4 compared with the annual index values SVI, DVI and AI (Crête) 1755-1983, since 1963 (availability of stratospheric temperature measurements) also including VEI = 4 (definitions VEI, SVI, DVI and AI see text) In the last column (AI) the year of assumed deposition in the polar ice is indicated in the parentheses where "?" means that no relative maximum can be detected (similar DVI values in parenthesis).

Notes. The numbers in the first column refer to Fig. 2. The AI series ends in 1972. In this series some "missing" major volcanoes are indicated (each second year is the year of deposition): 1780/1781, 1800/ 1801, 1831/1832; in addition Lakagigar (Laki) 1783/1788, No. 2 (maximum of AI data).

Note that the annual data autocorrelation is near zero in the case of SVI so that the volcanic eruptions can be interpreted to be independent events. The extreme positive skewness sk points also to this characteristic feature where high index values are extremely more seldom than small values (logarithmic distribution). The DVI data involve the highest autocorrelation because Lamb (1970, 1983) assumes a very slow decrease of the stratospheric particle loading (about 3 - 5 years residence time in the stratosphere). The AI data autocorrelation is in between that of SVI and DVI which may point to the fact that the real residence time is somewhat shorter than supposed by Lamb (1970), approximately 1 - 4 years (Table 2).

The intercorrelations of the volcanic activity parameters are relatively weak and more pronounced in the recent two centuries when compared with the 1500 - 1980 (1972) interval. The index level of some prominent eruptions, see Table 2 and Fig. 1 (in particular those denoted by numbers), is quite different although, for example, Katla (1755, No. 1), Tambora (1815, No. 3), Krakatau (1883, No. 5) and Agung (1963, No. 9) are prominent in all these parameter series, perhaps also Laki (1783, No. 2), Cosiguina (1835, No. 4) and Novarupta (1912, No. 7). Galunggung (1822), Bezymianny (1956) and some other eruptions cannot be identified in the AI series (Santa Maria, 1902, No. 6, only very weak). On the other hand, some VEI $\leqq$ 4 eruptions are very prominent in the AI series, see Table 2. To summarize, the relatively weak intercorrelations of the volcanic activity parameters and their shortcomings indicate that it is not justified to prefer any particular parameter, namely DVI or AI, as often done in the literature.

3. Statistical analysis of volcanism-climate relationships

3.1 Simultaneous stratosphere-troposphere analysis

The expected effect of explosive volcanism in the atmosphere, as outlined in the Introduction (upper warming, lower cooling), may be appropriate for a hypothetical identification of volcanism-climate relationships. In Fig. 2 which covers the recent three decades the SVI time series (logarithmic scale, lower plot) is compared with corresponding air temperature series (all data are annual and Northern Hemisphere average). The stratospheric data "A/K" from Angell and Korshover (1984), 100 - 30 hPa mean (corresponding to 16 - 24 km), are uncertain before 1970 as already mentioned (see Introduction; the 1964 warming, however, may be more or less correct), whereas the data "L" from Labitzke *et al.* (1984, 1986a) are representative for the 30 hPa layer (24 km). The data concerning the atmospheric layer near surface are from Jones (1985a). According to Table 2, the VEI $\geqq$ 4 eruptions are indicated as far as they can hypothetically be related to the simultaneous temperature effects (upper warmings, lower coolings).

Evidently, some stratospheric warmings are very pronounced, for instance in 1964 (one year after the Agung eruption), 1968 (Fernandina ?) and 1982 (El Chichón). Labitzke and Naujokat (1983) have analized these stratospheric warmings and state that in 1964 and particularly in 1982 the effects are very significant (1982 signal exceeding three times the temperature data standard deviation). The 1968 signal is somewhat problematic because it can be attributed also to the Kelut, Awu and Oldoinyo (1966) eruptions. All these stratospheric warmings, hypothetically attributable to volcanism, coincide with coolings of the atmosphere near the surface but these latter temperature effects are very weak and not significant. It may be of interest that from this point of view the climatic influence of the St. Helens eruption (1980) cannot be identified. It may be that this eruption is overestimated and El Chichón is underestimated by the VEI classification or that the chemical properties of the El Chichón eruption were more effective in a climatological sence (higher sulfur content) or that other non-volcanic effects dominated in 1980/81. The 1983 warming of the atmospheric layer near surface - in the same year a further cooling of the stratosphere was observed - could have been due to the strong ENSO event in that year.

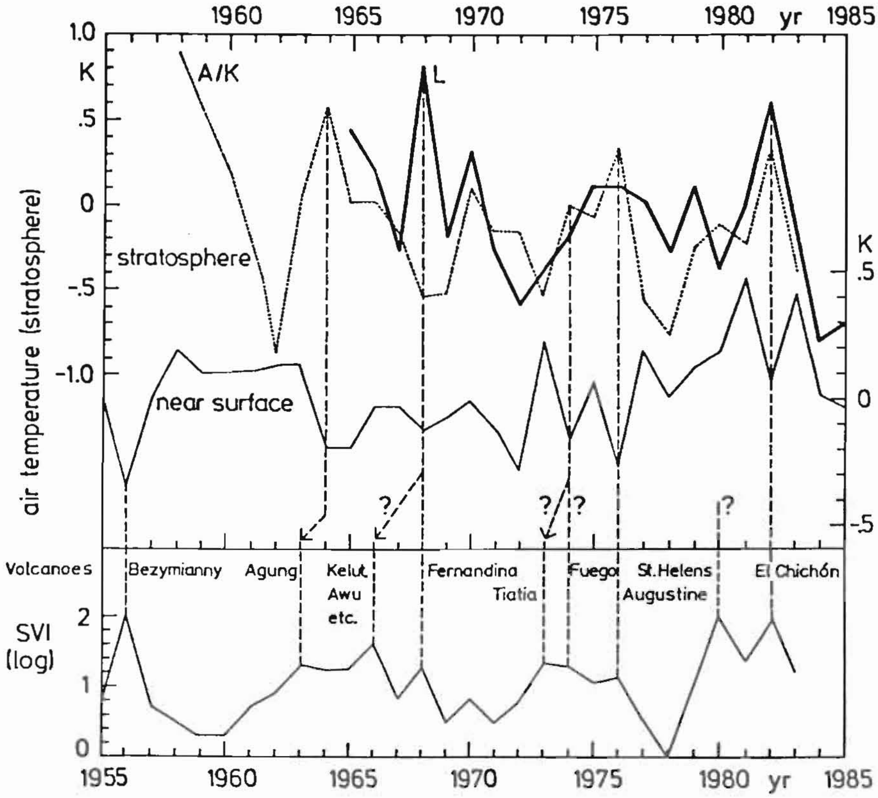

Fig. 2. Mean Northern Hemisphere annual temperature variations (deviations from the average) of the stratosphere level 30 hPa (24 km) "L" after Labitzke *et al.* (1986) or "A/K" after Angell and Korshover (1984; uncertain before 1970) and of the atmospheric level near surface (as in Fig. 1). Some major volcanic eruptions are indicated along with the annual SVI data (see Fig. 1).

3.2 Long-term correlation and coherence analysis

Because it is possible to relate some prominent explosive volcanic eruptions not only to the atmospheric backscattering measurements but also to both the stratospheric and tropospheric (near surface) temperature response it may be justified to look on long-term correlations of volcanism and temperature near the ground on the base of the available data of the recent centuries. In a previous paper (Schönwiese, 1986) it has been demostrated by means of a moving correlation analysis that there are no correlations of the volcanic activity parameters (DVI, AI and SVI) and the mean Northern Hemisphere temperature (near surface) detectable before approximately 1765. This may be due to unreliable data in respect to both the volcanic activiy parameters (confirming the statements of Newhall and Self, 1982) and the temperature reconstructions. Moreover, it was demonstrated that in the time interval since c. 1765 the correlation of SVI and temperature are relatively stable with time, in contrast to AI (enormous correlation increase within the recent decades) and DVI where the latter parameter may systematically overestimate the relationships.

Table 3, columns 1 - 4, specifies the correlation coefficients not only of the mean Northern Hemisphere by also of the mean arctic as well as the Hohenpeissenberg and Philadelphia temperature time series with the SVI and DVI parameters. Note that the SVI correlations exceed only the 90% confidence level. In contrast to that, the DVI correlations exceed the 95% confidence level in the case of the 1781 - 1984 Northern Hemisphere series and even the 99% confidence level in the case of the 1738 - 1984 Philadelphia series. All correlation confidence tests are corrected for autocorrelation by reduced degrees of freedom and for non-Gaussian distributed quantities by means of the Fisher transformation. If one maintains the assumption that the DVI parameter overestimates the relationships, the overall correlations are very weak and not far from speculations.

temperature series	time interval	correlation coefficients annual		correlation coefficients LP		signals (signal - to - noise ratios) annual		signals (signal - to - noise ratios) LP	
		SVI	DVI	SVI	DVI	SVI	DVI	SVI	DVI
northern hemisphere*	1851-1983	-.17	-.27	-.34	-.62	-.28K(1.12)	-.38K(1.52)	-.26K(1.04)	-.57K (2.28)
	1781-1983	-.12	-.34	-.38	-.51	-.47K(1.68)	-.62K(2.21)	-.70K(2.50)	-.57K (2.04)
arctic (65° - 85° N)	1851-1983	-.18	-.28	-.34	-.64	-.73K(1.22)	-.95K(1.58)	-.61K(1.02)	-1.37K(1.58)
Philadelphia (USA)	1738-1983	-.11	-.32	-.26	-.48	-.99K(1.74)	-1.24K(2.18)	-.91K(1.60)	-.96K(1.68)
Hohenpeissenberg(FRG)	1781-1983	-.06	-.12	-.22	-.30	-.63K(0.83)	-.43K(0.57)	-.69K(0.91)	-.56K(0.74)

*) average based on grid-point assessments of Jones (1985)

**) similar but 65 ° N to 85 ° N

Table 3. Correlations and signals of annual or 10 yr low-pass filtered (LP) air temperature data (near surface) in respect to the volcanic activity indices SVI or DVI. The signal-to-noise ratios are added in parenthesis where the "noise" is simply the observed temperature data standard deviation. Correlation confidence level exceeded: - - - 90%, — 95%, = 99% (autocorrelation is taken into account for by means of reduced degrees of freedom, non-Gaussian distributed series by means of the Fisher transformation).

The squared coherence analysis, however, see Fig. 3 (spectrally desintegrated correlation analysis), reveals a very important result. All volcanic forcing parameters, including SVI, prove to be significantly correlated with the Northern Hemisphere mean temperature TNH in the long-term domain where the periods greater than roughly 20 or 30 years exceed the 99% confidence level. This confirms the hypothesis that single volcanic events - except very few extremely explosive eruptions - are climatologically less meaningful than relatively long-term fluctuations. Qualitatively the results presented in Fig. 3 are hard to interprete. It may be that not only accumulation effects of volcanogenic aerosols due to their stratospheric residence time but also volcanism itself occuring in typical long-term fluctuations (Fig. 1) are responsible for the results of the coherence analysis. In detail, these results are open for discussion and further investigations.

In order to study some details of the volcanism-temperature relationships in the long-term domain it is possible to use low-pass filtered data which focus the attention on the long-term fluctuations. There is, however, a statistical complication. The more intensive the low-pass filtering of the time series data the greater is the autocorrelation which hampers the identification of the real correlation of the time series. Therefore, a relatively weak low-pass filtering is used, 10 yr Gaussian low-pass

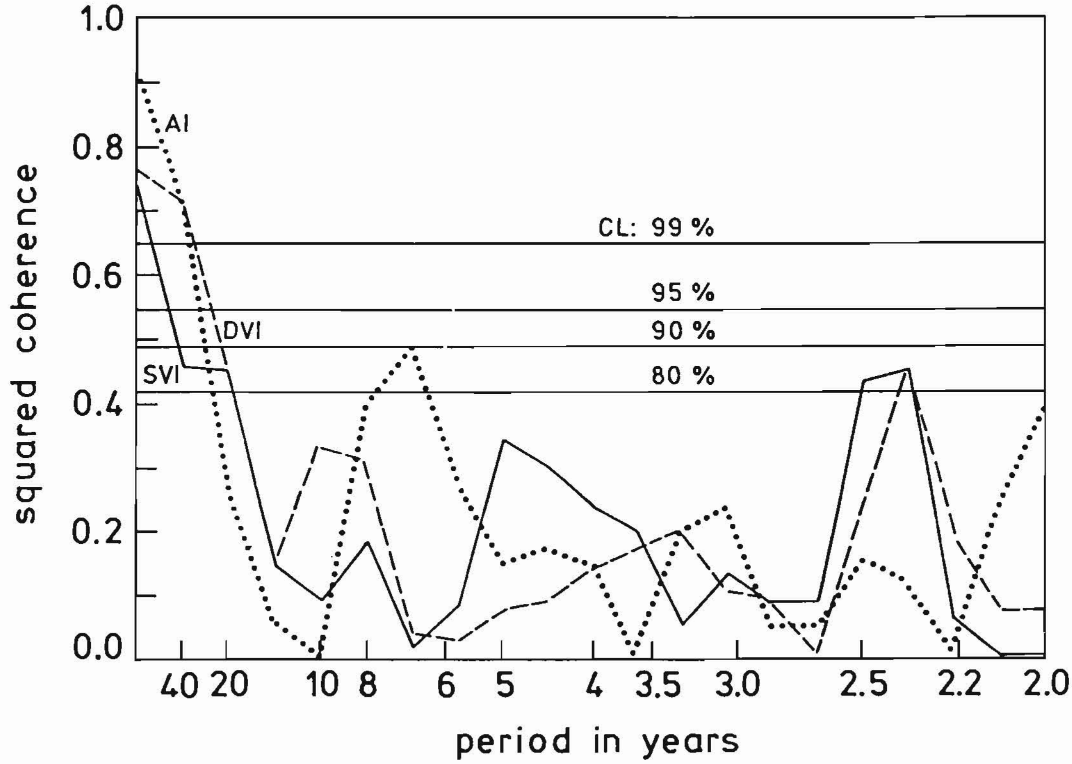

Fig. 3. Squared coherence (disintegrated correlation) spectra of the mean Northern Hemisphere annual air temperature data near surface 1881-1980 correlated with the volcanic activiy parameters, AI, DVI and SVI (compare Fig. 1). CL indicates the confidence levels 80% (error probability 0.2) ... 99% (0.01).

filtering (Fig. 1), and in addition all computations were performed using unfiltered annual data. In Table 3 (column 5 and 6) "LP" means low-pass filtered data and it can be seen that the correlations increase in case of low-pass filtering but these correlation coefficients are not significant (due to autocorrelation). One needs both, the coherence analysis which specifies the long-term relationships to be more significant than the relationships in the annual domain and the low-pass filtered data in order to study the details of the fluctuations in time.

This is done in Fig. 4 where the Northern Hemisphere mean annual temperature variations TNH, 20 yr low-pass filtered, are compared with the corresponding time series of SVI and DVI. Since roughly 1800 some cool epochs can be related to high levels of SVI (see arrows) and DVI, namely c. 1810-1820, 1880-1890, 1905-1915 and 1965-1975. Note that in earlier times SVI and DVI are sometimes contradictory, for example 1760-1770. While the relationships in earlier times remain problematic it seems to be very important that since approximately 1880 the anticorrelations of temperature and the SVI parameter are outstanding. In particular, the temperature increase c. 1910-1940 (more pronounced in the earlier part of this interval) and the subsequent decrease until c. 1965/1970 coincide very well with the opposite trends of the SVI parameter where SVI is the only parameter which could "explain" the onset of this decrease as early as approximately 1940. This result may be meaningful in the context of multivariate analyses of temperature fluctuations implying the effect of the anthropogenic rise of greenhouse gases (see e.g., Hansen *et al.,* 1981; US Department of Energy, 1985; Schönwiese, 1987a).

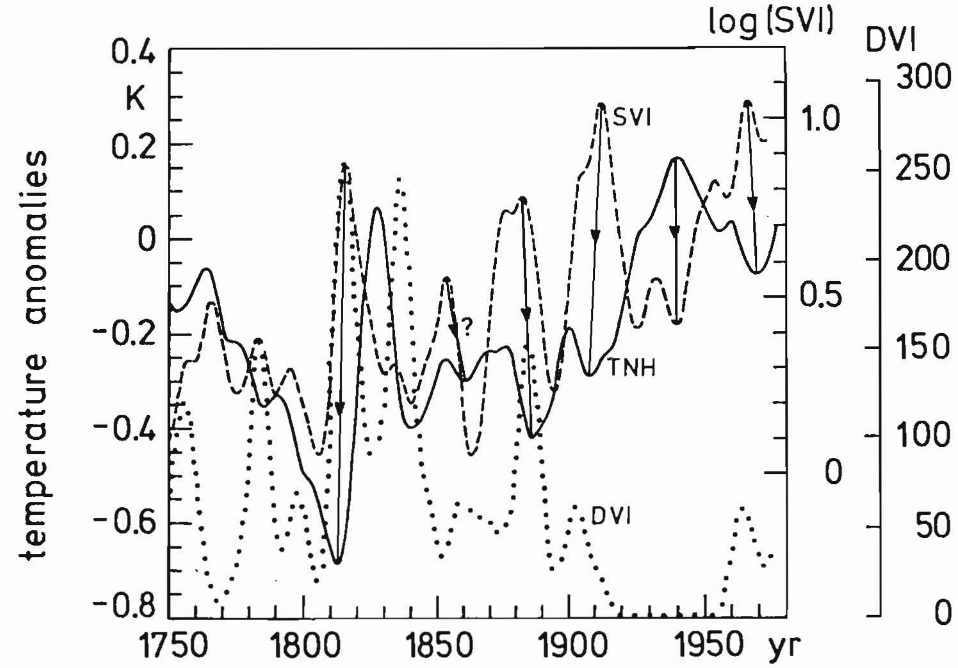

Fig. 4. 20 yr Gaussian low-pass filtered data of the mean Northern Hemisphere annual air temperature variations compared with correponding data of the volcanic activity parameters SVI (dashed line) and DVI (dotted line). The arrows indicate some negatively correlated maxima or minima.

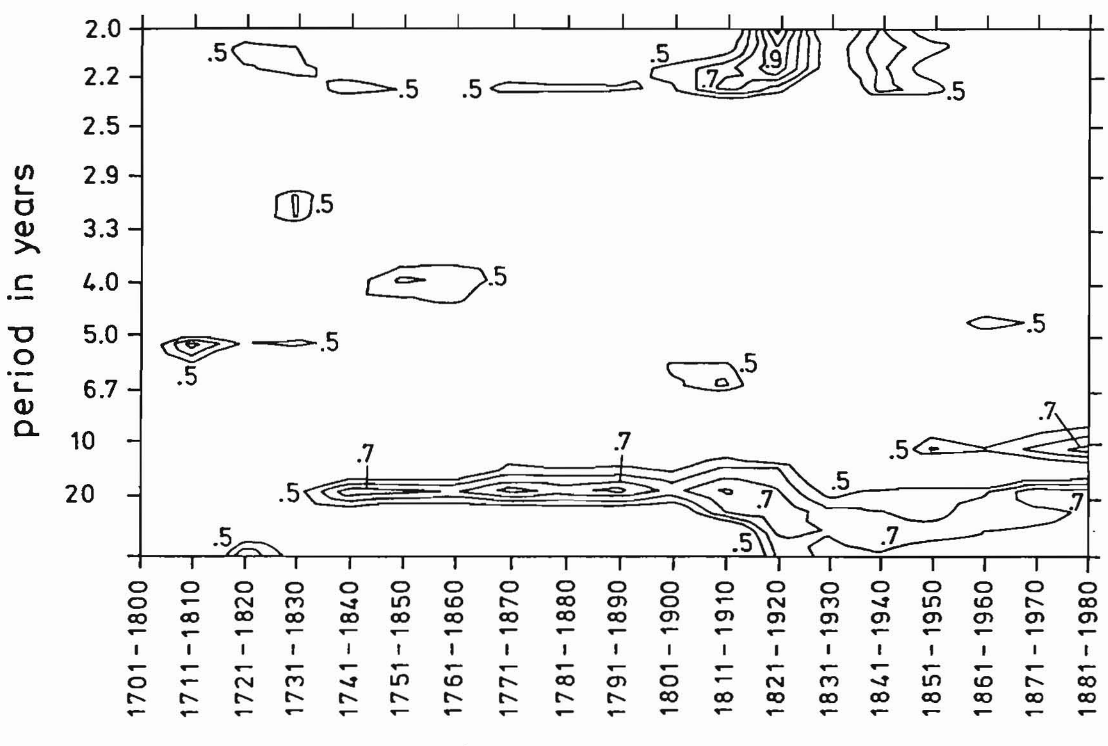

Fig. 5. Moving squared coherence spectrum of the mean Northern Hemisphere annual air temperature variations near surface correlated with the volcanic activity parameters DVI (100 yr subintervals moved in 10 yr steps 1701-1800, ... , 1881-1980). The contour lines indicate correlation coefficients $r^2 \geqq 5$.

Figs. 5 and 6 present a moving squared coherence analysis where the coherence of 100 yr subintervals in 10 yr steps (1701-1800, 1711-1810, ...) is computed. The results are plotted in the terms of contour lines of the correlation coefficients ($r^2 \geqq .5$). Note that in case of SVI the correlations concentrate in the long-term part of the spectrum with a well-marked interruption of coherence within the subintervals c. 1821-1920 (after Tambora eruption) until 1851-1950 (before Agung eruption) whereas in case of DVI the correlations seem to concentrate in a c. 15-25 yr period band. In addition, the DVI parameter points to a pronounced year-to-year coherence with respect to the 1821-1920 subinterval (compare eruptions of Tambora, Krakatau, Santa Maria and Novarupta in this subinterval, see Table 2). In summary, moving coherence analysis confirms the predominant long-term volcanism-climate relationships but also indicates that these relationships are not stable in time. In particular, the SVI parameter reflects the weak volcanic activity and, in consequence, the weak relations with climate in the 1821-1920 → 1851-1950, subintervals.

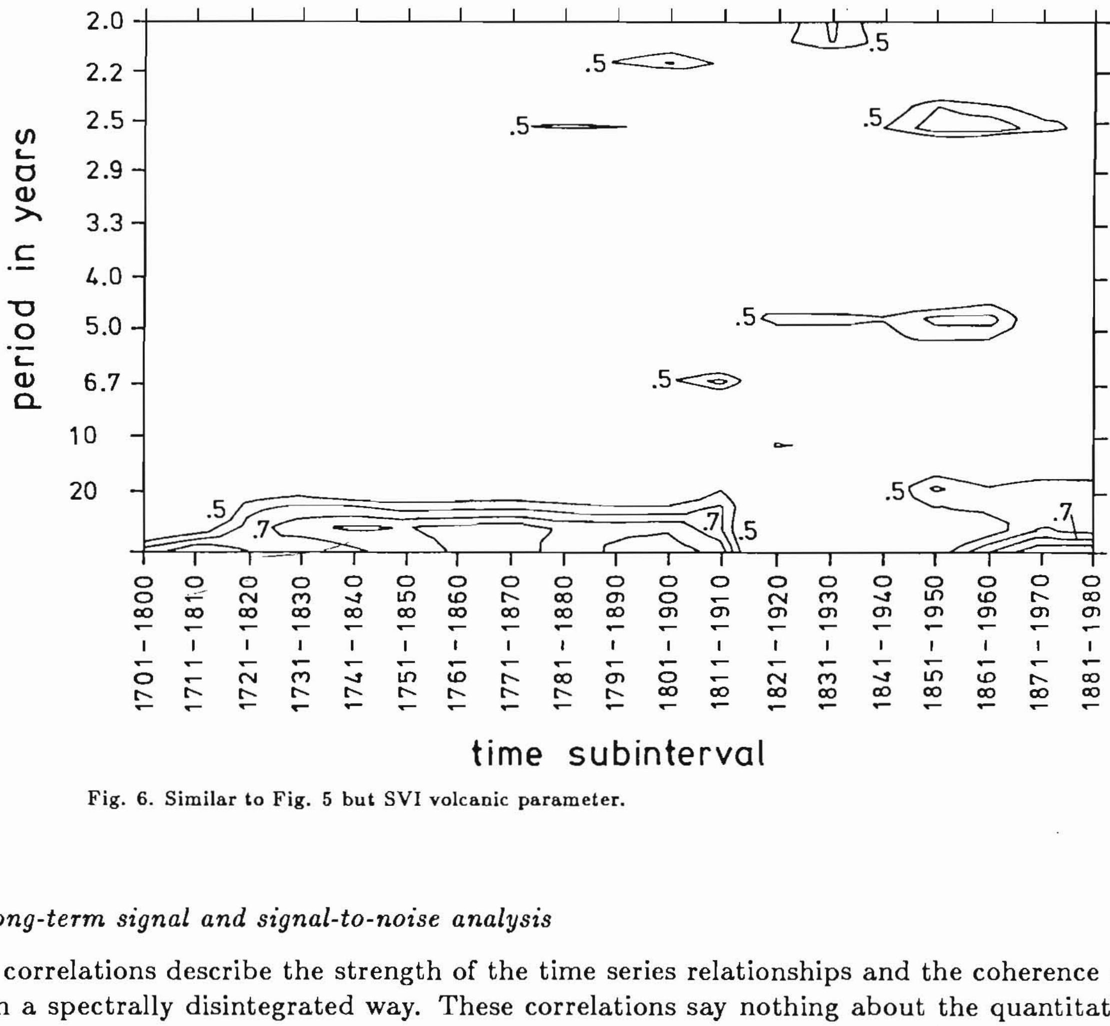

Fig. 6. Similar to Fig. 5 but SVI volcanic parameter.

3. 3 Long-term signal and signal-to-noise analysis

The correlations describe the strength of the time series relationships and the coherence does the same in a spectrally disintegrated way. These correlations say nothing about the quantitative temperature effects both in the year-to-year as well as in the long-term domain. (It may be possible to find small temperature effects despite of high correlations and vice versa). Therefore, the correlation and regression analysis must be extended in the way that also the volcanogenic temperature anomalies or "signals" are computed and these "signals" must be compared with the total observed data variability referred to as "noise". In this context an observational-statistical measure of "noise" is used represented by the observed climatic annual data standard deviation.

Table 3 summarizes not only the correlations with respect to the unfiltered and 10 yr low-pass filtered data but also to the related maximum temperature effects. First, in case of the annual data, the numbers based on the DVI parameter are again greater than those based on the SVI parameter. If one assumes that the SVI results may be more realistic then it can be seen that the mean Northern Hemisphere temperature signals are in the order of .3 K but .7 K in the arctic region both based on the 1851-1983 interval (Northern Hemisphere 1781-1983 c. .5 K). These numbers are computed in the way that the observed maximum and, alternatively, minimum value of SVI (or DVI, respectively) is used in the corresponding regression equation in order to assess a temperature decrease (forced by the difference of the DVI or SVI extreme values). This temperature decrease is called the "signal" which can be hypothetically attributed to volcanic forcing. Note that in case of Philadelphia this signal is as high as 1 K (or even 1.2 K based on the DVI parameter) and that also on the mountain Hohenpeissenberg signals of .6 K (or .4 K) are found despite of the extreme weak (and strictly non-significant) correlations.

Performing the same procedure in the long-term domain (10 yr low-pass filtered data) the signals increase considerably in case of the Northern Hemisphere data 1781-1984 and based on SVI (in the arctic region a weak decrease is found). Using the DVI parameter this increase is found in case of Northern Hemisphere 1851-1980, Hohenpeissenberg 1781-1984 and very pronounced in case of the arctic data 1851-1984.

Most of the signal-to-noise ratios exceed the observed annual data standard deviation (numbers > 1), except Hohenpeissenberg. The most confident results (signal-to-noise ratio > 2 corresponding to > 95% confidence level) are obtained in case of the low-pass filtered Northern Hemisphere data, except SVI 1851-1984 (similarly confident annual data, DVI 1781-1984).

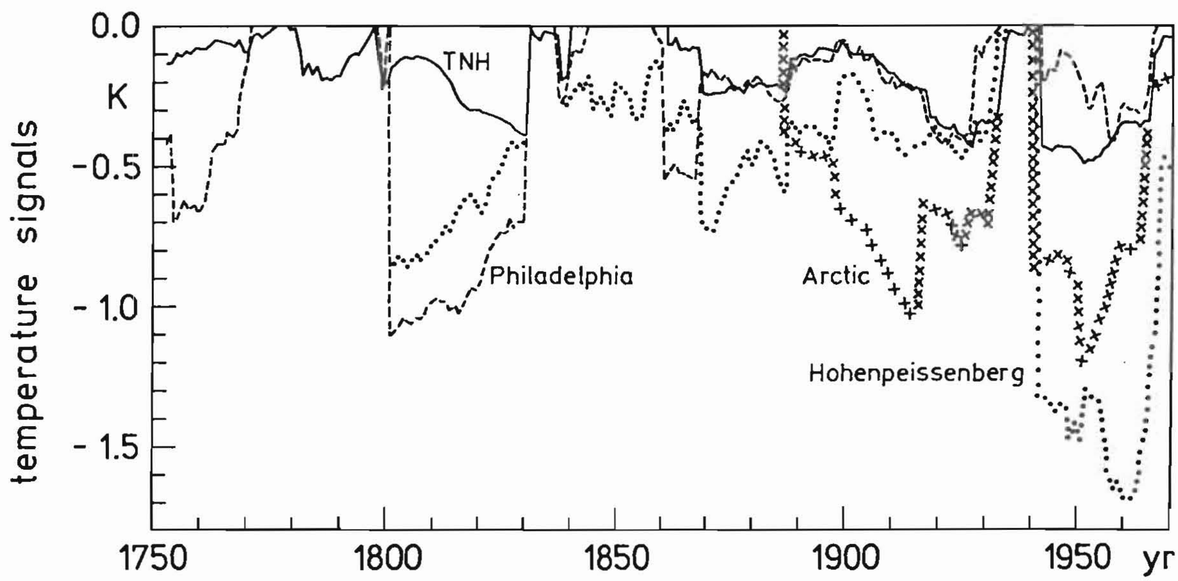

Fig. 7. Moving temperature signal analysis concerning the volcanic parameter SVI and the following annual air temperature variations: mean Northern Hemisphere TNH (solid line), mean arctic (crosses) as well as the stations Phyladelphia (USA, dashed line) and Hohenpeissenberg (FRG, dotted line), 30 yr subintervals moved in 1 yr step (1750-1779, 1751-1780, ..., 1951-1980).

Finally, the concept of moving signal analysis allows to study the temperature effects in respect to particular epochs of the climate history. In Fig. 7 the results of a moving signal analysis are plotted where 30 yr subintervals are moved in 1 yr steps (1750-1779, 1751-1780,..., 1951-1980). These results point to sudden influences of particular volcanic eruptions at particular stations: Tambora signal c. -1.1 K in Philadelphia and c. - .9 K in Hohenpeissenberg; Krakatau signal c. -.7 K in Hohenpeissenberg; Agung signal c. -1.3 K in Hohenpeissenberg; in Philadelphia a further signal is indicated which should be attributed to any volcanic eruptions approximately in 1770 (in terms of 30 yr subinterval moving analysis the signals appear 15 yr before the center of the time interval. The mean Northern Hemisphere signals are in the order of not more than c. -.4 K at maximum. Note that in general signals decrease slowly after their sudden appearance with the exception of the Tambora signal in the Northern Hemisphere data and the Agung signal in the Hohenpeissenberg data where the signal increase with time. This can be only interpreted in the sense of an accumulation effect due to additional volcanic eruptions. These signals are quite different from those found by Angell and Korshover (1985) by means of the superposed epoch method with the exception of the mean Northern Hemisphere data where some similarities can be seen (-.25 K signal in case of Krakatau and -.31 K in case of Agung).

Conclusions

The analysis of volcanism-climate relationships on an observational-statistical basis and within the recent centuries from where directly measured climatic data are available must be emphasized on temperature effects although an influence on the atmospheric circulation and precipitation may also be possible. The parameterization of volcanism which is needed for an analysis of volcanism-climate relationships can be based on the VEI (volcanic explosivity index) chronology of the US Smithsonian Institution (Simkin *et al.,* 1982, 1985) where the "SVI" parameter (Smithsonian volcanic index. based on the VEI data) presented in this paper may be an appropriate alternative hypothesis to other volcanic activity parameters. This parameter is focussed on the major explosive eruptions but includes also some "volcanic noise".

Some particular outstanding eruptions can be hypothetically identified simultaneously by stratospheric warmings and cooling of the atmospheric layer near surface. Particularly the cooling effects in the atmosphere near surface are, however, very weak on a year-to-year time scale and it can be suggested that they are often masked by additional superimposed processes.

The statistical technique of coherence analysis, however, "integrated" and moving with time, reveals that the volcanism-temperature correlations become significant in the relatively long-term domain of the variance spectrum, whereas only very few singular volcanic events are climatologically meaningful. Moving signal analysis, finally, shows that - particularly in this long-term domain - the influence of volcanism on climate is not negligible and must be taken into account in multivariate analyses of climate variations.

Further improvements of volcanism parameterization are necessary. Two points of view seem to be predominantly important. The residence time of volcanogenic particles must be taken into account for the case of the SVI parameter (Schönwiese, 1988) and, still more important but not easy ,to realize, the chemical properties of the volcanic ejecta must be considered in order to enable a more justified classification of volcanic eruptions for climatological purposes.

Acknowledgements

This study was supported by the German Goverment Climate Research Programme (BMFT, Project No. K. F. 2012 8) I am grateful to H. Jäger (Garmisch-Partenkirchen, FRG), K. Labitzke (Berlin West) and T. Simkin (Washington, USA) for providing data and also for some comments, in addition to C. Newhall (Vancouver, USA) for critical suggestions concerning an earlier draft of this paper.

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