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Statistical signal and signal-to-noise assessments of the seasonal and regional patterns of global volcanism-temperature relationships

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RESUMEN

Con el fin de investigar el forzamiento volcánico de la temperatura del aire en una escala global, se usan cinco series de tiempo de parámetros de actividad volcánica, de las cuales dos representan nuevas modificaciones de evaluaciones previas. Estas series de tiempo se comparan entre sí y con las variaciones de las observaciones troposféricas (1851-1984) y estratosféricas (1964-1984), de las cuales en el caso de temperaturas troposféricas (cerca de la superficie) hay disponibles 108 "cajas" regionales de series de tiempo de datos estacionales.

Además del análisis de correlación, que incluye técnicas con movimiento en el tiempo, se usa un modelo de regresión múltiple, que incluye también forzamiento solar, ENSO y CO_2 antropogénico. De este modelo se obtienen los signos de la máxima temperatura del aire estacional y regional que puedan deberse al forzamiento volcánico. Estos signos, así como las razones de signo-ruido, se presentan en sus promedios hemisféricos zonales y en un mapeo regional en todo el mundo.

ABSTRACT

In order to investigate the volcanic forcing of air temperature on a global scale five different volcanic activity parameter time series are used, two of them representing new modifications of earlier assessments. These parameter time series are compared with each other and with the observed tropospheric (1851-1984) and stratospheric (1964-1984) temperature variations whereby in case of the tropospheric temperature (near suface) 108 regional 'boxes' of seasonal data time series are available.

In addition to a correlation analysis, including techniques moving in time, a multiple regression model is used which includes also solar, ENSO and anthropogenic CO_2 forcing. From this model the seasonal and regional maximum air temperature signals are derived which may be due to volcanic forcing. These signals as well as the signal-to-noise ratios are presented in their hemispheric and zonal mean averages and in regional mapping all over the world.

1. Introduction and Data Base

The climate of the Earth is influenced by a number of different forcing mechanisms. If we focus our attention on secular time scales, the following forcings of interannual climatic changes have to be discussed: variations of stratospheric dust loading due to volcanic eruptions, changes of solar activity, man-made atmospheric concentration increase of greenhouse gases, interactions of different subsystems of the climate system (for example ENSO) and stochastic variations. Among these forcings, volcanism is one of the most important, because in this case a wellknown physical basis of volcanism-climate relationships exists. Moreover, volcanism might be the most important natural counterpart of the man-made greenhouse effect.

Explosive volcanic eruptions eject particles and gases into the stratosphere and form large-scale aerosol layers. Measurements (Hofmann and Rosen, 1983, 1987; Rampino and Self, 1984) have shown that silicate particles are removed after a few weeks, but sulphuric acid particles formed by gas-to-particle conversions have a stratospheric residence time of a few years and become, therefore, the dominant volcanogenic aerosol in the stratosphere. These stratospheric aerosols have the physical property to absorb and to scatter the solar irradiation which leads to a warming of the stratosphere, whereas the atmospheric surface layer is cooled (Ramanathan *et al.*, 1987).

In a number of theoretical, empirical and statistical investigations the stratospheric warming by a few degrees (Angell and Korshover, 1985; Labitzke *et al.*, 1987; Quiroz, 1983) and the cooling of the lower atmosphere (near surface) by a few tenths of degrees (Hansen *et al.*, 1988; Hunt, 1977; Gilliland and Schneider, 1984; Robock, 1989; Bradley, 1988; Schönwiese, 1988 a+b; Cress and Schönwiese, 1990) after large explosive volcanic eruptions were confirmed. Although the climate response to volcanic eruptions is a large scale phenomenon, most of the investigations are concentrated on some selected stations and regions and little is known about the global pattern of this response.

Angell and Korshover (1985), for example, found by means of a superposed epoch analysis regional surface air temperature anomalies between -1.5 °C in the USA and -1 °C in Europe after particular explosive volcanic eruptions. Lough and Fritts (1987) determined coolings in response to volcanism in large parts of the USA, which are most marked in summer, based on temperature reconstructions from tree-ring chronologies since 1602. Kondo (1988) reports that the summer temperatures in Japan are on average 1.3 °C $\pm$ 0.5 °C below the mean value after the recent large explosive volcanic eruptions, whereas the mean Northern Hemisphere air temperature decreases only by 0.2 °C.

This paper uses the global surface air temperature data set 1880-1984 based on 108 box data time series (monthly means) provided by Hansen and Lebedeff (1987) for the assessment of the possible regional temperature signals caused by explosive volcanic eruptions. The mean hemispheric and global response to volcanic forcing is considered by using three different temperature data sets provided by Jones (J; 1985; Northern Hemisphere 1851-1984; Southern Hemisphere 1858-1984 and global 1858-1984), Hansen and Lebedeff (H; 1987; Northern Hemisphere 1851-1984; Southern Hemisphere and global 1880-1984) and Vinnikov (V; 1990; Northern, Southern Hemisphere and global 1881-1984); details see Schönwiese, 1990. Stratospheric temperature records for the Northern Hemisphere are available since 1958 from Angell and Korshover (1984), alternatively from Labitzke *et al.* (1986) including zonal means, (Labitzke *et al.*, 1986) and for the Southern Hemisphere since 1965 from Angell (1988). These temperature records are correlated with the volcanic activity parameters described in the next section.

In order to determine the climate effects of volcanism on an interannual time scale it is necessary to evaluate long-term records of past volcanic activity. In that case records should take into account the column height of the eruption material, its volume, its sulphur content, its particle radius and its stratospheric residence time. Unfortunately, such detailed informations exist only for some recent eruptions (case studies, e.g. St. Helens, El Chichón, Nevado del Ruíz) and all available long-term vocanic activity parameter time series fail for cover this complex information. In particular, the chemical properties of the ejecta are not known. These shortcomings should be realized in all analyses and interpretations of volcanism - climate relationships.

In some previous papers including this journal we have described some of these available long-term volcanic activity parameter time series (Schönwiese, 1988b; Cress and Schönwiese, 1989, 1990). This includes the "dust veil index" (DVI) from Lamb (1970, 1983), the acidity index AI (based on ice core reconstructions, station Crête, Central Greenland, provided by Hammer *et al.* (1977, 1980) and Smithsonian volcanic index (SVI) based on the comprehensive volcano chronology (volcanic explosivity index VEI) of the Smithsonian Institution (USA, Simkin *et al.*, 1981, 1984), see papers from Cress (1987), Schönwiese (1988), Schönwiese and Cress (1988), Cress and Schönwiese (1989, 1990). These papers discuss also the advantages and disadvantages of these volcanic activity parameters. The AI index, for example, overestimates the signals from adjacent eruptions (e.g. Laki, Hekla, Katmai, Bezymianni). This is why the AI data may be multiplied by a latitudinal dependent correction factor (see also Lamb's regression equations and Hammer, 1977) in order to obtain a time series which may be more or less representative for the Northern Hemisphere. We used the following latitudinal corrections:

3	for eruptions between 20°N - 20°S	
2	for eruptions between 21°N - 50°N	
1	for eruptions between 51°N - 90°N	(1.1)

implying information from the DVI and SVI indices. This modified AI parameter is called AI1 and included in our analysis. In addition to these parameters (DVI, SVI, AI, AI1) we also use a modified SVI index called SVI* in this paper. This SVI* index takes into account the volcanogenic stratospheric particle residence time by means of a comparison between the SVI (eruption) and AI (deposition) data using the following equation:

$$c = c_o \exp(-Bt) \tag{1.2}$$

where c is the particle concentration at time t, c_o the initial concentration just after any eruption ($t = 0$) and B an empirical factor. The Tambora eruption in 1815 (VEI = 7, AI = 495) appears to be a proper "experiment" for the assessments of B at time t_1 (one year after the eruption), t_2 (two years after the eruption) etc. Using c_o = SVI in equation (1.2), a residuum concentration c can be evaluated for the subsequent years. These values are added to the SVI data year by year. For further details see Schönwiese, 1988a, 1989b; Cress, 1987; Schönwiese and Cress, 1988, Cress and Schönwiese, 1990. Both SVI and SVI* are available as annual data time series 1500-1984 representative for the Northern and Southern Hemisphere such as for global effects (DVI Northern Hemisphere again 1500-1984, Southern Hemisphere 1880-1984; AI and AI1 only Northern Hemisphere 1500-1972).

The correlations of these volcanic parameter time series are small but significant (correlation coefficients between +0.16 and 0.43). Some problems arise, however, from the fact that these correlations are not stable in time (Schönwiese 1988a, Cress and Schönwiese, 1990). Although these volcanic activity indices are really not perfect proper state-of-the-art parameters, they should be used, however, due to their different advantages and disadvantages and their weak intercorrelations in an alternative way.

2. Statistical analysis of the volcanism-temperature relationships

2.1 Univariate analysis

Obviously, volcanism-temperature relationships are much more pronounced than correlations with other climate elements (Schönwiese *et al.*, 1990; Schönwiese and Runge, 1988). In a first step an univariate correlation analysis of the volcanic activity parameters and the mean hemispheric and global surface air temperature records is performed. The results, see Table 1, confirm qualitatively the assumption based on physical mechanisms and models: negative correlation coefficients are congruent with a cooling of the atmospheric surface layer in case of an increased volcanic activity. Simultaneously, the correlation coefficients of the mean stratospheric air temperature series and the volcanic activity parameters are positive, see Table 2, indicating a warming of the stratosphere due to increasing volcanism. Obviously the Northern Hemisphere and global air temperatures show a better correlation than the Southern Hemisphere and global

Table 1. Cross correlation coefficients of the annual mean air temperature records averaged for the Northern Hemisphere (NH), Southern Hemisphere (SH), and the globe (GL), data source Jones (J), Hansen and Lebedeff (H), Vinnikov (V), and the volcanic activity parameter records DVI, SVI, SVI*, AI and AI1; references see text. The numbers in parentheses indicate the phase shifts in years (volcanic forcing leading). Underlining specifies the confidence levels exceeded: - - - 90%, —— 95%, ═══ 99% (autocorrelation is taken into account by means of reduced degrees of freedom, non-Gaussian distributed series by means of the Fisher transformation).

temperature	period	Volcanic activity parameter				
		DVI	SVI	SVI*	AI	AI1
TNH-J	1880-1984	-0.46(5)	-0.35(5)	-0.47(5)	-0.32(5)	-0.65(5)
TNH-J	1851-1984	-0.38(5)	-0.24(5)	-0.32(5)	-0.24(5)	-0.42(5)
TNH-H	1880-1984	-0.48(8)	-0.31(5)	-0.44(5)	-0.62(5)	-0.65(5)
TNH-H	1851-1984	-0.41(8)	-0.19(5)	-0.25(5)	-0.35(5)	-0.47(5)
TNH-V	1881-1984	-0.44(4)	-0.29(5)	-0.42(5)	-0.58(5)	-0.59(5)
TSH-J	1880-1984	-0.21(8)	-0.27(2)	-0.39(1)	------	------
TSH-J	1858-1984	- - -)*	-0.19(2)	-0.28(1)	------	------
TSH-H	1880-1984	-0.18(0)	-0.28(2)	-0.42(1)	------	------
TSH-V	1881-1984	-0.17(7)	-0.23(8)	-0.39(8)	------	------
TGL-J	1880-1984	-0.51(8)	-0.32(5)	-0.45(5)	-0.59(5)	-0.63(5)
TGL-J	1858-1984	-0.40(8)	-0.23(5)	-0.31(5)	-0.44(5)	-0.45(5)
TGL-H	1880-1984	-0.54(8)	-0.30(5)	-0.41(5)	-0.60(5)	-0.66(5)
TGL-V	1881-1984	-0.54(8)	-0.27(5)	-0.39(5)	-0.59(5)	-0.63(5).

Table 2. Cross correlation coefficients of the mean annual stratospheric temperature records averaged for the Northern and Southern Hemisphere, data source Angell (A) and Labitzke (L), and the volcanic activity parameter records SVI* and DVI, period 1965-1984. The numbers in parentheses indicate the phase shifts in years. Underlining specifies the confidence levels exceeded: - - - 90% —— 95%, ═══ 95%.

Temperature	volcanic activity paramenter	
	DVI	SVI*
TNH-L	+0.46 (0)	+0.39 (0)
TNH-A	+0.33 (0)	+0.38 (0)
TSH-A	+0.49 (1)	+0.36 (1)

air temperatures. The reason is that most of the (land-based) volcanic eruptions are concentrated on the Northern Hemisphere. The highest correlations exist between the modified "acidity index" AI1 and the different air temperature series whereas the SVI parameter shows the smallest. The alternative temperature series reveal no significant difference of the correlations. In Figure 1 the correlation coefficients for the stratospheric (16-24 km, Labitzke *et al.*, 1986; 1965-1984) and surface layer (Hansen and Lebedeff, 1987; 1880-1984) air temperatures and a selected volcanic parameter (SVI*) are compared. The change of sign is remarkable in respect to the stratospheric air temperatures (significantly positive to significant negative correlations) in the latitude belt 60°N- 70°N. The reason may be that the radiation emission of the volcanic aerosol layers becomes the dominant effect in the polar night.

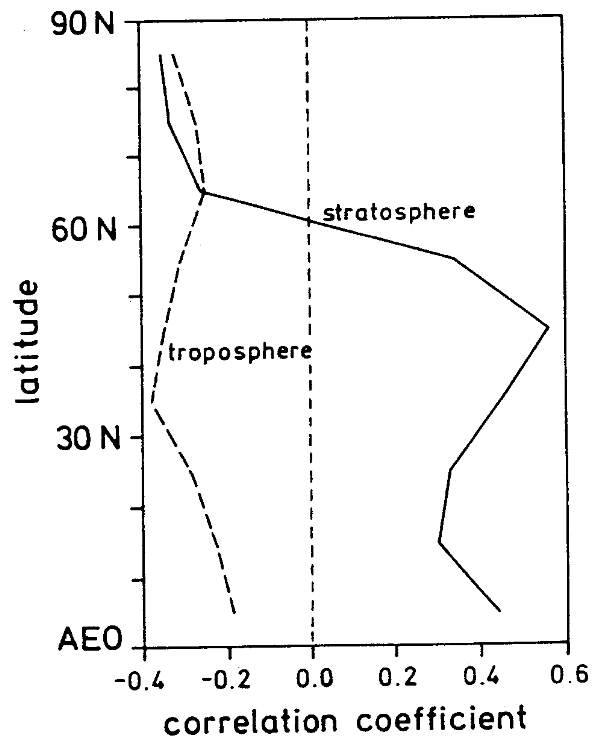

Fig. 1. Annual mean correlation coefficients of the zonal mean Northern Hemisphere tropospheric (near surface, 1880 -1984) and stratospheric (1965-1984) air temperatures and the volcanic activity parameter SVI*.

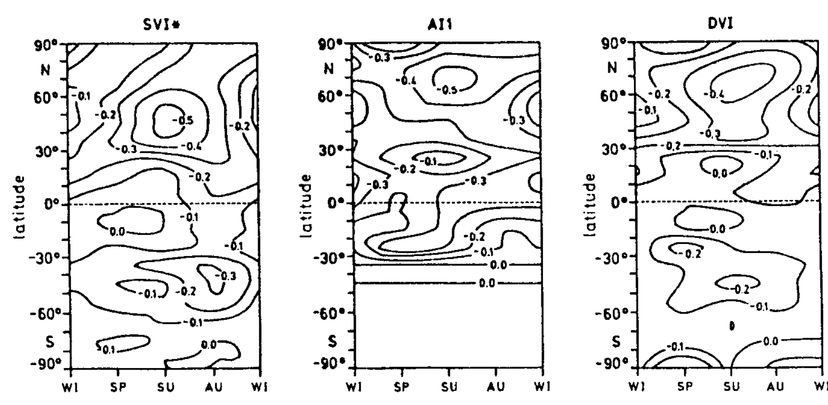

Fig. 2. Correlation coefficients of the volcanic activity parameters SVI*, AI1, and DVI and the latitudinal-seasonal surface air temperature (data source Hansen and Lebedeff, 1987), period 1880-1984.

The seasonal-latitudinal correlation pattern between the surface air temperature after Hansen and Lebedeff (1987) and the three different volcanic activity parameters are presented in Figure 2. In the Northern Hemisphere, the highest correlations are found in summer in middle and high latitudes, whereas in winter weaker relationships are revealed. The correlation maximum between the surface air temperature and the SVI* parameter appears between 40°N and 50°N, displaced somewhat to the North if the DVI or AI1 indices are used. Only small relationships are realized in low latitudes. The correlation coefficients on the Southern Hemisphere are generally smaller than on the Northern Hemisphere indicating a maximum between 30°S and 50°S in summer and spring.

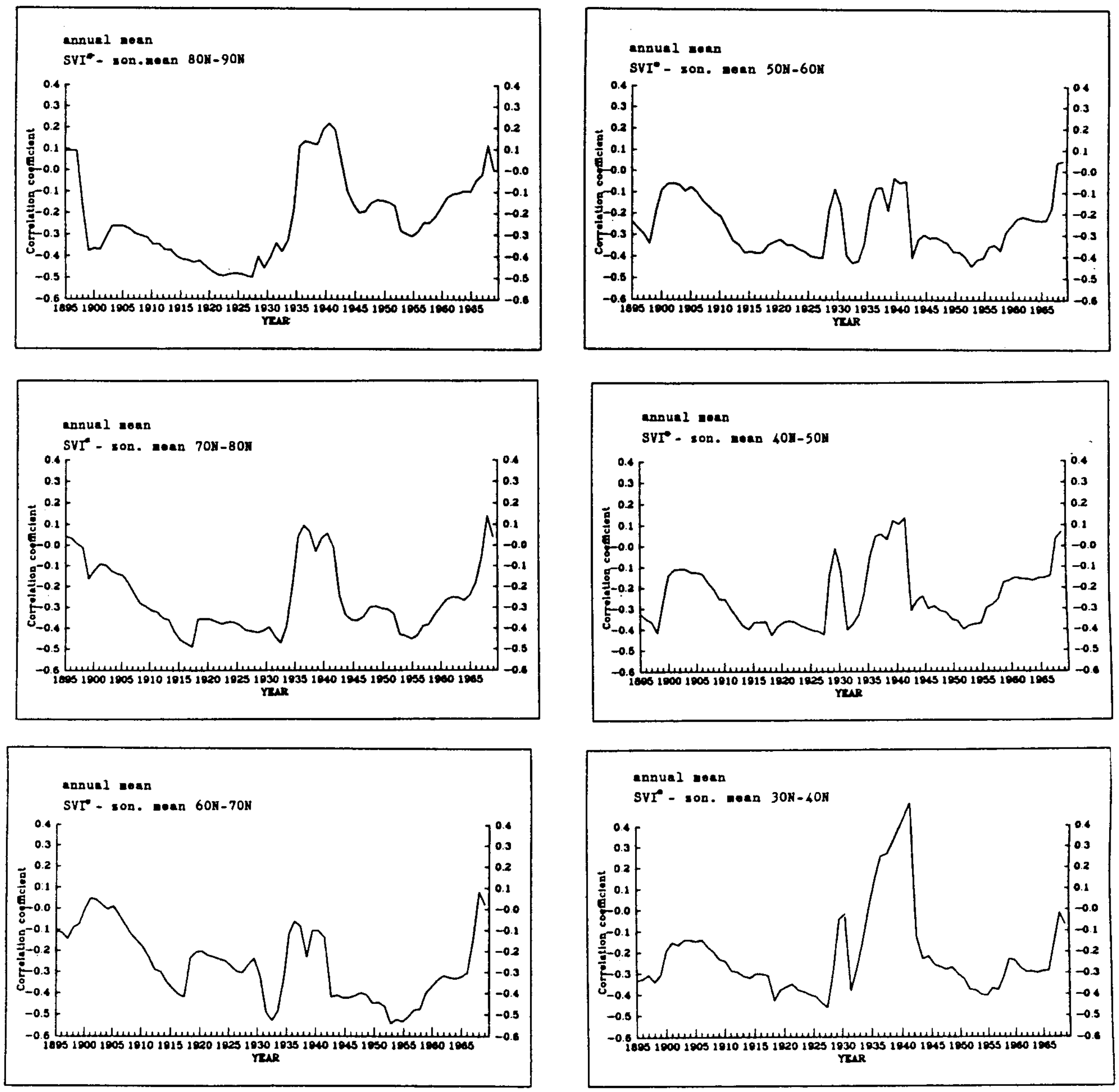

Fig. 3. Moving correlation coefficients (30 year subintervals moved in one year time steps) of the zonal mean surface air temperature, (data source Hansen and Lebedeff, 1987) and the volcanic activity parameter SVI* (annual mean data, latitude zones indicated).

In recent years, the long-term effects of volcanic eruptions came up for discussion in respect to the observed warming of the Northern Hemisphere in the 1920s and 1930s which may have occurred in connection with weak volcanic activity and the Northern Hemisphere cooling in the 1950s and 1960s, which may be due to a possible increase of volcanic activity (Robock, 1989; Schönwiese, 1986, 1988a, 1988b; Schönwiese and Cress 1988; Cress and Schönwiese, 1990). In a moving correlation analysis (Fig. 3) we examined the temporal stability of the relationships between the volcanism (using the SVI* parameter) and the zonal mean air temperature (data from Hansen and Lebedeff, 1987) for the time interval 1880-1984. A strong discontinuity is detectable in the interval 1915-1945 (interval center, 1930) leading from significant negative correlations to insignificant positive correlations and a similar jump from positive values to significant negative correlations in the interval 1930-1960 (interval center, 1945). Moreover, the instabilities are strongest in high northern latitudes decreasing in direction to lower latitudes. The results are in fair agreement with the observed course of temperature since 1920: a warming until the 1940s, especially in high northern latitudes, and a cooling of the air temperature since 1945. Due to these results a connection between the warming (surface air temperature) in the 1920s and 1930s, the following cooling in the 1950s and 1960s and volcanic activity cannot be excluded. (For coherence analyses which reveal the low-frequent correlations of volcanism and temperature see e.g. Schönwiese, 1988.)

2.2 Multiple analysis

The correlations described in the previous section verify the relationships between the volcanic and temperature time series more or less qualitatively, but nothing is said about the quantitative temperature effects (*signals*) due to volcanic activity. Moreover, additional forcings, which may be in competition with volcanic forcing, are neglected. For this reason, in a second step a multiple linear regression model

$$y = a_o + \sum a_i x_i \tag{2.1}$$

(y = climate predictant (here, global temperature box data near surface from Hansen and Lebedeff, 1988), x_i = predictors and a_i = regression coefficients) was applied in order to separate the temperature signals hypothetically forced by volcanic activity from the total observed temperature data variability referred to as *noise*. In addition to volcanism the following forcing parameters were used as predictors in order to explain statistically a predominant part of the observed temperature variance:

- four alternative solar parameters (solar activity variations and related hypotheses; solar diameter variations)
- atmospheric CO_2 concentration time series
- SOI (El Niño/southern oscillation) parameter (details, see Cress and Schönwiese, 1990; Schönwiese *et al.*, 1990).

Only one of the volcanic and solar parameter types are alternatively used in each equation. Hence, 20 alternative regression equations are available from where the hypothetical temperature decrease due to the observed minimum value (temperature without volcanic influence $\rightarrow t_1$) and maximum value (t_2; signal $= t_2 - t_1$) of the volcanic parameters can be assessed. In order to remove some interannual (maybe stochastic) variability a 3-year low pass filter is used.

The results of a corresponding signal and signal-to-noise assessment is summarized in Table 3. The mean signals for the Northern Hemisphere are obviously in good agreement with the observations (Angell and Korshover, 1985; Bradley, 1988) and numerical model simulations (e.g. Hansen *et al.*, 1988), whereas the Southern Hemispheric signals are weaker and less significant. The most significant signals are found in case of the AI index and the Northern Hemisphere temperatures. Again the SVI-index reveals only small effects.

Table 3. Statistical assessments of the 3 yr low pass filtered maximum volcanism-induced temperature (annual and hemispheric or global averages) signals in respect to the different volcanic activity parameters based on multiple linear regression models, period 1882-1984. The signal-to-noise ratios are added in parentheses where the "noise" is the observed temperature data standard deviation (based on unfiltered data). Underlining specifies the confidence levels exceeded: - - - 80%, —— 90%, ═══ 95%. All signals in K.

temperature	volcanic activity parameter record				mean signal	s
	DVI	SVI	SVI*	AI		
TNH-J	-0.37(1.54)	-0.23(0.96)	-0.30(1.25)	-0.46(1.92)	-0.34(1.41)	0.24
TNH-H	-0.54(1.73)	-0.25(0.96)	-0.35(1.35)	-0.47(1.81)	-0.38(1.47)	0.26
TNH-V	-0.41(1.77)	-0.20(0.87)	-0.32(1.41)	-0.44(1.91)	-0.34(1.48)	0.23
TSH-J	-0.16(0.84)	0.05(0.26)	-0.15(0.79)	-0.18(0.94)	-0.11(0.56)	0.19
TSH-H	-0.18(1.07)	0.02(0.10)	-0.16(0.97)	-0.20(1.18)	-0.13(0.76)	0.17
TSH-V	-0.17(0.88)	0.06(0.30)	-0.08(0.43)	-0.14(0.76)	-0.08(0.45)	0.19
TGL-J	-0.30(1.50)	-0.12(0.59)	-0.18(0.91)	-0.32(1.60)	-0.23(1.15)	0.20
TGL-H	-0.40(1.81)	-0.17(0.77)	-0.27(1.23)	-0.38(1.73)	-0.30(1.39)	0.22
TGL-V	-0.29(1.46)	-0.08(0.39)	-0.18(0.90)	-0.29(1.45)	-0.21(1.07)	0.20

Figure 4 illustrates the seasonal and latitudinal pattern of the maximum volcanism-induced temperature signals as average values of all regression equations. The largest temperature decrease is found in polar regions of the Northern Hemisphere in winter, in coincidence with Robock (1989) who stresses that the sea ice thermal inertia feedback is responsible for this strong tem-

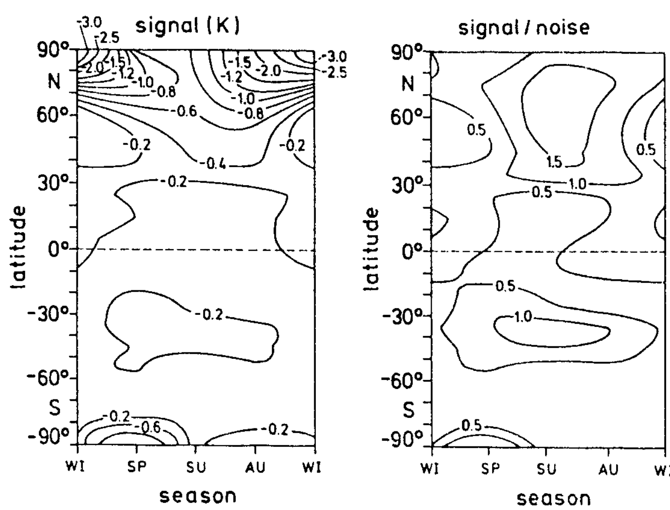

Fig. 4. Seasonal-latitudinal assessments of the maximum volcanism-induced temperature signals and signal-to-noise ratios based on the multiple regression model described in the text (averaged for all volcanic activity parameters).

perature response. In mid latitudes the maximum signal is found in summer which is, however, very weak. In contrast to that, the signal-to-noise ratios (S/N) and their confidence (S/N = 1 corresponding to more than 67% confidence), see Figure 4, exceed the S/N values of 1 in summer and fall in mid and highnorthern latitudes with a maximum signal-to-noise ratio (> 90% significance) in summer, 40°N - 80°N, in correspondence with results from Bradley (1988). The reason is that in these latitudes the *noise* of the temperature data is weaker in summer than in winter. The Southern Hemisphere indicates only a small signal belt between 30°S - 45°S which exceeds S/N = 1 in summer. In addition to the zonal mean temperature signals induced by volcanic eruptions, Figure 5 presents the regional distribution of the temperature signals for summer and winter. Supplementary, in Figure 6 the corresponding regional signal-to-noise ratios are shown. In the winter season, see Figure 5a, the maximum signals (up to -3°C) are found again in high northern latitudes. Considerable secondary maxima are indicated in the north-eastern USA, in Northern Africa and in the 60E region of Antarctica. There are no cooling signals in the Asiatic Continent and in Europe, due to dynamical reasons. The cooling centers in summer (Fig. 5b) are situated in the central parts of America and Canada and in the Northern Pacific area. Obviously, the whole Northern Hemisphere is affected by the cooling, but the signals are

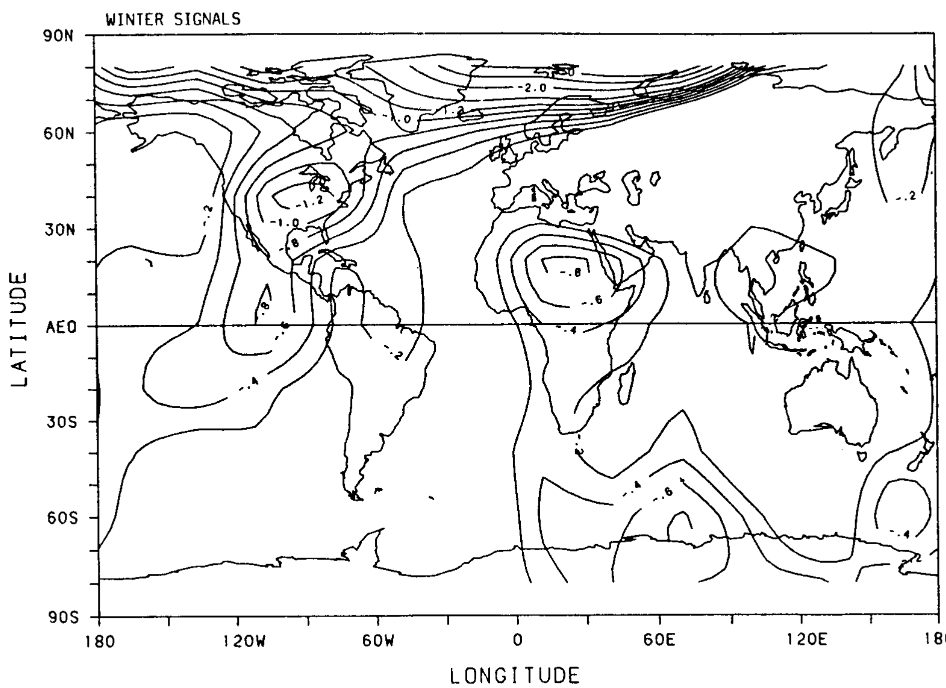

Fig. 5a. Regional assessments of the maximum volcanism-induced temperature signals for the winter season based on the multiple regression model described in the text (averaged for all volcanic activity parameters).

weaker than in winter. The corresponding signal-to-noise ratios (Fig. 6a) specify the maximum values (S/N $\geq$ 1) in winter over the polar region (exceeding the 90% significance level), in parts of south-eastern USA and Central Africa. This picture changes in summer (Fig. 6b), when the maximum signal-to-noise ratios are detected in the central part of Asia (exceeding the 90% significance level) and a secondary maximum can be detected in the polar regions and central parts of the USA (S/N $\geq$ 1).

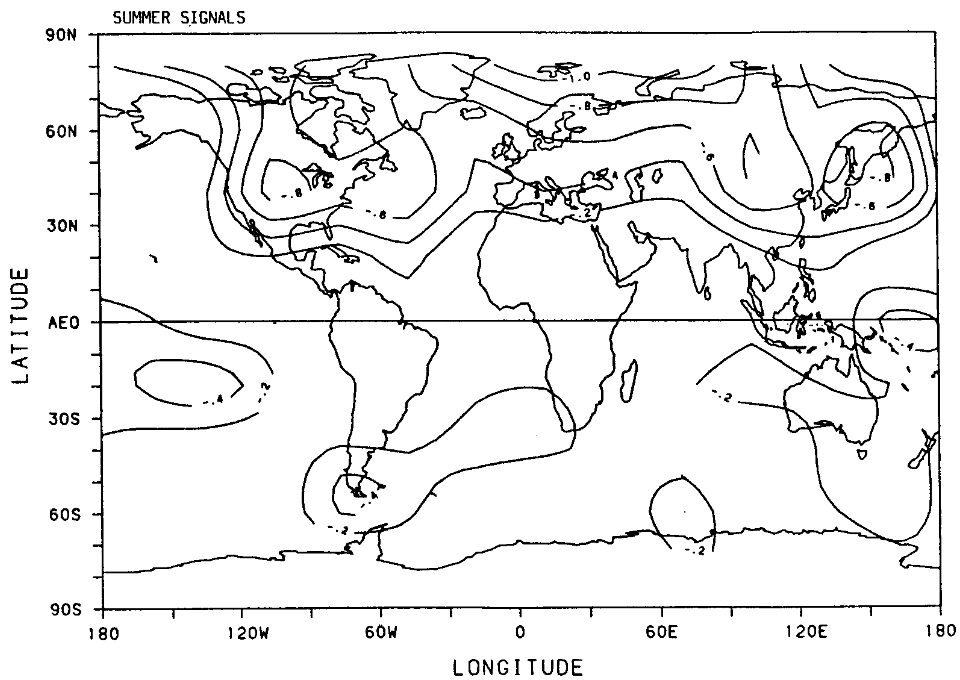

Fig. 5b. Similar to Fig. 5a, but summer.

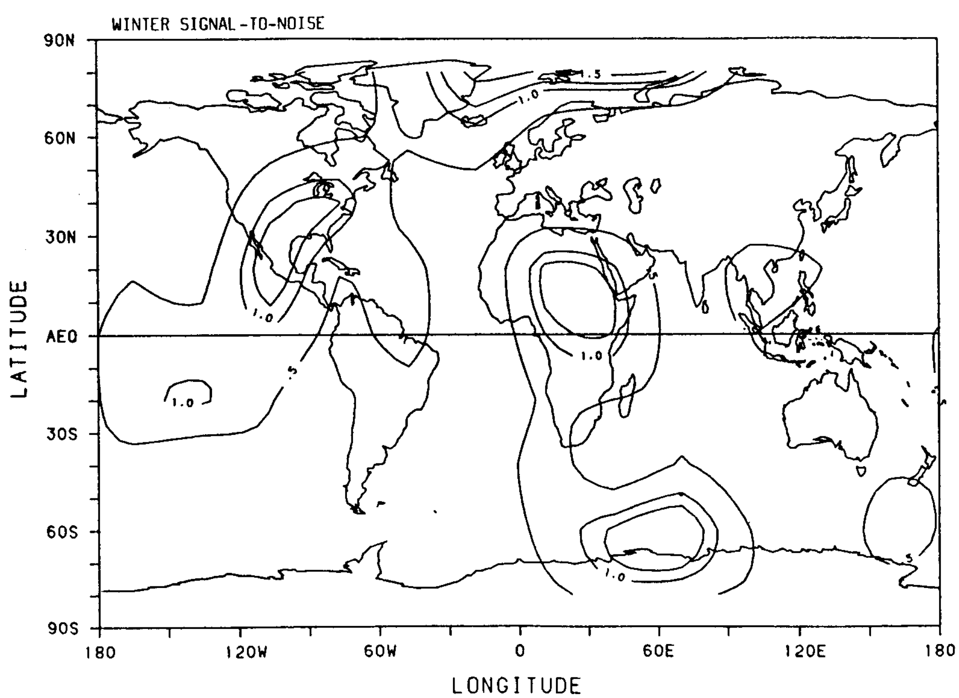

Fig. 6a. Regional assessments of the maximum volcanism-induced signal-to-noise ratios, winter (compare Fig. 5a).

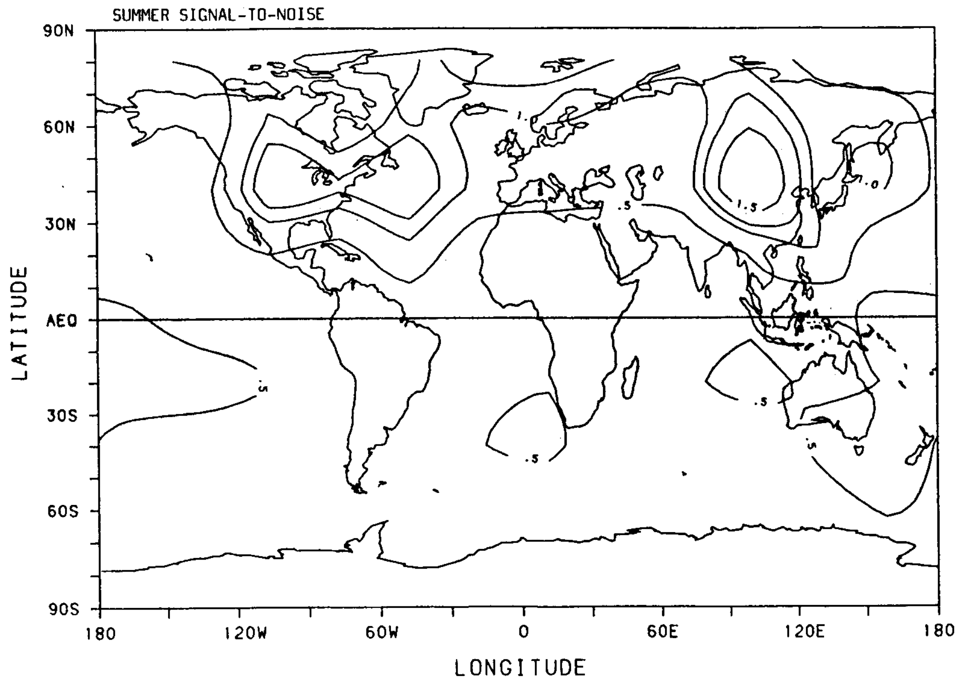

Fig. 6b. Similar to Fig. 6a, but summer.

The seasons spring and fall, see Figure 7, exhibit a remarkable wave-like structure of the cooling isothermes, particularly the Eurasian Continent is affected by an extreme cooling in autumn. The maximum volcanism-induced temperature decrease in autumn is indicated in the

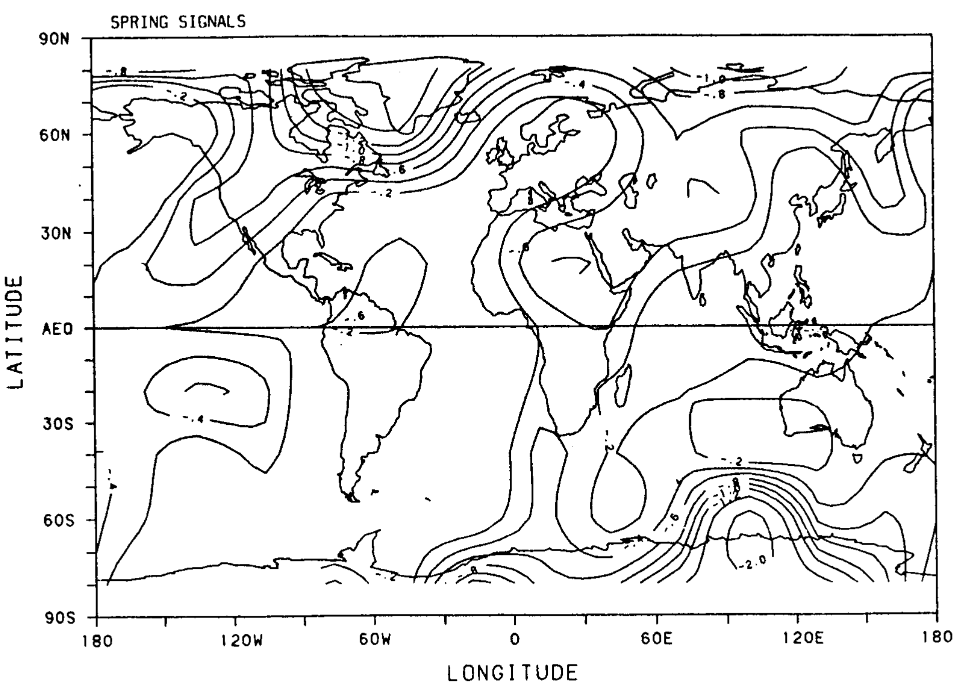

Fig. 7a. Similar to Fig. 5a (signals), but spring.

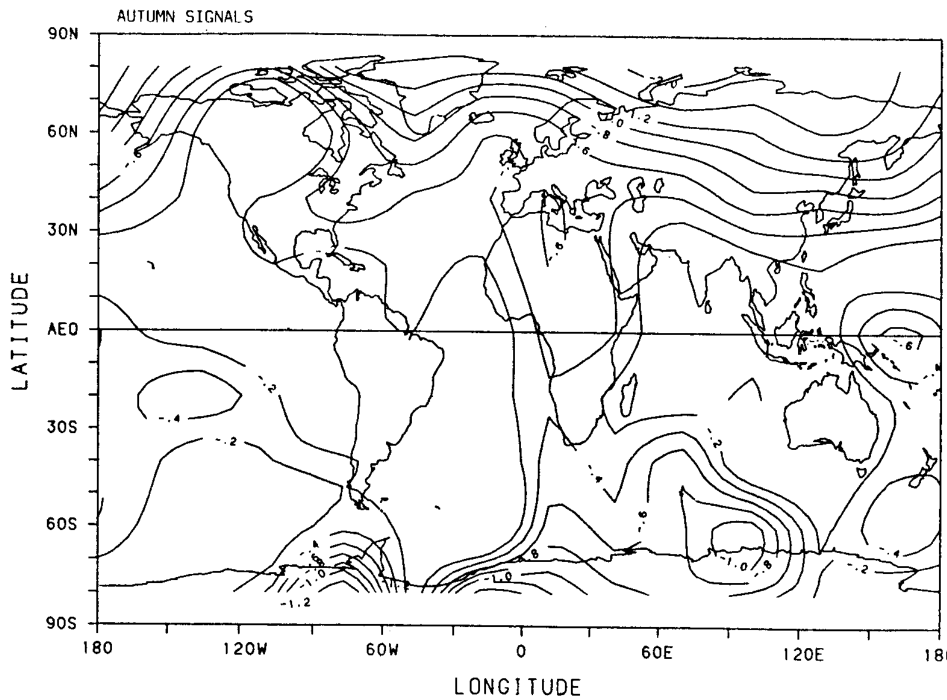

Fig. 7b. Similar to Fig. 5a, but autumn.

northern polar region of the USSR. Remarkable is an also cooling tongue from Greenland over the eastern parts of Canada and USA up to middle America. In contrast to that, the maximum cooling center in spring is to be found over Greenland and north-eastern Canada. From there,

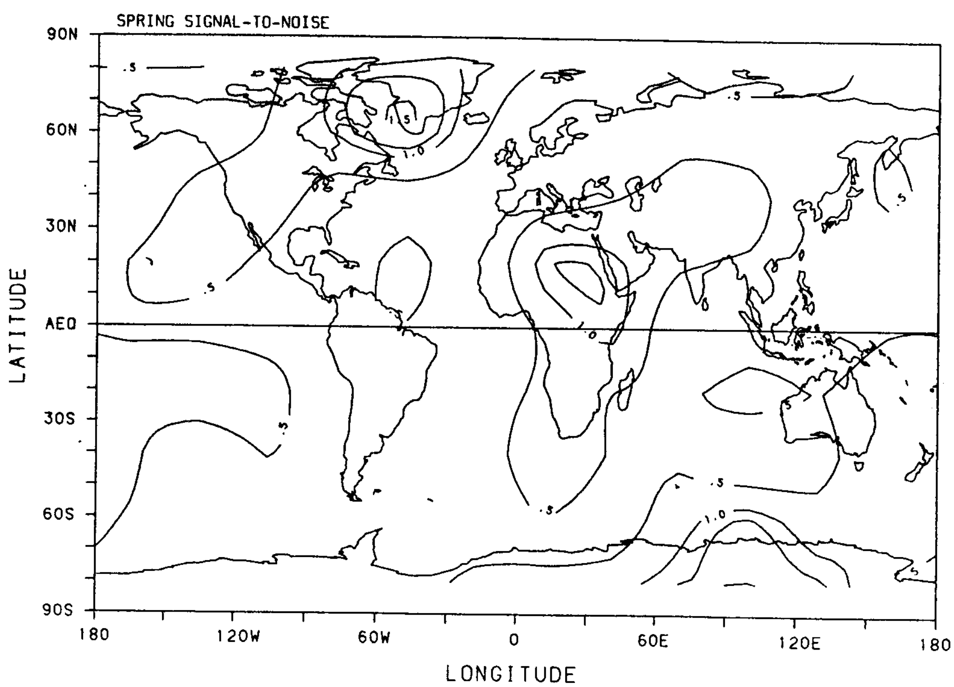

Fig. 8a. Similar to Fig. 6a (signal-to-noise ratios), but spring.

the cool air covers the whole North American Continent, whereby a tongue of warm air spreads over the European Continent. Note also the strong cooling signals in the Antarctic region for both seasons. Due to the small data base in that region a statistical significance assessment of the determined temperature signals is not possible. On the other hand the regional signal-to-noise ratio pattern for spring and autumn illustrated in Figure 8, reveals maximum values in Greenland (> 90% significant) in spring (Fig. 8a) and in contrast to this large S/N ratio in the north eastern part of the Pacific and Japan in autumn. In addition to that a maximum S/N ratio exceeding the 90% significance level in spring and in autumn is detectable in Central Africa.

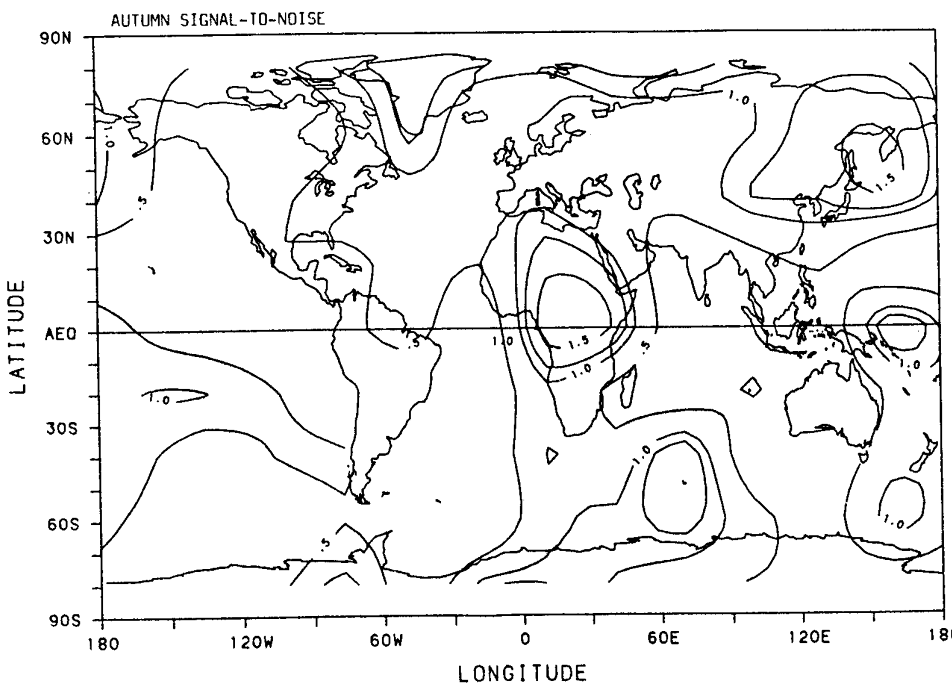

Fig. 8b. Similar to Fig. 8a, but autumn.

3. Conclusions

The statistical analysis of volcanism-climate relationships on an interannual time scale covering the recent centuries requires long-term volcanic activity parameters. Two modified volcanic parameters, SVI* and AI1, introduced in this paper, lead to substantial improvements of the volcanism-temperature correlation assessments. Moving correlation techniques reveal a possible influence on the observed very pronounced surface air temperature increase 1910-1940, and the decrease later on, particularly in northern latitudes > 40°N if the SVI* parameter is used. Latitudinal-seasonal correlation analyses indicate the most significant negative values in summer in middle and high northern latitudes, both decreasing in winter and low latitudes. A corresponding latitudinal analysis for the stratosphere shows the expected positive correlations till 60°N - 70°N changing to negative correlations in the high northern latitudes. In addition to the more or less qualitative correlation analysis of the volcanism-temperature relationships based on univariate statistical methods, a quantitative estimation of the volcanism-induced temperature signals based on multiple techniques is necessary in order to separate volcanism-induced temperature signals from the climatic residuum variance.

Multiple regression models are appropriate for these assessments which imply, in addition to volcanic forcing, the influence of further natural and anthropogenic forcing (greenhouse gases). These assessments reveal a meridional increase of the signals from low to high latitudes up to -3°C in winter in polar regions, whereas the signals in summer are smaller but more significant. The regional and seasonal signal pattern illustrates that in winter the north polar region, Greenland and North America are most affected by volcanic-induced coolings. Coolings of Europe and Asia are, in a smaller magnitude, detectable in summer. The Southern Hemisphere shows only weak and hardly significant signals.

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