VOLCANISM AND CLIMATE

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ABSTRACT: Apart from anthropogenic impact on climate, there are a variety of natural impacting mechanisms which overlap in climate observation data, so considerably complicating the determination of causes and effects. One of these mechanisms is explosive volcanism, which leads to various kinds of particles being released into the stratosphere. These particles scatter and absorb parts of incoming solar radiation, causing the stratosphere to grow warmer and at the same time the lower atmosphere (troposphere) to grow cooler. Therefore volcanism is an antagonist of the "Greenhouse Effect".

INTRODUCTION

Climate is a multi-faceted problem and accordingly it is difficult to determine causes of the many-fold climate variations[1,2]. Even if we limit our scales of space and time to global climate (very wide reaching phenomena) and to long-term processes over decades or centuries, we have to deal with at least the following events:

- anthropogenic enrichment of the atmosphere with trace gases which effect climate (CO_2, CH_4, CFC, N_2O) etc.; anthropogenic addition – "greenhouse effect";
- anthropogenic effects of urban climate
- anthropogenic sulphate particles and other "aerosols" of the lower atmosphere (troposphere), including soot;
- volcanism;
- solar effects (solar activity, etc.);
- ENSO, i.e. (El-Nino-/Southern-Oscillation-Phenomenon (the tropical Pacific episodically growing warmer, combined with certain air pressure variations of the southern hemisphere)
- Stochastic variations in the climate system, i.e. variations which cannot be

explained and are thought to be random.

In cases of anthropogenic influences, we attempt to suppress effects of urban climate, at least as far as global temperature data is concerned, by making adequate corrections or evaluating its importance.

In order to distinguish quantitatively the rest of the effects, Hansen *et al.*[3], for example, have made highly simplified model calculations, which allow comparisons at least in relation to world average temperature (atmosphere near to the ground), see Figure 1. In this example a solar influence of 1% has been reduced to the more realistic variation of solar constants of 0.2% and the probable maximum stochastic effect on global temperature has not been taken into account by Hansen *et al.*[3]. (The assumption that the length of the quasieleven-year-long cycle of the sun spot has a dominating effect on climate can be considered invalidated[4].

Taking into account the limited regional effect of anthropogenic tropospheric aerosols, the disputability of rising future trends, and probably also, as hinted at in Figure 1, the compensation of these effects (sulphate versus soot; natural desert aerosol can be left out here), it makes sense to look closer at volcanism, probably the most important natural antagonist to the "Greenhouse Effect". In this article I will attempt this briefly and with reference to 6,7.

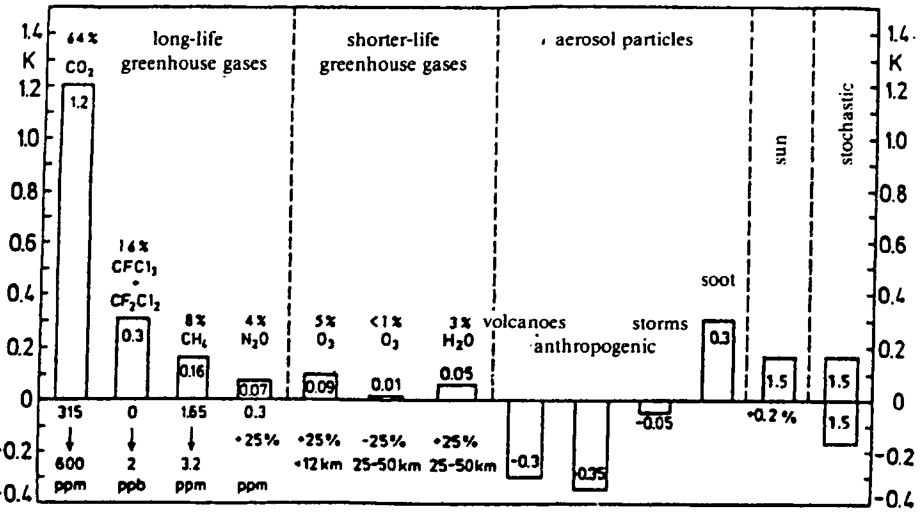

Figure 1. Influence of Greenhouse gases, aerosol particles and other processes affecting climate on near ground world average temperature, maximum scenarios for coming decades, after simplified climate model calculations[3,5], modified.

RELEVANCE OF VOLCANIC ERUPTIONS ON CLIMATE

Volcanoes show a great variety of behaviour[8]. However, only explosive volcanic eruptions are relevant for climate as these release particles and gases into the stratosphere; this is the atmospheric layer between about 10 and 50 km in height. Most important of all are sulphurous gases, which after a few months following the eruption turn into especially effective sulphate particles. When this process is completed but partly immediately following direct particle release into the stratosphere, there appear in good weather conditions typical purple to lilac colorings at dusk. More importantly for climate, radiation effects can then be detected in the atmosphere: in the stratosphere, where volcanogenic climate-effective particles are found, parts of the incoming solar energy is absorbed, consequently leading to increasing stratospheric temperature. Because of this and because of scattering processes, the atmosphere becomes less transparent to solar radiation and this deficit leads to cooling effects in the lower atmosphere (trosposphere, especially near surface), i.e. in our living space. Whether these effects actually occur and become noticeable depends on further factors. As mentioned before, climate is a multi-faceted problem.

The impact on climate of by volcanism can be clearly noted in only a few especially spectacular cases. For example, transmission of solar radiation at Mauna-Lao-Observatory (Hawaii) was temporarily reduced by 15% following the eruption of El Chichon (Mexico 1982)[9]. LIDAR Measurements of stratospheric scattering of particles, as taken amongst other places in Garmisch Partenkirchen since 1976[10]), allow a few other volcanic eruptions to be identified – see Figure 2. Here it is striking that short-term signals of single eruptions are contrasted by long-term trends which have led to comparative maxima in 1982/83 and in 1991/92. This reflects the fact that as a rule in the stratosphere particles remain for several years, in contrast to the lower atmosphere where the residence time amounts to only days. This means, that in case of series of eruptions over the years or, given the circumstances over decades, very effective stratospheric dust veils ("Aerosol layers") can be formed by means of accumulation. Furthermore, effects on even longer time scales are known in paleoclimatology.

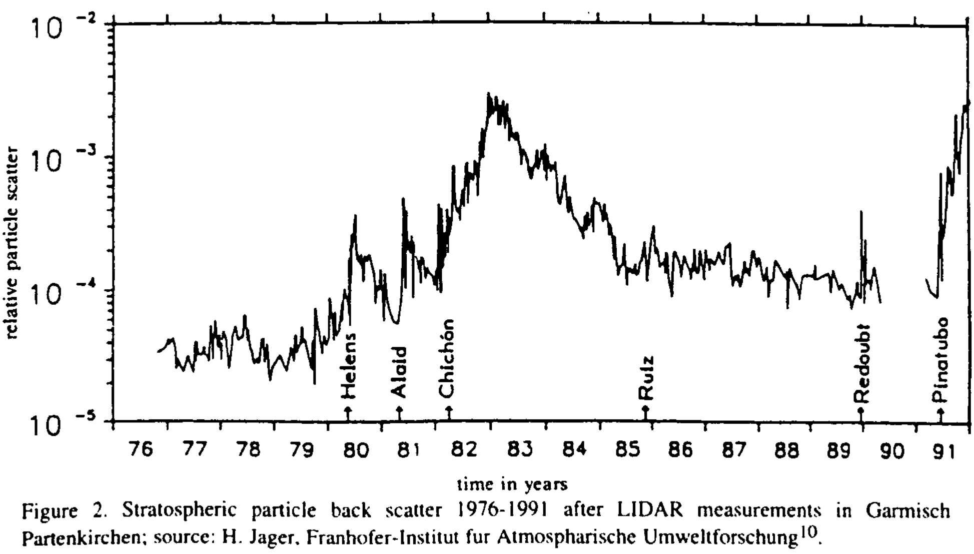

Figure 2. Stratospheric particle back scatter 1976-1991 after LIDAR measurements in Garmisch Partenkirchen; source: H. Jager, Franhofer-Institut fur Atmospharische Umweltforschung[10].

With regard to effects on temperature and therefore to actual climatic consequences, Figure 3 clearly shows that following a few explosive volcanic eruptions the stratosphere is warmed whilst the biosphere is simultaneously cooled, in this case noted as an average for the northern hemisphere and for the year. Especially strong were the effects following eruptions of Agung (1964) and El Chichon (1982) – see also the chronology in the appendix – although there was a very intensive El-Nino effect in the latter, which brought with it a certain level of compensation in the troposphere. Given different circumstances the cooling effect in the latter case would have been much stronger. Although Pinatubo (1991) led to considerably higher concentration of sulphate than El Chichon, impact on climate appears to be similar or even smaller according to current findings[13]. Figure 3 also allows us to notice the long-term trend to a warmer troposphere and the simultaneous trend to a cooler stratosphere, which could be taken as an indication for the anthropogenic "Greenhouse Effect".

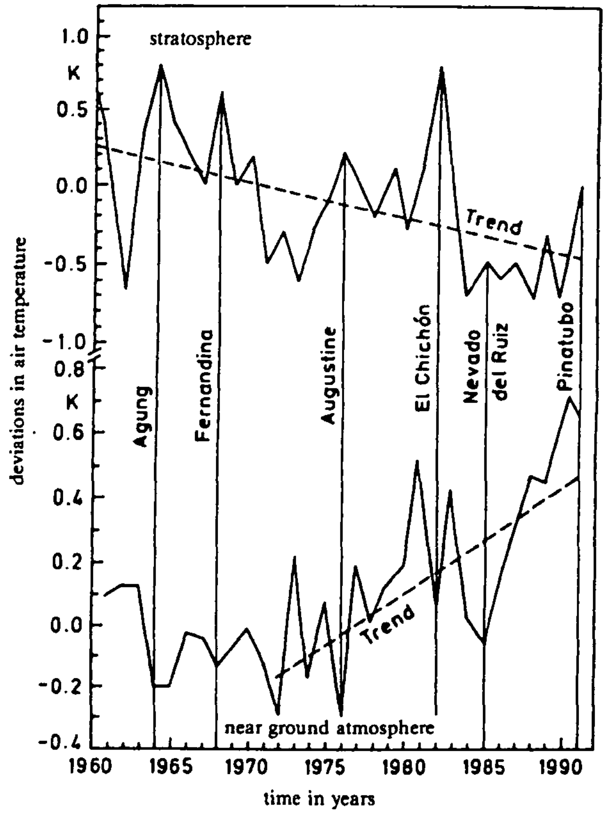

Figure 3. Temperature deviations taken yearly in northern hemisphere 1960-1991 (deviation from average) in the stratosphere (above 12) and in near ground atmosphere (below 11), indicating a few volcanic eruptions and long term trends of temperature.

The fact that volcanically determined effects cover large areas and even reach hemispheric dimensions, especially following a series of eruptions but also occasionally following a single especially strong eruption, is explained by stratospheric flow dynamics. Apart from a two yearly cycle of strong easterly and westerly winds, especially to be found in the tropics (quasi-biennial oscillation, QBO), there exists in this area also a tendency for air masses to be transported in the direction of the poles. Volcanic particle clouds, therefore, quickly circle the earth according to the dominant wind directions, either westerly or easterly, and in the course of a few months gradually spread in the direction of both poles. With regard to large area impacts, for this reason tropical volcanoes have a greater impact than those in the Arctic or Antarctic, because an originally tropical cloud of particles can cover the whole of the hemisphere in the course of time. This is possible even up to the turning radius of the opposite hemisphere, depending on tropical air mass exchange. On the other hand, for instance Arctic volcanoes mainly impact only in their respective climatic zone. However, the northern hemisphere provides far more volcanic eruptions with climatic impact than the southern hemisphere which is mainly covered by the oceans.

Of special interest are long-term temporal variations of volcanic activity, not only in relation to a few special eruptions, but also in relation to all, which may have influenced the stratosphere and therefore climate. Only when we have information about the extent of explosive volcanic activity, well analysed in terms of time and if possible in form of yearly tables, can we classify and interpret the effects of volcanism on the history of climate.

CHRONOLOGIES OF VOLCANIC ACTIVITY

The English climatologist Lamb[14] has estimated yearly levels of the so called *Dust Veil Index* (DVI), which is meant to describe the concentration of stratospheric volcanic dust, for the northern hemisphere since 1500 AD and for the southern hemisphere since 1890. However, many volcanologists prefer the *Volcanic Explosivity Index* (VEI), which is not yearly but relates to each single volcanic eruption, and is meant to classify volume of ejecta as well as heights reached – it does not consider climatological consequences. This is the most comprehensive existing volcanic chronology, put together by the North American Smithsonian Institution[15]. On the basis of this chronology, Bissolloi[16] and Schonwiese[17], later also Cress and Schonwiese[18], attempted to deduce from it a yearly index table from 1500 for the northern hemisphere, called *Smithsonian Volcanic Index* (SVI). If one includes the tropics in the northern hemisphere, by far the most volcanic eruptions take place there and so there are also measurements of consequential depositions in polar ice, which will not be taken into account here (for this topic see references 18 and 19). For the period since 1750, the appendix includes a list of all volcanic eruptions in the northern hemisphere, including 10 degree south, which show a VEI greater than 4. However, from 1960, eruptions with a VEI = 4 are included (compare to Figure 3; 10 VEI + 3.5 indicates volume of particle ejection in m^3). The most powerful eruption of this period (VEI = 7), also of the whole of historical time, was the eruption of Tambora in April 1815, which over large areas of the earth brought with it the so called "Year without Summer". For the same year, Lamb also comes up with the highest level of DVI.

Figure 4 compares yearly volcanic activity chronologies DVI and SVI from 1750 with each other and with the northern hemispheric average temperature. The numbers 1 to 12 or 14 indicate a few especially violent eruptions, which are also noted in the appendix. Chronologies have similarities as well as differences. In the cases of eruptions 3 (Tambora, 1815) and 5 (Krakatau, 1883) there can be found quite good corroboration. On the other hand e.g. eruption no. 7 (Novarupta, 1912) is considered relatively small in DVI chronology. Clear differences in the volcanic chronologies obviously exist also with regard to long-term trends. Thus, the coefficient of correlation between DVI and SVI yearly data since 1500 is only +033[18].

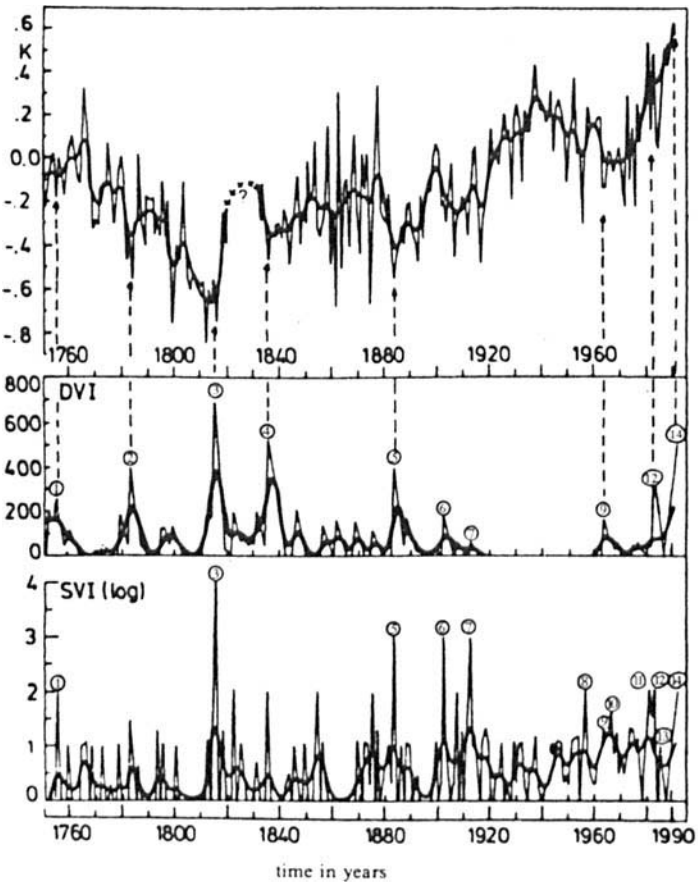

Figure 4. Average deviations of near ground temperature taken in northern hemisphere[11] 1750-1990. Data smoothed out yearly and ten-yearly, in comparison with parameters of volcanic activity DVI and SVI, described in the text (temperature added, design and analysis after[7,18]).

Which chronology is the best? As all chronologies, named and unnamed, have certain advantages and disadvantages, it is hardly possible to answer this question satisfactorily; for discussion see Refs. 7 and 18. As the SVI table is based on VEI classification, which is the most comprehensive historical volcanic chronology and also one defined without a climatological "motive", it should at least be an objective table and not merely based on single events. But even here there are limitations: the increasing trend of total observed volcanic eruptions, especially in the 20th century; uncertainties in the VEI classification; finally and most importantly chemistry and the related gas particle conversion have not been sufficiently taken into account. Finally, one will have to consider more than one volcanic chronology in climatological examinations, in order not to be too dependent on the disadvantages of any one particular chronology.

ANALYSIS OF CLIMATOLOGICAL DATA

Analysis of correlation, especially by the statistically important method of coherence analysis (spectral, i.e. correlation calculation classified according to the characteristic time), show that connections between volcanism and climate are clearer in the long-term than in year by year variations (details[18,20]). In this way, we arrive at the following coefficients for correlation of yearly data displayed in Figure 4 for temperature: DVI, $r = -0.40$; SVI, $r = -0.17$; but for curves which were smoothed out and include only parts of variations from decades upwards: DVI, $r = -0.52$; SVI, $r = -0.38$. The DVI chronology is probably over-estimating connections. (At this point, statistical problems like disturbing persistency of correlation calculations and tests of significance of coherence analysis cannot be considered). These results may not be perfect, but at least they appear to confirm connections between volcanism and temperature.

Results of analysis, classified yearly and regionally, can be seen in Figure 5, whereby calculations are based on multiple statistical models and apart from volcanism have taken into account solar effects, the El-Nino-phenomena and the anthropogenic "Greenhouse Effect" (Cress und Schönwiese[18,20]). Based on these calculations, the left part of Figure 5 shows the maximum volcanically determined cooling of near-ground atmosphere estimated for the past 100 years and able to be ascribed to volcanic activity. It is evident that the strongest cooling effects of up about 3°C appeared in winter in higher latitudes of the northern hemisphere, whilst south of about 50°N these effects remain below 0.5°C.; the average for the northern hemisphere is ca. 0.2-0.3°C. When comparing these cooling or warming effects (during decreasing volcanic activity) with the total variability, or rather more exactly when dividing the calculated signals by the standard deviations of temperature data in the relevant region and season, these so called signal/signal noise patterns do not show their maximum in winter, but in summer between about 40° and 80° North.

This means that volcanically determined climatic impact can better be identified in summer, when it is more noticeable, not least because of agricultural consequences which then appear. Closer analysis prove this to be true especially for North America and East Asia.

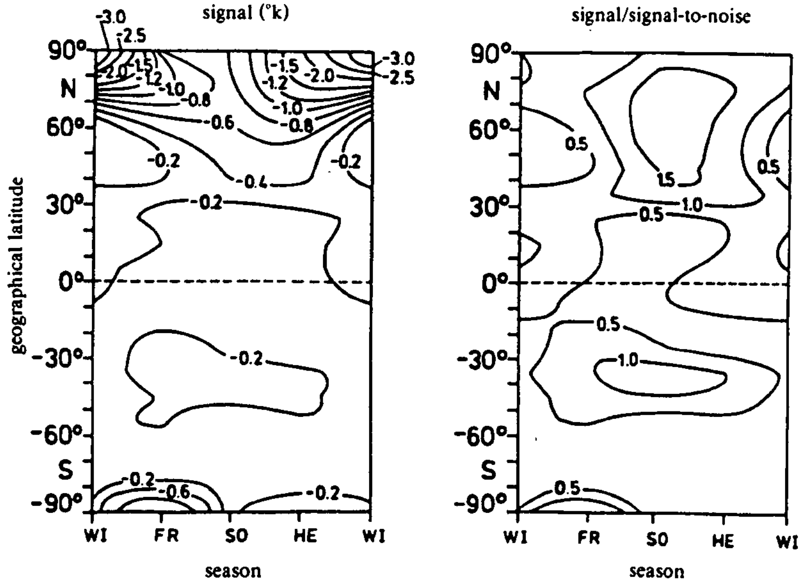

Figure 5. Multiple statistical analysis allowed this estimate of maximum temperature signals in °K (cooling effects, near ground atmosphere), period of time 1890-1990, in seasonal and meridian organisation on the left, as well as conditions of signals/signal-to-noise, whereby the "noise" has been calculated from deviations from standard of temperature data[20].

As all these analysis are based on climate observation data offering statistical explanation, it is important to validate such data by means of deterministic (physics) model calculations. Up until now this has happened only rarely. Hansen *et al.*[3] estimate, with the help of such model simulations, the maximum impact of volcanic activity on global average temperature to be –0.3°C, (comp. Figure 1). This level can be used also as an average for the northern hemisphere. Air pressure anomalies, caused by volcanoes, which may have had an impact of the kind described here, were found by Graf[21] with the help of the Hamburg atmospheric circulation model (Max-Planck-Institut for meteorology). Far-reaching conclusions, however, cannot be drawn from these simulations.

Attempts to find connections between volcanism and climatic elements other than temperature are considerably more problematic. Fluctuations in precipitation for example could well be connected with volcanic eruptions, as these cause higher concentrations of aerosols (floating particles) in the lower atmosphere (troposphere), which act as condensation and ice nuclei in formation of clouds and precipitation. Moreover, the changes of temperature discussed above, have an impact on atmospheric circulation and therefore on precipitation activities. However, their nature makes it difficult to recognise such connections.

OUTLOOK

From a deterministic as well as statistical point of view there are many arguments in favour of connections between volcanism and climate. On the other hand there are many open questions, especially about the impact on other climatic elements than temperature, but also about temperature-signals themselves.

Answering these questions is important for many reasons. One of these is to be given here as a final point. The question whether man changes global climate permanently through emissions or carbon dioxide and other trace gases is a heavily discussed topic. This question can only be answered satisfactorily if we succeed in separating this anthropogenic "Greenhouse Effect" from natural climatic influences. As we know, a gradual rise in temperature (Greenhouse Effect) caused by anthropogenic trace gas impact is expected, as seen in Figure 4 round about 1840 and 1940 and in Figures 3 and 4 from about 1970. Can this theory be invalidated by the subsequently observed fall of temperatures between ca. 1940 and 1970 (Figure 4)? This is certainly not the case, because – as stressed previously – climate reacts to a variety of influences and accordingly only "multiple" examinations can lead us ahead. If for example the fall in temperatures in the northern hemisphere between ca. 1940 and 1970 can be explained by volcanic impact, as it seems to be suggested in Figure 6 by the SVI parameter (but not in the other two volcanic activity chronologies, of

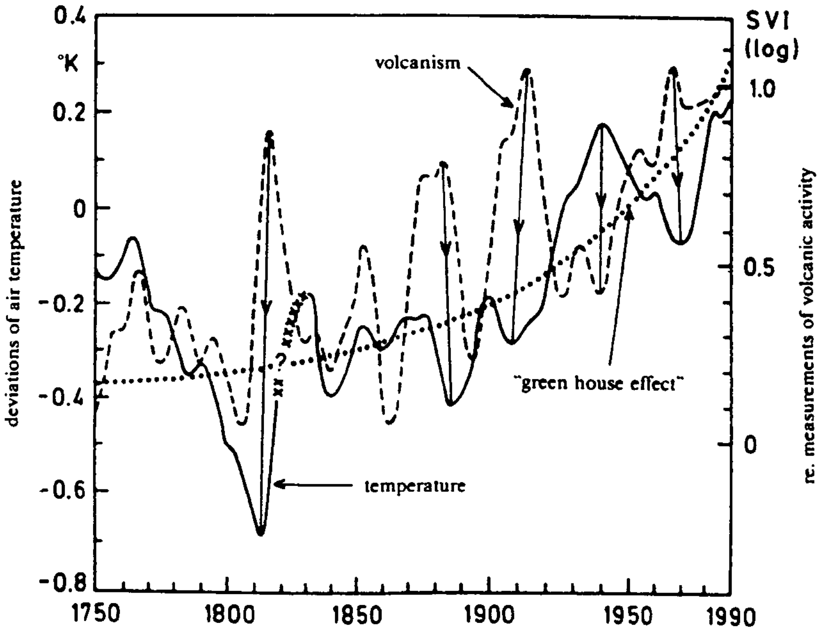

Figure 6. Comparison of northern hemispheric average temperature deviations 1750-1990, similar to Figure 4, but evened out and stretched, with parameter of volcanic activity SVI in lines, and with "green house effect", i.e. rise in temperatures caused by anthropogenically emitted trace gases (CO_2 etc.), in dots, estimated by means of multiple statistical analysis[2].

Figure 4), this would be an important result for the discussion of the Greenhouse Effect and at the same time an important indication for impact on climate caused by volcanism.

In order to answer these questions, further intensive examinations with the help of all known methods are necessary. This is true also for the question which has not been covered here, about impact on stratospheric ozone layer by volcanism (chlorine emissions). It would be wrong to under-estimate natural mechanisms when facing anthropogenic problems.

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APPENDIX

Chronology of a few explosive volcanic eruptions since 1750, important for the northern hemisphere (compare also numbers in Figure 4) with strength index VEI[15]. In contrast, indexes SVI[18] and DVI[14] are for the whole relevant year and possibly include further volcanic eruptions. (Index VEI sums up height of eruption and volume of ejecta; from VEI = 3 the stratosphere may be affected, from VEI = 4 this impact is certain[15,18].

No.	Volcan	Coordinates	Height (abv.NN)	Year (and month)	VEI	Strength SVI	DVI
1	Katla	63.6 N 19.0W	1363 m	1766 (19)	5	100	255
2	Lakagigar (Laki)	64.1 N 18.3 W	500 m	1783 (6)	4	30	400
3	Tambora	8.3 S 118.0 E	2861 m	1815 (4)	7	10001	695
	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
	Sheveluch	56.8 N 161.6 E	3395 m	1854 (2)	5	102	0
	Askja	65.0 N 16.8 W	1510 m	1875 (3)	5	101	120
5	Krakatau	6.1 S 105.4 E	300 m	1883 (8)	6	1012	400
6	Santa Maria	14.8 N 91.6 W	2700 m	1902 (10)	6	1032	180
	Ksudach	51.8 N 157.5 W	1079 m	1907 (3)	5	104	60
7	Novarupta (Katmal)	58.3 N 155.2 W	2285 m	1912 (6)	6	1001	60
8	Bezymianny	56.1 N 160.7 E	2800 m	1956 (3)	5	103	0
9	Agung	8.3 S 115.5 E	3142 m	1963 (3)	4	20	160
	Sheveluch	56.8 N 161.6 E	3395 m	1964 (11)	4	17	(120)
	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	44	80
10	Oldoinyo Lengai	2.8 S 35.9 E	2880 m	1966 (8)	4	44	80
	Awu	3.7 N 125.5 E	1320 m	1966 (8)	4	44	80
	Fernandia	0.4 S 91.6 E	1495 m	1968 (6)	4	19	60
	Tiatia	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
	Polsky Tolbachik	55.9 N 160.5 E	3085 m	1975 (7)	4	13	(40)
	St Augustine	55.4 N 153.4 W	1227 m	1976 (1)	4	14	65
	Bezymianny	56.1 N 160.7 W	2800 m	1979 (2)	4	12	(20)
11	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)	4	25	(40)
12	El Chichon	17.3 N 93.2 W	1350 m	1982 (3,4)	5	107	365
	Una Una	0.2 S 121.6 E	508 m	1983 (7)	4	18	160
13	Nevado del Riuz	4.9 N 75.4 W	5400 m	1985 (12)	4	12	20
	St. Augustine	55.4 N 153.4 W	1227 m	1986 (4)	4	11	10
	Redoubt	60.5 N 152.7 W	3108 m	1989 (12)	4	2	60
14	Pinatubo	15.1 N 120.4 W	1745 m	1991 (6-8)	5	100	500