Russian Journal of Earth Sciences, Vol. 22, ES6005
https://doi.org/10.2205/2022ES000803

"Danjon Effect", Solar-Triggered Volcanic Activity, and Relation to Climate Change

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Received 10 July 2022; accepted 9 September 2022; published 23 December 2022.

The "Danjon effect" is a phenomenon that presents a tendency to concentrate the so-called "dark" total lunar eclipses (DTLE) near solar sunspot cycle minimum phases. It was a starting point for the present study, whose main subject is a statistical analysis of relationship between solar and volcanic activity for the maximum long time. To this end, the Smithsonian National Museum of Natural History's volcanic activity catalog was used. On its basis, a time series of the total annual volcanic eruptions for the period 1551–2020 AD has been built and explored for cycles of possible solar origin. Cycles with duration of 10–11, 19–25, ~60, and ~240 years (all with possible solar origin) has been established. It has also been found that there are two certain peaks of volcanic activity during the sunspot activity cycle: the first one is close to or after the sunspot minimum (sunspot cycle phase $0.9 \leq \Phi \leq 1.0$ and $0.1 \leq \Phi \leq 0.2$), and the second is wider – close to the sunspot cycle maximum ($0.3 \leq \Phi \leq 0.5$). A third maximum is detected about 3–4 years after the sunspot cycle maximum ($0.7 \leq \Phi \leq 0.8$) for the "moderate strong" volcanic eruptions with volcanic eruptive index VEI = 5. It corresponds to the geomagnetic activity secondary maximum, which usually occurs 3–4 years after the sunspot maximum. Φ is calculated separately on the basis of each sunspot cycle length. Finally, without any exclusions, all most powerful volcanic eruptions for which VEI $\geq$ 6 are centered near the ~11-year Schwabe-Wolf cycle extremes. Trigger mechanisms of solar and geomagnetic activity over volcanic events, as well as their relation to climate change (in interaction with galactic cosmic rays (GCR) and/or solar energetic particles (SEP)), are discussed. The Pinatubo eruption in 1991 as an example of a "pure" strong solar–volcanism relationship has been analyzed in detail.

Keywords: volcanic activity, solar activity, geomagnetism, Sun-climate relationships

Citation: Komitov, B., and V. Kaftan, (2022), "Danjon Effect", Solar-Triggered Volcanic Activity, and Relation to Climate Change, *Russian Journal of Earth Sciences*, Vol. 22, ES6005, doi: 10.2205/2022ES000803.

1 Introduction

The problem for the relationship between solar activity and tectonic events has been discussed at least since the beginning of the 20th century. Good overviews of the first studies in this direction presented before 1920 were given by *Chizhevsky* [1976]. There are many studies concerning solar and seismic activity relationships, but the corresponding number for solar–volcanic connections is too small. There are only sporadic papers concerning the problem [*Mazzarella and Palumbo*, 1989; *Qu et al.*, 2011; *Stothers*, 1989; *Střeštik*, 2003]. In summary, the anti-correlation between solar and volcanic activity is the most often suggested conclusion according to these publications.

As an additional independent argument supporting this conclusion is the "Danjon effect" – a relatively higher frequency of "dark" total lunar eclipses (DTLE) during the solar minimum epochs (one-to-two years after the Schwabe-Wolf sunspot

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cycle minimum), which was established by the French astronomer Andre-Louis Danjon [*Danjon*, 1921] about 100 years ago. The dark total lunar eclipses (DTLE) events are in strong relationship with the volcanic dust concentration in the Earth's atmosphere. Evidence for the presence of possible solar modulated long-term volcanic activity cycles of centurial and supercenturial duration (80–90 and 200–215 years) is also given [*Qu et al.*, 2011; *Střeštik*, 2003]. It could be said that there is a consensus between researchers that possible physical mechanisms of the solar volcanic activity relationship are of trigger-type nature.

The problem of the existence and statistical significance of possible solar–volcanic activity relationship is very important if we take into account that volcanic activity is one of important terrestrial factors that affect the small gaseous compounds like O_3 and NO_x, aerosols, clouds, and, as the final result, the Earth's climate. The problem of the effects of strong volcanic eruptions on climate is the subject of many studies [*Briffa et al.*, 1998; *Brönnimann and Krämer*, 2016; *Cole-Dai et al.*, 2009; *Kasatkina et al.*, 2018; *Robock*, 2000]. Thus, the possible solar–volcanism relationship could turn out to be a significant indirect and not accounted for up to the present day channel for solar effect on climate.

As it has been pointed out in our earliest work [*Komitov and Stoychev*, 2011], there is evidence that essential part of strong volcanic eruptions (VEI ≥ 5) is connected no only to solar minima, but also occur during the sunspot maximum epochs. The recent study of Komitov and Kaftan supports this conclusion [*Komitov and Kaftan*, 2020, 2021].

This fact leads to many additional questions concerning the solar–volcanic activity relationship in different time scales and epochs, as well as their possible physical mechanisms. The possible answers to some of them are the subject of the work. It is a continuation of our abovementioned previous studies, which have been presented at two scientific conferences [*Komitov and Kaftan*, 2020, 2021]. Unlike the last ones, the present work contains a large discussion section 4.

The investigation was carried out in two main stages. The first one is focused on the general and long-time tendencies in behavior of the annual volcanic eruption number N_er, i.e., the existence and statistical confidence of trend and cycles. (It is important to note that N_er only presents eruptions that started in the corresponding calendar year, while those that are "old", i.e., started in previous calendar years, are not taken into account.)

The dependence of relative frequency and/or absolute number of volcanic eruptions with different magnitudes (volcanic eruptive index, VEI) from the sunspot Schwabe-Wolf cycle phase is studied at the second stage. The obtained results and their analysis for both stages are described in the section 3. The obtained results in the course of the possible physical mechanisms of the "Sun-geotectonics" relationships, as well as the consequences for the understanding of the "Sun-climate" relationships in the section 4, are presented. The strong relationship between the different phases of Pinatubo eruption and the corresponding helio-geophysical conditions during the spring of 1991 as an "extreme" example is given.

2 Data and methods

This work uses the volcanic eruption data that are published in the Smithsonian National Museum of Natural History's Global Volcanism Program (GVP) web site (https://volcano.si.edu). On the basis of the abovementioned data, a relatively reliable scenario about volcanic activity approximately since 1550 AD could be build.

We can say, that the larger parts of Circum-Pacific Fire Belt, namely, the western seaside of Central and South America, Japan, the Philippines, and Indonesia, where the larger half from of the entire planetary volcanic activity is formed, has been known to the European scientists approximately since the middle of 16th century. We should add to them volcanic regions in the Atlantic Ocean (Caribbean Sea, Iceland, Canary Islands) and the Mediterranean Sea, already well-known in this epoch. Thus, we may say that moderate and strong volcanic eruptions (VEI ≥ 4) have been monitored relatively fully and continuously at least since ~1550 AD.

We can consider the middle of 18th century, after the beginning of regular Russian expeditions and settlements built in Kamchatka and Alaska, as a next serious stage for improving planetary volcanic activity information. These territories plus the Hawaii Islands and New Zealand, also discovered during this time, as well as the adjacent islands, also give significant information on the Earth's volcanic activity. In our opinion, the above speaks in favor of the upward trend in the yearly planetary volcanic eruption numbers N_er after the middle of 18th century Figure 1.

According to the data published in the GVP database, 6215 volcanic eruptions occurred during the period 1550–2020 AD. Taking the trigger mechanism hypothesis as the basis, a time series of annual newly generated (i.e. during the corresponding year) volcanic eruptions (N_er) was build. Thus, volcanic events that started in a previous calendar year and continued during the corresponding year were excluded from the research process.

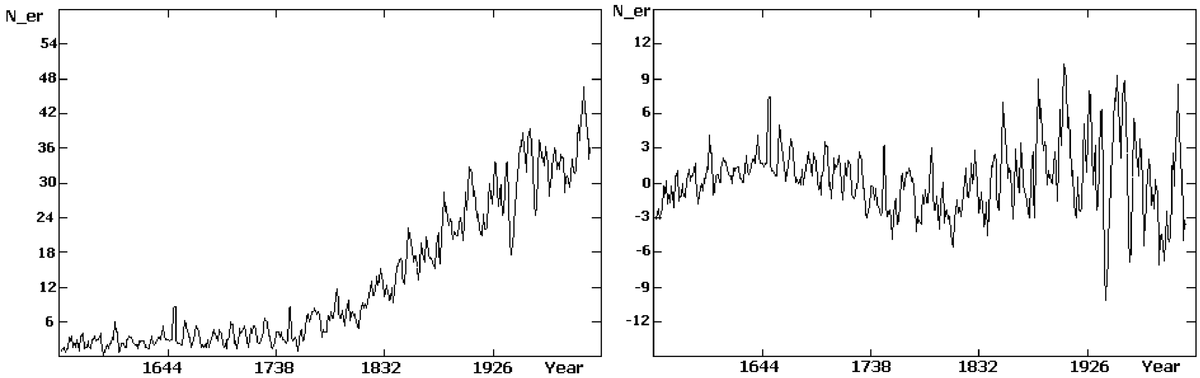

Figure 1: Left: The smoothed 3-year annual volcanic eruptions number N_er; Right: The residual series (ΔN_er) (after removing the nonlinear general trend).

Note that the optimal time resolution for calendar moments of volcanic eruptions (i.e., a time series step) in our study is one year. This is a typical interval of confidence for most volcanic eruptions before 19th century. There are also eruptions for which this interval exceeds one year, but its relative number is too small – less than 1% of the entire data set used. The moments of eruptive maximum phases in many cases are significantly shifted relative to the starts of events, usually by days, weeks, or months, but almost always during the same calendar year. Exceptions can usually occur if the volcanic eruption starting moments are close to the end of the corresponding calendar year, but such cases are too few).

The ~11-year Schwabe-Wolf sunspot cycle extremes for the epoch 1551–1610 AD are given in Schove's series [*Schove*, 1955, 1983], the corresponding data for the epoch 1610–1749 AD are taken from [*Waldmeier*, 1961], while, for the epoch after 1749 AD, they could be found in many sources. Here we use one of the newest releases, which is published on the site of the World Data Center for the production, preservation, and dissemination of the international sunspot number to the Royal Observatory of Belgium (`https://wwwbis.sidc.be/silso/cyclesminmax`). The calendar moments of sunspot minima after 1749 AD (the start of the standard sunspot Zurich series) are given at the time resolution of one month. However, the moments of sunspot cycle minima between 1550 and 1750 AD are known by an essentially higher confidence interval (about ±0.5 yr before 1749 AD). This circumstance is too essential especially for the grand solar Maunder minimum (1642–1720 AD). Thus, the precision of 1 year both for the calendar moments of volcanic eruptions and sunspot solar cycle minimum moments is most adequate for the aims of our study.

The time series of N_er so obtained is shown in Figure 1. A strong upward trend is visible here. With high confidence we may suggest that the last one is caused primarily by a very probable lack of data during the earlier part of the time series (~1550–1750 AD; see in the text above), but some contribution of a real upward effect is too difficult to take or reject.

By using the ordinary least square procedure (OLS), we looked for the best approximation of the general trend. A series of a few algebraic power step polynomials has been tested. Finally, it has been found that the best fitting for the trend is the full algebraic polynomial of 3rd degree.

After removing the trend of the initial time series, a 3-year smoothing procedure has been done for the residuals. In our opinion, the 3-year smoothing is optimal for the best discovery of length oscillations of about 11 years, i.e., the mean duration of Schwabe-Wolf's sunspot cycle. The smoothed residual time series has been studied for the existence of statistically significant cycles using two methods: the T-R periodogram algorithm [*Komitov*, 1997, 2021, 1986] and wavelet analysis [*Torrence and Compo*, 1998].

By using of histograms the absolute number and frequency of the volcanic eruptions (distribution density) with a different VEI in relation to Schwabe-Wolf's sunspot cycle phase Φ were studied too. To this end, the data for the individual lengths of sunspot cycles during the epoch 1550–2019 AD was used. There are not yet published quantitative estimations for 2020 AD on the GVP site. That's why the data for 2020 are not used in the histograms. The obtained results and their analysis are described below.

3 Results and analysis

3.1 Time series analysis of residuals (ΔN_er)

The T-R spectrum (T-R correlogram) of the smoothed volcanic eruption "residual" time series (ΔN_er) is shown on the left panel of Figure 2. The right panel of the same figure demon-

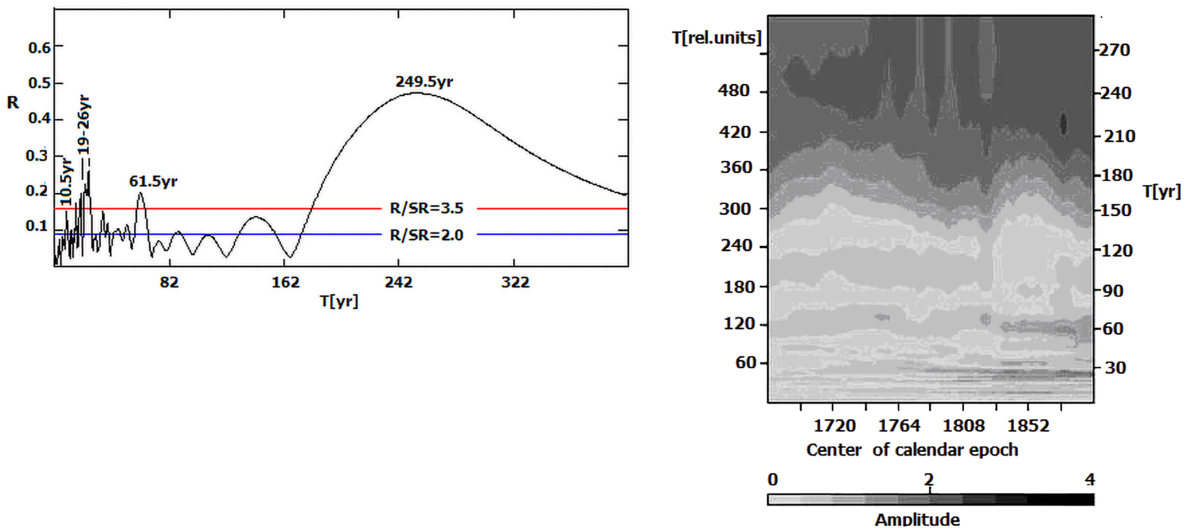

Figure 2: Left: The T-R spectrum of the ΔN_er series (1551–2019 AD); Right: A scalogram of the same series.

strates by scalogram the evolution of the amplitudes of the oscillations detected by T-R periodogram method for different parts of the time series is. The scanning window width is 300 years, while the time step of scan is 1 year. Figure 3 shows the corresponding wavelet scalogram and the global wavelet spectrum of the same series.

Statistically significant cycle durations of 11, 19–25 (multiplet), 61.5, and powerful ∼249.5 years are visible in the T-R spectra. These results are generally in agreement with the global wavelet spectra where cycles of 11, 25, 60, and ∼240 years are shown.

There are many solar, as well as other space climate, analogues of almost all of the detected cyclic oscillations in the “residual” VEI time series. The 11-year oscillation corresponds to the mean duration of Schwabe-Wolfs's sunspot activity cycle plus a large number of related solar and geophysical activity indexes and events, such as solar flares, coronal mass ejections (CME), geomagnetic activity, galactic cosmic rays (GCR), etc. The ∼20–22 year oscillation, which is an important component in the quasi bidecadal multiplet (19–25 yr), corresponds to the Hale's solar magnetic dipole cycle (∼22 years). A cycle duration of ∼60 years has been established in middle-latitude aurora activity (MLA), as well as in “cosmogenic” ^{10}Be isotope production [*Komitov*, 2009]. A sunspot cycle duration of 5 or 6 Schwabe-Wolf's cycles (55–66 yr) has been discussed by *Du* [2006].

The possible origin of quasi bicenturial 240–250-year cycle in the residual ΔN_er series will be discussed in the section 4 below.

3.2 The volcanic eruptions and phase of Schwabe-Wolf's sunspot cycle

As was pointed above, the study of the absolute number and/or frequency of volcanic eruptions in relation to Schwabe-Wolf's sunspot cycle phase using histograms is the second main purpose of this study.

Section 2 stated that the total volcanic eruption number during the interval 1550–2020 AD according to the GVP catalog is 6215. After excluding 26 new eruptions during the last year 2020 whose VEI are not yet published, there remains overall 6189 registered eruptions for the interval 1551–2019 AD. For each such event, the current Schwabe-Wolf's sunspot cycle phase was calculated as $\Phi(t) = \frac{t-t_0}{L_{SW}}$, where t is the current calendar year, t_0 and L_{SW} are the calendar year of minimum and the length of current sunspot cycle, respectively. The relative number of volcanic eruptions with different VEI indexes in percents for corresponding phase Φ with a step of 0.1 from 0 to 1 are shown in histograms in Figure 4.

These histograms trace a tendency for concentration of volcanic events near two “preferred” phases of the sunspot cycle ($0.9 \leq \Phi \leq 1.0$ and $0.3 \leq \Phi \leq 0.5$). The first one corresponds to the sunspot solar cycle minimum, while the second one, to the pre-maximum and near maximum phases of the same one. It also has traces that this tendency is clearly visible for the overall volcanic eruption data set (VEI $\geq$ 0; the left upper panel) and separately for the weak eruptions ($0 \leq$ VEI ≤ 2). The total number of the last ones for the interval 1551–2019 AD is 5255 or 84.9% for the all volcanic events.

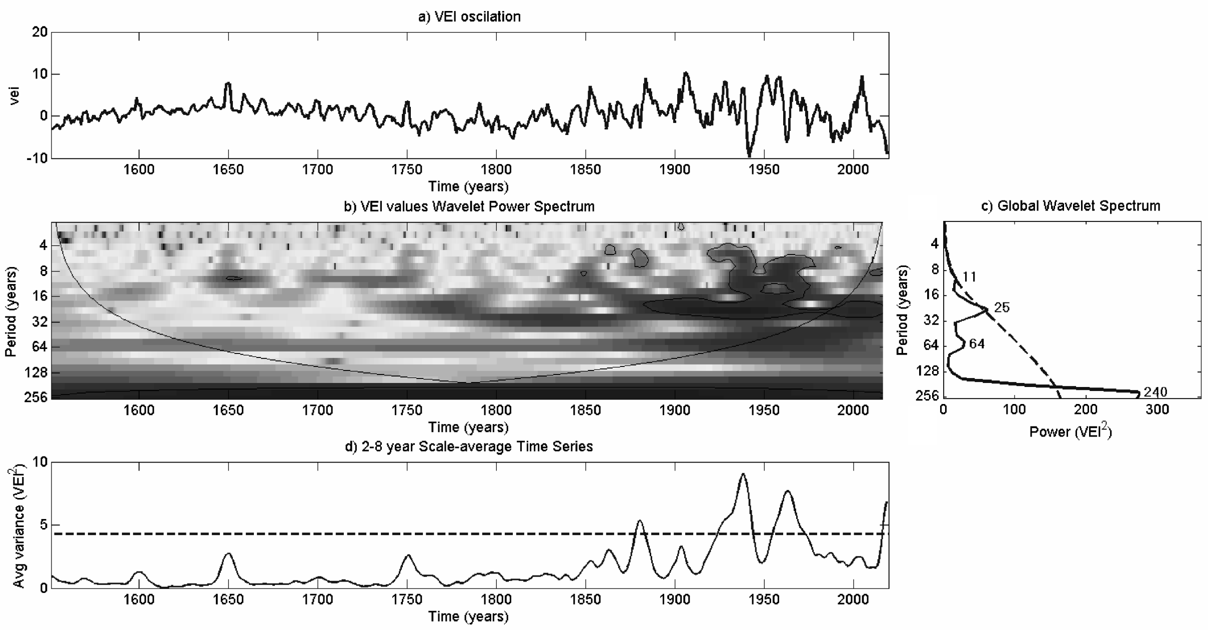

Figure 3: Left: The wavelet scalogram of residual ΔN_er time series; Right: The corresponding global wavelet spectrum.

The two-peak tendency in histograms in Figure 4 is less expressed for the moderate and moderate – strong eruptions (3 ≤ VEI ≤ 4). Moreover, it is almost damaged for VEI = 3 (in Figure 4, the third row from bottom, right). The total relative part of the events for which VEI = 3 or 4 is ~14.5%.

The two-peak tendency for concentration of events around both sunspot cycle extremes forces again for the powerful volcanic eruptions with VEI ≥ 5 (the both histograms in the bottom of Figure 4 It shows an almost equal relative number of eruptions F ≈ 20% for the both sunspot extreme phases (0.4 ≤ Φ ≤ 0.5, close to the sunspot maximum and 0.9 ≤ Φ ≤ 1.0, close to the sunspot cycle minimum).

It is important to note that the asymmetric “left” position of the near-sunspot maximum volcanic activity peak (0.4 ≤ Φ ≤ 0.5) corresponds very well to the mean structure of the Schwabe-Wolf's

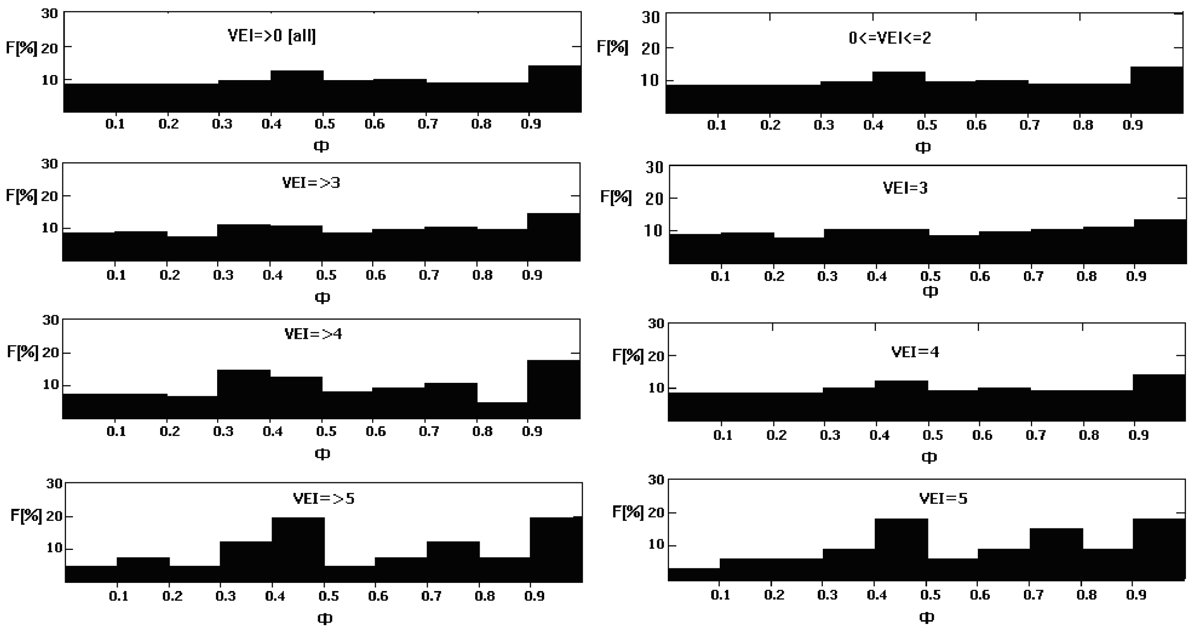

Figure 4: The relative number F[%] of volcanic eruptions with different magnitudes (VEI) during the separate phases Φ of Schwabe-Wolf's sunspot cycle for the calendar interval (1551–2019 AD).

sunspot cycle. The ascendant phase is shorter (usually ~4 years) as the top-down one (~7 years).

The two-peak tendency is best expressed for the most powerful eruptions, where VEI ≥ 6. There have only been 8 such events since 1550 AD (see Figure 5). As is shown, there are no events outside intervals 0 ≤ Φ ≤ 0.2, 0.3 ≤ Φ ≤ 0.5, and 0.9 ≤ Φ ≤ 1.0; i.e., all of them were during the near-minimum and near-maximum phases of Schwabe-Wolf's sunspot cycles.

There are also two other interesting features, concerning the histograms for the "moderate-strong" and very strong volcanic eruptions (VEI ≥ 4) (the first and second rows of histograms from the bottom of Figure 4, which are not visible for the weaker eruptions.

The first feature is a local maximum of *F* for the interval 0.7 ≤ Φ ≤ 0.8. As it could be traced in Figure 4 it is well shown for VEI = 4 and even better for VEI = 5, but is absent for the most powerful eruptions where VEI ≥ 6 (Figure 5). Having in view the mean length of Schwabe-Wolf's sunspot cycle (~11 years) the above phase corresponds to 3–4 years after the sunspot cycle maximum.

The second feature relates to the trace of weakly expressed peak on histograms for VEI ≥ 5 in the interval 0.1 ≤ Φ ≤ 0.2 (the bottom-left histogram). It is not visible on the histograms of weak and moderate volcanic eruptions. The reason about this relatively weakly expressed phenomena will be discussed below.

The existence of two main peaks (near to sunspot maximum and minimum), as well as a third one, which is placed on 3–4 years after the sunspot maximum, indicates not one but two or three solar-modulated trigger mechanisms over the volcanic activity.

The first peak, from Φ from 0.9 to 1 and after that from 0 to 0.2, corresponds to the end of one and the beginning of the next Schwabe-Wolf's sunspot cycle. The sunspot cycles minima relate to galactic cosmic rays (GCR) flux maxima. The absolute maxima of the last one occur usually ~1 year after the sunspot cycle minima, i.e., at phase 0.1 ≤ Φ ≤ 0.2. It relates to the minimal parameters

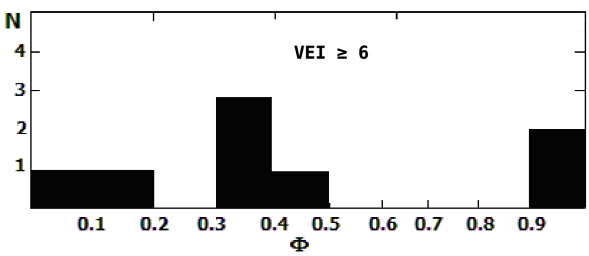

Figure 5: The strongest volcanic events number N (VEI ≥ 6) and the corresponding sunspot cycle phase Φ.

of Sun's heliosphere, which helps the GCR flux penetration in the inner part of the Solar system and the Earth's atmosphere in particular [*Usoskin*, 2013]. The anti-correlation between the GCR flux penetrating into the Earth's atmosphere and the sunspot cycle phase is often labeled as one of the so-called "Forbush effects" [*Forbush*, 1954, 1958]. As it has been shown by many authors [*Svensmark and Friis-Christensen*, 1997; *Tinsley*, 2000; *Yu*, 2002], GCR flux changes reflect through many terrestrial processes: aerosol and cloud formation, terrestrial current systems, atmospheric circulation, etc. The possible physical mechanisms of GCR influences over volcanic activity and optical parameters of the Earth's atmosphere will be discussed in the next section 4.

The phase 0.1 ≤ Φ ≤ 0.2, which also belongs to the near-sunspot cycle, minimum relates except to the high level of GCR flux, but, in our opinion, could also reflect the initial phase of solar flare activity and connect first large peaks of coronal mass ejections (CME) with them for the new Schwabe-Wolf's cycle. This occurs usually during the second year after the sunspot minima.

The well expressed third peak (0.7 ≤ Φ ≤ 0.8) is in good coincidence with the secondary peak of geomagnetic activity, which usually occurs on the 3rd–4th year after the sunspot cycle maximum. It is of a "mixed" solar origin. The primary solar sources of this geomagnetic activity are both the strong solar flares, forcing from one side, and the solar coronal holes (CH) – large open magnetic field structures in the Sun's atmosphere, coming from the other. The last ones are already well developed during this sunspot cycle phase. They are primary sources of high solar wind streams (HSS). These streams cause geomagnetic activity (CH HSS effects) if the Earth gets in the corresponding sector of interplanetary space. Sometimes the corresponding geomagnetic activity level could reach a strong geomagnetic storm (*Kp*-index more than 6).

4 Discussion

The problem for possible solar-generated trigger mechanisms of volcanic events is of high importance in interdisciplinary scientific standpoint at least for two reasons: 1 – It is interesting for a better understanding of conditions when strong volcanic eruptions could occur with higher probability; 2 – The important role of volcanic activity over the Earth's climate change is out of doubt [*Briffa et al.*, 1998; *Brönnimann and Krämer*, 2016; *Cole-Dai et al.*, 2009; *Kasatkina et al.*, 2018; *Robock*, 2000]. Consequently, it is quite possible that an essential part of the "Sun-climate" relation is caused not by solar electromagnetic radiation changes but rather by triggering solar activity processes in the lithosphere and particularly volcanism.

As was mentioned in section 3, an indication that the solar trigger forcing volcanic activity is realized by physical natural processes, miscellaneous but close and/or similar between themselves, is the fact of the existence of two or three peaks in the F-Φ histograms. The galactic cosmic rays and solar energetic particles (SEP, protons of ≥ 10 MeV) are able to overcome the Earth's magnetic field and penetrate in the middle and lower parts of the atmosphere. The SEP events very often accompany strong solar flares (power class M5 and higher), big coronal mass ejections, and related strong geomagnetic storms. Both solar-modulated physical agents are of a corpuscular nature, but their maxima are in different phases of the sunspot cycle – GCR during the near sunspot cycle minima, while the peaks of solar flares, CMEs, SEP, and strong geomagnetic storms – near sunspot cycle maxima. If the main physical factor of solar forcing over the volcanic activity is predominantly closely connected with the sunspots and faculae (for example, the electromagnetic indexes such as the solar radioflux at 2800 MHz (F10.7), the total solar irradiance (TSI) index) in F-Φ histograms should be only one, but not two or three peaks observed.

Thus, in our opinion, the trigger mechanisms of the "Sun-volcanism" relationship is mainly realized due to cosmic electric charged particle interactions with the Earth's magnetic field, atmosphere, and different terrestrial current systems. A serious support for this is the third peak in F-Φ histograms (mainly for VEI = 5) on the downward branch of the sunspot cycle at $0.7 \leq \Phi \leq 0.8$. As was already mentioned, it corresponds to high geomagnetic activity, whose primary sources are both strong solar flares and accompanying events (CMEs and SPEs) and high speed solar wind streams, caused by coronal holes.

The two- or three-peak structure of histograms, the fact that the third (CH) peak relates not to all but to a narrow-magnitude range of volcanic eruptions (VEI = 5) points that there is not a single solar triggering mechanism. Most likely, there is a wide collection of triggering phenomena, which act under a great many of circumstances, depending on the current magma chamber conditions, the geological structure, rock and mineral composition, and current seismic conditions of the region, and its tectonic history (recent volcanic eruptions and/or earthquakes), as well as the current space weather, space climate conditions, and related phenomena and parameters (GCR flux, solar flare, and CME activity, solar proton events (SPE), geomagnetic and atmospheric conditions).

The most possible ways of solar triggering of volcanic activity, in our opinion, are based on:

1. Changes of the low and middle atmosphere conductivity and electrical potentials between the ionosphere and the Earth's surface current systems during strong solar flares and CME phenomena and related geomagnetic and radiation storms. *Svensmark and Friis-Christensen* [1997] and *Yu* [2002] considered the GCR flux, increasing during the sunspot cycle minima, as a serious source for increasing electrical charges in the lower atmosphere. Such events may be affected by conditions in magma chambers due to electrostatic interactions between electric charges in the lower atmosphere and the upper regions of the magma chamber. It could be closely related to the thunderbird activity, which is detected during many volcanic eruptions [*Smith et al.*, 2021].

2. Magnetostriction (reverse piezoelectric effect) phenomena could occur during the geomagnetic storms in regions with well-developed geological faults and block structures if they are rich in SiO_2 or other minerals with well-expressed piezoelectric features. This requirement could be valid mainly for the continental (rich in SiO_2), but not for the oceanic, lithosphere. The above phenomena could cause additional mechanical stress in the regional fault structures plus trigger effects of mechanical energy escape (earthquakes) and/or volcanic eruption if the magma parameters in the chamber (temperature, pressure, etc.) are near critical levels.

3. Microfluctuations in the Earth rotation period (Length of Day (LOD) index), caused by strong geomagnetic storms. The latter can causes not large but remarkable disturbances of the terrestrial dynamo regime and, as a result, some of the observed disturbances in the Earth rotation and inertial forces around the contact zones between the lithosphere blocks. On their part, they can cause trigger effects for some volcanic eruptions and/or earthquakes as was already described in 2.

All the three types of phenomena can lead to trigger-effects separately or in combinations. Note that there are also numerous other nonsolar trigger mechanisms, which can act separately or in combinations with the Sun, modulated ones.

It is important to note that there have been too many studies about the sunspot + other space weather parameters and Earth's seismic activity relationships since the beginning of the 20th century and up to date. An interesting and recently published result in this course has been presented by *Marchitelli et al.* [2020]. An instrumental data set for the near-Earth solar wind proton density and velocity, measured on the board of the SOHO spacecraft, and earthquakes data taken from a catalog for 20-year-long interval from 1996 up to 2016 AD have been compared. It has been found with very high confidence (>0.99999) that there is a strong relationship between increasing solar-wind events and strong earthquakes (with magnitude M>5.6) worldwide. The phase relationship shifting (delay of earthquake events to a change in solar wind parameters) is in the range of one day. The statistical analysis has been provided on two stages: establishing a relationship based on the data set between 1996 and 2006 AD and "epignosis test" since 2006 AD. A reverse piezoelectric effect as a possible physical mechanism for triggering earthquakes is suggested by the authors.

Both earthquakes and volcanic eruptions are tectonic events, which are caused by instabilities around the lithosphere blocks boundaries. Hence it follows that a significant part of trigger events should be similar. That is why the above study of *Marchitelli et al.* [2020]. supports our results for the Sun-volcanism relationship. This especially true of sunspot eruptive events (flares, CMEs, GLEs) and geomagnetic activity as triggers near the sunspot activity maximum and the secondary peak in histograms in the sunspot phase Φ between 0.7 and 0.8.

Thus, our point of view about the physical mechanisms of solar triggering of the volcanic activity, based on analysis of the present results, is quite different from the hypothesis of *Stothers* [1989]. This author assumes that the "Sun-volcanic activity" relationship is based on the atmospheric pressure changes over volcanic chambers, while the atmospheric pressure changes are modulated by the solar activity forcing over the weather and climate. Such mechanism should not be totally excluded, but its role is relatively small. In our opinion, the "Sun-volcanic activity" connection is almost independent from the atmospheric conditions. Moreover, it may be one of the most important factors in the overall "Sun-climate" relationship.

How to explain the "Danjon effect" during the DTLE, taking into account all discussed above? Why is it related to the volcanic activity peak only near the sunspot cycle minima and why are such eclipses almost absent during the maxima and other sunspot cycle phases? The possible answer is that volcanism is a necessary, but not sufficient, circumstance for DTLE. Consequently, additional important factor are also present during the sunspot cycle minima except for the volcanic activity peak.

The GCR-flux enhancements during the sunspot minimum epochs lead to higher ion–electron concentrations in the lower troposphere. The latter remains a few orders of magnitude lower in relation to ionosphere (10^{-4} to 10^{-2} cm^{-3} in the troposphere vs. 10^5 cm^{-3} to 10^6 cm^{-3} in the ionosphere). However, this increase could change seriously the near surface atmosphere electric conductivity and, as a result, lead to significant changes in atmosphere–lithosphere electric potentials. As was mentioned above (see 1), the latter could produce a trigger effect for volcanic eruption if the magma chamber conditions approached a critical limit.

As was also mentioned above, *Svensmark and Friis-Christensen* [1997] and a few years later *Yu* [2002] proposed the idea that the enhanced GCR flux and the related ion-electron production in the lower atmosphere during sunspot minima epochs could stimulate the aerosol and cloud formation, and, as a result, more precipitations and climate cooling should be observed in these epochs. As was pointed out by *Yu* [2002], the process should be essentially more effective if there were a significant quantity of volcanic materials (dust and acid molecules, such as SO_2, H_2SO_4, HCl, HF) in the atmosphere. It helps a more effective building of condensation nuclei (CN) and, as result, a more effective forcing of aerosol and cloud generation processes. That is why the "Danjon effect" occurs predominantly during the sunspot minimum epoch. It follows, that during the sunspot cycle maxima, the aerosol production should be relatively low in spite of a possible higher volcanic eruptive activity. The "Danjon effect" in this case should be a much less probable phenomenon. As an additional factor that can complicate this picture in some degree is ENSO (El Nino/La Ninja phenomena [*Yu*, 2002]) by means of its influence over the humidity and air temperature. Figure 6 shows the principal scheme of the above processes.

A delay by 1–2 years of a DTLE peak in relation to the sunspot cycle minimum could be caused by two factors: 1 – The typical delay of aerosol formation in the atmosphere as a result of a volcanic eruption is about 1 year [*Barnes and Hoffman*, 1997]; 2 – The maximum GCR flux also means a delay of the absolute sunspot cycle minima by ~1 year, corresponding to the minimum heliosphere parameters during the same time [*Usoskin*, 2013].

No doubt, the most famous result in our present study is the powerful ~240–250-year cycle in T-R and wavelet spectra. In our opinion, there are three hypotheses to explain this. According to the first one, it is related to specific solar activity regions like the giant (naked eye visible) sunspot groups [*Vaquero et al.*, 2002]. It corresponds well

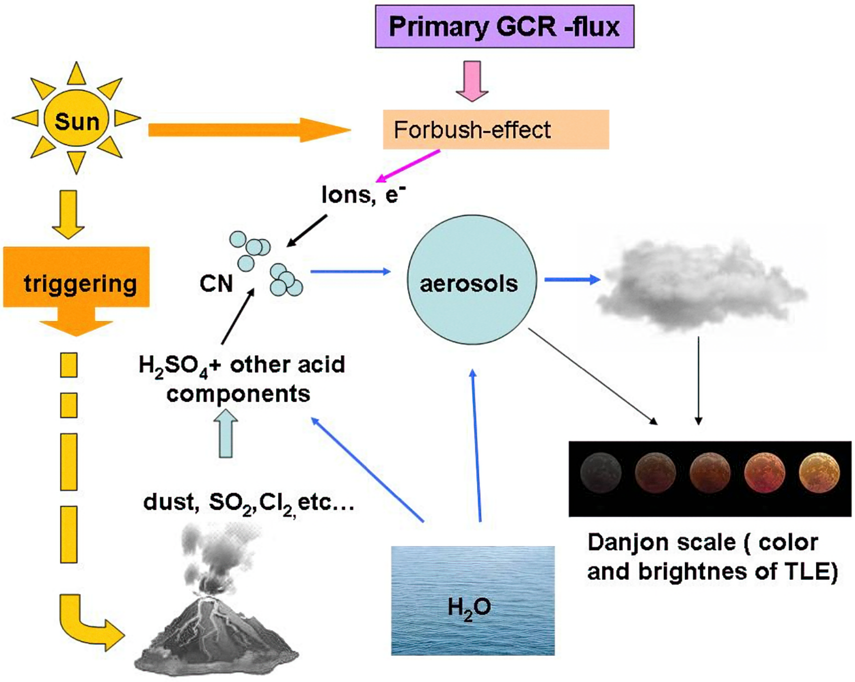

Figure 6: An intercoupling relationship between the solar modulated GCR-flux changes (one of the "Forbush-effects"), solar triggering of volcanic activity, aerosol and cloud generation and the Danjon scale magnitude of total lunar eclipses (TLE).

with the solar triggering mechanism and seems to be most probable.

According to the second hypothesis, the 240–250-year cycle of volcanic activity is caused by the influence of induced Venus's magnetosphere, while the third one assumes that the primary source of this cycle is a tidal effect of Venus over the Earth's lithosphere. It follows from these hypotheses that a 243-year cycle should be observed [*Wilson*, 2014]. In our opinion, the second and third hypotheses seem to be less probable. This is due to the fact that the sharply increasing phases of strong solar flares and related space weather events correspond much better to the trigger nature of its forcing over volcanic hearths during strong volcanic eruptions as weak and monotonic changes related to the tidal effect of the planet. The induced Venus's magnetosphere effect is too hypothetical and even if it exists, it should be much weaker than the Venus tidal effect.

Thus, we may assume that the 240–250-year cycle is most probably of solar origin and relates mainly to solar flare events, associated with large sunspot groups. On the other hand, quasi bicenturial cycle has been detected in the historical messages for the aurora activity by D. J. Schove [*Schove*, 1955, 1983]. One of the authors of [*Komitov*, 2009] established a 220-year oscillation in the mid-latitude aurora activity during the 18th and 19th centuries. In the latter work, published historical data from the catalog of *Křivský and Pejml* [1988] was used. There is also a 200–210-year cycle in "cosmogenic" radio isotopes (^{14}C, ^{10}Be), relating to GCR flux variations [*Damon and Sonett*, 1991; *Dergachev*, 1994; *Komitov and Kaftan*, 2004; *Stuiver and Quay*, 1980; *Suess*, 1980]. All these facts support the solar origin of the ~200–250-year cycle in the volcanic eruption time series during the past ~470 years. It also corresponds well to the detected 215-year cycle in the Stotcher's work [*Stothers*, 1989].

Finally, the quasi bicenturial 200–250-year cycle in volcanic eruption time series is less or more directly connected to different processes, whose primary sources are on the Sun.

As an "extreme" example, which confirms the high probability of the solar triggering hypothesis is the Pinatubo volcano activity in 1991 AD. The very close coincidences between the main separate phases of volcanic activation, on the one hand, and the solar flare activity with the accompanying space weather events and the volcanic chamber activity, on the other, were first described by *Komitov and Stoychev* [2011] (Figure 7).

The main phases of the Pinatubo eruption between March and June 1991 AD are numbered by symbols from 1 to 5 in Figure 7 (the upper panel). As is shown there, all the main phases of the Pinatubo eruption are in coincidence with well-expressed solar X-ray flux peaks (very strong

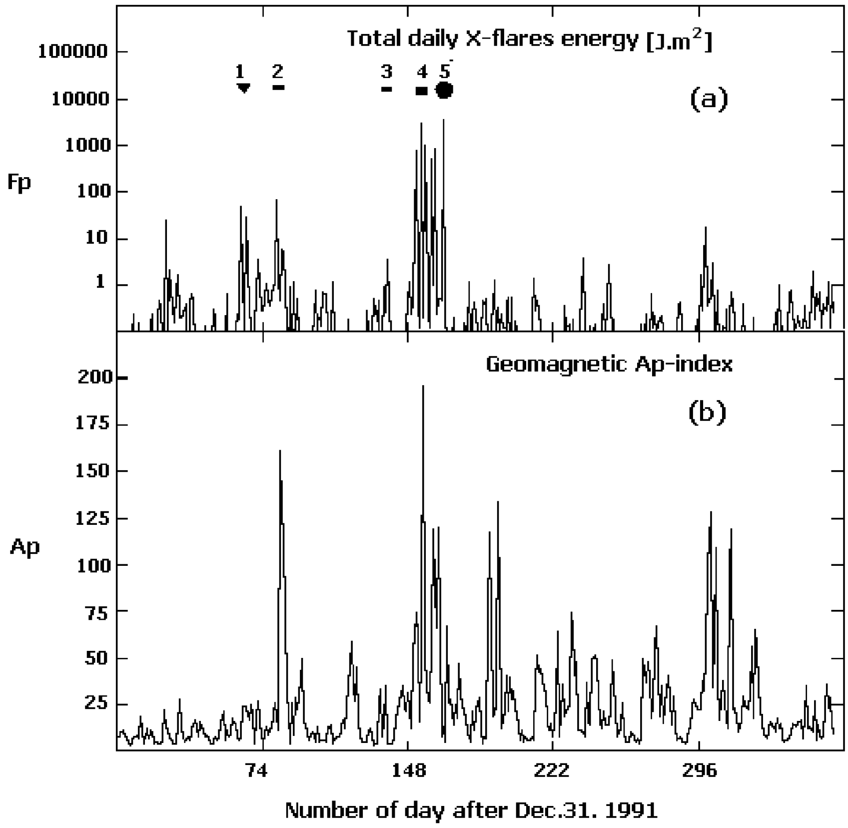

Figure 7: Upper panel: Solar X-ray flux energy during 1991 AD in natural logarithmic scale with the main phases of the Pinatubo eruption in 1991 AD: (1) seismic activity near volcanic chamber in March; (2) first magma eruption on April 02; (3) increase in eruptive activity in May; (4) first volcanic explosion on June 07; (5) a series of volcanic explosions between June 12 and 15; bottom panel: Planetary *Ap*-index in 1991 AD [*Komitov and Kaftan*, 2020].

solar flares of magnitude class > X9.0 (so called "mega-flares"). The first one with magnitude class X9.4 occurred on March 22. The most interesting period began on June 01 and ended on June 15, when 6 solar mega-flares with magnitude class ~X12 each occurred on June 01, 04, 06, 09, 11, and 15. They belong to the top 20 most powerful solar flares since 1976 AD, i.e., the beginning of regular observations of solar X-ray flux changes by satellites of the GOES series.

These flares were accompanied by solar proton events (SPE) (see https://umbra.nascom.nasa.gov/SEP/). The first started on May 31 and reached maximum on June 01; the second started on June 04 and reached maximum on June 11, while the third one started on June 14, and its maximum was on June 15. An extremely large SPE event closely preceded the first magma eruption on April 02. It started on March 23 and reached maximum on March 24. Another weak SPE occured on March 29–30.

The Pinatubo eruption in 1991 demonstrates a rare case when the trigger mechanism is almost of a pure solar nature. A good monitoring is possible in this case based on very detailed and miscellaneous satellite and ground observations of the space weather parameters.

As was mentioned above and shown in Figure 5, three of the total eight strongest volcanic eruptions of VEI ≥ 6 since 1550 AD have occurred near sunspot cycle maxima. Except for Pinatubo in 1991, such were the eruptions of Krakatoa in 1883 AD and Tambora in 1815 AD, respectively. The Krakatoa eruption occurred during the near maximum phase of Zurich sunspot cycle 12 (SC12), while Tambora, during the maximum phase of sunspot cycle 6 (SC6). However, the space weather circumstances (the solar and geomagnetic activity and the related phenomena) are not well known in corresponding epochs as in 1991 AD. However, the Pinatubo eruption circumstances are at least somewhat valid for the Krakatoa and Tambora eruptions too.

The evidence of solar–volcanic triggering may be considered as the basis for a new stage of the "Sun–climate" debate. Since the volcanic activity has been considered as a serious climate factor [*Robock*, 2000], we may assume that an important part of the whole "Sun–climate" relationship is masked by strong volcanic eruptions. It seems that the climatic phenomena "Year without summer" in 1816, related strongly to the Tambora eruption [*Brönnimann and Krämer*, 2016; *Cole-Dai et al.*, 2009], may be considered as a good example for this one.

5 Conclusions

This study evidences solar activity triggering effect on the following volcanic eruptions:

1. Statistically significant cycles of 11, 19–26, ~60, and 240–250 years in a time series of annual volcanic eruptions have been established using two independent methods (the T-R periodogram and wavelet analysis). They have analogues in solar and geomagnetic activity.

2. There are two peaks in the relative and absolute number of strong volcanic eruptions F–Φ histograms, corresponding to sunspot minima and sunspot maxima, respectively. These peaks are less expressed for the "moderate" strong volcanic eruptions (VEI = 4) and better, for the most powerful ones (VEI ≥ 5).

3. A third well expressed peak in range $0.7 \le \Phi \le 0.8$ is shown in the F–Φ histogram for the volcanic eruptions of magnitude class VEI = 5. It relates to strong secondary geomagnetic activity peaks on the downward sunspot Schwabe-Wolf's cycle branches.

4. Most probably the primary sources of solar (and space weather) triggering over volcanic activity are solar flares and the accompanying phenomena, such as coronal mass ejections (CMEs), solar energetic particles (SEPs), ground level enhancements (GLEs), and related geomagnetic storms.

5. It is quite possible that the solar–volcanic triggering is a serious indirect nonaccounted component of the total "Sun–climate" relationship.

Acknowledgments. The authors are grateful to the Global Volcanism Program Team of the Smithsonian National Museum of Natural History and to the MATLAB team [*MathWorks*, 2021] regarding the possibility of using their wavelet analysis software module. This work was supported within the framework of a state assignment at the Institute of Astronomy and National Astronomic Observatory, Bulgarian Academy of Sciences, and the Geophysical Center, Russian Academy of Sciences approved by the Ministry of Education and Science of the Russian Federation.

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