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Acknowledgments

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LIST OF ACRONYMS AND SYMBOLS

ETNH          extra-tropical Northern Hemisphere
ETSH          extra-tropical Southern Hemisphere
fd            first difference
T             tropics
VEI           volcanic explosivity index
NOMENCLATURE

\[m\] mean
\[N\] number
\[P\] probability
\[r\] rate (decadal)
\[sd\] standard deviation

1. INTRODUCTION

Volcanoes are found on every continent of the Earth and undersea. According to Simkin and Siebert, more than 1,500 volcanoes have been active in the past 10,000 yr, accounting for ≈8,000 known eruptions. About 400 volcanoes erupted during the 20th century. Some two-thirds of the volcanoes are located in the Northern Hemisphere and, similarly, some two-thirds are found to lie around the Pacific Ocean margin, reflecting a predilection of the occurrence of volcanic eruptions to tectonic plate movements.

Episodes of temporary cooling have long been suspected of being related to the occurrences of large volcanic eruptions. For example, Franklin suggested that perhaps the eruption of an Icelandic volcano was responsible for the unusual weather of 1783–1784 in Europe, and Lamb described many of the unusual meteorological effects that followed particular large volcanic eruptions. These effects, lasting for months to years, include strange sunsets and reduction of the direct measurement of normal-incidence solar radiation by 10 percent or more, in addition to temporary cooling. Furthermore, large volcanic eruptions have been linked to enhanced sulfate concentrations in ice cores and to changes in tree ring densities. According to Robock, large volcanic eruptions influence climate by injecting large amounts of chemically and microphysically active gases and solid aerosol particles directly into the stratosphere. These gases and aerosol particles have an e-folding residence time of ≈1 yr. They affect the Earth’s radiation balance and disturb the chemical equilibrium of the stratosphere, leading to cooling at the Earth’s surface (0.1–0.2 °C) and heating in the stratosphere, with these effects often lasting 2–3 yr or more. Following the eruption, the cloud of sulfate gases and aerosol particles spread outward from the eruption site, encircling the globe and expanding toward both poles in a matter of weeks. The actual degree of spreading depends upon the particular distribution of winds at the time of the eruption and the latitude of the volcano. The sulfur species (mainly sulfur dioxide) react with the hydroxy group (OH) and water to form sulfuric acid. It is the resulting sulfuric acid aerosols that produce the dominant radiative effects.

Recently, Hyde and Crowley noted that a number of climate model predictions indicate that the average global temperature should rise about 0.1–0.3 °C over the next 10–15 yr. Furthermore, they suggested that the occurrences of large volcanic eruptions might mask the global warming effects of carbon dioxide. Specifically, on the basis of a 600-yr chronology of Northern Hemispheric eruptions inferred from ice cores, they determined probability density functions that allowed for the estimate of the probable occurrence within the next 10 yr of one or two climatically significant volcanic eruptions. They found that the probability of a radiative perturbation of ≈1 W m−2 or larger occurring in the next 10 yr is about 35–40 percent, the
probability of two such eruptions is \( \approx 15 \) percent, and the probability of three such eruptions is \( \approx 5 \) percent. (They found the probability of no such eruptions to be \( \approx 44 \) percent.) Also, they deduced that the probability of a Pinatubo-scale eruption (volcanic explosivity index (VEI) = 6) in the next decade is \( \approx 20 \) percent, and the probability for an El Chichón-scale eruption (VEI = 5) in the next decade is \( \approx 25 \) percent. Hyde and Crowley conclude “that there is a reasonable chance of a volcanic eruption influencing the evolution of the anthropogenic signal over the next 10 years.”

In this study, the number of known cataclysmic volcanic eruptions per decade over the past 250 yr (between 1750–1993), based on the compilation of Simkin and Siebert,\(^1\) is determined. A cataclysmic volcanic eruption is one having a VEI \( \geq 4 \), and it is these that are believed most likely to influence climate. (Strictly speaking, it is the sulfur richness of the eruption that determines whether or not it will have a significant effect on global climate.) A simple two-point moving average is applied upon the resultant time series to ascertain the expected number of cataclysmic volcanic eruptions during the present decade (2000–2009). Then by means of Poisson statistics, various probabilities of occurrence are estimated. Thus this study provides an alternate way of determining the likelihood that a climatically significant volcanic eruption will occur within the next 10 yr, as compared to that of Hyde and Crowley.\(^2\)
2. RESULTS

Figure 1 plots the number of cataclysmic volcanic eruptions per decade, known to have occurred between 1750 and 1993, taken directly from Simkin and Siebert. The eruptions are divided by hemispheric subgroupings: Panel (a) is the extra-tropical Southern Hemisphere (N(ETSH)), panel (b) is the tropics (N(T)), panel (c) is the extra-tropical Northern Hemisphere (N(ETNH)), and panel (d) is the combined data set (N(Combined)) which ignores the hemispheric location of the eruption. The number of events, mean, and standard deviation are given for each subgrouping. Additionally, for the combined grouping, a two-point moving average is displayed (the heavy line), showing that prior to about 1860, the number of cataclysmic eruptions per decade appears fewer than thereafter—an indication, perhaps, that the record might be less reliable before the mid-1800’s. Across the top are filled triangles, denoting the occurrences of volcanic events with a VEI ≥5. These particular events are identified for convenience in table 1. Such events are routinely identified as being among the largest of stratospheric-aerosol-producing volcanic eruptions.

Using the combined data set, one finds that since 1750, there have been at least 123 cataclysmic volcanic eruptions. Slightly more than half occurred in the tropics and only ≈4 percent occurred in the extra-tropical Southern Hemisphere. The largest value yet observed for the two-point moving averages is found to have occurred in the 1910’s, having a value of 8.00 (being associated with the peak number of actual events for the entire sample which measures 11.00). Since then, the two-point moving averages have remained relatively flat, varying between 5.00 and 6.00, at least, until the 1980’s when it suddenly jumped to 6.50. (The trend of the two-point moving averages since the 1930’s appears to be directed upward.)

Figure 2 displays the variation of the first differences (fd’s) of the two-point moving averages. The first difference is computed as the next two-point moving average minus the present two-point moving average. For 16 of 23 decades (70 percent), the observed fd has been within one unit of the last available value of the two-point moving average. Hence, one approximates the next two-point moving average as being equal to the last available two-point moving average plus/minus one unit. Thus the decade of the 1990’s should have a two-point moving average of ≈6.50 ± 1.00, providing it is not a statistical outlier, implying that the actual rate of cataclysmic volcanic eruptions for the present decade (2000–2009) should be 6.50 ± 1.00.

Table 2 gives the observed decadal rate (r) of cataclysmic volcanic eruptions and the associated Poisson probability distribution for each of the groupings shown in figure 1. The Poisson distribution is quite useful for measuring the probability of occurrence in positively (rightward) skewed discrete distributions, where knowledge of the mean number of random events that occur within a given time interval is plainly known. One finds that at least two events per decade have been seen since 1750, using the combined data set. The probability of having one cataclysmic volcanic eruptions during the decade of 2000–2009 is computed to be only 0.7 percent, implying that the probability of having at least one event is >99 percent.
Figure 1. The number of occurrences per decade of cataclysmic volcanic eruptions (1750’s–2000’s). The decade marked 1800’s includes one event that has no VEI value associated with it, but instead was identified on the basis of an ice core reading and tree ring density pattern—the 1809 “unknown” eruption. (Confirmed by Robock, private communication.) See text for details.
Table 1. Volcanic eruptions having VEI ≥ 5 (1750–1993).*

<table>
<thead>
<tr>
<th>Year</th>
<th>Volcano</th>
<th>Latitude</th>
<th>VEI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>St. Helens</td>
<td>46.2°N</td>
<td>5</td>
</tr>
<tr>
<td>1815</td>
<td>Tambora</td>
<td>8.3°S</td>
<td>7</td>
</tr>
<tr>
<td>1822</td>
<td>Galunggung</td>
<td>7.3°S</td>
<td>5</td>
</tr>
<tr>
<td>1835</td>
<td>Cosiguina</td>
<td>13.0°N</td>
<td>5</td>
</tr>
<tr>
<td>1853</td>
<td>Chikurachki</td>
<td>50.3°N</td>
<td>5</td>
</tr>
<tr>
<td>1854</td>
<td>Sheveluch</td>
<td>56.7°N</td>
<td>5</td>
</tr>
<tr>
<td>1883</td>
<td>Krakatau</td>
<td>6.1°S</td>
<td>6</td>
</tr>
<tr>
<td>1886</td>
<td>Okataina (Tarawera)</td>
<td>38.1°S</td>
<td>5</td>
</tr>
<tr>
<td>1902</td>
<td>Santa Maria</td>
<td>14.8°N</td>
<td>6</td>
</tr>
<tr>
<td>1907</td>
<td>Ksudach</td>
<td>51.8°N</td>
<td>5</td>
</tr>
<tr>
<td>1912</td>
<td>Novarupta</td>
<td>58.3°N</td>
<td>6</td>
</tr>
<tr>
<td>1932</td>
<td>Azul, Cerro (Quzapu)</td>
<td>35.7°S</td>
<td>5</td>
</tr>
<tr>
<td>1956</td>
<td>Bezymianny</td>
<td>56.0°N</td>
<td>5</td>
</tr>
<tr>
<td>1980</td>
<td>St. Helens</td>
<td>46.2°N</td>
<td>5</td>
</tr>
<tr>
<td>1982</td>
<td>El Chichón</td>
<td>17.4°N</td>
<td>5</td>
</tr>
<tr>
<td>1991</td>
<td>Pinatubo</td>
<td>15.1°N</td>
<td>6</td>
</tr>
<tr>
<td>1991</td>
<td>Hudson, Carro</td>
<td>45.9°N</td>
<td>5</td>
</tr>
</tbody>
</table>

*Taken from Simkin and Siebert†

Figure 2. The first difference of the two-point moving average, based on the combined data set. See text for details.

From table 2, one finds that the actual observed range of cataclysmic eruptions per decade is 2–11. Presuming that the decadal rate (r) will be 7 ± 4 for the decade of 2000–2009, from the Poisson probability distribution one computes the probability for such a rate to be ≈ 87 percent. Hence, one infers a very strong likelihood that several cataclysmic eruptions will be seen during this decade.

Table 3 gives the observed decadal rate (r) of VEI events ≥ 5 and the associated Poisson probability distribution for the combined data set. The probability of occurrence of one of these largest of events within the next decade, with the associated large stratospheric-aerosol injections, is ≈ 49 percent. The probability of at least two such events is ≈ 15 percent, while the probability is ≈ 4 percent that at least three such events will occur. Although not shown, the probability of at least one VEI event ≥ 6 occurring within the next 10 yr is ≈ 18 percent and the probability of at least two such events occurring is ≈ 2 percent. It is only ≈ 0.1 percent for three or more such events occurring.
Table 2. The distribution of the decadal rate \( r \) of cataclysmic volcanic eruptions (1750–1993) and the associated Poisson probability distribution for selected groupings of eruptions.

<table>
<thead>
<tr>
<th>( r )</th>
<th>( N(ETSH) ) Obs</th>
<th>( p(r) )</th>
<th>( N(T) ) Obs</th>
<th>( p(r) )</th>
<th>( N(ETNH) ) Obs</th>
<th>( p(r) )</th>
<th>( N(Combined) ) Obs</th>
<th>( p(r) )</th>
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<tr>
<td>0</td>
<td>20</td>
<td>0.8187</td>
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<td>0.1637</td>
<td>4</td>
<td>0.2028</td>
<td>5</td>
<td>0.2438</td>
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<td>6</td>
<td>0.2681</td>
<td>5</td>
<td>0.0883</td>
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<tr>
<td>3</td>
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<td>0.0011</td>
<td>5</td>
<td>0.2146</td>
<td>6</td>
<td>0.1966</td>
<td>3</td>
<td>0.1449</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.0001</td>
<td>2</td>
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<td>5</td>
<td>0.1082</td>
<td>3</td>
<td>0.1782</td>
</tr>
<tr>
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<td>0.0000</td>
<td>2</td>
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<td>0</td>
<td>0.0476</td>
<td>4</td>
<td>0.1754</td>
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<tr>
<td>6</td>
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<td>0.0000</td>
<td>1</td>
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<td>0.0174</td>
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<td>0.1438</td>
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<tr>
<td>9</td>
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<td>0</td>
<td>0.0009</td>
<td>0</td>
<td>0.0004</td>
<td>1</td>
<td>0.0340</td>
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<tr>
<td>10</td>
<td>0</td>
<td>0.0000</td>
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<td>11</td>
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<td>0.0001</td>
<td>0</td>
<td>0.0000</td>
<td>1</td>
<td>0.0075</td>
</tr>
</tbody>
</table>

\( m \) = 0.20 2.52 2.20 4.92

Table 3. The distribution of the decadal rate \( r \) of VEI ≥5 eruptions and the associated Poisson probability distribution.

<table>
<thead>
<tr>
<th>( r )</th>
<th>( N(Combined) ) Obs</th>
<th>( p(r) )</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
<td>1</td>
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\( m \) = 0.68
3. DISCUSSION AND SUMMARY

Since the 1880’s, a prominent feature of long-term temperature studies has been the appearance of warming. This warming is directly attributable to both natural climate variability and the increasing effects of human activity on climate. Differentiating the relative proportion of each has been and continues to be both scientifically and politically important.

Recently, Karl et al. have reported that during the interval of May 1997 to September 1998, each month broke the previous monthly all-time-record high temperature. In fact, researchers have found that the inferred average temperature in the 20th century is probably the warmest of the past five centuries.

As previously noted, Hyde and Crowley have recently examined the statistical properties of a proxy record of climatically significant volcanic eruptions to determine the likelihood of future eruptions within the next 10-15 yr. Furthermore, they noted that the occurrence of one or more major volcanic eruptions likely would confuse the debate regarding temperature trends and the effects of human activity on climate. Their results indicated that there is indeed a reasonably good chance that a major volcanic eruption will occur within the next 10 yr, one that might influence the evolution of the anthropogenic signal. Specifically, they determined that there is a 20-percent probability for a Pinatubo-scale eruption (VEI = 6) and a 25-percent chance for an El Chichón-scale eruption (VEI = 5), both archetypes known to have temporarily cooled the Earth’s surface air temperatures.

This complementary study, using actual counts of cataclysmic volcanic eruptions (i.e., those of VEI ≥4) over the past 250 yr, taken from Simkin and Siebert, and Poisson statistics, determined the probability distribution for such events. Over the past 25 decades, each has seen at least two cataclysmic volcanic eruptions, usually located in the tropics or extra-tropical Northern Hemisphere. On average, nearly five such eruptions per decade were seen, with the largest number having occurred in the 1910’s (11 events). Many of these cataclysmic events are known to have produced short-term global cooling, as evinced from surface air temperature records and proxies (i.e., ice cores and tree rings). The actual proportion of cataclysmic events that have known associations with short-term global cooling arguably is 0.1 to nearly 1, depending upon the size, location, and time of year of the eruption. For the largest of events (VEI ≥5), there appears to be an ≈49 percent chance that at least one will occur within the next 10 yr and an ≈15 percent chance that at least two will occur. The usual behavior of the first difference of the two-point moving averages of the number of cataclysmic volcanic eruptions suggests that one should expect ≈7 ± 4 during the present decade, having a probability of occurrence of ≈87 percent. The probability of at least one El Chichón-scale event (VEI = 5) is computed to be 47 percent (slightly higher than that found by Hyde and Crowley), while it is ≈14 percent that at least two will occur and ≈3 percent that at least three will occur. The probability of at least one Pinatubo-scale event (VEI = 6) is computed to be 15 percent (slightly less than that found by Hyde and Crowley), while there is an ≈1 percent chance that at least two will occur, and <0.1 percent that at least three will occur. The probability of at least one event where VEI is >6 is 18 percent. Therefore, as previously recognized by Hyde and Crowley on the basis of proxy volcanic data (sulfate measurements in the ice core record), it seems quite reasonable to expect at least one climatically significant volcanic eruption within the next 10 yr.
REFERENCES


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**Abstract**

Since 1750, the number of cataclysmic volcanic eruptions (volcanic explosivity index (VEI) $\geq 4$) per decade spans 2–11, with 96 percent located in the tropics and extra-tropical Northern Hemisphere. A two-point moving average of the volcanic time series has higher values since the 1860's than before, being 8.00 in the 1910's (the highest value) and 6.50 in the 1980's, the highest since the 1910's peak. Because of the usual behavior of the first difference of the two-point moving averages, one infers that its value for the 1990's will measure $\approx 6.50 \pm 1$, implying that $\sim 7 \pm 4$ cataclysmic volcanic eruptions should be expected during the present decade (2000–2009). Because cataclysmic volcanic eruptions (especially those having VEI $\geq 5$) nearly always have been associated with short-term episodes of global cooling, the occurrence of even one might obscure our ability to assess the effects of global warming. Poisson probability distributions reveal that the probability of one or more events with a VEI $\geq 4$ within the next 10 yr is $>99$ percent. It is $\approx 49$ percent for an event with a VEI $\geq 5$, and 18 percent for an event with a VEI $\geq 6$. Hence, the likelihood that a climatically significant volcanic eruption will occur within the next 10 yr appears reasonably high.