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Volcanism, Cold Temperature, and Paucity of Sunspot Observing Days (1818–1858): A Connection?

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August 1998

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BY ROBERT M. WILSON

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Space Administration

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

TECHNICAL PUBLICATION

VOLCANISM, COLD TEMPERATURE, AND PAUCITY OF SUNSPOT OBSERVING DAYS (1818–1858): A CONNECTION?

1. INTRODUCTION

Although sunspots have been observed on occasion with the naked eye for thousands of years and routinely using the telescope since the early 17th century,[1–3] it was not until the mid 19th century that the quasi-periodic variation of the spottedness of the Sun was truly recognized.[4, 5] Today, we call this cyclic variation of the number of spots on the Sun with time, simply, the "sunspot cycle."

The person who first suggested the existence of the sunspot cycle was Samuel Heinrich Schwabe, a German apothecary and amateur astronomer,[6] who diligently and meticulously observed the Sun for more than four decades (1826–1868)[3] from Dessau, Germany, in the mid 19th century. His observations of the annual number of "clusters of spots" and annual number of "days when no spots were observed" showed clearly that the spottedness of the Sun varied from a minimum in number (when the count of clusters was least and the count of days without spots was greatest) to a maximum in number (when the relative counts were reversed) and then again to another minimum over an interval, or period, of about 10 yr, with the rising portion (minimum to maximum) being shorter in duration than the declining portion (maximum to minimum).[2, 7–9] (While Schwabe is credited with being the first to publicly acknowledge the existence of the sunspot cycle, Hoyt and Schatten[3] have noted that the basis for a sunspot cycle of decadal length was clearly evident in the observations of monthly mean number of sunspot groups that were recorded by Christian Horrebow and his colleagues in 1761–1777.)

Following this discovery, Rudolf Wolf, a Swiss astronomer from Zürich, Switzerland set out to establish whether or not the cyclic appearance of sunspots, as deduced by Schwabe, was a real and continuing effect (also, he wanted to show a causal connection between terrestrial and solar events, like aurora and sunspots).[5, 9, 10] In order to accomplish this task, in 1848 Wolf introduced his now famous "relative sunspot number" (i.e., $r = k(f + 10g)$, where f is the number of individual spots counted on a specific day, g is the number of sunspot groups counted on the same day, and k is a factor that is dependent upon the qualities of the observer, the observing site, and the telescope) and used it to reconstruct the historical record of sunspot variation (from various sources) as far back in time as he could go. From his efforts, he was able to confirm the existence of the cyclic nature of sunspots, as purported by Schwabe, deducing the average period to be closer to about 11 yr in length, rather than 10 yr. More importantly, his efforts to initiate a means whereby one would have a coherent, continuous record of numbers of sunspots resulted in the successful establishment of an international collaboration involving many countries from around the world that continues even today to faithfully monitor and report the daily number of spots on the Sun, so that the record is now complete (without gaps) from 1849.

While Wolf's record of sunspot number is only complete since 1849, the reconstructed portion prior to 1849 (based on many observers from many sites) is found to vary, from nearly complete coverage during some portions of a year to nearly devoid coverage during other portions of the year, back to 1818, Wolf's first entry for monthly mean sunspot number based on daily values (e.g., see the daily listings as given in Waldmeier[10]). Interestingly, Schwabe's record (based on an individual observer from a single site—Dessau, Germany) also is found to vary in similar fashion, but because he followed his own unique way of carefully observing the Sun, the variation in daily coverage is found to continue beyond 1848, certainly up until 1858, the last available entry for this study. Thus, for an interval of at least 40 yr (1818–1858), one has a daily record of observing sunspots that is found to sometimes vary considerably (regarding its completeness) from one year to the next.

A dedicated observer, as Schwabe undoubtedly was,[11] will always follow his passion—to observe. Therefore, his lack of observations (also noticed in Wolf's reconstructed record) may well bespeak of something that must have influenced his (and also those who contributed to Wolf's quest) ability to observe. Whatever caused this paucity of observations, certainly must have been pervasive, affecting much of Europe, and apparently, was quite persistent as well. Indeed, close examination of Schwabe's and Wolf's records shows that the paucity/profusion of annual sunspot observing days occurred, not haphazardly, but rather in an orderly progression (pattern), described here as an abrupt decrease in number of observing days per year that is followed by a gradual increase (to levels that existed before the decrease began), with each episode lasting typically 1–3 yr (or more). So, while Waldmeier[10] has suggested that the gaps in the early sunspot record arise from "bad weather conditions," their persistence and coupled behavior strongly suggest an association with some sort of short-term climatic fluctuation, perhaps due to either large, cataclysmic volcanic eruptions (known to globally perturb climate[12–14]) or, less likely, to the occurrences of near moderate to very strong El Niño events,[15, 16] which somehow may have affected Europe.

The purpose of this investigation, then, is to examine the annual and monthly counts of sunspot observing days from the historical records of Schwabe and Wolf for the interval of 1818–1858, comparing these records with estimates of annual mean temperatures (i.e., equivalents of mean temperature, based upon spot measurements of temperature), as recorded at Armagh Observatory[17] and with the occurrences of large, cataclysmic volcanic eruptions[18] and of near moderate to very strong El Niño events.[19] The result of this statistical study is that, indeed, large, cataclysmic volcanic eruptions appear to account for the paucity of sunspot observing days during the early years of sunspot observation (1818–1858) and that colder annual mean temperatures, likewise, are associated with them. In particular, the effects of Tambora (1815), Galunggung (1822), Cosguina (1835), and, perhaps, Hekla (1845) are found to be quite dramatic.

2. RESULTS AND DISCUSSION

2.1. Annual Numbers of Sunspot Observing Days (1818–1858)

Schwabe[7] reports annual numbers of observing days (i.e., cumulative counts, along with annual numbers of clusters of spots and of days when no spots were seen) when he actually observed sunspots from Dessau, Germany, during the interval of 1826–1843. Each year subsequent to this, Schwabe[20–34] routinely reported monthly numbers of observing days (along with monthly numbers of clusters of spots and of days when no spots were observed) for the interval of 1844–1858. Because Schwabe died in 1875, it may be that published reports for additional observing years might exist beyond 1858. Unfortunately, appropriate issues of *Astronomiche Nachrichten*, which is the journal containing his yearly summaries, were not readily available for these intervening years (at Redstone Scientific Information Center, Huntsville, Alabama). Consequently, this preliminary study is limited to those years prior to 1859. (As previously noted, according to Hoyt and Schatten,[3] Schwabe continued to make and report his observations until 1868; so, eventually his final 10 yr of monthly reports may be recovered.)

Wolf's reconstructed record can be found in Waldmeier[10] and McKinnon,[35] which easily allows for a determination of the number of sunspot observing days (per month and/or per year) for the interval of 1818–1848. Recall that the record is complete after 1848, so no gaps in coverage exist after this date.

Figure 1 displays the number of observing days per year for the interval of 1818–1860, spanning the decline of cycle 6 through the maximum of cycle 10. Schwabe's numbers are shown as the heavy line, while Wolf's numbers are shown as the dashed line. Also displayed as the thin line is the number of observing days per year when J.W. Passtorff (Drossen, Germany) observed the Sun between 1819–1833, taken from Hoyt and Schatten.[11] Across the top are marked the occurrences of the minima (unfilled triangles) and maxima (filled triangles) for cycles 7–10, where the placement of maximum for cycle 7 is found to differ, dependent upon whose annual data are being used (i.e., Schwabe's, denoted S, maximum number of clusters of spots, as compared to Wolf's, denoted W, maximum relative sunspot number). Also identified in Figure 1 is the occurrence of the "Dalton minimum" (also called the "Little Maunder minimum" by Eddy[36]), a brief interval of inferred reduced solar activity between about 1795 and 1823.

Quite noticeable in Figure 1 are several dips (listed sequentially from 1 through 7), or decreases, in the annual number of observing days. Dip number 1, unique to Wolf's reconstructed record, refers to the broader timeframe before 1822, when the number of observing days per year was rising, rather than specifically to the local dip in 1820. Dip number 2, also unique to Wolf's reconstructed data set, occurs during the rise of cycle 7, while Dip number 3, which is found in all three records, occurs near sunspot maximum for cycle 7. Dip number 4, noted in both Wolf's reconstructed record and Schwabe's actual observational record, is quite large (about a 40–50 percent decrease in annual number of observing days) and long-lasting (several consecutive years of reduced annual number of observing days) and occurs during the rising portion and maximum phase of cycle 8. Dip number 5, also noted in both Wolf's reconstructed record and Schwabe's actual observational record, occurs during the rising portion and maximum phase of cycle 9. Finally, two very small 1-yr dips (of questionable significance) occur about 1853 and 1855, during the declining portion of cycle 9.

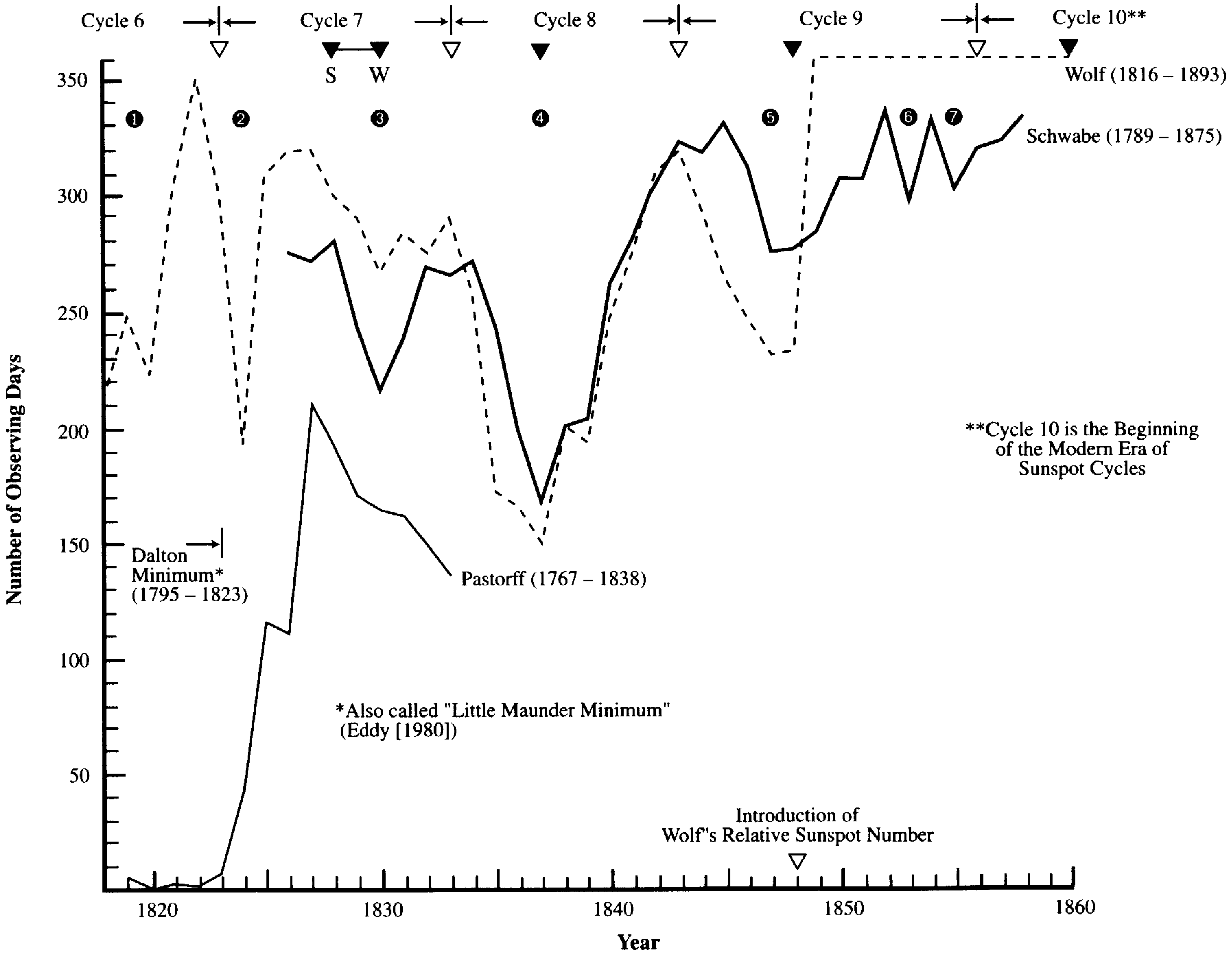

Figure 1. Annual frequency of observing days: 1818–1860. Schwabe's yearly counts are plotted as the heavy solid line, Wolf's reconstructed yearly counts are plotted as the dashed line, and Pastorff's yearly counts are plotted as the thin solid line. The birth-death years for each of the observers is identified beside their names. Several Dips, numbered 1–7, appear in the annual frequency of observing days.

Simple runs testing[37] shows that both of the annual number of observing days as reconstructed by Wolf for the interval of 1818–1848 and as reported by Schwabe for the interval of 1826–1858 are found to vary nonrandomly; hence, the dips are probably not due to chance. For example, based on Wolf's reconstructed record, a median of 268 observing days per year is found, with 16 yr having a value larger than or equal to the median and with 15 yr having a value less than the median, occurring in seven runs. Such a distribution strongly suggests that the variation in Wolf's annual number of observing days is nonrandom (at <5 percent level of statistical significance, equivalent to >95-percent level of confidence). Similarly, based on Schwabe's actual observational record, a median of 282 observing days per year is found, with 17 yr having a value greater than or equal to the median and with 16 yr having a value less than the median, occurring in six runs. This distribution, likewise, strongly favors a nonrandom variation for Schwabe's annual number of observing days (at <5 percent level of statistical significance). So, it seems highly probable that the variation in observing days per year, whether one subscribes to Wolf's reconstructed record or to Schwabe's actual observational record, is not due to chance (random noise). Because many of the dips are found in both records (with one occurring in three records), the occurrences of the dips suggest that they are real and symptomatic of some sort of regional (global?) short-term climatic perturbation that affected, at least, much of Europe during the premodern era years of sunspot observations.

2.2. Comparison of Annual Numbers of Sunspot Observing Days to the Annual Variation of Equivalent Mean Temperature at Armagh Observatory and to the Occurrences of Near Moderate to Very Strong El Niño and of Large, Cataclysmic Volcanic Eruptions

Figure 2 replots the annual number of observing days from Wolf's reconstructed record and Schwabe's actual observational record (following the same format as shown in Fig. 1), identifying the dips (numbers 1–7) with shading, and plots the equivalent mean temperature (°C) at Armagh Observatory, both as a yearly mean (taken from Butler and Johnston[17]) and as a 4-yr moving average (also called the 5-yr running mean, shown as the heavier line; the 4-yr moving average ignores single year decreases), with the shading corresponding to the occurrences of the intervals containing the dips in annual number of observing days. The Armagh Observatory is located at 54° 21.2' N (latitude) and 6° 38.9' W (longitude) at an altitude of about 64 m above sea level near the city of Armagh, Northern Ireland. Daily air temperature measurements have been made at Armagh from 1795 to the present day and are complete, except for a brief 9-yr period from 1825–1833 when no data have yet to be found (hence, this period will be called the "lost record years"). Prior to 1833, the record is based on daily measurements obtained three times each day (8 a.m., noon, and 8 p.m.), while it is based on twice daily readings (10 a.m. and 10 p.m.) from 1833. Butler[38] and Butler and Johnston[17, 39] have discussed the relevance of the Armagh temperature records, in particular, as related to the subject of climatic change, two chief reasons being its extraordinary length (over 200 yr) and its strong correlation with the northern hemispheric mean temperature record (1880–1985), as given by Hansen and Lebedeff.[40] (The provisional annual mean temperature data set, called Series I, actually extends to 1882, thereafter, being discontinued in lieu of another provisional annual mean temperature data set, called Series II, that began in 1843 and continues through today, being based on the use of maximum and minimum thermometers. The provisional records are presently being reexamined by Butler and his colleagues to see whether or not any additional corrections are necessary—cf. Wilson.[41])

Identified above the temperatures are the occurrences of near moderate to very strong El Niño events (where unfilled triangles refer to the occurrences of moderate events and filled triangles refer to the occurrences of strong events), the annual frequency of known volcanic eruptions (having a Volcanic

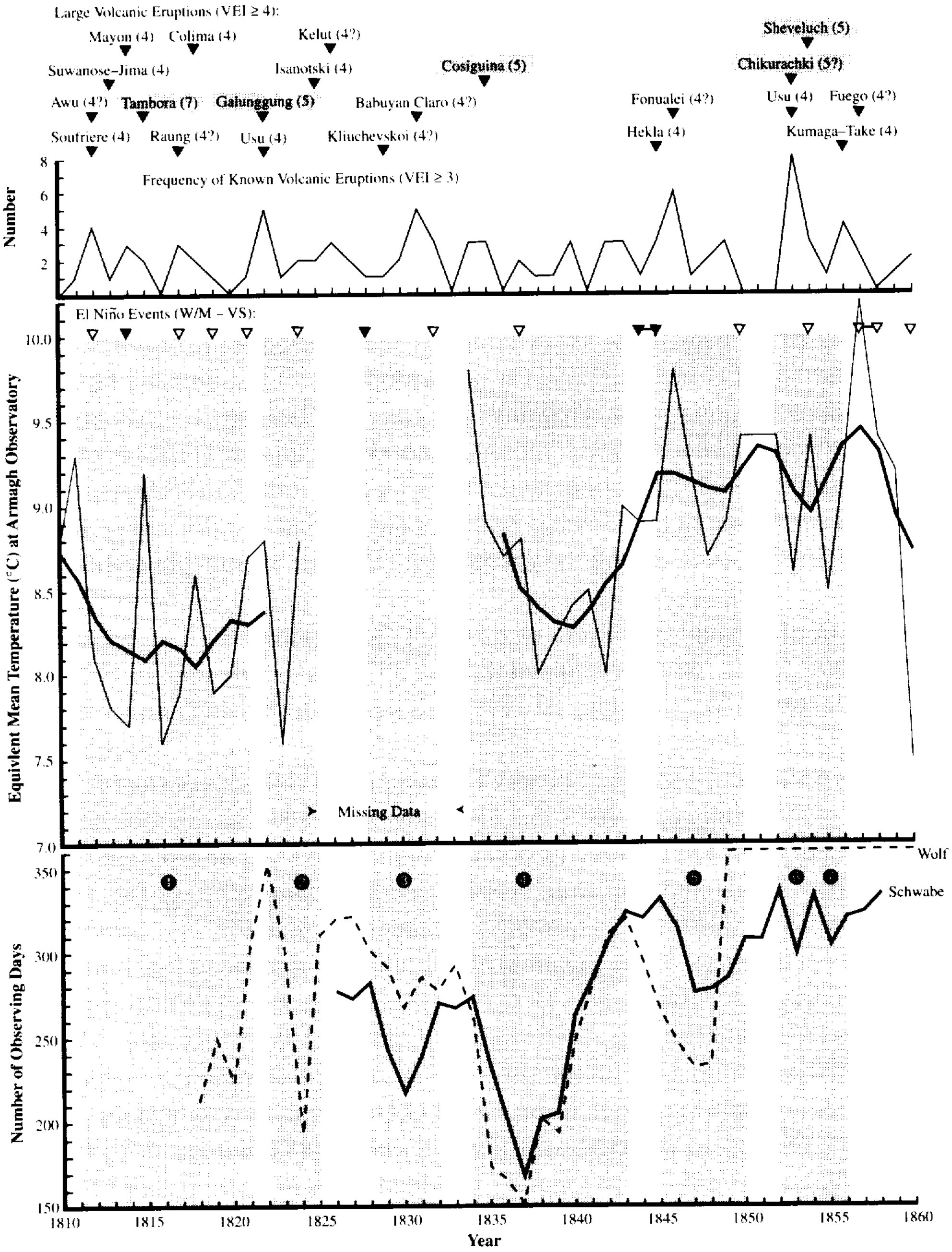

Figure 2. Comparison of annual frequency of observing days (bottom panel) with annual variation of equivalent mean temperature at Armagh Observatory (middle panel) and with occurrences of near moderate to very strong El Niño events and of major volcanic eruptions. Dips numbered 1–7 are shown in the bottom panel. The "lost record years" of 1825–1833 are indicated (as missing data) in the middle panel. Strong El Niño events are those identified by filled triangles, above the temperature data. Bars connecting triangles mean that the event spanned 2 consecutive years. The frequency of known volcanic eruptions, having a Volcanic Explosivity Index (VEI), ≥3 is plotted above the El Niño event timeline. Individual large, cataclysmic (VEI ≥4) volcanic eruptions are identified, with their corresponding VEI in parentheses. Those of VEI ≥5, including Tambora (7), Galunggung (5), Cosiguina (5), Chikurachki (5?), and Sheveluch (5), are highlighted.

Explosivity Index (VEI) ≥3), and the occurrences (by name and VEI) of the larger, cataclysmic volcanic eruptions (i.e., those having a VEI ≥4). The listing of near moderate to very strong El Niño events is taken from Quinn et al.,[19] while the annual frequency of known volcanic eruptions and the listing of large, cataclysmic volcanic eruptions are taken from Simkin and Siebert.[18]

The historical El Niño activity (from the early 1500's to 1987), as determined by Quinn et al.,[19] was deduced by them primarily on evidence obtained from the west coast region of northern South America and its adjacent Pacific Ocean waters, and emphasizes stronger events (i.e., weaker events were not included in their listings). The evidence was initially limited to descriptions from published writings, involving five languages (Spanish, English, German, French, and Dutch), although with the passage of time, meteorological, hydrological, and oceanographic data became increasingly available and were used by them to augment their findings. While, strictly speaking, these historical El Niño events were determined on the basis of their regional characteristics, it is now apparent that they are better perceived as being manifestations of a larger, oceanic-atmospheric phenomenon, known as the El Niño-Southern Oscillation (ENSO) event (which has been linked to unusual weather episodes on the global scale[42–49]). It is also noteworthy that Quinn et al.[19] have emphasized that the period of 1812–1832, of which this study is concerned, in part, was unusually active, with some eight events of near moderate to very strong intensity occurring in the brief span of just 20 yr (inferring a frequency of one event per 2.5 yr, as compared to one event per 3.8 yr, on average).

The chronology of volcanic eruptions, as determined by Simkin and Siebert,[18] provides an exhaustive record of all volcanism known to have taken place in each year (from before 8000 B.C. to the end of 1993). Following Robock and Mao,[12] it has become clear in the last decade that the effect of a volcano on climate is most directly related to the sulfur content of emissions that reach into the stratosphere and not directly to the explosivity of the eruption, although the two are highly correlated.[50, 51] The sulfur gases (e.g., SO_2) eventually convert to a global layer of sulfuric acid (H_2SO_4) aerosols and sulfate particles, which persist for several years (typically, 1–2 yr or more) in the stratosphere and efficiently scatter incoming sunlight, thereby, reducing the direct and total solar radiation reaching the ground. Furthermore, the volcanic dust veil (or pall; see Lamb[52]) and aerosols (see Carroll[14]) absorb long-wave and short-wave radiation, thereby, heating the stratosphere and producing anomalous stratospheric circulation when there is a gradient in the heating. Because less explosive volcanic eruptions (i.e., those having a VEI ≤2) are considered unlikely candidates of stratospheric injection of sulfur gases,[53] in figure 2 only the yearly occurrences of eruptions having a VEI ≥3 are shown (as previously noted, taken from Simkin and Siebert[18]). (It may be of interest to note that during this span of time, no extra-tropical southern hemispheric volcanic eruptions of VEI ≥4 are known to have occurred; all 21 events identified at the top of figure 2 are either tropical events or events that occurred in the extra-tropical northern hemisphere. Lamb[52] and Legrand and Delmas[54] have noted that extra-tropical volcanic eruptions seem only to affect the hemisphere in which they are located, while tropical eruptions can have a direct influence on both hemispheres. Hence, any induced short-term climatic perturbation that might result from a volcanic eruption seems to be of concern to Europe only when it occurs either in the tropics or in the extra-tropical northern hemisphere.)

Simple statistical testing (based on Bernoulli trials and the binomial formula)[37] shows that there is a close statistical association between the dips in number of observing days per year and periods of colder temperature as measured at Armagh Observatory. For example, discarding Dip number 3 (owing to a lack of mean temperature data because of the "lost record years"), one finds that each of the remaining six dips (shaded portions) is found to contain at least one major yearly temperature decline as well. The probability of this occurring by chance is easily computed to be 1.6 percent. So, it may be that this inferred statistical association between decreases in number of observing days per year and declines in mean temperature is indicative of real, consequential behavior (which, in turn, may be the result of the episodic appearance of persistent bad weather—overcast conditions involving much, if not all, of Europe; i.e., short-term climatic fluctuation). Support for this conjecture is also found from the behavior of the 4-yr moving average of equivalent mean temperature when it is compared to the occurrences of the dips in number of observing days per year, which shows that each dip starts when a decline in temperature first begins to appear and ends when the temperature is nearly fully recovered. (Similar dips appear in the June mean temperature records for New Haven, Connecticut, as recorded by former presidents of Yale;[55] thus, the dips in temperature appear to be pervasive, spanning both sides of the Atlantic Ocean in the northern hemisphere.)

Figure 3 plots yearly equivalent mean temperature at Armagh against the yearly number of observing days, separately for Schwabe (left panel) and Wolf (right panel). Surprisingly, when the comparison is between temperature and Schwabe's number of observing days, a preferential association between the parameters is strongly suggested, whereas none is suggested when the comparison is between temperature and Wolf's reconstructed (or blended) number of observing days. For the former comparison (i.e., between temperature and Schwabe's number of observing days; left panel), on the basis of Fisher's exact test[56] one computes the probability of obtaining the observed 2×2 contingency table (i.e., the one formed by the medians, shown as the thin vertical and horizontal lines, parallel to the x and y axes), or one more suggestive of a departure from independence (chance), to be 1.3 percent, while it is 50 percent for the latter comparison (i.e., between temperature and Wolf's number of observing days; right panel). For Schwabe's data, at least, this suggests that when the number of observing days was ≥304 (the median), the yearly equivalent mean temperature at Armagh was usually ≥8.9 °C (the median), while when the number of observing days was <304, the yearly equivalent mean temperature was usually <8.9 °C (and vice versa). On the basis of linear regression analysis between temperature and Schwabe's number of observing days, one infers that a loose ($r = 0.5$), yet statistically significant (at >98 percent level of confidence), positive correlation seems to exist between them (shown in Figure 3 as the diagonals, $\hat{y}$ and $\hat{x}$, for the two cases of using Schwabe's data or temperature as the independent variable, respectively). Thus, from Schwabe's observational record, because of the observed decrease—Dip number 3 (with the decrease beginning after 1828 and ending by 1834)—to 217 observing days in 1830, one infers that a corresponding dip in yearly equivalent mean temperature, quite possibly, occurred, as well (i.e., during the "lost record years"). The inferred temperature in 1830 is estimated from the regression to have been about 8.6 °C, while it is estimated to have been about 9.0 °C in 1828. (The lack of a statistically significant association between yearly equivalent mean temperatures at Armagh and Wolf's reconstructed record of observing days suggests that the blending of data, that Wolf needed to have to reveal the workings of the sunspot cycle, unfortunately, destroyed whatever temperature-observing day relationship for Switzerland that might have been found to exist, had he chosen not to blend his data with those from others.)

Returning to Figure 2, one can compare separately first differences in yearly temperatures and/or number of observing days against the yearly occurrences of El Niño years and large, cataclysmic volcanic eruptions to determine which event, El Niño or volcano (if either), might potentially be the causal agent for the inferred, induced short-term climatic fluctuation. Figure 4 displays the results of this analysis.

All the top panels in Figure 4 show the resultant 2×2 contingency tables, comparing first differences (in particular, answering the question, yes or no, that the value of the first difference is ≥0) of equivalent

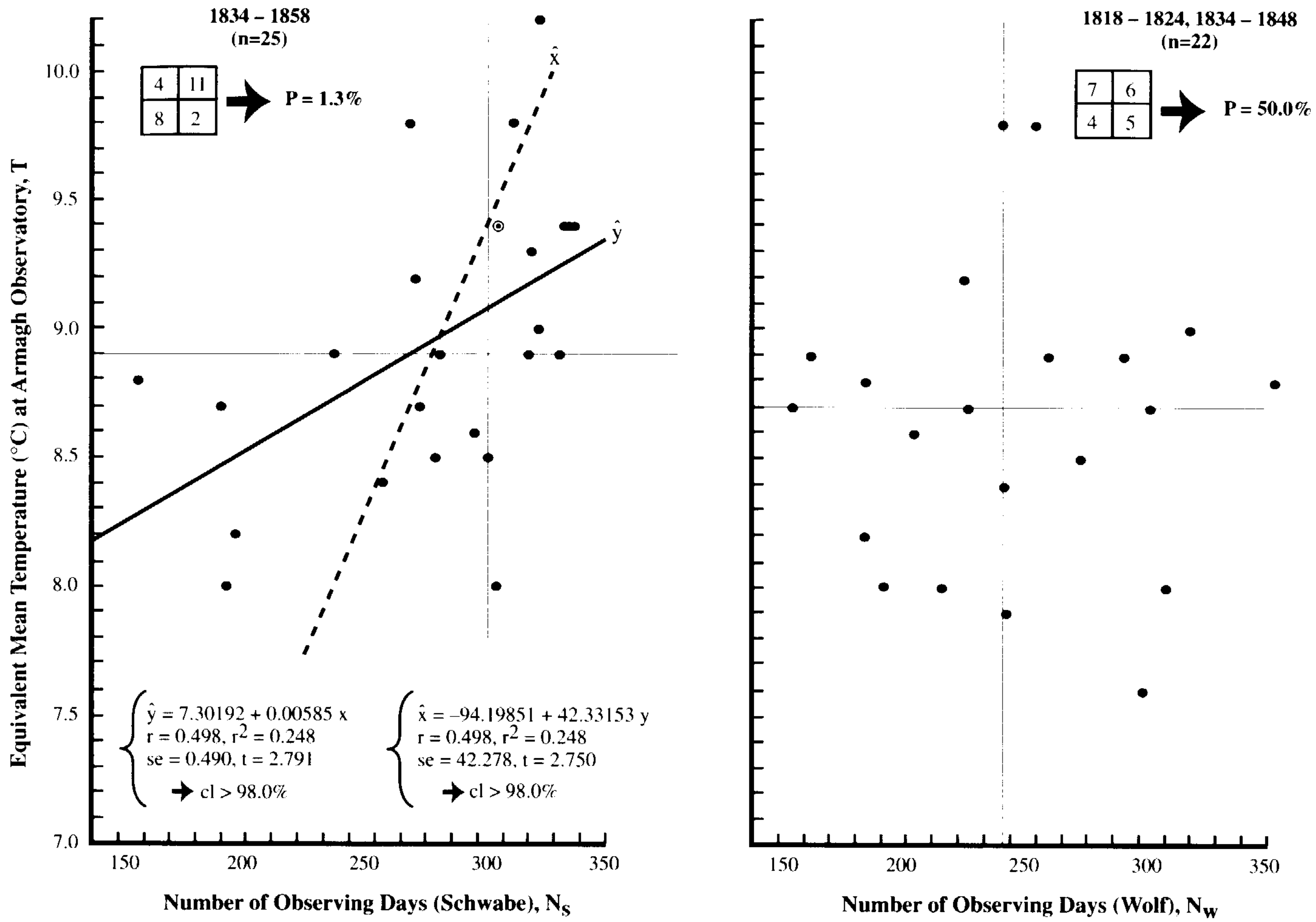

Figure 3. Equivalent annual mean temperature versus annual frequency of observing days, based on Schwabe's data (left panel) and Wolf's reconstruction (right panel). Surprisingly, a statistically significant association is found to exist between temperature and Schwabe's number of observing days, but not between temperature and Wolf's reconstruction. The results of Fisher's exact test for the observed 2x2 contingency table (based on Schwabe's data), or one more suggestive of a departure from independence, is given, inferring that a preferential relationship is indicated between the two parameters at the 2-percent level of significance (P = 1.3 percent). For Schwabe's data, linear regression analysis yields a correlation coefficient $r = 0.5$, a coefficient of determination $r^2 = 0.25$, a standard error of estimate (using Schwabe's data as the independent variable) $se = 0.5$, a Student t value (from hypothesis testing of the inferred slope of the regression in comparison to the null slope) $t = 2.79$, the inferred confidence level for the regression cl >98 percent, and the regression equation $y = a + bx$, where a is the y-axis intercept and b is the slope. (The regression equation using temperature as the independent variable is also given as $x = a + by$.)

mean temperature (upper left), Schwabe's yearly number of observing days (upper middle), and Wolf's yearly number of observing days (upper right) to whether (yes) or not (no) an El Niño event occurred during a given year, while all the bottom panels show the resultant 2×2 contingency tables, comparing the parametric first differences to whether or not a large, cataclysmic volcanic eruption occurred during a given year. Recall that the first difference of a parameter is simply the numeric difference between next year's value with this year's value. Thus, the first difference provides an additional means whereby one can easily determine whether or not a preferential association might exist between the observed parametric behavior (higher or lower value in the next year, corresponding to either the yes or no response, respectively) and a suspected causal agent (here, either the year marking the occurrence of an El Niño event or of a large, cataclysmic volcanic eruption).

Concerning the behavior of the first difference in equivalent mean temperature (left panels), one finds that there appears to be no preferential association between it and whether or not an El Niño event occurred during any given year. The probability of obtaining the observed result (i.e., the 2×2 contingency table, 8:5:13:15), or one more suggestive of a departure from independence, is computed to be (from Fisher's exact test) 44.7 percent, inferring that chance alone can easily account for the observed result. In contrast, a preferential association (of marginal statistical significance) is indicated between the first difference in equivalent mean temperature and whether or not a large, cataclysmic volcanic eruption occurred during any given year. The probability of obtaining the observed result (5:9:9:18), or one more suggestive of a departure from independence, is computed to be 5.9 percent. Thus, when a year is described as being (or not being) an El Niño year, this alone is insufficient to estimate the direction of the trend in temperature at Armagh (i.e., warmer or colder in the next year), while when a year is described as being (or not being) a large, cataclysmic volcanic eruption year, the probable trend may be reckoned (i.e., colder in the next year when the answer is yes and warmer in the next year when the answer is no).

Concerning the behaviors of the first difference in Schwabe's (middle panels) and Wolf's (right panels) yearly number of observing days in comparison to whether or not an El Niño event or a large cataclysmic volcanic eruption occurred, one finds that the resultant 2×2 contingency tables, similarly (a la the first difference in equivalent mean temperature), do not support the contention that a preferential association exists between the first difference in yearly numbers of observing days and the occurrence of an El Niño year, while they do favor the existence of a preferential association, at least, for Schwabe's case, between the first difference in yearly number of observing days and the occurrence of a large cataclysmic volcanic eruption year (statistically speaking, the inferred preferential association is only of marginal statistical significance—8.5 percent). Thus, when a year is described as being (or not being) an El Niño year, this alone is insufficient to determine the direction of the trend in yearly number of observing days (whether one uses Schwabe's record or Wolf's reconstructed record), while when a year is described as being (or not being) a large cataclysmic volcanic eruption year, the probable trend may be reckoned (i.e., a reduction in the yearly number of observing days in the next year when the answer is yes and an increase in the yearly number of observing days in the next year when the answer is no).

To summarize this subsection, statistically speaking, there appears to be evidence suggesting a preferential association between dips in yearly numbers of observing days in Europe (i.e., a paucity of observing days) and episodes of colder clime as recorded at Armagh Observatory (Northern Ireland), with both, possibly, being the consequence of large cataclysmic (VEI ≥4) volcanic eruptions that occurred either in the tropics or in the extra-tropical northern hemisphere. In the following subsections, closer examination

		First Difference Temp. ≥ 0 ?			First Difference N_S* ≥ 0 ?			First Difference N_W* ≥ 0 ?		
		No	Yes		No	Yes		No	Yes	
El Niño Year?	Yes	5	8	P = 44.7%	4	4	P = 33.2%	4	4	P = 61.8%
	No	13	15		8	16		12	11	
LCVE* Year?	Yes	9	5	P = 5.9%	6	4	P = 8.5%	6	3	P = 25.0%
	No	9	18		6	16		10	12	

***LCVE**	means "Large Cataclysmic Volcanic Eruption"
N_S	means "Number of Observing Days" (Schwabe's Data)
N_W	means "Number of Observing Days" (Wolf's Data)

Figure 4. 2×2 contingency tables comparing years of El Niño occurrences (top tier) and years of large, cataclysmic volcanic eruptions (bottom tier) against the first difference in temperature (left column) and number of observing days in the middle (Schwabe) and right (Wolf) columns. For El Niño events and large, cataclysmic volcanic eruptions, a yes response means that such an occurrence was seen for that year, while a no response means that such an occurrence was not seen for that year. Similarly, a yes response for the first difference means that the first difference is ≥0, inferring that temperature is either the same or warmer and number of observing days is either the same or more in the following year, while a no response means that the first difference is <0, inferring that temperature is cooler and number of observing days is fewer in the next year. The 2×2 tables suggest that El Niño events do not appear to be the causal agent for changes in temperature at Armagh or changes in number of observing days, while they support (marginally) the contention that large, cataclysmic volcanic eruptions may induce the observed changes in temperature and number of observing days.

of the larger specific dips, numbers 1, 2, 4, and 5, will be accomplished, using appropriate monthly counts of observing days relative to the month of occurrence for particular large, cataclysmic volcanic eruptions, the ones suspected as being the causal agents.

2.3 Specific Examples

Prior to the examination of these dips, because one now will be using monthly data, it is essential that any seasonal effects, should they be found to exist, be removed. Figure 5 plots the monthly averages of number of observing days based, separately, on Schwabe's observed record (the solid line) and Wolf's reconstructed record (the dashed line). Clearly, a seasonal effect, indeed, is found in both, with the number of observing days per month, on average, being lowest for November through February and highest for May through August, and with the months in between showing transition (i.e., increasing in number of observing days in March–April and decreasing in number of observing days in September–October). The question now is, after correcting for this seasonal effect in the data, do the number of observing days still vary in any preferential way? One anticipates that if a real preferential association truly exists between the behavior of number of observing days and the occurrence of a large, cataclysmic volcanic eruption, then evidence for a persistent behavioral pattern should remain. In particular, one expects either that many, if not most, of the months following a large, cataclysmic volcanic eruption (either as an immediate response or, possibly, as a delayed response, dependent upon the time of year of the eruption and its location[52, 57]) to, generally, be below average in number of observing days as compared to times when an eruption either did not occur or has not occurred for sometime—or that certain seasons might contribute more strongly to the paucity of observing days, as compared to others.

Figures 6 (Wolf's data) and 7 (Schwabe's data) plot the number of observing months per year when below average, seasonally adjusted number of observing days occurred and shows the occurrences of specific large, cataclysmic volcanic eruptions. For Wolf's data (1818–1848), a fairly strong, seemingly preferential, response is found for the eruptions of Tambora (1815), Galunggung (1822), Cosiguina (1835), and Hekla (1845), corresponding to Dips numbered 1, 2, 4, and 5, respectively, with a possible (but obviously weaker) response found for Kliuchevskoi (1829), corresponding to Dip number 3. For Schwabe's data (1844–1858; recall that his earlier data, 1826–1843, have only been published in terms of yearly counts), because they are available in monthly format only from 1844, a fairly strong, seemingly preferential, response is found only for Hekla (1845), corresponding to Dip number 5. It is noteworthy that the eruptions of Tambora and Cosiguina have been identified as the source regions (i.e., causal agents) for specific signatures in the Greenlandic/Antarctic ice core deposits,[54, 58–64] thereby, indicating that these events were truly globally effective.

2.3.1. Tambora (1815): The Interval of 1818–1821 (Dip Number 1)

Figure 8 displays the monthly residual determined from Wolf's data (defined here as NW – S(NW), where NW is the number of observing days per month and S(NW) is the appropriate interval monthly average; i.e., the seasonal adjustment term), where negative values indicate a loss of observing days and positive values indicate an excess of observing days for each month as compared to the average frequency, for the interval of 1818–1821, which corresponds to Dip number 1, and is plotted in relation (elapsed time) to the eruption of Tambora (VEI = 7), located on Sumbawa Island, Indonesia (8.25°S, 118.00°E), in April 1815. The Tambora event is the largest (and deadliest), cataclysmic volcanic eruption that is known to have

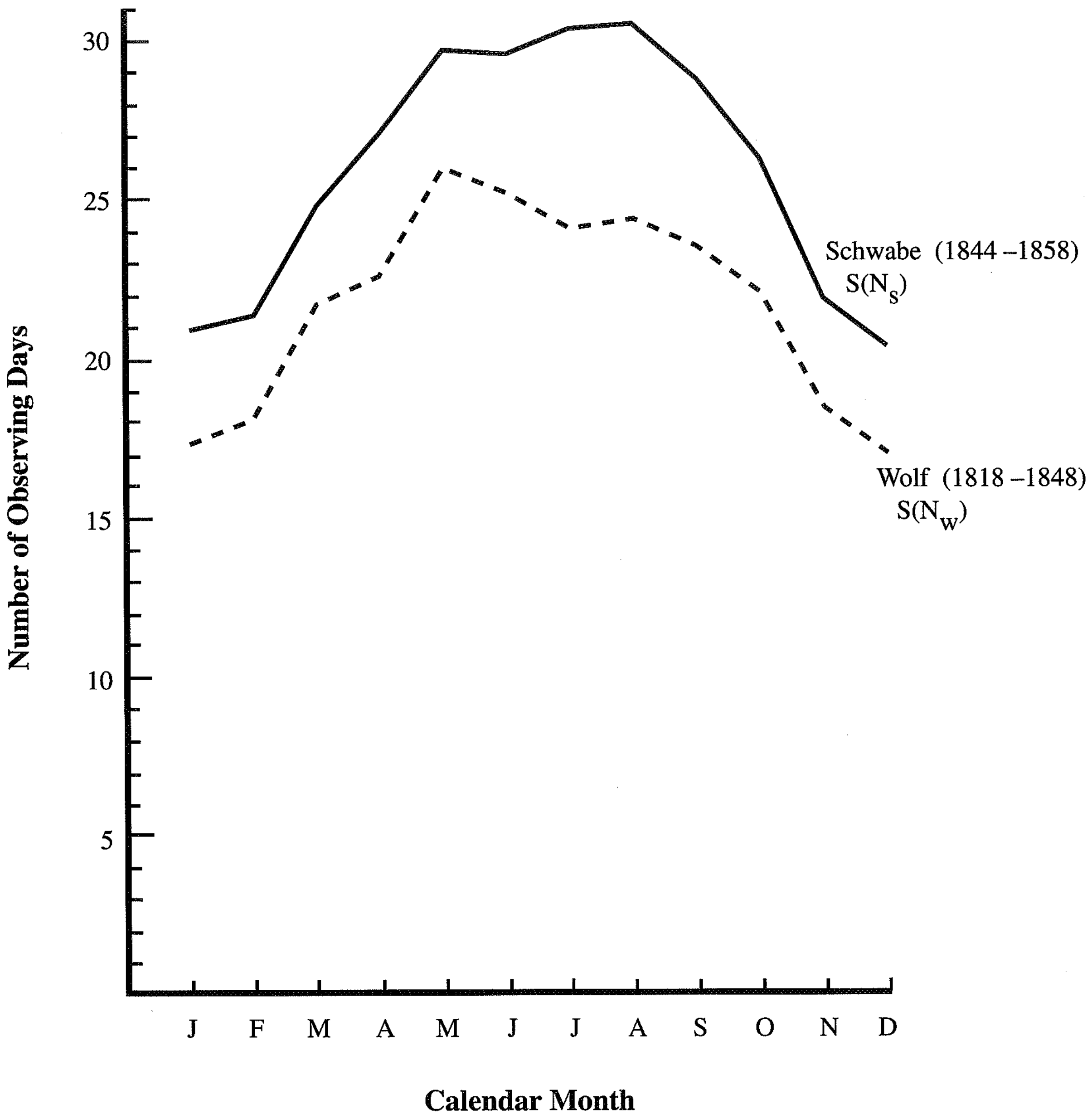

Figure 5. The average monthly number of observing days over a year. The solid line refers to Schwabe's data (1844–1858) and the dashed line refers to Wolf's reconstructed data (1818–1848). The winter months of December–February, on average, tend to have the fewest number of observing days.

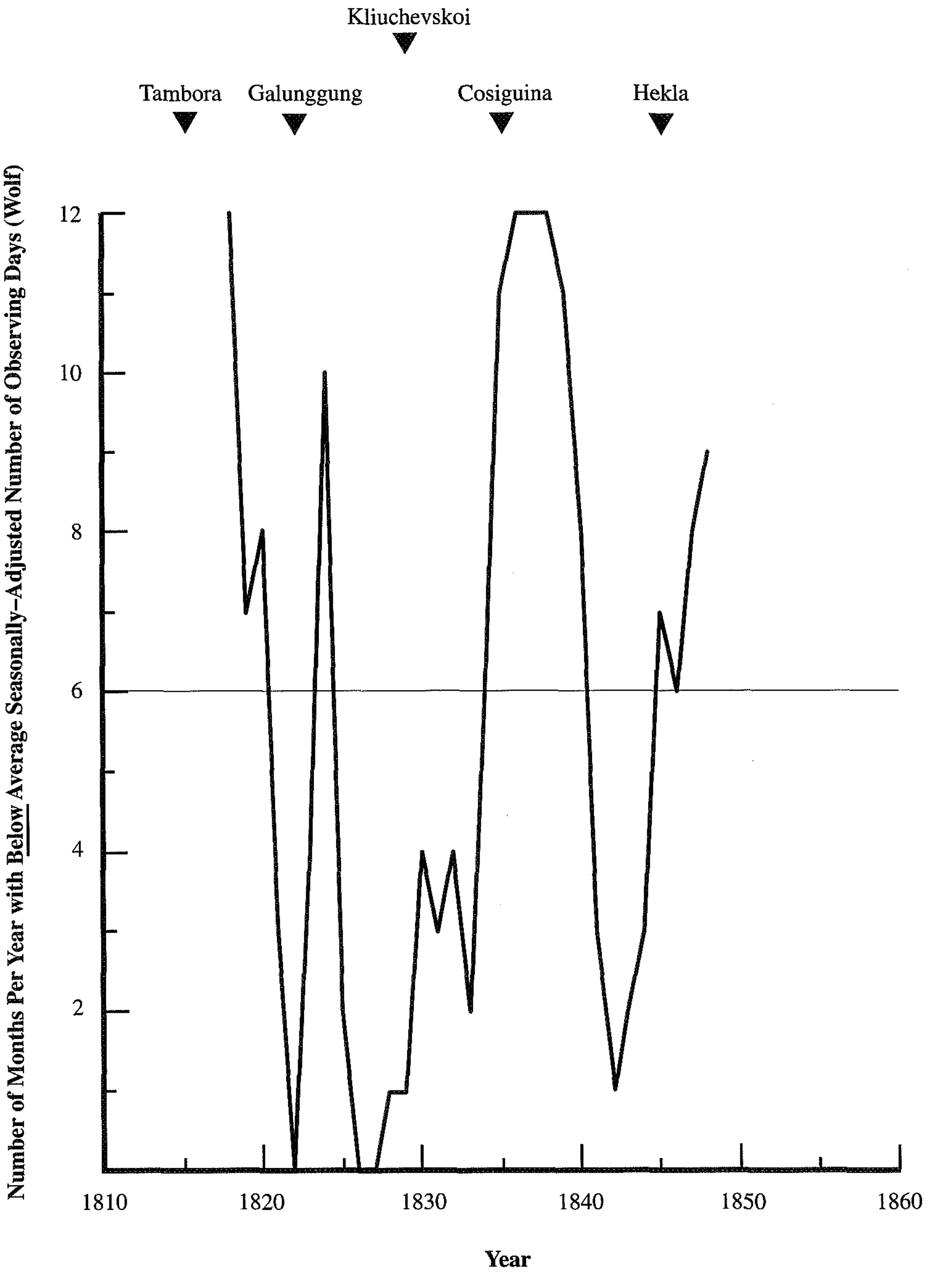

Figure 6. Number of months within a year that are below the seasonally adjusted average, using Wolf's reconstructed data. The years of 1818–1820, 1824, 1835–1840, and 1845–1848 are found to be, more often than not, years when the number of observing days were markedly reduced. The remaining years are found to be, more often than not, years when the number of observing days were markedly enhanced. The occurrences of specific volcanic eruptions are given.

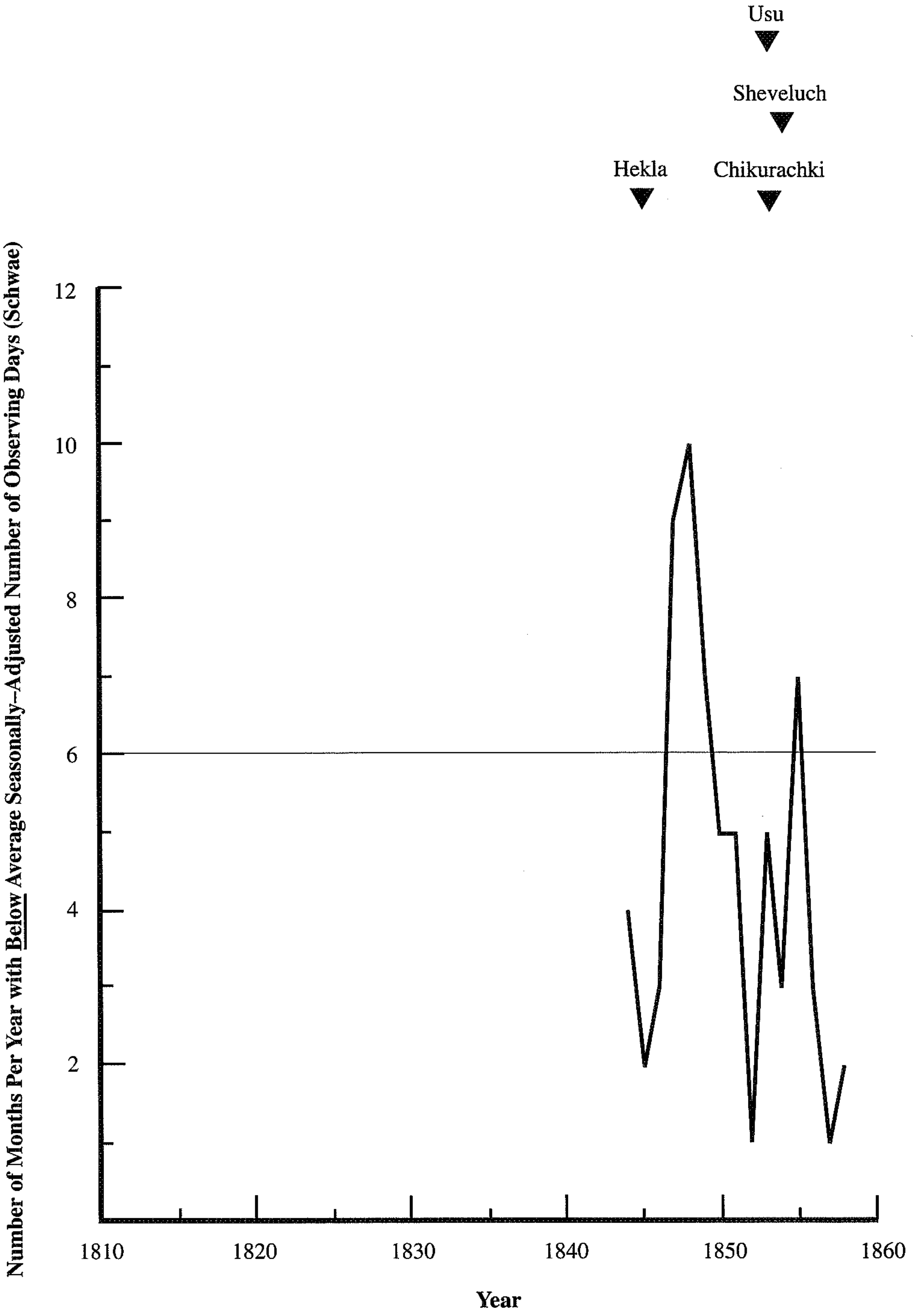

Figure 7. Number of months within a year that are below the seasonally adjusted average, using Schwabe's data. The years of 1847–1849 and 1855 are found to be, more often than not, years when the number of observing days were markedly reduced. The remaining years are found to be, more often than not, years when the number of observing days were markedly enhanced. The occurrences of specific volcanic eruptions are given.

occurred in, at least, the past 500 yr (possibly even longer), and it has been associated with the "year without a summer" in 1816 (see Stommel and Stommel,[55] Stothers,[65] and references cited therein). The heavier line is the 4-mo moving average (which ignores single-month variations) and the shaded portions correspond to the winter seasons (December–February). Two smaller eruptions (in 1817 and 1818) are also identified that may be related to a restrengthening of the decrease after 1819.

It is unfortunate that the record of monthly observations begins in 1818 rather than some earlier time before 1815. Had the observing record begun at a slightly earlier date, one would have been able to see the full ramification of the suspected, induced climatic perturbation (that surely must have accompanied it) of this truly spectacular event, instead of just speculating about it, especially, with regards to the loss in observing days (perhaps, to a number of observing days substantially smaller than was seen in 1818). Figure 8 shows that, while the number of observing days, as reconstructed by Wolf, was slowly increasing between 1818 and 1819 (typically, the net loss was worst in the winter seasons of 1817–1818 and 1818–1819), throughout all of 1818 it was negative in value (i.e., below average in number), and it continued so until the spring of 1819 when recovery appears to be finished. From this, one infers that the effects of the Tambora event lasted approximately 4 yr (in agreement with Stother's optical depth curve).[65] Following recovery, another dip (of smaller size) is suggested which may be related (as noted above) to the smaller eruptions of Raung (VEI = 4?) on the island of Java (Indonesia) in January 1817 and/or Colima Volc. Complex (VEI = 4) in Mexico in February 1818. The smaller, gentler dip that seems to begin in 1819 and ends in early 1821 has its greatest monthly losses in July 1819 and July 1820, as well as the winter season of 1820–1821.

The initial behavior of increasing number of observing days from 1818 through 1819 is taken as evidence for improving atmospheric conditions following the Tambora event. Recall, that the estimated stratospheric loading of sulfur (based on ice core records; e.g., Delmas et al.[61]) that has been attributed to the Tambora event of 1815, the event marking the end of a 3-yr period of continuous volcanic activity of Mt. Tambora (1812–1815), is the largest loading that has been found in the ice core records over the past five centuries. It measures about twice that of a suspected, yet unidentified, volcanic eruption that is believed to have occurred in the tropics around 1809[57, 61, 64] and measures several times larger than that attributed to the eruptions of Krakatau (VEI = 6) in 1883 or Agung (VEI = 4) in 1963,[61] both of these events also being located in Indonesia.

According to Landsberg and Albert,[66] Stothers,[65] and Simkin and Siebert,[18] the devastating Tambora event of 1815 reduced the height of Mt. Tambora from 4 km to about 2.85 km; it took the lives of about 92,000 people; it was audible from at least 2,600 km away; it generated a tsunami of 1–4 m in height that spread outward at least 1,200 km; it caused pitch darkness, lasting up to 2 days, over a distance of 600 km; it created unusual twilight and atmospheric conditions in North America and Europe that persisted from months to years; and it appears to have evoked (or, at least, contributed to) a global cooling in surface temperature that did not recover until the end of the second decade of the 1800's, a cooling that, very well, is of similar or greater magnitude than that which was seen following the more recent eruptions of Krakatau (VEI = 6) in 1883, Santa Maria (VEI = 6) in 1902, Katmai (VEI = 6) in 1912, Agung (VEI = 4) in 1963, El Chichón (VEI = 5) in 1982, and Pinatubo (VEI = 6) in 1991.[12, 13] The inferred cooling, and subsequent warming, is quite apparent in the Armagh record of equivalent mean temperature (see Figure 2; also, it is very apparent in the June mean temperature records for New Haven, Connecticut[55]), and the increasing number of observing days per month (from Europe), following the event, certainly hints that some sort of recovery process was taking place between 1818 and 1819. Furthermore, it seems noteworthy that the years (and individual seasons) following the Tambora event rank near the top in several categories of anomalous behaviors as gleaned from tree ring studies. For example, Lough and Fritts[67] have found the summer and fall seasons of 1815 and the winter and spring seasons of 1816 to be among the most anomalous of periods, based on tree ring chronologies from North America. Also, Briffa et al.[68, 69] have found the reconstruction of surface temperature, based upon "maximum latewood densities," to suggest that, beginning about 1812, a sharp lowering of temperature in Europe and North America occurred which persisted until about 1820, with the years 1812, 1814, and 1816 being extremely cool, especially the summers (see also, Jones et al.[70]).

2.3.2. Galunggung (1822): The Interval of 1822–1825 (Dip Number 2)

Figure 9 displays Wolf's residual for the years of 1821–1828, which spans the interval of 1822–1825, corresponding to Dip number 2. Galunggung (VEI = 5), located on the island of Java, Indonesia (7.25°S, 108.05°E) erupted in October 1822. Prior to the eruption and continuing a few months after the eruption, the residual is found to be well in excess of the average monthly frequency, indicating very good weather (and warmer clime) in Europe. Following the first winter season, however, the number of observing days falls precipitously from an excess of more than 13 days above average in January 1823 to a loss of about 18 observing days below average for February 1824, with the winter of 1823–1824 being extremely harsh, as adjudged by the number of lost observing days. Thereafter, in a series of ups and downs, spanning the spring and summer seasons of 1824, the number of observing days increases and returns to prevent levels (indicative of better weather and warmer clime; see Figure 2). According to Simkin and Siebert,[18] about 4,000 people perished in this event, the fourth largest number of deaths attributed to the largest volcanic eruptions of the 19th and 20th centuries (the top three are Tambora–1815, 92,000; Krakatau –1883, >36,000; and Santa Maria–1902, >5,000).

Although mention of this event is lacking in the chronology of Cole-Dai et al.,[64] it is interesting to note that their Figure 6 (p. 16, 768) seems to show the presence (i.e., a spike) of an elevated SO_4^{2-} concentration of nearly the size of the inferred unknown event of 1809 at about the appropriate place for the Galunggung event of 1822. Perhaps, researchers can reexamine their data in the vicinity of this eruption to yield more information about its inferred stratospheric loading. Certainly, the behavior of the residual for this event is most striking and, when coupled with the apparent plunge in equivalent mean temperature at Armagh Observatory (see Figure 2), strongly suggests that this event induced a real, short-term, globally effective, climatic perturbation.

2.3.3. Cosiguina (1835): The Interval of 1834–1843 (Dip Number 4)

Figure 10 shows Wolf's residual for the years of 1834–1840, corresponding to the bulk of the interval associated with Dip number 4 (being the longest—at least 7 yr in duration and being one of the two deepest, the other being Dip number 2—at least, 40–50 percent reduction in number of observing days per year—of the dips that are known from start to finish; see figs. 1 or 2). The residual is drawn in relation to the eruption of Cosiguina (VEI = 5), located in Nicaragua (12.98°N, 87.57°W), in January 1835. Following the eruption, the residual is observed to precipitously decline from an excess of more than 4 observing days per month (above average) in January 1835 to a loss exceeding 22 observing days per month (below average) in August 1835, with recovery extending beyond 1840. The 4-mo moving average is found to slowly decline through 1836 and into 1837 before trending upward.

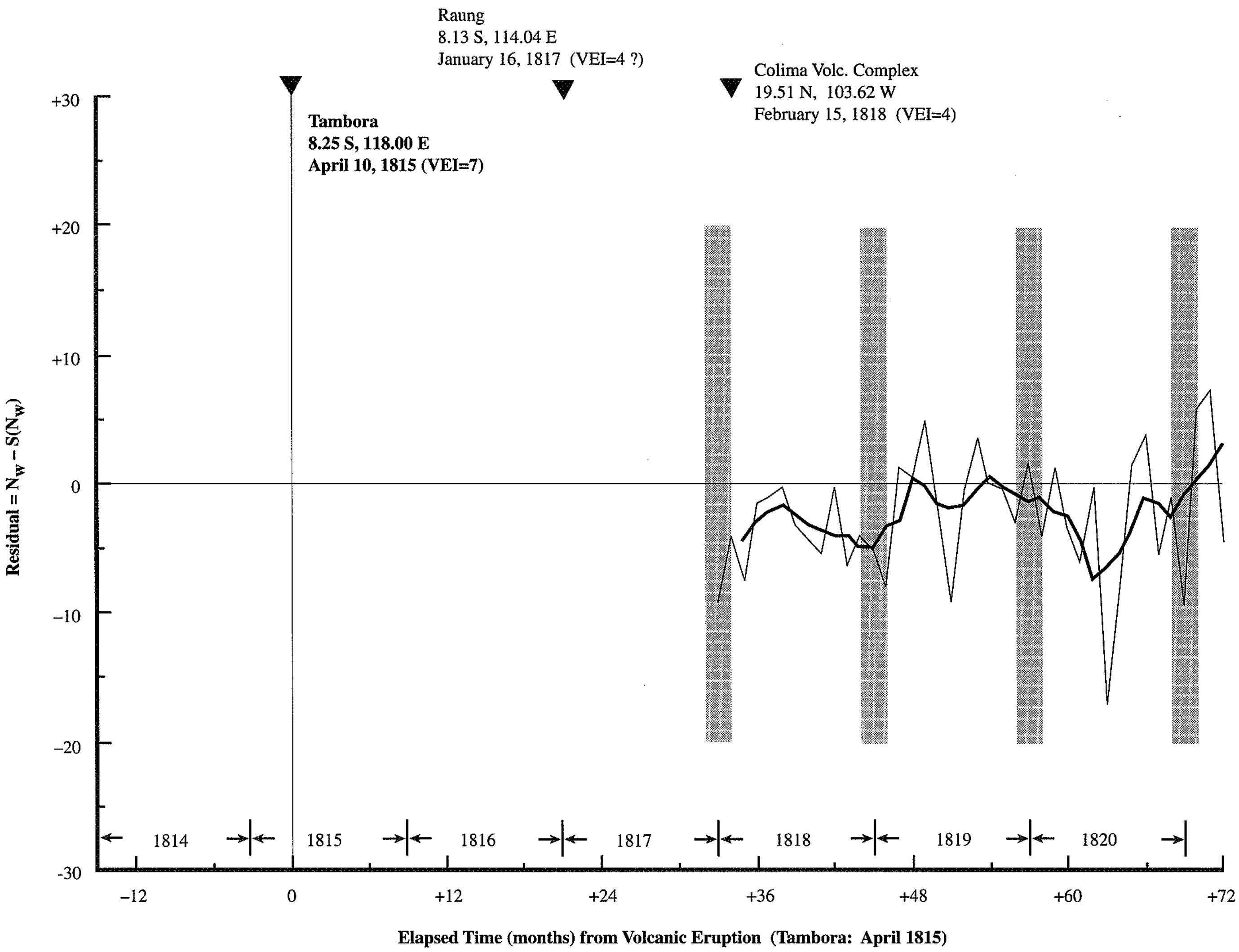

Figure 8. The residual (associated with Dip number 1), based on Wolf's reconstructed data, in relation to the occurrence of the Tambora blast in April 1815. Negative residual means fewer observing days than usual, while positive residual means more observing days than usual. The shaded portions refer to the winter season (December–February). Other, possibly, contributory eruptions are identified. This same format will be followed in all succeeding charts (for Dip numbers 2–7).

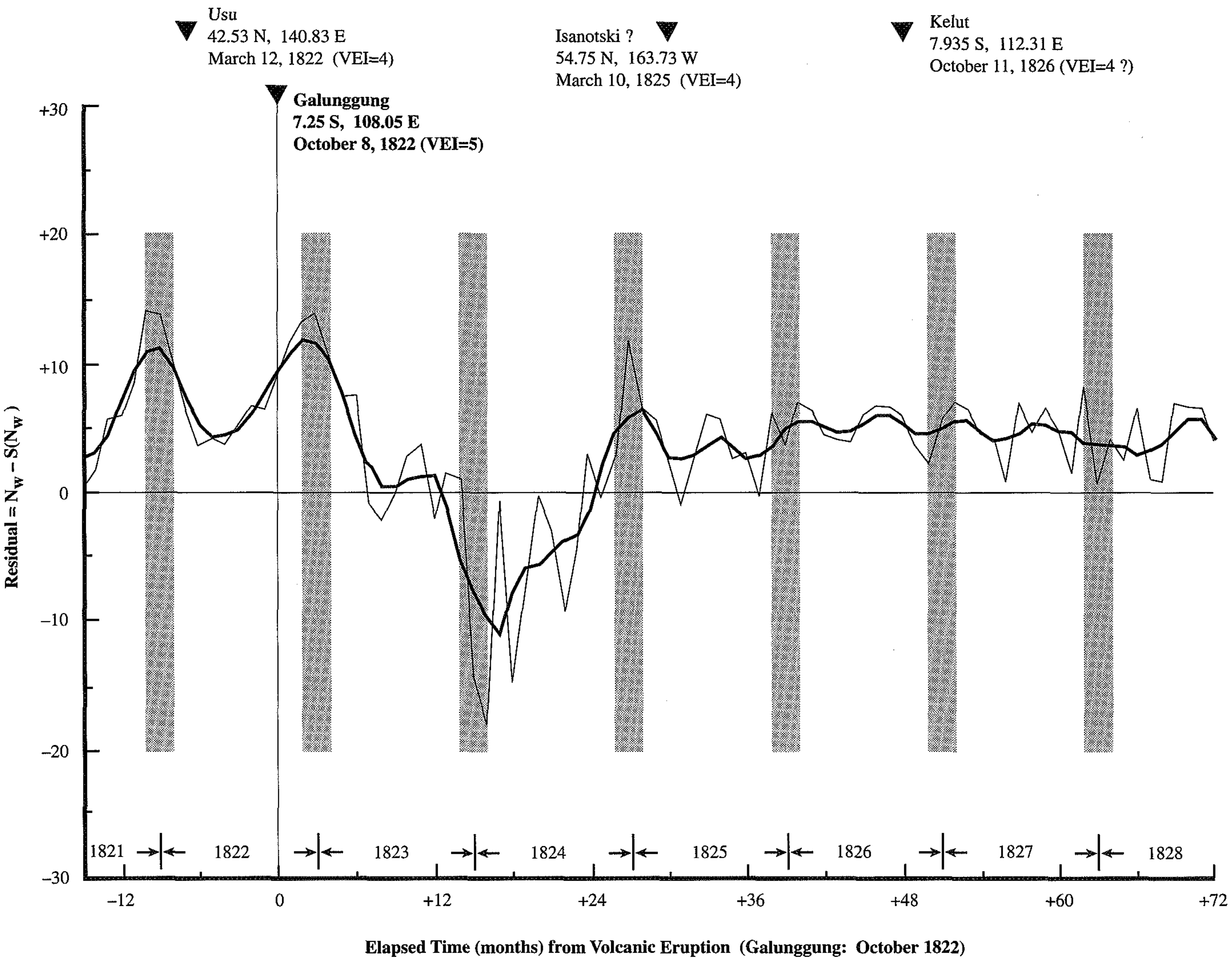

Figure 9. The residual (associated with Dip number 2), based on Wolf's reconstructed data in relation to the Galunggung blast of October 1822.

As previously noted, this particular eruption has been associated with elevated sulfuric acid depositions found both at Greenland[57, 58] and Antarctica.[54, 60–64] In particular, Cole-Dai et al.[64] note that the deposition in Antarctica from the Cosiguina eruption lasted about 3 yr as determined from the $SO_4{}^{2}$-flux calculation at Dyer Plateau and about 2 yr at Siple Station.

Supporting evidence for the global effectiveness of this event is the short-term climatic fluctuation that is seen in the equivalent mean temperature record at Armagh Observatory in Northern Ireland (see Fig. 2; also, see the decrease in June mean temperature for New Haven, Connecticut, in 1836 as described by Stommel and Stommel[55]), and the findings of Briffa et al.[68] that the summers over Europe in the 1830's were cooler than usual, especially in the north (Scandinavia), based upon the reconstruction of temperature from maximum latewood densities of conifers. In another study, Briffa et al.[69] note that the summers in the Mackenzie Valley of Canada in the 1830's were also cool, with the summer of 1836 being notably cold (true also for the regions of Quebec and Labrador), likewise, based upon the reconstruction of temperature from maximum latewood densities of conifers, and they suggested that the eruption of Cosiguina in 1835 was the causal agent for the inferred cooler clime in central North America (see also Jones et al.[70]).

2.3.4. Hekla (1845): The Interval of 1845–1850 (Dip Number 5)

Figure 11 displays the monthly residual using Schwabe's data (i.e., $N_S - S(N_S)$, where N_S is the number of observing days per month, according to Schwabe, and $S(N_S)$ is the appropriate interval monthly average; i.e., the seasonal adjustment term), plotted in relation to the eruption of Hekla (VEI = 4), located in Iceland (63.98°N, 19.70°W), in September 1845. While the largest eruption occurred in September 1845, Simkin and Siebert[18] have noted that Hekla continued to be active well into 1846. From figure 11, one finds that the residual clearly was positive in value, indicating an excess of observing days above normal, from late 1845 through about September 1846, when the residual precipitously decreased to negative values, having the lowest values in the winter of 1846–1847, indicating a loss of about 11 days below normal. In terms of the 4-mo moving average, one finds that it stayed negative in value until about mid to late 1849, when recovery appears to be over. Because of its high northern latitude (64°N), one expects that the Hekla eruption should not have a discernible signature in the ice core record of Antarctica and, indeed, none has been found; however, it probably should appear in the ice core record of Greenland, especially if the eruption truly is considered large and cataclysmic in nature (thereby, causing the inferred short-term climatic fluctuation). Unfortunately, it is not found in the recent listing of Zielinski et al.[57]

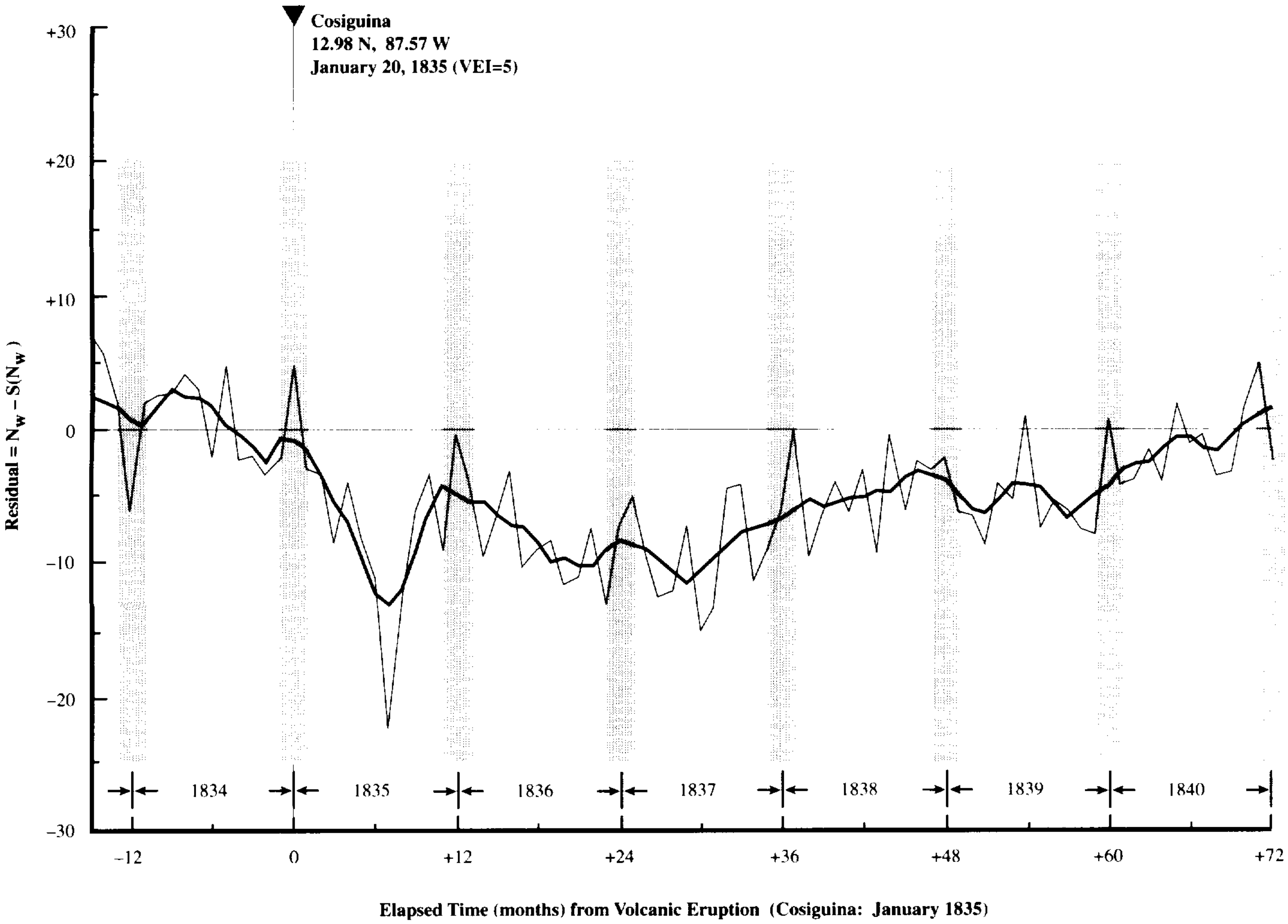

Figure 10. The residual (associated with Dip number 4), based on Wolf's reconstructed data in relation to the Cosiguina blast of January 1835.

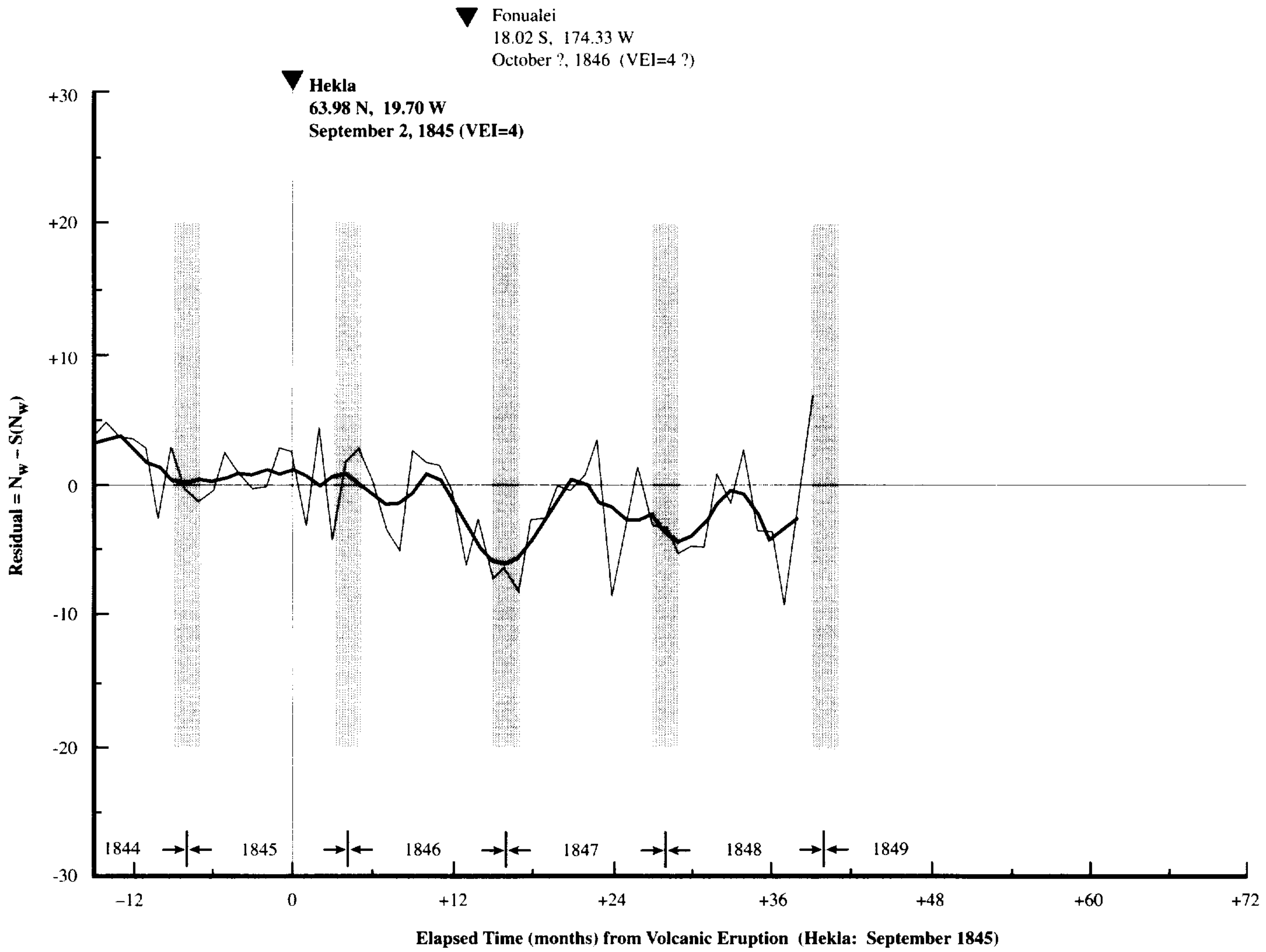

Figure 11. The residual (associated with Dip number 5), based on Schwabe's data in relation to the Hekla blast of September 1845.

3. SUMMARY AND CONCLUSIONS

The June 1991 eruption of Pinatubo (VEI = 6) in the Philippines (15°N) produced the largest sulfur dioxide cloud detected by the Total Ozone Mapping Spectrometer aboard the Nimbus-7 satellite during its operational life.[71] The SO_2 cloud (and other byproducts of the explosion) was observed to encircle the Earth within about 3 wk, straddling the equator ±20–30° in latitude, and, over time, to migrate poleward (towards both poles), thereby, essentially blanketing the entire Earth.[72] McCormick et al.[73] have noted that the volcanic plume associated with the eruption of Pinatubo exceeded 30 km in height and injected into the stratosphere an aerosol mass loading of about 30 Tg, the largest aerosol perturbation believed to have occurred this century, although smaller than that estimated from the eruptions of Tambora in 1815 (>100 Tg) and Krakatau in 1883 (~50 Tg). The aerosol loading has been associated with an induced global cooling of the Earth's surface temperature, which only recently has returned to the pre-Pinatubo level,[13, 74] inferring that the Pinatubo blast was globally effective for about 4 yr.

While the Pinatubo blast is a remarkable event, affecting the entire Earth, historically, it is by no means unique. Another keen example of a large, cataclysmic volcanic eruption that affected world climate is the August 1883 blast of Krakatau (VEI = 6).[75] One August 27, 1883, the island of Krakatau, Indonesia (6.10°S, 105.42°E) blew up, injecting a considerable amount of volcanic gases and debris to more than 30 km into the atmosphere, which quickly spread over the face of the Earth, causing colorful displays at twilight (including a blue, purple, and green Sun and moon). In late November 1883, the drifting pall arrived over Europe, and researchers at Montpellier Observatory in the south of France noticed a most peculiar and unexpected happening. They observed the amount of solar energy received from the Sun (i.e., the insolation) to dramatically decrease from 30 percent above normal to 20 percent below normal, and to remain 10 percent below normal for the next 3 yr. Obviously, the eruption on Krakatau was globally effective for at least 3 yr.

Robock and Mao[12] have examined the 15 largest stratospheric-aerosol-producing volcanoes since 1866 and have concluded that the volcanic timescale is about 2 yr. Also, they have noted that surface cooling of about 0.1–0.2 °C generally follows an eruption, with the timing of the cooling being dependent upon the location (high latitude versus low latitude) of the blast and the season when it occurred. Furthermore, Delmas et al.[61] and Cole-Dai et al.[64] have listed a number of large, cataclysmic volcanic eruptions whose signatures are found in the ice core records of Antarctica, and Zielinski et al.[57] have listed those whose signatures appear in the ice core records of Greenland. Additionally, Delmas et al.[61] have noted that the deposition in the ice cores in Antarctica suggest durations of, typically, 1–4 yr (averaging about 2–3 yr in length) and Stuiver et al.[76] have found that volcanic aerosols depress central Greenland annual temperature and annual $^{18}O/^{16}O$ for about 4 yr after each major eruptive event. From this, one can infer that a large, cataclysmic volcanic eruption is capable of producing a globally distributed aerosol (presuming the eruption to occur in the tropics), having a residence time of up to several years, that can induce a short-term climatic fluctuation (especially, as related to insolation or surface air temperature).

In this investigation, evidence has been presented that suggests that large, cataclysmic (VEI ≥4) volcanic eruptions in the tropics and extra-tropical northern hemisphere induced short-term climatic changes in Europe during the early premodern era years of sunspot observations (1818–1858). The effect is clearly seen in the annual mean temperature record of the Armagh Observatory (Northern Ireland), as a temporary cooling, and in the actual observing record of Samuel Heinrich Schwabe (in Dessau, Germany) and the blended (reconstructed) record of Rudolf Wolf, as a temporary reduction in the number of observing days available for viewing the Sun. In particular, the eruptions of Tambora (VEI = 7; Indonesia) in 1815, Galunggung (VEI = 5; Indonesia) in 1822, Cosiguina (VEI = 5; Nicaragua) in 1835, and, perhaps, Hekla (VEI = 4; Iceland) in 1845 show the effect most dramatically—a decline in temperature of up to several tenths of a degree Celsius or more, with a corresponding reduction in the number of observing days, in some cases, extremely large reductions. Additionally, this novel finding, linking volcanic eruption, temperature change, and paucity in number of observing days, suggests that during "the lost record years" of the Armagh Observatory (1825–1833), a brief cooling occurred in Europe that might be related to the eruption of Kliuchevskoi (VEI = 4; Kamchatka, Russia) in 1829. Wolf's attempt to generate a continuous (no gaps) record of relative sunspot numbers from an international cadre of observers, while very useful from the sunspot cycle perspective, is seen to have unwittingly undermined the potential gains of using number of observing days as an instrument for monitoring short-term climatic change at a particular locale.

REFERENCES

1. Bray, R.J., and R.E. Loughhead: *Sunspots*, John Wiley & Sons, New York, 1965.
2. Schove, D.J.: *Sunspot Cycles*, Hutchinson Ross Publ. Co., Stroudsburg, Pennsylvania, 1983.
3. Hoyt, D.V., and K.H. Schatten: *The Role of the Sun in Climate Change*, Oxford University Press, New York, 1997.
4. Kiepenheuer, K.O.: Solar activity (Chapter 6), *The Sun*, G. P. Kuiper (ed.), The University of Chicago Press, Chicago, pp. 322–465, 1953.
5. Schröder, W.: Some aspects of the early history of solar-terrestrial physics, *Planet. Space Sci., 45*, 395–400, 1997.
6. Newkirk, G., Jr., and K. Frazier: The solar cycle, *Phys. Today, 35*, 25–34, April 1982.
7. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1843, *Astron. Nach., 21*(495), 233–236, 1844.
8. Meadows, A.J.: *Early Solar Physics*, Pergamon Press, London, 1970.
9. Eddy, J. A.: Historical evidence for the existence of the solar cycle, *The Solar Output and Its Variation*, O.R. White (ed.), Colorado Associated University Press, Boulder, Colorado, pp. 51–71, 1977.
10. Waldmeier, M.: *The Sunspot-Activity in the Years 1610–1960*, Schulthess & Co., Zürich, 171 pp., 1961.
11. Hoyt, D.V., and K.H. Schatten: A revised listing of the number of sunspot groups made by Pastorff, 1819 to 1833, *Solar Phys., 160*, 393–399, 1995.
12. Robock, A., and J. Mao: The volcanic signal in surface temperature observations, *J. Climate, 8*, 1086–1103, 1995.
13. Hansen, J., R. Ruedy, M. Sato, and R. Reynolds: Global surface air temperature in 1995: Return to pre-Pinatubo level, *Geophys. Res. Lett., 23*, 1665–1668, 1996.
14. Carroll, M.R.: Volcanic sulphur in the balance, *Nature, 389*, 543–544, 1997.
15. Horel, J.D., and J.M. Wallace: Planetary-scale atmospheric phenomena associated with the Southern Oscillation, *Mon. Wea. Rev., 109*, 813–829, 1981.

16. Halpert, M.S., and C. F. Ropelewski: Surface temperature patterns associated with the Southern Oscillation, *J. Climate, 5*, 577–593, 1992.

17. Butler, C.J., and D.J. Johnston: A provisional long mean air temperature series for Armagh Observatory, *J. Atmos. Terr. Phys., 58*, 1657–1672, 1996.

18. Simkin, T., and L. Siebert: *Volcanoes of the World*, 2nd Ed., Geoscience Press, Tucson, Arizona, 394 pp., 1994.

19. Quinn, W.H., V.T. Neal, and S.E. Antunez de Mayolo: El Niño occurrences over the past four and a half centuries, *J. Geophys. Res., 92*, 14,449–14,461, 1987.

20. Schwabe, H.: Sonnenuflecken, *Astron. Nach., 22*(527), 365–368, 1845.

21. Schwabe, H.: Sonnenflecken im Jahre 1845, *Astron. Nach., 24*(564), 185–186, 1846.

22. Schwabe, H.: Sonnen-Beobachtugen im Jahre 1846, *Astron. Nach., 25*(595), 293–298, 1847.

23. Schwabe, H.: Sonnen-Beobachtungen des Jahres 1847, *Astron. Nach., 27*(638), 219–222, 1848.

24. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1848, *Astron. Nach., 28*(667), 301–302, 1849.

25. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1849, *Astron. Nach., 30*(704), 125–126, 1850.

26. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1850, *Astron. Nach., 32*(751), 109–110, 1851.

27. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1851, *Astron. Nach., 33*(789), 359–360, 1852.

28. Schwabe, H.: Sonnen-Beobachtungen im Jahre 1852, *Astron. Nach., 36*(848), 121–122, 1853.

29. Schwabe, H.: Sonnen-Beobachtungen des Jahres 1853, *Astron. Nach., 38*(895), 111–112, 1854.

30. Schwabe, S.H.: Sonnen-Beobachtungen des Jahres 1854 in Dessau, *Astron. Nach., 39*(933), 331–334, 1855.

31. Schwabe, S.H.: Sonnen-Beobachtungen im Jahre 1855, *Astron. Nach., 42*(1001), 269–270, 1856.

32. Schwabe, S.H.: Sonnen-Beobachtungen im Jahre 1856, *Astron. Nach., 45*(1063), 111–112, 1857.

33. Schwabe, S.H.: Sonnen-Beobachtungen im Jahre 1857, *Astron. Nach., 47*(1124), 319–320, 1858.

34. Schwabe, S.H.: Sonnen-Beobachtungen im Jahre 1858, *Astron. Nach., 50*(1182), 93–96, 1859.

35. McKinnon, J.A.: Sunspot numbers: 1610–1985, based on "The Sunspot-Activity in the Years 1610–1960," Report UAG–95, World Data Center A for Solar-Terrestrial Physics, Boulder, Colorado, 112 pp., January 1987.

36. Eddy, J.A.: The historical record of solar activity, *The Ancient Sun: Fossil Record in the Earth, Moon, and Meteorites*, R.O. Pepin, J.A. Eddy, and R.B. Merrill (eds.), Pergamon Press, New York, pp. 119–134, 1980.

37. Lapin, L.L.: *Statistics for Modern Business Decisions*, 2nd Ed., Harcourt Brace Jovanovich, New York, 1978.

38. Butler, C.J.: Maximum and minimum temperatures at Armagh Observatory, 1844–1992, and the length of the sunspot cycle, *Solar Phys., 152*, 35–42, 1994.

39. Butler, C.J., and D.J. Johnston, The link between the solar dynamo and climate—The evidence from a long mean air temperature series from Northern Ireland, *Irish Astron. J., 21*, 251–254, 1994.

40. Hansen, J., and S. Lebedeff: Global trends of measured surface air temperature, *J. Geophys. Res., 92*, 13,345–13,372, 1987.

41. Wilson, R.M.: Evidence for solar-cycle forcing and secular variation in the Armagh Observatory temperature record, *J. Geophys. Res. (Atmos.)*, in press, 1998.

42. Rasmusson, E.M., and J.M. Hall: El Niño—The great equatorial Pacific Ocean warming of 1982–1983, *Weatherwise, 36*, 166–175, August 1983.

43. Philander, S.G.H.: El Niño Southern Oscillation phenomena, *Nature, 302*, 295–301, 1983.

44. Philander, S.G.H.: Niño and La Niña, *J. Atmos. Sci., 42*, 2652–2662, 1985.

45. Philander, S.G.: *El Niño, La Niña, and the Southern Oscillation*, Academic Press, New York, 1990.

46. Rasmusson, E.M., and J.M. Wallace: Meteorological aspects of the El Niño/Southern Oscillation, *Science, 222*, 1195–1202, 1983.

47. Rasmusson, E.M.: El Niño and variations in climate, *Am. Sci., 73*, 168–177, March–April 1985.

48. Philander, S.G. and E.M. Rasmusson: The Southern Oscillation and El Niño, *Adv. Geophys., 28A*, 197–215, 1985.

49. Ramage, C.S., El Niño, *Sci. Am., 255*, 76–83, June 1986.

50. Rampino, M.R. and S. Self: Sulphur-rich volcanic eruptions and stratospheric aerosols, *Nature, 310*, 677–679, 1984.

51. Hansen, J., M. Sato, A. Lacis, and R. Ruedy: The missing climate forcing, *Phil. Trans. R. London B, 352*, 231–240, 1997.

52. Lamb, H.H.: Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance, *Phil. Trans. R. London A, 266*, 425–533, 1970.

53. Newhall, C.G., and S. Self: The Volcanic Explosivity Index (VEI): An estimate of explosive magnitude for historical volcanism, *J. Geophys. Res., 87*, 1231–1238, 1982.

54. Legrand, M., and R.J. Delmas: A 220-year continuous record of volcanic H2SO4 in the Antarctic ice sheet, *Nature, 327*, 671–676, 1987.

55. Stommel, H., and E. Stommel: The year without a summer, *Sci. Am., 240*, 176–186, June 1979.

56. Everitt, B.S.: *The Analysis of Contingency Tables*, John Wiley & Sons, New York, 1977.

57. Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S. Whitlow, M.S. Twickler, M. Morrison, D.A. Meese, A.J. Gow, and R.B. Alley: Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system, *Science, 264*, 948–952, 1994.

58. Hammer, C.U.: Past volcanism revealed by Greenland ice sheet impurities, *Nature, 270*, 482–486, 1977.

59. Hammer, C.U., H.B. Clausen, and W. Dansgaard: Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, *Nature, 288*, 230–235, 1980.

60. Moore, J.C., H. Narita, and N. Maeno: A continuous 770-year record of volcanic activity from East Antarctica, *J. Geophys. Res., 98*, 17,353–17,359, 1991.

61. Delmas, R.J., S. Kirchner, J.M. Palais, J.-R. Petit: 1000 years of explosive volcanism recorded at the South Pole, *Tellus, 44B*, 335–350, 1992.

62. Langway, C.C., Jr., K. Osada, H.B. Clausen, C.U. Hammer, and H. Shoji: A 10-century comparison of prominent bipolar volcanic events in ice cores, *J. Geophys. Res., 100*, 16,241–16,247, 1995.

63. Langway, C.C., Jr., K. Osada, H.B. Clausen, C.U. Hammer, H. Shoji, and A. Mitani: New chemical stratigraphy over the last millennium for Byrd Station, Antarctica, *Tellus, 46B*, 40–51, 1994.

64. Cole-Dai, J., E. Mosley-Thompson, and L.G. Thompson: Annually resolved southern hemisphere volcanic history from two Antarctic ice cores, *J. Geophys. Res., 102*, 16,761–16,771, 1997.

65. Stothers, R.B.: The great Tambora eruption in 1815 and its aftermath, *Science, 224*, 1191–1198, 1984.

66. Landsberg, H.E., and J.M. Albert: The summer of 1816 and volcanism, *Weatherwise, 27*, 63–66, April 1974.

67. Lough, J.M., and H.C. Fritts: The Southern Oscillation and tree rings: 1600–1961, *J. Clim. Appl. Meteorol., 24*, 952-966, 1985.

68. Briffa, K.R., P.D. Jones, and F.H. Schweingruber: Summer temperature patterns over Europe: A reconstruction from 1750 A.D. based on maximum latewood density indices of conifers, *Quaternary Res., 30*, 36–52, 1988.

69. Briffa, K.R., P.D. Jones, and F.H. Schweingruber: Summer temperatures across northern North America: Regional reconstructions from 1760 using tree-ring densities, *J. Geophys. Res., 99*, 25,835–25,844, 1994.

70. Jones, P.D., K R. Briffa, and F.H. Schweingruber: Tree-ring evidence of the wide-spread effects of explosive volcanic eruptions, *Geophys. Res. Lett., 22*, 1333–1336, 1995.

71. Bluth, G.J.S., S.D. Doiron, C.C. Schnetzler, A.J. Krueger, and L.S. Walter: Global tracking of the SO2 clouds from the June, 1991 Mount Pinatubo eruptions, *Geophys. Res. Lett., 19,* 151–154, 1992.

72. Trepte, C.R., R.E. Veiga, and M.P. McCormick: The poleward dispersal of Mount Pinatubo volcanic aerosol, *J. Geophys. Res., 98*, 18,563–18,573, 1993.

73. McCormick, M.P., L.W. Thomason, and C.R. Trepte: Atmospheric effects of the Mt. Pinatubo eruption, *Nature, 373*, 399–404, 1995.

74. Dutton, E.G., and J.R. Christy: Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo, *Geophys. Res. Lett., 19*, 2313–2316, 1992.

75. Wexler, H.: Volcanoes and world climate, *Sci. Am., 186*, 74–80, April 1952.

76. Stuiver, M., P.M. Grootes, and T.F. Braziunas: The GISP2 δ18O climate record of the past 16,500 years and the role of the Sun, ocean, and volcanoes, *Quaternary Res., 44*, 341–354, 1995.

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13. ABSTRACT *(Maximum 200 words)*

During the interval of 1818–1858, several curious decreases in the number of sunspot observing days per year are noted in the observing record of Samuel Heinrich Schwabe, the discoverer of the sunspot cycle, and in the reconstructed record of Rudolf Wolf, the founder of the now familiar relative sunspot number. These decreases appear to be nonrandom in nature and often extended for 1–3 yr (or more). Comparison of these decreases with equivalent annual mean temperature (both annual means and 4-yr moving averages), as recorded at Armagh Observatory (Northern Ireland), indicates that the temperature during the years of decreased number of observing days trended downward near the start of each decrease and upward (suggesting some sort of recovery) just before the end of each decrease. The drop in equivalent annual mean temperature associated with each decrease, as determined from the moving averages, measured about 0.1–0.7°C. The decreases in number of observing days are found to be closely related to the occurrences of large, cataclysmic volcanic eruptions in the tropics or northern hemisphere. In particular, the interval of increasing number of observing days at the beginning of the record (i.e., 1818–1819) may be related to the improving atmospheric conditions in Europe following the 1815 eruption of Tambora (Indonesia; 8°S), which previously has been linked to "the year without a summer" (in 1816) and which is the strongest eruption in recent history, while the decreases associated with the years of 1824, 1837, and 1847 may be linked, respectively, to the large, cataclysmic volcanic eruptions of Galunggung (Indonesia; 7°S) in 1822, Cosiguina (Nicaragua) in 1835, and, perhaps, Hekla (Iceland; 64°N) in 1845. Surprisingly, the number of observing days per year, as recorded specifically by Schwabe (from Dessau, Germany), is found to be linearly correlated against the yearly mean temperature at Armagh Observatory ($r = 0.5$ at the 2 percent level of significance); thus, years of fewer sunspot observing days in the historical record seem to indicate years of probable cooler clime, while years of many sunspot observing days seem to indicate years of probable warmer clime (and vice versa). Presuming this relationship to be real, one infers that the observed decrease in the number of observing days near 1830 (i.e., during "the lost record years" of 1825 to 1833) provides a strong indication that temperatures at Armagh (and, perhaps, most of Europe, as well) were correspondingly cooler. If true, then, the inferred cooling may have resulted from the eruption of Kliuchevskoi (Russia; 56°N) in 1829.

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