Sun/dust correlations and volcanic interference

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Received 4 February 2002; revised 19 March 2002; accepted 3 April 2002; published 15 May 2002.

[1] We examine the relationship between the GISP2 dust profile, a proxy for the Northern Hemisphere atmospheric dust load, and the Wolf sunspot number, a proxy for solar activity. The two records are positively correlated, but the phase of the relationship is disturbed by the effects of explosive volcanism. Similar correlation failures have already been noted for many other climatic indicators. Our work suggests that a large fraction of the correlation failures may be attributed to explosive volcanic activity. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1827 Hydrology: Glaciology (1863); 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 2104 Interplanetary Physics: Cosmic rays; 2162 Interplanetary Physics: Solar cycle variations (7536)

1. Introduction

[2] There is evidence [*Ram et al.*, 1997; *Ram and Stolz*, 1999] that solar variability has modulated the Greenland Ice Sheet Project 2 (GISP2) dust concentration profile at radiocarbon periods of 11, 22, 90 and 200 years. This sun/dust link was attributed [*Ram and Stolz*, 1999] to solar modulation of the terrestrial cosmic ray flux (CRF), which can influence cloud cover [*Dickinson*, 1975; *Svensmark and Friis-Christiensen*, 1997] and hence precipitation patterns and aridity. The dust modulations reported [*Ram et al.*, 1997; *Ram and Stolz*, 1999] were for pre-Holocene ice, and it was not possible to compare their timings with actual changes in sunspot numbers (SSN), which are only known for recent times. In an effort to determine the exact phasing between GISP2 dust modulations and the solar cycle, we used laser-light scattering (LLS) from meltwater [*Ram and Illing*, 1994] to measure the variations in dust concentration along the top 120 m of GISP2 ice corresponding to the most recent 400 years, a period for which sunspot data are available. The resulting dust profile spans the period from 1598 to 1988 A.D. (Figure 1) and has an average sampling frequency of more than 13 samples per year. Seasonal dust maxima (i.e. annual layers) are clearly resolved throughout the core and are used to corroborate the established GISP2 depth-age scale [*Meese et al.*, 1997]. We limited our analysis to the time period 1752 to 1988 A.D., for which our dust record is continuous. This is approximately the timespan covered by the Wolf monthly SSN [*SIDC*, 2000], which we use as a proxy for the 11-year cycle of solar activity.

2. Sun/Dust Correlations

[3] We employ moving correlation analysis to examine the relationship between the GISP2 dust profile and the SSN. The moving correlation, $r(n_w)$, is the correlation coefficient calculated between two data sets for all points within a window that is n_w points wide. The window is moved along the data, and $r(n_w)$ is calculated at every x_i for $i = (n_w/2)$ to $i = N - (n_w/2)$, where N equals the total number of points in the data series. The center of the moving correlation window corresponds to the time axis of the results.

[4] Since we were most interested in an eleven-year cycle in the dust profile, we used an 8 to 15 year bandpass filter to smooth the data (Figure 2a). The moving correlation between the GISP2 dust profile and the Wolf SSN is shown in Figure 2b. The result is generally insensitive to the choice of smoothing operation. As Figure 2b shows, the relationship between the dust profile and the SSN is not a simple one. The longest periods of relatively high correlation (>90% significance) are all positive, including 1860 to 1882 and 1944 to 1966. There is a long period of zero correlation from 1799 to 1835. In addition, there is a prominent negative correlation phase from 1904 to 1916. The total number of years with $r(n_w)$ that exceed 90% significance equals 27% of the total length of the data set, and the majority of high correlations occur in three continuous periods, as opposed to being randomly scattered throughout the data. This indicates that the high correlations are not due to random chance.

[5] The behavior of the sun/dust moving correlation can be explained by two competing processes: electroscavenging of ice-forming nuclei [*Tinsley et al.*, 2000, 2001] and ion-induced nucleation of ultrafine aerosol particles [*Dickinson*, 1975; *Yu and Turco*, 2000, 2001] (see Figure 3). Both mechanisms are enhanced by increases in the CRF, as for example during solar minima, but they have opposite effects on the atmospheric dust load. Electroscavenging of ice-forming nuclei increases contact ice nucleation and the production of precipitation by the Wegener-Bergeron-Findeison process, and appears to be the explanation for the results of *Kniveton and Todd* [2001], who found a strong relationship between CRF and precipitation over the southern oceans at mid to high latitudes. Increased precipitation results in higher soil moisture and therefore lower dust [*Pye*, 1989]. In this case, the sun/dust correlation is expected to be positive. In contrast, ion-induced

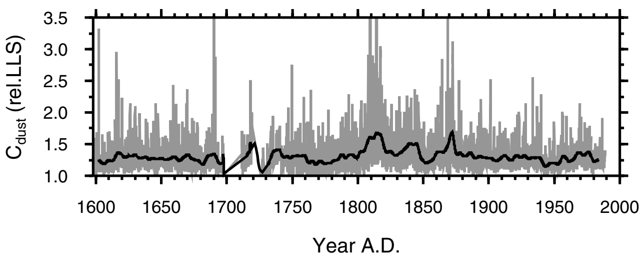

Figure 1. The GISP2 dust concentration profile, in relative LLS units, from 1598 to 1988 A.D. The gray line represents the raw data, and the black line represents a 10-year moving Gaussian-weighted average. Instrumental error is less than 3% and the errors in dating are approximately 1% [*Meese et al.*, 1997]. Sections of ice, from 1698 to 1711 and from 1719 to 1727, as well as shorter sections at 1729, 1736, 1742, and 1751, were previously sampled and therefore unavailable to us for analysis and resulted in gaps in the dust profile.

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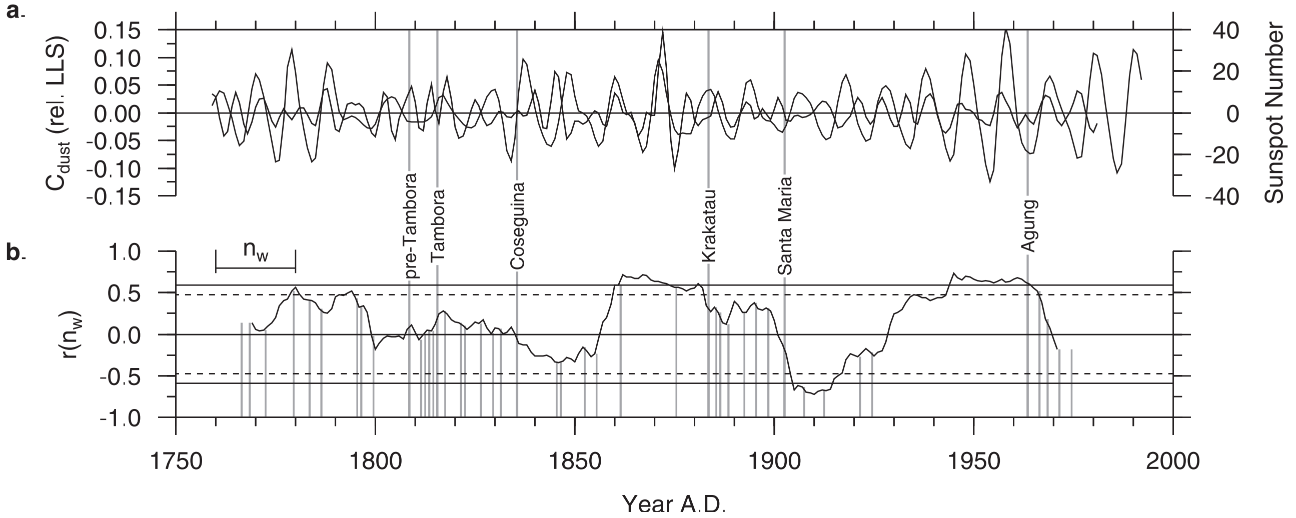

Figure 2. (a) The filtered Wolf SSN (thin line) and GISP2 dust concentration profile (thick line). Both data sets were smoothed in the time domain using moving Gaussian-weighted averages with 50% cutoff periods of 8 and 15 years. The 8 year smoothed data were subtracted from the 15 year smoothed data, and resampled such that Δt equals one year. (b) Moving correlation between the data sets in (a), with n_w equal to 20 years. The width of the correlation window, n_w, is indicated in the upper left corner. The thin dashed and solid horizontal lines indicate the 90% and 95% confidence limits, respectively, after correcting the degrees of freedom for autocorrelation of the time series [*Dawdy and Matalas*, 1964]. The vertical gray bars indicate all volcanic eruptions from Lamb's Dust Veil Index (DVI) [*Lamb*, 1970] with global DVI equal to or greater than 100, as well as the so-called pre-Tambora eruption [*Dai et al.*, 1991; *Chenoweth*, 2001]. The largest eruptions of the time period shown are labeled with the volcano name.

nucleation produces sulfate particles that are typically only a few nm in diameter. If these particles grow to a diameter of about 60 nm or more, they add to the ambient concentration of cloud condensation nuclei (CCN). As a result, the available cloud water is distributed among more droplets of smaller average size, which increases cloud lifetime. Positive correlations between cloud cover and the CRF [*Svensmark and Friis-Christiensen*, 1997; *Marsh and Svensmark*, 2000; *Pallé Bagò and Butler*, 2000] suggest that the ion-induced nuclei do indeed grow to the size required for small droplet development. This reduces the amount of precipitation produced by the cloud. Lower rainfall decreases soil moisture, resulting in more dust. The sun/dust correlation is therefore expected to be negative during times when ion-induced nucleation is enhanced. Electroscavenging is likely to be the dominant mechanism, especially at high latitudes (Tinsley, personal commumication), which is consistent with our observation that the sun/dust correlation tends to be positive.

3. Volcanic Interference

[6] There is evidence [*Kelly*, 1977; *Mass and Schneider*, 1977; *Robock*, 2000] that large, explosive volcanic eruptions have a number of effects on climate, including global cooling for one to three years, following the eruption. Indeed, *Stuiver et al.* [1995] showed that the GISP2 $\delta^{18}O$ record, and therefore central Greenland surface temperatures, decreased in the years following explosive volcanic activity. Based on this evidence, it is reasonable to assume that the climatic processes governing dust production will also be affected by volcanic forcing. In the context of the physical mechanisms outlined in Figure 3, eruptions that produce a high mixing ratio of H_2SO_4 in the stratosphere can supply the troposphere with H_2SO_4 and enhance the ion-induced nucleation of sulfate particles for up to three or more years, causing a decrease in precipitation. Thus, the abrupt phase reversals and correlation failures evident in Figure 2b could possibly be due to volcanic activity. A number of observations support this conjecture. First, the longest periods of positive sun/dust correlation, from 1860 to 1880 and from 1945 to 1963, coincide with periods of low volcanism. Second, the longest period of zero sun/dust correlation (1799 to 1835) coincides with a period of frequent volcanism that includes the great eruption of Tambora in 1815. Finally, there is a sudden, temporary reduction in the sun/dust correlation that coincides with the 1883 eruption of Krakatau (Figure 2b).

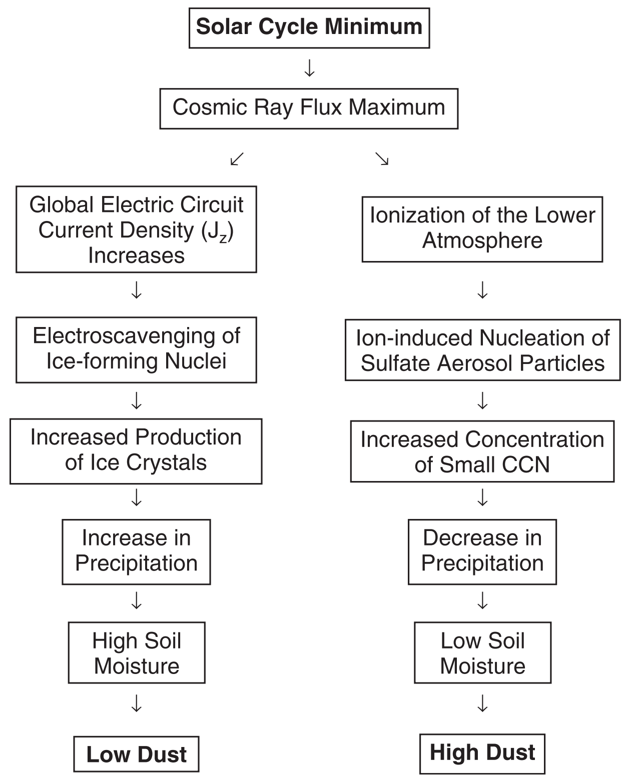

Figure 3. Proposed flowchart of physical processes involved in the sun/dust relationship.

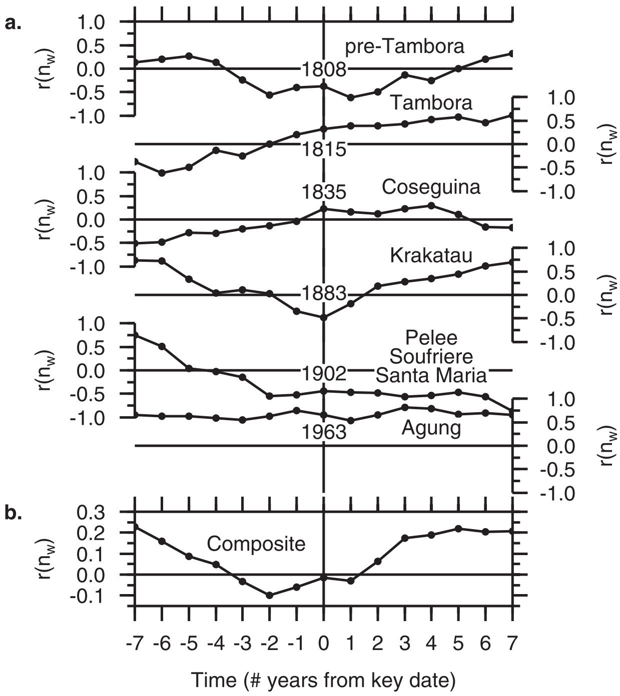

Figure 4. Superposed epoch analysis of the effects of volcanic eruptions on the sun/dust moving correlation with n_w equal to 10 years. Subsets of the data were chosen at the position of the selected key years, and averaged together to form a composite. The extracted epochs contain seven years preceding the key date and seven years following the key date, for a total length of 15 years. This minimizes the possibility that eruptions adjacent to each key date are included in the background calculation, and ensures that some of the background points in the composite are independent of the key date. The non-parametric methods of *Prager and Hoenig* [1989] were used to evaluate the significance of the response of the sun/dust correlation to the key volcanic years under investigation. (a) Extracted epochs surrounding each key year. (b) Composite of the epochs in (a).

[7] We used compositing, or epoch analysis [*Prager and Hoenig*, 1989], to determine if there is a detectable response of the sun/dust correlation to explosive, low-latitude volcanism. The analysis was limited to the eruptions in *Lamb*'s [1970] compilation that have a global Dust Veil Index (DVI) greater than 500, Volcanic Explosivity Index (VEI) [*Newhall and Self*, 1982] greater than 3, and are within 20° latitude from the equator, since such eruptions have the strongest effects on climate [*Robock*, 2000]. We also included an unknown 1808 eruption (hereafter referred to as pre-Tambora), which has been shown [*Dai et al.*, 1991; *Chenoweth*, 2001] to be a low-latitude event comparable in magnitude to the 1883 eruption of Krakatau. The results of our epoch analysis are given in Figure 4.

[8] Explosive volcanic eruptions can affect the observed sun/dust correlation in two ways. One is by direct injection of dust to the GISP2 site, which is most likely to occur during the northern hemisphere (NH) spring, a time when there is an increased degree of atmospheric mixing between low and high latitudes. The second is by impacting climate in ways that affect dust production, for example, by enhancing the mechanism of ion-induced nucleation. To illustrate this, we show, separately, the contributions to the epoch analysis of each of the chosen volcanoes (Figure 4a). Both pre-Tambora and Tambora erupted in the NH spring and resulted in direct injection of dust to Greenland, producing a strong enhancement in the dust profile (Figure 1). Since pre-Tambora occurred during solar minimum, it resulted in a decrease in sun/dust correlation, which is clearly what we observe. Tambora, however, occurred during solar maximum and caused the sun/dust correlation to increase. In addition, there were several other prominent, low-latitude eruptions, including Awu and Soufrière in 1812, and Mayon in 1814, which may have contributed to a broad volcanic effect on the dust profile. In contrast, Krakatau erupted in the summer, when the atmospheric mixing between low and high latitudes is less vigorous, and did not produce any enhancement in the GISP2 dust profile (Figure 1). In this case, the sharp drop in sun/dust correlation we observe is probably due to climatic effects of the eruption. The Coseguina eruption does not seem to have a significant effect on the sun/dust correlation. This is consistent with the claim that the climatic effects of this eruption may have been seriously overestimated in the past [*Self et al.*, 1989]. There is also no noticeable effect on the correlation by the 1963 eruption of Agung. This is consistent with the observations of *Rampino and Self* [1982], who claim that the eruption at 8°S produced very small optical depth changes in the NH as compared to the Southern Hemisphere. The epoch around 1902 exhibits a prominent correlation reversal that lingers over many years. We attribute this to the fact that there were three large eruptions that year (Pelée and Soufrière in May, and Santa Maria in October), a time of solar minimum (we note a large dust spike in our GISP2 record of that period, but cannot attribute it to a particular eruption). In addition, there were two, more proximal eruptions, Ksudach in 1907 and Katmai in 1912, that could have impacted the sun/dust correlation during this epoch.

[9] Overall, the composite of the selected epochs (Figure 4b) indicates that the sun/dust correlation shifts strongly towards low values in response to the eruptions under investigation. Ideally, the composite should show a sharp decrease in correlation at the key year which then decays after one to two years back to the level of the background. However, the ten-year moving correlation window smears the response, and we see that the decrease in correlation begins five years (half the width of the moving window) prior to the key year, gradually attains a minimum in correlation, and then returns to positive correlation values. Also, we note that the minimum is established two years prior to the key year. A similar effect was observed by *Stuiver et al.* [1995] in their epoch analysis of $\delta^{18}O$ from the same GISP2 ice core. They attributed this lag to possible core dating problems, which they believe could be off by as many as two years. After adjusting for this discrepancy, we find that the minimum in Figure 4b is significant at the 95% confidence level. These results give credence to our conjecture that the sharp shifts and failures in sun/dust correlation seen in Figure 2b could be due to volcanic effects.

4. Conclusions

[10] *Schneider and Mass* [1975] incorporated solar and volcanic effects in reconstructing earth's temperature record for the past 400 years, and achieved some remarkable success in reproducing the Little Ice Age cold period. The work presented here further emphasizes the important interplay of sun and volcanoes in influencing earth's climate, and demonstrates how explosive volcanic eruptions can mask sun/climate relationships during the Holocene. The climatic interference caused by volcanism, which is evident in our sun/dust correlations, may help explain why researchers have had problems establishing a link between solar activity and earth's climate [*Hoyt and Schatten*, 1997]. Continental dust concentrations in ice cores were considerably higher in glacial (pre-Holocene) times than during the Holocene [*Hammer et al.*, 1985; *Ram and Koenig*, 1997; *Steffenson*, 1997], and volcanic eruptions would have been less likely to mask sun/dust relationships. Indeed, dust concentration measurements on GISP2 pre-Holocene ice reveal [*Ram et al.*, 1997; *Ram and Stolz*, 1999] very prominent solar modulations that stand out clearly above the background, more so than during the dust-quiet Holocene.

[11] **Acknowledgments.** We thank Brian Tinsley for reading an early version of the paper and for incisive comments, and for suggesting electroscavenging as a competing mechanism to ion-induced nucleation. All figures were made using GMT (Wessel, P. and W. H. F. Smith, Free software helps map and display data, EOS Trans. AGU, 72, 441, 1991). This work was supported in part by the National Science Foundation.

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