Cosmic rays and stratospheric aerosols: Evidence for a connection?

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[1] In the search for the hypothetical missing link between a variety of atmospheric parameters and solar variability, we apply a Granger causality test to monthly averages of neutron counts (a proxy for cosmic rays), as measured at the Climax station, and stratospheric aerosol number densities, derived from extinction coefficients measured by the Stratospheric Aerosol and Gas Experiment II. A causal connection between the two time series is suggested. Further study of the cross-correlation coefficient confirms this finding, indicating that cosmic rays influence stratospheric aerosols through a process with a time response of a few months. Our results have important implications for the hypothesis of a physical mechanism that links both quantities. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 2104 Interplanetary Physics: Cosmic rays; 1650 Global Change: Solar variability; 2162 Interplanetary Physics: Solar cycle variations (7536); 8409 Volcanology: Atmospheric effects (0370)

1. Introduction

[2] In recent years, surprising results have been obtained by the study of the correlation between galactic cosmic ray time series and a number of atmospheric variable time series (see e.g., [*Kniveton and Todd*, 2001; *Tinsley*, 2000; *Pudovkin et al.*, 1997; *Lu and Sanche*, 2001]). Most strikingly were the results of [*Svensmark and Friis-Christensen*, 1997], which show a very strong correlation between detected neutron count rates (that are good proxies of cosmic ray fluxes) and total cloud cover data. If there is a physical mechanism that causes this observed correlation, then this potentially could have a severe impact on climate studies. The results are nevertheless controversial, and criticism is mostly based on the absence of any decisive physical explanation [*Jorgensen and Hansen*, 2000].

[3] Despite the lack of a physical connection that is well understood, it is believed that ionization by cosmic rays has an influence on cloud droplet production. Closely related to this hypothesis are recent studies that indicate a new aerosol formation process, through ion-mediated nucleation. These studies focus mainly on tropospheric aerosols, and theoretical calculations are able to simulate many features that are being observed in the behaviour of ultra-fine particles [*Yu and Turco*, 2001; *Turco et al.*, 1998; *Yu and Turco*, 2000].

[4] These recent findings have inspired us to search for a possible connection between cosmic ray flux and stratospheric aerosol density. We do not attempt to draw any conclusions about the possible underlying physics, but simply compare two independently measured time series, and try to find a significant relation. In previous work, we derived particle size distribution parameters from SAGE II extinction data (C. Bingen, F. Vanhellemont and D. Fussen, Retrieval of stratospheric aerosol size distributions from SAGE II data for the period 1984–2000, submitted to Annales Geophysicae, 2002). The resulting data series should be long enough to see some possible signature from the hypothetical cosmic ray influence. In this study, the cosmic ray flux itself is represented by the neutron counts, measured by the Climax neutron monitor.

2. Data

[5] The Climax station, located in Colorado, USA (39°N, 106°W), is the oldest continuously operating neutron monitor in the world. The measured neutrons originate in the nucleonic cascade that results when a galactic cosmic ray particle enters the atmosphere. Neutron counts can thus be considered as a proxy of the incoming cosmic ray flux. Daily average values obtained at the Climax station are available from 1951 to the present (http://ulysses.uchicago.edu). We should mention here that, although measured neutron fluxes differ considerably at different latitudes (see for example the time series measured at stations in Haleakala, Hawaii and Huancayo, Peru), normalized variations in these fluxes are very similar [*Svensmark and Friis-Christensen*, 1997]. This implies that the relative temporal variability of the Climax data can be considered as representative for all latitudes.

[6] The Stratospheric Aerosol and Gas Experiment II (SAGE II) [*Chu et al.*, 1989] is a solar occultation experiment that started its mission in 1984, and it is still operational. The experiment provides the longest continuous measurement of stratospheric aerosols on a global scale. In a recent work, we were able to derive aerosol particle size distribution parameters from measured SAGE II extinction data. A lognormal distribution was assumed, characterized by the parameters N (total particle number density), r_m (size parameter) and σ (distribution width). In this study we investigate N, since it is the number density that reflects a possible creation of new particles.

[7] Occultation experiments pose some problems in the sense that their temporal and spatial coverage is limited, but also contains gaps. To obtain continuous aerosol density time series without gaps, we decided to group the data in monthly bins, and three different latitude bins: a southern polar bin, [80°S–40°S], a tropical bin, [40°S–40°N], and a northern polar bin, [40°N–80°N]. In order to make a comparison possible, the Climax neutron counts were also averaged for each month. The set of time series that were obtained in this way span a time range from October 1984 to March 2000 (186 months).

3. Pre-Processing

[8] An intercomparison between stratospherical aerosol data and neutron counts cannot be performed directly. The

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Climax neutron counts are a measure of incoming cosmic ray flux, a quantity that varies primarily via delayed modulation by the solar cycle. Stratospheric aerosols on the other hand are frequently disturbed by strong volcanic eruptions that inject large amounts of SO_2 gas in the stratosphere, leading to the formation of new H_2SO_4/H_2O aerosols. Eruptions therefore represent a strong and independent aerosol source term, and it would be inappropriate to use the raw aerosol data in a comparative study. Instead, we decided to investigate the short-term variability of both SAGE II and Climax data.

[9] Classical time series analysis theory mainly deals with stationary signals, i.e. signals with a mean, variance and autocorrelation function that is constant in time. Stationarity can be pursued by the application of some preliminary transformations. First, we apply the commonly used Box-Cox transformation [*Brockwell and Davis*, 2002]:

$$T(y_t) = \ln y_t \quad (\lambda = 0)$$
$$= \frac{y_t^\lambda - 1}{\lambda} \quad (\lambda \neq 0) \tag{1}$$

in which the parameter λ is chosen to achieve maximum stability in the variance. To obtain a constant mean, a smoothed version of the signals is calculated by the application of a Savitzky-Golay filter [*Press et al.*, 1992] with a sliding window size of 5 data points (2 left, one center and 2 right values) and a polynomial degree of 0. The mean of the signals is then made independent of time by subtracting the smoothed signal from the original signal. Finally, all signals are normalized with mean 0 and variance 1 to obtain the signals for cosmic rays (C_t) and aerosols (S_t). An example of the entire procedure is given in Figure 1.

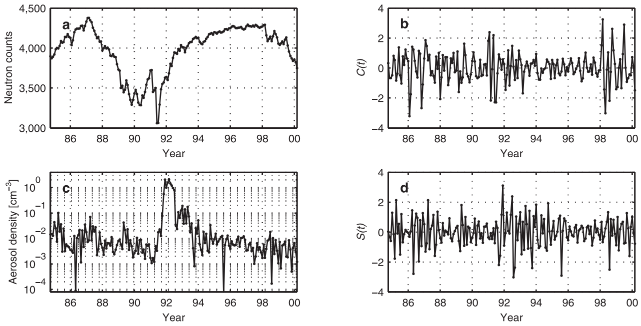

Figure 1. (a) Monthly averages of neutron counts, as measured by the Climax neutron monitor. (b) The transformed signal $C(t)$. (c) SAGE II aerosol number density in the southern bin at an altitude of z = 26.5 km. (d) The transformed signal $S(t)$.

4. Granger Causality

[10] One way to find out if there is a causal connection between both time series is the application of a Granger causality test. The concept of Granger causality originated in the field of econometrics [*Granger*, 1969], but has recently found entrance in other fields, such as the atmospheric sciences [see e.g., *Kaufman and stern*, 1997]. Although developed in the general framework of vector autoregression (VAR) models, it is also applicable for single-equation autoregressions. At a discrete time t, we express the aerosol signal S_t as a linear combination of p aerosol values in the past, an additional linear combination of q past values of the Climax signal, $C(t)$, and a random error component ϵ_{1t}:

$$S_t = \sum_{i=1}^{p} \delta_{1i} S_{t-i} + \sum_{i=1}^{q} \phi_{1i} C_{t-i} + \epsilon_{1t} \tag{2}$$

[11] This equation represents the 'unrestricted' model. The coefficients δ_{1i} and ϕ_{1i} can be determined by carrying out a linear least-squares regression of this model on the observations S_t. The squared sum of the regression residuals is denoted by RSS_u. In a second regression, we constrain the coefficients ϕ_{1i} to be zero, hereby assuming that S_t is a function of its own past exclusively. This forms the 'restricted' model, and after the regression the squared sum of residuals RSS_r is also evaluated. Since the restricted model has fewer regression parameters, we always have $RSS_r \geq RSS_u$. To find out if this restriction is significant, we evaluate the test statistic ω_1:

$$\omega_1 = \frac{(RSS_r - RSS_u)/q}{(RSS_u)/(n - p - q)} \tag{3}$$

with n the number of observations. Obviously, when $\omega_1 = 0$, the restriction has no effect whatsoever (no causal order). Thus, the statistical test reads:

$$\text{null hypothesis } H_0 : \omega_1 = 0$$
$$\text{alternative } H_1 : \omega_1 > 0 \tag{4}$$

[12] The test statistic ω_1 is F-distributed with q and $n - p - q$ degrees of freedom in the numerator and denominator, respectively. If the value of ω_1 exceeds a critical value ω_c, corresponding with a chosen level of significance α, then we can reject the null hypothesis of no causal order.

[13] In exactly the same way, the other causal direction can now be tested by applying this procedure to the autoregressive unrestricted model for cosmic ray prediction:

$$C_t = \sum_{i=1}^{p} \delta_{2i} S_{t-i} + \sum_{i=1}^{q} \phi_{2i} C_{t-i} + \epsilon_{2t} \tag{5}$$

and subsequently to the corresponding restricted model where the δ_{2i} are set to zero. From the regression residuals, we can calculate the test statistic ω_2.

[14] For both autoregressions separately, the number of lags (p, q) was determined by minimizing the Akaike information criterion [*Akaike*, 1973], a quantity that represents a trade-off between underfitting due to a lack of descriptive parameters and overfitting by using too many parameters. The obtained fractions of $f_1 = \omega_1/\omega_c$ and $f_2 = \omega_2/\omega_c$ (critical values ω_c are associated with the α = 10% level) at different altitudes for the three latitudinal bins are presented in Figure 2. The asymmetry of the autoregression test is clear: while f_1 exceeds 1 many times, f_2 does almost not. The null hypothesis 'aerosols do not influence cosmic rays' is therefore not rejected, while the null hypothesis

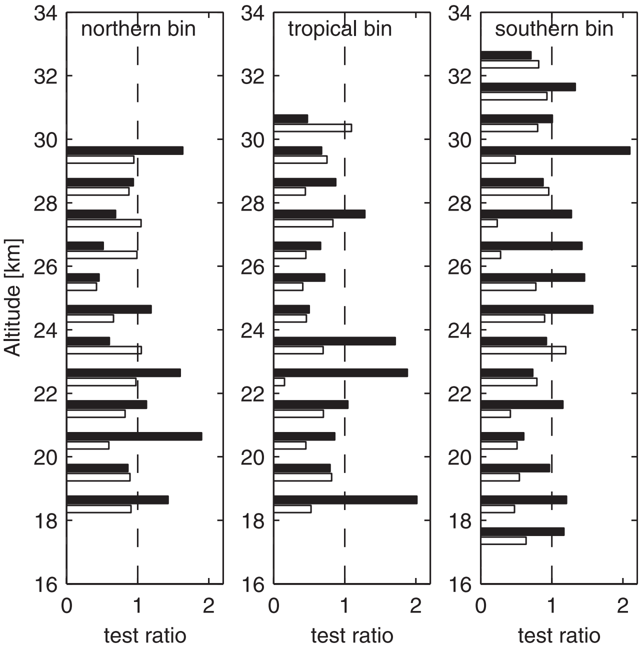

Figure 2. Granger test results f_1 (filled bars) and f_2 (empty bars) for the three latitude bins. Values larger than one indicate significant causality.

'cosmic rays do not influence aerosols' has often to be withdrawn with 90% certainty.

5. Cross-Correlations

[15] It is worth pointing out that, although the time series S_t and C_t are stationary, they are not necessarily realizations of white noise processes, since in general stationary time series are autocorrelated. This fact makes the interpretation of the cross-correlation coefficient ρ_{cs} quite difficult, because of its dependence on the autocorrelation functions ρ_c and ρ_s of C_t and S_t respectively. The best way to test the statistical significance of ρ_{cs} is by *prewhitening* both C_t and S_t, so that $\rho_c(h) = \rho_s(h) = 0$ for lags $h \neq 0$. In such conditions, theory tells us that, if both time series are independent, ρ_{cs} is normally distributed with mean 0 and variance $1/n$ [*Brockwell and Davis*, 2002].

[16] Autoregressive models, such as Equations 2 and 5 can in fact be considered as time-causal linear filters that transform time series into white noise (the residuals of the autoregression). Therefore, we calculate ρ_{cs} from the residuals of the *restricted* autoregressions (not the unrestricted regressions, where cross-correlations have also been filtered out). The results for some altitudes are presented in Figure 3, together with the 95% confidence intervals under the hypothesis of independence ($\pm 1.96/\sqrt{n}$). It speaks for itself that care must be taken to interpret these results, since a few values will inevitably fall outside the confidence bounds, although they do not represent dependency. Having said this, significant correlations show up systematically at negative time lags in the range of [−7 0] months, suggesting that cosmic rays affect stratospheric aerosols by a mechanism with a time response of several months. The most striking manifestation of this behaviour can be observed in the southern bin, where a strong peak at −5 months shows up systematically.

[17] It can be argued that the observed correlations are entirely accidental. Indeed, by examining the time series for neutron counts and aerosol number density (Figure 1), we observe that by some remarkable coincidence the largest cosmic ray Forbush decrease in the 16-year series occurs

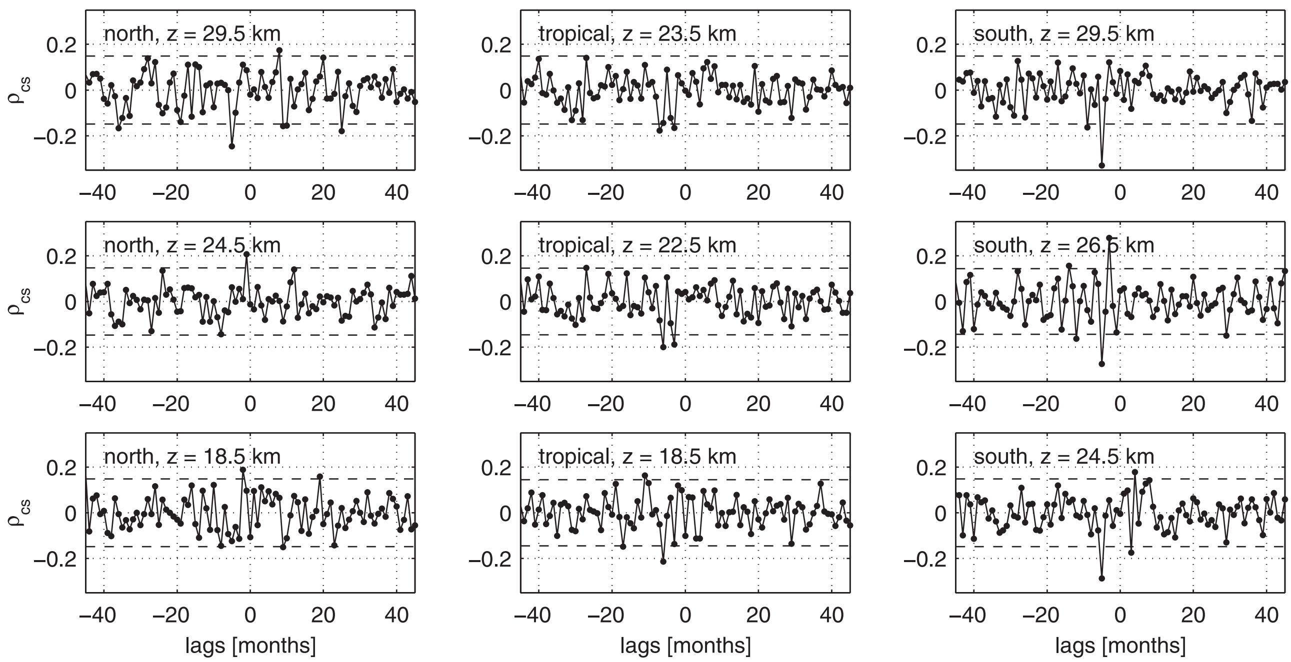

Figure 3. The correlation coefficient ρ_{cs} for different time lags and altitudes, respectively for the northern bin (left), the tropical bin (middle) and the southern bin (right). Negative lags correspond to the case where aerosols 'lead' cosmic rays. Also shown are the 95% confidence levels under the assumption of independence (dashed lines). Notice the elevated correlation coefficients at negative time lags of several months.

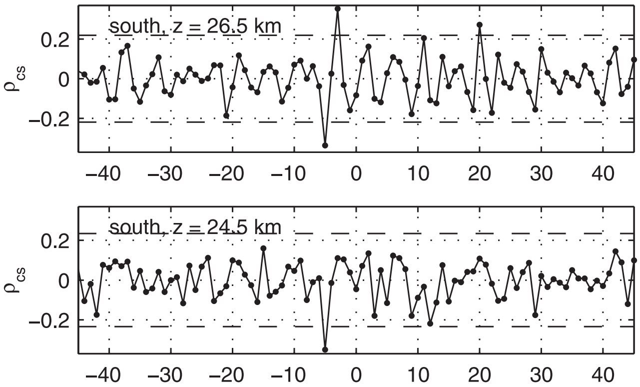

Figure 4. Examples of correlation coefficients ρ_{cs}, now calculated from the time series between October 1984 and May 1991, hereby excluding the Pinatubo period. The elevated coefficients at negative time lags are still present.

almost simultaneously with the strong aerosol loading caused by the June 1991 Pinatubo eruption. To eliminate this possible effect, we have calculated ρ_{cs} using only the data up to May 1991, one month before the eruption. This signal truncation poses severe limitations on the obtained results, since only 80 months are left to work with. Nevertheless, the elevated correlation coefficients remain present in many cases, such as the ones presented in Figure 4. The finding positively confirms that the observed link is not accidental.

6. Conclusion

[18] To summarize, a Granger causality test was applied to galactic cosmic ray and stratospheric aerosol time series, and the results indicate that a causal relation exists, where cosmic rays ‘cause’ aerosols while the reverse is not true. This observation is affirmed when we study the cross-correlation of the two suitably filtered time series. The results suggest that cosmic rays influence stratospheric aerosols by a mechanism with a time response of a few months. We use the word *suggest* because a statistical test does not have the power to prove the existence of such a process. The main conclusion here is that we have identified a statistically significant relation, of which further study has the potential to reveal an important (and presently not understood) atmospheric phenomenon.

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