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Latitudinal dependence of low cloud amount on cosmic ray induced ionization

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[1] A significant correlation between the annual cosmic ray flux and the amount of low clouds has recently been found for the past 20 years. However, of the physical explanations suggested, none has been quantitatively verified in the atmosphere by a combination of modelling and experiment. Here we study the relation between the global distributions of the observed low cloud amount and the calculated tropospheric ionization induced by cosmic rays. We find that the time evolution of the low cloud amount can be decomposed into a long-term trend and inter-annual variations, the latter depicting a clear 11-year cycle. We also find that the relative inter-annual variability in low cloud amount increases polewards and exhibits a highly significant one-to-one relation with inter-annual variations in the ionization over the latitude range 20–55°S and 10–70°N. This latitudinal dependence gives strong support for the hypothesis that the cosmic ray induced ionization modulates cloud properties. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 1650 Global Change: Solar variability; 2162 Interplanetary Physics: Solar cycle variations (7536). **Citation:** Usoskin, I. G., N. Marsh, G. A. Kovaltsov, K. Mursula, and O. G. Gladysheva (2004), Latitudinal dependence of low cloud amount on cosmic ray induced ionization, *Geophys. Res. Lett.*, *31*, L16109, doi:10.1029/2004GL019507.

1. Introduction

[2] A possible influence of solar variability on climate has been discussed for some time. Although the direct solar influence on climate is apparent, variations of the solar irradiance are estimated to be an order of magnitude too small to explain the observed changes in climate [e.g., *Stott et al.*, 2003]. Therefore, an indirect mechanism linking solar variability to climate should be involved. According to some modeling studies, a response in atmospheric circulation can amplify the terrestrial effect of solar irradiance changes [*Haigh*, 2002]. On the other hand, cosmic rays can noticeably affect the Earth's climate [*Svensmark and Friis-Christensen*, 1997; *Marsh and Svensmark*, 2000a, 2000b; *Carslaw et al.*, 2002; *Shaviv and Veizer*, 2003]. While the energy deposited by cosmic rays into the Earth's atmosphere is negligible compared to that from solar irradiance, they are the main source of ionization in the troposphere [see, e.g., *Bazilevskaya*, 2000].

[3] A possible qualitative link has been proposed that relates cosmic ray induced ionization (CRII) in the troposphere and cloud properties [*Svensmark and Friis-Christensen*, 1997; *Marsh and Svensmark*, 2000a, 2003a]. Ions created by cosmic rays rapidly interact with molecules in the atmosphere and are converted to complex cluster ions (aerosols) [*Gringel et al.*, 1986; *Hoppel et al.*, 1986]. These cluster ions may grow by ion-ion recombination or ion-aerosol attachment and thus affect the number of aerosols acting as cloud condensation nuclei (CCN) at typical atmospheric supersaturations of a few percent [*Viggiano and Arnold*, 1995; *Yu and Turco*, 2001]. Others have suggested that a CRII-cloud link could also arise through changes in the global electric circuit affecting aerosol-cloud interactions at the edges of clouds (see, e.g., *Tinsley* [2000] or a review of possible mechanisms in *Harrison and Carslaw* [2003]). Both mechanisms require that an amplified effect of cosmic rays on climate is realized through the important role that clouds play in the radiation budget of the atmosphere by both trapping outgoing long wave radiation and reflecting incoming solar radiation. Although a detailed physical model quantifying this connection is still missing, correlation studies support its validity. *Marsh and Svensmark* [2000a] found a highly significant correlation between low clouds below ~3.2 km (rather than clouds at other altitudes) and the cosmic ray flux during the period 1983–1994. This basic result has subsequently been confirmed by other independent studies [*Pallé and Butler*, 2000; *Yu*, 2002]. There is also evidence for the reduction of cloud coverage during strong Forbush decreases at time scales of a few days [*Pudovkin and Veretenenko*, 1996]. This implies that the proposed cloud-cosmic ray relation may also be significant at short-time scales. More recently *Marsh and Svensmark* [2003b] found that the low cloud-cosmic ray correlation can be extended until 2001 but only after the globally averaged cloud data are re-calibrated. However, the variability in low cloud amount (LCA) cannot be uniquely ascribed to a single mechanism when using globally averaged data since the observed long-term changes in the global LCA correlate with different solar-related indices including solar irradiance and cosmic rays.

[4] In this paper we study the spatial distribution of LCA and CRII over the period 1984–2000. In all previous studies the count rate of a single neutron monitor was used as a measure of cosmic rays, and assumed to represent the global CRII. (After submission of this paper we were made aware of the Ph.D. thesis by *Pallé* [2001] where CRII was also calculated. However, none of the main conclusions of this paper were obtained or discussed by Pallé.) Although useful for qualitative correlation studies, this approach does not give quantitative estimates since the cosmic ray intensity varies strongly over the globe due to the shielding by the

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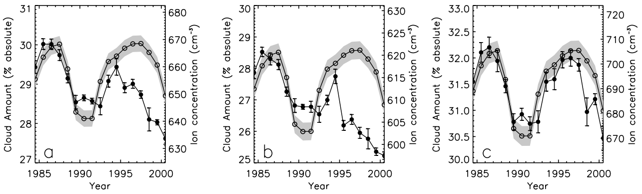

Figure 1. Time profiles of LCA in percent of the area coverage (solid symbols, left axis) and CRII (open symbols, right axis) for a) the global average (60°S < λ < 70°N), b) tropics (|λ| < 25°), and c) mid-latitudes (60°S < λ < 25°S and 25°N < λ < 70°N). Error bars for LCA (±σ) are estimated for each annual average from the corresponding monthly fluctuations, after removal of the seasonal cycle. Any effects due to instrument or calibration uncertainties are neglected. Errors in CRII (±σ, grey shading) correspond to ±50 MV uncertainties in the reconstructed annual modulation strength [*Usoskin et al.*, 2002].

geomagnetic field. Here we study the global distribution of CRII and compare that with the measured LCA distribution.

2. LCA-CRII Relations During 1984–2000

[5] Following previous studies [*Marsh and Svensmark*, 2003b], we use the low cloud amount obtained from the ISCCP-D2 database limited to IR radiances. ISCCP provides monthly observations of the global cloud cover based on an intercalibration of up to 5 satellites for the period from July 1983 to September 2001. Satellites detect a cloud when radiance observations differ significantly from clear sky values. However, uncertainties can arise if atmospheric transparency is influenced by processes other than clouds, e.g., aerosol loading from Mt. Pinatubo [*Luo et al.*, 2002]. We note that LCA as defined from satellite observations is restricted to clouds with their tops below 640 hPa (3.2 km), which is different from ground-based observations. In the present analysis annual LCA averages are used (in order to avoid seasonal variations) on a 5° × 5° latitude-longitude grid for the period 1984–2000 inclusive.

[6] Recently, the global distribution of CRII has been calculated for the troposphere (0–10 km) since 1951 [*Usoskin et al.*, 2004]. First, the electromagnetic-nucleonic cascade initiated by cosmic rays in the atmosphere was simulated for different conditions using the CORSIKA Monte-Carlo package [*Heck et al.*, 1998]. Then the annually averaged ion production rate in the troposphere at a given latitude was calculated using the respective cosmic ray spectra parameterized by the average heliospheric modulation strength [*Usoskin et al.*, 2002]. Finally, the equilibrium ion concentration was calculated at a given location, taking into account processes of recombination and aerosol attachment. Here we use CRII values calculated at 3 km altitude which corresponds roughly to the limiting altitude, as defined by ISCCP-D2, below which low cloud forms.

Table 1. Correlation Coefficients (and Their Significance Levels in Parentheses) Between LCA and CRII for the Period of 1984–2000 for Different Regions: Global (60°S < λ < 70°N), Tropics (|λ| < 25°), and Mid-Latitudes (60°S < λ < 25°S and 25°N < λ < 70°N)

Data	Global	Tropics	Mid-Latitudes
Raw data	0.46 (61%)	0.14 (26%)	0.81 (98%)
De-trended data	0.84 (>99%)	0.61 (94%)	0.90 (>99%)

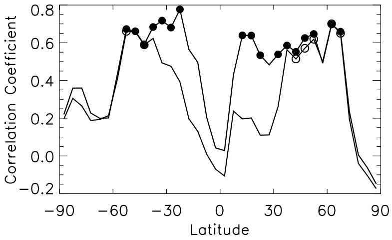

Figure 2. Latitudinal dependence of the cross-correlation coefficient between LCA and CRII for 1984–2000. Results for raw and detrended LCA data are shown by thin and thick lines, respectively. Correlation coefficients above 90% significance level are indicated with symbols.

[7] Time profiles of measured LCA and calculated CRII are shown in Figure 1 for different regions, the corresponding values of the correlation coefficient (c.c.) and their significance levels are summarized in the first row of Table 1. Polar regions (λ > 60°S and λ > 70°N) are excluded from the analysis in order to avoid the problems associated with cloud detection over ice. The rest of the globe (60°S < λ < 70°N) is further divided into two latitudinal regions: tropics (|λ| < 25°) and middle latitudes (λ = [25° − 60°]S and [25° − 70°]N). Similar to previous studies [*Marsh and Svensmark*, 2003b], the statistical significance of the c.c. has been estimated using the random phase test [*Ebisuzaki*, 1997].

[8] The c.c. between zonal averages (within 5° latitudinal belts) of CRII and LCA are depicted by the thin line in Figure 2. The global distribution of the significant c.c. within a 5° × 5° grid is shown in Figure 3a. One can see that the significant coefficients are not uniformly distributed over the globe. The correlation is high at middle latitudes

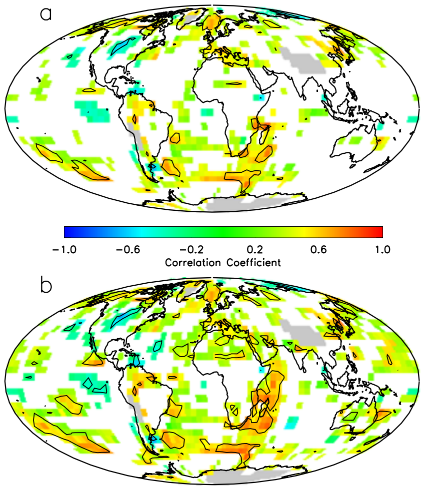

Figure 3. Global distribution of the correlation coefficients between CRII and LCA for 1984–2000 using the raw (panel a) and detrended (panel b) cloud data. Only areas with significant correlation (significance level >68%) are shown while areas of highly significant correlation (>90%) are indicated by the thick contour line. Areas with no data are given in grey.

Table 2. Fraction of the Global Surface (Areas With No Cloud Data are Excluded) Covered by Significant (s.l. >68%) and Highly Significant (s.l. >90%) Correlation (Positive and Negative Separately) Between CRII and Raw and Detrended LCA Data

Data	Significant Negative	Highly Significant Negative	Significant Positive	Highly Significant Positive
Raw data	4%	1%	25%	6.5%
De-trended data	4.5%	1%	39%	15%

but is suppressed in tropical regions, leading to a moderate global correlation (see also Figure 2). A similar conclusion has been drawn for total clouds by *Svensmark and Friis-Christensen* [1997] and for low clouds by *Marsh and Svensmark* [2003b] who suggested that ENSO dominates inter-annual variability in the tropics.

[9] LCA and CRII behave very similarly to each other at middle latitudes, both depicting the dominant 11-year cycle (Figure 1c), but are somewhat different in the tropics. While the CRII time series has qualitatively the same form in all geographical zones, LCA behaves differently. A strongly decreasing trend of about 0.2% per year is apparent in LCA time profile in the tropical regions (Figure 1b) onto which an 11-year cycle is superimposed. The trend is also clearly seen in the global LCA average (Figure 1a) [cf., *Marsh and Svensmark*, 2003b], while the corresponding trend in CRII is close to zero (0.2±0.5 cm^{-3}/year). The trend is not uniform over the globe – while the trend is mostly weak in mid-latitude regions, tropical regions are dominated by areas of strong decreasing trend. Such a trend can mask the agreement between the variations of LCA and CRII during the period 1984–2000. Accordingly, LCA can be decomposed into a long-term trend and shorter-term inter-annual variations around this trend. The origin of this trend could be related to physical processes, e.g., a change in the global circulation pattern or an increased loading of atmospheric aerosol, or to an instrumental effect, e.g., the inter-calibration of satellites providing global cloud observations as suggested by *Marsh and Svensmark* [2003b]. In the following only the detrended inter-annual variations of LCA are considered. We suggest that CRII is not the main source of cloud formation but rather "modulates" it, and that the long-term trend results from other processes, which are outside the main focus of this study.

[10] Using a linear approximation for the long-term trend during 1984–2000, $\overline{LCA}(t) = LCA_o + B \cdot t$, we have investigated the detrended variations of LCA, $\Delta LCA \equiv LCA - \overline{LCA}$. Figure 3b shows the spatial distribution of the c.c. between ΔLCA and CRII. While the total area of significantly negative c.c. is very small and is not greatly affected by detrending LCA, areas of significantly positive c.c. occupy a large fraction of surface covered by the cloud data (see Table 2). We note that areas of significantly positive c.c. show a tendency towards the geographical pattern reminiscent to that of warm ocean currents flowing from the equator towards higher latitudes. Comparing the two maps in Figure 3 one can see that detrending LCA greatly improves the correlation with CRII (see also Tables 1 and 2). This is also clearly seen from the correlation between zonal averages of ΔLCA, and CRII represented by the thick line in Figure 2. Due to detrending of LCA data, the latitude range possessing highly significant positive c.c. (s.l. >90%) is increased from [50–55°S; 40–70°N] to [20–55°S; 10–70°N] (see Figure 2). Figure 4 illustrates that there is now similarity between ΔLCA and CRII time profiles all over the globe (excluding polar regions).

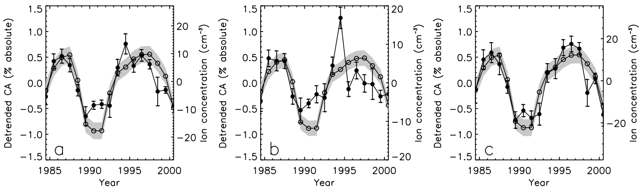

Figure 4. The same as in Figure 1 but for the detrended variations of LCA and CRII.

[11] Using the latitudinal zones with highly significant c.c.'s (see Figure 2) we try to quantify the relation between detrended LCA and CRII (Figure 4). For want of a physical model relating LCA to CRII, a quantitative phenomenological relation is assumed in the form of a direct proportionality between normalized variations of LCA, $\delta(LCA) = \Delta LCA/\overline{LCA}$, and CRII, $\delta(CRII) = (CRII - \overline{CRII})/\overline{CRII}$, where $\overline{CRII}$ is the zonal mean CRII value during 1984–2000. The scatter plot of $\delta(LCA)$ vs. $\delta(CRII)$ is shown in Figure 5a. Despite the wide scatter of points, there is a highly significant correlation between $\delta(LCA)$ and $\delta(CRII)$ (c.c. = 0.6, s.l. >98%), with the corresponding linear relation as follows:

$$\delta(LCA) = (1.02 \pm 0.08)\delta(CRII). \qquad (1)$$

The fact that the proportionality coefficient is close to unity implies that inter-annual variations of LCA around the long-term trend can be directly ascribed to the variations of CRII. Moreover, the amplitude of cyclic relative variations in $\delta(LCA)$ and $\delta(CRII)$ shows a similar latitudinal dependence (Figure 5b). These results strongly favor the idea that the variations of LCA are related to CRII rather than other mechanisms, e.g., solar irradiance, which cannot naturally explain such a latitudinal dependence.

3. Conclusions

[12] While in earlier studies data from a single neutron monitor was used as a proxy of cosmic ray intensity, we

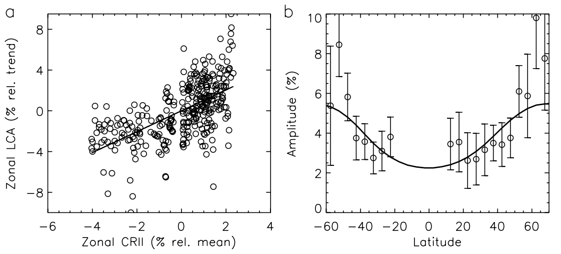

Figure 5. Latitudinal relation between relative variations of $\delta(LCA)$ and $\delta(CRII)$ for the period 1984–2000 within the latitude range 55°–20°S and 10°–70°N. a) Scatter plot of $\delta(LCA)$ versus $\delta(CRII)$, each dot representing an annual value within a 5° latitudinal bin. Solid line depicts the best linear fit (equation (1)). b) Latitudinal dependence of the amplitude of cyclic variations in $\delta(LCA)$ (dots) and $\delta(CRII)$ (line). The amplitude is found by fitting a 10-year sinusoid to the respective time profiles.

have explored the quantitative relationship between temporal and spatial variations of LCA and CRII over the globe for the period 1984–2000. We suggest that the LCA time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting a clear 11-year cycle in phase with CRII. The trend whose nature is beyond the scope of the present study, is strong in tropical regions and possibly masks the LCA-CRII relation. We then find a highly significant correlation between the detrended inter-annual LCA variations and CRII over the globe (polar regions being excluded). A quantitative regression model was obtained (equation (1)), which implies a one-to-one relation between the relative variations of LCA and CRII over the latitude range 20–55°S and 10–70°N. The amplitude of relative variations in LCA was found to increase polewards, in accordance with the amplitude of CRII variations but in contrast to the insolation which decreases polewards. These results thus support the idea that LCA is modulated by CRII, rather than by solar irradiance, at inter-annual timescales between 1984–2000.

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