GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L03802, doi:10.1029/2004GL021167, 2005

Possible satellite perspective effects on the reported correlations between solar activity and clouds

E. Pallé

Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City, California, USA

Received 31 July 2004; revised 21 October 2004; accepted 16 December 2004; published 1 February 2005.

[1] Recently some correlations between low cloud cover and solar activity have been reported in the literature. In this paper we show how the flux of GCR is found to correlate positively with the low clouds and negatively with higher clouds, supporting previous theoretical predictions linking atmospheric ionization by cosmic rays and cloud cover at different altitudes. All these correlations are however only marginally significant and the only strongly significant (negative) correlation is found between low and higher cloud layers. Thus, there is strong evidence that the solar-like variability in low cloud may be artificially induced by the satellite observing perspective. **Citation:** Pallé, E. (2005), Possible satellite perspective effects on the reported correlations between solar activity and clouds, *Geophys. Res. Lett.*, *32*, L03802, doi:10.1029/2004GL021167.

1. Introduction

[2] Solar irradiance measurements from space have revealed that for the last three activity cycles, the solar irradiance is about 0.1% (0.3 Wm^{-2}) greater at activity maximum than activity minimum [*Fröhlich*, 2000]. Considering the oceans' thermal inertia, it is widely accepted that this is several times too small to be climatologically significant over the solar cycle [*Lean*, 1997; *Houghton et al.*, 2001]. Nevertheless, an 11-year periodicity signal of order 0.1K has been detected in surface, atmospheric, and ocean temperatures at several timescales [*Stevens and North*, 1996; *Ram and Stoltz*, 1999]. Whilst it is unlikely that this modulation could be due directly to the observed change in solar irradiance, it is feasible that it derives from an amplification of the solar signal by an indirect mechanism.

[3] Several 'indirect' mechanisms have been proposed in the literature, one of which, namely a link between cloud cover and the flux of galactic cosmic rays (GCR), is of particular interest here. *Svensmark and Friis-Christensen* [1997] studied International Satellite Cloud Climatology Project (ISCCP) data over the 1983–1991 period and found a 3–4% greater cloud cover at solar activity minimum. Subsequent ISCCP satellite data (1991–1994) showed that the correlation was preserved only in the low-lying clouds [*Pallé and Butler*, 2000; *Pallé et al.*, 2004b; *Marsh and Svensmark*, 2000]. As low clouds have a large impact on the albedo it was suggested that they could provide a significant climate forcing coupled to solar variability. Although so far only low clouds have been reported to significantly correlate to GCR, *Yu* [2002] indicated that high clouds may also correlate to GCR if the effects of El Niño–Southern Oscillation (ENSO) and volcanic eruptions where taken into account.

[4] ISCCP data are now updated to September 2001. With the addition of new data, the correlation between low clouds and GCR weakens [*Pallé et al.*, 2004b], and an overall decreasing trend similar to that of total cloud cover starts to dominate the low cloud record.

2. Solar Signals in Cloud Records

[5] The ISCCP data sets provide 3-hourly global coverage of cloud of different types and at various heights. Total cloudiness is determined using both visible (VIS - daytime only) and infrared (IR - 24 hour) radiances, whereas the separation into low, mid and high level cloud types uses IR radiances only. The data are given for 280 × 280 km^2 cells with the cloud fraction in each cell determined by dividing the number of cloudy pixels by the total number of pixels per cell. A detailed description of the ISCCP D data set is given by *Rossow et al.* [1996].

[6] The ISCCP global mean cloud cover record (Figure 1a) shows a slight increase from 1984 to 1987, followed by a strongly significant decreasing trend from 1987 to 2001 (totaling about 4% in 14 years), with about half (2–3%) due to low clouds and half (2%) to high clouds. Mid-level clouds, on the other hand, have increased by 1% or less. *Marsh and Svensmark* [2003] have suggested that the ISCCP post-1994 low cloud data may suffer from a calibration error, however no such error has been reported by the ISCCP group. In fact, such an error now looks unlikely as the total (and low) cloud amount decrease is consistent with independent measurements of: (1) reflected SW and outgoing IR radiation from space [*Wielicki et al.*, 2002; *Cess and Udelhofen*, 2003]; (2) surface solar radiation measurements from radiometer data (B. Liepert and M. Wild, personal communication) and, (3) since 1994, earthshine albedo measurements [*Pallé et al.*, 2004a].

[7] Here we reexamine the possible influence of solar activity and the flux of GCR on the three ISCCP IR cloud types (low, mid, high). We have reduced the number of series to two by combining the mid and high clouds together. The rationale is that if the solar cycle is visible in the low clouds but not in the total cloud amount, then other cloud types are probably compensating for it. This has proved to be crucial in gaining new insights into the variability of the several cloud types. Both series show a clear decreasing trend over 14 years, similar to that of the IR and VIS+IR total cloud amounts (Figures 1a–1c). But a closer look at Figures 1b and 1c also reveals an apparent anti-correlation between the low clouds and the mid+high clouds. A solar-like modulation with an amplitude of about

0094-8276/05/2004GL021167$05.00

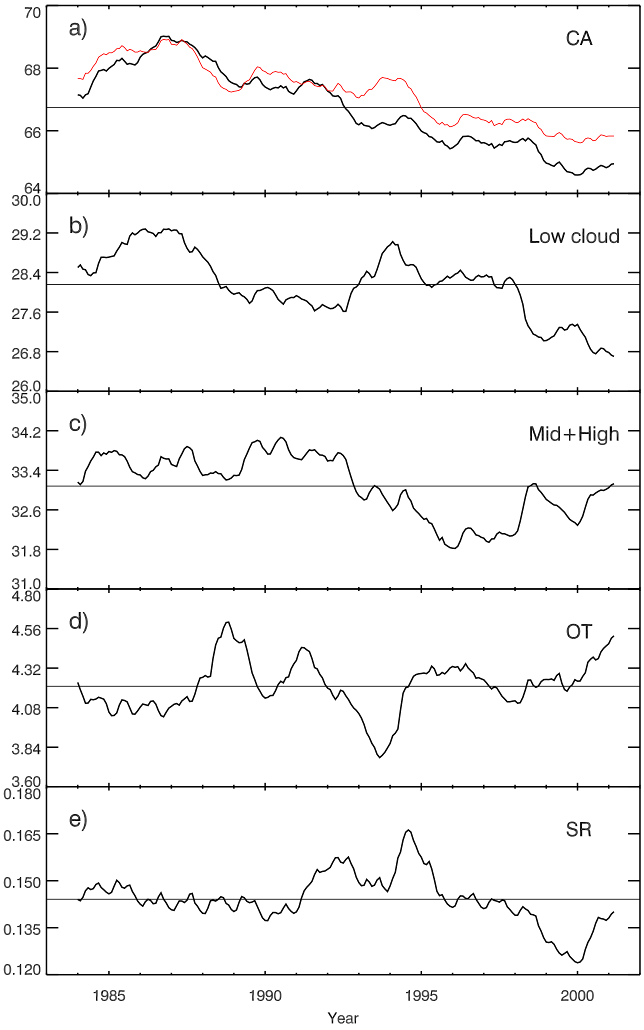

Figure 1. ISCCP global mean over the 1983–2001 period of: a) Total cloud amount (black) and total IR clouds amount (red); b) IR low cloud amount; c) IR mid+high cloud amount; d) cloud optical thickness; e) surface reflectance. The total IR cloud amount has been artificially increased by +6% for plotting purposes.

1.5% in cloud amount and with opposite sign for the low and mid+high clouds is superimposed to the common decreasing trend.

[8] When assessing the significance of the correlation of these slowly varying data sets it is crucial to determine the number of degrees of freedom and to account for possible field correlations. To calculate the significance of the correlation we have used Monte Carlo techniques following *Pallé et al.* [2004b]. Also, cloud amount has a seasonal variation which needs to be removed in order to compare their inter-annual variation with that of solar activity. The overall long-term decrease, not related to GCR [*Pallé and Butler*, 2002], and other climate phenomena like ENSO will also have a large impact on clouds. Thus, one should not be too strict in evaluating the statistical significance of a possible correlation of cloud amount with GCR. The globally averaged correlation between the low and the mid+high IR cloud series with the flux of GCR is significant ($r = 0.4$, $P > 90\%$; $r = -0.6$, $P > 99\%$; respectively for the 12-month running mean in cloud amount).

[9] A common trend affecting both the low and mid+high cloud series can be effectively removed by taking the ratio or the difference between the two series. This ratio is plotted in Figure 2 together with the flux of GCR from Climax station. Because of the opposite sign of the correlation with solar activity for the two cloud records, the solar imprint on the cloud records becomes clearer (see Figure 2) ($r = 0.87$, $P > 99.9\%$). A high degree of correlation between the GCR and the ratio of the two cloud series is apparent. Only around 1998, does the strong correlation between the ratio of low and mid + high clouds and the flux of GCR disagree. This is the time when the largest ENSO event on record took place. Several authors have already pointed out the strong links between total and low cloud changes and ENSO events [*Farrar*, 2000; *Marsh and Svensmark*, 2003].

3. Satellite Perspective Effects on the Cloud Records

[10] Because of their observing geometry, Earth observation satellites cannot see low lying clouds if a higher layer of clouds is present. Thus, to estimate the possible effect of the overlapping cloud layers, we have studied the geographical distribution of the GCR-cloud correlations. In Figure 3 the correlation maps of low, mid + high and the ratio of the two cloud series with the flux of GCR are plotted.

[11] We note that there is a widespread positive correlation of low cloud amount with the flux of GCR, although the results are only marginally field significant (Figure 3a). For the mid + high clouds there are only negative significant correlations (Figure 3b). Taking the ratio between the two cloud series does not seem to improve the correlation map, as it does for the global averages. That is because the large decreasing trend in cloud amount is restricted to the tropical and sub-tropical regions (isccp.giss.nasa.gov) where the GCR-cloud correlations are poor.

[12] In Figure 3g, the correlation map between low and mid+high clouds is plotted. One can observe that the negative (positive) correlations of the mid+high (low) cloud amount with GCR occurs in areas where the anti-correlation between the two cloud data sets is stronger and where the mean cloud

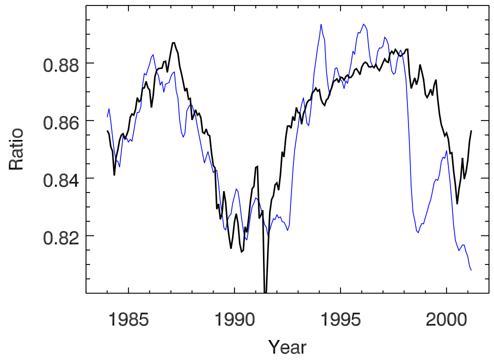

Figure 2. The 12-month running mean (blue) of the ratio between low cloud cover and the sum of mid and high clouds. In black, the Climax neutron monitor galactic cosmic ray flux (www.ngdc.noaa.gov) is overplotted on an arbitrary scale.

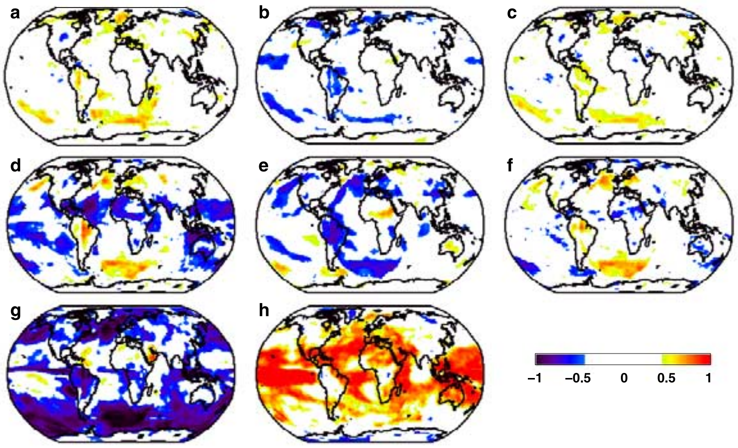

Figure 3. The geographical distribution of the correlation between: (a) low IR clouds and the flux of GCR; (b) mid+high IR clouds and the flux of GCR; (c) the ratio between low and mid+high cloud amounts and the flux of GCR; (d) low IR clouds and ENSO; (e) mid+high IR clouds and ENSO; (f) the ratio between low and mid+high cloud amounts and ENSO; (g) IR low and mid+high cloud amounts; (h) IR mid and high cloud amounts. In all maps only correlations with statistical significance larger than 95% are plotted.

amount is larger (80–100%), increasing the chances for overlapping cloud layers (Figures 3a, 3b, and 3g). Moreover, significant correlations between low clouds and GCR are not observed in areas where mid and high clouds are scarce and low clouds are plentiful (i.e., the west coasts of Africa, Latin America and Australia; Figure 4b). This, together with the fact that the solar-like modulation has the same amplitude (1.5%) over the trend in both low and mid+high clouds and that the signal disappears when the two data sets are added (IR total, Figure 1a), leads us to suspect that the solar-like signal in the low clouds may be artificially induced by changes in higher cloud layers.

[13] *Marsh and Svensmark* [2003] studied the effects of overlapping cloud layer on the correlation between low clouds and GCR. They defined areas of unobstructed view of low clouds and determined a strong correlation with GCR over those areas. The discrepancies with the work presented here are probably due to the different ISCCP cloud subset used in their analysis. *Marsh and Svensmark* [2003] used the ISCCP data from 1983–1994. Over that period mid+high cloud amount does not change significantly and the anti-correlation of the two data sets is poor. But the anti-correlation becomes more evident when the full 1983–2001 data set is used, especially if one takes into account the trends in total cloud amount.

[14] One might also suspect that mid-level clouds may also be obscured by high clouds but this does not seem to be the case. The correlation map between mid and high clouds are plotted in Figure 3h. The widespread positive correlation of the two data sets, which cannot be caused by the observing geometry, is evident. Also note that panels g and h seem to be complementary.

[15] For illustration purposes, we have also reproduced in Figures 3d–3f the geographical distribution of the correlation between low and mid+high clouds and the ENSO index (www.cru.uea.ac.uk). The purpose here is to illustrate that, as for the GCR, the correlations/anti-correlation of low and mid + high clouds with ENSO follow similar patterns but with opposite sign. Areas where the correlation with ENSO is significant for both low and mid+high cloud layers have opposite sign. That reinforces the notion that year-to-year low cloud variability is greatly influenced by higher cloud layers. Also note that the cloud correlations with ENSO are more widespread (and significant) than those with GCR, and that the sign of the correlation for a given cloud type varies geographically. Thus global cloud averages will weaken the ENSO signal while at the same time reinforce the correlation with GCR.

4. Discussion and Conclusions

[16] *Yu* [2002] suggested that ISCCP high clouds could correlate with GCR if periods of strong ENSO and volcanic activity where excluded. Here we find that high clouds do correlate with GCR, without the need to exclude data, when combined with mid level clouds. This argues for similar physics of the mid and high level ISCCP cloud types with regards to a possible solar influence.

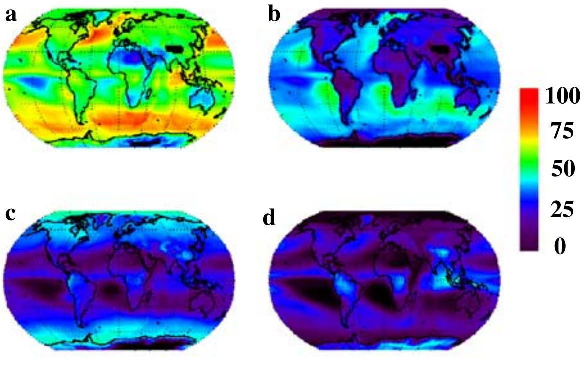

Figure 4. Mean cloud amount of the: (a) total (VIS+IR) cloud cover; (b) Low IR cloud cover; (c) Mid level IR cloud cover; (d) High IR cloud cover.

[17] In view of the above results, we need to ascertain what could lead to a negative correlation between high clouds (altitude > 3 km) and a positive correlation of low clouds with GCR. Either a physical mechanism related to the flux of GCR is acting on both low and higher cloud layers (with opposite sign) at the same time (or only on the high clouds if the low cloud signal is artificial), or there are dynamical changes associated with all cloud types that make it more likely for clouds to form at higher or lower altitudes depending on the solar cycle stage. In the latter case, a possible Sun-Earth connection would act, not through the creation of more or less cloudiness, but through a redistribution of the cloud types, perhaps following mechanisms similar to those proposed by *Haigh* [1996] and others.

[18] *Tinsley and Yu* [2004] have published a review of the several proposed links between solar activity, atmospheric ionization and clouds, and the patterns of latitude/altitude correlations to be expected from these mechanisms. Among the most promising mechanisms is the ion mediated nucleation. *Yu* [2002] modeled the response of aerosol production to variations in GCR intensity as a function of altitude. His results show a positive correlation in the lower troposphere and a negative correlation on the upper troposphere. More recently *Kazil and Lovejoy* [2004] have used a similar model to that of *Yu* [2002] to study tropospheric ionization and aerosol production. Their results also indicate a ion induced nucleation capable of particle production, with the same altitude dependence of *Yu* [2002]. However they point out that at low altitude ($p > 680$ hPa) this could be inhibited by enhanced evaporation. These results are consistent with the results found here, where a negative correlation between mid + high clouds ($p < 680$ hPa) to GCR is found. This anti-correlation is likely translated into a positive correlation in the low clouds ($p > 680$ hPa), although a direct influence of GCR in the low clouds cannot be definitely dismissed.

[19] Changes in the Sun's radiative or particle output over the past few decades cannot explain the large Earth and sea surface warming observed during the past two decades. Over this period it is the large decrease in cloud amount, combined with changes in other cloud properties, that has governed the SW variability in the ERB [*Wielicki et al.*, 2002; *Pallé et al.*, 2004a]. However, if the mechanism driving cloud changes in recent decades is either short-term (decadal) natural variability or anthropogenic in origin, at longer time scales (prior to the industrial revolution) the Sun-clouds connection may have acted alone, and we speculate that this may be the mechanism driving the strong Sun-climate connections seen in long-term climate records. However, even if a Sun-cloud indirect mechanism is operating, it is not sufficient to simply change the amount of clouds to produce an amplification of the solar signal. The size (or even sign) of this amplification will also be influenced by cloud properties like the optical thickness, particle distribution and cloud altitude. Thus longer time observations of clouds and the ERB are needed to identify and quantify the possible influence of solar activity on cloud formation, as it may have an important role on past, present and future climates.

[20] **Acknowledgments.** This research was supported in part by a grant from NASA (NAG5-11007). The cloud D2 data sets were obtained from the NASA Langley Research Center EOSDIS Distributed Active Archive Center. The author would also like to thank Drs. C. J. Butler, P. R. Goode and P. Montañés Rodríguez for their comments on earlier versions of this manuscript.

References

Cess, R. D., and P. M. Udelhofen (2003), Climate change during 1985–1999: Cloud interactions determined from satellite measurements, *Geophys. Res. Lett.*, *30*, 1019, doi:10.1029/2002GL016128.

Farrar, P. D. (2000), Are cosmic rays influencing oceanic cloud coverage—Or is it El Ninõ?, *Clim. Change*, *47*, 7.

Fröhlich, C. (2000), Observations of irradiance variations, *Space Sci. Rev.*, *94*, 15.

Haigh, J. D. (1996), The impact of solar variability on climate, *Science*, *272*, 981.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 881 pp., Cambridge Univ. Press, New York.

Kazil, J., and E. R. Lovejoy (2004), Tropospheric ionization and aerosol production: A model study, *J. Geophys. Res.*, *109*, D19206, doi:10.1029/2004JD004852.

Lean, J. (1997), The Sun's variable radiation and its relevance for Earth, *Annu. Rev. Astron.*, *35*, 33.

Marsh, N., and H. Svensmark (2000), Low cloud properties influenced by cosmic rays, *Phys. Rev. Lett.*, *85*, 5004.

Marsh, N., and H. Svensmark (2003), Galactic cosmic ray and El Niño–Southern Oscillation trends in International Satellite Cloud Climatology Project D2 low-cloud properties, *J. Geophys. Res.*, *108*(D6), 4195, doi:10.1029/2001JD001264.

Pallé, E., and C. J. Butler (2000), The influence of cosmic rays on terrestrial clouds and global warming, *Astron. Astrophys.*, *41*, 18.

Pallé, E., and C. J. Butler (2002), The proposed connection between clouds and cosmic rays: Cloud behavior during the past 50–120 years, *J. Atmos. Sol. Terr. Phys.*, *64*, 327.

Pallé, E., P. R. Goode, P. Montañés-Rodriguez, and S. E. Koonin (2004a), Changes in the Earth's reflectance over the past two decades, *Science*, *304*, 1299, doi:10.1126/science.1094070.

Pallé, E., C. J. Butler, and K. O'Brien (2004b), The possible connection between ionization in the atmosphere by cosmic rays and low level clouds, *J. Atmos. Sol. Terr. Phys.*, *66*, 1779–1790.

Ram, M., and M. R. Stoltz (1999), Possible solar influences on the dust profile of the GISP2 ice core from central Greenland, *Geophys. Res. Lett.*, *26*, 1763.

Rossow, W. B., A. W. Walker, D. E. Beuschel, and M. D. Roiter (1996), International Satellite Cloud Climatology Project (ISCCP): Documentation of New Cloud Datasets, *WMO/TD-737*, 115 pp., World Meteorol. Org., Geneva.

Stevens, M. J., and G. R. North (1996), Detection of the climate response to the solar cycle, *J. Atmos. Sci.*, *53*, 2594.

Svensmark, H., and E. Friis-Christensen (1997), Variations on cosmic rays flux and global cloud coverage—A missing link in solar climate relationships?, *J. Atmos. Sol. Terr. Phys.*, *59*, 1225.

Tinsley, B. A., and F. Yu (2004), Atmospheric ionization and clouds as links between solar activity and climate, in *Solar Variability and Its Effects on Climate*, *Geophys. Monogr. Ser.*, vol. 141, edited by J. M. Pap and P. Fox, p. 321, AGU, Washington, D. C.

Wielicki, B. A., et al. (2002), Evidence for large decadal variability in the tropical mean radiative energy budget, *Science*, *295*, 841.

Yu, F. (2002), Altitude variations of cosmic ray induced production of aerosols: Implications for global cloudiness and climate, *J. Geophys. Res.*, *107*(A7), 1118, doi:10.1029/2001JA000248.

E. Pallé, Big Bear Solar Observatory, New Jersey Institute of Technology, 40386 North Shore Lane, Big Bear City, CA 92314, USA. (epb@bbsp/njit.edu)