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Solar activity, cosmic rays, clouds and climate – an update

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Abstract

Eighteen years of monthly averaged low cloud cover data from the International Satellite Cloud Climatology Project are correlated with both total solar irradiance and galactic cosmic ray flux from neutron monitors. When globally averaged low cloud cover is considered, consistently higher correlations (but with opposite sign) are found between low cloud variations and solar irradiance variations than between variations in cosmic ray flux and low cloud cover. The correlations are not significant at the 0.1 level, but it should be noted that non-solar effects such as El Niño and volcanic eruptions have not been removed. When spatial regression patterns between low cloud cover and total solar irradiance are studied, the Pacific Ocean exhibits patterns reminiscent of the Pacific Decadal Oscillation. A possible interpretation is that the solar signal interacts with variability modes in the ocean to give this kind of pattern. Correlating low cloud cover with its own global average shows that most of the variability is coming from the subtropical oceans, where the bulk of the Earth's low clouds are found. In conclusion, the updated analysis is not inconsistent with a modulation of marine low cloud cover due to variations in solar irradiance causing changes in lower tropospheric static stability, but many details are still missing. A cosmic ray modulation seems less likely, but can not be ruled out on the basis of the present analysis.

Keywords: Clouds and climate; Solar activity; Cosmic rays

1. Introduction

Throughout Earth's history its climate has undergone large variations on various time scales. It is believed that the Sun has contributed significantly to these variations, through, e.g., variations in the Earth's orbit around the Sun, and variations in solar irradiance. It is also clear that changes in the Earth's albedo due to volcanic dust and meteorite impact have played an important role. Since 1850 the Earth's climate has undergone considerable warming, and the causes of this warming are the subject of some debate. The warming before 1950 is generally believed to be due to a combination of several factors (e.g., Lean and Rind, 1998; Folland and Karl, 2001), including increased greenhouse gas concentrations, little volcanic activity, internal variability of the coupled atmosphere–ocean system and enhanced solar irradiance. The last component is supported, e.g., by a fairly steady rise in sunspot number in this period. This contrasts to the exceptionally low sunspot number (Maunder Minimum) during the Little Ice Age of the 17th century (Eddy, 1976). After 1950 the global temperature fell slightly until the mid-1970s, while it has risen sharply since, in particular after about 1985. Several investigators have attributed most of this warming to human activity (e.g., Mitchell et al., 2001), but the role of the Sun has not been entirely clarified. The sunspot number, which is probably a good proxy for solar irradiance (Lean et al., 1995), has decreased slightly in this period. There has been more controversy about other parameters such as the open solar flux from the Sun, the geomagnetic *aa* index and the galactic cosmic ray (GCR) flux, which varies inversely with solar activity.

Svensmark and Friis-Christensen (1997) suggested a modulation of the Earth's total cloud cover by variations in the GCR flux. This hypothesis was subsequently modified by Marsh and Svensmark (2000) to a link between GCR flux and low clouds, which have a

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particularly strong cooling effect on climate. It was suggested that a GCR flux decrease over the 20th century had resulted in a decrease of low cloud cover by more than 8%, hence accounting for a significant fraction of the observed global warming. The proposed physical explanation for a GCR-cloud connection has been subject to controversy, but due to insufficient understanding of aerosol formation and growth in the atmosphere, it is difficult to draw firm conclusions at this point (Carslaw et al., 2002). The assumption of a significant decrease in GCR flux during the 20th century, was based on an investigation by Lockwood et al. (1999), suggesting a 40% increase in the solar magnetic field between 1964 and 1996 and more than a doubling during the 20th century. This result has recently been challenged by Richardson et al. (2002), who found no significant trends for either sunspots, GCR flux or the interplanetary magnetic field (IMF) over the last 50 years. Positive trends in sunspot number and *aa* index during the first half of the 20th century are undisputed, however.

Unfortunately, reliable cloud cover data with full global coverage are currently only available for an 18-year period (1983–2001), i.e., less than two solar cycles. The cloud data are produced by the International Satellite Cloud Climatology Project (ISCCP), using a combination of visible, near-infrared and infrared channels on geostationary and polar orbiting satellites. This data set makes a distinction between high (above 420 hPa), middle (between 420 and 680 hPa) and low clouds (below 680 hPa, i.e., approximately 3.5 km). The low clouds are obtained by two alternate methods, hereafter referred to as IR-low and Daytime-low, respectively, and it was argued by Kristjánsson et al. (2002) that the latter is the more reliable of the two. While Marsh and Svensmark (2000) found a very high correlation between GCR flux and IR-low cloud cover during the period 1983–1994, the correlation drops substantially after 1994. According to ISCCP scientists the ISCCP analysis had calibration problems in 1994, but these problems were subsequently resolved in a way which should not influence the long term stability (i.e., homogeneity) of the data record, meaning that the data after 1994 are at least as reliable as those before 1994 (William Rossow, pers. comm.). On the other hand, it has also been suggested (Nigel Marsh, pers. comm.) that the calibration of the ISCCP data is wrong after 1994, resulting in a spurious downward jump in cloud cover in the data series. Our analysis has not revealed such a jump except in IR-high cloud cover, which is not of interest here. Consequently, it is assumed in the following that the ISCCP low cloud cover data are consistent throughout the time interval of interest. Kristjánsson et al. (2002) demonstrated a large negative correlation between total solar irradiance and low cloud cover for the whole period 1983–1999, with no discrepancies after 1994. They suggested a causal relationship between the two, implying that any positive correlation between GCR flux and low cloud cover would be coincidental. The suggestion was that solar maximum leads to changes in the large scale circulation (Haigh, 1996) and a slight warming of the oceans (White et al., 1997), and that these effects together cause a reduction in low cloud cover in the subtropics, where low clouds are most prominent. Thereby, since low clouds are cooling climate, subtropical low clouds may act as a positive feedback on climate.

In this investigation, we discuss in more detail the possibility of a causal link between solar irradiance variations and variations in low cloud cover. Following an update of the statistical analysis presented by Kristjánsson et al. (2002) in Section 2, we present a careful look at spatial correlation patterns in Section 3, linking the present results with earlier work on variability modes on decadal time scales. Finally, in Section 4 a summary is given, together with the major conclusions of this study.

2. Statistical analysis

We will now look at the statistical relations between ISCCP low cloud cover and different measures of solar activity over the last 18 years. We will assume that there are no calibration errors affecting the time series of low clouds. Compared to Kristjánsson et al. (2002), almost two years of new data have been added, covering the period January 2000–September 2001. For galactic cosmic rays we use the same time series as in previous papers, i.e., the combined series of Huancayo, Peru and Hawaii. Total solar irradiance has been measured by many different satellites and satellite instruments since these measurements began in November 1978. In order to get a continuous time series for the whole period these different contributions need to be combined into one ("composite") time series. As new data keep coming in, the composite time series is prolonged, but at the same time there is a recalibration of the different instruments with respect to each other. For the purpose of this study, version 25 of the composite data set has been used, obtained from PMOD/WRC in Davos, Switzerland. It turns out that there are significant differences between version 25 and version 19, which was used by Kristjánsson et al. (2002). These differences lead to lower correlation with ISCCP low cloud cover than the previous version. The new correlation coefficients are given in Table 1. None of the correlations given in the table are significant at the 0.1 level, using the non-parametric technique of Ebisuzaki (1997). Hence, it cannot be ruled out on statistical grounds that all these correlations are caused by chance. Nevertheless, the impression from Fig. 1 is that the correlation coefficients for TSI and low

Table 1
Correlation coefficients between galactic cosmic ray flux (GCR) or total solar irradiance (TSI) and two different measures of ISCCP low cloud cover

	GCR vs. IRLOW	GCR vs. DAYLOW	TSI vs. IRLOW	TSI vs. DAYLOW
Raw data	0.179/*0.263*	0.114/*0.147*	−0.387/*−0.370*	−0.288/*−0.287*
No Ann. Cyc.	0.261/*0.427*	0.124/*0.168*	−0.527/*−0.563*	−0.346/*−0.356*
Annual	0.373	0.214	−0.699	−0.523
Run. mean	0.351	0.177	−0.697	−0.511
Low pass	0.326/*0.552*	0.172/*0.229*	−0.678/*−0.689*	−0.473/*−0.445*
High pass	−0.050	−0.092	−0.057	0.016

No lag is assumed. The numbers in italics are for detrended low cloud cover data.

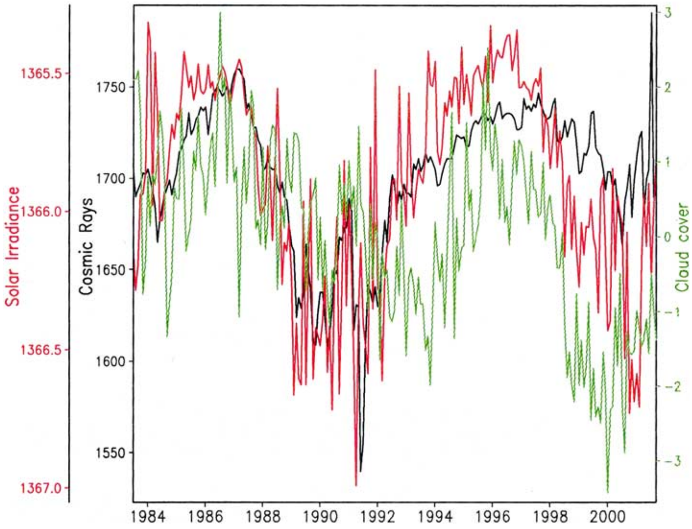

Fig. 1. Temporal variations in globally averaged Daytime low cloud cover (green), total solar irradiance (red) and galactic cosmic ray flux (black).

clouds are high enough to raise interest in possible causal mechanisms. Here it should be noted that no attempt has been made to remove non-solar signals such as El Niño/Southern Oscillation (ENSO) and major volcanic eruptions (e.g., Pinatubo, El Chichón) that might affect the correlations.

The same correlations after detrending the cloud cover data are shown in italics in Table 1. The argument for using detrended data is that the general downward trend may be caused by variability or change in the climate system that has nothing to do with solar-related forcing. It is currently not known whether this trend has any relationship to the ongoing global warming (Chen et al., 2002; Wielicki et al., 2002). The detrending was carried out by assuming that the two peaks in low cloud cover corresponding to solar minima should be of equal magnitude. We note from Table 1 that the detrending leads to significantly higher correlations than before for cosmic rays and low clouds, although the absolute value of the correlation is still lower than for solar irradiance and low clouds. The large sensitivity to detrending is due to the high cosmic ray values in the period 1998–2001, at the same time as low cloud cover has a minimum. Clearly, if global warming was largely caused by a reduction in cosmic ray flux and a consequent reduction in low cloud cover, as suggested by Svensmark (1998), detrending would not be required. Another thing to note from Table 1 is that the correlations are mainly on rather long time scales, e.g., associated with the 11-year solar cycle, while the high-pass filtered data do not show any correlation. Pallé and Butler (2001) also found no correlation between cosmic ray events on short time scales (Forbush decreases) and cloud amount, but their cloud analysis was only regional in nature and did not distinguish between clouds at different levels.

Potentially more meaningful than global correlations are correlation coefficients computed at different geographical locations. Such maps have in the past been very helpful for understanding atmospheric teleconnections related to, e.g., the Pacific North American (PNA) pattern, the North Atlantic/Arctic Oscillation (NAO/AO) (Thompson and Wallace, 2000) or ENSO (Horel and Wallace, 1981). Figs. 2(a) and (b) show the spatial correlations between TSI and the two versions of low cloud cover. Considering the large negative correlations between TSI and low cloud cover in Table 1, it is at first sight somewhat surprising to find large areas of positive correlations in Figs. 2(a) and (b). In particular, the positive correlations off the coast of California are interesting, since they occur in an area where low clouds

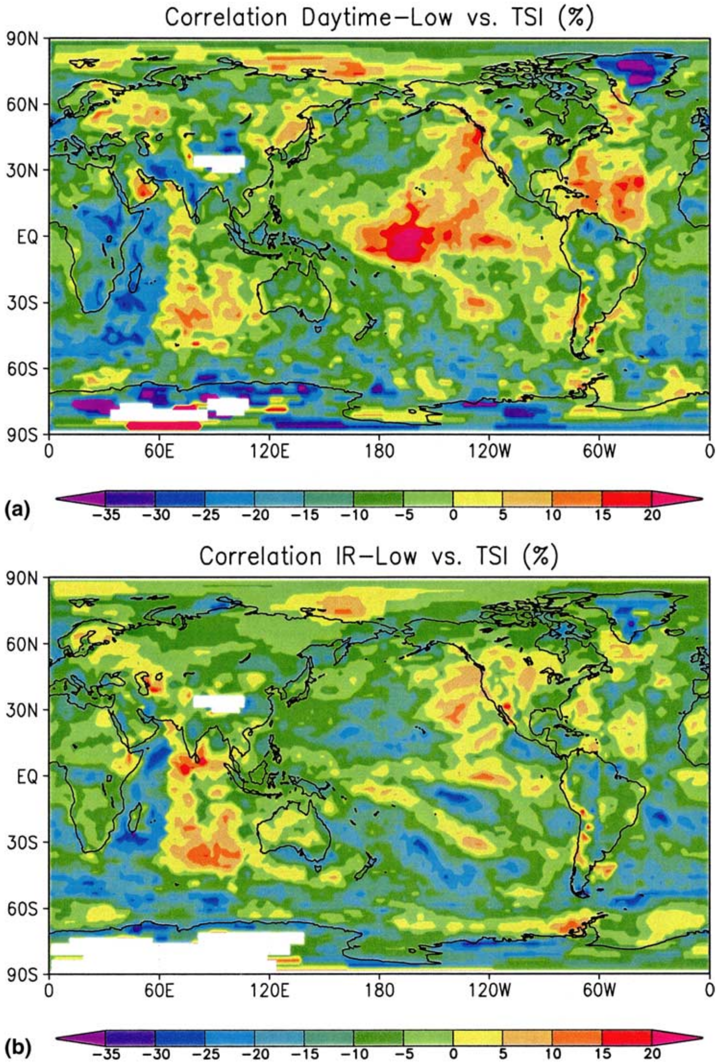

Fig. 2. Spatial correlations between solar irradiance and low cloud cover for the period 1983–2001. No filtering has been applied to the data: (a) Daytime low clouds; (b) IR low clouds.

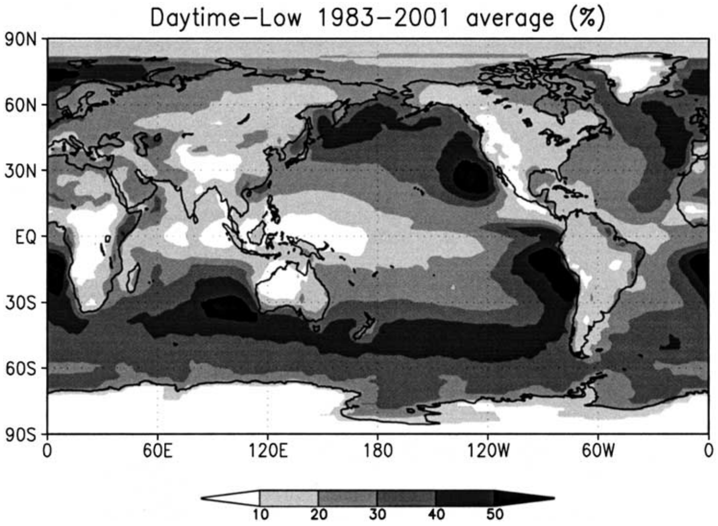

Fig. 3. Geographical distribution of Daytime low cloud cover from 18 years of ISCCP data.

dominate (see Fig. 3). A more careful look at Fig. 2(a) reveals that the spatial pattern found over the Pacific Ocean is similar to decadal or interdecadal patterns in sea-surface temperature (SST) and sea-level pressure previously reported by Mantua et al. (1997) and Tourre et al. (2001). The former investigation described the so-called Pacific Decadal Oscillation (PDO), while the latter described several different patterns of various time scales including the Inter-decadal Pacific Oscillation (IPO, Power et al. (1999)). It turns out that at solar maximum the SSTs off the coast of California are lower than normal, while they are higher than normal at solar minimum.

According to Kristjánsson et al. (2002), assuming no other change in tropospheric temperature, the lower SSTs off the Californian coast at solar maximum would be expected to enhance low cloud cover, while the higher SSTs elsewhere would cause less low cloud cover, in agreement with Fig. 2(a). This argument was based on Klein and Hartmann's (1993) finding of a strong positive correlation between low cloud cover and lower tropospheric static stability over ocean, regions dominated by low clouds. Kristjánsson et al. (2002) presented a figure showing the correlations between SST and low cloud cover, which had very similar spatial patterns to that of Fig. 2(a). Fig. 2(b) for the IR data set gives somewhat similar results to that of Fig. 2(a), although the Pacific pattern is not as pronounced here. In both Figs. 2(a) and (b) large negative correlations are found off the east coast of Africa, which is not one of the favoured regions for low clouds, see Fig. 3. The reason for this is not understood, but the sharp transition between these negative values and fairly high positive values slightly farther east is clearly an artifact of the data analysis, since the boundary of this transition coincides with the boundary between the footprints of two of the geostationary satellites used in the ISCCP retrievals. The problem seems less severe, though, than in Sun and

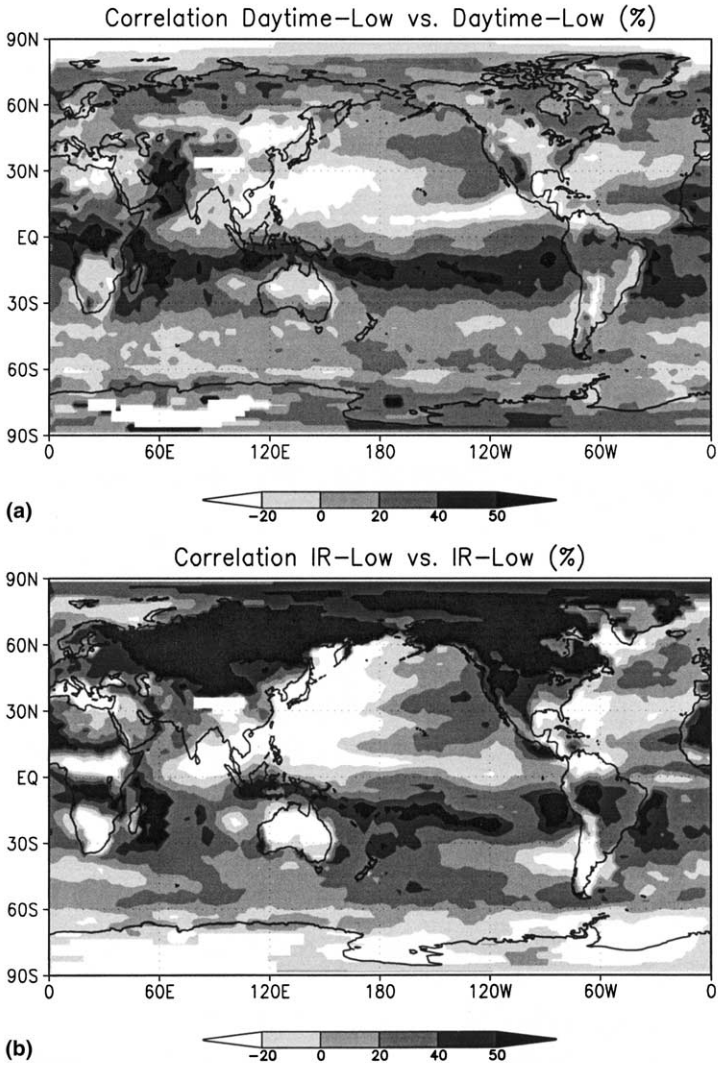

Fig. 4. Spatial correlations between globally averaged low cloud cover and low cloud cover itself for the period 1983–2001: (a) Daytime low clouds; (b) IR low clouds.

Bradley's (2002) analysis correlating ISCCP low clouds from 1983–1993 with cosmic ray flux.

Figs. 4(a) and (b) show the correlation coefficients for low cloud cover against its own global average. Hence, Figs. 4(a) and (b) indicate what geographical regions are contributing most to the overall variations in globally averaged low cloud cover seen in Fig. 2. As shown by Norris (2000) such an analysis can be an effective way of finding spurious features in the data, such as those discussed at the end of the last paragraph. No such suspicious features are found in Figs. 4(a) and (b). Instead, Fig. 4(a) shows in general a high correlation in the subtropics, especially in the southern hemisphere. Negative correlations are mostly found in regions where low clouds are not widespread according to ISCCP, such as over Australia, along the Intertropical Convergence Zone and in the northern part of the tropical western Pacific region. The only suspicious signal is the very high positive correlations over the Asian and North American continents in the IR-data (Fig. 4(b)), which may be related to the IR-channel's inability to distinguish between brightness temperature variations due to variations in surface temperature and those due to variations in low cloud cover (K.-G. Karlsson, pers. comm.).

3. Possible mechanisms

In general, the following interpretations of the results presented in the Section 2 are possible: (1) There is no causal relationship between either TSI or GCR and low cloud cover, and the relatively high correlations between TSI and low cloud cover are purely coincidental. (2) There is a causal relationship acting through GCR and low clouds. The high correlation with TSI is an indirect consequence of the relation between solar irradiance and the interplanetary magnetic field. (3) There is a causal relationship between TSI and low clouds. The high correlation between GCR and low clouds between 1983 and 1993 is an indirect consequence of the relationship between GCR and TSI. (4) There is no causal relationship at all. The relatively high correlations are artifacts due to the way the ISCCP data are processed, resulting in a spurious solar signal. Below, we will discuss possibilities (1), (2) and (3). Possibility (4) may deserve further investigation, but will not be explored in any detail in this study.

With respect to (1) and (3), Haigh (1996, 1999) suggested, based on observational and modelling evidence, a slight modification of the atmospheric general circulation in response to the solar cycle. According to Haigh, at solar maximum the Hadley circulation at low latitudes becomes weaker and broader, especially in the summer hemisphere, leading to a poleward displacement of the subtropical highs. Since a large fraction of the Earth's low clouds are located over the subtropical oceans, this could potentially lead to changes in the amount of low clouds, large enough to explain the correlations; seen in Table 1 and Fig. 1. In Haigh's mechanism, the solar signal starts with ozone changes in the stratosphere and then propagates downwards from the stratosphere to the troposphere, e.g., through the action of large-scale atmospheric waves. If so, the near-surface temperature in the subtropics might be warmed up by a few tenths of a degree before SST has time to respond, explaining the 1–2 years lag found by White et al. (1997) between the; solar signal and the SST variations and the virtual absence of lag in Fig. 1. During this transition period, the static stability at the surface (i.e., the difference between the air temperature just above the surface and the surface temperature) would be enhanced and as a consequence the upward fluxes of moisture would be weakened. Since this flux is necessary to maintain the clouds, such a mechanism might explain a smaller subtropical cloud cover in connection with solar maximum than at solar minimum.

A relationship between solar irradiance variations and low cloud cover of the kind just described relies on the assumption of a high correlation between lower tropospheric static stability and low cloud amount, as demonstrated by Klein and Hartmann (1993) for stratus clouds. In order to find out how robust that relationship is we have repeated their analysis of analysing lower tropospheric static stability and low cloud cover, using the same definition of lower tropospheric static stability, i.e., the difference in potential temperature between air at 700 hPa (about 3 km height) and at 1000 hPa (near surface). While they used manual cloud cover observations published by Warren et al. (1988), we have used the ISCCP satellite data. Also, we have obtained the static stability from the 50-year reanalysis data set from the National Center for Environmental Prediction (NCEP), while Klein and Hartmann used surface data from the Comprehensive Ocean–Atmosphere Data Source (COADS) and upper air data from the European Centre for Medium Range Weather Forecasts (ECMWF). We have divided the analysis into five regions favouring low clouds, seen in Fig. 3. These are the same regions indicated by Warren's data. Fig. 5 shows the result of this analysis, including the correlation coefficients for the different geographical regions. It is seen that in four of the five regions there is a strong positive correlation between Daytime low cloud cover and static stability. Even higher correlations are obtained, in particular for the Australian region (not shown) if only the optically thicker clouds are used, termed stratus and stratocumulus (see Rossow and Schiffer, 1999 for details). Also, note the steep slope of this relationship (about 6% per degree), confirming Klein and Hartmann's result of a strong sensitivity of "stratus" cloud cover to variations in static stability. This large sensitivity is crucial, in order for the proposed mechanism

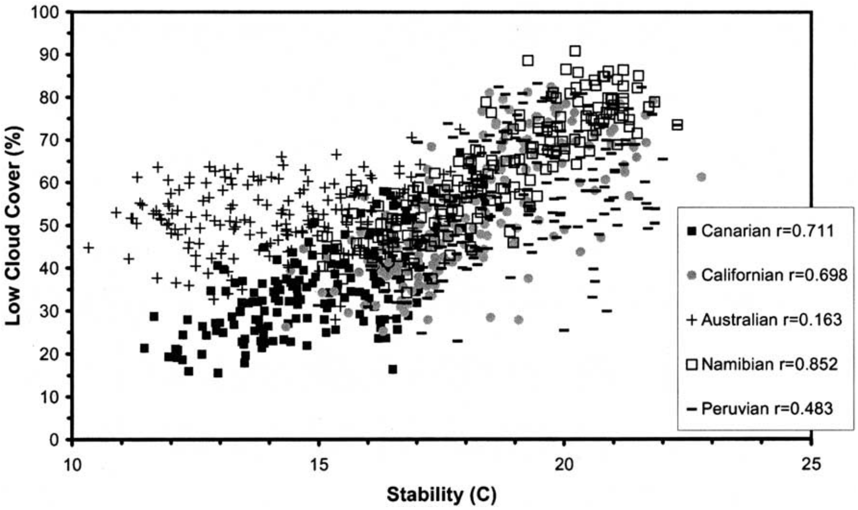

Fig. 5. A scatter plot showing the relation between lower tropospheric static stability as defined by Klein and Hartmann (1993) and ISCCP Daytime low cloud cover, over different oceanic regions.

of solar irradiance induced changes in low cloud cover to work.

In order to evaluate (2), i.e., the GCR-cloud hypothesis, it is important to consider possible mechanisms, in addition to the statistical analysis already presented. Model calculations by Yu and Turco (2001) suggested that the increase in tropospheric ionisation due to GCR from solar maximum to minimum was sufficient to yield a significant increase in the concentrations of nanoparticles. The authors suggested that in marine environments in particular, ionisation was a limiting factor to aerosol formation, assuming the presence of aerosol precursors (e.g., H_2SO_4 gas) in significant concentrations. It is important to point out here that cloud condensation nuclei (CCN) in the atmosphere are usually between 0.1 and 1 μm radius, and Yu and Turco's results (e.g., their Fig. 7) do not seem to yield any increase in the concentrations of such large particles from solar maximum to solar minimum. On the other hand, Turco et al. (2000) demonstrated a 4% increase in the stable aerosol population related to a 25% increase in ionisation. The relevance of this to CCN was not investigated. Those marine environments that are dominated by sea salt will probably be even less favourable to small CCN, since the large sea salt CCN will prevent the supersaturation from reaching levels required for the smaller CCN to become activated (e.g., Rosenfeld et al., 2002). Recently, Yu (2002) suggested that the changes in ionisation associated with the solar cycle would be of opposite sign in the upper and the lower troposphere. The relevance of this to cloud evolution hinges on the sensitivity of CCN to ultrafine aerosol formation as well as the increased collection efficiency of charged ice nuclei by supercooled water, suggested by Tinsley et al. (2000) and Tripathi and Harrison (2002).

As for possible implications for climate, it is important to keep in mind that there were no trends over the last 50 years in any of the most common indicators of solar activity such as sunspot number, GCR, the *aa* index, the IMF or the solar cycle length (e.g., Richardson et al., 2002; Thejll and Lassen, 2000; and inferred from figures in Lockwood, 2002). Hence, taking e.g., sunspot number as a proxy for solar irradiance, one may conclude that neither the coupling between solar irradiance and low clouds suggested by Kristjánsson et al. (2002) nor the coupling between cosmic rays and low clouds suggested by Marsh and Svensmark (2000) would have any impact on the global warming in this 50 year period. This does not mean that it is not important to explore these couplings, however, as they help us to understand the natural forced variability of the climate system.

4. Summary and conclusions

The purpose of this study was to investigate recent suggestions of couplings between solar activity and low cloud cover using the most updated data sources available. This was done mainly through an updated statistical analysis, but also by a consideration of some of the possible physical mechanisms. Broadly speaking, the analysis has confirmed a previous suggestion of a large negative correlation between globally averaged low cloud cover and total solar irradiance. However, we do not find this correlation to be statistically significant. The correlation between low cloud cover and galactic cosmic rays is much weaker than that for solar irradiance and low clouds, although detrending of the cloud cover data substantially increases the correlation. It was argued that spatial correlation patterns are more meaningful than correlations using globally averaged fields. An analysis of spatial correlations between TSI and low cloud cover revealed patterns over the Pacific Ocean similar to those previously found for SST and surface pressure. One possible interpretation, pursued here, is that it represents an interaction between a solar signal, as explained by Haigh (1996), and coupled atmosphere–ocean variability modes, as evidenced by, e.g., the PDO.

Spatial correlations of cloud cover onto its own global average support the notion that it is mainly the low clouds in the subtropics that are of interest for determining the global signal. This is a region where SST variations and cloud cover are inversely related (Hartmann and Michelson, 2002), which is consistent with the solar-low cloud mechanism suggested by Kristjánsson et al. (2002). Here, that hypothesis has been modified by noting that the displacement of the subtropical highs during solar maximum (relative to solar minimum) may affect low clouds directly through the atmospheric circulation, and that the SST will be slower to respond than the atmosphere. The underlying assumption of a strong sensitivity of low cloud cover to small changes in lower tropospheric static stability, suggested by Klein and Hartmann (1993) was confirmed here, using independent data.

The suggestion of a link between variations in solar irradiance and low cloud cover is of interest for the understanding of past climate variations, since it may indicate a reinforcement of the solar signal by the climate system, i.e., a positive feedback. However, we do not feel that it is of significance for the present global warming, since solar irradiance does not appear to have increased over the last 50 years. Likewise, such a mechanism would not explain the recent downward trend in low latitude cloud cover indicated by Chen et al. (2002) and Wielicki et al. (2002), for the same reason.

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