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A new look at possible connections between solar activity, clouds and climate

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[1] We present a re-evaluation of the hypothesis of a coupling between galactic cosmic rays, clouds and climate. We have used two independent estimates of low cloud cover from the International Satellite Cloud Climatology Project, covering 16.5 years of data. The cloud cover data are used in conjunction with estimates of galactic cosmic ray flux and measurements of solar irradiance. It is found that solar irradiance correlates better and more consistently with low cloud cover than cosmic ray flux does. The correlations are considerably lower when multichannel retrievals during daytime are used than retrievals using IR-channels only. Due to large autocorrelations, the statistical significance of the results is marginal. A mechanism is suggested whereby solar irradiance variations are amplified by interacting with sea surface temperature (SST), and subsequently low cloud cover. The feasibility of such a mechanism is supported by negative correlations between SSTs and low cloud cover in subtropical regions. *INDEX TERMS:* 1650 Global Change: Solar variability; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 2104 Interplanetary Physics: Cosmic rays. **Citation:** Kristjánsson, J. E., A. Staple, J. Kristiansen, and E. Kaas, A new look at possible connections between solar activity, clouds and climate, *Geophys. Res. Lett.*, *29*(23), 2107, 10.1029/2002GL015646, 2002.

1. Introduction

[2] Variations in solar irradiance are recognized as a fundamental forcing factor in the climate system. For instance it is generally believed that the main cause of the Little Ice Age around the year 1700 was reduced solar irradiance [*Lean and Rind*, 1998; *Shindell et al.*, 2001]. It is estimated that since then solar irradiance has increased by about 0.3%–0.4% [*Lean and Rind*, 1998]. The solar irradiance also varies by about 0.1% over the 11-year solar cycle, which would appear to be too small to have an impact on climate. Nevertheless, persistent claims have been made of 11-year signals in various meteorological time series, e.g., sea surface temperature [*White et al.*, 1997] and cloudiness over North America [*Udelhofen and Cess*, 2001].

[3] The flux of galactic cosmic rays (GCR) varies inversely with the solar cycle. A few years ago *Svensmark and Friis-Christensen* [1997] suggested that GCR enhance cloud formation, explaining variations on the order of 3% in global total cloud cover over a solar cycle. Since clouds have a net cooling effect on climate, this would imply [*Svensmark*, 1998] that the estimated reduction of cosmic ray flux during the 20th century [*Marsh and Svensmark*, 2000] might have been responsible for much of the observed warming. As pointed out by *Kristjánsson and Kristiansen* [2000], the correlation between global total cloud cover and cosmic rays disappeared after 1989, or so, using the International Satellite Cloud Climatology Project (ISCCP) data set. In fact, if this analysis is extended to 1999 (not shown), the correlation is negative. Recently, *Marsh and Svensmark* [2000] demonstrated a high correlation between GCR and low clouds, based on infrared (IR) measurements in the ISCCP data set. Low clouds have a particularly strong cooling effect, which is consistent with *Svensmark*'s [1998] hypothesis.

[4] The purpose of this paper is to re-evaluate the statistical relationship between low cloud cover and solar activity adding 6 years of ISCCP data that were recently released.

2. An Update of the ISCCP Cloud Cover Data

[5] The ISCCP was aimed at providing an accurate and comprehensive data set of the earth's cloud cover and other cloud parameters (optical depth, water content, liquid/ice phase, particle size), with full global coverage [*Rossow and Schiffer*, 1999]. The ISCCP data have been processed in several steps. After making several improvements to the retrieval algorithms [*Rossow and Schiffer*, 1999], the D-series data set was initially released in 1999. The period 1983–1993 was covered, but recently the years 1994–1999 were added.

[6] Various algorithms have been designed to obtain the vertical partitioning of the cloud cover. One of them uses IR instruments only. This offers full temporal coverage, but the errors are likely to be significant, e.g., due to the inability of IR instruments to distinguish a low cloud from an underlying surface having the same temperature. Also, thin cirrus clouds may go undetected or be spuriously classified as low clouds [*Rossow and Schiffer*, 1999]. In another version, daytime observations from visible (VIS), near-infrared (NIR) and IR channels have been combined to yield 9 classes of clouds, determined by height and optical thickness. Adding up these 9 classes gives a global cloud cover, which deviates from total cloud cover by less than 1% (not shown), while the corresponding deviation using the IR-data is 5–6%.

[7] In the daytime data set we had to correct the low and high cloud cover data for a contamination of the visible

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Table 1. Correlation Coefficients Between Solar-Related Parameters and Different Estimates of Low Cloud Cover for the Period July 1983–December 1999 From ISCCP

Data handling	GCR vs. IR-Low	GCR vs. Daytime Low	Solar vs. IR-Low	Solar vs. Daytime Low	Sunspots vs. IR-Low	Sunspots vs. Daytime Low
Raw	0.209	0.117	*−0.365*	−0.325	−0.299	−0.178
No ann. cycle	0.308	0.124	−**0.571**	−0.405	−0.436	−0.238
Low Pass	0.399	0.190	−**0.741**	−0.537	−0.541	−0.323
High Pass	*−0.147*	−0.204	0.027	0.015	0.036	0.094
Annual mean	0.456	0.175	*−0.800*	*−0.608*	−0.619	−0.345

All cloud data are global averages. For cosmic rays the stations Huancayo/Hawaii have been used. In the second row, the annual cycle was removed from the cloud cover data by subtracting the long term average of the actual month. Low and High pass filtered data are obtained using Fourier analysis with a separation at $T = 1$ year. Annual means were computed for the calendar years 1984–1999. Correlations significant at the 95% level are given in bold and those significant at the 90% level in italics, based on the method of *Ebisuzaki* [1997]. No lag is assumed in the analysis.

channel by Pinatubo aerosol [Figure 7, *Rossow and Schiffer*, 1999], as follows: First, measurements of aerosol optical depth from the Pinatubo eruption, given by *Jäger et al.* [1995], were used to define the shape of the correction curve. This implies a rapidly increasing correction from June 1991 to a maximum in October 1991, and then gradually decreasing, until it becomes zero in the spring of 1993. The amplitude of the correction was determined by comparison with Figure 7 in *Rossow and Schiffer* [1999]. The correction function (positive values) was then subtracted from the daytime low cloud cover data and added to the daytime high cloud cover data. The correction was constrained not to cause jumps in the daytime low or high cloud cover data sets.

3. Solar Irradiance, Cosmic Rays and Cloud Cover

[8] The correlation coefficients between the solar-related and the cloud cover data sets are given in Table 1. The Huancayo/Hawaii site is assumed to be representative of variations in GCR flux globally [*Marsh and Svensmark*, 2000]. Looking first at GCR and IR-low cloud cover (Figure 1a) we see that the two are very well correlated between 1983 and 1993. Interestingly, however, the correlation is much poorer after 1993, as the cosmic ray flux continues to increase and then flatten out in 1997–1998, while the IR-low cloud cover gradually decreases after 1993, apart from extremely low values in late 1998, probably associated with high global SSTs following the 1997–98 El Niño. Figure 1b displays results for the daytime low cloud cover. We immediately notice that this quantity has a much poorer correlation with cosmic rays than the IR-low cloud cover does. They both peak in 1986–1987, and then fall off, but the two have markedly different evolutions between 1989 and 1996.

[9] According to the mechanism suggested by *Marsh and Svensmark* [2000] to explain the positive correlation between GCR and low cloud cover, there should be no lags on monthly time scales between the GCR and cloud cover, but rather an almost immediate response of cloud cover to rapid variations in GCR. We have therefore calculated high pass filtered data permitting only oscillations faster than 1 year, and looked for correlations or co-varying features in these data. Surprisingly, there seems to be a negative correlation between GCR and cloud cover on these time scales (Table 1). If correct, this would contradict the Svensmark hypothesis, while at the same time suggesting a link between GCR and clouds on 1–12 month time scales. Only further investigations of high frequency data can resolve this controversy.

[10] By comparison, consider now the variations in solar irradiance at the top of the atmosphere during 1983–1999 in

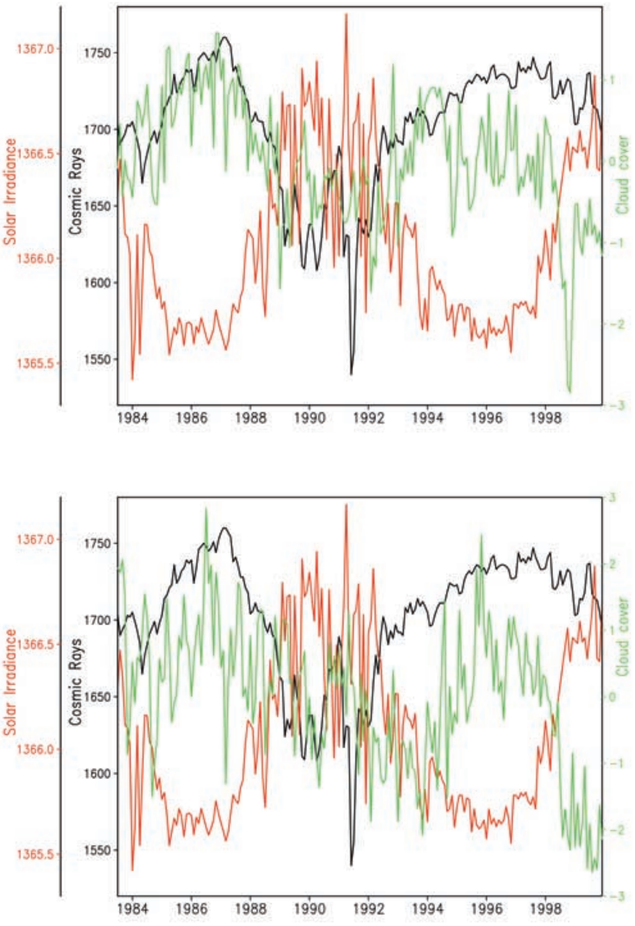

Figure 1. Temporal variations from 1983–1999, after removal of annual cycle in cloud cover data. (a) Black curve: Galactic Cosmic Ray Flux; Red curve: Solar Irradiance; Green curve: IR-Low Cloud Cover. Significance level of correlations: 67% for cosmic rays and low clouds, 98% for solar irradiance and low clouds. (b) Black curve: Galactic Cosmic Ray Flux; Red curve: Solar Irradiance; Green curve: Daytime Low Cloud Cover. Significance level of correlations: 30% for cosmic rays and low clouds, 90% for solar irradiance and low clouds.

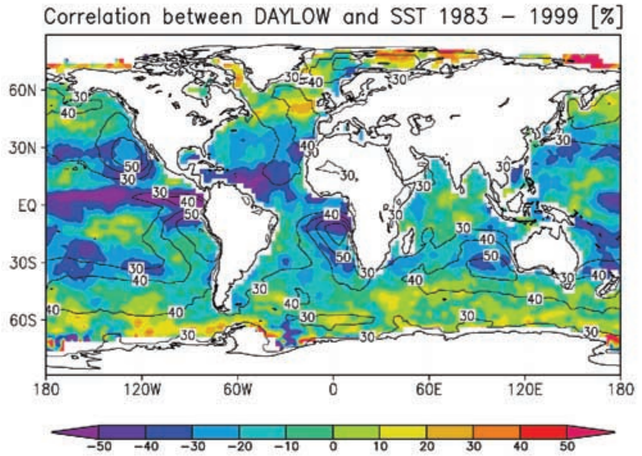

Figure 2. Shading displays percentwise correlation between Daytime Low Cloud Cover and Sea Surface Temperature, while isolines are Daytime Low Cloud Cover (percent).

Figures 1a and 1b. Apart from the sign, it is seen that solar irradiance correlates well with low cloud cover (Table 1). These high correlations persist over the whole period of study, and it is worthwhile to consider possible causal mechanisms. As expected if there were a causal relationship, lagged correlations between solar activity and low clouds (annual cycle removed) reveal a maximum correlation between solar irradiance and low clouds when the former leads the latter by 1 month for the IR data (r = −0.591) and 4 months for the daytime low clouds (r = −0.454). In the case of cosmic rays, the correlation with IR cloud cover is highest (r = 0.344) when the cloud signal leads the cosmic ray signal by 2 months (not shown), while the correlation with daytime low clouds is highest when there is a 6 month lag (r = 0.200).

[11] A physical mechanism connecting solar irradiance and low clouds might contain the following components: (1) Over the solar cycle the flux of ultraviolet (UV) radiation varies by several %, and even more so in the short wavelength component of the UV. This affects the propagation of planetary waves from the troposphere to the stratosphere, which in turn affects weather patterns in the troposphere [*Haigh*, 1996], including the strength and location of the summertime subtropical highs. Since the subtropical oceans are favoured regions for low clouds (Figure 2), especially in summer, such changes in weather patterns may conceivably affect low cloud cover in the manner seen in Figure 1. (2) *White et al.* [1997] showed that there is a significant solar signal in multi-decadal time series of SST over the world oceans. The amplitude of the solar signal can be as much as 0.3°C for some solar cycles. One may relate this to the findings by *Klein and Hartmann* [1993] of a large sensitivity of marine stratus cloud amount to lower tropospheric static stability, defined as the difference in potential temperature between 700 hPa and the surface. According to their results, a 1°C increase in static stability would correspond to a 6% increase in cloud cover. This means that an increase of SST by 0.3°C, assuming no other change in tropospheric temperature, would lead to a 2% decrease in low cloud cover, which is very close to the observed amplitude in Figures 1a and 1b. We have tested this hypothesis by correlating the ISCCP low cloud cover with SST data for the same period. As Figure 2 shows, there is generally a negative correlation between the two quantities, in particular in the subtropical stratocumulus regions. This result lends support to the kind of mechanism we propose. One may hypothesize a positive feedback between a weak, positive solar irradiance anomaly a slight warming of the ocean surface, a slight reduction in low cloud cover, and consequently a further increase in solar input to the surface, etc.

4. On Autocorrelations and Statistical Significance

[12] An obvious problem with the use of the ISCCP data for evaluating solar connections is that the time series are short. Since the ISCCP data and the cosmic ray data we use both have a 1-month resolution, the number of data points for the period July 1983–December 1999, that we consider, is 198. However, these 198 data points are not statistically independent, and the effective number of data points is therefore considerably smaller than this figure, reducing the statistical significance of the correlations. A comprehensive treatment of this problem was given by *Quenouille* [1952], who derived the following formula for the number of independent data points in a time series:

$$n_{eff} = \frac{n}{1 + 2r_1r'_1 + 2r_2r'_2 + \ldots\ldots + 2r_nr'_n} \qquad (1)$$

where n is the actual sample size, n_{eff} is the effective sample size, r_1 is the lag-1 ("lag one") autocorrelation of the one data series (e.g., cloud cover) and r'_1 is the lag-1 autocorrelation of the other data series (e.g., cosmic rays or solar irradiance), r_2 and r'_2 are the corresponding lag-2 autocorrelations of the two time series, etc. Using this formula, we find the effective number of data points to be between 10 and 30 for the raw data and between 4 and 13 after removal of the annual cycle, the lowest values being found for the IR-data. Hence, the statistical significance is much lower than a naive interpretation of the correlations in Table 1 might suggest. In Table 1 we indicate the statistical significance obtained using the non-parametric method of *Ebisuzaki* [1997].

5. Summary and Conclusions

[13] We have presented a re-evaluation of the hypothesis of possible links between solar activity and low clouds. Due to a falling correlation between IR-low cloud cover and cosmic rays after 1993, we conclude that even though the two series are rather well correlated, the statistical significance is low. For the more reliable daytime low cloud cover data, the correlations are significantly lower than for the IR-data. Furthermore, we find a negative correlation between high pass filtered cloud cover data and cosmic rays. We conclude that this new analysis significantly weakens the evidence for the cosmic ray-cloud coupling suggested by *Svensmark* [1998].

[14] Another major conclusion from this study is that low clouds appear to be significantly inversely correlated with solar irradiance. We have presented a possible mechanism for a link between solar irradiance and low clouds. The

mechanism acts through UV in the stratosphere affecting tropospheric planetary waves and hence the subtropical highs, modulated by an interaction between sea surface temperature and lower tropospheric static stability. The mechanism relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics.

[15] **Acknowledgments.** The ISCCP cloud cover data were obtained via the NASA GISS ftp-server. The GCR data were obtained from NOAA's NGDC web site. The solar irradiance data are unpublished data from the VIRGO Experiment on the cooperative ESA/NASA Mission SoHO, obtained from PMOD/WRC, Davos, Switzerland (version 19). The SST data are from the GISST data set, obtained from the UK MetOffice web site. The authors have benefited from stimulating discussions with Karl-Göran Karlsson, Peter Laut, Claudia Stubenrauch, Tom Wigley, Rasmus Benestad and Petra Udelhofen. Aaron Staple's stay at the University of Oslo was supported by IAESTE.

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