2003

Reply to Comment by N. D. Marsh and H. Svensmark On "Solar Influences On Cosmic Rays and Cloud Formation: a Reassessment"

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Received 22 December 2003; revised 16 April 2004; accepted 22 April 2004; published 28 July 2004.

INDEX TERMS: 1620 Global Change: Climate dynamics (3309); 1610 Global Change: Atmosphere (0315, 0325); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620);
KEYWORDS: reply, cosmic ray, cloud formation

Citation: Sun, B., and R. S. Bradley (2004), Reply to comment by N. D. Marsh and H. Svensmark on ''Solar influences on cosmic rays and cloud formation: A reassessment,'' *J. Geophys. Res.*, *109*, D14206, doi:10.1029/2003JD004479.

1. Introduction

[1] *Svensmark and Friis-Christensen* [1997] (hereinafter referred to as SFC97) proposed a "galactic cosmic ray (GCR), clouds, and climate" hypothesis that cosmic ray flux, modulated by solar activity, may modify global total cloud cover (TCC) and thus global surface temperature by changing the number of ions in the atmosphere and thus the cloud droplet formation. This GCR-TCC hypothesis has been questioned by many authors who examined correlations of GCR with various satellite cloud properties and over different time intervals. We note that the SFC97 hypothesis differs from the one proposed by *Marsh and Svensmark* [2000] (hereinafter referred to as MS00), who postulated that the GCR influence on cloudiness is restricted to low cloud cover (LCC).

[2] All the articles in this debate were based on satellite data and limited to the ocean. By contrast, *Sun and Bradley* [2002] (hereinafter SB02) combined short-period satellite data (from the International Satellite Cloud Climatology Project, ISCCP) with long-term visual total cloud observations to reassess the GCR-TCC relationship over the ocean and the land as well. The SB02 study was initialized in early 2000, focusing on the GCR-TCC hypothesis. In the early spring of 2001 we added to our revision several comments regarding the GCR-LCC hypothesis. We concluded in our analysis that there is no solid evidence for the existence of a GCR-cloud correlation (either total cloud or low cloud cover).

[3] *Marsh and Svensmark* [2004] (hereinafter referred to as MS04) raised five comments about our analysis and finally claimed that "On the basis of satellite observations, there continue to be strong indications of a globally distributed correlation between cosmic rays and low-cloud cover." We will demonstrate in this reply that their comments are either unfounded or illogical. All of their comments are dealt with in section 2, but issues relevant to the GCR-LCC hypothesis will be separately addressed in section 3. New evidence will be present in section 3 to indicate that the quality of the ISCCP infrared (IR) LCC data set, which MS00 and *Marsh and Svensmark* [2003] (hereinafter referred to as MS03) used to create the GCR-LCC hypothesis, is highly questionable. This reply confirms the view we expressed on the work of SB02 that there is no solid GCR-cloud relationship.

0148-0227/04/2003JD004479

2. Replies

[4] 1. As demonstrated by SB02, both ISCCP C2 and D2 TCC data sets match very well seasonally and interannually with surface cloud measurements made by human observers over the major countries of the Northern Hemisphere where high-quality long-term data are available. SB02 indicated that there is no GCR-TCC correlation over those countries. We averaged ISCCP TCC from global land grids, and no correlation was found between GCR and global land TCC either. *Kristjánsson and Kristiansen* [2000] pointed out that the correlation between GCR and global TCC disappeared after 1989 or so, and "if this analysis is extended to 1999 (not shown), the correlation is negative" [*Kristjánsson et al.*, 2002, p. 1].

[5] 2. SB02 noticed that the best GCR-TCC correlation for 1983–1991 in global total cloud cover (TCC) occurs over the Atlantic but that correlation breaks down after 1991 (see Figures 4 and 8 of SB02). Also, the high Atlantic correlation found by SB02 arises most probably from the suspicious satellite data, which will be discussed in section 2.4.

[6] 3. *Yu and Turco* [2000, 2001] proposed that under certain atmospheric conditions changes in GCR ionization rate can cause a variation in concentrations of ultrafine particle and condensation nuclei (CN). It remains unclear, however, if a notable change in CN can significantly affect the population of cloud condensation nuclei (CCN) and cloud properties. In fact, as *Yu and Turco* [2001] suggested, a wide range of uncertain and variable parameters can influence the growth of GCR-induced CN to CCN, including direct sources of CCN, cloud processing, and atmospheric temperature and humidity conditions. So far, there

has been no evidence showing that the contribution of GCR ion-mediated nucleation to CCN formation and cloudiness is detectable. Therefore, as stated by SB02, there is a lack of evidence for MS00 to claim that GCR is physically related to LCC. The use of ISCCP visible (VIS)/IR LCC, a more reliable LCC data set, will verify that LCC is not correlated to GCR (see section 3).

[7] 4. Because of short satellite measurements, independent long-term surface cloud data are needed to help understand the statistical GCR-cloud relationship as SB02 did over the land. SB02 did not find any correlation between GCR and long-term TCC over the North Atlantic where ship observations were dense spatially and temporally. An upward trend was found in the globally averaged ocean TCC time series (1953–1995), which is inconsistent with the SFC97 hypothesis (as GCR did not show any significant change). SB02 also noticed a discrepancy between ISCCP D2 and ship data in the satellite era. Presently, no evidence has been identified or documented for a change in observing practice responsible for the interdecadal change in ocean clouds [*Norris*, 2000]. However, the evident footprint of the Mesosat satellite surrounding the whole Atlantic basin demonstrated in the spatial correlation map of grid box time series with globally averaged ISCCP D2 TCC time series [*Norris*, 2000, Figure 1] showed a problem in the ISCCP TCC time series over the Atlantic. *Norris* [2000, p. 377] therefore cautioned that "the ISCCP time series presented in Figure 1 is probably spurious, and any resemblance to time series of other parameters (e.g., *Marsh and Svensmark*, 2000) is merely coincidental."

[8] 5. Low clouds can be obscured by higher level clouds in satellite observations. This problem was neglected in MS00 and corrected by MS02. However, MS02 (including MS00 too) employed the unreliable IR LCC data set in their correlation calculation, which makes the GCR-LCC hypothesis questionable.

3. On Reliability of ISCCP IR LCC and the GCR-LCC Hypothesis

[9] ISCCP D2 provides two types of cloud cover information: (1) low, middle, and high cloud covers obtained from IR-only channels and (2) cloud covers of nine individual cloud types measured from the combination of VIS and IR channels. These cloud types were given names of surface-observed cloud types in an attempt to relate them to the traditional classification of clouds. ISCCP low cloud types (below 680 hPa) are composed of cumulus (Cu), stratocumulus (Sc), and stratus (St). As suggested by *Rossow and Schiffer* [1999], significant errors are likely to be present in the ISCCP IR cloud data, as the satellite IR channels are not able to distinguish low clouds from underlying surfaces which have the similar temperatures. Also, thin cirrus clouds may be undetected or spuriously classified as low clouds.

[10] A simple way to validate the quality of two types of ISCCP LCC data is to compare them with the independent surface cloud observations as SB02 did for TCC. Unfortunately, accurate surface cloud data on the global scale are not available. We restrict the comparison to the United States where surface LCC is derived from cloud sky condition and cloud base height information collected in the national data archive [*Sun and Groisman*, 2004].

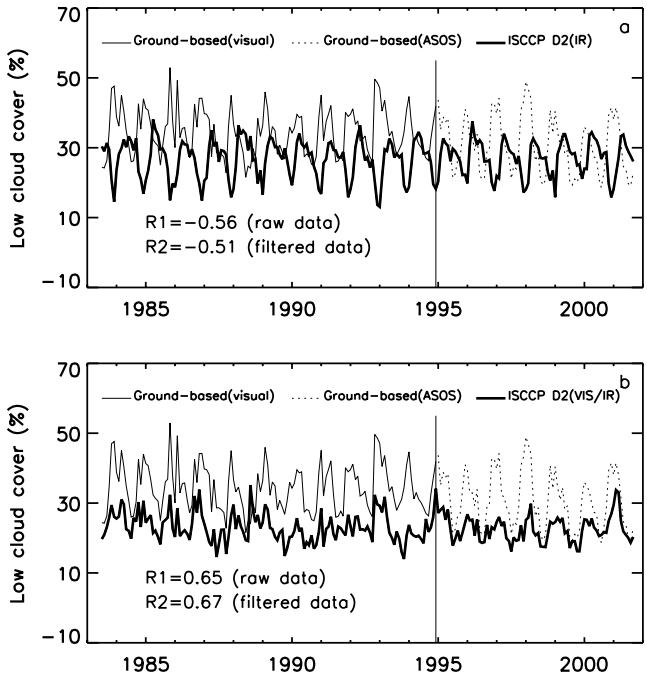

Figure 1. (a) Daytime low cloud cover time series over the contiguous United States. The thin solid curve represents the surface visual observations and the thin dashed curve represents the ASOS observations. The thick solid curve denotes ISCCP IR LCC. The vertical line at the end of 1994 denotes the time after which the ASOS system has become the major nationwide provider of cloud observations. R1 represents the correlation between visual and satellite cloud data sets, and R2 represents the correlation after the removal of seasonal cycles. (b) Same as Figure 1a except for thick solid curve, which stands for ISCCP VIS/IR LCC_{sfc}. (See text for the definition.)

[11] Surface low cloud types are those whose base heights are below 2 km. They include St, Sc, Cu, bad weather St/Cu, cumulonimbus (Cb), and nimbostratus (Ns). To match this "definition" of surface low clouds, we added together amounts of St, Sc, Cu, Cb, and Ns from the ISCCP VIS/IR data set. This "surface-based" VIS/IR LCC is defined as VIS/IR LCC_{sfc} in Figure 1, to distinguish it from the ISCCP-defined VIS/IR LCC which is calculated from amounts of St, Sc, and Cu and is used in all other comparisons and correlations in the article.

[12] Figures 1a and 1b show the daytime comparison of ISCCP IR LCC and VIS/IR LCC_{sfc} with surface data, respectively. In the United States, starting in September 1992, the Automatic Surface Observing System (ASOS) has gradually replaced human observers and has become the major nationwide provider of cloud observations after 1995 (denoted by vertical thin solid line). Compared to visual LCC, there is a systematic underestimation in ASOS LCC because some scattered clouds are misrepresented by the ASOS laser beam ceilometers as clear skies [*Sun and Groisman*, 2004].

[13] Except for the systemic difference arising primarily from the "top down" versus "bottom up" view, the VIS/IR

Table 1. Correlations of Globally Averaged ISCCP VIS/IR and IR Low Cloud Covers With GCR[a]

	July 1983 to Aug. 1994		July 1983 to Dec. 1997	
VIS/IR				
Sc + St	0.12	*0.11*	0.19	*0.16*
Cu	−0.08	*0.07*	−0.40	*−0.31*
LCC	−0.05	*0.11*	−0.25	*−0.15*
IR				
LCC	0.63	*0.65*	0.35	*0.27*

[a]The correlations and their significance are estimated using the Spearman rank correlation method. The numbers in italics are correlation coefficients calculated from the time series after excluding the Mount Pinatubo event (July 1991 to March 1993). The correlations are calculated from the monthly time series after the removal of the seasonal cycle. The GCR measurements were made in Climax, Colorado.

LCC_{sfc} data match well with the surface data on interannual timescales. However, the IR LCC variations basically are out of phase with the surface LCC variations. We also calculated the correlation of surface visual LCC with VIS/IR LCC. This correlation coefficient is 0.46 (after the seasonal cycle removed), in contrast to −0.51 for the surface visual LCC and IR LCC correlation. These comparisons lead us to believe that the ISCCP IR LCC data set should be considered as unreliable and the high GCR-IR LCC correlation in 1983–1994 shown by MS00 and MS02 is most probably spurious.

[14] Temporal variations in convective and stratiform cloud amounts generally are not on the same phase. The GCR signal, if existing, might be more clearly seen in one of the components of low clouds. Next we therefore also calculate correlations of GCR with stratiform and cumulus cloud covers in addition to VIS/IR LCC. All the correlations are calculated using the whole ISCCP data set (up to 1997) and the data set with the exclusion of the Mount Pinatubo eruption event (July 1991 to March 1993). The use of the latter data set is to eliminate the possible volcanic aerosol contamination on ISCCP satellite retrieval of optically thin clouds including Cu over the ocean [*Rossow and Schiffer*, 1999; *Luo et al.*, 2002].

[15] The reason we use the ISCCP data set up to the end of 1997 is because the data after 1998 could be affected by the use of wrong snow information in the retrieval (according to NASA Langley Atmospheric Sciences Data Center), although no significant influence is thought to have occurred over the United States (Figure 1b). MS02 noticed that the GCR-IR LCC correlation becomes weaker if the data period extends from 1983–1994 to 1983–2001. They attribute this to the problem in satellite intercalibration in 1994–1995, though it has not been well documented. We also calculate the correlation for July 1983 to August 1994, during which period the cloud data are supposed to be free of problems.

[16] Table 1 shows all the correlations discussed in this section. The correlations are calculated using the Spearman rank correlation technique, a nonparametric method. The effective number of degrees of freedom calculated using the method of *Quenouille* [1952] is considered in the estimation of the significance of the correlation. Except the marginally significant correlation shown in globally averaged IR LCC in July 1983 to August 1994, no meaningful relationship is found in any other scenarios including all globally averaged VIS/IR low-cloud cases. *Kristjánsson et al.* [2002] drew a similar conclusion on the GCR-VIS/IR LCC correlation.

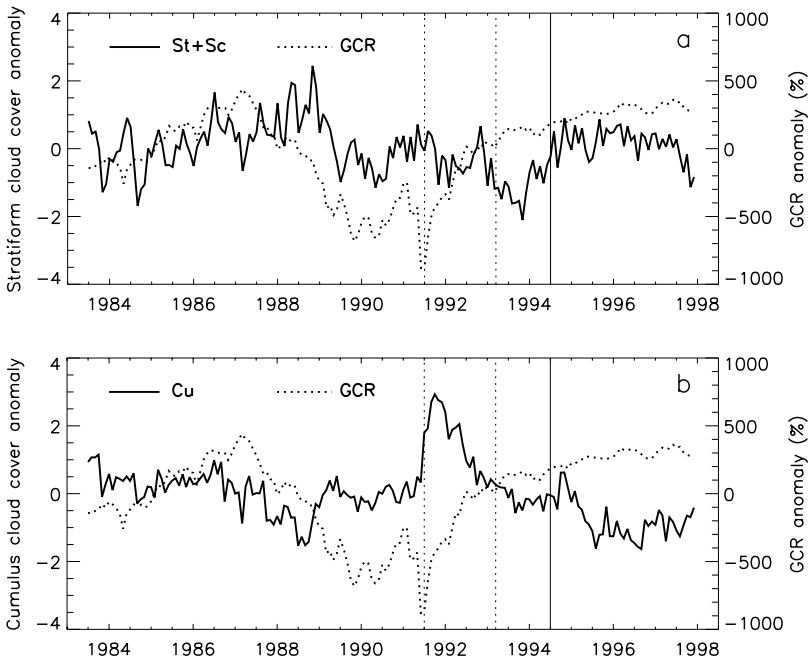

Figure 2. (a) Monthly anomaly time series of globally averaged ISCCP VIS/IR stratiform cloud cover (percent) against GCR. The interval between the two dashed lines denotes the Mount Pinatubo eruption event. The solid line positioned at August 1994 indicates the time around which an ISCCP intercalibration problem might occur [*Marsh and Svensmark*, 2003]. (b) Same as Figure 2a except for ISCCP VIS/IR cumulus cloud cover (percent) against GCR.

After removing the possible volcanic aerosol effect based on the relationships between aerosol optical thickness and thin cloud type amounts, they calculated the GCR-VIS/IR LCC correlation (1983–1999) and found it considerably lower than GCR-IR LCC and statistically insignificant. These results suggest that MS04's claim that globally averaged ISCCP IR LCC is well correlated to VIS/IR LCC is invalid.

[17] The readers are referred to *Kristjánsson et al.* [2002, Figure 1] for the contrast of globally averaged VIS/IR versus IR LCC time series. Here we present the time series of globally averaged stratiform (Sc plus St) and Cu cloud cover time series against GCR (Figures 2a and 2b) to visually illustrate their insignificant correlations. The time interval between two dashed lines in Figures 2a and 2b represents the Pinatubo eruption event. As shown by *Rossow and Schiffer* [1999, Figure 7], Figure 2 suggests that the volcanic aerosol effect, if it exists, mainly affects thin Cu and cirrus detection. We do not notice a significant discontinuity in stratiform cloud cover around 1994–1995. There is a decrease in Cu (by ~1% in absolute value) in late 1994, but changes with a similar magnitude are also found in 1987–1989. We therefore think the 1994–1995 intercalibration problem that MS02 claimed from the IR data needs further investigation. Nevertheless, the difference between low-cloud type and GCR variations is well demonstrated in their temporal evolutions. Both GCR and stratiform cloud cover increase from 1983. However, GCR reaches its 11-year cycle peak around the end of 1986, while stratiform cloud cover peaks around the end of 1988; GCR shows an overall increase after 1990–1991, while the latter remains relatively stable after 1991. In contrast to the changes in GCR, Cu remains quite stable from 1983 up to the Pinatubo eruption in July 1991; the decrease in Cu after late 1994 is also inconsistent with the gradual increase in GCR. We note that the GCR-VIS/IR low-cloud inconsistency is found not only on low-frequency timescales (as we described in this paragraph) but also on monthly timescales [*Kristjánsson et al.*, 2002].

4. Summary

[18] Using long-term surface visual cloud observations, SB02 indicated that no GCR-TCC correlation was found over major countries of the Northern Hemisphere and over the ocean. Considering the global GCR-ISCCP TCC correlation map, a high correlation occurs primarily over the Atlantic, but it breaks down after 1993. However, this high Atlantic correlation could be an artifact owing to a possible satellite intercalibration problem [*Norris*, 2000]. Comparison of ISCCP LCC with surface cloud observations indicates that the IR LCC data set is unreliable, making the GCR-LCC hypothesis proposed by MS00 and MS02 and summarized by MS04 highly questionable. Correlations of GCR with global VIS/IR LCC and its subsets (stratiform and Cu cloud covers), which we believe are more reliable ISCCP cloud data sets, did not reveal the existence of GCR-LCC correlation. This reply thus further confirms our earlier conclusion that there is a lack of evidence to support the GCR-cloud hypothesis.

[19] **Acknowledgments.** Thoughtful comments from an anonymous reviewer are acknowledged. The galactic cosmic ray intensity data set was downloaded from the University of New Hampshire, and the ISCCP data were downloaded from the NASA Langley Atmosphere Sciences Data Center. Our original work on this topic was supported by grants from NSF (Climate Dynamics) and the Department of Energy.

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