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Solar influences on cosmic rays and cloud formation: A reassessment

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[1] *Svensmark and Friis-Christensen* [1997] proposed a "cosmic ray-cloud cover" hypothesis that cosmic ray flux, modulated by solar activity, may modify global cloud cover and thus global surface temperature by increasing the number of ions in the atmosphere, leading to enhanced condensation of water vapor and cloud droplet formation. We evaluate this idea by extending their period of study and examining long-term surface-based cloud data (from national weather services and the Global Telecommunication System) as well as newer satellite data (International Satellite Cloud Climatology Project (ISCCP) D2, 1983–1993). No meaningful relationship is found between cosmic ray intensity and cloud cover over tropical and extratropical land areas back to the 1950s. The high cosmic ray-cloud cover correlation in the period 1983–1991 over the Atlantic Ocean, the only large ocean area over which the correlation is statistically significant, is greatly weakened when the extended satellite data set (1983–1993) is used. Cloud cover data from ship observations over the North Atlantic, where measurements are denser, did not show any relationship with solar activity over the period 1953–1995, though a large discrepancy exists between ISCCP D2 data and surface marine observations. Our analysis also suggests that there is not a solid relationship between cosmic ray flux and low cloudiness as proposed by *Marsh and Svensmark* [2000]. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 1650 Global Change: Solar variability; 1610 Global Change: Atmosphere (0315, 0325); 1704 History of Geophysics: Atmospheric sciences; *KEYWORDS:* global climate, greenhouse gas, anthropogenic, solar irradiance, cloud

1. Introduction

[2] The pronounced increase in global temperatures over the last century has given rise to concerns over the relative importance of "natural" forcing factors as compared to anthropogenic influences resulting from the buildup of greenhouse gases in the atmosphere. Although there is evidence that anthropogenic effects now have a discernible effect on global climate [*Santer et al.*, 1996], some are concerned that there has been a "rush to judgment" on this issue and that other potentially important factors have been overlooked or ignored [e.g., *Calder*, 1997]. A recurrent theme in such criticisms is that the effects of solar activity have been underestimated. In particular, it has been proposed that solar irradiance variations affect changes in global cloudiness and that these changes play a major role in modulating global temperature [*Svensmark and Friis-Christensen*, 1997].

[3] *Svensmark and Friis-Christensen* [1997] argued that changes in solar irradiance modulate the cosmic ray flux to the atmosphere (periods of high irradiance corresponding to low cosmic ray flux and vice versa). Although the mechanism is not entirely clear, they suggested that cosmic rays increase the number of ions in the atmosphere and thus lead to enhanced condensation of water vapor and cloud droplet formation. Figure 1 shows the relationship between large-scale cloud cover (from International Satellite Cloud Climatology Project (ISCCP) C2 monthly data) and cosmic ray intensity (as recorded at Climax, Colorado) during the late 1980s as reported by *Svensmark and Friis-Christensen* [1997]. Figure 2 shows a composite of various cloud data sets and cosmic ray data over a slightly longer period. Figures 1 and 2 show a statistically significant positive relationship (<0.01 level) that warrants further examination.

[4] *Svensmark and Friis-Christensen* [1997] used C2 ocean cloud data (60°N–60°S) for the period 1983–1991 from the ISCCP. They did not use C2 land data because they claimed that [*Svensmark and Friis-Christensen*, 1997, p. 1225] "cloud cover over sea behaves markedly differently from the cloud cover over land," perhaps an artifact of the satellite-derived data. Thus their cosmic ray flux-cloud cover hypothesis is based only on cloud cover data over ocean areas. Their hypothesis has been questioned by several people. *Kuang et al.* [1998] checked the variations of cloud optical thickness and their relationship with cosmic ray flux intensity and El Niño–Southern Oscillation (ENSO) activity over the period 1983–1991. Given the short duration of the cloud data set, they concluded that it is

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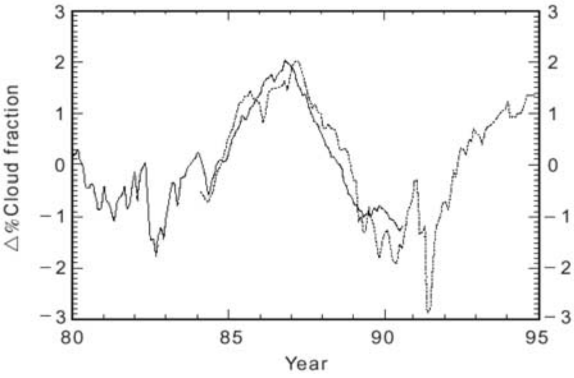

Figure 1. Twelve-month running averages of total cloud cover given as changes in percent (International Satellite Cloud Climatology Project (ISCCP) C2 data) (thick line). Data are from the area over the oceans covered by geostationary satellites. End points of the ISCCP C2 curve (first and last six points) have been discarded. The thin line is the normalized monthly mean counting rate of cosmic ray intensity from Climax, Colorado, drawn to the same scale. Normalized Climax data are representative of global variations in cosmic ray flux (reproduced from *Svensmark and Friis-Christensen* [1997]).

not clear if cloud variations are caused by the solar cycle or by the ENSO cycle. *Farrar* [2000], on the other hand, tended to believe that oceanic total cloud coverage variations are related to the ENSO cycle and do not require or support a cosmic ray flux influence. It has also been argued that no statistical relationships exist between cosmic ray flux and individual cloud types [*Kernthaler et al.*, 1999] or cloud radiative forcing at the top of the atmosphere [*Kristjánsson and Kristiansen*, 2000]. *Kristjánsson and Kristiansen* [2000] also showed that there is a large discrepancy between Defense Meteorological Satellite Program (DMSP) and ISCCP cloud cover data and therefore it is not appropriate to use DMSP data as an extension of ISCCP. We note that ISCCP observations, which cover less than one solar cycle, are the major data set used in previous cosmic ray-cloud-climate studies, including all the studies mentioned above.

[5] In view of the controversial nature of the cosmic ray-cloud cover hypothesis and of the uncertainty and short time duration of satellite data [*Klein and Hartmann*, 1993; *Rossow et al.*, 1993], in this article, long-term surface-based cloud data are (1) checked and compared with improved ISCCP cloud data, the D2 version [*Doutriaux-Boucher and Sèze*, 1998; *Rossow and Schiffer*, 1999], to establish the correspondence between the two (and any limitations in these two data sets) and (2) compared with long-term (1953–1995) cosmic ray data to determine if the relationship observed by *Svensmark and Friis-Christensen* [1997] is sustained over a longer period over both land and ocean. Section 2 is a description of various cloud data sets used in this investigation and includes a comparison of ISCCP C2 and D2. Section 3 shows our results on the cosmic ray flux and thetotal cloud cover relationship for the land and the ocean, respectively. Section 4 discusses whether there is solid evidence to support the recent conclusions of *Marsh and Svensmark* [2000], who argued that the influence of galactic cosmic rays on clouds is limited to low-level cloudiness.

2. Data

[6] In this study, two sets of surface-based cloud data are used: (1) observations made by national weather services [*Groisman et al.*, 2000] and (2) observations made by national weather services (over land) and volunteer observing ships (over ocean) but transmitted by the Global Telecommunication System (GTS) [*Hahn and Warren*, 1999]. These surface-based cloud observations are available for many decades. Cloud characteristics in these two data sets are visual observations, including total and low-cloud amounts, and low, middle, and high cloud types. Cloud data of *Groisman et al.* [2000] were collected from ~1500 meteorological weather stations over northern land areas,

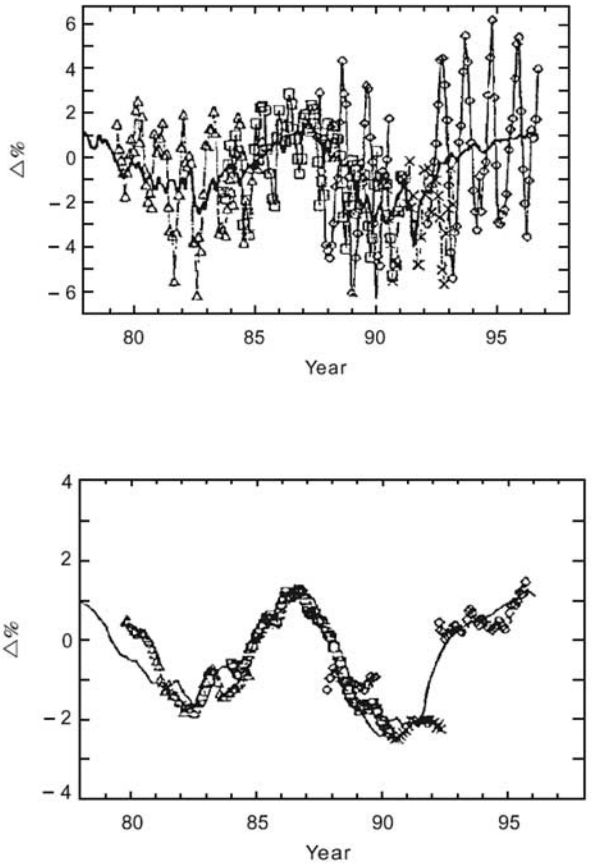

Figure 2. Normalized cosmic ray fluxes from Climax, Colorado (thick line), and four satellite cloud data sets: Nimbus 7 (triangles), ISCCP C2 (squares), DMSP (diamonds), and ISCCP D2 (crosses). (top) Monthly values illustrating the variability of the monthly cloud data sets. (bottom) Data smoothed by a 12-month running mean. Nimbus 7 and DMSP data are total cloud cover for the Southern Hemisphere oceans, and the ISCCP data have been derived from the geostationary satellites over oceans, with the tropics excluded (reproduced from *Svensmark and Friis-Christensen* [1997]).

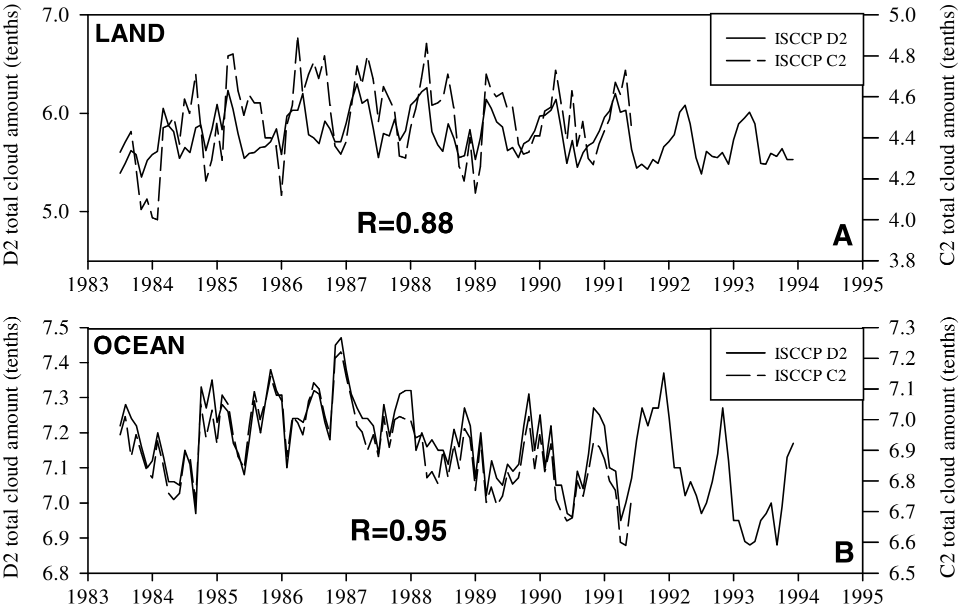

Figure 3. Monthly total cloud cover comparison between ISCCP C2 and D2 data sets over (a) land and (b) ocean. The correlation coefficient *R* between the two data sets is calculated, after the removal of the seasonal cycle, over the period July 1983 to June 1991.

with the main distribution of stations in middle latitudes. *Groisman et al.* [2000] data have hourly/3-hourly/6-hourly time resolution, and the data sets from major countries including the United States, the former USSR, and China are 40–50 years in length. *Hahn and Warren* [1999] cloud data over land span 26 years (1971–1996) with 3-hourly time resolution. In this data set, there are ~3615 stations over global land areas with at least 20-year records over the period 1971–1996. The practices used in processing *Hahn and Warren* [1999] land data (i.e., the GTS data) differ in several ways from those for *Groisman et al.* [2000] data (i.e., the national archive data). For example, cloud amount in the *Groisman et al.* [2000] data was measured in tenths, while it was recorded in octas in *Hahn and Warren* [1999] data (in this work, cloud amount in the *Hahn and Warren* [1999] data over both the land and the ocean was converted to tenths by multiplying by 1.25); cloud type in the *Groisman et al.* [2000] data over each country was reported following the particular reporting policy of that country, while cloud type in the *Hahn and Warren* [1999] data from almost all over the world was recorded using the *World Meteorological Organization* [1975] synoptic code. A detailed comparison between these two surface-based cloud data sets was made by *Sun et al.* [2001]. These two sets of surface-based cloud data passed necessary quality controls and have been widely used in climate studies [i.e., *Warren et al.*, 1986; *Henderson-Sellers*, 1992; *Kaiser*, 1998; *Dai et al.*, 1999; *Sun and Groisman*, 2000]. The *Hahn and Warren* [1999] ocean cloud data are available from 1952 to 1995. The ocean data used by *Hahn and Warren* [1999] are 3-hourly surface ship observations obtained from the Comprehensive Ocean-Atmosphere Data Set (COADS) [*Woodruff et al.*, 1987]. Cloud parameters in the *Hahn and Warren* [1999] ocean data were recorded using rules similar to those used with the *Hahn and Warren* [1999] land data. The ocean data used by *Hahn and Warren* [1999] are sparse over the Southern Hemisphere and over central areas of northern oceans but are relatively dense over coastal areas of the northern continents and middle latitudes of the North Atlantic. More information regarding the *Hahn and Warren* [1999] ocean data is also given by *Bajuk and Leovy* [1998] and *Norris* [1999].

[7] Two versions of the ISCCP cloud data, C2 and D2, are monthly averaged data based on measurements every 3 hours. Cloud cover was measured as the percentage of cloudy pixels (4–7-km horizontal resolution per pixel) on a 280-km grid. In order to be comparable with surface-observed land cloud cover, the satellite cloud cover percentage was divided by 10, thus making it equivalent to surface-measured cloud cover in tenths. The C2 data set, which *Svensmark and Friis-Christensen* [1997] used, has recently been replaced by the improved D2 data set [*Rossow and Schiffer*, 1999]. A major improvement in the D2 data set is the more accurate detection of cirrus clouds over land areas and of low clouds over snow-and ice-covered areas. The D2 data set was extended from June 1991 in the original C2 data set to December 1993 and thus includes one solar cycle. In this work, D2 instead of C2 data are therefore used to compare the surface-based cloud data.

[8] Because of the difference of the algorithm in retrieving C2 and D2 data sets, it is necessary to check whether the two data sets are comparable and whether the cosmic ray-cloud cover relationship which *Svensmark and Friis-Christensen* [1997] found from C2 data still exists in D2 data. Figure 3 shows the comparison of total cloud cover between the C2 and D2 data sets over the land and the ocean. It is seen from Figure 3 that total cloud cover over the global ocean in D2 (the left *y* axis) is slightly larger than that in C2 (the right *y* axis) (by 4% for the annual mean in the period July 1983 to June 1991) but total cloud cover in D2 over the land is higher than that in C2 by 22% for the annual mean (total cloud cover in D2 is 5.81 and in C2 is 4.49) and by 26% for the winter

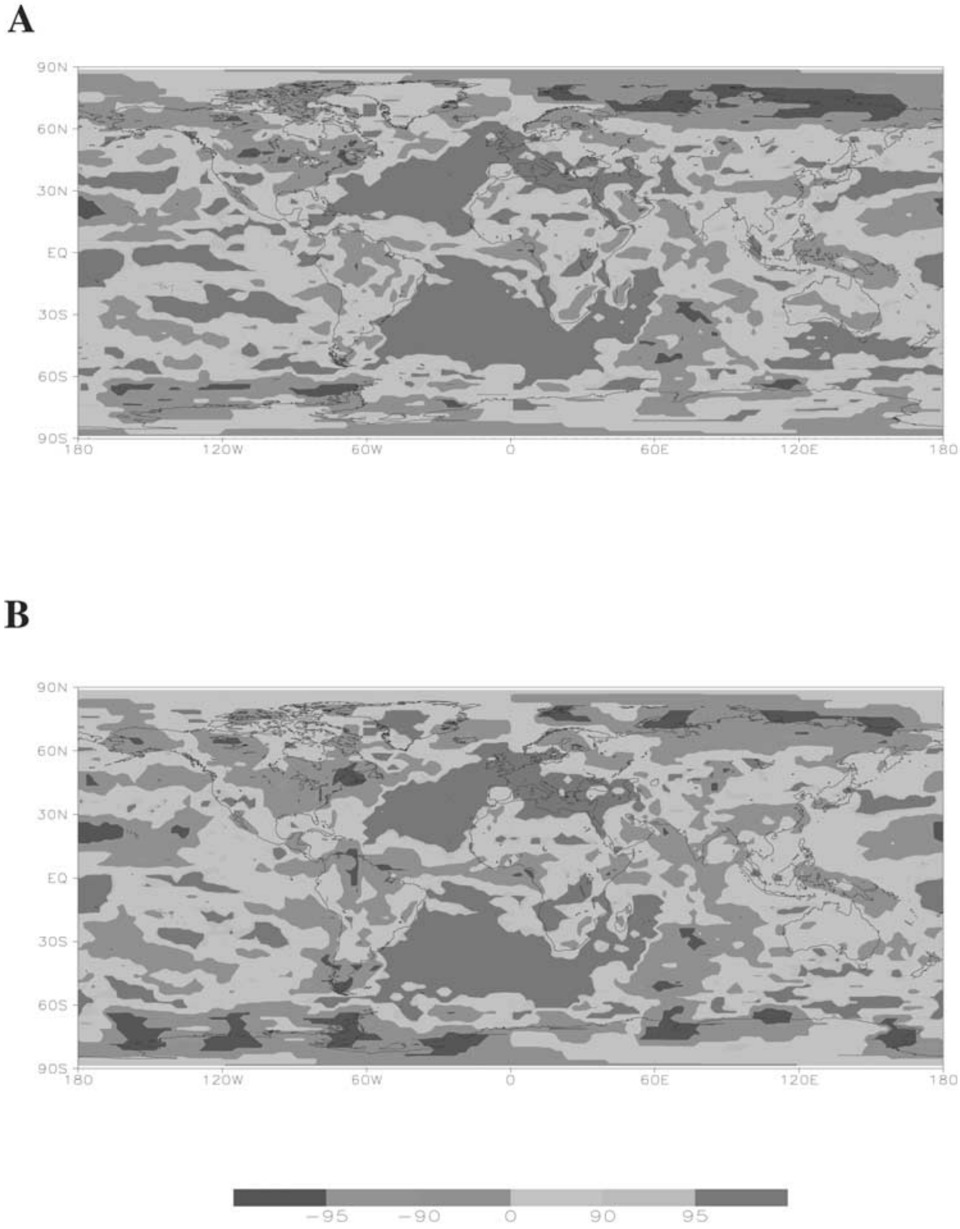

Figure 4. Correlation between monthly cosmic ray intensity recorded in Climax, Colorado, and total cloud cover (after removal of the seasonal cycle) from ISCCP (a) C2 and (b) D2 for the period July 1983 to June 1991. The magnitude of the value in the color scale denotes the significance level, and the sign of the value indicates whether the correlation is positive or negative. For example, red means that cloud cover and cosmic ray intensity is correlated at above the 0.05 significance level. See color version of this figure at back of this issue.

season (total cloud cover in D2 is 5.85 and in C2 is 4.34). The smaller seasonal variability in D2 land data may be primarily due to larger low and high cloud cover amounts at high latitudes in cold seasons as compared to those in C2 land data [*Doutriaux-Boucher and Sèze*, 1998]. In spite of the differences in total cloud cover and seasonal amplitude, Figure 3 indicates that the two data sets match well with each other on seasonal cycles. The correlation coefficient between them is 0.61 for the land and 0.94 for the ocean, and it is 0.88 for the land and 0.95 for the ocean after the removal of the seasonal cycle, suggesting that they are quite consistent with each other, particularly over the ocean.

[9] The spatial correlation of cosmic ray intensity with monthly cloud cover (after the removal of the seasonal cycle) from July 1983 to June 1991 is shown in Figure 4a for C2 data and in Figure 4b for D2 data. Cosmic ray flux intensity data recorded at Climax, Colorado, are similar to those measured elsewhere in the last 40–50 years [cf. *Svensmark and Friis-Christensen*, 1997] and are thus used in this study as being representative of global variations in cosmic ray flux. The significance level of the correlation which is shown in Figure 4 is estimated based on the Student-t test. Red denotes areas where cloud cover is positively and significantly correlated to cosmic ray intensity (above the 95% significance level) and

that therefore are statistically consistent with *Svensmark and Friis-Christensen*'s [1997] hypothesis. Figure 4a indicates that except over a small area surrounding the Mediterranean Sea, no meaningful relationship is exhibited over the land between cosmic ray intensity and C2 cloud cover. *Svensmark and Friis-Christensen* [1997] argued that this could be due to incorrect satellite measurements. Over the ocean, aside from several narrow belts over the central and eastern equatorial Pacific and the midlatitude Pacific (around 30°N and 30°S), the significant correlation appears mainly over the Atlantic Ocean of both hemispheres extending from 5° to 60° north and south. Therefore the cosmic ray-cloud cover relationship, which *Svensmark and Friis-Christensen* [1997] proposed, is largely due to the high correlation over the Atlantic. The D2 correlation map (Figure 4b) is very similar to that using C2 data. The positive correlation over the Atlantic and its eastern extension is also shown in D2 data, with a slight eastward shift of the area of significant correlation over the North Atlantic. We have no explanation for this large-scale correlation, but it has motivated the examination of the available data.

[10] Next we will use D2 data (rather than C2) to determine whether the surface-based *Groisman et al.* [2000] and *Hahn and Warren* [1999] cloud data are comparable with satellite data and to see if the cosmic ray-cloud cover correlation for 1983–1991 is also true for later periods. The longer surface-based cloud observations enable a test of the *Svensmark and Friis-Christensen* [1997] hypothesis to be made for earlier periods. Results are given for the land and the ocean separately. Detailed procedures of data processing are described in section 3.

3. Comparison of Time Series for Total Cloud Cover and Cosmic Ray Flux

3.1. Land

[11] Figure 5 shows a comparison of monthly cloud cover over the coincident time period (July 1983 to December 1993) for *Groisman et al.* [2000], *Hahn and Warren* [1999], and D2 data. This comparison is made over the contiguous United States, China (east of 110°E), and the former USSR (south of 60°N), where surface weather stations are homogeneously and densely distributed. The number of stations with temporally complete records over 1983–1993 is 180 for the *Groisman et al.* [2000] data and 132 for the *Hahn and Warren* [1999] data over the contiguous United States, 100 for the *Groisman et al.* [2000] data and 260 for the *Hahn and Warren* [1999] data over eastern China, and 155 for the *Groisman et al.* [2000] data and 810 for the *Hahn and Warren* [1999] data over the southern former USSR. In Figure 5 the monthly cloud cover data set from D2 (thick solid line) and from *Hahn and Warren* [1999] (dashed line) is constructed from 3-hourly measurements. It is also created from 3-hourly records for the *Groisman et al.* [2000] data (thin solid line) over the United States and the former USSR, but over China the data set from *Groisman et al.* [2000] is built from 4-hourly measurements. Cloud cover series in each country and each data set are calculated using an area-averaging program which accounts for the spatial inhomogeneity of station distribution [*Kagan*, 1997; *Sun et al.*, 2001]. Figure 5 indicates that the seasonal cycles of cloud cover match very well between the two surface-based data sets over all three regions under consideration. In spite of the difference in the number of stations participating in area averaging, the value of cloud cover is approximately the same in the *Groisman et al.* [2000] and *Hahn and Warren* [1999] data over the contiguous United States and eastern China. Over the southern former USSR the value of cloud cover in the *Groisman et al.* [2000] data is larger than that in the *Hahn and Warren* [1999] data by 6%. This discrepancy is caused, perhaps, by a quality problem in the *Hahn and Warren* [1999] data (only ~10% of the station data from *Hahn and Warren* [1999] were officially transferred by the USSR Hydrometeorological Service via the GTS, according to P. Y. Groisman (personal communication, 2000) at the U.S. National Climatic Data Center) and/or by the different number of stations in these two surface data sets. It is also clear from Figure 3 that total cloud cover in D2 is systematically higher than that in the surface observations for the period July 1983 to June 1991. For example, over the contiguous United States, annual total cloud cover in D2 is 6.3, while it is 5.4 in the *Hahn and Warren* [1999] data. The lower value of total cloud cover in the surface data can be caused by nighttime cloud detection bias due to poor illumination [*Hahn et al.*, 1995], but our calculation (see also Figure 6) indicates that the nighttime negative bias lowers surface-based cloud cover by ~0.25 for the annual mean. Therefore, over the contiguous United States the difference of total cloud cover between D2 and the *Hahn and Warren* [1999] data is still as large as 0.64, even taking the nighttime bias into account. The higher bias in ISCCP D2 data revealed in Figure 5 is caused mainly by the higher sensivity of the satellite observations to cirrus clouds over land areas, as pointed out by *Rossow and Schiffer* [1999], who found that the ISCCP cloud cover amount is ~0.5 higher than surface observations. Of course, the underestimate of high clouds by surface observations [*Hahn et al.*, 1995] also contributes to the positive bias in ISCCP D2 data. Despite the systematic difference in cloud cover value, the seasonal cycle of cloud cover in D2 is quite consistent with that in the two sets of surface data over the contiguous United States and eastern China. The inaccurate detection of low cloud cover over snow-covered surfaces [*Rossow et al.*, 1993] is responsible for the poorer seasonal match over the former USSR. After the removal of the seasonal cycle from the cloud data sets, the correlations between the satellite-based and the surface-based data over the United States and China, as well as over the former USSR, are all statistically significant above the 0.05 level. Thus the two sets of surface-observed cloud cover match well with each other and also match well on seasonal cycles with the satellite D2 data over land areas. Therefore it is also reasonable for us to use surface data to check the cosmic ray-cloud cover relationship back in time over land areas.

[12] The interdecadal change in surface-based cloud cover over the contiguous United States, eastern China, and the southern former USSR, as well as the change in cosmic ray intensity, are shown in Figure 6. Annual mean cloud cover from the *Groisman et al.* [2000] data in all three regions was constructed from the same daily data as those used in Figure 5. Annual cloud series created from all cloud observations (thin solid line) and cloud observations with only light illumination (thin dashed line) from the *Groisman et al.* [2000] data are also depicted in Figure 6. The cloud series are calculated using the same area-averaging program

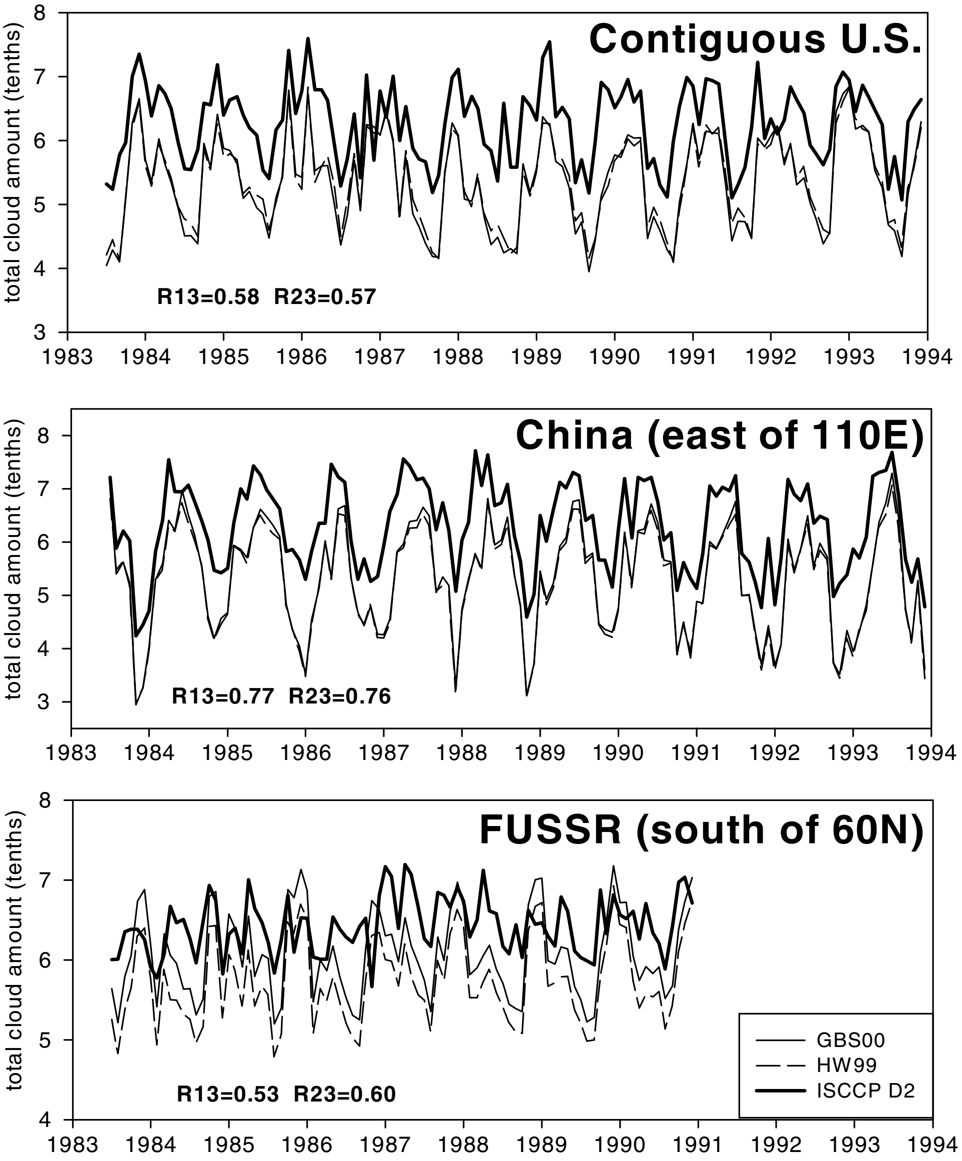

Figure 5. Monthly total cloud cover intercomparison of three data sets: *Groisman et al.* [2000] (GBS00), *Hahn and Warren* [1999] (HW99), and D2 (ISCCP D2) over the contiguous United States, China (east of 110°E), and the former USSR (south of 60°N). R_{13} and R_{23} are the correlation coefficients between D2 and *Groisman et al.* [2000] data and between D2 and *Hahn and Warren* [1999] data, respectively, calculated after the removal of the seasonal cycle.

as for Figure 3. However, ~10–15% of total stations from *Groisman et al.* [2000] have shorter records. In order to avoid or reduce the bias in the area-averaged time series which could be caused by the temporal instability of the *Groisman et al.* [2000] station network (the station network used by *Groisman et al.* [2000] is very stable during 1971–1995 over the three regions aforementioned), the following data preprocessing was performed before the area-averaging program was applied. We first calculated the mean annual value of 1961–1990 data at each station; stations that did not have at least a 25-year record during 1961–1990 were excluded from any further consideration. Then, we calculated the annual anomaly by subtracting the mean value of 1961–1990 data at each station. Finally, the anomalies and means at all stations of a region were area averaged. The annual mean time series of cloud cover shown in Figure 6 was thus created by adding the area-averaged anomalies and means for each region.

[13] Despite the different practices used in recording cloud cover between *Groisman et al.* [2000] and *Hahn and Warren* [1999], the consistency of variation between *Groisman et al.* [2000] and *Hahn and Warren* [1999] on both annual and decadal scales shown in Figure 6 again indicates that surface-based cloud data are likely to be reliable. It is also realized from Figure 6 that nighttime cloud detection bias indeed lowers annual cloud cover by ~0.2–0.3 but does not affect the decadal variation of cloud cover. In contrast to the dominant 11-year cycle in cosmic ray flux intensity recorded, our spectrum analysis (not shown) indicates that cloud variations over these three

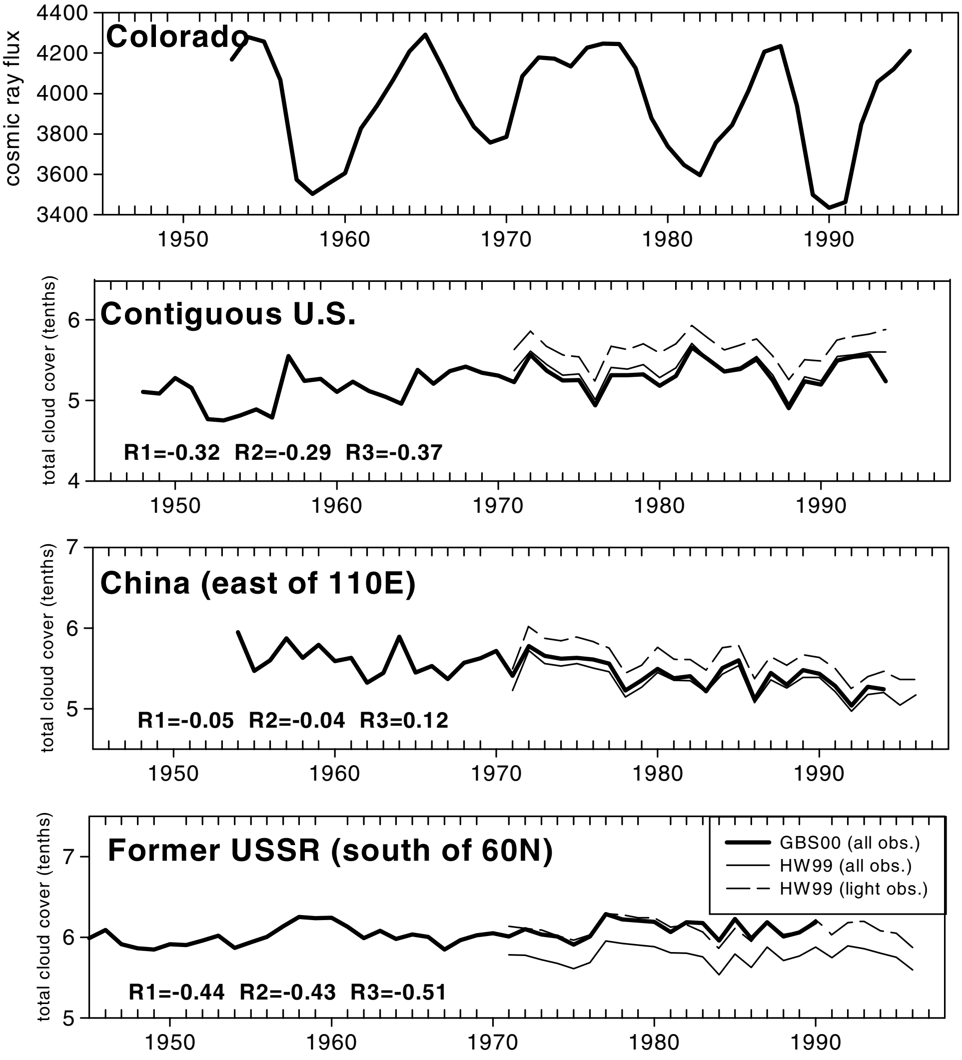

Figure 6. Cosmic ray intensity recorded at Climax, Colorado and comparisons between annual mean cosmic ray intensity and surface-based total cloud cover over the contiguous United States, China (east of 110°E), and the former USSR (south of 60°N). R_1, R_2, and R_3 are the correlation coefficients between cosmic ray intensity and unaltered, detrended, and 3-year running averaged annual cloud cover, respectively.

regions demonstrate mainly a significant 2- to 3-year variability, in addition to an increase over the contiguous United States, a decrease over China, and no significant long-term change over the former USSR, which also have been documented by *Kaiser* [1998], *Dai et al.* [1999], and *Sun and Groisman* [2000]. The correlation coefficients (shown in Figure 6) also confirm that no meaningful relationship between cosmic ray intensity and cloud cover is found for unaltered, detrended, or 3-year running averaged *Groisman et al.* [2000] cloud data sets. Therefore the significant cosmic ray-cloud cover relationship proposed by *Svensmark and Friis-Christensen* [1997] from satellite ocean data does not exist over the three major countries of the Northern Hemisphere over the period since the 1950s.

[14] *Hahn and Warren* [1999] data over the period 1982–1995 exhibit a temporally complete and spatially dense distribution over northern extratropical land areas as well as over tropical land areas of both hemispheres. Cloud data from *Hahn and Warren* [1999], instead of those from *Groisman et al.* [2000], were therefore used to check the cosmic ray-cloud cover relationship over latitudinal land belts. In order to eliminate the seasonal fluctuations in cloud data and make different data sets comparable, we smoothed the monthly anomaly time series (after subtracting the mean values for 1982–1995) by applying 12-month running means, and the monthly anomaly data sets were then further normalized by dividing the root of mean squares of the anomaly series. The time series of cloud cover and cosmic ray intensity over tropical (20°S–20°N) (thin dashed line) and extratropical (20°N–60°N) (thin solid line) land areas shown in Figure 7 are thus normalized anomalies. Cloud cover variations over both the tropical and the extratropical land did not vary in phase with cosmic ray intensity. For example, during the solar maximum in early 1991, cloud cover over land areas had high values. It is also notable that the high correlation over the land area northwest of the Mediterranean Sea (one portion of high-correlation areas surrounding the Mediterranean Sea shown in Figure 4) also

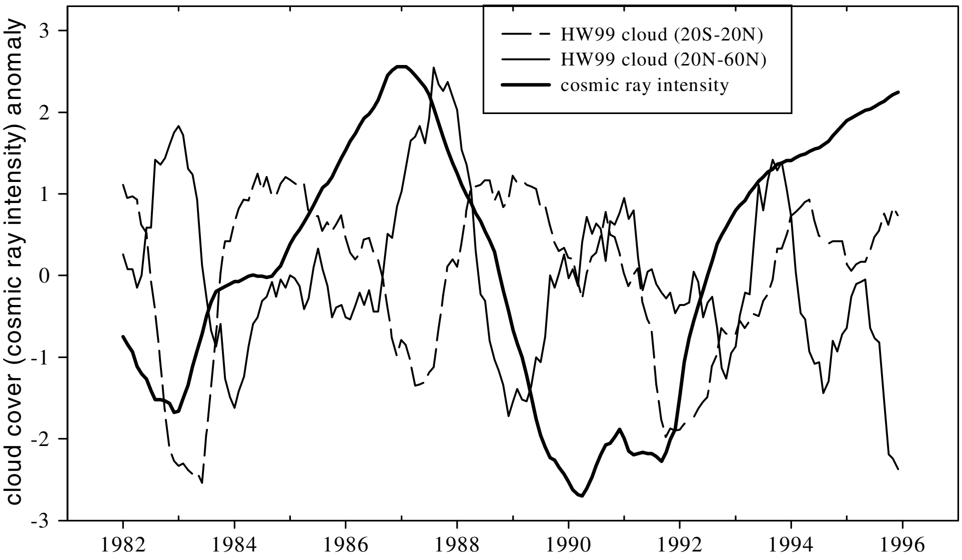

Figure 7. Comparison between normalized monthly anomalies of cosmic ray intensity and *Hahn and Warren* [1999] land total cloud cover over tropical (20°S–20°N) and extratropical (20°N–60°N) land areas. Data sets are first smoothed by a 12-month running average after subtracting the means for the period 1982–1994 and then normalized by dividing the root of mean squares of the anomaly series.

appears in the 1983–1991 *Hahn and Warren* [1999] land data, but turns out to be insignificant in the 1982–1995 *Hahn and Warren* [1999] land data (not shown).

[15] In summary, over land areas, surface-based cloud cover data made by national weather services [*Groisman et al.*, 2000] and by data from the Global Telecommunication System [*Hahn and Warren*, 1999] match well with each other, and they are also consistent on seasonal cycles with ISCCP D2 data. However, no meaningful relationship between cosmic ray intensity variations and cloud cover is found for major land areas, even back to the 1950s.

3.2. Ocean

[16] Figure 4 reveals that the significant correlation between satellite cloud cover and cosmic ray intensity for July 1983 to June 1991 appears mainly over the Atlantic Ocean. Next we will check if the relationship over the Atlantic continues to December 1993 in the D2 data and if the long-term ship-based marine observations given by *Hahn and Warren* [1999] support the satellite result.

[17] Figure 8 describes the relationship between cosmic ray intensity and D2 cloud cover from July 1983 to December 1993 over the North Atlantic (0°–60°N) (thin solid line) and South Atlantic (0°–60 °S) (dashed line). The time series of cloud cover and cosmic ray intensity in Figure 8 are monthly normalized anomalies calculated using the same method as for Figure 7. The period to the left of the vertical line (prior to 1991) is that used by *Svensmark and Friis-Christensen* [1997] (using C2 data), and the relationship they noted is confirmed by the D2 data

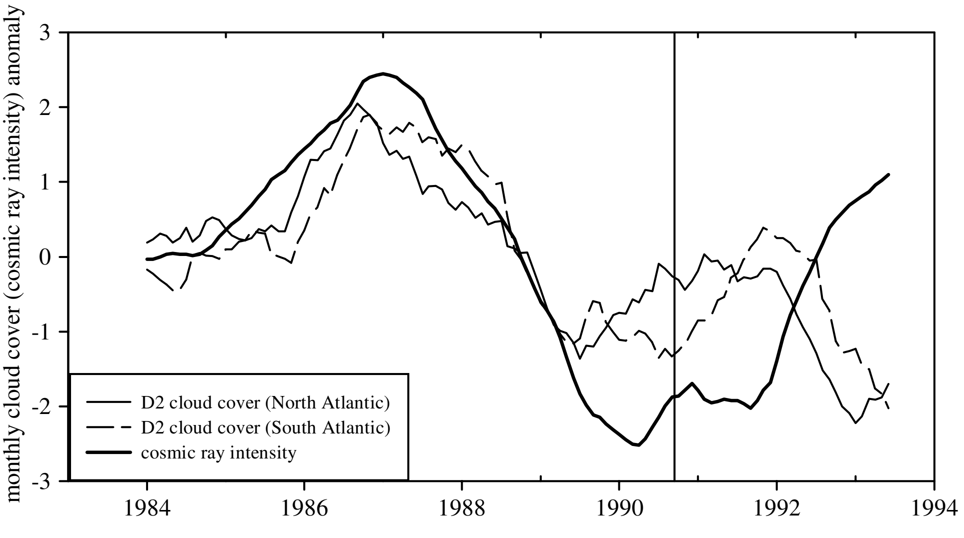

Figure 8. Same as Figure 6 except for D2 total cloud cover over the South Atlantic (0°–60°S) and the North Atlantic (0°–60°N). Cosmic intensity is also shown.

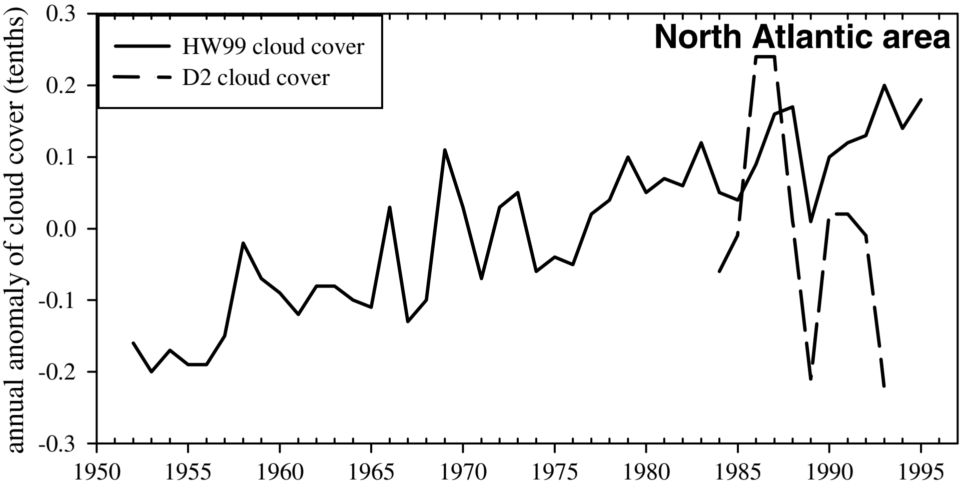

Figure 9. Annual mean total cloud cover comparison between *Hahn and Warren* [1999] and D2 over the North Atlantic (0°–50°N) with the exclusion of the southeast area. Cloud cover series are annual anomalies from the means of the period 1952–1995 [*Hahn and Warren*, 1999] and 1984–1993 (D2).

analyzed here. Cloud cover variation over both the North and South Atlantic generally followed the variation of solar activity before 1991: from 1984 to the end of 1986, cloud cover increased with the increase of cosmic ray intensity; cloud cover decreased from 1987 to late 1990 following the decline of cosmic ray intensity. However, we see from Figure 8 that the maximum cosmic ray intensity in late 1986 lagged the maximum cloud cover by ~2–3 months and the minimum cosmic ray intensity in early 1991 lagged the minimum cloud cover by ~10 months over the North Atlantic and by ~3 months over the South Atlantic. Furthermore, this correlation breaks down after 1991, as cloud cover over the Atlantic decreased in spite of the rise of cosmic ray intensity. The cosmic ray-total cloud cover relationship found by *Svensmark and Friis-Christensen* [1997] is thus largely weakened when the extended ISCCP cloud cover data set is investigated.

[18] Given the short time period of satellite data, it is difficult to give a definite conclusion on the oceanic cosmic ray-cloud cover relationship, and observations with long-term records are therefore needed. The ocean cloud data set given by *Hahn and Warren* [1999] is the longest one currently available. However, *Hahn and Warren* [1999] ocean data are spatially inhomogeneous. In order to avoid sample bias, we selected an area with a better data density to create a longer-term cloud time series: the North Atlantic (0°–50°N with the exclusion of the southeastern area), where at least 10 observations at a given hour during a month within a 2.5° × 2.5° grid box are available. Cloud data were first averaged into monthly means on these 2.5° × 2.5° grids over the North Atlantic. Monthly anomaly time series were created by subtracting the mean values for the period 1952–1995. These monthly anomalies were then averaged into annual anomalies and area averaged, weighted by latitude, to establish the annual anomaly series (solid line) shown in Figure 9. The cloud cover series from D2 (dashed line) over the same area is also shown in Figure 9. It is clear that there is a large discrepancy in cloud cover between ship and satellite observations from 1984 to 1992: *Hahn and Warren* [1999] cloud cover data increased while D2 data cloud cover decreased. We also found that except for several very small areas located between 20°N and 50°N, no large-scale high-correlation (between cosmic ray flux and cloud cover) pattern over the Atlantic is found in the *Hahn and Warren* [1999] cloud data over the period July 1983 to December 1993. Calculations of the correlation between cosmic ray intensity and 3-year running averaged (after the removal of linear trend) total cloud cover show no meaningful relationship over the period 1953–1995. The strong upward trend of *Hahn and Warren* [1999] cloud cover data revealed in the North Atlantic (Figure 9) also exists over other ocean areas [*Norris*, 1999]. Presently, no factors or reasons have been identified or documented to explain the differences between these two ocean data sets. Our knowledge of physical mechanisms for cloud variations is still limited, though some studies [*Croke et al.*, 1999; *Tselioudis et al.*, 2000] suggest that cloud cover variability is closely related to the variation of surface pressure systems. Nevertheless, neither the long-term synoptic ship observations nor the ~10 years of ISCCP D2 data strongly support the cosmic ray-total cloud cover relationship proposed by *Svensmark and Friis-Christensen* [1997].

[19] The significant correlation between cosmic ray intensity and total cloud cover seen in the period 1983–1991 over the Atlantic, which largely contributes to the establishment of *Svensmark and Friis-Christensen's* [1997] hypothesis, is weakened when the extended satellite data (1983–1993) are examined. No solar activity related signal is found in the ship-observed total cloud cover over the period 1952–1995 in relation to cosmic ray intensity variation, though a discrepancy exists between *Hahn and Warren* [1999] ocean data and ISCCP data.

4. Discussion

[20] Section 3 indicated that no significant correlation exists even back to the 1950s between galactic cosmic ray flux and total cloud cover. Total cloud cover is composed of cloud covers with different heights, usually denoted as low, middle, and high clouds. The microphysical conditions and

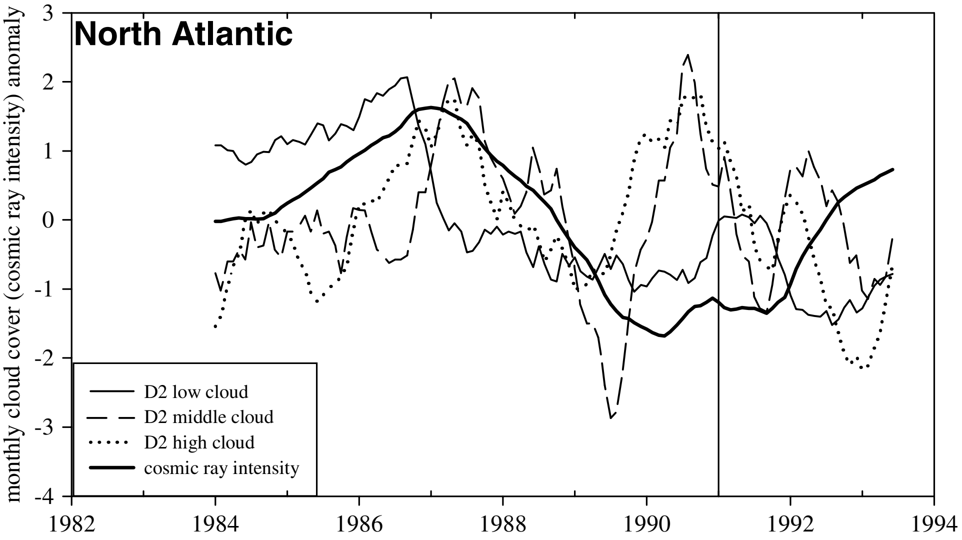

Figure 10. Same as Figure 6 except for D2 cloud cover at low, middle, and high level over the North Atlantic (0°–60°N).

processes for cloud formation differ at different levels. Is it possible that the impact of cosmic rays on cloud formation is limited to only one of these height levels? Figure 10 shows the relationship between cosmic ray intensity and cloud cover at low (thin solid line), middle (dashed line), and high (dotted line) levels over the North Atlantic. The correlation coefficients for the period July 1987 to December 1993 between cosmic ray flux and nonsmoothed monthly low, middle, and high cloud covers is 0.19, 0.07, and 0.00, respectively. The poor relationship between cosmic ray flux and high clouds suggests that the relatively strong galactic cosmic ray ionization at higher altitudes does not have an effect on higher-level cloud cover. The high correlation between cosmic ray flux and low cloud cover comes mainly from the period before 1990 (low cloud cover variation is opposite to cosmic ray variation after 1990). Similar results were also found over the South Atlantic (not shown). *Kristjánsson and Kristiansen* [2000] reported similar relationships between cosmic ray flux and low (middle and high) clouds but over global midlatitude oceans. *Marsh and Svensmark* [2000] thus postulated that the influence of galactic cosmic ray flux on cloudiness may be restricted to lower altitude cloud properties. They speculated that atmospheric ionization produced by galactic cosmic rays, by affecting ultrafine aerosol formation [*Yu and Turco*, 2000], could affect cloud condensation nuclei and thus cloudiness at lower levels in the atmosphere, where concentrations of trace gases are high. The area of high correlation between cosmic ray flux and low-cloud properties, including cloud amount and particularly cloud top temperature as revealed by *Marsh and Svensmark* [2000], is concentrated over the tropics.

[21] However, questions remain regarding the *Marsh and Svensmark* [2000] cosmic ray-low cloud hypothesis. First, as stated by *Marsh and Svensmark* [2000], *Yu and Turco* [2000] did indicate that the aerosols needed for cloud condensation nuclei can be influenced by ions, based on studies at a field site (Idaho Hill, Colorado). However, *Marsh and Svensmark*'s [2000] global correlation map [see *Marsh and Svensmark*, 2000, Figure 2] did not show any significant relationship between galactic cosmic ray flux and low-cloud properties over the continental United States and most of the other middle-to high-latitude land areas. Furthermore, *Turco et al.* [1998], *Yu and Turco* [2000], and other related studies indicate that the fraction of ion-related nucleation events strongly depend upon the abundance of precursor atmospheric sulfuric acid vapor. However, as shown in *Marsh and Svensmark*'s [2000] Figure 2, the regions with very little background sulfate and other trace concentration, including the oceans of the Southern Hemisphere, exhibit a significant cosmic ray-cloud correlationship similar to the regions with a high level of atmospheric sulfur compounds, including East Asia and the Indian subcontinent. Actually, the ion-mediated nucleation process involving complicated chemical/physical interactions is not yet well defined, and its contribution to the formation of cloud condensation nuclei and cloudiness is also not clear. There is a lack of evidence to claim that the high cosmic ray flux-low cloudiness correlationship shown by *Marsh and Svensmark* [2000] is physically based. Second, if the cosmic ray-low cloud hypothesis proposed by *Marsh and Svensmark* [2000] were correct, we would expect a worldwide decrease in low cloudiness in at least the last few decades (*Marsh and Svensmark* [2000] stated that the strength of the solar magnetic flux has increased and the cosmic ray flux has decreased by 3.7% since 1964). However, ship observations [*Norris*, 1999] revealed that there is a steady upward trend (an increase of 3.6% between 1952 and 1995) in low cloudiness over the global ocean, including the tropics. Over most of the land areas, precipitating clouds have shown an increase in the past 40–50 years [*Dai et al.*, 1997]. An increase of 2.3% per decade in surface-based cloud occurrence frequency (extracted from *Marsh and Svensmark*'s [2000] data set) over the contiguous United States for 1952–1992 is also reported by *Sun et al.* [2001]. Third, low-cloud detection from satellites could be biased if low cloud is overlapped by higher-level clouds. Figure 10

shows that cloud covers at middle and high levels basically match before late 1991, but variations in low-cloud cover differ. At several time points, including mid-1987 and mid-1990, the extreme cloud cover amount values at high or middle levels are opposite to those at low levels. The reason for this cloud cover amount compensation at different levels can be that satellites generally underestimate low clouds if high clouds are present. Therefore the high correlation of cosmic ray flux with low-cloud properties derived from satellite measurements revealed by *Marsh and Svensmark* [2000] can be due to an artifact in low-cloudiness data.

[22] From the above discussions, we tend to think that there is no solid physical evidence for the galactic cosmic ray-low cloudiness relationship shown by *Marsh and Svensmark* [2000]. Because of the direct close functional relationship between cloud condensation nuclei concentration and cloud optical depth [*Slingo*, 1989], if cosmic ray flux really had a detectable effect on cloud condensation nuclei concentration by affecting ultrafine aerosol formation, then cloud optical depth or reflectivity should be largely changed. Our judgment would be more robust if we could find that there is no correlation between cosmic ray flux and low-cloud optical depth or reflectivity. Unfortunately, we do not have low-cloud radiative characteristic data to check this idea.

5. Conclusion

[23] Using ISCCP C2 ocean total cloud cover data for 1983–1991, *Svensmark and Friis-Christensen* [1997] argued that cosmic ray flux intensity, modulated by solar activity variations, may modify global cloud cover and thus global surface temperature by altering cloud condensation nuclei. In this study, long-term surface-based cloud data made by national weather services [*Groisman et al.*, 2000] and by the Global Telecommunication System [*Hahn and Warren*, 1999], as well as ISCCP D2 (1983–1993) cloud data, were used to reexamine the *Hahn and Warren* [1999] hypothesis for land and ocean separately. The ISCCP D2 cloud data set, retrieved from an improved algorithm, is a new version of the C2 product, but it has been extended from June 1991 to December 1993. The high correlation between cosmic ray intensity and C2 cloud cover over the Atlantic Ocean in both hemispheres, which is the only large area on the globe with correlations at or above the 0.05 significance level and which largely contributed to *Svensmark and Friis-Christensen*'s [1997] hypothesis, exists also in D2 data over the period 1983–1991.

[24] Over land, the two sets of surface-based total cloud cover match well with each other on seasonal, annual, and decadal timescales. Surface-based total cloud cover in both *Groisman et al.* [2000] and *Hahn and Warren* [1999] data, though lower than the satellite-based cloud cover value, is quite consistent with the latter in terms of seasonal cycle. No meaningful relationship was found between cosmic ray intensity and total cloud cover over tropical and extratropical land areas when the period back to the 1950s was considered. Over the Atlantic Ocean the high cosmic ray-cloud cover correlation is greatly weakened when the extended satellite data set is used. Cloud cover from ship observations [*Hahn and Warren*, 1999] over the North Atlantic, where ship measurements are denser, did not show any relationship with solar activity over the period 1952–1995, but a large discrepancy exists between ISCCP D2 data and surface marine total cloud observations. Finally, we find that there is no solid evidence for the existence of the galactic cosmic ray flux-low cloud relationship as suggested by *Marsh and Svensmark* [2000].

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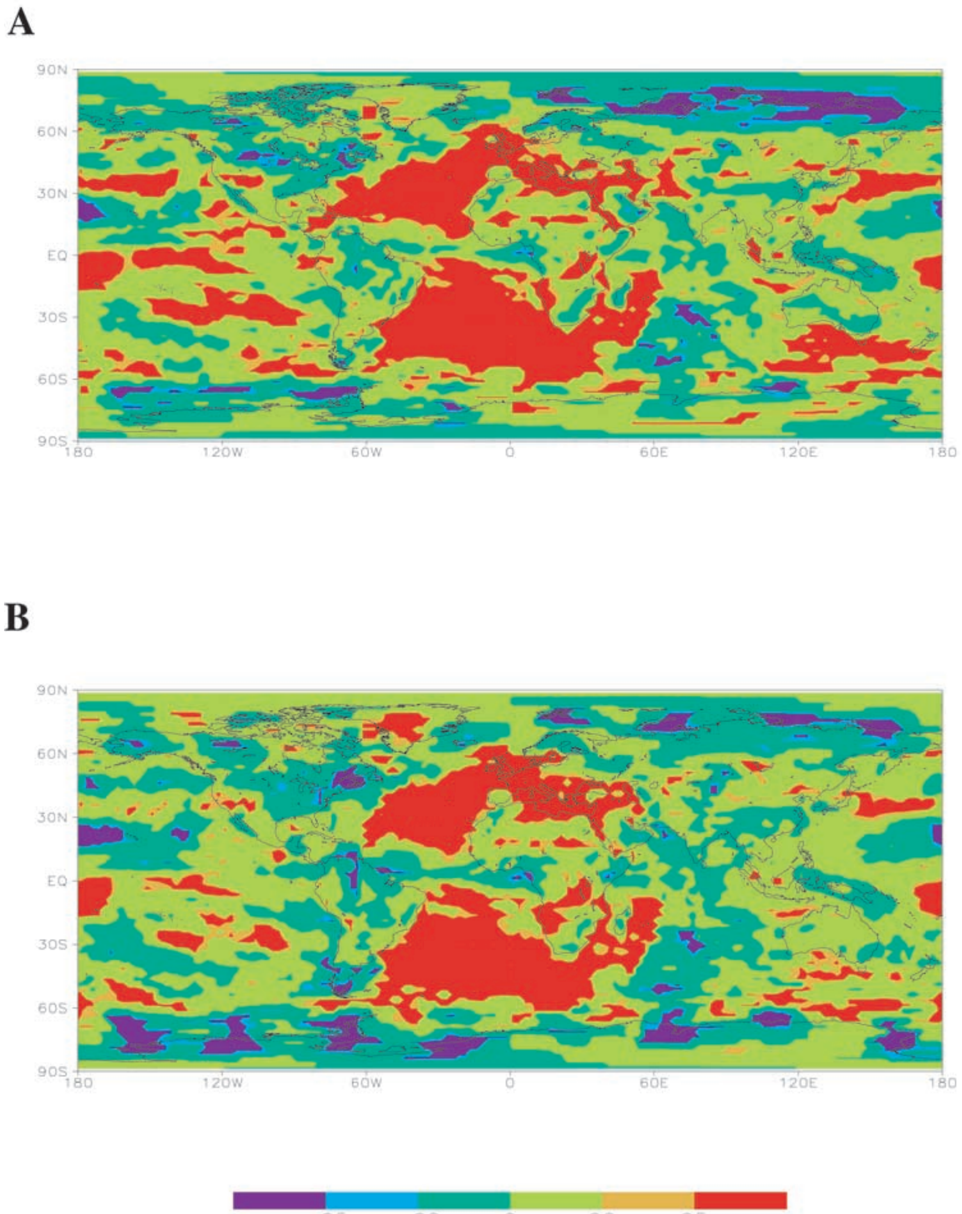

Figure 4. Correlation between monthly cosmic ray intensity recorded in Climax, Colorado, and total cloud cover (after removal of the seasonal cycle) from ISCCP (a) C2 and (b) D2 for the period July 1983 to June 1991. The magnitude of the value in the color scale denotes the significance level, and the sign of the value indicates whether the correlation is positive or negative. For example, red means that cloud cover and cosmic ray intensity is correlated at above the 0.05 significance level.