Relationship of Lower-Troposphere Cloud Cover and Cosmic Rays: An Updated Perspective

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ABSTRACT

An updated assessment has been made of the proposed hypothesis that galactic cosmic rays (GCRs) are positively correlated with lower-troposphere global cloudiness. A brief review of the many conflicting studies that attempt to prove or disprove this hypothesis is also presented. It has been determined in this assessment that the recent extended quiet period between solar cycles 23 and 24 has led to a record-high level of GCRs, which in turn has been accompanied by a record-low level of lower-troposphere global cloudiness. This represents a possible observational disconnect, and the update presented here continues to support the need for further research on the GCR–cloud hypothesis and its possible role in the science of climate change.

1. Introduction

Since the early work by Svensmark and Friis-Christensen (1997) that related galactic cosmic rays (GCRs) to satellite-observed total global cloud cover (updated by Svensmark 1998), there has remained strong and growing interest in the possible importance of such to the science of climate change. Marsh and Svensmark (2000) subsequently changed the observational hypothesis by replacing the ‘‘total cloud cover’’ with the ‘‘lower-troposphere cloud cover.’’ The original work by Yu (2002), coupled with the overview by Carslaw et al. (2002) provide a nice summary of the physical processes that make up the GCR–cloud hypothesis. Briefly, the ‘‘ion-aerosol clear air’’ hypothesis states that increased GCRs during solar quiet periods (QPs) result in more particles (through ionization) and the formation of sulfate aerosols, which can aggregate into sulfate aerosol clusters that serve as cloud condensation nuclei (CCN). Several decades of GCR data exist at many surface stations around the earth; however, global cloudiness data are not as extensive since these records started in 1983 with the establishment of the International Satellite Cloud Climatology Project (ISCCP). Since the early overview by Dickinson (1975), GCR data were compared with the total tropospheric global cloud cover (as noted above), which was subsequently done by Marsh and Svensmark (2000) for the surface to the 680-hPa level (~3.2 km). Their observational result is supportive of a GCR and global lower-troposphere cloudiness relationship for the initial period 1983–95 (which captured a portion of solar cycle 21 and all of solar cycle 22). Later, this observational result was updated (Svensmark 2007), which extended the GCR and lower-troposphere global cloudiness comparison through 2005 (which included solar cycle 23). These updated findings continued to support the potential effect of GCRs on lower-troposphere cloudiness (and thus the impact on climate variations). Interestingly, Laut (2003) has brought into question the validity of the results regarding the relationship of lower-troposphere global cloud cover to the intensity of GCRs. Laut suggests that low-cloud data, based exclusively on satellite IR data, may be adversely affected by the presence of high clouds. Pallé (2005) has also questioned the validity of using the satellite-observed low-level cloud cover, showing the adverse effects of overlying cloud layers. Damon and Laut (2004) raise a more general concern about the pattern of errors in data analysis that relates solar activity to the terrestrial climate.

Given the observational evidence, Pierce and Adams (2009) considered a general circulation model (GCM) with aerosol microphysics to examine the GCR–cloudiness relationship. Their study concluded that the changes in CCNs (due to GCRs) during a solar cycle were two orders

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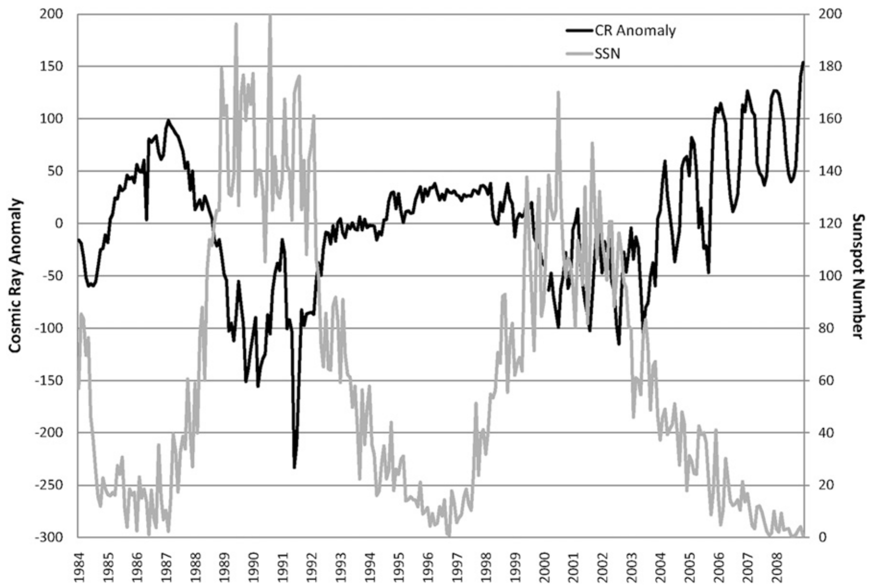

FIG. 1. Surface-based neutron counter at Beijing depicting cosmic ray anomaly vs international sunspot number. The solar QPs for cycles 21–22, 22–23, and 23–24 are seen to correspond with high values of cosmic rays (as expected). The Beijing Neutron Monitor is located at 39.08°N, 116.26°E, at an altitude of 48 m above sea level, with a geomagnetic cutoff rigidity of 9.56 GV.

of magnitude too small to affect changes in cloud properties. However, a more recent study by Laken et al. (2010), also based in part on GCM studies, suggest that the hypothesis of the GCR–cloudiness relationship may have value and that the influence of GCRs can be clearly distinguished from changes in solar irradiance and the interplanetary magnetic field (particularly for observed rapid midlatitude cloud changes and corresponding changes in surface-level air temperature). Snow-Kropla et al. (2011), using a global chemical transport model, have concluded that the effect of cosmic rays on CCN and clouds is limited by dampening from aerosol processes.

In view of the above-referenced studies, the controversial GCR and CCN relationship seemingly continues, with observational support. However, the principal objective of the current assessment, reported on in this paper, shows a clear disconnect between ISCCP lower troposphere global cloud cover and galactic cosmic ray effects. GCRs have achieved a record-high level (Phillips 2009), while ISCCP lower-troposphere global cloudiness is at a record-low level. The observational comparisons have not stood the test of time (as shown and discussed below).

2. The data

Galactic cosmic rays that can potentially reach the earth's lower atmosphere are shielded by the solar interplanetary magnetic field, which is most effective during an active sun. The earth in particular is further shielded by its own magnetosphere. However, during the extreme QP between cycles 23 and 24 (see Agee et al. 2010), there has been a record-maximum level of GCRs measured at the earth's surface. The unusual length of cycle 23 has been addressed by Dikpati et al. (2010) and more recently by Nandy et al. (2011). The latter study in particular explains the extended deep QP between cycles 23 and 24 and the effect of the sun's very weak polar magnetic field. This in turn explains the record-high GCR levels during the cycle 23–24 QP (see Phillips 2009). Therefore, the stated objective of this paper is to show an update of the relationship (if any) between the deep QP with its record-high GCRs and the ISCCP lower-troposphere global cloudiness.

a. *Galactic cosmic rays (1984–2008): Beijing and Kiel*

Figure 1 is presented to show the plot of GCR trends through 2008, based on neutron counts from Beijing, China, plotted against the international sunspot number R (a similar plot for Kiel, Germany, was also prepared but not presented). Both the Beijing and Kiel plots show the rise and fall of the GCR record and the well-known respective negative correlation with R. It is noted that the annual/semiannual variations that can occur in cosmic ray data (see Attolini et al. 1982) have not been filtered out of the Beijing data from April 2000 through 2008 (which is irrelevant in this assessment). More recent evidence of record-setting GCR intensities (through 2009) is also given by Mewaldt et al. (2010), which further

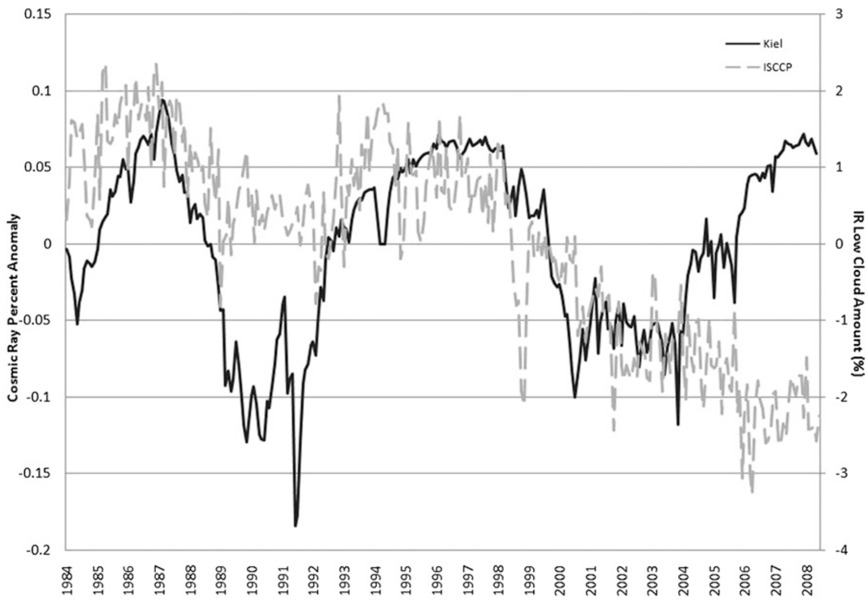

FIG. 2. Surface-based neutron counter at Kiel depicting cosmic ray percentage anomaly vs the ISCCP lower-troposphere global cloudiness. The Kiel Neutron Monitor is located at 54°N, 10°E, at an altitude of 54 m above sea level, with a geomagnetic cutoff rigidity of 2.32 GV. (Note that the Beijing GCR record. 1 is very similar to the Kiel plot shown above. 2.)

shows the unusual behavior of the sun as it moved through the extended deep QP between cycles 23 and 24. Mewaldt et al. (2011) has also noted the record-setting GCR intensities. Solar activity and the GCR record at the earth's surface is well understood, but any effect of increased GCRs on cloud climatology (and climate change) remains controversial (also see Carslaw 2009). To help pursue an understanding of this possible relationship, Project Cosmics Leaving Outdoor Droplets (CLOUD) has been developed (and continues) at the European Organization for Nuclear Research (CERN) Proton Synchrotron in Switzerland (see Duplissy et al. 2010). The efforts of Project CLOUD to date, however, remain inconclusive as to the role high-energy cosmic rays can play (through ionization) in aerosol formation.

b. ISCCP cloudiness (1984–2008)

The ISCCP continues (see http://isccp.giss.nasa.gov/products/onlineData.html), and the lower-tropospheric global cloudiness has been updated. These new data can now be compared with the GCR record to examine the observational hypothesis that GCRs are positively related to the lower-troposphere (infrared sensed) global cloudiness. Figure 2 is presented to show the ISCCP cloud trend versus the Kiel GCR data (similar to Beijing, which is not shown). It is clearly evident that the positive trend in previous solar cycles and lower-troposphere cloudiness has not continued for the cycle 23–24 QP, which adds to the controversy of the GCR–CCN hypothesis. Not only has the GCR count reached a record-high level during the cycle 23–24 QP but the lower-troposphere global cloudiness has dropped to a record-low level, further challenging the validity of the hypothesis. This is the principal finding in this short contribution, but it is an extremely important result that suggests the need for more research into the GCR–CCN connection. It is noted again that the ISCCP lower-troposphere cloud data may not be sufficiently reliable to detect GCR–cloud correlations.

3. Summary and conclusions

Several studies, as referenced here, have continued to promote the controversial cosmic ray–cloud connection hypothesis, both from the standpoint of errors in data analysis as well as scientific links that establish GCR–CCN as a viable contributor to climate change. It is also important to note (see Carslaw et al. 2002) that there are two mechanisms by which cosmic rays may affect cloud droplet number concentrations or ice particles: (i) an ion-aerosol clear-air mechanism and (ii) an ion-aerosol near-cloud mechanism. Recent attempts have also been made to further resolve the GCR–CCN controversy by examining the global cloudiness response to very short-term solar variations (namely, Forbush decreases,[1] which are approximately of 1-week duration). Calogovic et al.

[1] A "Forbush decrease" is defined as a sudden and short-lived decrease in GCRs due to a solar coronal mass ejection (CME) that strengthens the solar interplanetary magnetic field.

(2010) have found no response in global cloud cover to Forbush decreases at any altitude and latitude. Svensmark et al. (2009), however, have shown that Forbush decreases associated with a CME passage results in lower-troposphere clouds containing less liquid water. Their results, in general, show global-scale influences of solar variability on both cloudiness and aerosols. The work by Harrison and Ambaum (2010) also shows a positive relationship between cloudiness and large GCR changes associated with Forbush decreases (as observed at Shetland, Scotland). However, Laken and Kniveton (2011) find no evidence of any relationship between liquid cloud fraction and GCRs.

It is concluded that the observational results presented, showing several years of disconnect between GCRs and lower-troposphere global cloudiness, add additional concern to the cosmic ray–cloud connection hypothesis. In fact, this has been done in the most dramatic way with the measurement of record-high levels of GCRs during the deep, extended quiet period of cycle 23–24, which is accompanied by record-low levels of lower-troposphere global cloudiness. Research on the GCR–cloud correlations must continue, particularly in view of the two physical mechanisms mentioned above (as well as the uncertainty in the reliability of the ISCCP lower-troposphere cloudiness to show the proposed correlations). Finally, it is clearly known that other factors can affect mean global cloudiness besides solar variability, due to internal forcing mechanisms on different time scales (such as ENSO).

REFERENCES

Agee, E. M., E. Cornett, and K. Gleason, 2010: An extended solar cycle 23 with deep minimum transition to cycle 24: Assessments and climate ramifications. *J. Climate,* **23,** 6110–6114.

Attolini, M. R., S. Cecchini, and M. Galli, 1982: On the annual semiannual variation of cosmic rays. *Proceedings of the 17th International Cosmic Ray Conference,* C. Ryter, Ed., Vol. 10, D. Reidel Publishing Company, 163–166.

Calogovic, J., C. Albert, F. Arnold, J. Beer, L. Desorgher, and E. O. Flueckiger, 2010: Sudden cosmic ray decreases: No change of global cloud cover. *Geophys. Res. Lett.,* **37,** L03802, doi:10.1029/2009GL041327.

Carslaw, K., 2009: Cosmic rays, clouds and climate. *Nature,* **460,** 332–333.

——, R. G. Harrison, and J. Kirby, 2002: Cosmic rays, clouds, and climate. *Science,* **298,** 1732–1737.

Damon, P. E., and P. Laut, 2004: Pattern of strange errors plagues solar activity and terrestrial climate data. *Eos, Trans. Amer. Geophys. Union,* **39,** 374, doi:10.1029/2004EO390005.

Dickinson, R. E., 1975: Solar variability and the lower atmosphere. *Bull. Amer. Meteor. Soc.,* **56,** 1240–1248.

Dikpati, M., P. A. Gilman, G. de Toma, and R. K. Ulrich, 2010: Impact of changes in the sun's conveyor-belt on recent solar cycles. *Geophys. Res. Lett.,* **37,** L14107, doi:10.1029/2010GL044143.

Duplissy, J., and Coauthors, 2010: Results from the CERN pilot CLOUD experiment. *Atmos. Chem. Phys.,* **10,** 1635–1647.

Harrison, R. G., and M. H. P. Ambaum, 2010: Observing Forbush decreases in cloud at Shetland. *J. Atmos. Sol.-Terr. Phys.,* **72,** 1408–1414.

Laken, B., and D. Kniveton, 2011: Forbush decreases and Antarctic cloud anomalies in the upper troposphere. *J. Atmos. Sol.-Terr. Phys.,* **73,** 371–376.

——, ——, and M. R. Frogley, 2010: Cosmic rays linked to rapid mid-latitude cloud changes. *Atmos. Chem. Phys.,* **10,** 102 941–102 948.

Laut, P., 2003: Solar activity and terrestrial climate: An analysis of some purported correlations. *J. Atmos. Sol.-Terr. Phys.,* **65,** 801–812.

Marsh, N. D., and H. Svensmark, 2000: Low cloud properties influenced by cosmic rays. *Phys. Rev. Lett.,* **85,** 5004–5007.

Mewaldt, R. A., and Coauthors, 2010: Record-setting cosmic-ray intensities in 2009 and 2010. *Astrophys. J.,* **723,** L1–L6.

——, R. Leske, E. Stone, K. Lave, and M. Wiedenbeck, cited 2011: Update on record-setting galactic cosmic ray intensities in 2009-2010. [Available online at http://www.srl.caltech.edu/ACE/ACENews/ACENews134.pdf.]

Nandy, D., A. Muñoz-Jaramillo, and P. C. H. Martens, 2011: The unusual minimum of sunspot cycle 23 caused by meridional plasma flow variations. *Nature,* **471,** 80–82.

Pallé, E., 2005: Possible satellite perspective effects on the reported correlations between solar activity and clouds. *Geophys. Res. Lett.,* **32,** L03802, doi:10.1029/2004GL021167.

Phillips, T., cited 2009: Cosmic rays hit space age high. [Available online at http://www.physorg.com/news173445919.html.]

Pierce, J. R., and P. J. Adams, 2009: Can cosmic rays affect cloud condensation nuclei by altering new particle formation rates? *Geophys. Res. Lett.,* **36,** L09820, doi:10.1029/2009GL037946.

Snow-Kropla, E. J., J. R. Pierce, D. M. Westervelt, and W. Trivitayanurak, 2011: Cosmic rays, aerosol formation and cloud-condensation nuclei: Sensitivities to model uncertainties. *Atmos. Chem. Phys.,* **11,** 4001–4013.

Svensmark, H., 1998: Influence of cosmic rays on earth's climate. *Phys. Rev. Lett.,* **81,** 5027–5030.

——, 2007: Cosmoclimatology: A new theory emerges. *Astron. Geophys.,* **48,** 1.18–1.24.

——, and E. Friis-Christensen, 1997: Variation of cosmic ray flux and global cloud coverage—A missing link in solar-climate relationships. *J. Atmos. Sol.-Terr. Phys.,* **59,** 1225–1232.

——, T. Bondo, and J. Svensmark, 2009: Cosmic ray decreases affect atmospheric aerosols and clouds. *Geophys. Res. Lett.,* **36,** L15101, doi:10.1029/2009GL038429.

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