REFLECTIONS ON THE LATE COSMOCLIMATOLOGY

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Abstract. For many years the prospect that the solar-modulated cosmic ray flux could alter Earth's clouds and climate stood as a tantalising hypothesis. A version of this idea, termed Cosmoclimatology, involved a link between cosmic ray induced ionization and the nucleation and growth of aerosols that could modify clouds. If true, it would have overturned mainstream climate science. However, over time, results from experiments, models, and observations showed Cosmoclimatology to be false. In this work, we outline the perspective from satellite observations at long and short time-scales. We also reflect on the implications of the cosmic ray flux on clouds via a second pathway, the Global Electric Circuit to the future of this research field.

Key words: Cosmic ray flux - clouds - climate - Solar activity - composite analysis - global electric circuit - Cosmoclimatology

1.   Introduction

Paleoclimatological studies have reported evidence of pervasive links between solar activity and regional climate (Ram and Stolz, 1999; Beer *et al.*, 2000; Bond *et al.*, 2001; Fleitmann *et al.*, 2003; Versteegh, 2005). However, the Total Solar Irradiance (TSI) variations occurring during these studies are insufficient to directly account for significant climate changes without amplifying mechanisms—a notion discussed in more detail in Gray *et al.* (2010). This lead to the widely held conclusion that one or more indirect mechanisms played a role in relaying solar-influences into the Earth's climate system over the past. Proposed mechanisms include: *e.g.* top-down changes from stratospheric ozone heating induced by solar UV variations (Roy and Haigh, 2010); bottom-up feedbacks amplifying TSI changes (Meehl *et al.*, 2008). Another possibility is a relationship between the solar modulated cosmic ray (CR) flux and terrestrial cloud properties (Ney, 1959; Dickinson, 1975). In relation to this, several specific pathways related to atmospheric
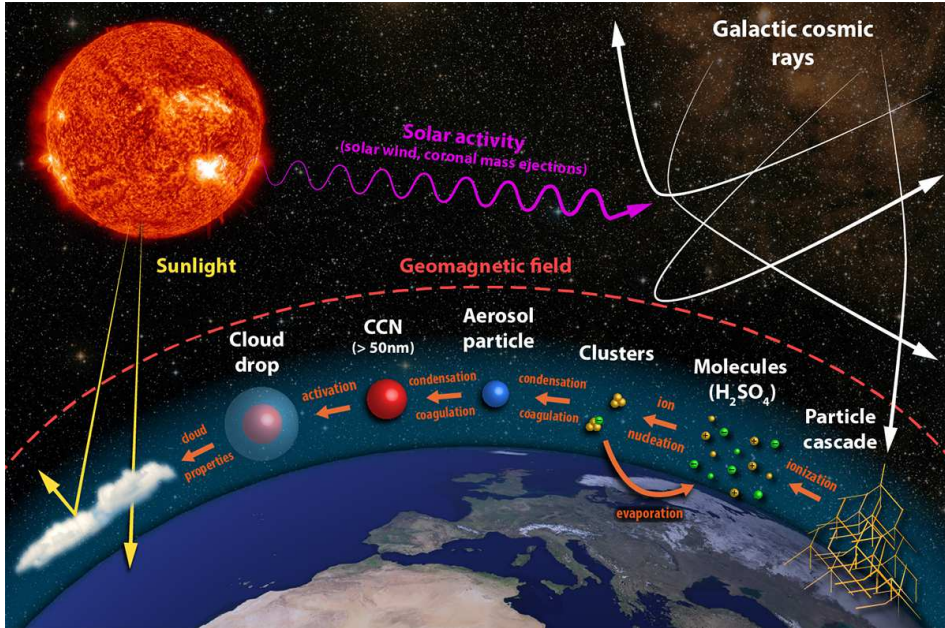
Figure 1: Illustration of the hypothesized '*clear-air*' mechanism: Cosmic rays collide with the nuclei of atoms in the Earth's atmosphere with enough force to generate particle cascades throughout the atmosphere, producing ionization. Under certain conditions this may increase the nucleation of new aerosol particles and alter their grow-rates. If the particles persist and grow to CCN sizes, they may influence cloud properties.

electricity and cloud micro-physics have been proposed (as described in Carslaw *et al.*, 2002).

One pathway, the so-called '*clear-air*' mechanism depicted in Figure 1, links cosmic ray induced ion production to the nucleation and altered-growth of aerosol particles. If increased numbers of aerosols survive and grow to cloud condensation nuclei (CCN) sizes, this may influence cloud properties such as droplet concentration and precipitation, consequently altering the reflectivity and lifetime of clouds (Carslaw *et al.*, 2002). Altering such properties leads to a considerably amplified effect relative to the originally small energy input of the cosmic rays, as clouds have a significant impact on Earth's radiative balance (Ramanathan *et al.*, 1989).
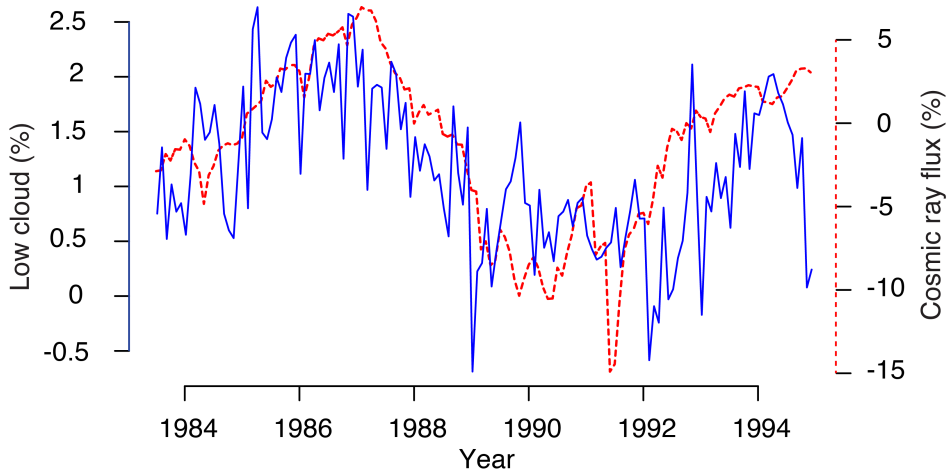
Figure 2: A reproduction of the Marsh and Svensmark (2000) correlation between low-level cloud cover (<3.2km) from ISCCP (blue line), and the cosmic ray flux (red dashed line, values on right-hand axis) from the Climax Colorado and Moscow neutron monitor data.

2. Correlation, Controversy and Cosmoclimatology

2.1. A Brief History

Using data from the International Satellite Cloud Climatology Project (IS-CCP), Svensmark and Friis-Christensen (1997) compared the CR flux and cloud cover. They reported a positive association and suggested that cloud cover may change by 2–4% over an 11-year solar cycle. However, in subsequent analyses these claims were restricted to low clouds (Figure 2) (Marsh and Svensmark, 2000; Pallé and Butler, 2000; Marsh and Svensmark, 2003). This gave a basis for the hypothesis, later referred to as 'Cosmoclimatology' (Svensmark, 2007), that argues that the Earth's climate system is in-fact solar-driven, and the contributions of humans to recent climate change have been relatively minor.

Cosmoclimatology sought to overturn the mainstream view of climate science (Svensmark and Calder, 2008). This has appealed to politically-motivated interest groups seeking to delay or reverse action on climate change, such as the Nongovernmental International Panel on Climate Change (NIPCC) (Idso and Singer, 2009). Consequently, the idea has received a disproportionate level of attention in relation to the strength of its evidence. In

this work we review some recent lines of evidence, largely from modern observational datasets and concerning analytical approaches that demonstrate the degree to which this hypothesis can be considered defunct.

2.2. The View from Experiments and Models

Recently, results from both the SKY experiment (Enghoff *et al.*, 2011) and the CERN Cosmics Leaving Outdoor Droplets (CLOUD) experiment (Kirkby *et al.*, 2011; Almeida *et al.*, 2013) have confirmed that the presence of ions increases the nucleation rate of aerosols compared to binary neutral nucleation. They showed that ionization enhances aerosol nucleation by a factor of 2–10 times. However, this mechanism is only effective under specific low temperature conditions, characteristic of the upper-troposphere, with low concentrations of amines and organic molecules. The importance of ion-induced nucleation appears to be low, as the presence of acid amine trace gases, present in the troposphere, results in nucleation rates $10 \times^5$ faster than ion-mediated nucleation (Almeida *et al.*, 2013).

Although this result confirms that ionization can speed-up the birth of new aerosol particles, it remains unclear from the experiments how effectively the process operates in the Earth's atmosphere. Modelling studies from both Pierce and Adams (2009) and Kazil *et al.* (2012) seeking to address this question have concluded that global cloud condensation nuclei (CCN) are not sensitive to changes in the ion-induced nucleation rate over a solar cycle. Although the clear-air mechanism causes small aerosol particles to form faster than they would without ionization, these particles remain at small sizes for relatively long time periods. At such small sizes they are susceptible to scavenging by larger pre-existing aerosols, and so are unlikely to survive long enough to grow to CCN sizes. Consequently, as the majority of the troposphere is rich in pre-existing aerosols, the clear-air mechanism is unlikely to alter the number of CCN available to sufficiently impact clouds. The ultimate impact on CCN concentrations over the 11-year solar cycle is estimated to be an approximately ~0.2% change for aerosols of >80 nm in diameter (Pierce and Adams, 2009).

2.3. Complications from Climate Variability

In the scientific literature, claims of a CR–cloud link, made first by Svensmark and Friis-Christensen (1997) and later by others, received heavy crit-

icism on multiple fronts, including: limitations of decadal time-scale correlations, data handling, analysis methods, and interpretation of the results (Kernthaler *et al.*, 1999; Farrar, 2000; Wagner *et al.*, 2001; Sun and Bradley, 2002; Damon and Laut, 2004; Kristjánsson *et al.*, 2002, 2004; Laut, 2003; Sloan and Wolfendale, 2008; Laken *et al.*, 2012b).

Analyses of climate parameters such as cloud cover are often complicated by the limitations of these data. Firstly, when comparing fluctuations in climate to external forcings, such as a particular solar parameter, low-time resolution data make disambiguating potential forcings problematic or even impossible. This is because solar parameters are co-varying (e.g. the cosmic ray flux varies inversely with the solar wind), and so isolating a potentially causal link amidst large background noise is a significant issue (Haigh, 1996; Tinsley, 2000; Meehl *et al.*, 2008; Roy and Haigh, 2010). Due to the co-variance of solar parameters, and the ambiguity with regards to which solar parameter is important to climate (if any), the CR flux may simply be considered as a proxy for solar activity. Hence the detection of a significant CR-climate link may not unambiguously confirm a CR-related mechanism, but rather could simply be agnostic with regards to the particular mechanism, merely confirming if a solar link exists at all (Laken and Čalogović, 2011).

Secondly, oscillations internal to the Earth's climate system (such as El Niño) or volcanic eruptions, which operate over similar time-scales to the solar cycle compromise our ability to attribute cloud changes to a solar forcing. They produce multi-year variations in climate, and make distinguishing the cause of observed cloud variations highly problematic (Farrar, 2000).

Additionally, the cloud data itself has significant quality issues. The most commonly used ISCCP cloud data (Rossow and Schiffer, 1991) is subject to large long-term errors and spurious trends (Campbell, 2004; Norris, 2000, 2005; Evan *et al.*, 2007). These errors come from numerous sources, such as changes in the number of contributing satellites over time, changes in the calibration satellites, and degradation of the instruments. Due to the calibration issues, even the scientific team responsible for the ISCCP data stated that the clouds records are not suitable for long-term analysis (Brest *et al.*, 1997; Stubenrauch *et al.*, 2013). Furthermore, since the satellite instruments are non-cloud penetrating (high-clouds obscure the view of low clouds) measurements of low-cloud cover, that were from interest in some studies and showed the positive response to a CR changes, are known to be
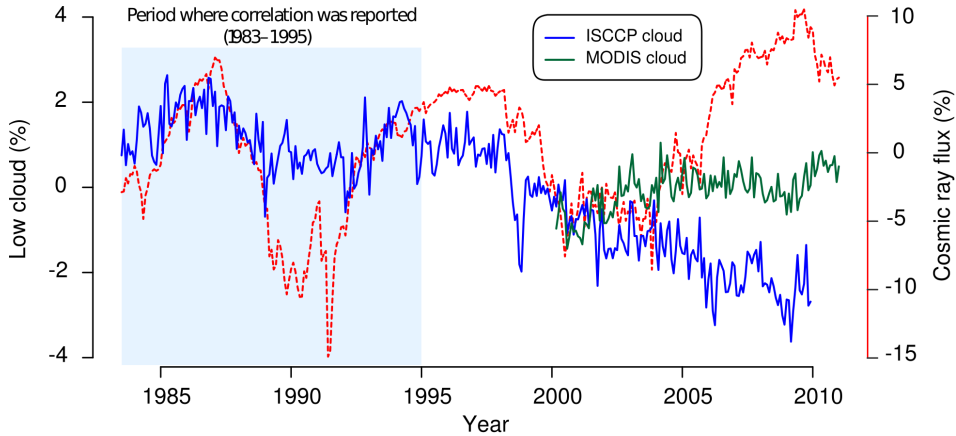
Figure 3: Low-level cloud cover estimated from ISCCP and MODIS, adapted from Laken *et al.* (2012a). Anomalies for ISCCP (blue line) and MODIS (green line) are calculated against the total period of each dataset. Cosmic ray flux (red dashed line, values on right-hand axis) is calculated from the Climax Colorado and Moscow neutron monitor data. The time period during several studies obtained a good correlation with smoothed data is marked with light blue (e.g. Marsh and Svensmark, 2000).

unreliable (Laken *et al.*, 2012a). Errors within the satellite data have played a strong role in affecting the results of the original correlation studies such as Marsh and Svensmark (2000, 2003). A detailed review of these errors is given in Laken *et al.* (2012a).

   More recent and independent data from the MODerate resolution Imaging Spectrometer (MODIS) program (King *et al.*, 1992), together with updates from ISCCP cloud datasets, have show no evidence of a cosmic ray–cloud link (Figure 3).

3.   Short-term Studies and Statistical Pit-falls

A common approach to overcome the limitations of long-term studies, is by examining unusually large changes in the cosmic ray (CR) flux over short (hours–daily) time-scales. Using these events is a basis for superposed epoch analyses (also called Chree, composite analysis, or conditional averaging) and it is used in numerous fields including geostatistics, fluid dynamics, and plasma physics. It is useful for isolating low-amplitude signals within data where background variability would otherwise obscure signal detection (Chree, 1913, 1914).

Composite analysis has been frequently employed to examine a hypothesized link between atmospheric properties and sudden decreases in cosmic ray intensity over daily time-scales. These reductions, termed Forbush Decrease (FD) events (Lockwood, 1971; Cane, 2000), occur as a result of solar wind and interplanetary magnetic field disturbances caused by interplanetary coronal mass ejections (ICME) or co-rotating interaction regions (Dumbović *et al.*, 2011; Maričić *et al.*, 2014). Changes in the cosmic ray flux during large FD events are of the same order of magnitude as changes experienced over the 11-year solar cycle, but occur over a period of several days. The short time-scales enable the separation of specific solar forcing parameters, as changes in TSI propagate from the Sun at the speed of light, while solar-related CR flux variations travel at the slower speed of propagating ICMEs. Sudden increases in the solar cosmic ray flux have also been explored based on so-called Ground Level Enhancement (GLE) events (e.g. Laken and Čalogović, 2011; Dragić *et al.*, 2013).

On aggregate, composite studies have produced inconsistent results, increasing confusion within the field. Some studies have reported significant positive correlations between cosmic rays and cloud properties (Tinsley and Deen, 1991; Pudovkin and Veretenenko, 1995; Todd and Kniveton, 2001, 2004; Harrison and Stephenson, 2006; Svensmark *et al.*, 2009; Dragić *et al.*, 2011; Harrison *et al.*, 2011; Aslam and Badruddin, 2015), while some found negative correlations (Okike and Collier, 2011; Troshichev *et al.*, 2008) or reported null results (Lam and Rodger, 2002; Kristjánsson *et al.*, 2008; Sloan and Wolfendale, 2008; Erlykin and Wolfendale, 2013). Reinvestigation of several studies reporting the strongest relationships revealed that data treatment and statistical issues produced false positive results. When proper data treatment and statistical approaches were applied, the experiments produced null results (Čalogović *et al.*, 2010; Laken *et al.*, 2011; Laken and Čalogović, 2011; Laken *et al.*, 2012c; Laken, 2015).

There are several non-trivial drawbacks of FD and GLE studies: autocorrelation is a common feature of geophysical data, hence satellite cloud datasets show both spatial and temporal autocorrelation. Consequently, when variance and standard deviation are calculated using the standard formulas, they will be smaller than the true values. Many statistical tests commonly applied to composite analyses make assumptions about the distributions and degrees of freedom of the data that are invalid due to autocorrelation effects. As a result, miscalculation of statistical significance

and type-1 statistical errors (false-positives) are common in FD and GLE studies.

If autocorrelation effects are taken into account, thresholds of statistical significance in analyses (often indicated by confidence intervals) will be larger than when autocorrelations are ignored, making it less likely that a fluctuation in the data will be interpreted as indicative of a causal relationship.

In addition to autocorrelation effects, when dealing with short time-scale data signal-to-noise ratio must also be carefully considered. The high-levels of meteorological variability (noise) must be taken into account in order to detect any solar-related changes (signal). Common practice is to apply composite analysis, wherein similar disturbances are averaged together to reduce noise. For a detailed description of these procedures and their application to the field of solar–terrestrial studies see Laken and Čalogović (2013).

Many composite studies have taken the approach of sub-setting their data, either in terms of area or number of events, (e.g. Todd and Kniveton, 2001, 2004; Kristjánsson *et al.*, 2008; Svensmark *et al.*, 2009; Laken and Kniveton, 2011; Dragić *et al.*, 2011, 2013). However, these restrictions have a dramatic effect on the amount of noise in a composite sample, as illustrated in Figure 4. The spatial area (a) and composite size (n) have an inverse and exponential relationship to noise as indicated by the 97.5^{th} percentile values of derived from Monte Carlo samples (for further details see Laken and Čalogović (2013)). Composite sizes are frequently small in FD studies, as there are typically less than 10 FDs with amplitudes larger than 10% during one solar cycle (Belov *et al.*, 2009), meaning investigators have only a small population of events to select from.

For example, if a given composite considers an area of ∼2% of Earth's total (around the size of Europe), and there are 10 FD events composited, the meteorological variability (noise) of the ISCCP cloud cover will be around 5%. Consequently, if a hypothetical CR signal in clouds is smaller than 5%, it will be undetectable against the background noise.

4. The Global Electric Circuit: a Second CR–cloud Mechanism

In addition to the '*clear-air*' mechanism, a separate theoretical pathway concerning the CR flux has also been suggested, known as the '*near-cloud*
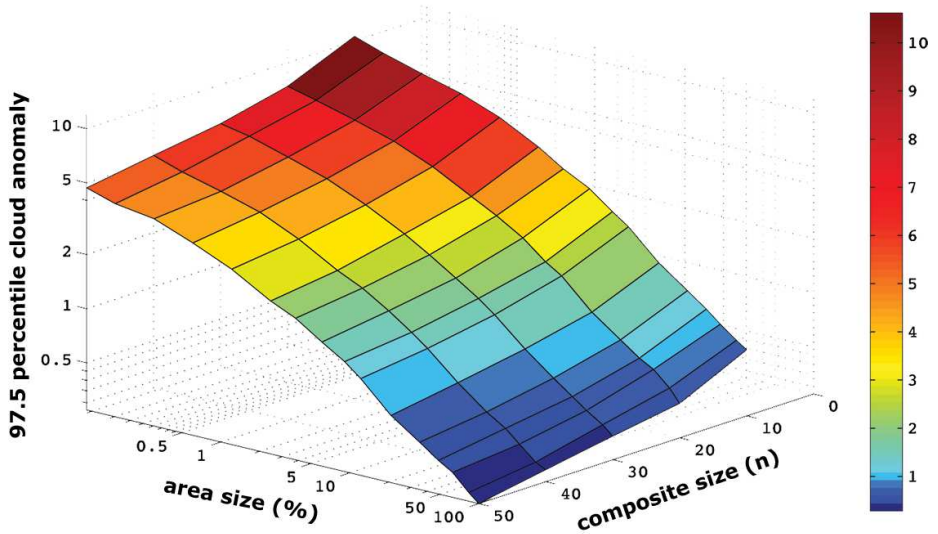
Figure 4: The relationship between increasing sample area (as a percentage of global area: x-axis, denoted by a) and number of events in a composite (z-axis, denoted by n) on noise levels indicated by the 97.5^{th} percentile mean cloud fraction anomalies (%, y-axis) within composites. These values constitute the upper $p = 0.05$ confidence interval. Each data point is calculated from 10,000 Monte Carlo (MC) simulations from cloud cover anomaly data (21-day running mean subtracted). Axes are logarithmic. Plot adapted from Laken and Čalogović (2013).

effect', which operates via the global atmospheric electric circuit (GEC). This mechanism is complex and its implications on cloud properties are still largely unknown.

First proposed by C.T.R. Wilson (1921), the GEC is a global-scale alternating and direct current circuit of positively charged ions flowing vertically from the ionosphere to the Earth's surface (and negatively charged ions moving in the opposite direction). The current flows across all fair-weather regions. The current density is continuously maintained across the globe by an upward flowing positive current, generated in thunderstorms and electrically active clouds. They act as a battery, maintaining the ionosphere at a potential (V_i) of ∼200–300 kV relative to the Earth's surface. The constant generation of atmospheric ions by the attachment of electrons generated from radon and cosmic rays to neutral air molecules maintains atmospheric conductivity, allowing a vertical current density (J_z) to flow

between the ionosphere and Earth's surface. The J_z is highly variable in space and time, largely due to changes in the cosmic ray flux, ranging from $\sim$1–6 pAm^{-2} (Tinsley and Zhou, 2006).

As clouds effectively scavenge ions, within clouds atmospheric conductivity is diminished by $\sim$3–30 times the amount it would be in cloud-free conditions (Griffiths *et al.*, 1974). As a result, clouds create areas of resistance within the GEC, and charge therefore accumulates at the boundaries of clouds generating measurable electric fields (like in a capacitor). Positive charge accumulates at cloud tops, and negative charges at cloud bases. Observations show that for stratiform clouds charges of as much as 200 pCm^{-1} (Nicoll and Harrison, 2010). The build-up of space charge at cloud boundaries—and the rapid attachment of this charge to both cloud droplets and aerosols—is thought to impact the micro-physics of clouds through cloud droplet formation, droplet-to-droplet collision efficiency, droplet-to-aerosol particle collisions, and so-called electroprotection and electroscavenging processes. Variations in the generation of atmospheric ionization by the cosmic ray flux may alter the atmospheric columnar resistance. Tinsley and Zhou (2006) estimated that the tropospheric resistance varies from 200 to 250 Ω depending on the cosmic ray flux, thereby linking solar activity to clouds via the GEC (see Tinsley, 2008).

It is important to note that the cosmic ray flux is only one parameter of the global electric circuit. The complexity and scale of the GEC and its feedbacks is such that further research is needed to understand even the net sign, let alone the importance, of cloud changes which may arise from cosmic ray induced variations to the system.

5.   Discussion

Even without all the aforementioned limitations in short- and long-term studies it is still plausible that a relationship between the CR flux and cloud exists, yet remains undetected. It may be the case that changes in the CR flux only produce small or dynamic changes to cloud over certain regions or during certain conditions. For example, modifying subtle properties such as vorticity strength, rather than altering net cloud cover (Tinsley and Deen, 1991; Tinsley *et al.*, 2012). If a CR–cloud relationship is indeed second order, with variations in the CR flux simply enhancing or retarding cloud dynamics under certain conditions, then it may prove most difficult

to detect it with currently available techniques and datasets (Laken *et al.*, 2010). Moreover, we note that if a CR–cloud relationship is a second order phenomena, detectable cloud changes may not necessarily be observable in association with FD and GLE events, as these are essentially random with respect to the climate system.

Detecting a second order CR–cloud relationship would likely require long observations, more sensitive than are currently available. Overall, the current satellite cloud datasets do not provide evidence supporting the existence of a solar–cloud link, and we may expect that this will remain the case for some time. However, we note that some positive results have been reported from ground-based studies (e.g. Harrison and Stephenson, 2006; Harrison and Ambaum, 2008, 2010; Harrison *et al.*, 2011): these data are localized and are suggested to be second-order effects, operating via global electric circuit based mechanisms, where the net effects may depend on numerous factors and vary greatly from one location to the next.

Consequently, it is unclear what the overall implications of a GEC based CR flux cloud relationship may be for the Earth's climate system as a whole. However, by virtue of a lack of strong evidence detected from the numerous satellite- and ground-based studies, it is clear that if a solar–cloud link exists the effects are likely to be low amplitude and could not have contributed appreciably to recent anthropogenic climate change. This is a conclusion supported by the most recent (fifth) assessment report of the Intergovernmental Panel on Climate Change (See 7.4.6 of IPCC, 2013).

6.   Conclusions

Both long- and short-term studies using the cloud satellite observations (ISCCP, MODIS) have produced conflicting results, due to both data and analysis issues. Bias may also be a significant factor: we note that many of these difficulties were presciently outlined in relation to solar–terrestrial studies by Pittock (1978, 1979, 2009). In relation to studies using satellite estimations of cloud cover we highlight the following commonly recurring issues:

- Satellite cloud estimates are fraught with limitations and calibration errors, meaning long-term analysis is problematic at best, and, as in the case of commonly used ISCCP data, is fundamentally flawed.

- Co-variance of solar-related parameters (UV, TSI, CR flux, solar wind) make signal attribution difficult.

- Climate variability and volcanic activity, operating over time-scales similar to the solar cycle, make disambiguating causes of cloud cover change difficult.

- Composite analysis of FD and GLE events is often compromised by the difficulties of statistical analysis of autocorrelated data. This is compounded by the application of inappropriate and black-box statistical tests.

- Changing signal-to-noise ratios connected to spatio-temporal restrictions in composites have generally not been sufficiently taken into account in composite studies, leading to widespread type-1 (false-positive) statistical errors.

We have found that many of these issues have been responsible for the apparent discrepancies between various cosmic ray-cloud composite studies based on satellite data. In conclusion, there is no compelling evidence to support a wide-spread cosmic ray cloud connection, as outlined in Cosmo-climatology. I.e. there is no basis to the claims that solar activity, via a modulation of the cosmic ray flux, is able to significantly alter global cloud cover, nor explain recent global warming. Despite that, there are still many open question in relation to atmospheric electricity, cloud micro-physics and the global electric circuit.

Acknowledgements

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