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ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **8** (2013) 045032 (9pp)
doi:10.1088/1748-9326/8/4/045032

Clouds blown by the solar wind

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Received 10 November 2013, revised 27 November 2013
Accepted for publication 29 November 2013
Published 20 December 2013
Online at stacks.iop.org/ERL/8/045032

Abstract
In this letter we investigate possible relationships between the cloud cover (CC) and the interplanetary electric field (IEF), which is modulated by the solar wind speed and the interplanetary magnetic field. We show that CC at mid–high latitudes systematically correlates with positive IEF, which has a clear energetic input into the atmosphere, but not with negative IEF, in general agreement with predictions of the global electric circuit (GEC)-related mechanism. Thus, our results suggest that mid–high latitude clouds might be affected by the solar wind via the GEC. Since IEF responds differently to solar activity than, for instance, cosmic ray flux or solar irradiance, we also show that such a study allows distinguishing one solar-driven mechanism of cloud evolution, via the GEC, from others.

Keywords: clouds, solar wind

1. Introduction

There is high interest today in quantifying the solar contribution to climate change. Despite the progress in understanding the processes driving the Earth's climate, quantifying the natural sources of climate variability, especially regarding solar effects, remains elusive (Solomon *et al* 2007, Gray *et al* 2010). Although climate models are highly sophisticated and include many effects, they are not perfect and observational evidences are modest and ambiguous. Empirical evidences suggest a causal relationship between solar variability and climate, particularly in the pre-industrial epoch (Bond *et al* 2011), but possible mechanisms are unclear and qualitative. The balance between reflected radiation from space and Earth at different wavelengths contributes to temperature variation in a significant manner (Hartmann *et al* 1992), thus cloud cover play a major role in the terrestrial radiation budget. Modeling cloud contribution to climate at different spatial and temporal scales is probably the most challenging area of climate studies (Vieira and da Silva 2006). Despite increasing number of solar-cloud studies, there is no clear understanding of solar effect on cloud cover. Indirect mechanisms are proposed that would amplify the relatively small solar input and could explain solar-related variability observed at different time scales (from days to decades) in various cloud parameters, as for instance cloud cover (Udelhofen and Cess 2001, Marsh and Svensmark 2000, Voiculescu and Usoskin 2012) or cloud base height (Harrison *et al* 2011, Harrison and Ambaum 2013).

One indirect mechanism relates to the fact that the solar spectral irradiance varies significantly in the UV band, whose effect is limited to the stratosphere, thus a stratosphere–troposphere–ocean coupling, 'top-down' effect, is required (Gray *et al* 2010, Meehl *et al* 2009, Haigh *et al* 2010). Another mechanism relies on possible variations of atmospheric aerosol/cloud properties, affecting the transparency/absorption/reflectance of the atmosphere and, consequently, the amount of absorbed solar radiation. Two possible physical links have been proposed: one via the ion-induced/mediated nucleation by cosmic ray induced ionization (CRII) (Dickinson 1975, Svensmark and Friis-Christensen 1997, Carslaw *et al* 2002, Kazil and Lovejoy 2004, Yu and Turco 2001) and the other via the global electric circuit (GEC) effects on cloud/aerosol

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properties (Tinsley 2000, Harrison and Usoskin 2010). The former mechanism might be hardly distinguishable from noise, especially at short-term scale, as demonstrated using in situ/laboratory experiments (e.g., Carslaw 2009, Kulmala *et al* 2010, Enghoff *et al* 2011, Kirkby *et al* 2011) and statistical studies (e.g., Calogovic *et al* 2010, Dunne *et al* 2012). Opposing, studies of Svensmark *et al* (2009), Enghoff *et al* (2011), Svensmark *et al* (2013), Yu *et al* (2008) have shown that an impact of ionization on new particle formation and cloud condensation nuclei (CCN) exists. Thus it is possible that the CRII-nucleation mechanism operates at longer time scales, but it might be spatially limited to the polar stratosphere (Mironova *et al* 2012). On the other hand, the GEC-related mechanism may be important (e.g., Tinsley 2000, Harrison and Usoskin 2010, Rycroft *et al* 2012), particularly for low-clouds and some links have been shown to exist between atmospheric electricity properties and cloud evolution/formation (Harrison *et al* 2013).

Since all solar drivers correlate to some extent, it may be difficult to evaluate which driver or combination of drivers is the best candidate for cloud cover modulation. An attempt to differentiate between solar irradiation (total or UV) and CRII effects on cloud cover has been made by Kristjánsson *et al* (2004), Voiculescu *et al* (2006, 2007), Erlykin *et al* (2010), who showed that various mechanisms might act differently at different altitudes and geographical locations. However, the GEC is affected by the solar activity in a different way, via the interplanetary electric field (IEF), so that only positive IEF plays a role, while negative IEF does not. Positive IEF corresponds to a interplanetary magnetic field (IMF) with a southward component, or negative z-component, which favors a direct energy transfer from solar wind to the magnetosphere and to ionosphere. For negative IEF (positive z-component of the IMF) the transfer is much less efficient and only a very small percentage of the solar wind energy is transferred to the magnetosphere (e.g. Dungey 1961, Papitashvili and Rich 2002, Siingh *et al* 2005). Thus, in contrast to other potential solar drivers which are expected to exert a monotonic influence, IEF is expected to affect clouds only when IEF is positive. This feature has a potential of separating the IEF effect from other drivers. Here we present results of correlation studies between the interplanetary electric field (IEF) and cloud cover, which might indicate the most probable mechanism that might affect cloud cover. We discuss here mainly results obtained for low cloud cover (LCC), but we also refer to middle- (MCC) and high-clouds (HCC).

2. Data analysis and method

A global picture of the cloud cover is usually obtained using space-based observations, scanning the entire Globe. A long series of continuous monitoring of the cloud cover was produced by ISCCP, which is an international project aiming at collecting a continuous database of clouds, starting in 1984 (Rossow *et al* 1996). We make use of the ISCCP data for the period 1984–2009 for low-clouds, identified by their top pressure, $P > 680$ mb (Rossow *et al* 1996). Middle- (MCC) and high-clouds (HCC) are identified also by their top pressure (440 mb $< P <$ 680 mb and $P <$ 440 mb, respectively). ISCCP remains the only provider of continuous database for the last almost 30 years but some errors in ISCCP retrieval procedure may have contributed to an artificial trend of clouds (Evan *et al* 2007). In order to avoid possible artificial trends in satellite data and to remove the strong CC seasonal cycle, data were annually averaged and linearly detrended, using a best square-fit regression.

The interplanetary electric field (IEF) data were collected from the OMNI webpage (http://omniweb.gsfc.nasa.gov/). The IEF is a derived quantity, defined as a product, $-V_{SW} \cdot B_z$, of the solar wind speed V_{SW} and the meridional component B_z of the interplanetary magnetic field in the Geocentric Solar Magnetospheric (GSM) system. The IEF data set is assumed to be error-free.

As the next step, correlation maps were computed, between each type of cloud (low, middle and high) and IEF anomalies. By anomaly we mean the resulting data obtained after removing the trend. A correlation map depicts the spatial distribution of the correlation coefficient between the local (within 5° × 5° longitude–latitude grid cells) cloud cover and IEF anomalies.

Maps were produced separately for positive and negative values of IEF in order to highlight possible differences between the effect of positive and negative IEF on cloud cover. Positive anomalies of the detrended electric field do not necessarily mean that the actual electric field was positive, thus we have identified all positive values in the detrended data and checked whether the actual IEF is also positive. A limit of 0.021 mV m^{-1} was imposed for IEF.

Correlation was assessed using Spearman rank correlation, which is a non-parametric measure of the dependence between two variables and is considered to be a robust alternative to the Pearson correlation coefficient (Wilks 2011). Spearman correlation identifies relationships which are not necessarily linear. Statistical significance of the computed correlation was assessed for each individual grid cell. Since years when positive and negative electric field are unevenly distributed, the t-test was used to assess the significance of the correlation coefficient. We note that this is sufficient since no autocorrelation is expected after data separation into positive and negative IEF subsets.

3. Results and discussion

A clear latitudinal effect for positive IEF is observed in figure 1, which shows the annual variation of IEF together with LCC zonal averages, in bands of 15°. Significant correlation between IEF and LCC at mid–high latitudes (45°–75°) but no correlation at lower latitudes is found in both hemispheres (figure 2, upper panel) is found in both hemispheres, but no correlation at lower latitudes. On the other hand, no correlation is observed for the negative IEF (figure 2, lower panel) wherever. This suggests that only positive IEF may affect CC in the latitudinal band roughly between 40° and 80°, but negative IEF has no effect. In order to illustrate this, figure 3 shows scatter plots of LCC versus

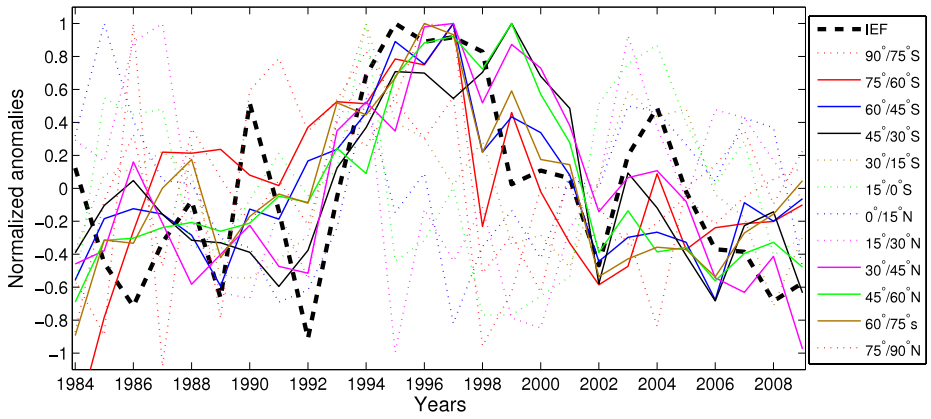

Figure 1. Variation of zonal low cloud cover in 15° bands: mid–high latitudes are shown as continuous lines, polar and tropical latitudes are dotted lines.

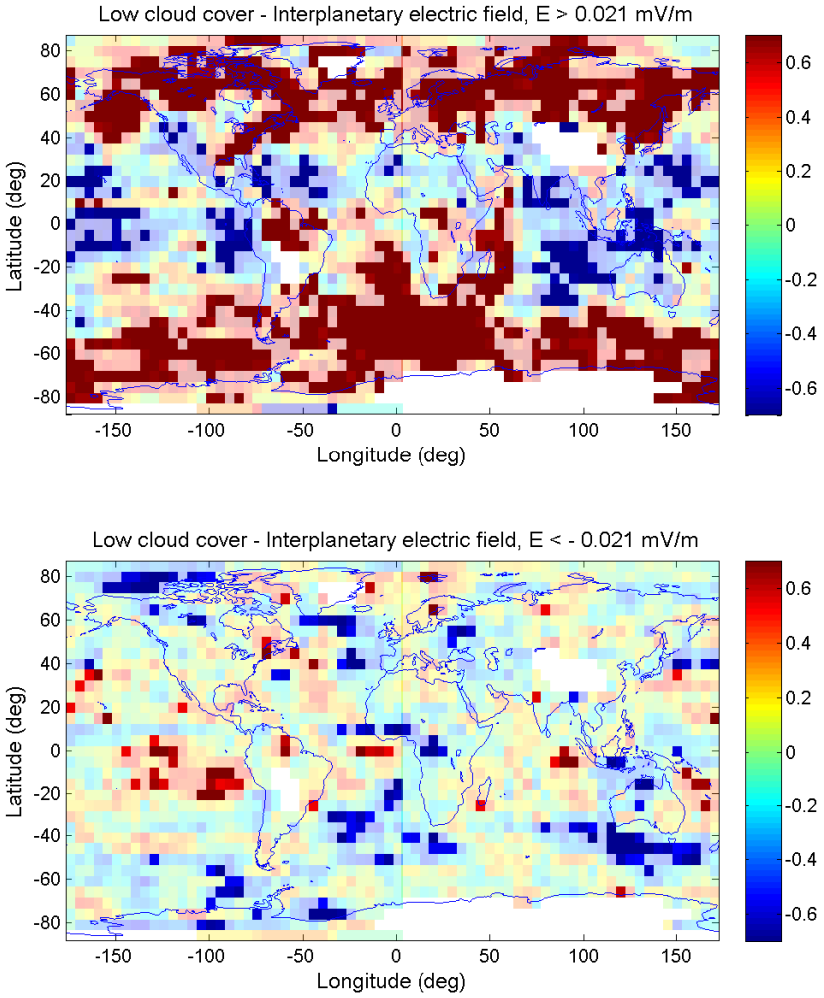

Figure 2. Correlation map between positive electric field (upper panel), respectively negative electric field (lower panel) and corresponding low cloud cover. Significant correlation at 90% is shown in strong color.

the IEF anomaly, where CC is averaged over latitudinal belts of 15° width.

The relation has a typical pattern at middle latitudes (between 30° and 75°), i.e. no dependence for negative IEF and a nearly linear dependence for positive IEF (right off the vertical dashed line of 0.02 mV m^{-1}). The relation appears highly significant, namely the null hypothesis of no relation can be rejected at a high confidence level (see table 1). The variation of the slope (Δ(LCA)/ΔIEF) and uncertainties at 95% with latitude are depicted in figure 4, which shows that there is no relation at polar (above 75°) and tropical (below 30°) latitudes. This pattern is consistent for both

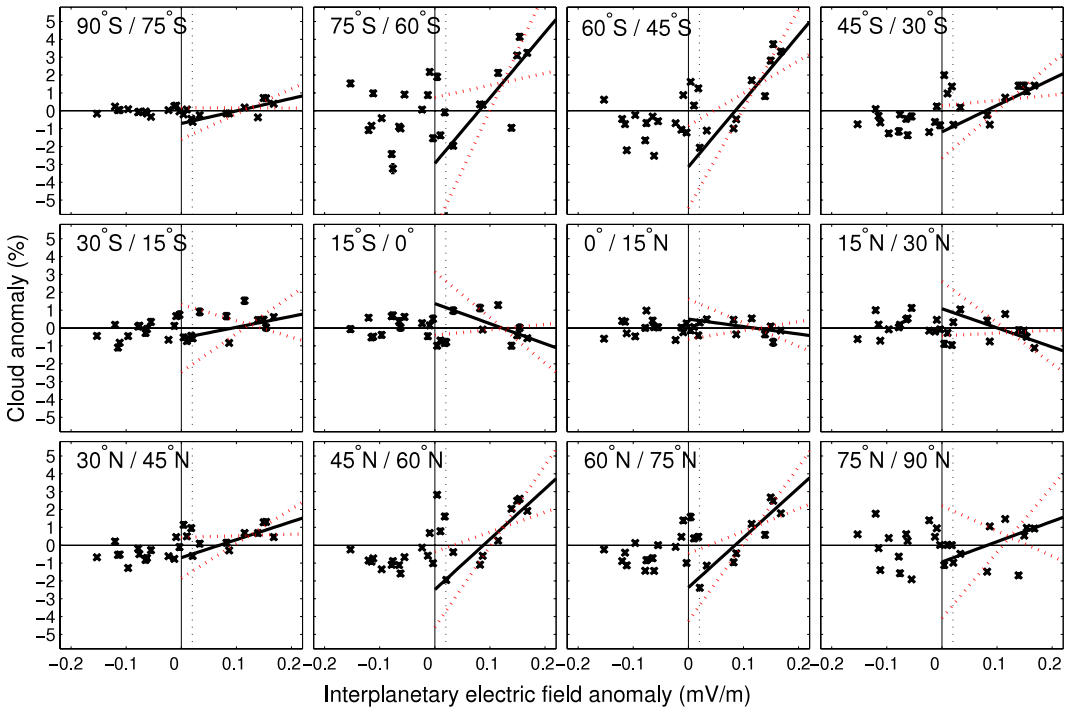

Figure 3. Scatter plots of low cloud cover and electric field for latitudinal belts of 15° and associated linear regression of low cloud cover on interplanetary electric field anomalies (black solid lines). Shown is also the 95% confidence interval for the slope for each latitudinal belt (red dotted lines).

Table 1. Parameters of the regression between low cloud cover and IEF in different latitudinal bands as shown in figure 3. Columns are: the latitudinal band, the slope, and uncertainties at 95% level. Slopes which are significantly different from zero with 95% confidence are shown in bold-face. The results are shown also in figure 4.

Lat. band	Slope (%CC/mV m^{-1})	95% uncert.
75–90° N	6.99	7.10
60–75°N	**36.67**	**29.92**
45–60°N	**36.89**	**18.68**
30–45°N	**14.80**	**11.89**
15–30°N	6.12	15.28
0–15°N	−11.25	14.28
0–15°S	−4.18	9.06
15–30°S	−10.71	12.28
30–45°S	**10.09**	9.23
45–60°S	**28.24**	17.16
60–75°S	**27.93**	15.32
75–90°S	11.38	25.50

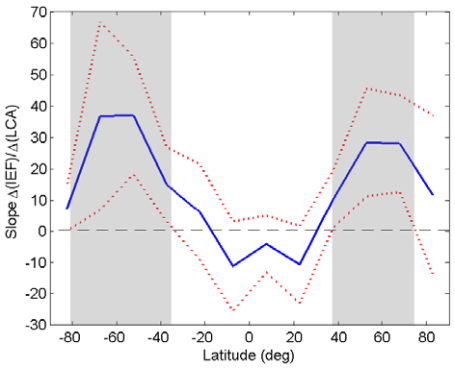

Figure 4. Variation of slope ΔIEF/ΔLCA with latitude (blue solid line) and 95% confidence interval (red dotted lines)—see table 1. Latitudes where the slope is significantly different from zero are highlighted.

hemispheres and complements results presented in figure 2. We note here that cloud data for the polar region are sparse and not very reliable, since they are at the edge of the ISCCP satellite view. Moreover, meteorological conditions in the polar region do not favor low-clouds formation, in general. At low latitudes, on the other hand, the magnitude of the effect is much lower, clouds are nearly 'saturated' by existing favorable conditions. Consequently, the effect is expected to be observed at mid–high latitudes (e.g., Tinsley 2012).

The values near zero IEF are quite uncertain, probably because of the averaging procedure but also because these data come from years when ENSO events took place. There is no relationship between various ENSO phases and low cloud cover at global level, but ENSO phenomena may lead to a decrease/increase in cloud cover in particular regions (Curtis and Adler 2003). Positive CC anomalies near IEF = 0 in the latitudinal band of 45–60°N are from years 1999 and 2000, which are ascribed to a strong La Nina event. The negative CC anomaly at IEF = 0.13 mV m^{-1} departing from the almost linear dependence of cloud cover, seen in figure 4, the 75–60°S latitudinal band, corresponds to year 1998, which is characterized by a strong El Nino event.

This pattern, i.e. a strong dependency of CC for positive IEF with no relation for negative IEF, is exactly what is expected for the GEC-related mechanism. Positive electric

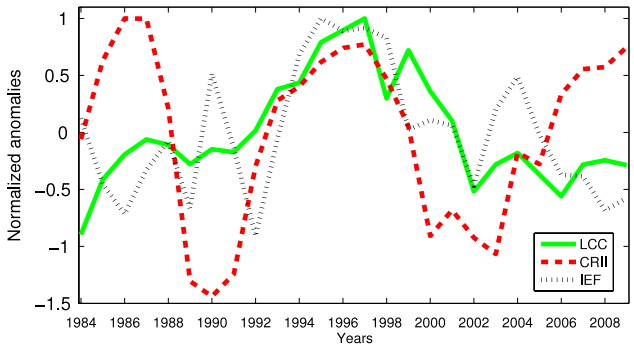

Figure 5. Variation of average mid–high latitude (30°–75°N and S) low cloud cover (green continuous line), interplanetary electric field (black dots) and cosmic ray induced ionization (CRII) at 700 hPa (red dash). CRII is calculated using the atmospheric ionization model of Usoskin *et al* (2010).

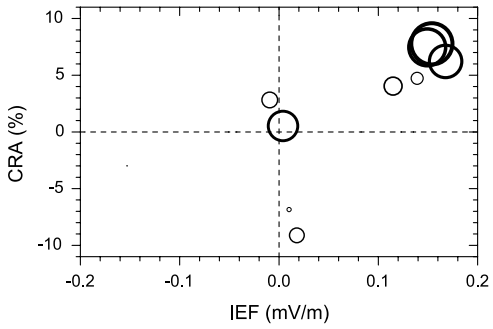

Figure 6. Positive anomalies of low cloud cover (zonal mean over 30°–75°N and S) as function of IEF (*x*-axis) and cosmic ray (*y*-axis) anomalies (CRA); data are the same as in figure 5. The size of the dots is proportional to the CC anomaly. Dots with thick boundaries correspond to CC anomalies exceeding one standard deviation.

fields are associated with negative z-component of the interplanetary magnetic field (IMF), which has a major impact onto the high latitude ionosphere by favoring the energetic transfer from solar wind to magnetosphere and ionosphere. When the electric field is negative (positive B_z), the magnetospheric energy input is significantly reduced (e.g., Dungey 1961, Papitashvili and Rich 2002). Separating between positive and negative electric fields allows to discern between various solar-related drivers, most of which are expected to provide a monotonic relation to CC.

A possible mechanism by which solar wind might modulate the GEC relates to changes in the ionospheric potential distribution in the polar caps due to magnetosphere–ionosphere coupling (Tinsley 2000). To explain the effect of IEF on cloud cover two paths should be considered: the magnetospheric input to the GEC and the role of atmospheric electricity in modulating cloud properties. Positive IEF increases the high latitude ionospheric potential, which changes the ionospheric current, which, in turn, affects the GEC.

Thus the separation between positive and negative IEF suggests that the GEC is a solar driver which can affect CC variations, therefore serves as an indirect climate driver. According to model results of Tinsley (2012), variations of the current density associated to solar wind input are important at latitudes higher than 60° in both hemispheres, slightly higher in the southern hemisphere, which is seen also in our figure 2.

A higher positive IEF results in higher ionospheric potential and increased atmospheric current j_z with effects on charge distribution at cloud edges (Tinsley 2000). According to Tinsley and Yu (2004) or Tinsley (2012), an increase of the vertical electric current in some types of warm cloud layers composed of water, especially over high latitude oceans, eventually leads to an increased concentration of small water droplets. Consequently, precipitation is less likely to occur and the lifetime of water clouds is longer. At long-term scale this is equivalent to an increase of low cloud cover associated to higher electric current flow, triggered by the increased ionospheric potential due to positive IEF. Moreover, positive IEF (i.e. negative B_z) is sometimes accompanied by increased particle precipitation, which contributes to the polar and high latitude conductivity, providing a supplementary increase of the atmospheric vertical current flow.

Droplet charge, which varies with j_z, modulates supersaturation conditions and, consequently, affects cloud formation, especially in stratiform clouds (Harrison and Ambaum 2008, Tinsley 2012). A close agreement in phase and sensitivity between the cloud base height and the diurnal variation of the atmospheric vertical current at polar sites in both hemispheres was observed by Harrison and Ambaum (2013).

Another possibility is that changes in surface pressure or tropospheric dynamics associated with GEC variability (Burns *et al* 2007) affect cloudiness. Changes in the meridional circulation were suggested as a possible reason for solar-like CC variability observed over the North America, but originating in top-down effects triggered by UV–ozone variations (e.g. Udelhofen and Cess 2001). Another possibility is that magnetospheric energy deposition into the ionosphere affects atmospheric gravity waves which, in turn, might affect atmospheric fronts and pressure dynamics (Tinsley 2000, Troshichev *et al* 2008).

The present result does not rule out the other possible CRII mechanism acting on the conductivity of the atmospheric layers (Tinsley 2000, Harrison and Usoskin 2010, Zhou and Tinsley 2012, Tinsley 2012). Figure 5 shows that CC increases especially when CRII anomaly is large and IEF is positive and large, which, in terms of solar effects on GEC, is the most effective combination. On the one hand the positive IEF increases the ionospheric potential, while cosmic ray induced ionization increases the conductivity, both leading to the increase of atmospheric current flow. Figure 6 depicts a relation between positive CC anomalies (zonal mean for mid–high latitudes) and the two drivers affecting the GEC: IEF and cosmic ray. One can see that three highest CC anomalies occur at the situation, when both IEF and CRII reach their largest values (large dots in the upper right corner). Out of nine positive CC anomalies, eight occurred during years with positive IEF (right-hand half of the figure), seven—during years with positive CR anomalies (upper half), six—during years of both CRII and IEF positive (upper right

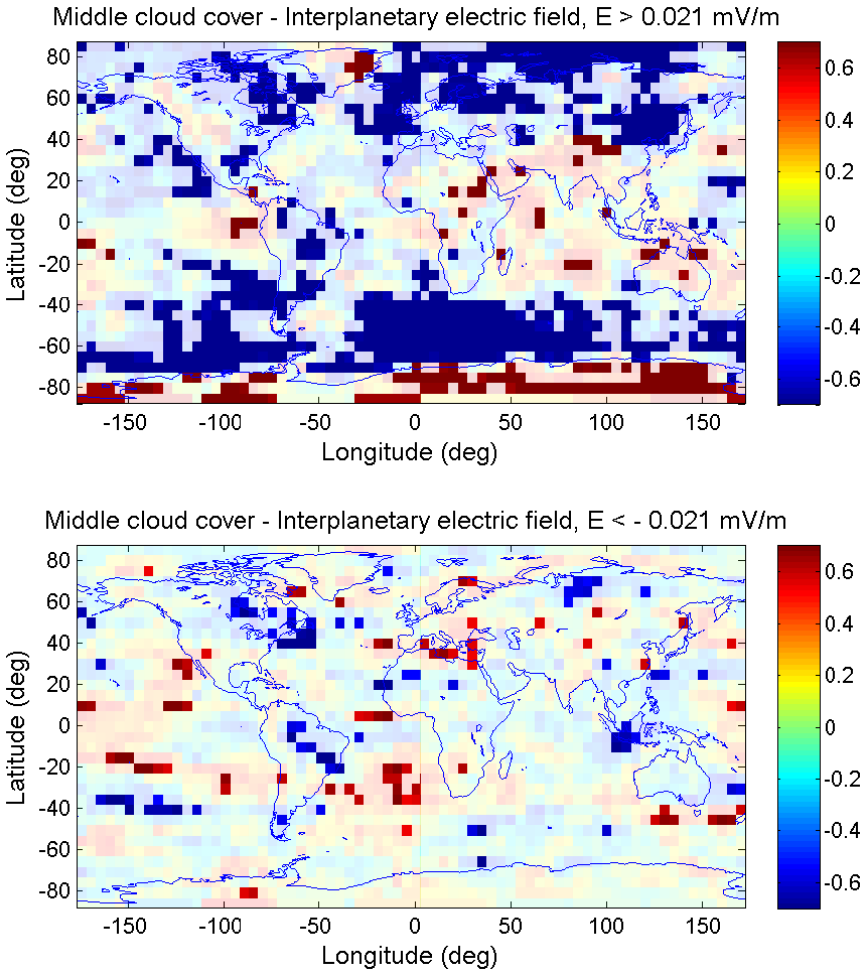

Figure 7. Correlation map between positive electric field (upper panel), respectively negative electric field (lower panel) and corresponding middle cloud cover. Significant correlation shown similar to figure 2.

quadrant) and none during the years with both CRA and IEF negative (left bottom quadrant). This is a non-trivial result since CRII and IEF are not correlated (see figure 5) and supports the hypothesis that GEC can be an important driver for cloud variability. This also means that GEC effects on cloud cover might be not distinguishable from noise when one of the two drivers does not favor an increase of the atmospheric current.

It is likely that these effects, which are small relatively to meteorologically induced cloud formation, are evident only when some particular conditions are met (wind, pressure, temperature, atmospheric stability). On the other hand, persistence of the longer-term j_z changes for decades–centuries would produce an integrated effect on climate, that could show up over short-term weather and climate variations, and explain the observed correlations (Tinsley 2000, Harrison *et al* 2013). An effect of the IEF on cloud cover may provide a link between atmospheric electricity and climate change, which is a crucially important topic for society today (Tinsley 2000, Harrison and Ambaum 2008, Gray *et al* 2010). When averaged over areas of the order of 10^3 km^2, changes in atmospheric electricity induced by solar wind variability (≅10%) are significantly higher than, for instance, ≅0.1% of total solar irradiance or ≅1% observed in solar UV (Tinsley 2000). Thus a more profound investigation of this probable effect on cloud cover might help in a better understanding of natural causes of natural variability.

Higher clouds (mid/high) also seem to respond to positive IEF, but in an opposite sense (i.e. anticorrelation between cloud cover and IEF). The effect is limited to smaller areas (coinciding with low pressure systems) and can be seen in figures 7 and 8, which also show that there is no relation between negative IEF and cloud cover. One possible explanation of the anticorrelation between IEF and mid–high clouds relies on the effect of electroscavenging (i.e. particle collection by falling droplets caused by electrical forces, Tinsley (2000)) on cold clouds, made of ice, with tops at temperatures below the freezing point. Tinsley and Yu (2004) have shown that an increase in the ionosphere-ground current density is followed by increased probability of precipitation due to a more efficient rate of contact ice nucleation producing larger droplets. Since tops of mid- and high-clouds are at negative temperatures, especially at high latitudes, their lifetime could decrease with increasing ionospheric-earth potential.

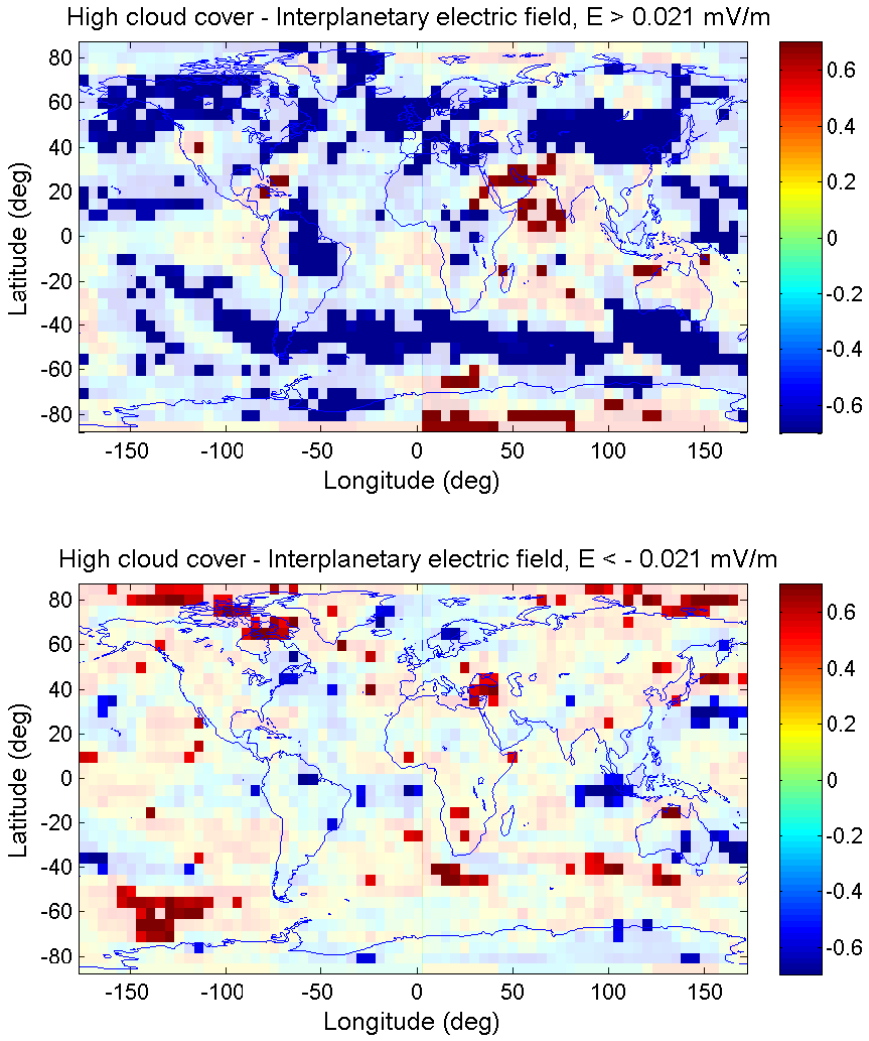

Figure 8. Similar as figure 7 for high cloud cover.

Previous results of various studies of solar effects on clouds at long-term scale (e.g. Voiculescu *et al* 2006, Voiculescu and Usoskin 2012, Erlykin *et al* 2010) have shown that low cloud cover responds better to solar radiation variations than to CR input, especially at low–mid latitudes and in defined geographical areas. Given our findings, it seems reasonable to conclude that, if existing, solar variability affects low cloud cover via the GEC at mid–high latitudes, while top-down mechanisms related to UV effects on ozone in the stratosphere might be at work at low–mid latitudes. These results, although not giving a direct proof of solar-driven GEC effects on cloud cover, are consistent with the hypothesis that low-clouds at mid- and high-latitudes can be affected by GEC, as proposed earlier by e.g. Tinsley (2000) and Harrison and Usoskin (2010).

4. Conclusion

Here we present a result of an empirical study showing that there is a weak but statistically significant relation between low cloud cover at middle–high latitudes in both Earth's hemispheres and the interplanetary electric field, that favors a particular mechanism of indirect solar activity influence on climate: global electric circuit affecting cloud formation. We show that all characteristics of the relationship are in line with what is expected if the interplanetary electric field affects cloud cover via the global electric circuit:

(1) the low cloud cover shows a systematic correlation, at interannual time scale, with positive interplanetary electric field, at mid- and high-latitude regions in both hemispheres;
(2) there is no correlation between low cloud cover and interplanetary electric field in tropical regions;
(3) there is no correlation between low cloud cover and negative interplanetary electric field over the entire globe.

As an additional factor, cosmic ray flux may also affect cloud cover in the presence of positive interplanetary electric field. No clear effect of cosmic ray flux during periods of negative IEF was found.

Similar, but less statistically significant results were found also for middle and high cloud cover, suggesting that

the primary effect is on low-clouds. The fact that the found statistical relation exists only for the periods of positive IEF and not for negative IEF disfavors other potential mechanisms of sun–cloud relations at mid–high latitudes, such as via ion-induced/mediated nucleation or UVI influence. However, the latter might work at low–mid latitudes. Although this empirical study does not give a clue for an exact physical mechanism affecting the clouds, as discussed above, it favors a particular solar driver, solar wind with the frozen-in interplanetary magnetic field, that affects the global electric current system at Earth. The result suggest that further research of solar-terrestrial influence ought to focus more also on this direction.

Acknowledgments

MV and SCB were supported by project PN-II-ID-PCE-2011-3-0709, SOLACE of the Romanian NPRDI-II, UEFISCDI. The COST ES1005 TOSCA project is also acknowledged. ISCCP project is acknowledged for cloud data. Goddard Space Flight Center is acknowledged for interplanetary field data, distributed via OMNIWeb plus page, at http://omniweb.gsfc.nasa.gov/.

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