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Proc. R. Soc. A 2011 **467**, 2777-2791 first published online 27 April 2011
doi: 10.1098/rspa.2011.0040

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Published online 27 April 2011

Cloud base height and cosmic rays

By R. Giles Harrison*, Maarten H. P. Ambaum and Michael Lockwood

Department of Meteorology, University of Reading, PO Box 243, Earley Gate, Reading RG6 6BB, UK

Cosmic rays modify current flow in the global atmospheric electrical circuit. Charging at horizontal layer cloud edges has been observed to be consistent with global circuit vertical current flow through the cloud, which can modify the properties of small and pure water droplets. Studies have been hampered by the absence of cloud edge observations, hence cloud base height information is investigated here. Cloud base height measured at the Lerwick Observatory, Shetland, UK, is analysed using threshold tests and spectral analysis. The cloud base height distributions for low cloud (cloud base less than 800 m) are found to vary with cosmic ray conditions. Further, 27 day and 1.68 year periodicities characteristic of cosmic ray variations are present, weakly, in the cloud base height data of stratiform clouds, when such periodicities are present in neutron monitor cosmic ray data. These features support the idea of propagation of heliospheric variability into layer clouds, through the global atmospheric electric circuit.

Keywords: atmospheric electricity; solar variability; solar–terrestrial coupling; natural climate variability

1. Introduction

One of the suggested coupling mechanisms linking solar changes with the lower atmosphere is through the vertical conduction current flowing in the global atmospheric electrical circuit. The conduction current responds to both the ionospheric electrification arising from thunderstorms and disturbed weather, and the finite conductivity of atmospheric air beneath the ionosphere, caused, in large part, by cosmic ray ionization (Rycroft *et al.* 2000, 2008). Galactic cosmic ray ionization changes induced by variations in the solar wind modulate the conduction current density, providing a route between solar changes and the lower atmosphere, and also, potentially, cloud processes. Evidence supports this solar link to the lower troposphere as, firstly, the modulation of cosmic ray ionization with the well-known 11 year (Schwabe) solar cycle (Bazilevskaya 2000) is well established, and, secondly, measurements of the ionospheric potential and conduction current show a positive relationship with cosmic ray activity (Markson & Muir 1980; Harrison & Usoskin 2010).

*Author for correspondence (r.g.harrison@reading.ac.uk).

Received 14 January 2011
Accepted 28 March 2011

The consequences of conduction current variations on lower atmosphere cloud properties are less well understood. Clouds vary considerably in response to the local thermodynamics of the atmosphere, but, for the specific case of extensive layer (stratiform) clouds in which convective overturning is small, passage of the conduction current through the horizontal cloud boundaries leads to the local accumulation of charge in a thin horizontal layer at the cloud edge. This is a consequence of Gauss's Law applied vertically to the sharp change in air conductivity in the transition from clear air to cloudy air: in steady state, the vertical current density on both sides of the boundary is the same and so the electric field is greater on the lower conductivity side of the boundary, requiring a space charge to reside on the boundary, referred to as the 'traffic jam' effect (Chalmers 1967). Recent experimental analyses have confirmed these theoretical expectations, both in that the current density does pass through cloud layers (Nicoll & Harrison 2009) and, quantitatively, that the layer cloud charge measured using balloon-carried instrumentation is consistent with predicted values (Nicoll & Harrison 2010). A response in cloud properties to conduction current changes, for example resulting from charge effects on the formation of small water droplets containing negligible dissolved salt (Harrison & Ambaum 2008), may therefore occur at cloud edges.

Cloud edge properties do not form part of operational meteorology; hence, investigations of cloud boundary responses to cosmic ray and conduction current changes have previously employed solar radiation measurements to infer changes in cloud droplet properties, such as those arising from increased scattering of sunlight by droplet concentration or size changes. For example, the proportion of diffuse radiation measured at the surface provides a measure sensitive to cloud changes (Harrison *et al.* 2008). One lower cloud boundary measurement made routinely, however, at some meteorological sites is the cloud base height. This is determined variously using cloud searchlights, modulated light beam techniques, or by a customized instrument (a *ceilometer*) employing, in modern versions, a laser time-of-flight measurement. The precise definition of cloud base is not necessarily as straightforward as it may seem, as cloud edges are generally extended regions of transitions between haze and drops (e.g. Koren *et al.* 2007). Here, the operational definition of cloud base, i.e. the height of the cloud boundary determined by the ceilometer, is used.

As cloud boundary droplet charging can influence droplet formation (Harrison & Ambaum 2008), cloud base height data for layer clouds may yield information on apparent cloud responses to cosmic ray changes, some of which seem likely to be electrical in origin (Laken *et al.* 2009). This is further motivated by observations that, at high-latitude sites, the averaged effect of large cosmic ray decreases has been reported to be accompanied by reductions in cloud (Pudovkin & Veretenenko 1995), particularly if the local cloud variability is relatively small (Harrison & Ambaum 2010).

2. Data sources

Previous work has studied cloud responses to cosmic rays at the Met Office's site at Lerwick, Shetland, UK, primarily because of its well-characterized atmospheric electricity climatology (Harrison & Nicoll 2008). For example, the Lerwick surface potential gradient[1] (PG) measurements are known to have common variations with: (i) simultaneous ionospheric potential measurements (Harrison & Bennett 2007; Rycroft *et al.* 2008) and (ii) distant PG measurements made in pristine oceanic air (Harrison 2004). In addition, the Lerwick vertical conduction current density (J_c) data show variations in phase with expected solar-induced cosmic ray variations (Harrison & Usoskin 2010). Lerwick Observatory's island location means that there are few sources of air pollution and frequent rainfall. Many meteorological quantities are observed, both automatically and manually. Analyses of indirect cloud data from Lerwick and neutron counter cosmic ray data using threshold tests (Harrison & Stephenson 2006), spectral properties (Harrison 2008) and Forbush step-changes in cosmic rays (Harrison & Ambaum 2010) are all suggestive of a cloud response to cosmic ray variations.

Lerwick Observatory data are considered further here, as their combination of extensive automatic measurements with continuous manual classification of clouds allows the specific case of extensive horizontal layer clouds to be selected from the considerable variety of clouds (e.g. convective, electrified, ice-cloud) more generally present. Cloud base height has been measured at Lerwick using a variety of methods since the 1950s, and a continuous record of automatic hourly cloud base data is available from 1983. The cloud base height was originally determined using a cloud base recorder (Met Office model Mk3A). This device operated by modulating a powerful searchlight beam with a rotating shutter, and phase-sensitive detection was used to retrieve the optical signal scattered by the cloud (HMSO 1982). The optical receiver was vertically beneath the cloud, with the light beam's elevation varied until the detector received light scattered by the cloud directly above. Knowledge of the baseline length between the transmitter and receiver and the elevation angle allowed the cloud base height to be calculated. The modern method now in use is a laser cloud base recorder, which uses a light beam passing vertically upwards. Through timing the interval between an emitted and returned pulse of light, the cloud base height is calculated. In general, the optical returns are much stronger for water droplets than for particles, allowing the cloud base to be distinguished from other aerosols present in the lower atmosphere.

To investigate the relationship between cloud base and cosmic rays, daily cloud base heights have been derived from the hourly measurements, to remove any diurnal cycle. As for previous studies, daily measurements from the Climax neutron monitor are used to provide information on the variations in cosmic ray fluxes, and associated atmospheric electricity changes, such as an increase in J_c with increased neutron count. Cosmic rays generate neutrons in the atmosphere, and the neutron monitor count rate at the surface, therefore, provides a measure of the cosmic ray flux incident upon the Earth's atmosphere.

(*a*) *Neutron data*

Figure 1*a* shows the variation in neutron counts observed at Climax, Colorado, during the period of cloud base measurements available from Lerwick. The effect of the 11 year cycle is apparent in the form of the cosmic ray maxima occurring

[1] It is a convention in atmospheric electricity to measure the PG F rather than the vertical component of the atmospheric electric field E_z. They are related by $F = -E_z$, and F is positive in fair weather.

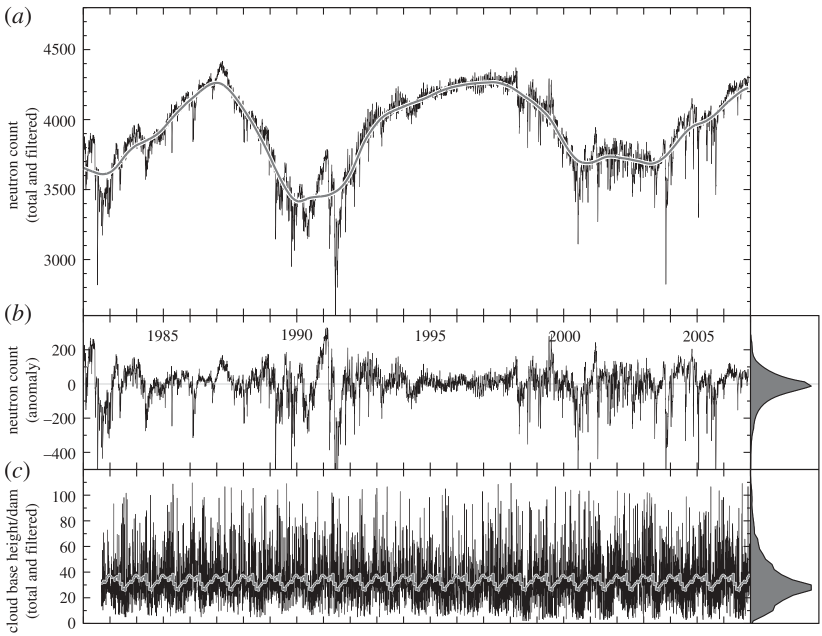

Figure 1. Time series of (a) Climax neutron data, (b) high-pass filtered neutron data and (c) Lerwick cloud base height, from 1983 to the end of 2007. A cosine tapered running mean filter of 1 year half width was added to (a) to generate the grey line and this was used to remove the secular and solar cycle variations, allowing the series of daily anomalies to be found, as shown in (b). (c) Also shows the seasonal cycle in cloud base height (grey line) in decametres, derived from semi-monthly averaging. The right-hand side of (b) and (c) show the associated histograms for the whole interval.

around 1987–1988 and 1998–1999. This difference follows a 22 year (Hale) cycle as the polarity of the solar magnetic field reverses roughly a year after each sunspot maximum. The effect of this on the drift of charged cosmic ray particles in the heliosphere is to cause alternate cosmic ray maxima at sunspot minima (e.g. Heber & Burger 1999) which are rounded (as for the 1998/1999) and peaked (as for 1987/1988). Around the cosmic ray minima (at sunspot maxima) sudden drops in neutron count (Forbush decreases) are also evident.

Solar ultraviolet radiation and the total solar irradiance also show a variation with the 11 year cycle, which is thought to have atmospheric effects. Hence, to reduce the ambiguity of cause and effect in any atmospheric response to periodic variations in cosmic rays and solar radiation, only variations with periods shorter than 11 years are considered here. To extract such high-frequency (i.e. daily) information, the data values were subtracted from the running mean shown in figure 1a (effectively passing the data through a filter of half width 1 year). Figure 1b shows the high-frequency data after removing the solar cycle variations, as anomalies from the running mean. The distribution of the values, shown to the right of the panel, shows a long tail of negative anomalies.

Table 1. Low cloud type descriptions of the World Meteorological Organization.

subset of low cloud type of genera stratocumulus, stratus, cumulus, etc.	
code	description
0	no stratocumulus, stratus, cumulus or cumulonimbus
1	cumulus with little vertical extent and seemingly flattened, or ragged cumulus, other than of bad weather, or both
2	cumulus of moderate or strong vertical extent, generally with protuberances in the form of domes or towers, either accompanied or not by other cumulus or stratocumulus, all having bases at the same level
3	cumulonimbus, the summits of which, at least partially, lack sharp outlines but are neither clearly fibrous (cirriform) nor in the form of an anvil; cumulus, stratocumulus or stratus may also be present
4	stratocumulus formed by the spreading out of cumulus; cumulus may also be present
5	not resulting from the spreading out of cumulus
6	stratus in a more or less continuous layer, or in ragged shreds, or both but no stratus fractus of bad weather
7	stratus fractus of bad weather or cumulus fractus of bad weather, or both (pannus), usually below altostratus or nimbostratus
8	cumulus and stratocumulus other than that formed from the spreading out of cumulus; the base of the cumulus is at a different level from that of the stratocumulus
9	cumulonimbus, the upper part of which is clearly fibrous (cirriform) often in the form of an anvil; either accompanied or not by cumulonimbus without anvil or fibrous upper part, by cumulus, stratocumulus, stratus or pannus

(*b*) *Cloud base data*

Figure 1*c* shows daily mean values of the cloud base height at Lerwick, from the hourly values available between 1983 and the end of 2006. The smoothed line shows the mean annual variation. To the right of the panel, the overall distribution of the measurements is given. The actual number of hourly cloud base height values available each day is weather dependent. A feature of the observations at Lerwick is that manual observations of the cloud type are also made hourly, which allows the specific selection of layer clouds. These are classified using the standard World Meteorological Organization (WMO) codes, and the subset of the WMO codes for low clouds (http://badc.nerc.ac.uk/data/surface/code.html) is given in table 1. These descriptions also serve to illustrate the considerable natural variability present in clouds, of which low cloud is only one category, and, within which, layer clouds represent a further subset.

During this series of cloud base measurements, the atmospheric electricity measurements of J_c and PG were unfortunately no longer recorded at Lerwick, those measurements having ceased at the end of 1983 (Harrison & Nicoll 2008). Hourly measurements of the PG during the Lerwick cloud base measurements were, however, made at the Nagycenk Observatory, Hungary. The response to variations such as Forbush decreases (Märcz 1997) and cosmic ray-specific periodicities of a few days and greater are on time scales long enough that they are not dominated by local effects and are seen globally (Harrison & Märcz 2007). Hence, the Nagycenk measurements provide indications of changes in the global atmospheric electrical circuit, which is known to be coupled to the surface atmospheric electricity at Lerwick through J_c. Further, the Climax neutron counter data, which are also available during the cloud base measurement series, provide a proxy for the local resistance of the atmospheric column at Lerwick and the associated J_c variations.

3. Analysis

One expected response of horizontal cloud edges to changes in J_c is enhanced droplet formation facilitated by the charging at cloud edges (Harrison & Ambaum 2008). Charging allows pure droplets to form at slightly reduced supersaturation compared with neutral droplets, lowering the cloud base. Cloud base height therefore, in principle, should provide a direct measurement of cloud response to cosmic ray changes modifying the current density. As mentioned above, *in situ* measurements of the current density are not available from Lerwick during the cloud base observations, but a positive relationship between neutron counter cosmic ray data and current density has been previously established for the site (Harrison & Usoskin 2010). Accordingly, the neutron counter data from Climax are regarded here as a measure of the current density passing through the cloud at Lerwick. Note that there are additional variations in the global ionospheric potential associated with the current density, for example the diurnal 'Carnegie' variation (Mülheisen 1977; Markson 1985). Two approaches are taken to determine cloud responses to cosmic ray changes. Firstly, the de-seasonalized cloud base data are divided into low and high neutron count anomalies, and, secondly, the cloud base height is analysed spectrally for times when specific spectral signatures are known to occur in the neutron counter data.

(*a*) *Neutron counter threshold tests*

To test for cloud base responses coincident with increases and decreases in J_c, high and low neutron counter anomalies are identified in the cloud base data using the upper and lower terciles of the Climax dataset for the interval studied. The neutron counter data are first high-pass filtered (i.e. the data in figure 1*b* are used), and then compared with the cloud base height anomalies after subtracting the mean seasonal variation shown in figure 1*c*. Figure 2 shows histograms of the cloud base anomalies on days having the upper tercile of high-pass filtered neutron counts (to the left) and the lower tercile of high-pass filtered neutron counts (to the right). The cloud base data were also selected for stratiform cloud with base below 800 m, i.e. for the specific case of layer clouds very likely to contain liquid water. These histograms of cloud base heights in the high and low cosmic ray circumstances have different shapes; the difference in shape is indicated with the solid line, which is the cumulative difference (starting with zero at the lowest cloud base) between the high neutron count events and low neutron count events. The fact that this cumulative difference at the lower cloud edges is positive means that for high neutron counts the distribution of cloud

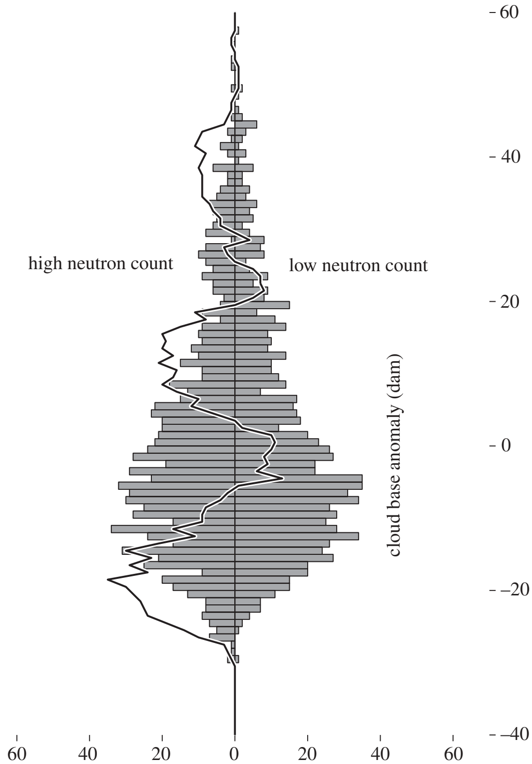

Figure 2. Histograms of cloud base height anomalies (in decametres) for the upper tercile of high-pass filtered neutron counts (left-hand side, labelled 'high neutron counts') and the lower tercile of high-pass filtered neutron counts (right-hand side, 'low neutron counts'). The cumulative difference between the two histograms is shown by the solid line. Only low cloud base values (less than 800 m) are considered, for stratus cloud (recorded as types 5–6) with 2817 data values in total.

edge heights is skewed towards lower cloud base heights, compared with the low neutron count case. This is consistent with an enhancement of droplet formation owing to increased edge charge.

For the high neutron count case, the calculated mean of the height anomaly distribution is shifted down by 7 m, but the median rises by 5 m. This is indicative of the fact that the first moment of the distribution is not the main response in the cloud base height distribution; rather, the shape, as measured by higher moments, is changing. Furthermore, it was found that these differences in mean and median were very sensitive to sampling variance. The precise structure of the cumulative difference was also sensitive to the choice of the parameters in our analysis, but the positive feature in the cumulative difference at the bottom end of the cloud heights is robust. Specifically, comparing the lower and middle terciles (and the lower tercile will contain some Forbush decreases in neutrons) there is a strong and uniformly positive signal in the cumulative difference, while comparing the middle and upper terciles, there is a much reduced and, for higher clouds, even an opposite signal. Hence, although the sampling noise is substantial, the positive cumulative difference for low clouds is robust.

(b) *Spectral analysis of cloud base data*

While the common occurrence of low cloud bases and enhanced current density does suggest a cloud boundary relationship with current density J_c, it does not uniquely associate J_c with the cloud boundary response. This is because other factors could co-vary with J_c or cosmic rays, such as solar or geophysical parameters. Forbush decreases in cosmic rays, which occur on time scales of days, provide one method previously used to attribute cloud changes to cosmic ray changes, for example at Lerwick (Harrison & Ambaum 2010). An alternative approach in investigating a direct link between the two parameters suggested to be causally related (i.e. cosmic ray-modulated current density and the cloud base) is used here, by considering whether two signatures known to be present in the power spectrum of cosmic rays are present in the cloud base data. These are (i) the 27 day variations known to be generated in the neutron counter data by a long-lived solar co-rotating interaction region (CIR) in the second half of 1996 (Rouillard & Lockwood 2007) and (ii) the 1.68 year periodicity characteristic of the heliosphere in the 1980s (Rouillard & Lockwood 2004).

To identify the periodicities present in different datasets, the Lomb spectral technique is used (Lomb 1976; Press *et al.* 2007). This spectral method was developed for analysis of intermittent data series in astronomy. It works by fitting periodicities to the available data, rather than the more standard technique of transforming a regularly sampled series of data. This makes it particularly suitable for meteorological quantities which are intermittent with weather conditions, such as the fair weather PG. By applying a moving window to select data around a central time and making successive applications of the Lomb technique on consecutive data windows, the variation in relative spectral power with time can be found.

(i) *Co-rotating interaction region 27 day periodicity*

The galactic cosmic ray flux reaching the Earth is influenced by interactions within the heliosphere, and consequently is closely related to solar conditions. In particular, isolated coronal holes can control shielding of galactic cosmic rays by the inner heliosphere. Such coronal holes enhance the solar wind outflow and influence the formation of CIRs, ahead of which shock waves and compression regions modulate the cosmic ray fluxes. During the second half of 1996 (near solar minimum), an active solar region modulated the galactic cosmic rays, as observed from a variety of solar and neutron monitors. Specifically, at the Climax neutron monitor, a well-defined approximately 27 day oscillation (close to the average solar rotation period) was observed in this latter part of 1996. This oscillation provides a marker in the cosmic ray data which may be propagated through the global atmospheric electric circuit yielding a response in stratiform clouds.

Figure 3*a* shows a time series of daily averages from the Climax neutron counter centred on the the latter part of 1996 (in black), together with the simultaneous PG measurements from the Nagycenk Observatory (in grey). The ‘marker’ period of oscillatory behaviour associated with CIR is clearly evident in the neutron data directly, even without further spectral analysis. Such a response is much less apparent in the PG data in which, in general, local variability can obscure global signals. During winter, however, reduced local meteorological

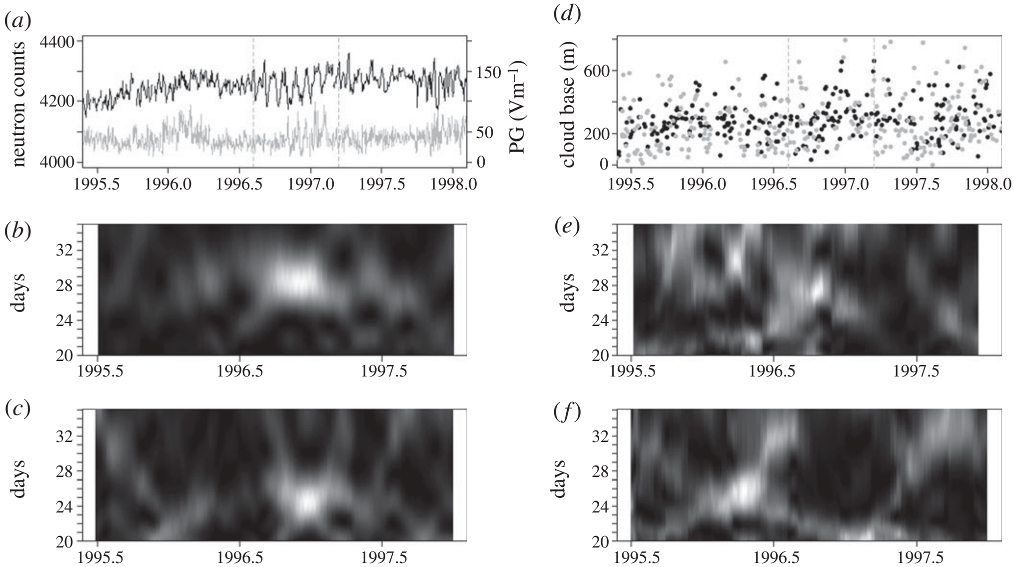

Figure 3. (*a*) Time series of daily Climax neutron data (black lines, left-hand axis) showing the 27 day periodicity induced by a long-lived, slowly evolving co-rotating heliospheric structure during the latter part of 1996 (1996.6–1997.2 marked), and the fair weather (daily averages from days with $0 \leq \mathrm{PG} \leq 120\,\mathrm{V\,m^{-1}}$ for 12 h or more) PG observed at the Nagycenk Observatory, Hungary (grey lines, right-hand axis). Moving window Lomb spectrograms for detrended data to which a cosine taper has been applied for (*b*) neutron data from (*a*) and (*c*) Nagycenk fair weather PG. (*d*) Time series of Lerwick cloud base data (beneath 800 m), bad weather cumulus or stratus fractus marked in black and stratus in grey. Moving window spectrograms for cloud base in the cases of (*e*) stratus and (*f*) fractus. (The moving window width in all cases is 0.5 years, with a cosine taper of 0.25 applied. The shading becomes whiter with increasing relative spectral power.)

variability can assist the observations of global signals, such as the retrieval of the diurnal Carnegie curve with less averaging than in other seasons (Israël 1973). Figure 3*b*,*c* shows the same time series as in figure 3*a*, but with a moving window spectral technique. Using a moving window of width 0.5 years, with a taper applied to reduce spectral leakage from data truncation at the window edges, successive periodograms have been calculated using the Lomb method. In figure 3*b*, the oscillatory period in the neutron data, which can be seen by eye, is clearly evident in the spectrogram. Although not a sharp spectral feature in terms of a narrowly constrained periodicity, it is relatively strong considered against other spectral features, and its occurrence coincides with the period of CIR oscillations. Figure 3*c* shows the corresponding spectrogram of the PG data from the same time. There is a dominant feature in the relative spectral power density at the same time as the CIR oscillations, but with a shorter period (approx. 24 days). For noisy time series containing only a few oscillatory cycles the periodicity retrieved is uncertain in its onset, finish and frequency; hence, this period of increased spectral power density can be broadly interpreted as a potentially similar spectral feature, which occurs simultaneously with the neutron data CIR variation.

Cloud base data from measurements made at Lerwick at the same time as the data in figure 3*a* are shown in figure 3*d*. Daily cloud base values have been calculated from the hourly values available on each day, for low cloud (beneath 800 m). Because the cloud boundary charging considerations only apply to layer clouds, these data have been divided into stratus cloud (recorded as cloud types 5–6 and shown in grey) and bad weather cloud (cumulus fractus or stratus fractus, recorded as cloud types 6.7–7.9 and shown in black), generating a further intermittent time series. Moving window spectrograms for these two cloud base time series and the stratus and fractus cases are shown in figure 3*e*,*f*, respectively. In the stratus case, there is increased relative spectral power with the same periodicity as for the neutron data spectrogram, in the first half of the time interval of the CIR periodicity as seen in figure 3*b*. In contrast, the spectrogram for the fractus case does not show spectral power at the same or similar periodicities in the CIR time interval. Additional spectral variability is also present in both spectrograms at other periodicities, expected from internal variability of the atmosphere.

Returning briefly to the PG spectrogram, figure 3*c*, the feature is only present during the second half of the corresponding feature in the neutron monitor data. We attribute this to changing local conditions at the Nagycenk Observatory that suppress the cycles. Close inspection reveals a good subsequent match between the two time series, for three full cycles of the oscillation; however, in the PG data, the oscillations begin halfway through a cycle. This onset reduces the derived period: whereas four full cycles of the neutron monitor data take place over 112 days (giving a mean period of 28 days), the first half of the PG cycle is missing and this appears to give four cycles over 98 days (an apparent period of 24.5 days). The closeness of the agreement between the neutron data and PG is apparent after bandpass filtering both datasets, using a phase-preserving bandpass filter centred around 27 days, passing periodicities between 25 and 30 days (figure 4). To generate the filtered results, missing values were replaced by random selection within the same data and the responses from multiple realizations averaged. When bandpass filtered, the neutron and PG agree in phase around the end of 1996 and beginning of 1997, which is not inconsistent with their variations having a common origin.

(ii) *Heliospheric 1.68 year periodicity*

A longer quasi-periodicity of approximately 1.68 years (approx. 614 days) has been identified in neutron counter data in some solar cycles, thought to originate in the heliosphere (Rouillard & Lockwood 2004). This provides a further periodicity characteristic of galactic cosmic rays, particularly during the early 1980s when it was strongest and most apparent in neutron data. This periodicity has previously been identified in daily diffuse fraction data at Lerwick (Harrison 2008), which is a surface-observed quantity providing a measure of the diffuse solar radiation scattered by cloud. Figure 5 shows the bandpass-filtered Climax neutron data with the moving window spectrogram technique applied, using 11 year window data following Rouillard & Lockwood (2004), together with a similar analysis of the Lerwick diffuse fraction data. A similar periodicity appears in the Lerwick cloud data in the mid-1980s, coincident with the maximum in the neutron counter data. The diffuse fraction variability

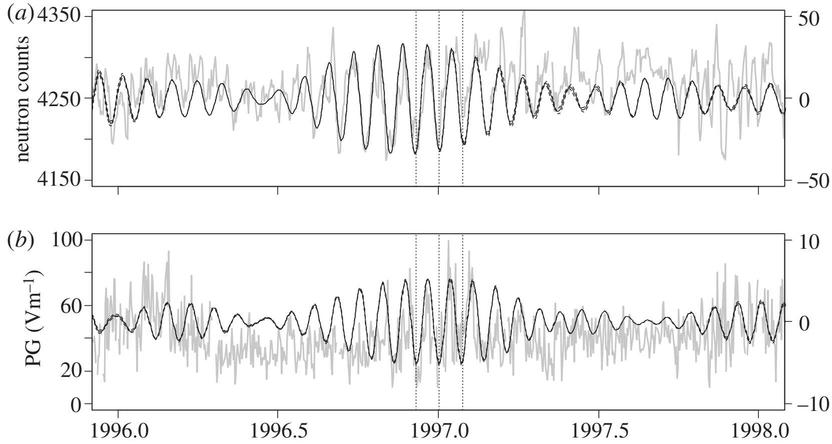

Figure 4. Daily time series (grey lines with scale on left-hand axis) of (*a*) Climax neutron counts and (*b*) Nagycenk potential gradient (PG), filtered using a phase-preserving Lanczos bandpass filter of length 150 days, centred on 27 days but passing periodicities in the range 25–30 days (black lines with scale on right-hand axis). Vertical lines marking minima in the bandpass-filtered neutron data around the beginning of 1997 are shown in (*a*), with vertical lines drawn at the same positions in (*b*).

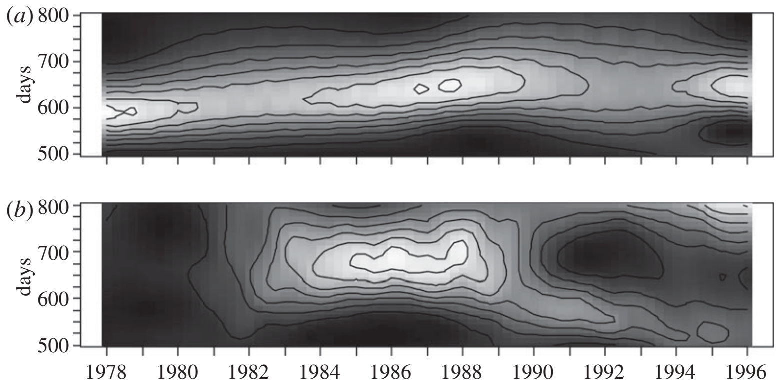

Figure 5. Moving window spectrograms (0.5 cosine-tapered 11 year width windows generated from daily data) of (*a*) bandpass (1.55–1.81 years) filtered Climax neutron data and (*b*) the diffuse fraction (ratio of diffuse to total solar radiation observed at the surface) at Lerwick. Both spectrograms have been generated around the 1.68 year (approx. 614 day) cosmic ray periodicity. (The shading becomes whiter with increasing relative spectral power; equally spaced contours have been added.)

observed may originate in cloud base changes, but unfortunately a similar moving window approach cannot be applied to the cloud base data because of their restricted duration.

Instead, the cloud base data are divided into two periods, during and after the maximum in the 1.68 year neutron counter periodicity. Figure 6 shows periodograms of neutron counter and cloud base data, during (*a*) 1983–1991 and (*b*) 1993–2001, with the periodicity at 1.68 years marked. The cloud base

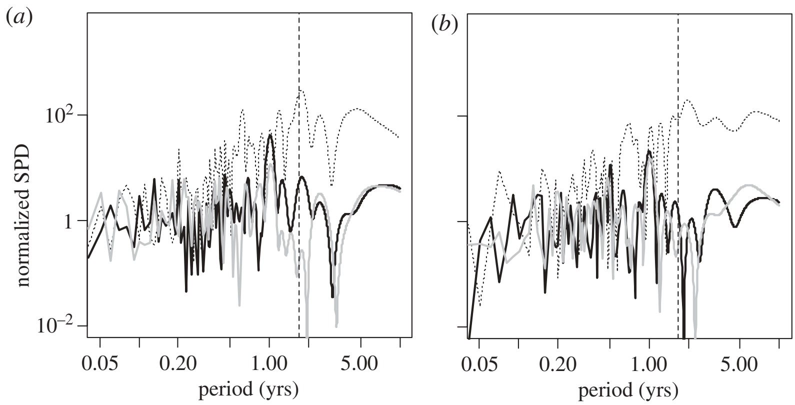

Figure 6. Power spectra from high-pass filtered daily neutron counter data (dotted) and daily Lerwick cloud base data (solid) for (*a*) 1983–1991 and (*b*) 1993–2001, with power spectra for cloud base of stratus (layer) cloud (black) and fractus (bad weather) cloud (grey). The dashed line marks a periodicity of 1.68 years.

data have again been divided into stratus and fractus cases. The stratus cloud also shows spectral power at 1.68 years in the earlier period (*a*), and indeed its spectral power varies similarly with the spectral power present in the neutron data for longer periodicities (up to the decadal scale of the solar cycle). In (*b*), there is no well-defined periodicity in the neutron data at 1.68 years, and the peak is also missing the stratus cloud base data in this case. In addition, several other periodicities present in the neutron power spectrum are similar to those in the stratus cloud base data power spectrum.

This analysis shows that cloud base data can provide complementary information to that obtained from solar radiation measurements beneath clouds, and indeed that the radiative effects previously observed may have arisen in cloud base changes.

4. Discussion

Physical reasoning argues that layer cloud edges are regions where response to atmospheric electricity changes induced by cosmic ray changes may be observable. Cloud base height observations may, therefore, provide information on any cosmic ray cloud effect at the lower cloud edge, and dividing the Lerwick cloud base data by upper and lower terciles of the neutron count does demonstrate that the distributions of cloud base height differ with neutron count differences, with lower clouds more prevalent at high neutron count rates. It is worth remarking that, while each of the results could have been subjected to an individual test of statistical significance, the outcomes would, as usual with significance tests, be based on the precise choices of null hypotheses and arbitrary significance thresholds. As discussed elsewhere (Ambaum 2010), significance tests alone cannot quantitatively support the hypothesis of electrical effects on cloud base height. Instead, the several lines of different evidence assembled here point in the same direction, although each individual aspect suffers substantially from sampling noise.

As there may be causes for this variability in the cloud base other than cosmic rays, adopting a spectral approach allows identification of cosmic ray-specific signatures in the cloud base data. The cosmic ray signatures studied have different time scales (27 days for the CIR and approx. 614 days for the heliospheric periodicity), and occur at different times (late 1996 and the early 1980s, respectively). In both cases, a weak but similar periodicity is apparent in the Lerwick stratiform cloud base heights at about the same time. In making these comparisons, it must be remembered that the neutron data are continuous whereas the cloud base data are sporadic (being only possible when stratus clouds are present). This argues for propagation of a signal through the atmosphere into the properties of low layer clouds; it is physically reasonable for such a signal to propagate through the global atmospheric circuit to the lower atmosphere because of the role of cosmic ray ionization in facilitating current flow. Although it is by no means an unambiguous signature, a CIR-like signal appears in PG data in late 1996, as well as a 1.68 year periodicity during the 1980s (Harrison & Märcz 2007).

While there is encouraging qualitative agreement, the signature in the PG data (taken at the Nagycenk Observatory) is only found in the second half of the series of 27 day oscillations in the cosmic ray data, and the stratus cloud base signature at Lerwick is only found in the first half of the sequence. This is attributed to local factors influencing the PG and cloud base data; for example, suppression of the fair-weather current by rain, fog or pollution at Nagycenk and the limited abundance of stratus clouds at Lerwick. The unfortunate cessation of the Met Office's PG measurements at Lerwick means that the presence of PG oscillations cannot be tested for directly at Lerwick when the cloud base oscillations were present at the same site. However, as figure 4 shows, the Nagycenk data do indicate that the cosmic ray oscillations coincide with PG oscillations as expected, and hence that the proposed association is viable.

Although a cloud base observation only provides information on the lower boundary of layer clouds, symmetry considerations in electrostatics broadly indicate that the upper boundary should respond similarly electrically. This would have implications for the radiative balance of the upper part of the cloud, and radiation to space. In practice, there are meteorological differences between the upper and lower edges of layer clouds; hence, the sensitivity of the response will depend on the droplet concentration gradient at the upper cloud boundary, which is likely to differ from the lower boundary's gradient.

The Climax neutron counter was supported by National Science Foundation grant ATM-9912341. Lerwick cloud base heights were obtained by the Met Office, provided in the MIDAS Land Surface Observation dataset by the NERC British Atmospheric Data Centre. Dr F. Märcz of the Geodetical and Geophysical Research Institute of the Hungarian Academy of Sciences provided the Nagycenk PG measurements. The contributions of the four anonymous referees are greatly appreciated.

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