Vertical profile measurements of lower troposphere ionisation

R.G. Harrison, K.A. Nicoll, K.L. Aplin

1. Introduction

Molecular cluster ions contribute to the finite electrical conductivity of atmospheric air, permitting current flow in the global atmospheric electric circuit (Rycroft et al., 2000). Cluster ions are formed in the lower troposphere by the ionising effects of natural radioactivity and galactic cosmic rays (GCRs), and, episodically, solar energetic particles (SEPs). Well above the continental surface, GCRs provide the principal source of ionisation. Several possible effects of cluster ions on atmospheric processes are now under active investigation, such as through the electrification of layer clouds associated with current flow in the global circuit (Nicoll and Harrison, 2010), ion-induced nucleation at cloud levels (Kirkby et al., 2011) or radiative absorption by cluster ions (Aplin and Lockwood, 2013). These all require an accurate determination of the spatial and temporal variations in atmospheric ionisation at the relevant altitudes and location.

Ionisation from GCRs can be measured using a number of techniques deployed, variously, at the surface, within the atmosphere or in space. Spacecraft sensors can be used to detect ionising particles, particularly SEPs, but as SEP emissions are sporadic and associated with solar storms, they do not contribute substantially to atmospheric ionisation in normal conditions, and hence are not considered further. When a primary cosmic ray particle, often a helium nucleus or a proton (Usoskin and Kovaltsov, 2006), enters an atmosphere it will interact with molecules to produce a cascade of secondary particles including protons, electrons, neutrons, and muons, many of which contribute to atmospheric ionisation. A range of GCR detection techniques can therefore be used as indirect measurements of atmospheric ionisation. Some ground-based experiments determine the energy of primary GCRs using Extensive Air Shower (EAS) arrays or Cherenkov radiation, but, as these modern astroparticle physics experiments are usually designed to detect only the highest-energy particles, they are unsuitable for routine monitoring of atmospheric ionisation (e.g. Abraham and the Pierre Auger Observatory Collaboration, 2004; Watson, 2011). The cosmogenic isotope $^{10}$Be is produced in the stratosphere and upper troposphere from the bombardment and breakdown (spallation), of N$_2$ and O$_2$ nuclei by GCR neutrons; inferring past $^{10}$Be generation through assessing its abundance in polar ice sheets provides an indirect (proxy) method for monitoring the long term GCR flux (Lal and Peters, 1967; Beer, 2000). Disadvantages of the $^{10}$Be technique are that its production occurs in the stratosphere, and obtaining reliable information from the $^{10}$Be record requires accurate representation of environmental processes controlling $^{10}$Be production, transport and deposition (Pedro et al., 2011). Surface measurements of GCRs can also be made using muon telescopes, which detect the muon component of the nucleonic cascade. As muons cause most of the GCR ionisation in the lower...
troposphere, this approach is useful for ionisation measurement, but the technology is not widely used, as the data has to be corrected for atmospheric variations to obtain the primary GCR flux (e.g. Duldig, 2000).

Extensive regular monitoring of GCRs utilises surface neutron monitors, introduced in the 1950s (Simpson et al., 1953). These devices are sensitive to the neutron component of the nucleonic cascade initiated by the primary GCR particles. As Aplin et al. (2005) pointed out, it is sometimes assumed that neutron monitor data also provides a good estimate of ionisation in the lower troposphere, rather than just at the neutron-producing region of the atmosphere. However, the contribution to atmospheric ionisation from lower-energy particles, which do not necessarily produce neutrons, is also required (e.g. Lindy et al., 2014). This means, for example, that the variability found in situ at the upper level intensity maximum is larger than that in the nucleonic component at the surface, e.g. by a factor of two (Brown, 1959). Models of lower atmosphere ionisation calculate the average vertical profile using standard atmospheric properties (e.g. Usoskin and Kovaltsov, 2006; Mishev, 2013), but, to determine the instantaneous ionisation rates in the real atmosphere, in situ measurements are still required.

A series of in situ soundings of atmospheric ionisation is described here, and compared with both neutron monitor data and modelled profiles. These soundings are evaluated in terms of their use in atmospheric electricity, both in providing parameters for the global atmospheric electric circuit, and for investigating radiative effects of ionisation, such as through effects on clouds.

2. Methodology

Standard meteorological balloon measurement systems, based on radiosonde packages, are routinely used to obtain vertical atmospheric profiles of temperature and relative humidity for weather forecasting purposes. This established infrastructure can also provide an inexpensive platform with which to make vertical measurements of ionisation. A new disposable instrument for meteorological radiosondes has recently been developed (Harrison et al., 2012, 2013a) which is based on two miniature Geiger tubes – a geigersonde – and a set of these instruments has provided the measurements considered here. The geigersonde approach to obtaining ionisation profiles is well-established (e.g. Pickering, 1943; Stozhkov et al., 2009), but, by using a digital interface system with a modern radiosonde (Harrison 2005a; Harrison et al. 2012), the radiosonde's meteorological data can also be retained. Hence, as well as telemetering the total number of events detected since switch-on by the two independent Geiger tubes, the standard meteorological measurements of temperature, pressure, relative humidity, as well as GPS location can be conveyed.

By using the radiosonde's height and position information, the tubes' count rates can provide the vertical ionisation profile. Furthermore, if a range of profiles are obtained that are well separated in time, changes between the launches can be investigated, for example that associated with the solar modulation (Neher, 1967; Sloan et al., 2011). Finally, by releasing the same design of instrument at different launch locations, the variation in ionisation profile with geomagnetic latitude can be determined. In each case, the validity of the ion production profiles can be confirmed through comparison with modelled values and simultaneous surface measurements made using neutron monitors.

The Geiger tubes used in these instruments are Neon–Halogen LND714 beta–gamma detectors, operated at a well-regulated bias voltage of 465 V (Harrison et al., 2013a). This tube has a small detection volume (33 mm length and 5 mm diameter) compared with typical tubes employed in atmospheric applications, so the count rates from the two tubes are summed to improve the statistics. (A laboratory experiment with an 18 kBq 60Co gamma source confirmed that combining the two count rates also reduced the effect of tube-to-tube variability to better than 2% for the LND714s tested.) The tube's response to gamma radiation from a 60Co source is specified by the manufacturer as 1.5 counts s⁻¹ per Roentgen of radioactivity.¹ Using this calibration to determine the charge generated per unit mass of air per count (for which the associated volume can be found under conditions of standard temperature and pressure, STP, defined here as 25 °C and 1000 hPa), and assuming that ions carry a unit elementary charge, the rate of ion production per unit volume of air 𝑞_{STP} associated with a count rate 𝑋 in events min⁻¹ can be found as

\[ q_{STP} = 2.95X, \]

where 𝑞_{STP} is the ionisation rate in number of ions cm⁻³ s⁻¹. As well as providing the bias voltage to operate the tubes, the electronic system records the total number of pulses received from each of the two tubes separately, the operating time, and the interval between the pulses. The pulse interval can provide additional resolution at low count rates, such as in the lower atmosphere, as, if only a few counts occur per minute, the proportional error in the count rate caused by a pulse occurring at the beginning or end of the measuring time can otherwise be appreciable (Harrison et al., 2013a). Measured quantities are transmitted over the standard UHF radio link every 30 s, interleaved with the meteorological data and position information. The data values are processed by calculating the count rates for each tube separately, using a moving 60 s window.

3. Results

3.1. Characterisation of soundings

Geigeronde launches were made from Reading University Atmospheric Observatory (51.442°N, 0.938°W) during 2013 and early 2014 using 200 g helium-filled carrier balloons. These launches were made when an instrument package had been fully constructed and tested, and the meteorological conditions allowed a straightforward single person release; these requirements amounted to a largely random set of releases. This is apparent from the trajectories taken by the geigerondes shown in Fig. 1 showing the different wind directions encountered, which also marks the position where the maximum height was obtained. (Full details of the flights are given in Table 1, including the times of the balloon release. Raw data is available through the corresponding author). Altitudes at which the balloon burst varied between the launches, but most reached at least 20 km.

Fig. 2 shows the vertical profile of measured count rate for soundings reaching at least 25 km, with the count rate obtained using the averaging window technique (Harrison et al., 2013a). In each sounding, the individual data points from the two tubes carried are shown using different plotting symbols, with a cubic spline fitted to smooth the data. All of these soundings show the characteristic form of a small count rate in the lowest few km, increasing sharply from about 5 km to reach a maximum value around 20 km (referred to here as the Regener–Pfotzer,² or RP.

¹ The Roentgen is no longer a standard unit of radioactivity. It remains useful for determining ion production rates, as it is characterised in terms of the charge released per unit mass (2.698 × 10⁻⁵ C kg⁻¹), from which the number of elementary charges produced per unit volume can be calculated.
² The important contributions of Erich Regener (1881–1955) whilst working at Stuttgart have been widely neglected (Watson and Carlson, 2014). Regener
The fitted spline provides the height of the RP maximum, and the associated time and count rate have been included in Table 1.

Because the count rates are small at low altitudes, the data from both tubes in the geigersondes have been combined to give a mean count rate in vertical layers of 1 km thickness, as shown in Fig. 3a. This is an alternative approach to use of a smoothing spline to reduce the variability, and allows visual comparison between the different flights. Air temperature measurements made during each sounding are provided for comparison in Fig. 3b, to show the associated atmosphere structure. The height at which the air temperature ceases to decrease with height, i.e. the base of the tropopause, varies (as is well known) with the time of year. The increase in temperature above this which marks the base of the stratosphere is broadly consistent with the position of the RP maximum. In comparison, the coarser vertical temperature profile from the US standard atmosphere only approximates each of the real soundings, particularly at the base of the tropopause. For the

### Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Launch time (UT)</th>
<th>Oulu neutron monitor count rate at launch time</th>
<th>Burst height (km)</th>
<th>Height at which maximum count rate reached (km)</th>
<th>Flight duration to reach maximum count rate (s)</th>
<th>Time at which maximum count rate reached (UT)</th>
<th>Oulu neutron monitor at time of maximum count rate</th>
<th>Meteorological properties (temperature T, pressure P and density ρ) at height of maximum ionisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th Feb 2013</td>
<td>1400</td>
<td>6301 ± 47</td>
<td>23.93</td>
<td>18.89</td>
<td>3629</td>
<td>1500</td>
<td>6321 ± 50</td>
<td>−63.4 66.8 111</td>
</tr>
<tr>
<td>15th Feb 2013</td>
<td>1210</td>
<td>6436 ± 49</td>
<td>20.78</td>
<td>19.16 (ascent)</td>
<td>4545 (ascent)</td>
<td>1330</td>
<td>6326 ± 49</td>
<td>−53.6 63.9 101</td>
</tr>
<tr>
<td>11th Apr 2013</td>
<td>1219</td>
<td>6304 ± 44</td>
<td>25.97</td>
<td>18.72 (ascent)</td>
<td>6350 (ascent)</td>
<td>1400</td>
<td>6317 ± 48</td>
<td>−52.7 68.4 108</td>
</tr>
<tr>
<td>12th Apr 2013</td>
<td>0831</td>
<td>6288 ± 42</td>
<td>18.18</td>
<td>indistinct</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15th May 2013</td>
<td>1420</td>
<td>6169 ± 30</td>
<td>25.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23rd May 2013</td>
<td>1329</td>
<td>6004 ± 46</td>
<td>29.14</td>
<td>19.48 (ascent)</td>
<td>4628 (ascent)</td>
<td>1350</td>
<td>6131 ± 50</td>
<td>−54.2 61.0 97</td>
</tr>
<tr>
<td>6th Jun 2013</td>
<td>1230</td>
<td>6111 ± 42</td>
<td>27.72</td>
<td>19.33 (descent)</td>
<td>6718 (descent)</td>
<td>1420</td>
<td>6138 ± 61</td>
<td>−52.8 62.3 99</td>
</tr>
<tr>
<td>23rd Aug 2013</td>
<td>0954</td>
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<td>29.62</td>
<td>10.34</td>
<td>4867</td>
<td>1115</td>
<td>6218 ± 46</td>
<td>−52.7 67.1 98</td>
</tr>
<tr>
<td>6th Jan 2014</td>
<td>1720</td>
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<td>20.36</td>
<td></td>
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<td></td>
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<tr>
<td>18th Feb 2014</td>
<td>1140</td>
<td>6115 ± 39</td>
<td>27.91</td>
<td>19.24 (descent)</td>
<td>6663 (descent)</td>
<td>1330</td>
<td>6089 ± 33</td>
<td>−51.6 63.2 99</td>
</tr>
</tbody>
</table>

Mean values (± 1.96 standard errors)

- T (°C)
- P (hPa)
- ρ (g m⁻³)
flight to flight differences in count rates apparent in Fig. 3a, other than the 11th April 2013 flight associated with a solar flare which is discussed elsewhere (Nicoll and Harrison, 2014), the variability cannot be straightforwardly associated with atmospheric structure differences.

3.2. Comparison with ion production rate modelling

Fig. 4 shows the count rates after conversion using Eq. (1) to provide the equivalent ion production rate under standard conditions, $q_{\text{STP}}$. In the left-hand panel of Fig. 4, the $q_{\text{STP}}$ values have been plotted against the air pressure at which they are obtained, as measured by the radiosonde’s meteorological sensor. To these values, the predicted ion production rate profile $q_{\text{model}}$ for Reading, UK using the model has been added. Below 20 km, there is good agreement between $q_{\text{model}}$ and $q_{\text{STP}}$, as also apparent in the right-hand panel. (The exception is in the lowest 1–2 km which is not readily seen in Fig. 4, where, because of surface radioactivity, the measured ionisation rate is up to twice that of the modelled values. This is, however, not a failing in the model, as it only seeks to represent the cosmic ray source of ionisation.) Above 20 km the agreement lessens between the measurements and the Usoskin–Kovaltsov model (worst case error 13%), although this is likely to be influenced by the diminishing amount of data available at the higher altitudes. Previously, for altitudes above the 50 hPa pressure level, Sloan et al. (2011) suggested a discrepancy between the Usoskin–Kovaltsov model and soundings of up to 20%.

(footnote continued)

originally identified the region of maximum ionisation, and subsequently described this in a joint paper with his student, Georg Pfotzer (Regener and Pfotzer, 1935). The long-standing use of the description “Pfotzer maximum” is therefore incomplete and historically inadequate.
The Usoskin–Kovaltsov model is able to predict the ionisation profile at any geomagnetic latitude. Three further soundings were made during 22nd and 23rd August 2013 in Reykjavik, Iceland, which is about 10° further north in geomagnetic latitude than Reading (see left panel of Fig. 5.) The average \( q_{\text{stp}} \) found from these three flights is shown in the right panel of Fig. 5, with the \( q_{\text{model}} \) values added as a line, and the equivalent values from Reading are also shown. There is, again, good agreement at altitudes below the 50 hPa pressure level, with the agreement diminishing as altitude increases. Notably, the RP maximum is much less distinct in \( q_{\text{model}} \) for the higher latitude of Reykjavik compared with the model results for Reading, which is supported by both the measured \( q_{\text{stp}} \) values, and previous observations at more northerly latitudes (e.g. Neher, 1967). However, the generic form of the ionisation profile, with a slow increase in the lower troposphere to a maximum in the lower stratosphere, is still apparent.

By combining the data obtained from all the flights from Reading where the RP maximum could be identified (Table 1), the mean pressure at the maximum was determined as (63.1 ± 2.4) hPa and the air temperature (−54.2 ± 2.6) °C, with an associated air density (0.101 ± 0.005) kg m\(^{-3}\), where the uncertainties represent 1.96 standard errors in each case. The (pressure) position of the maximum ionisation rate in the Usoskin–Kovaltsov calculations for Reading is at 73.3 hPa, which, under the standard atmosphere assumption, corresponds to −56.5 °C and an air density of 0.116 kg m\(^{-3}\).

### 3.3. Temporal variations

During the period of the launches listed in Table 1, variations in the galactic cosmic ray flux occurred, associated with the weak solar maximum conditions. Fig. 6 shows the daily time series of count rate at the Oulu neutron monitor (NM) with the dates of the launches marked. It is evident that the cosmic ray environment differed markedly between some of the launches. Variations in the surface NM count rates are expected to originate in the nucleonic generation rate at the RP maximum. Fig. 7 plots the count rate obtained when the balloon soundings are at the RP maximum against the NM count rate measured at the same time, as summarised in Table 1. The neutron monitor count rate and the RP count rates are positively correlated, and, if a linear fit is made between the two parameters assuming the least-squares criterion, the proportional changes in the RP count rate are (3.0 ± 1.2) greater than those in the NM, which is not inconsistent with the enhancement of 2.2 reported by Brown (1959).
3.4. Vertical profile information

As well as comparing the NM data with the count rates at the RP maximum, the count rates at all other available heights (vertical resolution 1 km as for Fig. 3) across the flights can be compared with the NM values at the same times. Fig. 8a shows the correlation between the geigersonde count rates and the associated Oulu NM count rate at the launch time. The number of values available at each height depends on the reliability of the telemetry and the burst height, which is given in Fig. 8b. Statistically significant correlations in Fig. 8a and c are identified with points. Fig. 8c shows the correlation between the geigersonde count rate at the RP maximum (for those flights when this could be identified) with the geigersonde count rates at other altitudes. The region of stronger significant correlations lies between about 8 km and 22 km, indicating that there is little information on the lower atmosphere ionisation rate available from the RP maximum ionisation region.

4. Discussion

Neutron monitor (NM) data has been widely used in the search for correlations between cosmic rays and atmospheric processes, notably that between galactic cosmic rays and satellite-derived observation of low cloud amount. The usefulness of neutron monitor data in providing information on the actual atmospheric
ionisation at cloud heights is therefore an important consideration (e.g. Harrison and Carslaw, 2003). From Fig. 8, it is apparent that the majority of strong and significant correlations are at the higher (10–20 km) altitudes, i.e. that the NM data are most useful for estimating the ionisation rate between 10 km and 20 km. Below 10 km, the possibility that the correlations obtained between the launch time NM count rate and the in situ count rate occur by chance cannot be discounted. Whilst this may be partially due to the small count rates at the lower levels, or indeed the contribution of surface radioactivity, Bazilevskaya et al. (2008) also show that the correlation between in situ measurements and NM data decreases substantially below 1 km. Hence it is unlikely that short-term variations in atmospheric ionisation are well predicted by NM data, for the typical timescales associated with balloon flights of a few hours. For monthly timescales, a closer agreement is apparent in the lower atmosphere, such as at 700 hPa (e.g. Usoskin and Kovaltsov, 2006). Consequently the rapid onset of a Forbush decrease which is apparent in NM data may not provide a good representation of the actual atmospheric short-term ionisation changes at cloud levels. This may, in part, provide an explanation for the differences found in the response of clouds to monthly and Forbush changes (Calogovic et al., 2010).

In terms of the atmospheric electricity changes arising from variations in atmospheric conductivity, the NM data may also be far from ideal for indicating transient or short-term changes. This is because the vertical profile of atmospheric conductivity has to be integrated to obtain the resistance of a unit area column of atmosphere between the surface and the ionosphere, which determines the local current flow. The majority of the integrated columnar resistance arises from the poorer conductivity in the lower atmosphere, with approximately 70% of the columnar resistance contributed by the lowest 3 km (Harrison and Bennett, 2007). In this region there will be variable contributions from surface radioactivity, and, as Fig. 8 shows, the NM data provides only a poor estimate of the GCR ionisation. At the upper levels from 10 to 20 km, where the NM data does provide a much better estimate of the total ionisation, only about 10% of the columnar resistance remains to be affected by GCR ionisation. Thus the NM data cannot be expected to provide a good estimate of the total columnar resistance in general, at least on the typical timescales of the balloon flights considered, for which improved parameterisations are needed. Instead, the columnar resistance can be calculated by using integrated in situ conductivity profiles, or through the use of simultaneous ionospheric potential and surface current density measurements (e.g. Harrison, 2005b). For longer period analyses, in which some of the random variability in the lower atmosphere can be expected to be reduced by averaging, the NM data can still provide an indication of the lower atmosphere ionisation changes (e.g. Harrison et al. 2013b).

Finally, the properties of the atmosphere assumed by using the US standard atmosphere only approximate the local atmospheric properties found in one particular season, as apparent from Fig. 3. As discussed in Aplin et al. (2005), reanalysis data from meteorological soundings is now widely available at better than daily resolution which will provide better representation of the atmosphere for modelling purposes than the standard atmosphere assumption. Of course, a particular advantage of using meteorological radiosondes for ionisation measurements is that temperature, pressure, height and location are measured simultaneously with the ionisation rate.

Acknowledgements

This work was funded by the Science and Technology Facilities Council (Airborne monitoring of space weather and radioactivity, ST/K001965/1). K.A.N. acknowledges support of the Leverhulme Trust (Grant No. ECF-2011-225) through an Early Career Fellowship. Rosy Wilson and Ian Read provided invaluable assistance with balloon launches and preparing prototypes. Ilya Usoskin provided the modelled ionisation rate data. The assistance of the Icelandic Meteorological Office, in particular Hermann Arngrimsson, Guðrún Nina Petersen, Sibylle von Löwis from the FUTURE-VOLC project, was central to obtaining the data presented in Fig. 5.

References
