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Vertical profile measurements of lower troposphere ionisation

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ABSTRACT

Vertical soundings of the atmospheric ion production rate have been obtained from Geiger counters integrated with conventional meteorological radiosondes. In launches made from Reading (UK) during 2013–2014, the Regener–Pfotzer ionisation maximum was at an altitude equivalent to a pressure of (63.1 ± 2.4) hPa, or, expressed in terms of the local air density, (0.101 ± 0.005) kg m^{-3}. The measured ionisation profiles have been evaluated against the Usoskin–Kovaltsov model and, separately, surface neutron monitor data from Oulu. Model ionisation rates agree well with the observed cosmic ray ionisation below 20 km altitude. Above 10 km, the measured ionisation rates also correlate well with simultaneous neutron monitor data, although, consistently with previous work, measured variability at the ionisation maximum is greater than that found by the neutron monitor. However, in the lower atmosphere (below 5 km altitude), agreement between the measurements and simultaneous neutron monitor data is poor. For studies of transient lower atmosphere phenomena associated with cosmic ray ionisation, this indicates the need for in situ ionisation measurements and improved lower atmosphere parameterisations.

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 assaying 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

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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 ^{60}Co 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 ^{60}Co 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

$$q_{STP} = 2.95X, \quad (1)$$

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

Geigersonde 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 geigersondes 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 (2.658×10^{-4} 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