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Focus on high energy particles and atmospheric processes

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EDITORIAL

Focus on high energy particles and atmospheric processes

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Abstract

The letters published in the 'Focus issue on high energy particles and atmospheric processes' serve to broaden the discussion about the influence of high energy particles on the atmosphere beyond their possible effects on clouds and climate. These letters link climate and meteorological processes with atmospheric electricity, atmospheric chemistry, high energy physics and aerosol science from the smallest molecular cluster ions through to liquid droplets. Progress in such a disparate and complex topic is very likely to benefit from continued interdisciplinary interactions between traditionally distinct science areas.

1. Introduction

High energy particles are constantly entering the atmosphere, from the Sun or from outside the solar system. They continually generate ionisation, but the subsequent effects in the atmosphere, and especially the lower troposphere, have long been a source of speculation, with physical mechanisms which can link the energetic particles with atmospheric chemistry and physics still under active investigation. One reason for this may be that the physical science communities concerned with studying ionising radiation (particle and cosmic ray physics), and the atmospheric effects of the ionisation (aerosol science, cloud physics and atmospheric electricity) have become distinct. This follows from the 1950s invention of the neutron monitor, moving away from the use of ionisation in particle physics. These topics were originally more closely related, for example in the work of CTR Wilson, winner of the 1927 Nobel Prize in physics for the visualisation of cosmic ray ions through condensation of water droplets, who was inspired by studying meteorological processes and atmospheric electricity (Harrison 2011).

Recent work investigating high energy particle effects on the lower atmosphere has mostly concentrated on evaluating possible effects on clouds, because of the sensitivity of climate to small changes in clouds and the ionisation known to be generated at cloud heights. Through this potential route and others, the solar modulation of high energy particles is increasingly recognised as presenting a range of possible solar indirect effects on climate. A central motivation in proposing this focus issue—encouraged by the unique position of *Environmental Research Letters* (ERL) in the physics community—was to strengthen the interdisciplinary links between atmospheric science and energetic particle physics. Such a need was implied by the 2013 IPCC report on the physical science basis for Climate Change, which, despite addressing possible climate effects of cosmic rays, nevertheless did not even list the long-established conjugate science areas of lightning, atmospheric electricity, ions or ionisation in its index. As well as the cloud effects, this ERL focus issue considers the radiative effects of ions in clear air, perturbations in the atmospheric circulation and triggering of lightning.

2. Statistical studies

The generic study of high energy particle effects on the atmosphere requires a combination of modelling and data analysis approaches, and a comprehensive review of the many possible processes is given by Mironova *et al* (2015). (These are summarised in table 1.) The more specific question of whether there is an appreciable effect on climate due to cosmic rays has often been considered

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Table 1. Summary of atmospheric processes associated with high energy particles (after Mironova *et al* 2015).

Location	Effect of high energy particles
MESOSPHERE	Chemical effects (e.g. OH production) of electron and solar proton precipitation
	NO production and subsequent downward propagation to deplete stratospheric ozone
STRATOSPHERE	Ozone depletion leading to cooling of polar vortex interior
	Aerosol enhancement
	Chemical effects (e.g. nitric acid production)
TROPOSPHERE	*Infra-red absorption of cluster ions*
	Changes in local lightning rates
	Changes in global atmospheric electric circuit
	Cloud effects

(Established effects are given in roman type, and suggested effects in italics.)

by comparing surface neutron monitor data with a climate or meteorological parameter. Such comparisons are necessarily statistical, using a variety of measured atmospheric parameters with good long term global coverage, which are amenable to investigation.

2.1. Regression methods

Benestad (2013) considered whether persistent responses to cosmic rays existed in global temperature, surface pressure and rainfall using multiple regression analysis. Whilst weak patterns in eastern Europe and the Norwegian sea were identified in temperature and surface pressure anomalies, these were not statistically significant. Sloan and Wolfendale (2013) surveyed a range of climate-related data sources on different timescales, and constrained solar influences to have contributed less than 10% of the twentieth century warming.

2.2. Superposed epoch methods

Averaging around many similar triggering events, which is known as a superposed epoch or compositing study, provides one method of reducing the effect of noise in the system being studied. A study of surface parameters using this approach was made by Laken and Calogovic (2013), by using the daily span of temperature (the diurnal temperature range, DTR) to provide an indirect measurement of cloud changes. This quantity, averaged over many sites, was examined for any response to common transient reductions (Forbush Decreases), or increases (Ground Level Enhancements) in cosmic ray ionisation. Allowing for the reduced sample sizes associated with the larger events, no robust change in DTR was found reaching the 5% significance level. Hence if there is an effect, it is too small to be detectable in DTR data.

2.3. Large events

Rather than averaging together multiple small effects, another approach to studying particle effects is to isolate a single but substantial event. The solar activity of early September 1859, and the flare observed visually by the astronomer Richard Carrington, provides a stimulus for such work. Calisto *et al* (2013) combined three-dimensional modelling of atmospheric chemistry with an ionisation model. For scenarios likely to represent the Carrington flare, for which only scarce and indirect energy information is available (Aplin and Harrison 2014), Calisto *et al* (2013)'s modelling found increases of NOx in the polar regions and up to a 20% decrease of stratospheric ozone. Resulting radiative changes also led to changes in the zonal winds.

3. Mechanistic cloud and clear air studies

Effects on clouds can be considered using direct measurements of specific cloud properties, as physical routes between the parameters have been proposed and are being evaluated. Carslaw *et al* (2002) distinguished between two proposed routes by which cosmic rays might affect clouds, (1) an ion-aerosol clear air mechanism and (2) an ion-aerosol near cloud mechanism. Since that review, the first mechanism, which concerns the generation of enhanced ultrafine aerosol concentrations able to affect the population of cloud condensation nuclei and ultimately cloud droplet properties, has received the most attention, and experimental work at CERN has identified circumstances in which the particle formation can occur (Kirkby *et al* 2011).

3.1. Ion-induced particle effects

Growth of ions to form particles sufficiently large to sustain droplet condensation at lower troposphere water vapour concentrations, which are orders of magnitude less than those generated in a Wilson cloud chamber, typically takes many hours. The growth is sensitive to the amount and composition of trace gas concentrations present and the loss of the trace gas to pre-existing particles or droplets. The process has to be comprehensively modelled to quantitatively evaluate the subsequent change in cloud, for comparison with other sources of variability. Yu and Luo (2014) used a detailed global atmospheric chemistry model to study the sensitivity of cloud condensation nuclei (CCN) generation to temperature. For the solar maximum to minimum change in cosmic ray ion production assumed (and this quantity itself varies between models and measurements), the CCN generation rate was shown to be enhanced by up to one order of magnitude under a 0.2 °C temperature change. Direct evidence exists for particle formation in the stratosphere. Mironova and Usoskin (2014) showed growth of aerosol particles occurring at 10 to 25 km, following increased ionisation associated with solar energetic particle events and ground level enhancements.

3.2. Layer cloud global circuit mechanism

Vertical current flow occurs throughout the atmosphere in fair weather regions through the global atmospheric electric circuit—a conceptual legacy of CTR Wilson—and cosmic ray ionisation. This provides a coupling mechanism between electrically-induced changes, for example from ionisation changes, and low level layer clouds. The ion current's passage through the cloud-clear air boundary, which also represents a change in electrical conductivity, leads to local charge separation in the droplet formation and evaporation region, in proportion to the current.

Voiculescu *et al* (2013) found a positive relationship between mid-latitude cloud cover and the interplanetary electric field, which they considered could be occurring through the global circuit mechanism. A further suggestion of a global circuit effect was made by Lam *et al* (2013), as part of the atmospheric response to the B_y component of the Interplanetary Magnetic Field. Lam *et al* (2013) showed differences in the surface pressure patterns between large and small circumstances of B_y. A defining characteristic of the global circuit is its single maximum diurnal variation, known as the Carnegie curve (Harrison 2013). Harrison and Ambaum (2013) reported an averaged diurnal variation in cloud base properties similar to that of the Carnegie curve, in separate series of data obtained during the polar night in the northern and summer hemisphere. Harrison *et al* (2015) have shown a sensitivity of cloud droplet distributions to charging of small droplets, such as that typical of layer cloud electrification induced by the global circuit.

3.3. Clear air ion absorption

The two previous ion related mechanisms of ion-facilitated particle formation or cloud droplet charging from ion transport represent complicated interactions between atmospheric ionisation, current flow and clear or cloudy air. A much simpler direct effect of cluster ions exists in principle through their absorption of infra-red radiation. Using a narrow band radiometer centred on an infra-red wavelength of 9.15μm, Aplin and Lockwood (2013) showed a transient change in radiative absorption following triggering events sensed by a cosmic ray telescope, likely to be associated with the ionisation from cosmic ray air showers. In principle, this direct effect can be included straightforwardly in climate models when the necessary cross-sections have been measured in the laboratory, although three dimensional radiative transfer modelling will be necessary to fully evaluate their contribution to the atmospheric radiation balance (Aplin and Lockwood 2015).

4. Lightning and transient electrical effects

CTR Wilson recognised that the strong electric fields of thunderclouds could accelerate electrons and even lead to upward propagating discharges (Wilson 1925a, Wilson 1925b). In this sense thunderclouds represent an internal source of high energy particles within the atmosphere. Low light detectors have subsequently demonstrated a wide range of faint discharges or Transient Luminous Events associated with active thunderclouds (e.g. Füllekrug *et al* 2013a). The use of two or three dimensional lightning mapping arrays provides a new tool in unravelling these complicated phenomena. Füllekrug *et al* (2013b) show that electron acceleration from a positive lightning discharge can precondition the above-thundercloud region as a plasma, facilitating formation of a relativistic electron beam in a subsequent discharge. The thermal and relativistic electrons were simultaneously detected by radiofrequency methods. Further remote detection possibilities require a detailed understanding of the electron acceleration. An analysis of the electron acceleration at the tip of a lightning streamer is given by Chanrion *et al* (2014), who, through Monte-Carlo modelling, show a decrease in peak electric field coincides with the streamer velocity. Electrons are also lost from the streamer tip, which in turn may influence subsequent streamer development.

Beyond their internally generated energetic particles, thunderclouds may also be influenced by external sources of particles. Statistical studies of particle effects on lightning rates are given by Scott *et al* (2014) and Owens *et al* (2014). Studies such as these require numerous well-defined particle source events, to allow comparison of averaged lightning rates during these events with lightning rates without such events. Scott *et al* (2014) used lightning data from the UK Met Office's radio detection system, and identified times of increase in low energy Solar Energetic Particles when the solar wind speed exceeded a threshold. These fast solar wind streams were associated with a substantial increase in lightning, and also thunder, as recorded manually from a range of UK sites. Owens *et al* (2014) interrogated the same lightning and thunderday data differently, categorising it by polarity of the Heliospheric Magnetic Field. The opposite polarities showed a 40 to 60% difference in lightning. Clearly, the meteorological conditions for a thunderstorm to develop are a pre-requisite for these effects to occur, but these studies strongly statistically support a solar effect on terrestrial lightning.

5. Conclusions

Whilst the interest in cloud effects through the nucleation route is a major motivation for studying the role of high energy particles in the atmosphere, this focus issue illustrates that the topic is more diverse,

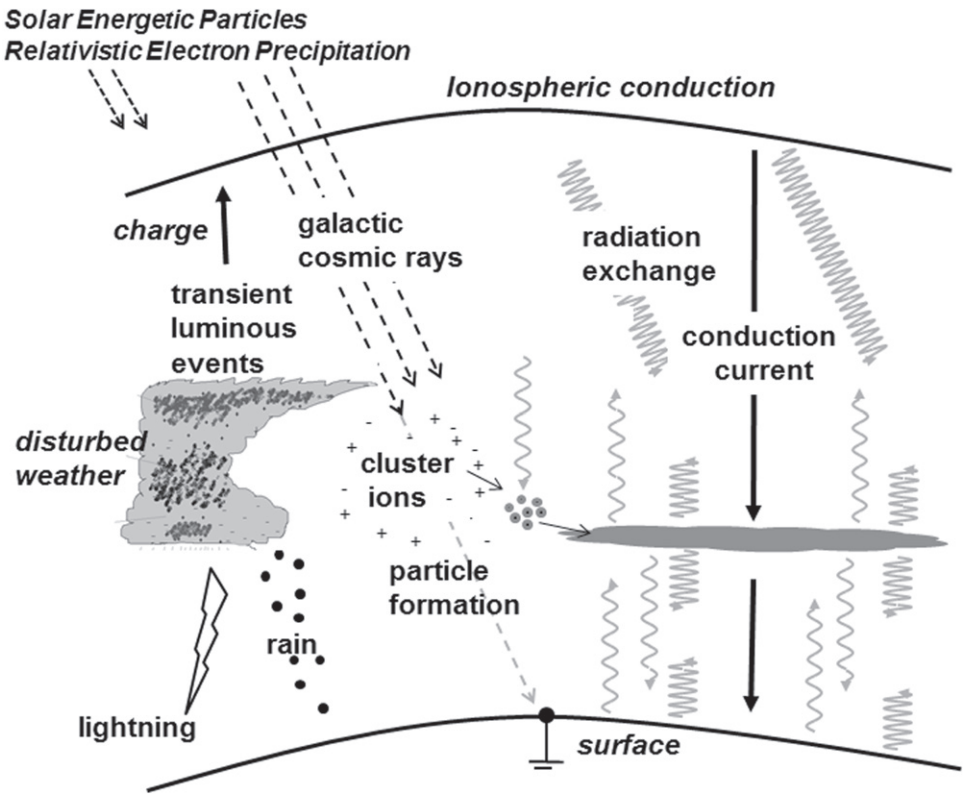

Figure 1. High energy particle effects in the conceptual framework of the global atmospheric electric circuit. Lightning is suggested to be affected by energetic particles, which may in turn influence the current flowing in the global circuit, as may changes in the interplanetary electric and magnetic fields or the solar wind. Influences on the atmosphere's radiation exchange via changes in the terrestrial long wave (infra-red) radiation and short wave (visible) radiation, can occur through the formation of cloud condensation nuclei, droplet charging effects in layer clouds or the direct absorption of long wave radiation by cluster ions.

and there are strong avenues of related work in lightning, global circuit response and atmospheric chemistry. A combination of atmospheric responses to high energy particles therefore seems likely, some of which are summarised in figure 1. One particular consideration for the statistical cloud studies and others is whether the tropospheric ionisation is well represented for low clouds by the neutron monitor count rates recorded at the surface, which is dominated by production in the stratosphere. Local effects of natural radioactivity and atmospheric variability provide a complicating factor.

The origin of the lightning effects is particularly intriguing, and Rycroft (2014) has suggested enhanced current flow in the global circuit might lead to increased lightning. It is possible that the solar wind influence on lightning, however, combined with conventional meteorological modelling could ultimately provide a new factor in forecasting hazardous weather.

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