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Brief Communication: Earthquake–cloud coupling through the global atmospheric electric circuit

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Abstract. We illustrate how coupling could occur between surface air and clouds via the global electric circuit – through Atmospheric Lithosphere–Ionosphere Charge Exchange (ALICE) processes – in an attempt to develop a physical understanding of the possible relationships between earthquakes and clouds.

1 Introduction

From time to time, papers are published suggesting that there are visible changes in the atmosphere that are associated with earthquakes, or that could even provide an earthquake precursor. Because of the widespread availability of high-quality satellite imagery, such optical possibilities are clearly compelling. Recently, for example, Guangmeng and Jie (2013) considered the potential for using observations of cloud changes as an earthquake precursor, by examining sequences of satellite images around the times of earthquakes. A full statistical climatology of the cloud behaviour in any earthquake region is essential before any cloud feature can be truly regarded as anomalous, but, more importantly, a plausible physical mechanism able to connect earthquakes and clouds has also been lacking.

Generating a physical mechanism linking earthquakes and clouds is troublesome because there is no clear agreement on what constitutes an "earthquake cloud", and a wide range of disparate cloud-related phenomena have been attributed to the effects of earthquakes. For example, there are several reports of anomalous cloud formations over fault zones

near earthquakes (e.g. Guangmeng and Jie, 2013; Guo and Wang, 2008), although the height of the clouds affected is not consistent. In some other cases the clouds described have been iridescent, implying that detailed droplet properties, such as size, might be affected by an underlying physical process. There are also observations of enhanced clear-sky emission in the thermal infrared radiation detected by satellites. Typically these are equivalent to a temperature change of a few Kelvin, beyond the natural variability (Tramutoli et al., 2005), appearing some days before the earthquake (e.g. Saraf et al., 2008; Guo and Wang, 2008).

At the simplest level, clouds require water vapour, which could be released from the Earth's crust by seismic changes. Whilst such plumes of water vapour might be initially buoyant from geothermal heating, mixing processes in the naturally variable lower atmosphere seem likely to remove the identity of the seismically generated water vapour (or water vapour fluctuations) as it ascends to cloud levels. (There is also little prospect of high-altitude clouds being affected in this way, such as those formed from ice). The thermal anomalies identified could also be generated by similar surface outgassing, such as the infra-red absorbing gases of carbon dioxide and methane (Saraf et al., 2008).

Changes in cloud features and associated thermal anomalies have been attributed to water condensation onto seismically-released ions (Pulinets and Ouzounov, 2011; Freund, 2013), which may exceed the existing natural background ionisation. A major difficulty with the ion-induced nucleation proposal is that condensation of water droplets on ions – a process exploited in the laboratory Wilson cloud
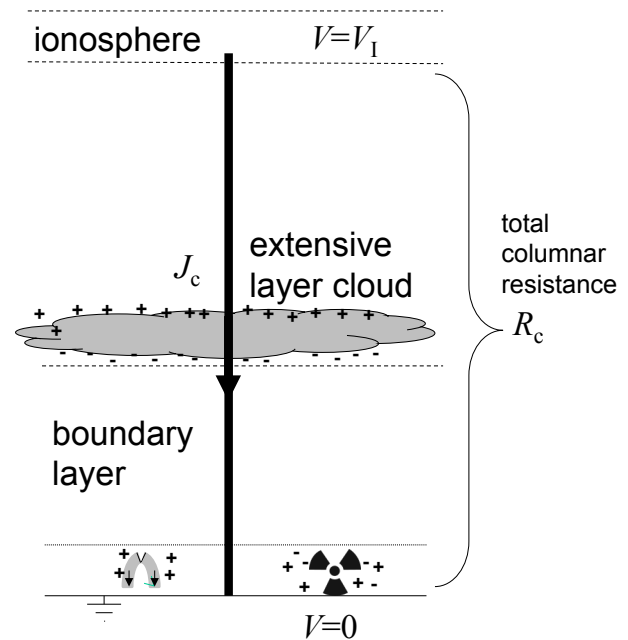
chamber to visualise cosmic ray tracks – requires extreme levels of water super-saturation of 400 % or more. This level of super-saturation is more than two orders of magnitude greater than that naturally occurring in the terrestrial atmosphere. Changes in ion properties through hydration have been reported, and nucleation to yield ultrafine particles has been observed, for example, in experiments using optimised gas mixtures (e.g. reviewed in Harrison and Carslaw, 2003). However, these molecular cluster ions or ultrafine particles remain much smaller than the minimum size of particle required for cloud droplet formation, which is typically a few hundred nanometers in diameter. Growth of ion clusters to these sizes in clean air with sufficient supply of condensable vapour requires many hours (e.g. Harrison and Carslaw, 2003). Hence, even if this growth process can occur without interruption in the real atmosphere where conditions are much more variable, the duration of the growth will allow the cluster ions concerned to be displaced by a considerable distance from their point of generation (~ 100 km for 10 h, with a small surface wind speed of $3 \, \mathrm{ms}^{-1}$). A rapid but continuous process, such as the flow of electric current, is therefore required if surface information is to be imprinted in clouds directly above seismic activity.

Changes in the surface structure of rocks under stress have also been suggested to lead to infra-red emission and subsequent thermal anomalies (Freund, 2013). Furthermore, seismically released atmospheric ions may themselves directly absorb infra-red radiation (e.g. Rycroft et al, 2012). Finally, a link between enhanced ionisation from radioactivity and clouds was suggested from the long-range cloud dissipation apparent in a satellite image of the Chernobyl reactor plume (Brandli and Leuck, 1987)[1].

Fig. 1. Coupling of surface ionisation changes to layer clouds through the global circuit. The conduction current flowing (density J_c) is related to the vertical columnar resistance R_c and the globally established ionospheric potential V_I. The boundary layer in the base of the lower atmosphere contributes the majority of the columnar resistance. Hence, ionisation released into this region by rock fracturing (shown on the left) or radioactivity (shown on the right) will reduce R_c and increase J_c for fixed V_I, from Ohm's Law. The charge accumulating on cloud droplets at the upper and lower cloud boundary is proportional to J_c and, therefore, in turn, to the surface ionisation. This charge may influence the cloud microphysical processes, e.g. via droplet interactions.

2 Global circuit coupling

An alternative route for earthquake coupling to clouds seems possible through atmospheric electricity. Previously, Harrison et al. (2010) argued that enhanced ionisation in the lower atmosphere (and, specifically, in the planetary boundary layer), will increase the vertical current flow always present in fair weather from the global atmospheric electric circuit (e.g. Rycroft et al., 2012). The importance of the vertical current density – denoted J_c – is that it links surface air ionisation changes directly to the ionosphere, unlike surface electric field changes, which are insufficient to cause ionospheric electrical changes (Denisenko et al., 2013). This mechanism of Atmospheric Lithosphere–Ionosphere Charge Exchange (subsequently referred to here by the acronym
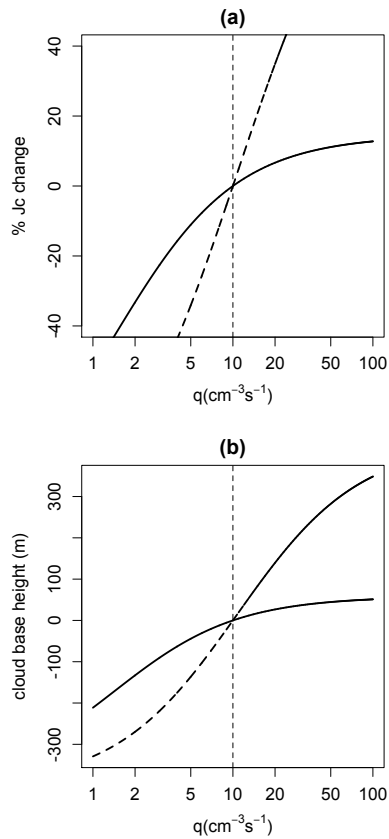
ALICE) provides an explanation for satellite observations of pre-earthquake changes in natural radio waves in nondisturbed weather. Encouraged by the agreement between the postulated changes and those now observed across a range of earthquakes (Piša et al., 2013), the ALICE mechanism is extended here to consider effects on simple cloud structures, horizontal layer clouds of water droplets (such as extensive low-level stratus clouds) in semi-fair weather, through which the vertical current must pass in overcast conditions.

The consequence of vertical current flow through the horizontal edge of a layer cloud is the local generation of charge at the horizontal cloud–air boundary (Fig. 1), which has already been directly observed within clouds using balloon-carried instrumentation (Nicoll and Harrison, 2010). Charging of the water drops at the upper and lower cloud boundaries is anticipated to influence, in some cases, the evaporation–condensation of drops, and also the collisional interactions between small droplets (Rycroft et al., 2012). These effects result from the charge obtained by the droplets after they have formed. The droplet charging is proportional to the vertical current flowing and the vertical gradient of the

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[1]Ionospheric changes during two major nuclear reactor accidents are inconsistent. Fuks et al. (1997) observed an ionospheric response following the Chernobyl incident, but Kakinami et al. (2011) did not consider the ionospheric changes around the Fukushima event to be unambiguously linked with the nuclear accident.

Fig. 2. Calculated response in atmospheric electric and cloud parameters to changes in the surface air volumetric ion production rate q for low pollution air (solid lines) assuming 2000 particles cm^{-3} of radius 0.25 μm, and polluted air (dashed lines), assuming 15 000 particles cm^{-3}. Variations are shown for **(a)** the vertical conduction current J_c and **(b)** changes in the observed cloud base height.

cloud to clear air transition, with the charge per unit volume ρ at the cloud boundary given by

$$\rho = -\varepsilon_0 J_c \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{1}{\sigma}\right), \tag{1}$$

in which the conductivity σ varies vertically with height z across the horizontal cloud–air boundary, and ε_0 is the permittivity of free space.

Equation (1) shows that properties of the cloud – specifically, the charge per unit volume at the cloud edge – are linked to the vertical current flow. Should the current flow be modified by ionisation changes near the surface, such as through the release of radon or the fracture of rocks (e.g. Freund, 2013), the cloud droplet charge would also vary in response. The global circuit current therefore provides a link between surface changes and the cloud directly above.

3 Quantitative considerations

Changes in the vertical conduction current from surface ionisation variations can be calculated by considering the balance between ion generation and loss to atmospheric particles, for a unit area column of atmosphere. The full methodology was discussed in the description of the ALICE mechanism given in Harrison et al. (2010). For an ionospheric potential V_I, which is assumed to be an equipotential region since the ionosphere's conductivity is many orders of magnitude greater than that of the air's conductivity below it, the conduction current density J_c is given by

$$J_c = \frac{V_I}{R_c} \approx V_I / \left[\frac{k}{\sigma_s} + R_{FT}\right], \tag{2}$$

where R_c is the resistance of a unit area column between the surface and the ionosphere. This resistance can be estimated using an approximate model based on the total surface layer conductivity σ_s, which is considered to represent the resistance in a layer of scale height k (~ 100 to $500\,\mathrm{m}$) together with the resistance of the upper ("free troposphere") part of the columnar resistance R_{FT}. The surface air conductivity σ_s depends on the concentration of small ions present n and their mean mobility μ, from

$$\sigma_s = 2n\mu e, \tag{3}$$

where e is the magnitude of the elementary charge (Harrison and Carslaw, 2003). The surface air conductivity can be determined in terms of the ion production rate q and loss rate by ion–ion recombination and ion–aerosol attachment as

$$\sigma_s = \mu e \frac{\left[\sqrt{(\beta^2 Z^2 + 4\alpha q)} - \beta Z\right]}{\alpha}, \tag{4}$$

where α is the ion–ion recombination coefficient ($1.6 \times 10^{-12}\,\mathrm{m^3\,s^{-1}}$), Z the monodisperse aerosol number concentration and β the ion–aerosol attachment coefficient, which is $\sim 4 \times 10^{-11}\,\mathrm{m^3\,s^{-1}}$ for $0.2\,\mathrm{\mu m}$ radius aerosol. Harrison et al. (2010) also pointed out that the response depends on the background aerosol concentration. This is because the sensitivity of the vertical conduction current to surface ionisation change is greater in polluted air, as ion loss to aerosol particles is less effective at removing ions than, in clean air, the annihilation of ions by recombination of a positive ion with a negative ion.

It can be seen from Eq. (4) that the air conductivity varies with the ion production rate q, and that, through Eq. (2), the conduction current will respond, leading, through Eq. (1), to a change in the cloud edge charge. Hence a long-range relationship exists between the surface ion production and the cloud properties.

Calculation of the sensitivity of the vertical conduction current requires some estimate of the likely changes in the ionisation rate associated with earthquakes, from both radon

Table 1. Summary and quantitative estimates of mechanisms by which rock stresses can produce excess ionisation in surface air before earthquakes.

Mechanism, example	Ionisation changes	Reference
Radon emission before 1995 Kobe earthquake	Radon increase measured, conservatively estimated at $10\,\mathrm{Bq\,m^{-3}}$. Ion balance equation used to infer a 40 % change in ion concentration. Measured increases in ion concentration before the earthquake of $1000\text{--}1400\,\mathrm{cm^{-3}}$ were consistent with changes inferred from the radon data. This implies a change in volumetric ionisation rate of 40–100 %, i.e. a rate of $14\text{--}20\,\mathrm{cm^{-3}\,s^{-1}}$.	Omori et al. (2007) and references therein Yasuoka et al. (2010) and references therein
Radon emission in general before earthquakes	Volumetric ionisation rate $= 100\text{--}10\,000\,\mathrm{cm^{-3}\,s^{-1}}$	Liperovsky et al. (2005)
Fractoemission during earthquakes and volcanic eruptions	Ions per unit area at rock surface given as $10^9\,\mathrm{cm^{-2}\,s^{-1}}$; vertical dimension of region into which the ions were released not available	Freund (2013)

release and fractoemission (Table 1). Measurements of ionisation rate anomalies before earthquakes are sparse and it is difficult to trace some of the quoted figures to reliable measurements. Nevertheless, there are good data available from the time of the Kobe earthquake in Japan in 1995 (e.g. Yasuoka et al., 2010), where radon concentrations increased for about 2 months before the earthquake, reaching a peak (at well over three standard deviations above the previous background) 17 days before the earthquake, which was sustained until the earthquake. When electricity supplies to the instruments resumed after the earthquake, radon levels had returned to the previous background level. Based on the radon increase of $10\,\mathrm{Bq\,m^{-3}}$, and concurrent ion measurements, Omori et al. (2007) estimated a 40 % change in ion concentration. In aerosol-free air, the ion concentration is proportional to the square root of the ion production rate and, in polluted urban air, the ion concentration scales linearly with the ionisation rate (e.g. Harrison and Carslaw, 2003). The enhanced radon concentrations observed therefore correspond to a change in the ion production rate of 40–100 %, i.e. $q = 14 - 20\,\mathrm{cm^{-3}\,s^{-1}}$, assuming a background ionisation rate of $q = 10\,\mathrm{cm^{-3}\,s^{-1}}$.

These values of q are relatively conservative when compared to other suggested values, but they are based on field measurements rather than models. (Liperovsky et al. (2005) estimate a much greater ionisation rate enhancement, of $100\text{--}10000\,\mathrm{cm^{-3}\,s^{-1}}$.) Fractoemission mechanisms proposed by Freund (2013) do not yet provide an adequate estimate of the volumetric ionisation rate, so a combination of the radon-enhanced ionisation rates presented in Table 1 has been used to estimate the enhanced ionisation rate as up to $100\,\mathrm{cm^{-3}\,s^{-1}}$.

4 Estimate of cloud response

Some indications of the modulation of cloud properties which might be expected from conduction current changes are available from studies of polar night clouds, showing an averaged response in the cloud base consistent with conduction current variations (Harrison and Ambaum, 2013). Polar night clouds were chosen for this analysis to remove the usual dominating influence of diurnal variations from solar heating, and the response was observed in the cloud base height. The determination of cloud base height is essentially a measurement of vertical visibility, which can be regarded as indicating a change in the cloud base droplet properties, such as droplet size or concentration. In this study, which averaged the polar night cloud base measurements made, a similar response was found for both the Arctic and Antarctic of about 4 m change in cloud base height for a unit percentage change in the conduction current density.

If this sensitivity is appropriate to semi-fair weather layer clouds in general (and a similar sensitivity was found through an entirely different approach at a mid-latitude continental site by Harrison et al., 2013), then the possible cloud response to earthquake-induced changes can be estimated in similar terms. Figure 2b applies this response to the calculations of current density change from ionisation, obtained from Fig. 2a. The sensitivity of the change in cloud properties is, as expected, greater in the polluted case, although it must be emphasised this is a highly idealised calculation which neglects any additional interactions between the cloud and pollution and indeed any other sources of variability. However, it still serves to illustrate the potential link between surface ionisation changes and cloud properties aloft.

5 Conclusions

In reality, there is always considerable variability present in the atmosphere and in clouds. Consequently there are many competing sources of cloud variability, such as that associated with local orography, which may obscure effects solely resulting from surface ionisation changes. Nevertheless, there may also be conditions in which a cloud response is observable, or indeed has possibly already been observed. Our purpose here is merely to suggest that there is a possible

physical mechanism which can provide earthquake–cloud coupling based on the ALICE ideas presented previously, which should be explored further. An appealing feature of this mechanism is that, rather than requiring transport of the surface ionisation up to the cloud despite appreciable ion loss processes (with uncertain or indeed unlikely responses in the cloud properties), the global circuit conduction current directly, and rapidly, connects surface air ionisation changes to the properties of the cloud above in semi-fair weather. Many details clearly remain to be worked out, which we hope can be achieved experimentally and theoretically despite the traditional discipline boundaries between atmospheric and Earth sciences.

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