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Electrostatic levitation of volcanic ash into the ionosphere and its abrupt effect on climate

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ABSTRACT

Large volcanic eruptions cause short-term climate change owing to the convective rise of fine ash and aerosols into the stratosphere. Volcanic plumes are, however, also associated with large net electrical charges that can also influence the dynamics of their ash particles. Here I show that electrostatic levitation of ash from plumes with a net charge is capable of injecting volcanic particles <500 nm in diameter into the ionosphere in large eruptions lasting more than a few hours. Measured disturbances in the ionosphere during eruptions, and the first discovery of polar mesospheric clouds after the A.D. 1883 Krakatau (Indonesia) eruption, are both consistent with levitation of ash into the mesosphere. Supervolcano eruptions are likely to inject significant quantities of charged ash into the ionosphere, resulting in disturbance or collapse of the global electrical circuit on time scales of 10^2 s. Because atmospheric electrical potential moderates cloud formation, large eruptions may have abrupt effects on climate through radiative forcing. Average air temperature and precipitation records from the 1883 eruption of Krakatau are consistent with a sudden effect on climate.

INTRODUCTION

Volcanic plumes are formed during explosive eruptions through convective rise of gas and tephra into the atmosphere, and can reach altitudes of 50 km, within the stratosphere (Sparks, 1986; Bonadonna and Costa, 2013). The injection of volcanic aerosols and ash at such high altitudes results in global dispersal and causes climatic changes owing to solar insulation and production of cloud nuclei (McCormick et al., 1995; Robock, 2000). Large volcanic eruptions thus cause short-term climatic instability.

Conventional wisdom suggests that volcanic tephra cannot be injected into higher layers of Earth's atmosphere because the temperature inversion of the stratosphere acts as a barrier to convective rise (Sparks, 1986; Bonadonna and Costa, 2013). Volcanic eruptions, therefore, are not considered to have a significant effect on the upper atmosphere. The frequent occurrence of volcanic lightning during explosive volcanic eruptions, however, indicates that eruption columns carry significant electrical charge (James et al., 1998, 2000; Mather and Harrison, 2006) that can produce non-thermal forces and affect the rise of charged ash particles.

Measurements of potential gradient anomalies in the ambient electric field associated with explosive eruptions suggest that volcanic plumes can have large net charges of up to ~10 coulombs (C) (James et al., 1998). Experiments on the charging of volcanic particulates imply that charging from fracturing, owing to ion emission, dominates over triboelectric charging owing to friction (Mather and Harrison, 2006; Harrison et al., 2010). Charging, therefore, is likely to occur within the volcanic conduit and in the gas thrust region above the vent where the majority of fragmentation occurs, although some additional charge is likely to develop higher in the plume (Harrison et al., 2010). Fragmentation, and thus charging, can be expected to increase with eruption magnitude (Mather and Harrison, 2006), although discharge by volcanic lightning may limit maximum net charges.

The net charges observed on volcanic plumes indicate that charge separation occurs during eruptions (Lane and Gilbert, 1992; Mather and Harrison, 2006). Models suggest that ash is commonly negatively charged while volcanic gas is mostly positively charged (Mather and Harrison, 2006). Physical separation of ash from gas by convection and wind transport results in a large net charge. Explosive volcanic eruptions are, therefore, effective generators and separators of electrical charge.

ELECTROSTATIC LEVITATION

Electrostatic levitation is a process that causes lofting of charged particles within an electrical field and is important on atmosphere-less bodies such as the Moon (Colwell et al., 2009) and asteroids (Lee, 1996). Electrostatic interaction between charged volcanic ash particles and plumes having a net charge of the same polarity will unavoidably cause levitation of particles.

The migration of volcanic ash liberated from the upper regions of a large plume was evaluated using a model of particle motion under the influence of electrostatic forces and atmospheric gas drag (see the methods in the GSA Data Repository[1]). The cloud of liberated ash was assumed to be sufficiently tenuous that interactions between particles could be ignored, and charge within the plume was generated as a field of point charges with a random distribution. A saturated surface charge on small particles of -1.0×10^{-5} C m^{-2} was assumed, consistent with measurements of charge on volcanic ash (Gilbert et al., 1991; Mather and Harrison, 2006). Particle charge was considered constant in the model.

The dynamic behavior of particles is shown in Figure 1 and suggests that particles 50, 100, and 500 nm in diameter, from eruption columns with net charges of −10 C that have reached altitudes of 50 km through convective rise, can reach altitudes of 110, 90, and 60 km, respectively, within periods of ~2 h. Given that large volcanic eruptions occur on longer time scales (e.g., the climactic phase of the A.D. 1991 Mount Pinatubo [Philippines] eruption was 9 h; Global Volcanism Program, 1991), sufficient time is available for levitated particles to reach maximum height if they remain charged over this period.

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[1] GSA Data Repository item 2018309, description of the the numerical model, experimental measurement of charge relaxation, and the climate data, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

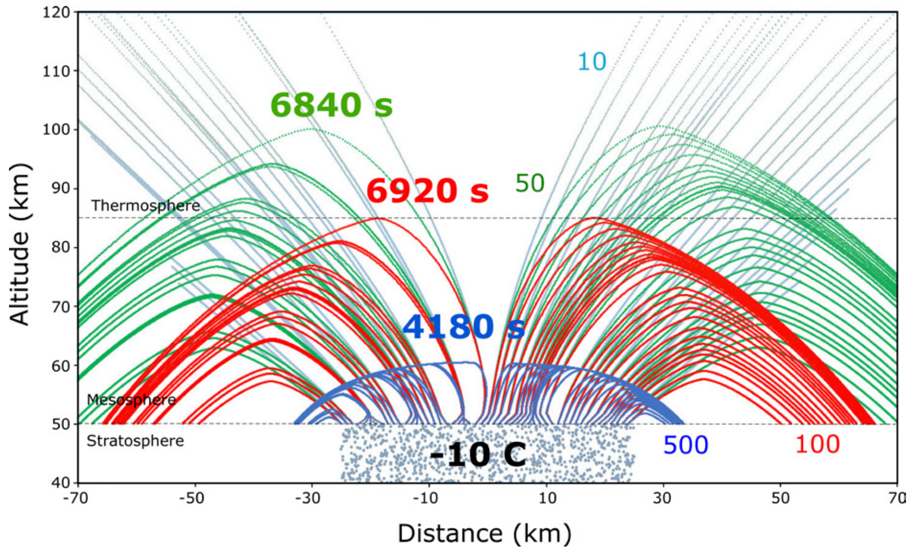

Figure 1. Trajectories of volcanic particulates 100 nm, 50 nm, and 10 nm in diameter over modeled 50-km-diameter volcanic plume with randomly distributed charge and net charge of –10 C. Particles have saturated surface charge of -1.0×10^{-5} C m^{-2}. Spacing of data points for 10 nm particles (gray) represents velocity. Gray dots in stratosphere represent point charges within plume. Bold labels show time to peak altitude.

Charge relaxation of volcanic particulates would, however, occur owing to interactions with positive ions in the atmosphere and would limit levitation. Charge relaxation times have been estimated at 100–1000 s based on gas kinetic theory, assuming a high charge-transfer efficiency (Mather and Harrison, 2006; Harrison et al., 2010). Volcanic ash produced in large explosive eruptions is generally silicic and is dominated by glass with subordinate silicate crystal fragments; both are insulators (the volume resistivity of quartz and glass, for example, are 10^{12}–10^{14} and 10^4 Ω·m, respectively; Telford et al., 1990) and are likely to have longer charge relaxation times than conductors owing to their limited charge mobility. To investigate the magnitude of charge relaxation, the decay of charge was measured on polycarbonate as an analog to quartz. Polycarbonate was used because it can be negatively charged by triboelectric techniques and has similar resistivity to quartz (see the Data Repository). A charge half-life of 7000 s was measured at positive ion densities of ~10^9 m^{-3} and a humidity of ~70% (Fig. 2). The charge half-life of volcanic particles, therefore, would likely be sufficiently long to allow levitation into the mesosphere, in particular to altitudes of <70 km where positive ion densities are low (10^7 m^{-3}; Arnold and Krankowsky, 1979; Fig. 3). Significant loss of charge from particles would, however, occur once they reached the ionosphere (D-layer >80 km) owing to the higher atmospheric ion densities of ~10^{10} m^{-3} (Arnold and Krankowsky, 1979). The longer charge half-lives of crystal fragments may also result in their more rapid levitation to higher altitude than glass particles.

Other factors might influence electrostatic levitation. The distribution of positively charged gas separated from the plume would likely affect the trajectories of particles; however, because this gas cannot rise through convection into the stratosphere, it would likely be dispersed laterally. Ash levitation may consequently be limited near the margins of volcanic plumes; however, considering that the 1991 Pinatubo eruption plume was ~200 km in diameter (Holasek et al., 1996) and the 630 Ma Yellowstone plume is suggested to have been 1000 km across (Mastin et al., 2014), this is unlikely to significantly affect the levitation of most ash from the upper regions of plumes. Ionospheric net charge is generally low (Arnold and Krankowsky, 1979) and unlikely to affect levitation.

CLIMATIC EFFECTS OF ELECTROSTATIC LEVITATION

While volcanic plumes with large net charges may induce changes in ionospheric potential through charge separation, electrostatic levitation delivers negative charge into the ionosphere, reducing atmospheric positive ion density. Global-scale disturbances in ionospheric current have been observed during several volcanic eruptions that testify to the effects of volcanic plumes on the ionosphere (Lastovicka, 2003; de Ragone et al., 2004). Although such disturbances have been explained as a result of gravity waves (Lastovicka, 2003; de Ragone et al., 2004), they could also be interpreted as the result of the addition of negative charge by levitated particles. Models of the response time of the ionosphere to the changes in charge indicate that global equilibration occurs in 10^2 s (Jánský and Pasko, 2014), suggesting that the electrostatic effects of large volcanic eruptions are immediate.

Observations of ionospheric disturbances by explosive volcanic eruptions indicate that they scale with eruption magnitude (de Ragone et al., 2004), consistent with increasing plume net charges and injection of larger masses of charge carriers into the ionosphere. The largest volcanic eruptions, such as the 630 Ma eruption of Yellowstone caldera, have plumes several orders of magnitude more massive than the 1991

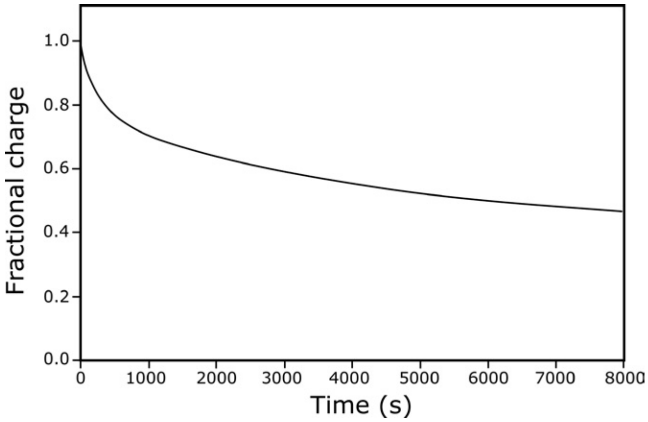

Figure 2. Fractional charge measured on polycarbonate disk as analog to charge relaxation on volcanic particles. Measurements were conducted under atmospheric positive ion density of ~10 m^{-3}.

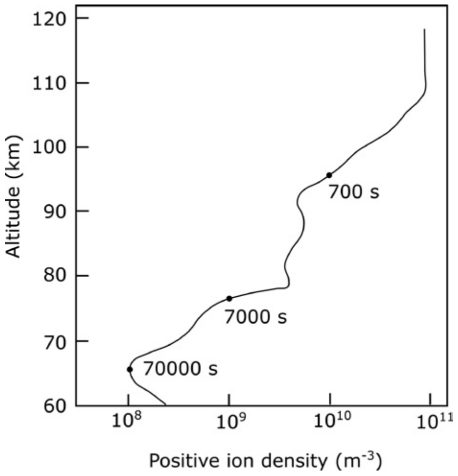

Figure 3. Positive ion density with altitude and estimated charge half-lives (dots) for volcanic ash. Positive ion densities are measured values from Arnold and Krankowsky (1979).

Pinatubo eruption (Holasek et al., 1996; Mastin et al., 2014) and would be expected to inject large amounts of ash into the upper atmosphere. The total charge on 500 t of saturated 200-nm-diameter volcanic ash is equivalent to the total charge stored in the global electrical circuit of 5×10^5 C (Rycroft et al., 2000) (the capacitor system formed by the ionosphere and ground), and if added to the ionosphere would likely cause global collapse of the atmospheric electrical potential. The mass of a supervolcano plume is ~10^{11} t (Mastin et al., 2014), and thus 500 t of levitated particles represents an exceedingly small fraction of the total mass. Estimating the mass of levitated ash, however, is complicated because it would likely depend on the dynamics of the upper region of the plume, in which mutual electrostatic interactions are important, and on the mechanisms of charge generation, separation, and dissipation, which influence local charge distribution. Levitation of charged ash also causes loss of charge, and thus continued charge generation by fragmentation and charge separation by removal of gas from tephra would be needed to enable levitation of significant masses. These mechanisms should, however, continue to operate throughout explosive eruptions. Large explosive eruptions could, therefore, have a significant effect on the global electrical circuit.

Atmospheric electrical potential moderates cloud formation owing to its effect on cloud microphysics, in particular in the formation of cloud nuclei through vertical ionic current flows, ionization of growing cloud nuclei, and droplet charging (Harrison and Ambaum, 2009). Electrical potential has been shown to affect the altitude of the cloud base (Harrison and Ambaum, 2013). Significant disruption of the atmospheric electrical field together with the short response time of the ionosphere, therefore, would likely disturb cloud formation during supervolcano eruptions, resulting in lower global cloud cover and precipitation. This contrasts with increased precipitation in the vicinity of volcanic plumes as a result of high aerosol load. Global suppression of cloud formation would be likely to increase atmospheric H_2O content, thus in the immediate aftermath of supervolcano eruptions, recovery of the ionosphere and resumption of normal cloud formation may result in enhanced cloud cover and precipitation. Electrostatic levitation of volcanic ash may, therefore, cause short-term changes in global climate that differ from those caused by stratospheric aerosols.

THE 1883 KRAKATAU ERUPTION

Air-temperature data after the 26 August 1883 eruption of Krakatau (Indonesia) were compiled from 47 stations in Europe, North America, Russia, and Australia, and are shown in Figure 4. Average maximum and minimum temperature for the stations exhibits a decrease beginning on 22 August 1883, after resumption of activity at Krakatau, until 12 September, when mean temperature reached 4 °C lower than the average over the preceding 8 yr. No one station or geographically restricted group of stations is responsible for the low average temperature. A minimum in the number of weather stations recording precipitation, out of a total of 138 stations, is also recorded from 22 August to 27 August, compared with the frequency of precipitation immediately before and after the Krakatau eruption. Observations of unusual optical phenomena at sunset and sunrise after the Krakatau eruption were documented in the Royal Society of London report on the eruption and record the arrival of stratospheric aerosols at different locations (Symons, 1888). The report records the first unusual twilight afterglows, produced by aerosols, in Surrey in the UK on 9 November 1883. The decrease in average temperature thus occurred before stratospheric aerosols reached in Europe.

Lower-than-average air temperatures at stations distributed globally would, however, be predicted if cloud formation was moderated by changes in the global electrical circuit. A decrease in the frequency of rainfall, in particular, is also consistent with suppression of cloud formation during the eruption. Such effects are likely complex because they are dependent on the prevailing weather conditions at a particular location, with little effect where cloud cover is already high or where cloud formation is inhibited by low humidity. The coincidence of a low average temperature and precipitation with the eruption is consistent with the predicted effect of levitated ash, but not conclusive evidence, considering the inherent variability of weather data on such short time scales. The 1883 eruption of Krakatau was volcanic explosivity index (VEI) 6 in magnitude but produced anomalously intense pressure waves (Self, 1992), and thus

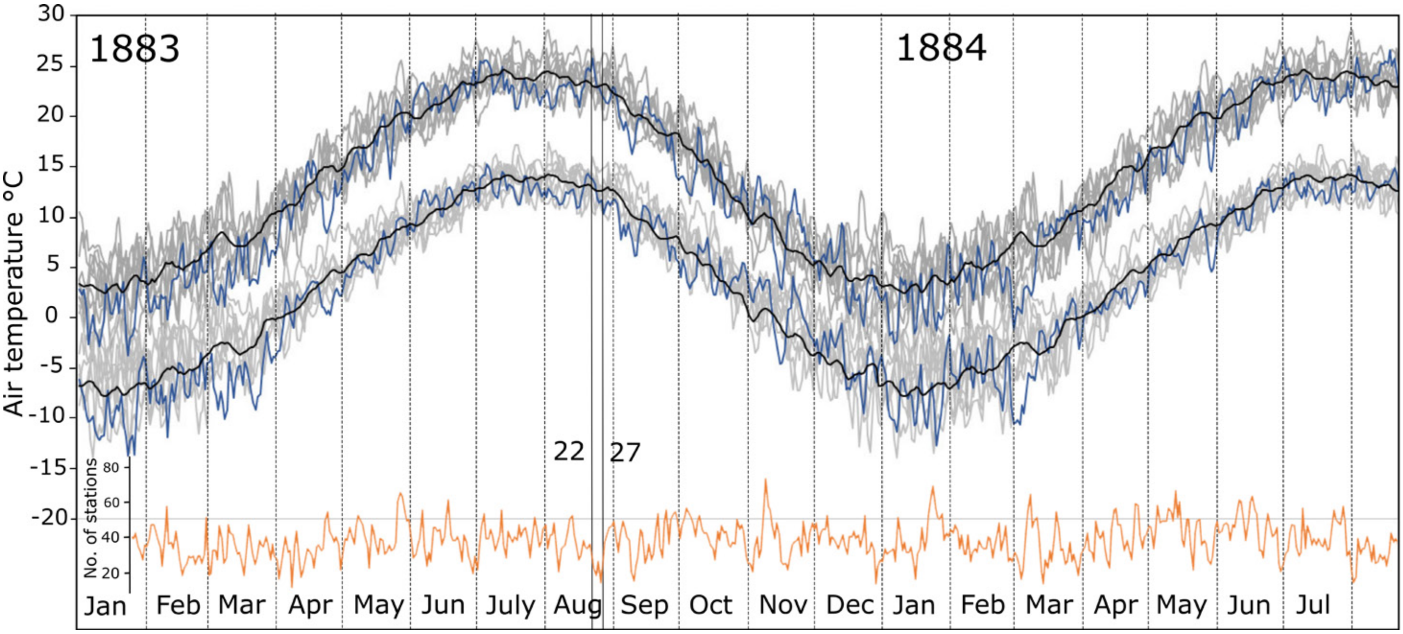

Figure 4. Average maximum and minimum daily air temperature measured at 47 stations in North America, Europe, Russia, and Australia in A.D. 1883 (blue lines). The Krakatau [Indonesia] eruption occurred between 22 and 27 August 1883. Black lines show the average daily temperatures for A.D. 1875–1882 smoothed over 5 d using moving average. Gray lines show range of average daily temperatures for the 47 stations for 1875–1882. Average air temperatures decreased from 22 August until 12 September 1883. Orange curve shows number of weather stations (out of 136) at which precipitation was recorded. This falls to minimum between 22 August and 27 August 1883 (interval marked by solid vertical lines). Data derived from U.S. National Oceanic and Atmospheric Administration climate database (https://www.ncdc.noaa.gov).

may not be representative of other eruptions of this magnitude.

Indirect evidence for electrostatic levitation of volcanic particles into the mesosphere by the 1883 Krakatau eruption, however, exists. Polar mesospheric clouds (PMCs; noctilucent clouds) were first discovered after the eruption in 1885 (Jesse, 1885); however, a causal link with the eruption has been dismissed because there was thought to be no mechanism to inject volcanic particles into the mesosphere (Austin, 1983). An analysis of the discovery statistics of PMCs (Thomas and Olivero, 2001), nevertheless, shows a pulse of observations between their discovery in 1885 and 1887, consistent with the injection of volcanic ash into the mesosphere by electrostatic levitation. Interestingly, the Royal Society report on Krakatau details an observation at sunset in Surrey on 9 September 1883 that strongly resembles descriptions of PMCs and could suggest the presence of volcanic ash within the mesosphere: "The remarkable feature in this condition [weather] was the great elevation of the cirro-cumulus above the cirrus, and the [rainbow] colours were certainly uncommon." (Symons, 1888, p. 159).

Few reliable weather data by which the effects of electrostatic levitation can be evaluated are available for the larger VEI 7 eruption of Tambora (Indonesia; Raible et al., 2016) in 1815. The months of May and June 1815, however, were notably wet in Europe (Wheeler and Demarée, 2006), following the end of the eruption in late April. The unseasonal weather in Europe, however, cannot be related to sulfate aerosols from the Tambora eruption, which did not reach the region until early 1816 (Clausen and Hammer, 1988), but it could be explained by suppression and subsequent recovery of cloud formation owing to levitation of volcanic ash. The wet weather in Europe has, furthermore, been noted by historians as a contributing factor in the defeat of Napoleon Bonaparte at the Battle of Waterloo (Wheeler and Demarée, 2006).

CONCLUSION

Electrostatic levitation of ash over large volcanic plumes is an unavoidable consequence of the high net charges generated during explosive eruptions. Simulations presented here suggest that volcanic ash <500 nm in diameter can reach high altitudes in the mesosphere within the duration of eruptions and would necessarily deliver charge to the ionosphere. The potential mass of ash required to deliver a charge equivalent to that stored within the global electrical circuit is furthermore insignificant compared to the mass of supervolcano plumes. Significant disruption of the atmospheric electrical potential would likely have an abrupt global effect on cloud formation, and thus climate. The magnitude of the effect can be expected to scale with eruption magnitude. Data from the 1883 eruption of Krakatau suggest that only minor effects occur for VEI 6 eruptions; however, supervolcano eruptions associated with continent-scale plumes and having extended durations would probably have evident immediate effects.

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