Effects of global circuit downward current flow on atmospheric dynamics: modeling of relevant cloud microphysics

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ABSTRACT: Much previous work shows large-scale winter atmospheric dynamic changes responding on the day-to-day timescale to inputs to the global circuit that produce regional changes in the downward current density Jz. Recent work shows surface pressure and geopotential height changes within the polar vortices responding to overhead ionospheric potential changes, separately due to solar wind changes and changes in the electrified cloud generators at low latitudes. A new analysis shows the North Atlantic Oscillation responding on the day-to-day timescale to changes in the solar wind speed associated with precipitation of relativistic electrons into the mesosphere and stratosphere; consistent with previous observations of atmospheric vorticity changes. The latter responses occur with Jz changes in winters with moderate to high stratospheric and mesospheric aerosol loading, and imply non-negligible column resistances in those regions at those times. They are also consistent with Boberg and Lundstedt's determination of NAO changes on the winter-to-winter timescale responding to solar wind electric field changes. A proposed mechanism involves electro-scavenging and electro-anti-scavenging of cloud condensation nuclei and ice nuclei by cloud and haze droplets, which are charged with space charge generated by the flow of Jz through gradients of conductivity. To facilitate modeling of such processes, parameterizations of new simulations of charge modulated scavenging of nuclei have been made. The simulations include diffusion as well as gravitational and phoretic forces. The parameterizations can be used in cloud microphysical models evaluating storm invigoration, cloud cover, and precipitation changes related to Jz.

INTRODUCTION

The evidence for global circuit downward current density, Jz, causing changes in atmospheric dynamics is now even stronger than as reviewed by Tinsley (2008).

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The responses are to a number of disparate external and internal inputs to the global circuit, as illustrated in Figure 1, from Tinsley (2010), which shows the latitude variation of the inputs, and their observed or inferred effect on regional Jz.

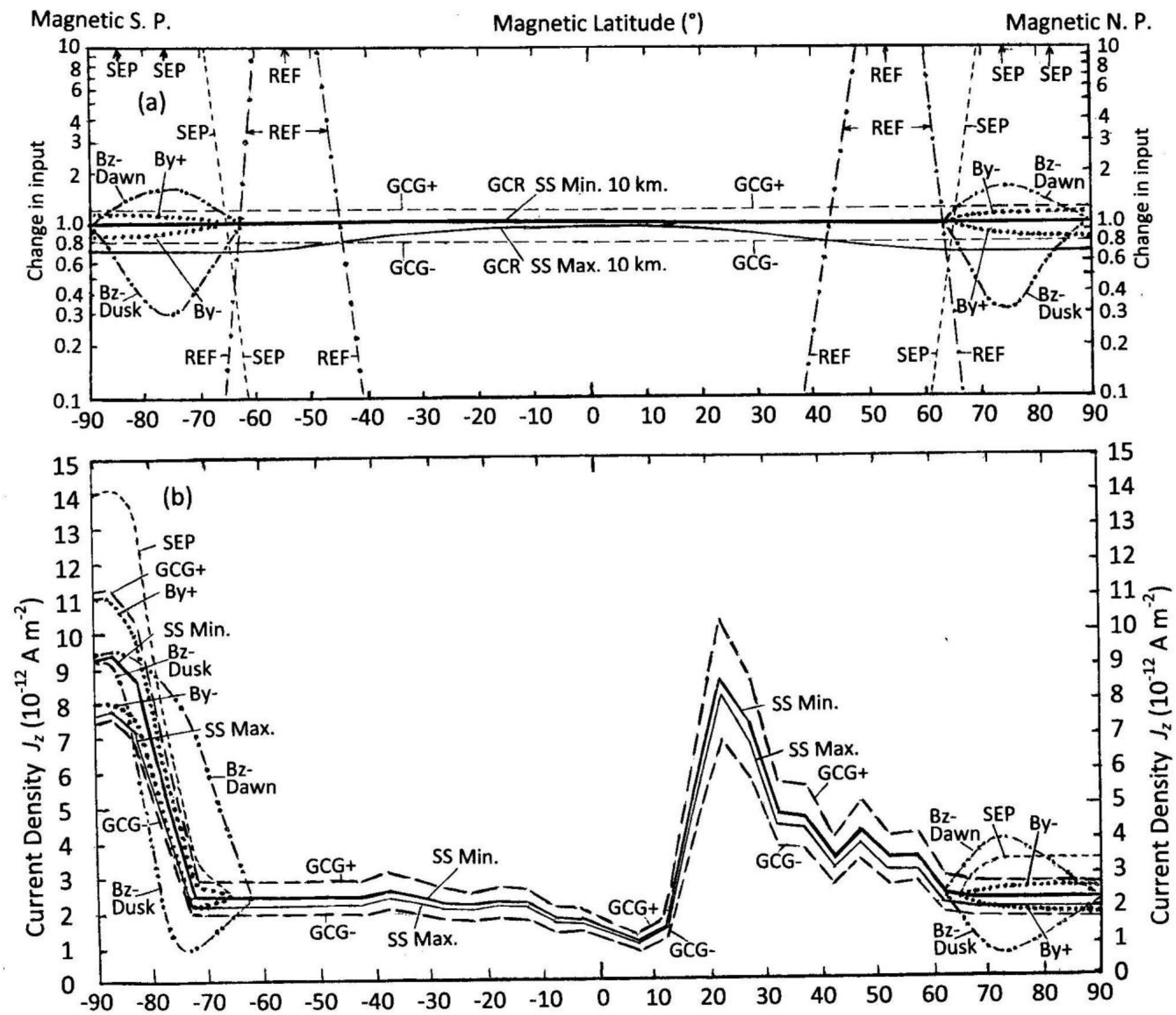

Figure 1. (a) Variations in magnetic latitude of inputs to Jz and (b) approximate responses at longitude 92.5°E. The low values near 8°N are due to anthropogenic aerosols, and the high values near 85°S and 22°N are due to the elevation of the Antarctic Plateau and the Himalaya Mountains. The inputs are the galactic cosmic ray flux (GCR); relativistic electron flux (REF); solar energetic particles (SEP); solar wind magnetic field (By+, By-,and Bz-); diurnal global circuit generators maxima and minima (GCG+ and GCG-).

Recently, new observations of atmospheric changes related to these inputs have been published. These include the effect of solar energetic particles on stratospheric aerosols (Mironova et al, 2012a), and geopotential height (Veretenenko and Thejll 2013); the effect of relativistic electrons on atmospheric vorticity (Tinsley et al. 2012; Mironova et al., 2012b; Hebert et al. 2012); the effect of Forbush decreases of galactic cosmic rays on mid-high latitude surface pressure (Artamonova and Veretenenko, 2013); the effect of the interplanetary electric field on cloud cover (Voiculescu and Usoskin 2012; Voiculescu et al. 2013), and on polar surface pressure (Lam et al. 2013); the effect of internal (low latitude) current generator changes on polar cloud base heights (Harrison and Ambaum 2013); the effect of minima in Solar Wind Speed and the geo-effective interplanetary electric field on day-to-day changes in the North Atlantic Oscillation Index and the Arctic Oscillation Index (Zhou et al. 2013).

The responses of the NAO and AO are shown in Figure 2, and are found in winters with high concentrations of stratospheric and mesospheric H_2SO_4 and aerosols; the minima in SWS are associated with minima in relativistic electron precipitation at sub-auroral latitudes. Most models of stratospheric and mesospheric conductivity assume it is so high as to offer negligible column resistance in series with the tropospheric column resistance, but the implications of the observations is that in the absence of ionization by relativistic electrons, and in the presence of H_2SO_4 and aerosols, the middle atmosphere column resistance can rise to non-negligible values. There is much uncertainty about aerosol particle nucleation and growth and ion concentration in the cold regions of the mesosphere and stratosphere when concentrations of NOx are low with low solar and geomagnetic activity. There is a need for more information on cosmic dust, meteoric smoke, and ion-induced nucleation affecting aerosol concentrations and conductivity.

We regard the evidence for tropospheric responses to Jz changes as compelling, because (1) the correlations are on the day-to-day time-scale, and although the amplitude of the responses is small, with tens to hundreds of events very high statistical significance has been demonstrated, and (2) there are five different types of inputs to the global circuit that cause day-to-day variability, and the responses agree in onset time, amplitude, and sign of response with each of the associated Jz variations. The inputs are galactic cosmic rays, relativistic electrons, solar energetic particles, the solar wind speed and interplanetary magnetic field components (solar wind electric fields) and the day-to-day changes in the upward current output of the thunderstorm and electrified cloud generators.

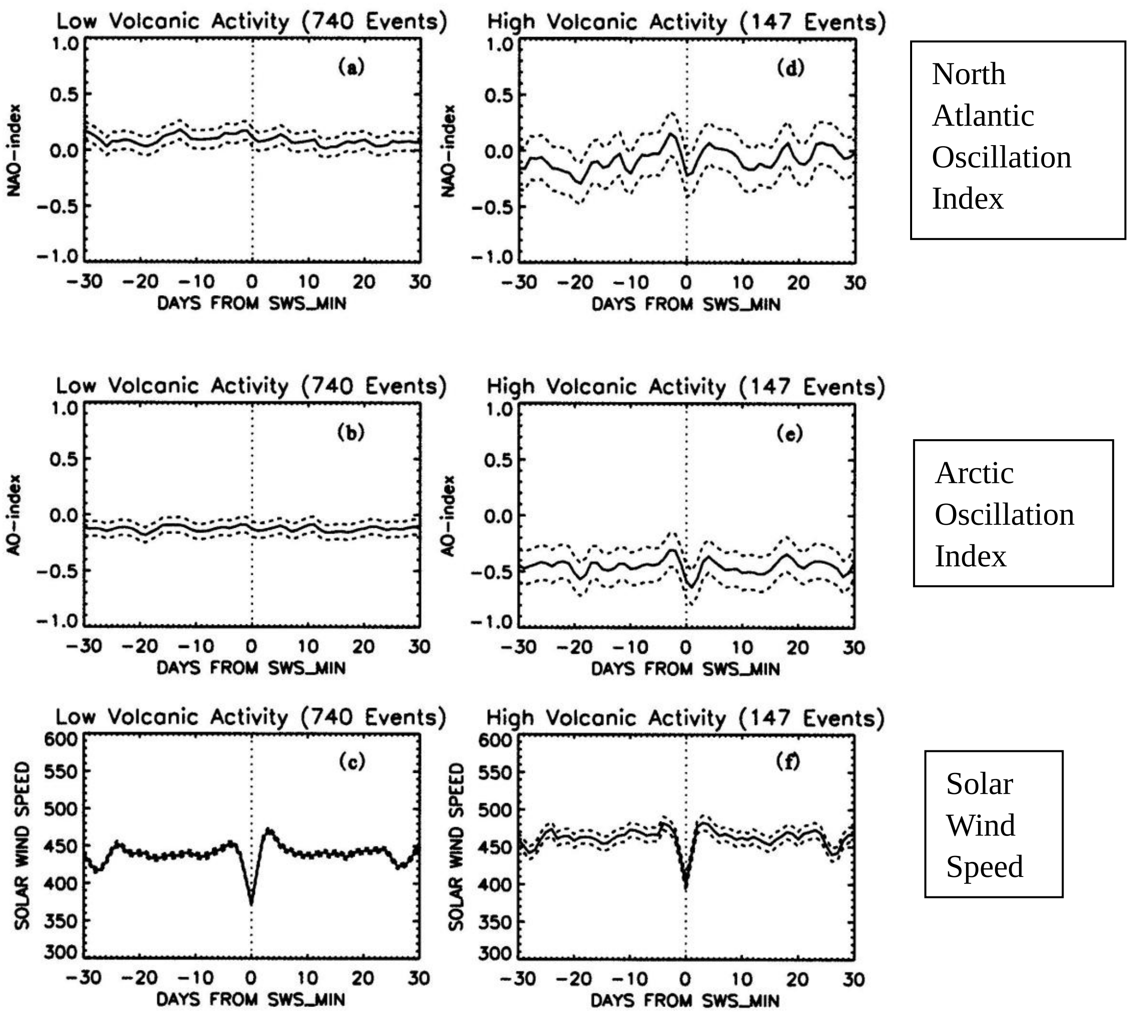

Figure 2. New results showing responses of the North Atlantic Oscillation and the Arctic Oscillation indices to solar wind speed minima, but only with high concentrations of volcanic H_2SO_4 aerosol in the stratosphere and mesosphere, during 1963-2011.

PROPOSED MECHANISM FOR TROPOSPHERIC RESPONSES

Link through cloud charging

There have been many measurements of droplet charges in clouds. For clouds and aerosol layers without deep convection positive charges are found at upper boundaries and negative charges at cloud bases, as illustrated in Figure 3. This is consistent with space charge accumulation required by Poisson's equation, as Jz flows through conductivity gradients (e.g., at boundaries of cloud or aerosol layers) and creates electric field gradients.

Schematic of Space Charge Accumulation, as in Oceanic Clouds

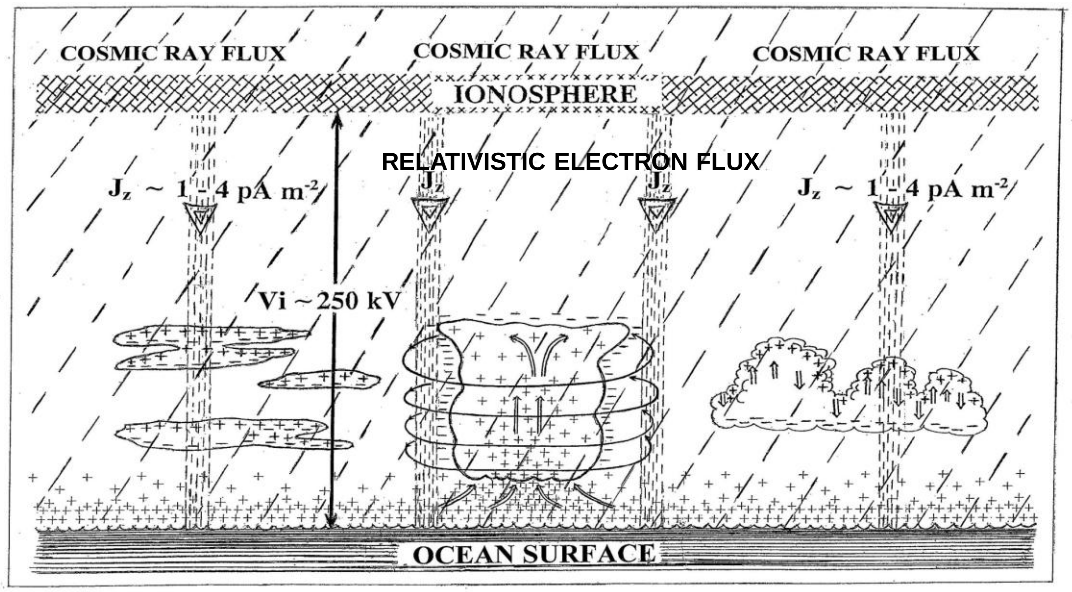

Figure 3. Schematic of cloud charging. Variable cosmic ray and other space particle fluxes ionize the atmosphere. In the magnetic polar caps the solar wind superimposes potentials on low latitude V_i.
The current density (J_Z) depends on stratospheric and tropospheric column conductivity, and on V_i (Ohms Law).
Space charge is formed as J_Z flows through conductivity gradients (Poisson's Equation).
Space charge attaches to aerosols in sea spray particles, haze, and fog near the ocean surface.
Space charge is convected into clouds by updrafts.

In layers near ocean surfaces charged fog and sea-salt aerosol particles can be lifted by updrafts into oceanic clouds – especially in the 'hook' or 'comma' cloud regions of oceanic cyclones.

The central processes of the proposed mechanism are that the cloud charge partitions between charged droplets and charged aerosol particles, particularly cloud condensation nuclei (CCN) and ice forming nuclei (IFN). The electric charge on nuclei affects their rate of collision with droplets (in-cloud scavenging). The charges can increase or decrease the scavenging rates, dependent on nuclei size, relative to scavenging rates in the absence of charge (Tinsley, 2008). The nuclei size distributions as well as the concentrations change. Such changes in CCN produce subsequent changes in droplet size distributions in successive episodes of condensation and evaporation of droplets. Also, scavenging of IFN by supercooled droplets in parts of clouds above the freezing level promotes contact ice nucleation and ice production.

Consequently, changes in cloud cover can occur in layer clouds. In convective clouds the changes in droplet size distribution affect droplet coagulation and initial precipitation losses and ice production; the release of latent heat of freezing promotes storm invigoration (see below), and in winter storms blocking and the amplitude of Rossby waves and upward propagation of wave energy may be affected. Figure 4 is a cartoon, illustrating and exaggerating storm invigoration. It contrasts storm development following a high Jz day with that following a low Jz day.

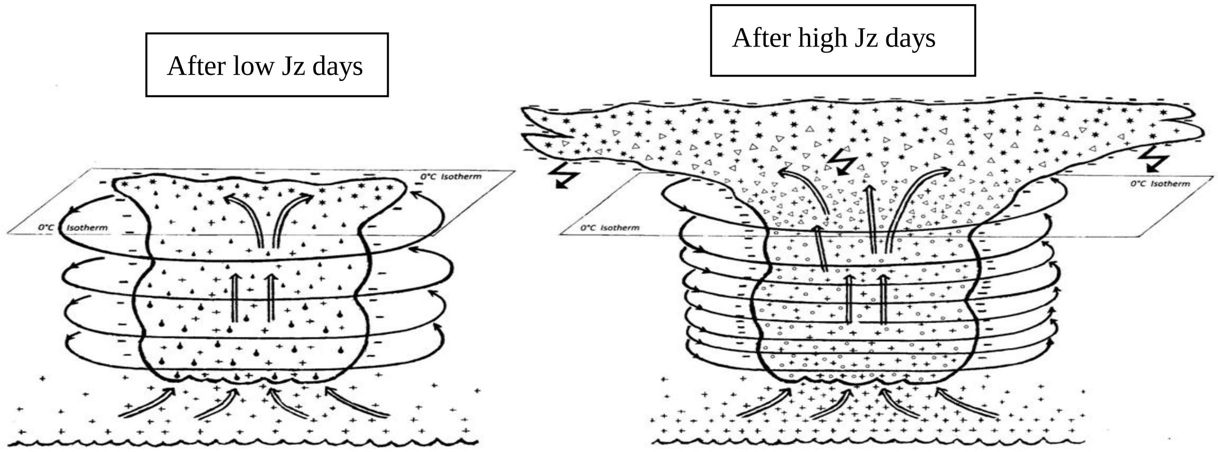

Figure 4. Schematic of effect of near-surface oceanic aerosol lifted by updrafts into cyclonic clouds.

Subsequent to a high J_z day, cloud formation with the J_z–modulated CCN and droplet size distributions gives reduced initial production of rain. More liquid water is carried above the freezing level and releases latent heat of freezing, which invigorates the updrafts (Rosenfeld et al., 2008). The strengthened updraft increases the vorticity, giving correlations of winter cyclone vorticity with J_z, as observed. The extra ice is also consistent with greater average winter lightning observed for greater GCR flux in 1990-2005, and less lightning following Forbush decreases (Chronis, 2009).

Pathways from microphysical to cloud-scale changes

There are a number of pathways from electrical changes in scavenging of CCN and IFN to changes in cloud dynamics and cloud cover. For both CCN and IFN there are changes in concentration accumulating in air masses for hours to days, and for IFN scavenged by supercooled droplets there is an immediate result in contact ice nucleation.

Pathway 1. IFN are generally larger than 0.5 μm radius, and the electrical effect is to increase the collision rate independent of the sign of Q/q. For droplets carried by updrafts above the freezing level, freezing does not occur until they are cooled below -15°C, unless contact ice nucleation occurs when the -5°C level is reached. Thus electro-scavenging giving contact ice nucleation at the tops of clouds with radiative cooling or only weak updrafts results in earlier and greater initial ice production, releasing latent heat of freezing and increasing updraft speed. For layer clouds there may be cloud cover and albedo changes.

Pathway 2. CCN radii range from 0.03 μm to several μm. The electrical effects on CCN include increases in scavenging rate for larger particles, 'electro-scavenging', decreasing their concentration independent of the sign of Q/q. Electro-scavenging also applies to all sizes of CCN with Q/q negative. 'Electro-anti-scavenging' occurs with smaller CCN in regions of space charge, for which Q/q is predominantly positive, resulting in concentrations remaining higher than for zero charging. The lifetime of CCN in an air mass is one to ten days. In later cycles of evaporation/condensation the CCN size distribution changes result in decreases of the concentration of large droplets and increase in those of small droplets. This reduces the rate of coagulation and initial precipitation, and updrafts carry more droplets above the freezing level. This produces more ice and increases the vigor and therefore the vorticity of baroclinic storms. It may also increase the amount of water released into the upper troposphere and change cloud cover and increase upward wave propagation.

Pathway 3. A special case of the previous pathways. The droplets, with their large size, carry much more charge than nuclei, and when droplets evaporate, the ‘evaporation nuclei’ retain that charge for 10 minutes or so. These highly charged nuclei have reaction rates one or two orders of magnitude more than the nuclei with equilibrium charge. Evaporation of charged droplets in downdrafts and in drier air entrained by turbulence near cloud boundaries often occurs in storms, and the highly charged evaporation nuclei are then rapidly scavenged. Again, the change in CCN concentration and size distribution can subsequently affect storm development.

Pathway 4. Turbulence and entrainment at cloud tops, if above the freezing level, can result in highly charged evaporation nuclei that can act as IFN in contact ice nucleation, promoting freezing and changing storm dynamics and cloud cover.

Pathway 5. The particles that act as IFN have different surface properties than CCN, and so are left as interstitial particles when cloud droplets are condensing on CCN. These interstitial IFN can experience electroscavenging in clouds below the freezing level, and then act as immersion freezing nuclei when the updrafts lift the droplets above the -15°C level. Again this enhances the formation of ice above the freezing level, affecting cloud and storm dynamics and cloud cover.

Other more speculative pathways involve ion-mediated nucleation of ultrafine particles, e.g. in volatiles released from evaporating droplets in space charge at cloud boundaries. The ultrafine nuclei may then grow into CCN with electro-anti-scavenging protecting against coagulation.

MODELLING

Although the evidence for Jz effects on atmospheric dynamics is compelling, and clouds appear to be the only agents, affected by the very small energy inputs of Jz, that have the capability to influence the much larger flow of energy in the atmosphere, the Jz-cloud hypothesis must be tested by quantitative modeling before its reality is firmly established. The following needs are apparent:

Needs for modelling cloud charging

For layer clouds, one-dimensional models of cloud boundary charging have been given by Zhou and Tinsley (2007, 2012). There is a need to extend these to 3-dimensions for application to convection in the cellular structure of marine stratocumulus.

For convective clouds, charged aerosols from near the surface, with charge originating with Jz, are carried by updrafts into the body of the cloud. In barotropic convective clouds (summertime cumulus), a simple model has been given by Vonnegut et al., (1962). For baroclinic oceanic cyclones, an outline has been given by Tinsley (2012). There is a need for detailed 3-dimensional models in both barotropic and baroclinic systems.

Simulations and parameterization of charge modulation of aerosol scavenging

Following work of Pruppacher and his students in the 1970s, trajectory simulations for in-cloud scavenging have been made, with the introduction Monte-Carlo simulation of diffusion by Tinsley (2010).

A parameterization of the simulations has been given by Tinsley and Leddon (2013) and with extended coverage in a more user-friendly format by Tinsley and Zhou (in preparation).

Figure 5 shows some of the results of simulations for droplets of radius 15 μm, in collisions with particles ranging from 0.005 μm to 3.75 μm in radius. Computing the trajectories for each point took about a day of computer time for the larger particles to several weeks for the smaller ones with high diffusion coefficients. The particle charges, q, ranged from -50e (elementary charges) to +50e, interacting with droplets of charge, Q, of 50e, 100e, and 200e. For the larger particles, image forces prevailed, and the droplet charge had little effect. For the smaller particles, the long-range Coulomb repulsion prevailed, proportional to the product Qq. Similar simulations have been made for particles interacting with droplets of radii 6 μm and 3 μm. However, there is a need for simulations and parameterization more comprehensively as a function of relative humidity, particle density, and particle shape.

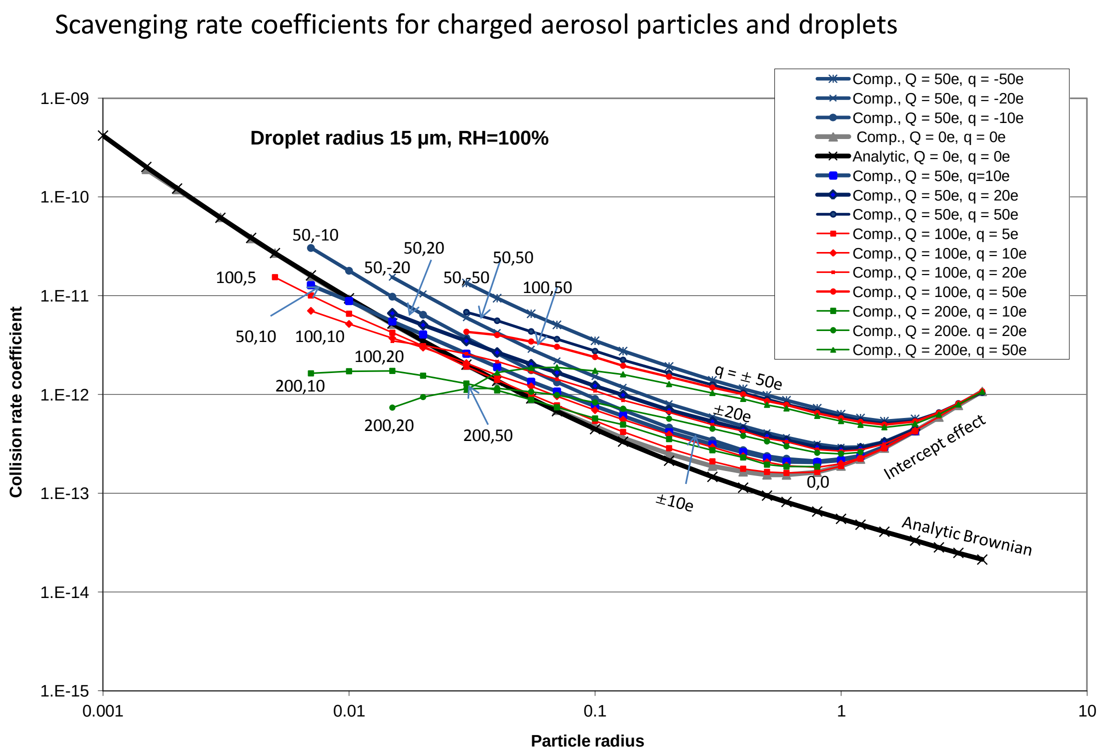

Figure 5. Collision rate coefficient ($m^{-6}s^{-1}$) for aerosol particles, of radius 0.005 µm to 3.75 µm, with droplets of 15 µm radius. Curves are labeled by droplet and particle charges 'Q,q'. The asymptotic change in electro-scavenging rate for larger particles is approximately proportional to the square of charge on the particle.

Needs for modelling of changes of dynamics and albedo due to electrical effects on microphysics

The parameterized scavenging rates can be used with cloud charging results in models of cloud formation and development. The microphysical pathways discussed involve changes in drop size distributions, ice production, latent heat release, cloud cover, and the dynamics of storms.

Changes in cloud cover affect the radiation budget of a region; this is the difference between cooling effect of clouds in backscattering solar shortwave radiation and the warming effect of trapping the infrared and re-radiating it down.

Changes in storm dynamics affect the general circulation, and the amplitude of Rossby waves that appear in the jet stream. Prolonged changes in circulation give rise to changes in regional/seasonal climate.

The application to GCMs is the final stage of modeling needed, after there are reliable parameterizations of charging of clouds and its consequences for microphysics and cloud dynamics.

CONCLUSIONS

The evidence for atmospheric dynamical responses to current density (Jz) changes in the global electric circuit is strong.

It is consistent with a mechanism involving electrical charging of clouds causing changes in cloud microphysics.

There is also evidence of changes in cloud cover, and these may be a direct result of microphysical changes, or an indirect result of dynamical changes. This uncertainty could be resolved by analysis of response times, or changes in occurrence of cloud properties with Jz.

Although the correlations are mainly for influences on the day-to-day timescale, the processes involved are expected to apply on the longer decadal and century timescales of solar variability as well.

While there are many measurements of charging of layer clouds, there is uncertainty in initial charging of cyclonic clouds, which could be resolved by in situ observations (by UAVs?) compared to observations of J_z away from the cloud (again by UAVs?) and by modeling.

There are uncertainties about which detailed microphysical pathways are most important. These could be resolved by cloud modeling and in-situ measurements which include aerosol size distributions and charges.

There is a need to model and measure stratospheric and mesospheric conductivity and composition during periods with and without volcanic aerosols, and during solar and magnetic quiet times in comparison to times of MeV particle precipitation.

The Jz – cloud - atmospheric dynamics connection involves basic cloud microphysics, and is not only relevant to solar influences on the atmosphere, but also to internal atmospheric connections, e.g., between low latitude climate cycles such as the El Niño Southern Oscillation, with changing cloud charging, and variations in high latitude atmospheric dynamics.

ACKNOWLEDGMENTS

This work was supported by NSF grant AGS 0836171 and by NSFC grant 41271054.

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