ARTICLE IN PRESS

Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Review article

Solar wind-atmospheric electricity-cloud microphysics connections to weather and climate

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A R T I C L E I N F O

Article history:
Received 13 August 2015
Received in revised form
16 October 2015
Accepted 23 October 2015

Keywords:
Solar wind
Atmospheric electricity
Cloud microphysics
Weather and climate

A B S T R A C T

We review recent research articles that present observations of the large-scale day-to-day dynamic tropospheric response to changes in the downward current density J_z of the global atmospheric electric circuit (GEC). The evidence for the global circuit downward current density, J_z, causing changes in atmospheric dynamics is now even stronger than as reviewed by Tinsley (2008) (Rep. Prog. Phys. 71, 066801). We consider proposed mechanisms for these responses, and suggest future directions for research.

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http://dx.doi.org/10.1016/j.jastp.2015.10.019
1364-6826/

1. Introduction

1.1. The global electric circuit (GEC) and the modulation of J_z and E_z

The world's thunderstorms and electrified clouds maintain a vertical electrical potential difference of about 250 kV between the ionosphere and the ground (e.g., Williams, 2005) as shown schematically in Fig. 1. The global electric circuit results from the upward current flow from these convective generators, spreading around the globe. The current returns to the surface as a downward current density J_z through the weakly ionized air and its embedded cloud and aerosol layers, where the associated vertical electric field is E_z. The ions are generated by the incoming galactic cosmic ray (GCR) flux, and their concentration decreases rapidly from the tropopause to the surface due to the attenuation of the GCR flux as it creates the ionization.

Our aim in this article is to provide a review of the observations of day-to-day meteorological effects correlating with J_z (typically a few pico-amperes per square meter), which shows variability with time and location over the globe. The action of the GEC on any timescale is of potential interest, and given present concerns about the effects of climate change on the planet, we are certainly interested in decadal scales and longer. However, the advantage of observing on daily timescales is that we can isolate the effects of the GEC on the atmosphere from the effects due to other mechanisms. There are a number of inputs to the atmosphere modulated by solar activity that all vary on the 11-year solar cycle, but on the day-to-day timescale their time variations are distinctly different. Also, in just a few years the day-to-day variations provide many events for evaluating the statistical significance of observed correlations. Furthermore, variability on the synoptic timescale of about 10 days may influence the development of longer term atmosphere-ocean variations such as the North Atlantic Oscillation (Hurrell et al., 2003, p. 16). Changes in the polar stratospheric vortex have been attributed to forcing by the upward propagation of planetary-scale Rossby waves originating in the troposphere (Andrews et al., 1987). In turn, downward dynamical propagation from the stratosphere on a timescale of months can affect longer term tropospheric dynamics and sea-surface temperature (Reichler et al., 2012). Thus there is a need to quantify short-term forcing and its long-term change in order to fully understand decadal and longer term climate changes.

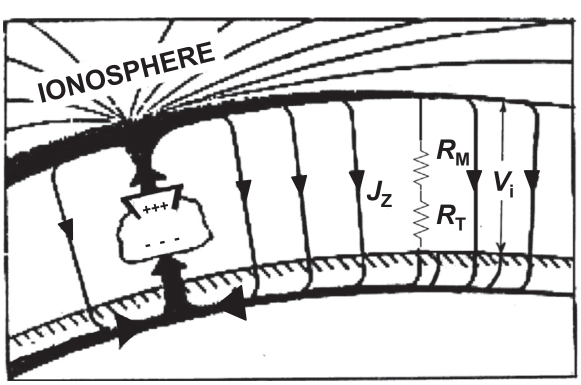

Fig. 1. Schematic of a section through the global atmospheric electric circuit (GEC). The circuit is mostly driven by the internal meteorological generator associated with thunderstorms and electrified clouds. Each of about 1000 highly-electrified storms around the globe sends about 1 A to the ionosphere, charging it to a voltage $V_i \sim 250$ kV. If R_M, and R_T are the column resistances (Ω m^2) of the middle atmosphere and troposphere respectively, then the local downward current density, J_z, is given by Ohm's Law in three dimensions: $J_z = V_i / (R_M + R_T)$. Any change in V_i, R_M, or R_T affects J_z. R_M and R_T vary with cosmic ray flux, relativistic electron flux, and solar proton flux. V_i varies diurnally (the Carnegie variation) and with IMF and solar wind speed changes. Volcanic aerosols, as well as energetic particles, affect R_M and R_T, with all acting together to modulate the ionosphere-earth current density J_z. Adapted from Mühleisen and Fischer (1987).

The studies reviewed in this paper, therefore, are useful for probing the nature of the links between solar variability and the atmosphere, and we show that they provide strong evidence for the GEC being one such link. We also explore mechanisms for tropospheric responses, which are proposed to operate via the action of J_z producing space charge (non-zero net charge) in clouds and affecting cloud microphysics. Finally we consider possibilities for future research efforts in this area that could lead to further progress.

One longstanding obstacle for the plausibility of J_z (also of cosmic rays) as a driver for tropospheric dynamical responses has been the very large energy amplification needed (e.g., Willis, 1976, Lean and Rind, 1998). However, in cloud processes there is continual conversion from thermal energy to potential energy to latent heat release, with outcomes affecting either, or both of, the atmospheric dynamics and the atmospheric radiative balance. Very small energy inputs can divert the energy flow. Two such situations where energy flow can be modulated by cloud microphysical responses to J_z changes are as follows:

(1) The process of storm invigoration (e.g., Rosenfeld et al., 2008) occurs with changes in the concentration and size distribution of aerosol particles acting as cloud condensation nuclei (CCN), which results in changes in the droplet size distribution as updrafts create cooling and condensation. For increasing concentrations of smaller CCN compared to normal, the available water vapor is converted into increased concentrations of smaller droplets. The CCN act as a regulator of coagulation and precipitation processes; with smaller droplets, more liquid water is carried above the freezing level instead of precipitating, and the freezing releases more latent heat of freezing, which invigorates the updraft. Smaller numbers of large CCN are expected to have the same effect, because smaller numbers of larger droplets are formed, which also inhibits the coagulation and precipitation processes. In addition, increases in collision rates of ice forming nuclei (IFN) with liquid droplets above the freezing level can induce droplet freezing and also contribute to the release of latent heat of freezing and invigoration.

(2) Changes in cloud albedo, cloud cover, and infrared opacity affect regional radiative balance, indirectly affecting regional atmospheric dynamics (e.g., IPCC (2013)). This is applicable to layer clouds where the concentration and size distribution of droplets, responding to changes in cloud microphysics, act as a valve on the flow of radiation. The droplet size distribution affects albedo and infrared opacity directly and also indirectly affects cloud cover because of changes in drizzle production and cellular structure in broken clouds (e.g., Rosenfeld et al., 2006). Similarly in mixed phase (water plus ice) clouds, changes in the fraction of ice affect the infrared opacity (Prenni et al., 2007).

For both of the above situations, the CCN and IFN can be viewed as agents in the partitioning of the energy flows. We present evidence and qualitative theoretical analysis supporting the view that the electric charges produced by cosmic rays and moved by current flow in the GEC modulates the properties of the agents and their regulation of the energy flows.

2. Review of observations

The large number of responses, on the day-to-day timescale, of the large-scale dynamics of the atmosphere that occur when regional changes occur in J_z, provide compelling evidence of a role

Please cite this article as: Lam, M.M., Tinsley, B.A., Solar wind-atmospheric electricity-cloud microphysics connections to weather and climate. Journal of Atmospheric and Solar-Terrestrial Physics (2015), http://dx.doi.org/10.1016/j.jastp.2015.10.019