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The response of longwave radiation at the South Pole to electrical and magnetic variations: Links to meteorological generators and the solar wind

John E. Frederick[a,*], Brian A. Tinsley[b]

[a] University of Chicago, Chicago, IL, USA
[b] University of Texas at Dallas, Richardson, TX, USA

ABSTRACT

An increasing body of evidence supports the conclusion that electrical variations in the Polar Regions influence atmospheric radiative properties. These influences can be transmitted (1) by the global electric circuit from remote thunderstorms and electrified shower clouds; (2) from local electric fields associated with ionospheric currents that generate magnetic activity, and (3) from local penetration of the solar wind electric field. A regression-based analysis reveals a positive relationship between downwelling longwave radiation observed during the dark portion of the year at the South Pole and the vertical electric field measured at the Antarctic stations Vostok and Concordia from 1998 to 2011, component (1). An increase in the electric field of 22.4 Vm^{-1}, equal to one standard deviation of the nighttime mean, is followed one day later by a longwave irradiance 2.78 ± 1.90% larger than would exist otherwise. In addition, a significant negative correlation with a lag of two days exists between longwave irradiance recorded from late 1993 to mid-2017 and the $\mathrm{A_p}$ index, which measures temporal variations in the surface magnetic field associated with electric fields of ionospheric origin, component (2). There is a weaker, less-definitive, positive correlation of longwave irradiance with the interplanetary magnetic field index B_y which is associated with the solar wind electric field, component (3). These results are consistent with previous work using visible radiation, and with the hypothesis that the ionosphere-earth current density influences the microphysics of polar clouds, with consequences for radiative processes and meteorological variables such as surface pressure.

1. Introduction

1.1. Surface pressure and atmospheric electricity

A response of surface pressure in the Arctic and Antarctic to changes in the solar wind magnetic field sector structure (Wilcox and Ness, 1965) has been reported; using 1964 surface pressure data by Mansurov et al. (1974); using 1964–1971 data by Page (1989); using 1998–2001 data by Burns et al. (2007, 2008); and using global reanalysis pressure data for 1999–2002 by Lam et al. (2013, 2014), with the pressure response propagating upward over several days. In addition, a response of Antarctic atmospheric temperature was reported by Lam et al. (2017). Tinsley and Heelis (1993) attributed the pressure responses to changes in the microphysics of clouds, due to the flow of an ionosphere-earth current density (J_z) through the clouds. Modulation of microphysical processes by electric charge on aerosol particles and droplets has been extensively discussed by Pruppacher and Klett (1997, chapter 18), and most recently by Zhang and Tinsley (2017). Electrical effects on aerosol collection rates affect their lifetimes and concentrations (Tinsley, 2010). For stratus clouds, changes in aerosol concentration can cause significant changes in cloud opacity (Twomey, 1977; Rosenfeld et al., 2006; Mauritsen et al., 2011).

The current density J_z is present all over the globe and varies with ionospheric potential. In the Polar Regions three sources of ionospheric potential change can be identified for variations on the day-to-day timescale. There is (1) the day-to-day change in the global meteorological generators (Hays and Roble, 1979: Roble and Hayes, 1979); these are upward currents due to thunderstorms and highly electrified clouds, mainly at low latitudes. These result in an ionospheric potential of about 240 kV (Markson, 2007), and this component varies in universal time but is uniform over the globe at any given time.

The other two sources producing components of J_z at high magnetic latitudes are due to the solar wind magnetic fields generating current flow in the polar ionospheres and potential changes there that map down to the surface. At the South Geographic Pole there is an input (2) that is important due to the closeness of the Austral auroral electrojets to this location. There are two main electrojets; one on the morning (dawn) side of the auroral oval, which increases the ionospheric potential there by several tens of kilovolts, and one on the evening (dusk) side which decreases it by a somewhat larger number of tens of kilovolts. The average effect over 24 h is not zero, but usually a few tens of kilovolts negative, becoming increasingly negative with increasing inputs from the solar wind, and with the ‘unloading’ in magnetic substorms of energy accumulated in the Earth's magnetosphere. The $\mathrm{A_p}$ index is one of several magnetic signatures of the strength of the electrojets, and of magnetic storms and substorms generally. Ground-based

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* Corresponding author. Department of the Geophysical Sciences, University of Chicago, 1950 E. Greyhound Pass, Box 18-199, Carmel, IN, 46033, USA.
E-mail address: frederic@uchicago.edu (J.E. Frederick).

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measurements of the electric field responses to geomagnetic activity have been reviewed by Frank-Kamenetsky et al. (2012).

The other solar wind input, (3), is the east-west (B_y) component of the solar wind magnetic field, also known as the interplanetary magnetic field, or IMF B_y. This is associated with a north-south (Lorentz) electric field which maps down magnetic field lines to the polar ionospheres, changing their potential, with greatest effect at the magnetic poles (e.g., Tinsley and Heelis, 1993). This potential change, illustrated by Lam et al. (2013), extends out to more than 15° from the magnetic poles, but it decreases with distance from these poles and is a minor influence compared to the electrojets at the South Geographic Pole. Changes in ionospheric potential in the Polar Regions associated with changes in auroral electrojet current systems and in B_y have been measured as offsets from the low latitude potential by polar orbiting satellites (e. g., Chen et al., 2015) and have been incorporated into an empirical model by Weimer (2001). Radar techniques have been used for ground based measurements (e.g. Cousins and Shepherd, 2010; Foster and Vo, 2002), and as noted, surface E_z measurements have been reviewed by Frank-Kamenetsky et al. (2012). The offsets due to B_y have opposite signs in the Arctic as compared to the Antarctic. An effect of given sign persists in either hemisphere with the duration of the signs of B_y in the solar wind sectors, which is about 13 days for an average two-sector solar wind structure (e.g. from 2000 to about the mid-2004), and about 7 days for an average four sector structure (e. g., from mid-2004 to mid-2007) but often of irregular length. Plots of solar wind parameters can be downloaded from the OMNI web site; for its URL see the Acknowledgements. Changes in J_z associated with relativistic electron precipitation at lower latitudes have been proposed to be the cause (via cloud microphysical changes) of small changes in atmospheric vorticity (Mironova et al., 2012; Tinsley, 2012; Lam and Tinsley, 2016), but are not considered further here.

Variations in the surface vertical electric field E_z, that are associated with changes in J_z and ionospheric potential, were measured at Vostok by Burns et al. (2005) on the East Antarctic plateau during 1998–2001. Vostok is near the South Geomagnetic Pole, and is not close to the electrojets, and their effect on surface electric fields there is small compared to that of B_y, which, as noted, is maximum at the Geomagnetic Pole. In addition to showing that changes in E_z and surface pressure were associated with changes in B_y in 1995–2005, Burns et al. (2007, 2008) showed that in 1998–2001 pressure changes were also associated with the day to day changes in E_z produced by the meteorological generators. Zhou et al. (2017) extended the study of such pressure responses globally, using the 1998–2001 E_z time series of Burns et al. (2008) and reanalysis data to identify regional as well as zonal pressure responses. They showed that the responses varied with season, being strongest in local winters in the Arctic and Antarctic. They also showed that zonal mean responses to the IMF B_y component persisted through 2007–2016 in addition to 1995–2006.

Fig. 1 is a flow chart that illustrates proposed links between the external and internal inputs to the current density J_z and space charge generation in clouds. This in turn affects the microphysical electro-scavenging and electro-anti-scavenging processes with consequences for cloud opacity and other meteorological quantities.

1.2. Clouds and atmospheric electricity

Based on satellite observations Kniveton et al. (2008) found correlations between regional cloud cover over East Antarctica and the Vostok E_Z daily averages for 1998–2001. Statistically significant links did not extend to the South Pole, perhaps due to limited data availability at the highest latitudes and uncertainties in distinguishing cloud signatures from the highly-reflecting ice. Frederick (2016) found that changes in cloud opacity in the visible, looking upward from Summit, Greenland, were associated with large magnetic storms as measured by the A_p index. Summit is close to the location of the Boreal auroral electrojet. A similar response was found at the South Geographic Pole, 90°S (Frederick, 2017), which as noted, is close to the Austral auroral electrojet.

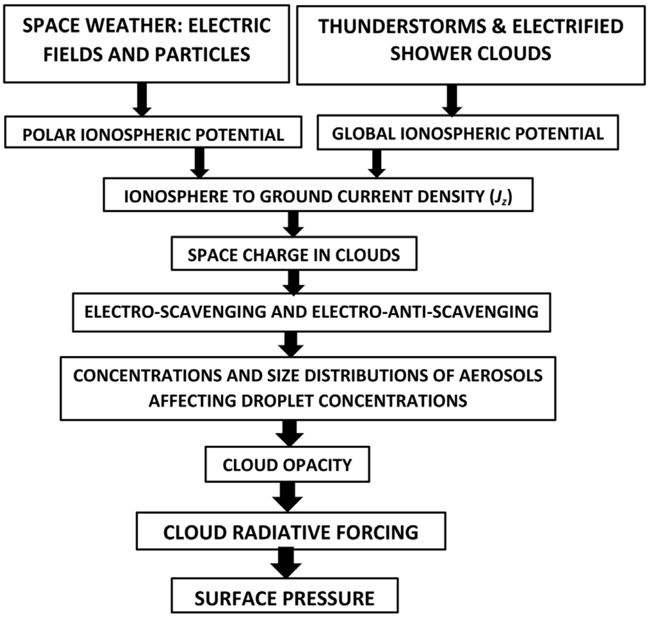

Fig. 1. Proposed links between electric fields of internal and external origin, the ionosphere-to-ground current density and effects in the lower atmosphere.

The nature of the clouds at the South Pole has been studied by Stone (1993), who found that, on average, during the winter they are moderately thick, extending up to 3 km above the top of the surface-based inversion layer. However, they are optically thin and non-black, having effective emissivities of 0.6. With temperatures below −40 °C they are composed of small ice particles, with little or no liquid water, and are overall similar to high-level cirrus clouds, observed at midlatitudes.

In the present work we examine associations of downward propagating longwave infrared radiation at the South Pole, with several parameters to characterize electrical and magnetic activity. These include (1) daily averages of the meteorologically generated component of the vertical electric field (E_z) during 1998–2001 and 2006–2011, obtained at Vostok (78.5°S, 107°E), supplemented during 2009–2011 by electric field measurements at Concordia (75.1°S, 123°E), (2) the daily A_p index, and (3) the daily average interplanetary magnetic field B_y in GSM coordinates.

2. Surface electric fields inferred from observations at Vostok and Concordia

2.1. Reducing the perturbations

Sets of 20-min observations of atmospheric electric field from Vostok (2006–2011) designated (VE_Z) and from Concordia (2009–2011) designated (CE_Z), described by Burns et al. (2017), have been accessed from the Australian Antarctic Division web site (the URL is in the Acknowledgements). They are used here to generate daily average E_Z values for those days on which short-term variability due to local meteorological disturbances is low enough to yield useable values. Previously measured E_z values for 1998–2001 are described by Burns et al. (2005). These observations made from the Antarctic ice plateau have very much less noise than observations of E_Z from stations on land at lower latitudes, owing to the very stable air most of the year in the temperature inversions at each site, and the absence of dust, water vapor and organic aerosols. However, the katabatic wind system, with winds of about 3–6 $\mathrm{m\,s^{-1}}$ at Vostok, and 2-4 $\mathrm{m\,s^{-1}}$ at Concordia, creates small scale turbulence in the electrode layer near the surface within the temperature inversion. This can generate minute-to-minute fluctuations