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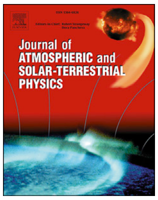

The zonal-mean and regional tropospheric pressure responses to changes in ionospheric potential

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ABSTRACT

Global reanalysis data reveal daily surface pressure responses to changes in the global ionospheric potential in both polar and sub-polar regions. We use 21 years of data to show that the pressure response to externally-induced ionospheric potential changes, that are due to the interplanetary magnetic field east-west (IMF B_y) component, are present in two separate decadal intervals, and follow the opposite ionospheric potential changes in the Arctic and Antarctic for a given B_y. We use the 4 years of available data to show that the pressure responses to changes in internally generated ionospheric potential, that are caused by low-latitude thunderstorms and highly electrified clouds, agree in sign and sensitivity with those externally generated. We have determined that the daily varying pressure responses are stronger in local winter and spring. The pressure responses at polar latitudes are predominantly over the Antarctic and Greenland ice caps, and those at sub-polar latitudes are of opposite sign, mainly over oceans. A lead-lag analysis confirms that the responses maximize within two days of the ionospheric potential input. Regions of surface pressure fluctuating by about 4 hPa in winter are found with ionospheric potential changes of about 40 kV. The consistent pressure response to the independent external and internal inputs strongly supports the reality of a cloud microphysical mechanism affected by the global electric circuit. A speculative mechanism involves the ionosphere-earth current density J_z, which produces space charge at cloud boundaries and electrically charged droplets and aerosol particles. Ultrafine aerosol particles, under the action of electro-*anti*-scavenging, are enabled to grow to condensation nuclei size, affecting cloud microphysics and cloud opacity and surface pressure on time scales of hours.

1. Introduction

1.1. Inputs to the global electric circuit

Mansurov et al. (1974) found that the surface pressure measured at stations in the Antarctic and Arctic during the International Quiet Sun years (1964–65) varied by a few hPa according to whether the solar wind magnetic field (Interplanetary Magnetic Field or IMF) in the vicinity of the Earth was directed towards or away from the Sun. The surface pressure changes were of opposite signs in the Arctic as compared to the Antarctic. It was pointed out by Tinsley and Heelis (1993) that the potential of the ionosphere in the polar cap regions changes by tens of kilovolts as the IMF changes sign. More specifically the east-west IMF component B_y changes sign, and because the interplanetary electric field (perpendicular to both B_y and the solar wind velocity) is therefore in the north-south direction in space, this raises the ionospheric potential in the Arctic while simultaneously depressing it in the Antarctic, and vice-versa. The polar ionospheric potential changes extend out 15°–20° from each magnetic pole, and are measured by spacecraft as offsets from the otherwise uniform global ionospheric potential which is internally generated by upward currents from thunderstorms and other highly electrified clouds.

While the internally generated component of the global ionospheric potential is spatially uniform outside the polar regions, it is temporally varying, averaging about 250 kV relative to the surface of the Earth (Markson, 1983). The upward currents from the meteorological generators, totaling 1000–2000 A globally, spread horizontally over the globe through the conducting ionosphere, and together with the solar component in the polar regions, return through the low-conductivity atmosphere to the Earth's surface in the form of a downward current density (J_z) of a few pAm^{-2} (Israel, 1973; Roble and Hays, 1979; Tinsley and Zhou, 2006; Rycroft et al., 2012; Baumgaertner et al., 2013). This upward and downward current flow, together with horizontal current flow in the ionosphere and in the Earth's land and ocean, constitutes the global electric circuit. The downward flow of current density, flowing through clouds, generates electric space charge in layers at the cloud boundaries (Zhou and Tinsley (2007), and near the surface produces downward electric fields (E_z) of order 100–200 Vm^{-1} (Whipple and

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Scrase, 1936), depending on the near-surface conductivity (Tinsley and Zhou, 2006).

The temporal variations of the ionospheric potential (V_i) and of E_z and J_z show a diurnal variation in universal time, as well as day-to-day variability, due to the local time and other variations of the meteorological generators, which are mainly low and middle latitudes mesoscale deep convective regions over land or islands with strong diurnal temperature changes. In addition, there is a component with relatively little diurnal variation that may be from oceanic sources, and/or frontal cloud systems. When the diurnal variations in universal time are averaged seasonally or annually a characteristic shape emerges, first determined as the 'Carnegie curve' from 'fair weather' shipboard observations made in the early 20th century (Ault and Mauchly, 1926; Torreson et al., 1946). Such oceanic measurements are relatively free of the electrical disturbances due to convection, even in 'fair weather', moving the space charge that is present near the surface over land and islands. Even less electrical noise is found under the optimum observing conditions on the Antarctic ice plateau, where convection is absent except for a few hours near noon in summer (Burns et al., 2005, 2006, 2012, 2017).

Analysis of measured values of E_z at Vostok on the Antarctic Plateau allowed separation of the solar wind (IMF B_y) generated potential from that due to the meteorological generators. This was determined by comparison of the E_z measurements with simultaneous IMF data, used as inputs to the satellite-based empirical Weimer (1996, 2001) models of the associated ionospheric potentials. Noise of local origin was minimized by identifying and eliminating data with large amplitude excursions due to blowing snow, as well as short term variations shorter than the response time of the global circuit. Thus a time series of the daily average values of the global meteorological contribution, with greatly reduced local meteorological noise and without the solar wind imposed ionospheric potential, has been obtained.

1.2. Responses of surface pressure to V_i and of E_z

The Mansurov effect was confirmed by Burns et al. (2007, 2008) by comparison of the daily surface pressure measurements from 11 Antarctic and 7 Arctic meteorological stations with the daily average IMF B_y values. The surface pressure changes were of opposite signs in the Arctic stations as compared to the Antarctic stations, as expected. At the Vostok station, in the annual average, the surface pressure varied by about 2 hPa for an IMF B_y change of 10 nT.

In addition, Burns et al. (2007) showed that the changes in day-to-day in surface pressure at Vostok were correlated with the daily average E_z at Vostok, corrected for the solar wind input. Such a response to the meteorologically generated component of overhead ionospheric potential changes is to be expected, for consistency with the Mansurov pressure response to the ionospheric potential component generated by the solar wind. There are some differences however; the autocorrelation time of the daily average E_z due to the global meteorological generators is 3–5 days, related to synoptic timescale variations of the electrified cloud generators, whereas that of the solar wind B_y generated component is up to 10 days, determined by the variable sector structure in the solar wind (Wilcox and Ness, 1965). Also the B_y-generated ionospheric potential changes are confined to the polar cap regions, whereas the potentials due to the global meteorological generators are, of course, global. Nevertheless, about the same pressure response was found at high southern magnetic latitudes (about 3.5 hPa in all-year data for an ionospheric potential change of 90 kV) for both the global and the solar wind generators (Burns et al., 2008; their Fig. 5).

Burns et al. (2008) also showed that the responses of surface pressure to V_i at Arctic coastal stations were comparable to the responses from Antarctic coastal stations, and were in the same sense as in the Antarctic, as expected, in contrast to the opposite sense of responses at those locations to the Mansurov effect. This pressure response to meteorologically-induced V_i changes was reviewed by Tinsley (2008) and Lam and Tinsley (2015) and is designated the Burns effect.

The study of the Mansurov effect was extended to the global scale by Lam et al. (2013) who used global reanalysis data (Kalnay et al., 1996) for the four years 1999–2002 to examine surface pressure variations, in relation to the IMF B_y-induced polar ionospheric potential changes. Their analysis of the surface pressure response to B_y showed that the effect extended away from the magnetic pole as far as mid-latitudes, considerably further than the B_y-induced ionospheric potential changes. Another analysis (Lam et al., 2014) showed that the Mansurov surface pressure changes in the Antarctic propagated vertically and reached the tropopause over a period of about 4 days.

Here we use 21 years of reanalysis data (1995–2015) to yield zonal mean (pole to pole) structure of the Mansurov effect, and use 1998–2001 data to provide a detailed zonal-mean and regional analysis of the Burns effect. The zonal mean variations at sub-polar latitudes are the longitudinal averages of regional structures with both positive and negative responses. Such structures have been previously noted for the Mansurov effect by Lam et al. (2013). We examine seasonal variations, and also lead-lag relationships to determine time delays of the pressure responses with respect to the E_z (and global V_i) variations. While the most plausible mechanism to explain the Mansurov and Burns effects, together with various other effects related to atmospheric electrical current flow in the global electric circuit, appears to be electric charge on condensation nuclei and ice-forming nuclei affecting cloud microphysics (Tinsley, 2008, 2012; Lam and Tinsley, 2015; Tinsley and Zhou, 2015), the detailed microphysical pathways remain to be determined in each case. In the present work we suggest a more specific pathway for the responses over the Antarctic plateau and the Greenland ice cap.

2. Data sources, background subtraction, and uncertainty estimates

We use 1995–2015 reanalysis data from the National Atmospheric and Oceanic Administration (NOAA) website, and the simultaneous IMF data from the NASA GFSC website. Data on the IMF is only intermittent, with about 50% coverage prior to 1995, which is the main reason why the analysis is for later periods. Another reason is that the pressure data from the Antarctic Plateau was also limited in earlier decades; there were only two stations (South Pole and Vostok) that predate the gradual introduction of automated weather stations there starting in the 1980s. In 1985 there were 5 stations in the whole plateau, and in 1997 there were 16. Thus, the earlier outputs from the reanalysis assimilative model are likely to be dominated by the near-free-running nature of the model, and less likely to show non-modelled pressure changes related to katabatic flow responding to inputs from atmospheric electricity. Together with the Vostok E_z observations, these sources are specified in the Acknowledgements section. We used a running mean (-13 to $+13$ days from the zero day) to remove effects due to interannual, seasonal, and longer term synoptic pressure variations, following the lead of Burns et al. (2008). The choice of 27 days was to isolate the dominant short term variations within the solar rotation and IMF sector structure period of 27-days.

For the zonal-mean pressure results, the uncertainty estimates are the standard error of the mean, with allowance of 9 days for persistence of temporal variations, and 1000 km for coherence of spatial variations. For the regional pressure results there is an allowance of 9 days for persistence of temporal variations.

3. Results

3.1. Zonal–mean annual average responses

In Fig. 1 we compare zonal means of surface pressure responses to ionospheric potential changes due to external and internal inputs to the global electric circuit; in Fig. 1(a) the ionospheric potential changes are due to the B_y-induced inputs to the ionosphere at high magnetic latitudes, which are opposite in sign in the Arctic as compared to the Antarctic for a change in sign of B_y (the Mansurov effect). In Fig. 1(b) the ionospheric