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Key Points:
- Common periodicities are found in solar wind, geomagnetic activity, and high-latitude atmosphere
- The whole atmosphere responds to geomagnetic perturbations driven by the solar wind
- The solar wind-atmosphere interaction processes include energetic electron precipitation and electrodynamic changes

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Solar Wind Signatures Throughout the High-Latitude Atmosphere

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Abstract A series of studies during the last decade have shown clear evidence of solar wind-related periodicities in the variations of different parameters of the lower (troposphere/stratosphere) and upper (thermosphere/ionosphere) atmosphere, over the high-latitude regions. This commentary is prompted by a recent study of the fluctuations of neutral density, winds, and temperatures near 90 km, which provides evidence of such a solar wind-related response in the mesosphere as well. It is timely to point out to the wider geophysical community that solar wind responses at different altitudes strongly indicate that the whole atmospheric column has a response to solar wind high-speed streams, something that few atmospheric scientists would have anticipated 10 years ago. Reviews of the wider body of work in this research field, however, conclude that different processes of solar wind-atmosphere coupling dominate at different altitudes and there remain unanswered questions about some of the details of these mechanisms and their relative importance. We therefore suggest that the studies considered here could usefully be extended in their methodology in order to constrain the mechanisms involved, rather than just identifying the solar wind driver. One example would be to examine time delays between the input, that is, the solar wind variations, and the response at different altitudes; another is to look for latitudinal variations in the amplitude of effects.

1. The Observations

The influence of solar wind structures and related geomagnetic perturbations on the Earth's atmosphere is a subject of great interest in the context of space weather-space climate. It pertains to different, nonlinearly related, physical processes such as solar wind driven electrodynamic changes, energetic particle precipitation, and atmospheric chemical changes (Gray et al., 2010; Lam & Tinsley, 2016; Mironova et al., 2015; Rycroft et al., 2012; Seppälä et al., 2014). The polar cap is an important laboratory for this research, since particle precipitation and solar wind-magnetosphere coupling occur mostly at polar latitudes where the geomagnetic field is interconnected with the magnetic field carried out by the solar wind.

In this commentary, we would like to draw attention to some studies that have quantified signatures of solar wind properties at different altitudes in the atmosphere. Starting with the top of the atmosphere (~100–400 km), it has been found that the periodic structure of the solar wind and associated geomagnetic perturbations, related to the Sun's synodic rotation period and subharmonics (i.e., ~27, 13.5, 9, and 7 days), are clearly observed in ionosphere and upper atmosphere parameters. For example, Lei, Thayer, Forbes, Sutton, et al. (2008) and Thayer et al. (2008) detected ~9 and 7-day oscillations, respectively, during 2005 and 2006, in the thermosphere neutral density from CHAMP satellite in a near polar orbit at ~400 km; these signals, basically due to the redistribution of the mass density by temperature changes, were associated with similar variations of the solar wind velocity and geomagnetic index *Kp*. Moreover, Lei, Thayer, Forbes, Wu, et al. (2008) found the same periodic oscillations in the 2005–2006 data of global mean total electron content and Tulasi Ram et al. (2010) observed the 9 and 13-day periodicities in the electron density at 300 km during 2008. In the lower thermosphere (105–120 km), Jiang et al. (2014) found 9 and 13.5-day oscillations of the temperature in response to recurrent geomagnetic activity, as observed in the *Kp* index, during the years 2002–2007; most importantly, they also found that the amplitude of the oscillations was larger at higher latitudes. The response to disturbed geomagnetic conditions in the high-latitude thermosphere is currently believed to be driven by Joule heating and particle heating (Jiang et al., 2014; Lei, Thayer, Forbes, Sutton, et al., 2008; Lei, Thayer, Forbes, Wu, et al., 2008).

In the lower atmosphere (~0–50 km), clear evidence of a solar wind-atmosphere coupling in the polar cap is revealed by the correspondence between ultralow frequency (ULF) geomagnetic fluctuations driven by the

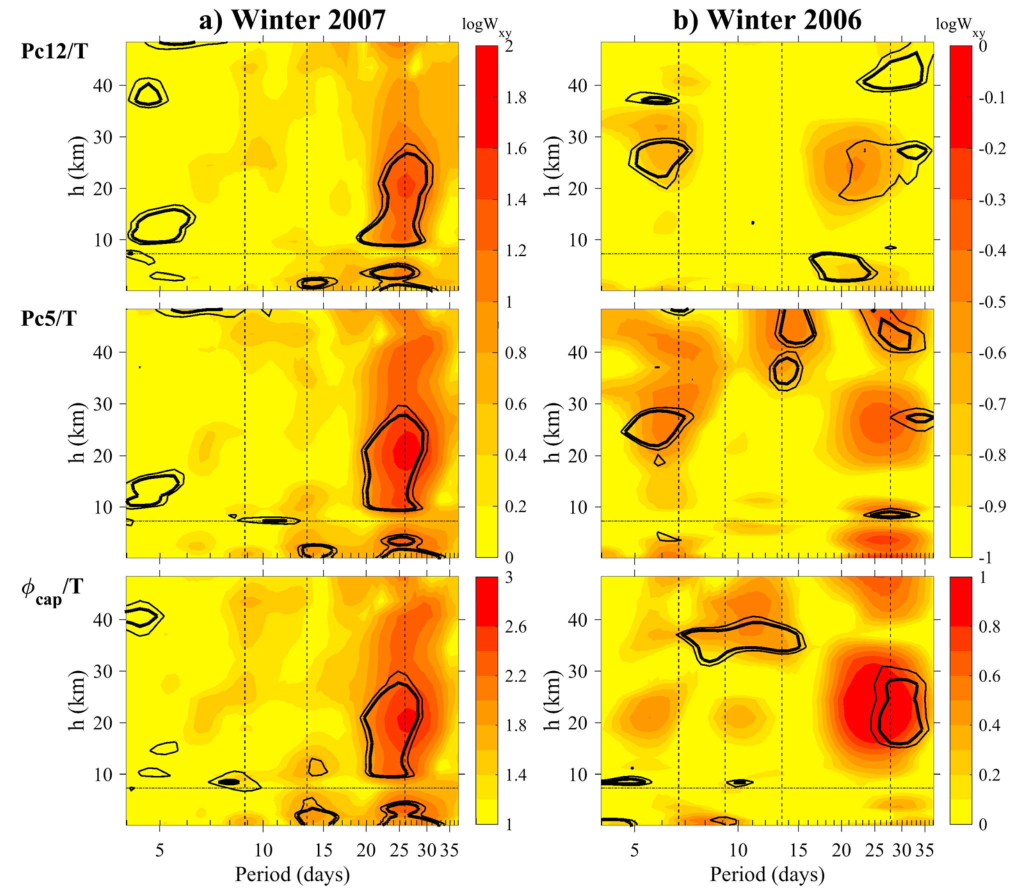

Figure 1. Evidence of solar wind signatures in the lower atmosphere. Time averaged cross-wavelet amplitude W_{xy} between the temperature T and the geomagnetic ultralow frequency (top row) Pc1–2 and (middle row) Pc5 activity and (bottom row) polar cap potential as a function of periodicities and altitude h during the winter months of 2007 (Figure 1a; Regi et al., 2016) and 2006 (Figure 1b). The black contour lines mark the 90% (thin) and 95% (bold) significance levels. The vertical lines indicate the 27, 13.5, 9, and 7-day periodicities. The horizontal lines indicate approximately the tropopause altitude.

solar wind and variations of atmospheric parameters. ULF Pc5 (2–7 mHz) and Pc1–2 (0.1–5 Hz) waves are directly involved in the acceleration and precipitation of energetic electrons from the radiation belts, respectively (Menk, 2011, and references therein). In particular, Francia et al. (2015) found common signals at 27, 13.5, and 9-day periodicities in the surface air temperature and ULF wave power at Terra Nova Bay (Antarctica, corrected geomagnetic latitude 80°S) during 2007 and 2008, associated with the recurrent solar wind streams which characterized those years; the observed signals were more clear during the local winter, that is, in absence of solar radiation. Moreover, Regi et al. (2016) provided evidence that both the ULF geomagnetic activity at Terra Nova Bay and the polar cap potential were significantly related at 27-day and subharmonic periodicities with the temperature and zonal wind in the troposphere and stratosphere over Terra Nova Bay, obtained from ERA-Interim reanalysis data set, during 2007 (Figure 1a). They suggested that the precipitation of electrons from the radiation belts, induced by ULF waves, and the intensification of the polar cap potential could modify the current system in the global electric circuit between the ionosphere and ground (Lam & Tinsley, 2016; Tinsley, 2008, and references therein), particularly the vertical downward current density J_z. It is hypothesized that these changes lead to a tropospheric and stratospheric response, due to charging of clouds with effects on cloud microphysics and, in turn, on cloud cover and precipitation.

Evidence of a solar wind signature in the mesosphere at ~90 km has recently been published. Yi et al. (2017) show evidence for 9 and 7-day periodicities in the mesospheric neutral density, temperature, and horizontal wind over Antarctica during 2005 and 2006. They observe the same periodicities in the solar wind and geomagnetic activity and suggest “a direct coupling between the Sun’s corona (upper atmosphere) and the Earth’s mesosphere,” although they do not indicate a clear mechanism for explaining the observed periodic fluctuations. It is unlikely that the observation at mesospheric altitudes is due to internal thermospheric effects.

Given the evidence, that we have presented here, of solar wind processes across a wide range of altitudes, we now compare the Yi et al. observations in the mesosphere with the lower altitude observations; to this purpose, following Regi et al. (2016), we perform the cross wavelet analysis between the temperature, provided by the MACC reanalysis data set, and the ULF activity and polar cap potential during the winter months of 2006. The results of the new analysis are shown in Figure 1b. We can observe the presence of the signature at the 7-day periodicity that characterized the solar wind in 2006; this signature, particularly significant for Pc5 waves, extends up to stratospheric altitudes of 40–50 km, that is, to the lower boundary of the mesosphere. Therefore, there is strong evidence of the 7-day periodicity in the troposphere, stratosphere, and mesosphere.

2. Concluding Remarks

The results obtained by Yi et al. (2017) in the mesosphere are important, since they fill an observational gap in the atmospheric layers; indeed, together with the results at higher and lower altitudes, they indicate that, at high latitudes, the whole atmospheric column, from the ground to the thermosphere, responds to geomagnetic perturbations driven by the solar wind. Our take-home message is that such a whole-column response was not anticipated a mere decade ago by the wider atmospheric science community and that it still needs further observational and theoretical exploration, including via numerical modeling.

The processes involved in each atmospheric layer are almost certainly different, and transport phenomena could be important. We propose that greater understanding of some of the studies presented here (e.g., those concerning the higher layers of the atmosphere) can benefit from studying the dependence on the interplanetary conditions and the time delays between the solar wind/geomagnetic observations and the associated response in the atmospheric parameters at different altitudes and latitudes.

For example, Regi et al. (2016) conducted also a latitudinal analysis of the 27-day oscillations in temperature and ULF activity/polar cap potential and found a significant coherence between 75°S and 90°S in troposphere and low stratosphere, while between 55° and 70°S just above the tropopause and in the high stratosphere.

In addition, Francia et al. (2015) investigated the correlations between the ULF activity and the surface air temperature also at different time lags. They found that the correlation peaked at 1 and 3 days with respect to Pc1–2and Pc5 activity. A similar result was obtained by Regi et al. (2017), who, using correlation and superposed epoch analysis approaches, compared Pc1–2 activity with tropospheric temperature, specific humidity, and cloud cover from the MACC reanalysis data set during 2003–2010. They showed that such atmospheric parameters significantly change, following the increase of Pc1–2 fluctuations within 0–2 days, especially when the interplanetary magnetic field B_z component was oriented southward ($B_z < 0$), that is, when the interplanetary electric field ($\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$) is transmitted to the polar ionosphere, increasing the dawn-dusk polar cap potential. The observed short time delays, which are also consistent with the characteristic times for the electron acceleration and precipitation, support the electrical mechanism as the possible coupling process between solar wind-driven geomagnetic perturbations and the lower atmosphere conditions.

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