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Planetary wave-like oscillations in the ionosphere retrieved with a longitudinal chain of ionosondes at high northern latitudes

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ABSTRACT

This paper examines the influence of neutral dynamics on the high latitude ionosphere. Using a longitudinal chain of ionosondes at high northern latitudes (52°–65° N), planetary wave-like structures were observed in the spatial structure of the peak electron density in the ionosphere. Longitudinal wavenumbers S_0, S_1 and S_2 have been extracted from these variations of the F layer. The observed wave activity in wavenumber one and two does not show any significant correlation with indices of magnetic activity, suggesting that this is not the primary driver. In addition, the motion of the S_1 ionospheric wave structures parallels that of the S_1 planetary waves observed in the winds of the mesosphere-lower-thermosphere derived from a longitudinal array of SuperDARN meteor-radar wind measurements. The time delay between the motions of the wave structures would indicate a indirect coupling, commensurate with the diffusion to the ionosphere of mesospheric atomic oxygen perturbations.

1. Introduction

There has long been an interest in the sources of ionospheric variability, particularly how this variability may be driven by the dynamics of the neutral atmosphere. Many investigations have found planetary wave-like oscillation in ionospheric parameters, particularly f_0F2, at periods between 2 and 20 days (e.g. Altadill, 1996, 2000; Borries et al., 2007; Forbes and Leveroni, 1992; Pancheva and Lysenko, 1988; Pancheva and Mukhtarov, 2012; Polekh et al., 2011; Shalimov et al., 2006), leading to the suggestion that planetary waves in the lower atmosphere are coupling to the ionospheric electron density. The presence of these oscillations is puzzling since model investigations show that planetary waves with these periods do not directly propagate above approximately 110 km (Forbes, 1995; Hagan et al., 1993; Pogoreltsev et al., 2007). Several potential mechanisms have been proposed to explain how planetary waves in the lower atmosphere could force these planetary wave-like oscillations in the ionosphere. These include planetary wave modulation of upward propagating tides or gravity waves imprinting that variability in the F-region, modulation of the O/N_2 density near the turbopause changing the F-region recombination rates, modulation of the E-region winds and dynamo-induced electric fields that modify vertical plasma drifts, or forcing from above by changes in solar EUV or solar wind pressure creating global scale patterns (Borries and Hoffmann, 2010, and references therin).

Many measurements of planetary wave-like oscillations in the ionosphere are based on temporal variations of specific wave modes with characteristic periods (e.g. 2-day or 16-day oscillations) in the ionosphere and the mesosphere or stratosphere. These rely on a specific wave mode being dominant at one station, or a series of stations, for several wave periods (e.g. Altadill, 2000; Forbes and Zhang, 1997; Pancheva et al., 1994). In the latter case, the phase progression between stations is used to infer the longitudinal wave component (e.g. wavenumber one, or S_1, etc.). The difficulty with this approach is that the velocity of these waves can be Doppler shifted by the background wind (Forbes, 1995; Laštovička et al., 2003), leading to unstable temporal periods and the possibility of the period-wavenumber relationship being incorrectly interpreted as a particular wave mode. It also excludes the identification of any stationary waves (Kleinknecht et al., 2014). In addition, in the presence of strong vertical wind gradients, individual temporal frequencies can be Doppler shifted to different frequencies at different levels, and some could be blocked by the Charney-Drazen criteria from ever reaching higher levels depending upon their horizontal propagation speed (Charney and Drazin, 1961). Even when correctly identified, the short periods of time for which a particular wave dominates the wave field at all levels preclude an examination of the seasonal variation (Laštovička et al., 2003).

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Later measurements of planetary wave-like oscillations in the ionosphere minimize this ambiguity by utilizing multi-satellite measurements to fit both the temporal period and spatial wavenumber for the individual component waves (e.g. Borries et al., 2007; Pancheva and Mukhtarov, 2012). However, these studies may rely on single satellite observations for the planetary waves in the lower atmosphere where spatial-temporal aliasing can lead to misinterpretation (Kleinknecht et al., 2014). In either case, each individual temporal mode of a given spatial wavenumber component of the ionospheric and lower atmospheric oscillation is compared separately in order to examine the possible coupling between the two regions. The difficulty with this procedure is that many of the mechanisms proposed for communicating the planetary wave information from the lower atmosphere into the ionosphere depend on the net wind or density structure formed by the superposition of all the temporal modes. That is, all the different temporal modes with different wave velocities, and hence temporal periods, of a wavenumber one component will superpose and form a total wavenumber one wave (e.g. Palo et al., 2005). The same is true for higher spatial wavenumbers. The amplitude and phase of this spatial component will change as the different velocity modes change, but it will maintain its wave one structure. Thus, it is this net wave-one structure that forms the background wind and density structure that interacts with tidal or gravity waves, and it is this structure that would create longitudinal structure in the upper atmospheric O/N_2 ratios or plasma drifts.

Here, we extract the total longitudinal wavenumber structures in the ionosphere as well as in the upper mesosphere-lower thermosphere (MLT) in order to examine whether the net phase velocities of the waves in the two regions are related. To extract the planetary wave-like structures in the ionosphere, the f_0F2 parameter from a longitudinal chain of ionosondes covering a limited, 13° latitude range is used. Data from a chain of ionosondes, in contrast to a single station, can be used to observe the spatial structure of planetary wave-like oscillations in the F-region and how it evolves in time. The spatial structure, representing the superposition of all temporal modes, will be stable with regard to Doppler shifting and the limited persistence of individual temporal modes (Laštovička et al., 2003). Thus, spatial mode analysis is used extensively to trace the vertical propagation of planetary waves in the strong wind gradients of the troposphere and stratosphere (e.g. Plumb, 2010, and references therein). Since observations from all the stations are made at the same time, there is no problem with aliasing spatial and temporal information that can occur with non-coincident satellite measurements. The technique used to extract the spatial wave information is similar to that described in Kleinknecht et al. (2014) for the meteor winds from a longitudinal chain of Super Dual Auroral Radar Network (SuperDARN) radars (Greenwald et al., 1985, 1995). This same technique is used to extract planetary-wave amplitudes and phases for spatial structures with wavenumbers one and two from the SuperDARN neutral meridional winds at 95 km for comparison with the ionospheric waves. The resulting structures and the temporal evolution of their phase velocities can be compared to ascertain whether the MLT waves are related to the ionospheric oscillations.

2. Data

The parameter f_0F2 (MHz) from the ionosonde is proportional to the peak electron density, N_mF2 (m^{-3}), at the F2 region peak near 250 km using the standard formula $N_mF2 = 1.24{\cdot}10^{10}{\cdot}(f_0F2)$. Hence, electron density variations associated with planetary wave dynamics will modulate f_0F2 (Altadill, 1996, 2000; Forbes and Leveroni, 1992; Pancheva and Lysenko, 1988). In order to characterize the longitudinal variation, and hence the zonal wavenumber of the disturbances, a chain of ionosondes within a latitude band between 52° and 65° N has been used. Given the latitudinal and temporal coverage of the stations, it is possible to extract planetary wave-like disturbances with longitudinal wavenumber 0, 1 and 2 in the F-region during 2001. The f_0F2 values were taken from the Space Physics Interactive Data Resource (SPIDR), http://spidr.ionosonde.net/spidr/ionoInventory.do. The list of the ionosondes included in this study, shown in Table 1, consists of all ionosonde stations located between 52° and 65° N with sufficent f_0F2 records for 2001 that were available on SPIDR.

The sampling of the f_0F2 values may vary anywhere between 15 min and 1 h from station to station. In order to maintain uniformity in the fitting, all observations have been averaged to hourly values.

Since planetary waves have periods of days, daily mean values for the f_0F2 frequency were produced that removed variations of the F-layer that occur with periods less than or equal to one day. These variations are mainly related to tides, photo-chemistry, ionization, and the rotation of the station under the auroral oval. To form daily mean values that were not influenced by these shorter period oscillations, the data analysis technique described in Kleinknecht et al. (2014) was employed.

This data processing takes place in two phases. In the first, the time series of data from an individual station is treated to obtain a daily station mean that is averaged over four days. In the second phase of data reduction, we examine these independent daily means from all the individual stations for a given day as a function of longitude, fitting spatial harmonics to the changes in longitude. To be identified as a planetary wave, the means of the individual stations must change in a periodic fashion with longitude, so that the variation of their means traces either a constant value (S_0), or one (S_1) or two (S_2) wavelengths around the globe.

In the first phase of data analysis, the hourly mean values at each station were divided into 4-day windows to provide a mean value averaged over 4 days. However, a simple boxcar or running-mean average would be skewed by the strong daily variation of ionization and the possible occurrence of a strong 2-day wave lying at the Nyquist frequency of our daily means. Thus, we fit the temporal harmonic components at 6 h, 8 h, 12 h, 24 h, and 48 h explicitly along with the mean value that represents the boxcar or running mean average of the residuals after the removal of the harmonic components. The window was then stepped in 1 day intervals and the process repeated to build up a time series of daily values for each station. To insure sufficient data coverage for the fit, 4-day windows that do not pass the quality control explained in Kleinknecht et al. (2014) were dismissed. Since the analysis for planetary waves uses daily means, the quasi-two-day wave that has been observed by e.g. Forbes and Zhang (1997), Pancheva et al. (1994) would lie at the Nyquist frequency. To prevent Doppler shifting by the mean winds aliasing this component, a length of 4-days was chosen for the windows to ensure adequate coverage of all daily periods 24 h or less, and to remove the quasi-two-day wave oscillation. Variations with periods less than four days will be effectively removed by the low pass filter imposed by the running-mean smoothing of the daily means over the 4-day window (Kennedy, 1980; Owens, 1978). Fig. 1 shows an example of the component fit to a 4-day window in January (05–08 January, 2001) from the ionosonde at King Salmon (KS759), while Fig. 2 shows the daily mean values for 2001 at all stations that are included in the study.

Table 1
Ionosondes between 52° and 65°N that produced sufficent available data during 2001 to be included in the study.

Station name	latitude	Longitude E+.W-
King Salmon (KS759)	58.4	−156.4
College (CO764)	64.9	−147.8
Gakona (GA762)	62.4	−145.0
Goosebay (GSJ53)	53.3	- 60.4
Narssarssuaq (NQJ61)	61.2	- 45.4
Chilton (RL052)	51.6	- 1.3
Juliusruh/Rugen (JR055)	54.6	13.4
Leningrad (LD160)	60.0	30.7
Moscow (MO155)	55.5	37.3
Novosibirsk (NS355)	54.6	83.2
Podkamennaya (TZ362)	61.6	90.0
Magadan (MG560)	60.0	151.0
Petropavlovsk (PK553)	53.0	158.7