OBSERVATION OF LARGE SCALE WAVES IN THE THERMOSPHERE-IONOSPHERE SYSTEM

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ABSTRACT

Atmospheric waves as planetary waves contribute essentially to the coupling between the lower and middle atmosphere and the thermosphere/ionosphere. Consequently, large scale periodic variations observed in the ionosphere are supposed to be - in addition to extraterrestrial forcing - the effect of planetary waves originating below.
Regional hemispheric maps of the total electron content (TEC), which are regularly produced by the DLR Neustrelitz since 2002, are a new opportunity to investigate planetary wave type oscillations on a hemispheric scale. Relative differences of the TEC to monthly median values (subsequently referred to as "relative differential TEC")
are analysed with respect to the occurrence of large scale wavelike disturbances. A few quasi-periodic variations are forced by the sun, as the 27day solar rotation period and its subharmonics. They are localized and filtered in the wavelet spectrum using a comparison to the wavelet spectra of the F10.7cm radio flux index and the solar wind speed, measured with the Solar Wind Experiment onboard the WIND satellite. The contribution of solar forced quasi-periodic variations to the variability of the relative differential TEC at middle to high latitudes on the northern hemisphere is estimated with 38-42%.
The variability of the filtered relative differential TEC, excluding the solar signal, shows some typical characteristics of planetary waves in the middle atmosphere, as the same seasonal dependency and periods corresponding to the atmosphere's Eigenfrequencies. Thus, planetary waves may have an important impact on the variability in the thermosphere-ionosphere system. The SWARM mission may deliver new essential data for the analysis of planetary wave type oscillations in the ionosphere.

INTRODUCTION

This paper deals with large scale oscillations in the F2-region ionosphere, having periods between 2 and 30 days and wavelength exceeding 10000km. In literature these waves are often suggested to be the effect of the planetary wave (PW) activity in the lower and middle atmosphere (e.g., [5],[6],[8]). Thus, PW are supposed to be an important component of coupling between the lower and middle atmosphere and the thermosphere. However, apart from some case studies [1],[2], this assumption could not be approved up to now. In contrast, modelling studies showed that most PW, in particular slowly travelling ones, are reflected or dissipate before 110km height has been reached (e.g., [11]). Thus, the oscillations observed in the ionosphere, having similar properties as PW, are referred to as PW type oscillations (PWTO). The origin of these PWTO in the F2-region ionosphere remains an open question which is addressed in this paper.
The ionosphere, which is characterized by its free electrons, can be monitored by estimating the total electron content (TEC, the vertically integrated electron density) using ground based GPS measurements. The DLR Neustrelitz produces regional TEC maps since 1995. In this paper, hemispheric North Pole TEC maps, which are available as a continuous data set since 2002, are analysed for PWTO. The aim is to extract information about the properties of these waves and on their origin.

DATA BASE AND ALGORITHMS

TEC Maps

Ground based GNSS measurements provided by the International GNSS Service (IGS), are used to compute the differential delay on code and carrier phase, which is in a first-order approximation proportional to the total electron content along the line of sight (slant TEC). After using a special calibration technique, the slant TEC is mapped to the

vertical by using a single layer approximation of the ionosphere at 400km height. The TEC data point distributed in northern middle and high latitudes are mapped into a regular grid (50°N to the North Pole). The measured data is combined with the empirical TEC model NTCMP2. With accuracy of the order of 1 TECU (10^{16}electrons/m^2), the TEC maps are suitable to monitor large scale perturbations. The North Pole TEC maps analysed in this paper are provided by the DLR Neustrelitz as a continuous data set since 2002. For more details on the establishment of TEC maps, the authors refer to [9].
The perturbations of TEC are studied by creating relative differential TEC maps (subsequently referred to as dTEC) as follows

$$dTEC = \frac{(TEC - TEC_{med})}{TEC_{med}} \cdot 100\% \quad (1)$$

The monthly median TEC maps are denoted with TEC_{med}.

Solar and Geomagnetic Data

Although the F10.7cm radio flux (F10.7 index) is not able to reproduce all the features of solar EUV variability (e.g.,[4]), it is still used as a common proxy of the solar EUV radiation. We also use the Kp-index as a measure for planetary scale geomagnetic disturbances.
There are different satellite missions observing the solar wind. In this paper, we use the measurements of the Solar Wind Experiment onboard the WIND satellite. For the spectral analyses hourly mean values of the absolute wind speed are calculated. The measurements are not continuous. During the period of investigation (2002-2007), there is a data availability of 94%. Data gaps are interpolated linearly.

Wavelet Analyses

For spectral analyses this paper mainly uses the wavelet transform

$$W_\psi f(s,\tau) = \frac{1}{\sqrt{s}} \int f(t) \psi_0^* \left(\frac{\tau - t}{s} \right) dt \, . \quad (2)$$

The wavelet transform is basically the convolution of a signal *f* with a scaled and translated version of a mother wavelet ψ_0. s and τ are the scaling and translation coefficients. As mother wavelet we choose the Morlet wavelet which is supposed to be best suited to image atmospheric waves, because it consists of a plane wave modulated by a Gaussean [12].
Using the Frequency-Wavenumber analyses, first described by [7], the TEC maps can be zonally decomposed in wave components described by wavenumber, frequency and propagation direction. It is basically a 2-dimensional spectral decomposition, first in space and second in time dimension. The application of the FK-analysis using the wavelet transform, as it is used here, is described in [3].

EXCLUDING SOLAR FORCED VARIATIONS FROM TEC RECORDS

The sun strongly controls the dynamics and variability of the upper atmosphere and its ionization. Main drivers for the ionization are the solar EUV radiation and solar wind. While the EUV radiation directly activates the ion production, the solar wind couples to the geomagnetic field and energetic particles enter the magnetosphere and can penetrate along the geomagnetic field lines into the polar ionosphere. Therefore, solar influence through the solar wind is supposed to be strongest at high latitudes. Because of the coupling of the solar wind to the magnetosphere, there is a strong correlation between the solar wind and the Kp-index. The mean correlation coefficient is 0.63. Thus, we also use the Kp-index for ascertaining solar forced variations.
The aim is to identify concurrent oscillations localized in time and frequency in the solar EUV, solar wind, Kp and dTEC. Therefore, we estimated the wavelet power spectra of the four data sets. In this case the discrete wavelet transform is applied, because the resulting wavelet coefficients are not redundant. The 95% significant coefficients in the wavelet power spectra of F10.7, solar wind and Kp identify and localize the solar forced variations. The dTEC signal is filtered such that its wavelet coefficients having the same location as the solar forced variations are set to zero and the filtered signal is reconstructed from the reduced wavelet spectrum. This method largely excludes variations owing to solar variability at all time scales under consideration.
The wavelet amplitude spectrum (using the continuous wavelet transform) and the corresponding filtered signal are demonstrated in Fig. 1 using the example of the dTEC signal at 15°E/55°N. The spectrum in the upper panel is obviously dominated by the 27day period, reflecting the impact of the solar rotation. In the spectrum of the filtered

signal (lower panel), the oscillations with periods between 10 and 30 days almost completely vanish, except for a few oscillations occurring mainly during winter. The estimation of the relative difference between the power of dTEC and the power of the filtered dTEC (not shown here) reveals that on average 38-42% of the periodic variability of dTEC is forced by solar variations. As expected, the percentage of EUV forced PWTO is higher during solar maximum (2002-2003). In contrast, the impact of the solar wind with periods similar to PW is higher during solar minimum (2006-2008). However, on average EUV and solar wind have the same contribution to ionospheric PWTO. In conclusion, a large fraction of the PWTO observed in dTEC has to be allocated to solar variability and the analysis of PWTO forced by PW from below has to be made with care. Attention has to be paid, that this method only minimizes periodic variations, and not sharp gradients or recovery phases with low TEC as it appears after ionospheric storm events. Thus, not all space weather forced variations can be eliminated from the dTEC signal using this filter method.

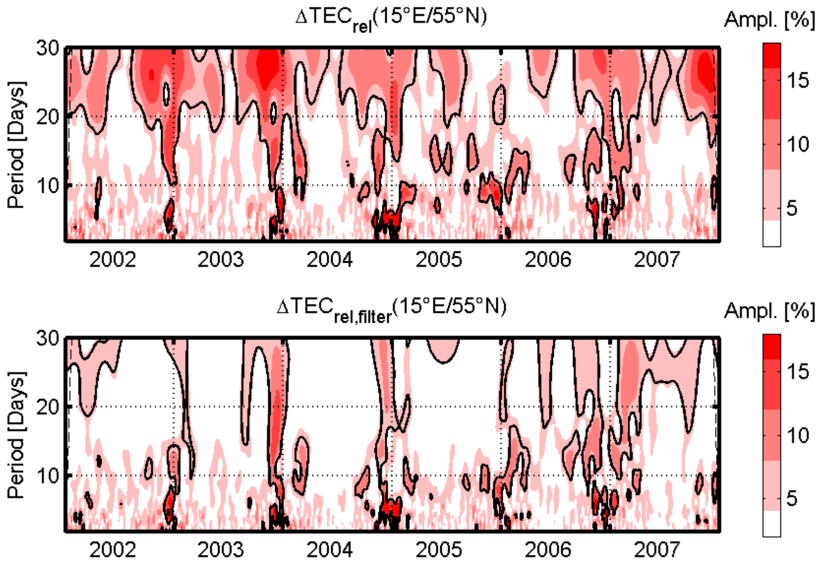

Fig. 1. Wavelet amplitude spectrum of dTEC (upper panel) and the filtered dTEC (lower panel). Black lines encapsulate 95% significant amplitudes.

SIMILARITIES OF STRATOSPHERIC PW AND IONOSPHERIC PWTO

The last section described how the solar signal in dTEC is minimized. In this section the filtered dTEC signal is regarded as free of solar forced periodicities, keeping in mind that storm effects might still cause "artefacts".
Wavelet FK-spectra are calculated for the wavenumbers 1 to 5 (not shown here). The 95% significant amplitudes $\tilde{W}_{\psi}^{(95)} f(s,\tau)$ in the FK-spectra indicate all PWTO occurring in the filtered dTEC. The RMS global wavelet amplitude spectrum, as described in Eq.3, represents the strongest and most frequent PWTO observed in the filtered dTEC.

$$RMS(s) = \sqrt{\int_{[0T]} |\tilde{W}_{\psi}^{(95)} f(s,\tau)|^2 \, d\tau} \;. \qquad (3)$$

An example for the RMS global wavelet amplitude spectrum for the propagating and standing waves with zonal wavenumber 1 is shown in Fig. 2. The RMS is calculated separately for each season. Fig. 2 demonstrates that PWTO in the filtered dTEC preferentially occur during winter (December to February) with periods of 3-4, 5-6, 7-8 and 11-15 days. Because PW are considered as free oscillations, typical periods are associated with the atmosphere's Eigenfrequencies. The Eigenfrequencies of oscillations with zonal wavenumber 1 in the atmosphere are 1.17, 5, 8 and 12 days [10]. In the lower and middle atmosphere, due to Doppler shifting the dominating periods of PW are about 2, 5, 10 and 16 days, while, however, the 2-day wave has wavenumber 3 or 4. The periods of the prevalent PWTO with zonal wavenumber 1 observed in the filtered dTEC agree with the Eigenfrequencies of the thermosphere and the PWTO can be accounted to free oscillations. This supports the assumption that the PWTO observed in the F2-region ionosphere correlate with PW of the lower and middle atmosphere.

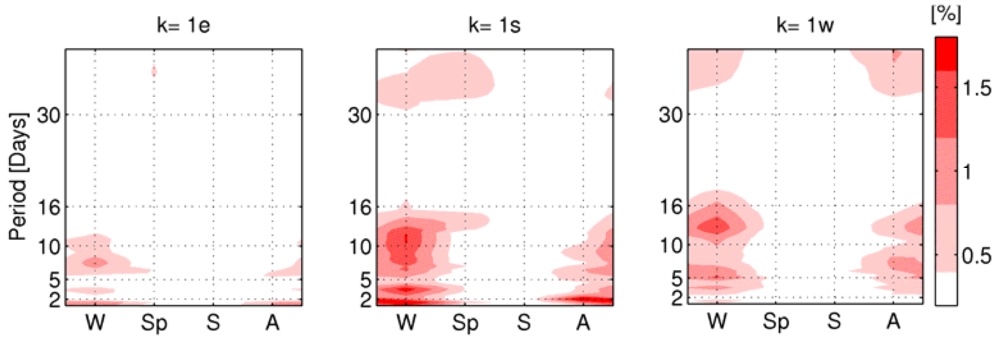

Fig. 2. RMS global amplitudes of PWTO with wavenumber 1 (left panel: eastward; middle panel: standing; right panel: westward propagating) at 70°N, 2002-2008. The RMS amplitudes are calculated and displayed separately for each season (W: Dec-Feb; Sp: Mar-May; S: Jun-Aug; A: Sep-Nov).

Further, the predominant winter activity of PWTO in the filtered dTEC corresponds to the seasonal behaviour of PW activity in the middle atmosphere, where easterly winds prohibit the propagation of most (the slowly travelling) PW during summer. Similar results, not shown here, are derived for the zonal wavenumbers 2 to 5.
Upward propagating stationary PWs (SPW) strongly affect the dynamics of the middle atmosphere. During winter their amplitudes are largest in the stratosphere. Strong stationary waves like the stratospheric SPW at midlatitudes (an example is shown in Fig. 3 for the zonal wind at 10hPa, green lines) cannot be observed with similar strength in the filtered dTEC (Fig. 3, red lines).

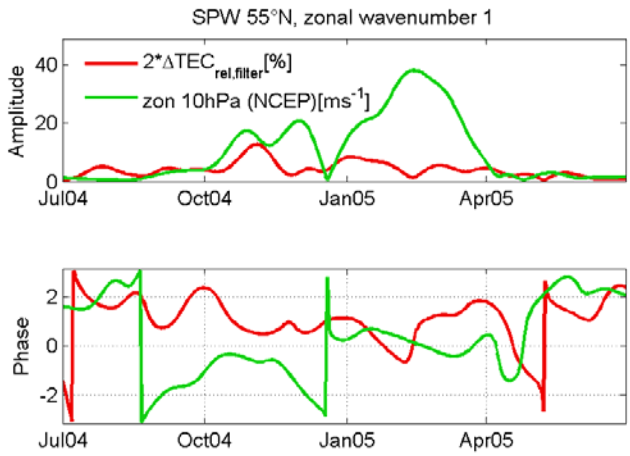

Fig. 3. Example of stationary waves with wavenumber 1 at 55°N, estimated with short time Fourier-analyses using a Gaussian window with 30 days window size. Red lines: filtered dTEC (amplitudes are doubled); Green lines: zonal wind from NCEP reanalyses.

Often, amplitude and phase of the stationary PWTO in the filtered dTEC vary with time. However, sometimes PWTO look like SPW. For example during November 2004 the amplitude of the stationary component of the waves with zonal wavenumber 1 in the filtered dTEC is larger than usual and also the phase remains quite constant. Moreover, the phase is close to the one of the SPW in the stratospheric zonal wind. This suggests, that energy of the stratospheric SPW might leak from time to time into the ionosphere. Further investigation is needed to identify the conditions for such a leakage.

SUMMARY AND CONCLUSIONS

TEC maps have been analysed for large scale oscillations, denoted as PWTO. The origin of a large part (38-42%) of these PWTO has been attributed to variations in the solar signal, as seen in EUV and solar wind. A wavelet transform filter has been used to minimize the solar impact on the TEC signal.
In summary, spectral analyses revealed a good agreement between the properties of the PWTO in the filtered dTEC and stratospheric PW. The PWTO observed in the filtered dTEC show the same seasonal dependency and periods

corresponding to the atmosphere's Eigenfrequencies. SPW are not common in the ionosphere. Nevertheless, from time to time there seems to be energy leaking from stratospheric SPW into the F2-region ionosphere.

Finally, the analyses revealed a few hints for a correlation between PW in the middle atmosphere and the PWTO observed in the filtered dTEC. Because PW cannot directly penetrate into the F2-region ionosphere, there must be additional processes transporting their energy upwards. Further investigation is needed on these mechanisms. The SWARM mission may deliver new essential data supporting these analyses.

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