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Study of ionospheric variability

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Preface

The aim of the work is to describe ionospheric variability and its connection to external (solar, geomagnetic) forcing and influence of neutral atmosphere to the state of the ionosphere. We covered large range of periods ranging from one day up to several solar cycles.

Analysis of wave–like oscillations of the sporadic E–layer (Es layer) and lower lying stratosphere (at potential height of 10 hPa) from three special summer campaigns (2004, 2006, 2008) is presented. We show domains of common oscillations in the neutral atmosphere temperature and parameters of the Es layer in range 1–32 days corresponding to an area of planetary periods. We suggest that coherent oscillations of foEs/hEs parameters and stratospheric temperature support strongly an idea of planetary wave effect to the Es–layer formation. We show that common power computed by means of Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) between stratospheric temperature and sporadic E–layers data cover large continuous area of periods between 4–32 days. Common periods detected by means of WTC are located predominantly on the periods close to planetary wave on domains of 2, 4, and 8 days (Rossby modes).

In a scaling analysis part, we focus on long–term data covering several solar cycles and we show the relation between ionospheric data obtained from ground based measurement and global (geomagnetic and solar) data. We compare scaling properties of ionospheric, solar and geomagnetic data at medium periods in range 2–32 days and show that ionospheric data are closely related to Kp and AE on selected domains while the solar flux F10.7 index and Dst have different scaling properties. We show that inner structure of data from six ionospheric station at periods 2–64 days is roughly linearly dependent to their geographical/geomagnetic latitudinal position where the stations located more to the geographic/geomagnetic north have more regular ionospheric behaviour on selected time scales.

We studied correlation coefficients between foF2 from 11 ionospheric stations and geomagnetic and solar indices (AE, Kp, Dst, F10.7, SSN). Results for pairs of foF2 and (AE, Kp, Dst, F10.7 and SSN) are strongly dependent to the time scale. Inter correlation coefficients for foF2 from the stations indicates that there exists a characteristic dimension 10°. Below this value the correlation coefficients of foF2 are very high which indicates quasi–collective behaviour of the ionosphere in the heights of F2 layer.

We show strong correlation between long–term data from various ionospheric stations even on short–term periods (daily scale) which suggests acting of wave activity in neutral atmosphere.

Ionospheric variability

The ionosphere is affected heavily by solar and geomagnetic activity on long–term (e.g., quasi 11 year solar cycles, and secular variations), medium–term (e.g., seasonal dependence, solar rotation) and short–term periods (e.g., solar events, geomagnetic disturbances, neutral atmosphere activity). The ionosphere is therefore a complicated system with a large variability over wide range of periods. Beside the extraterrestrial and geomagnetic forcing, neutral atmosphere is another important source of ionospheric variability. Atmospheric waves that originate in practically all atmospheric regions travel through the atmosphere and alter conditions in distant regions (Laštovička, 2006; Forbes, 1994; Pancheva, 2003). Classically, the description of ionospheric variability is split into long–term and short–term based descriptions of the system. Long–term we use hence for scales corresponding to 11–years solar cycle or seasonal dependence while the short–term is connected to the extreme solar activity and consequent changes in geomagnetic field.

Neutral gas in the ionosphere is ionized by means of Lyman–α, EUV flux and in smaller extent due to galactic rays and other inputs (Tascioni, 1994). Recombination of ionized particles has usually one or two steps and the concentration of particular neutral gas (especially N_2 and O_2) is of crucial importance. Transport of plasma is mostly connected to ambipolar diffusion, neutral winds interactions and drifts connected to electric fields. All described mechanisms are reflected in the profile of electron concentration which may be represented by means of ionospheric parameters (critical frequencies) measured by the ground sounding. The ionosondes and digisondes provide us with long datasets covering several solar cycles.

Wave–like oscillations in sporadic E–layers and connection to neutral atmosphere

Sporadic E–layers are formed in the height of the E region between approximately 90 to 150 km. The Es–layers may contain very high concentrations of ionized particles which may exceed maximum concentrations usually located in the F2 layer. Thus, the sporadic E–layers are very important for shielding and modification of propagation of electromagnetic waves. The sporadic E–layers mostly occur in midlatitudes during summer time (Haldoupis et al., 2006). The mechanism of Es formation has not yet been fully understood. However, widely accepted theory explains the Es dynamics as a result of geomagnetic field configuration and horizontal neutral winds interaction when long–lived metallic ions move vertically upward or downward according to the wind shear. Narrow, dense plasma convergence zone is formed by this mechanism (e.g., Whitehead (1961, 1989); Mathews (1998)). Collisions between ions and neutrals are very frequent below 125 km which means that the vertical plasma drift is collision dominated and controlled mainly by the zonal wind. At heights above 130 km, collision frequency decreases sufficiently and the plasma drift is controlled by the magnetic field. Except the electric and electromagnetic phenomena, the upward propagating waves in the neutral atmosphere are supposed to be of the greatest importance for the ionosphere (Laštovička, 2006; Šauli and Bourdillon, 2008) and the Es dynamics (Voiculescu et al., 2000; Haldoupis and Pancheva, 2002; Pancheva, 2003) through the action of diurnal and semidiurnal tides which are modulated by the planetary waves (PWs). Planetary waves (with periods of about 2–30 days) are predominantly of tropospheric origin and can penetrate up to heights of 100 km.

We studied data from three special campaigns with high sampling rate (26 July – 1 September 2004 with 5 min resolution, 31 May – 27 August 2006 and 29 May – 31 August 2008 with 15 min time resolution) measured at the Pruhonice station using the digisonde DPS–4 (Reinisch et al., 2005). Parameters describing the Es behaviour are critical frequency foEs and height of the Es layer hEs. Parameter representing stratospheric behaviour is temperature T at height corresponding to 10 hPa (ERA–40 reanalysis model, Uppala et al. (2005)) from a grid point 50°N, 15°E which is close to the location of Pruhonice (50°N, 14.5°E).

To detect periodicities in the data we used Continuous wavelet transform. For the investigation of common oscillations between stratospheric temperature T and Es data foEs and hEs we used Cross wavelet transform (XWT) and Wavelet coherence according to (Torrence a Compo, 1998; Grinsted et al., 2004). While the XWT serves to detect domains of high common power the WTC detects coherent structures between the data and emphasizes areas of coherent oscillations. It means that WTC finds regions in time–frequency/period space where the two time series co–vary, but they do not need to exhibit high common power.

Continuous wavelet transform of stratospheric temperature, foEs and hEs shows the diurnal period as the most pronounced in all datasets (Fig. 1). Besides that, there are significant oscillations in the period range 4–16 days laying in the planetary wave domain. Systematically, the periods between 1–4 days show relatively low power in the temperature data compared to longer periods. The scalograms of foEs reveal periodicities corresponding to planetary wave oscillations at 4 days (2004), 2–3 (2006) and 4–6 days (2008, Fig. 1, middle panel). The parameter hEs did not show significant oscillations at periods longer than one day during the 2004 campaign. Pronounced periods were present at 3–4, 8, and 16 days in the hEs during the 2006 campaign. There is a wide range of oscillation of the PWs nature and no general pattern can be established from these 3 particular campaigns based only on the basic spectral analysis (wavelet power spectra). Wave–like oscillations with periods 4, 8, and 10–16 days are present in the 2008 dataset (Fig. 1, bottom panel).

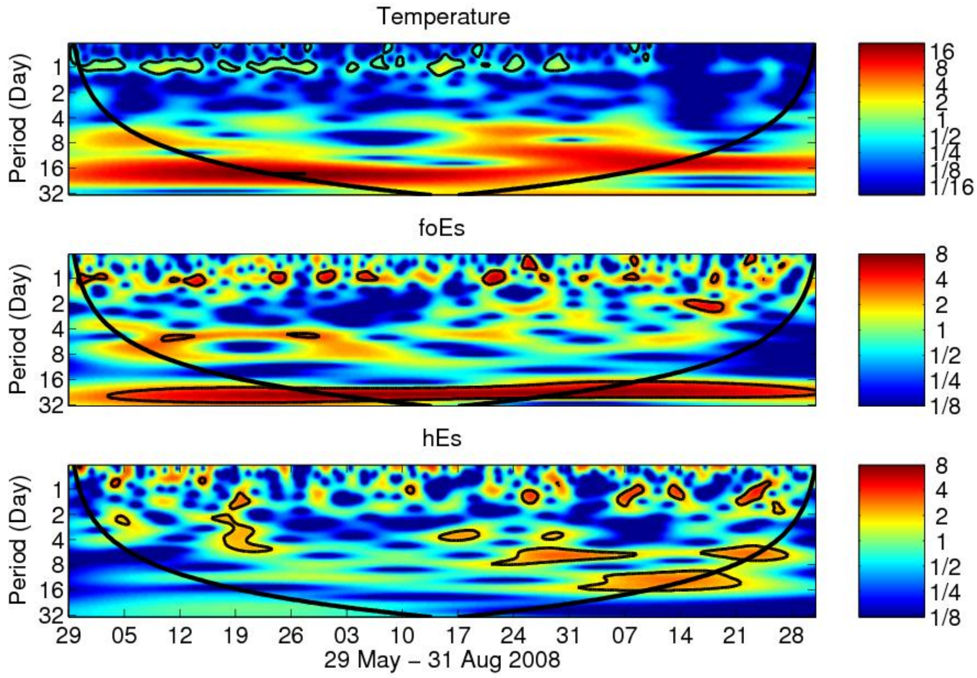

Figure 1: Continuous wavelet transform of stratospheric temperature T, critical frequencies foEs and heights of the layers hEs. The Cone of Influence (black line) denotes a region where edge effects become important (Mošna and Koucká Knížová, 2012).

Our analysis by means of XWT and WTC detects diurnal oscillations with a stable phase shift in a range of values $\pi/4 - \pi/2$ which means that the temperature data lead the Es data by 1/8–1/4 of the day. Longer periods corresponding to the planetary wave domain with increased power by means of XWT are detected at a whole interval of values higher than four days (Fig. 2, upper panels).

Coherent structures found by means of WTC have periods of about 2, 4, 8, and 16 days for both temperature–hEs and temperature foEs pairs during

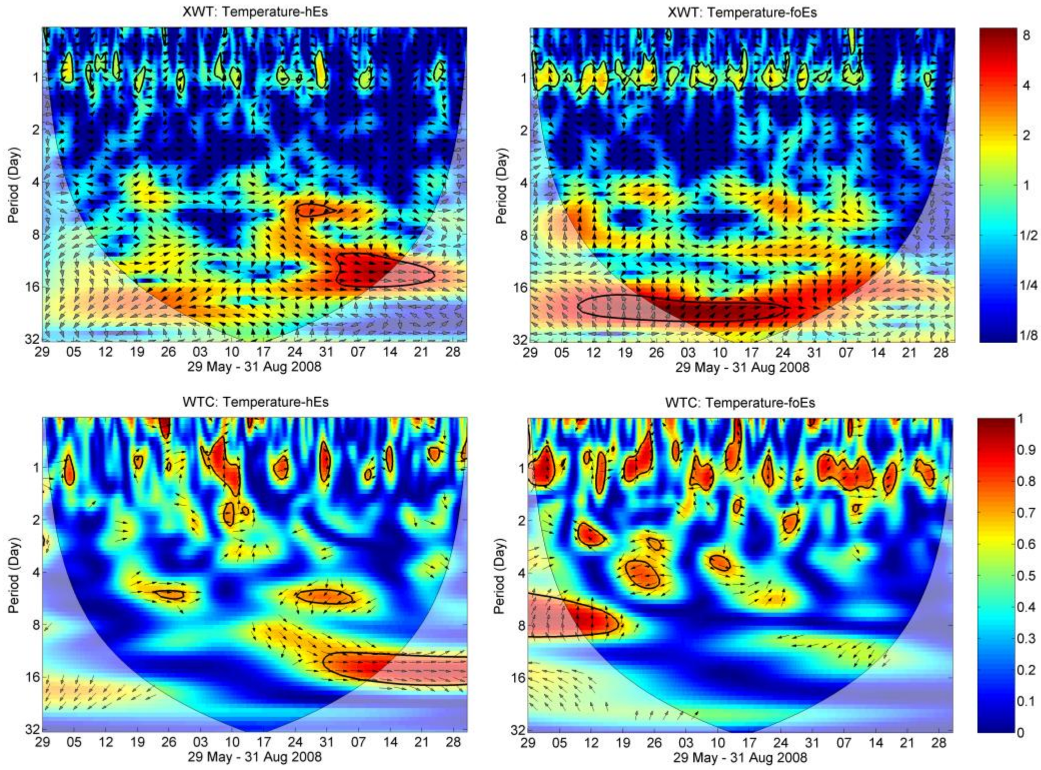

Figure 2: The left panels show the relation between stratospheric temperature T and height of the sporadic E–layer hEs. The right panels show the relation between the stratospheric temperature T and critical frequency foEs. Cross wavelet transform (upper panels) shows a continuum of common oscillations at diurnal period and periods longer than 4 days. Domains of common periods computed by the wavelet coherence are close to periods of planetary waves (bottom panels) (Mošna and Koucká Knížová, 2012).

all three campaigns. These findings support the idea that vertical coupling takes place predominantly on periods close to main planetary periods. Contrary to the diurnal periods, the phase shift is very variable and probably indicates a nonlinear relationship between planetary wave–type oscillations in temperature and Es layers behaviour.

Periods of 2, 4, 8, and 16 days are not random numbers. It is important to point out that through solving the general dynamical equations governing periodic atmospheric motion we obtain a collection of eigen oscillations (Forbes, 1994), or modes with periods close to the CWT detected bursts.

It is reasonable to assume that WTC detects PWs eigen modes (probably slightly shifted due to the Doppler shift) that are the principal modes of vertical coupling.

Scale dependent analysis of ionospheric, solar and geomagnetic indices

Scaling analysis is a tool to study the inner structure of the data. The similar properties of structure at particular periods indicate a possible connection between the datasets under study at these periods. This concept has been used in many geophysical studies (e.g., Davis et al. (1994, 1996); Burlaga and Klein (1986); Consolini et al. (1996); Vörös et al. (2002); Hnat et al. (2003); Lovejoy and Schertzer (2007). The ionospheric application has been only very limited.

Multiresolution coefficient $T_x(a,t)$ is a function of a scale a and a position t. It may be defined simply as $T_x(a,t) = X(t+a) - X(t)$, but use of the $d_x(a,t)$ based on wavelet decomposition is more suitable as this approach better reflects the scaling properties of the data and avoids problems of non-stationarity (Abry et al., 2000; Chainais et al., 2000). The exponent $\zeta(q)$ present on the right side of equation

$$E(|d_x(a,t)|^q) = c_q a^{\zeta(q)}, \qquad (1)$$

is called the scaling function, c_q is a general coefficient and $E(|...|)^q$ is q–th moment. It has been shown that this equation holds for many geophysical and other processes (e.g., Mandelbrot (1967); Muzy et al. (1994); Davis et al. (1994, 1996). The scaling function $\zeta(q)$ is a characteristics of the dataset. Processes that hold the equation 1 are called scale invariant. Data with the scaling function do not have dominant scales (or there is only a limited number of such scales), or, all scales are important (Barenblatt, 2003). The existence of scaling invariance is not accidental; it reflects important properties of the system (e.g., Abry et al. (2000)). Scaling refers to behaviour of the data on a range of scales rather than one particular scale. Linearity/nonlinearity of $\zeta(q)$ defines the monofractality/multifractality of the dataset.

The spectrum of singularities $D(h)$ is directly connected to the scaling function via the Legendre transform and it describes the distribution of Hölder exponents which describe the roughness, or singularities of the dataset at every point of the dataset. Thus, the value $\langle h \rangle$ is the most frequently occurring exponent in the dataset and the variance of h reflects the mono/multifractal character of the data (in an ideal monofractal situation, data have only one value of $\langle h \rangle$).

The results in this chapter are computed using the software of Dr. P. Abry and Dr. S. Roux, `http://perso.ens-lyon.fr/patrice.abry/software.html` and `http://perso.ens-lyon.fr/stephane.roux/`.

Analysis of h for long–term datasets F10.7, Dst, Kp, $\sum$Kp, and foF2

We studied daily values of foF2 from six European stations (Roma, Pruhonice, Juliusruh, Uppsala, Moscow, and Sodankylä, Mošna and Koucká Knížová (2011)). The ionosonde data were manually checked and were further analysed with solar flux F10.7 and indices of geomagnetic activity AE, Kp, $\sum$Kp and Dst. The analysis involves the time interval from four solar cycles from the years 1965–2004 with one day resolution for all datasets (except for the Kp where the resolution is 3 hours). The time series of foF2 are computed as a median from four near noon values. The solar flux F10.7 and Dst are mean values from each day. The AE indices are from the time interval 1965–1989 as later data are highly inconsistent due to missing measurement from Soviet/Russian stations.

Table 1 provides values of $\langle h \rangle$ from the datasets involved in the study at periods of 2–32 days. The lower limit was the result of a one–day temporal resolution of the data, the upper limit was chosen due to the occurrence of the 27–day period in the data. The results can be generally divided into two groups. The first group with $\langle h \rangle > 1$ consists of F10.7 and Dst indices. The second group with $\langle h \rangle < 1$ consists of Kp, $\sum$Kp, and AE indices and critical frequencies foF2 from all ionospheric stations under study. The values of $\langle h \rangle$ for Kp, $\sum$Kp, AE, and ionospheric data are located in a relatively small interval $[0.69, 0.89]$, which suggests a close relation between geomagnetic activity at midlatitudes and in the auroral zone and ionospheric processes at studied stations at chosen periods. It confirms the fact that geomagnetic activity is the dominant driver of ionospheric processes at medium period scales. The large difference between $\langle h \rangle$ for solar flux and foF2 suggests that the link between these series is more complicated than we expected and calls for more detailed analysis.

The multifractal behaviour is a consistent result for practically all the time series of foF2 from all analyzed stations, solar and geomagnetic data (see, e.g., the variance of h of Sodankylä foF2 in Fig. 3). The only dataset that was identified as monofractal was foF2 series from the Roma station.

Fig. 4 presents a relation between $\langle h \rangle$ and the geomagnetic and geographic latitudes of the stations. This finding shows that more northerly stations have more regular behaviour by means of the singularity of the data

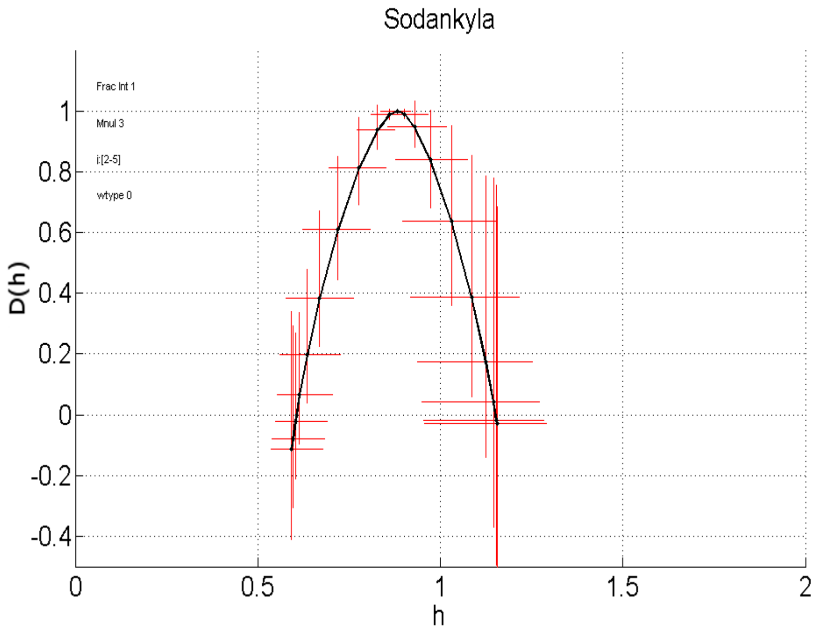

Figure 3: Distribution of values h from the Sodankylä foF2 dataset. The most probable value of h is denoted as $\langle h \rangle$. The width of the curve is a description of mono/multifractality (presented data are clearly multifractal). Red lines denote the 95% confidence intervals (Mošna and Koucká Knížová, 2011).

than those located further south. This result may be surprising as the stations close to the auroral region (Sodankylä, Uppsala) are supposed to be more affected by variable and disturbed conditions of solar and geomagnetic activity. A possible explanation is that the effects represented by the AE index are of shorter periods on minutes to hour scales and thus the polar/auroral activity is not reflected in our analysis at periods of the order of days.

Table 1: Parameters $\langle h \rangle$ for foF2 and solar and geomagnetic indices

Station	**Rome**	**Průhonice**	**Juliusruh**	**Moscow**	**Uppsala**	**Sodankylä**
geom. lat.	41.9	50.0	54.6	55.4	59.9	64
$\langle h \rangle$	0.79	0.80	0.86	0.87	0.86	0.89
Index	**AE**	**Kp**	**$\sum$Kp**	**Dst**	**F10.7**	
$\langle h \rangle$	0.77	0.69	0.79	1.02	1.71	

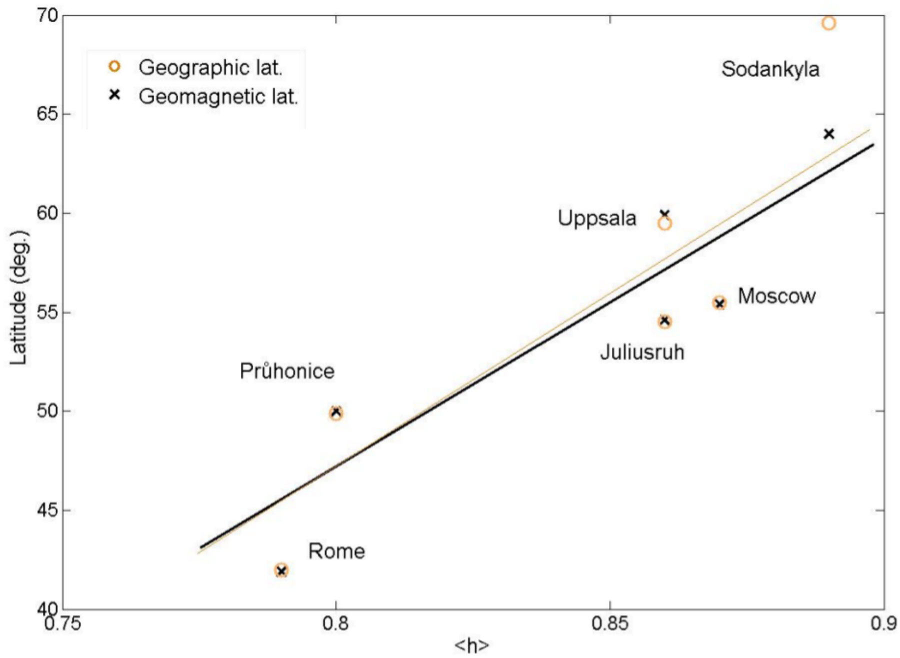

Figure 4: Relation between $\langle h \rangle$ and geomagnetic and geographic position of the ionospheric station. Higher values of $\langle h \rangle$ represent more regular behavior of the data. Thin and thick lines are regressions for geographic and geomagnetic position, respectively (Mošna and Koucká Knížová, 2011).

Despite the fact that the Sun is the most important source of ionization different values of $\langle h \rangle$ for F10.7 and foF2 suggest a more complicated relationship between both parameters at periods of 4–32 days. The index F10.7 is widely used to predict the value of foF2 for telecommunication and other purposes (Mikhailov et al., 1996; Zolesi and Cander, 2014). Although a high correlation exists between foF2 and F10.7 on long scales we show that the approximation of foF2 using F10.7 is at least problematic. Similarly, the Dst index which represents geomagnetic activity near the equatorial area is shown to have a different scaling parameter $\langle h \rangle$ than the ionospheric series of foF2.

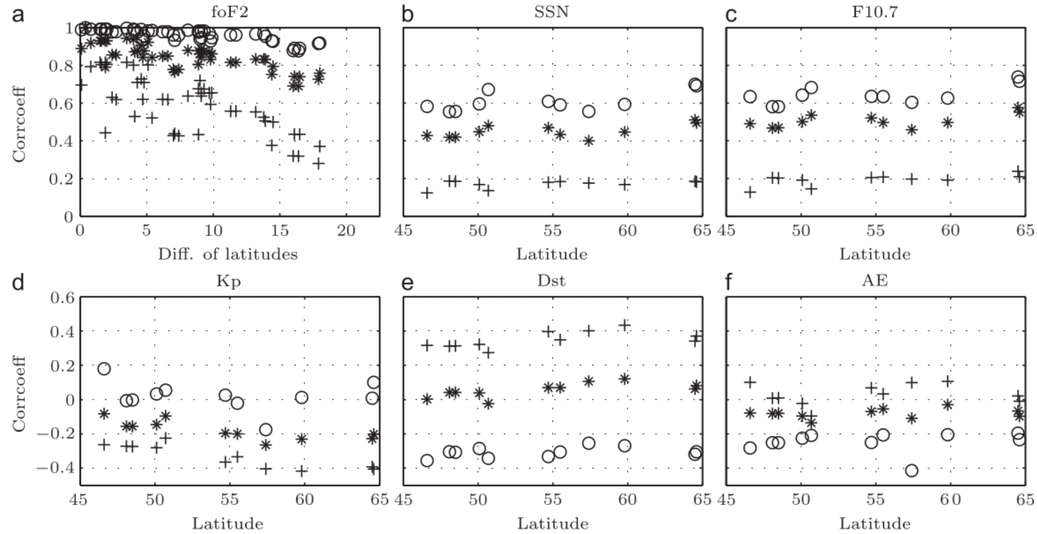

Figure 5: Correlation coefficients between foF2 from different ionospheric stations and latitudinal differences of the stations (panel a) and for foF2 vs. solar and geomagnetic indices dependent on the location of the stations (panels b to f). Stars (*) are raw data, circles (o) are trends, crosses (+) are fluctuations. The limiting value between trends and fluctuations is 64 days (Roux et al., 2012).

Intercorrelation between ionospheric, solar, and geomagnetic data using scaling analysis

Scaling analysis of 11 ionospheric datasets, geomagnetic, and solar indices from years 1971 to 1998 is used for correlations of the data at different scales (Roux et al., 2012). Trends X_a and fluctuations X_d are obtained from the dataset X by means of low–pass and high–pass filtering with a limiting value of 64 days (chosen arbitrarily) as $X = X_a + X_d$.

Fig. 5, panel a, shows the dependence of correlation coefficients to the difference between north latitudes of the stations. The correlation coefficients are very high for the difference 0°–10°. Above 10° the correlation coefficients decrease rapidly (both for fluctuations and trends). The stable values of the correlation coefficients between 0° and 10° suggest the probable existence of one common agent forcing the ionosphere. It could be considered as the influence of the lower–laying neutral atmosphere that affects the state of the ionosphere by upward propagating atmospheric (gravity) waves.

Correlation of foF2 and solar indices, and foF2 and geomagnetic indices

Panels b to f in Fig. 5 show dependence of the correlation coefficients between trends, fluctuations and raw data for pairs (foF2, SSN), (foF2, F10.7), (foF2, Kp), (foF2, Dst), and (foF2, AE) on the latitudinal location of the ionospheric stations.

Panel b (foF2 vs. SSN) and panel c (foF2 vs. F10.7) in Fig. 5 show very close results. Moreover, the correlation coefficients for the raw data are very little dependent on the position of the ionospheric station and are located in the range $0,4 \leq R \leq 0,5$, with pronounced maxima of correlations for stations located in midlatitudes (50°–55°. N). The correlation of trends shows the maximum for two north–latitude stations (Archangelsk and Lycksele, about 65° N). The correlation of fluctuations is relatively low (R is in the interval (0,15;0,20) for all ionospheric stations).

The latitudinal dependence of R(foF2,Kp) is shown in panel d, Fig. 5. The absolute values of R are very low both for the raw data and trends. Correlation coefficients for fluctuations are in the range R≈(-0,3; -0,4) with a low, but obvious latitudinal dependence (decrease of R towards the North).

A very pronounced effect of splitting the signals to trends and fluctuations can be seen for pairs (foF2, Dst). Practically zero correlations for raw data "changed" to R≈(0,35;0,4) for fluctuations and R≈(-0,4;-0,3) for trends. The positive correlation of short–term components (fluctuations) indicates the statistical majority of negative storms (decrease of foF2 correlates positively sith decrease of Dst) over positive storms. This result is in accordance with (Mošna et al., 2009a,b), where most of the solar events (coronal mass ejections and high sped solar streams) led to the negative storm effects. This finding is supported for example by the work of (Prölss, 1995). The values of R(foF2, AE) are shown in panel f, Fig. 5. Absolute values for the raw signal ($-0,1 \leq$R≤ 0), trends ($-0,4 \leq$R $\leq -0,2$) and fluctuations ($-0,05 \leq$R$\leq -0,15$) are i) surprisingly low, ii) practically independent of the position of the station. The second statement is surprising as the effect of processes represented by means of the AE index can seem stronger for stations located closer to the auroral region. However, the AE index seems to be of very low importance for periods longer than one day, even for such a northerly located stations as Lycksele and Archangelsk.

General conclusion

We studied the short–term and long–term variability of the ionosphere by means of critical frequencies and heights of the layers foEs, foF2, hEs, h'F2, and hmF2 and their connection to the solar, geomagnetic and neutral atmosphere activity. The fact that neutral atmosphere influences the ionosphere by means of wave activity is generally well accepted. We tried to contribute to this debate with the study of sporadic E–layers behaviour and its connection to the neutral atmosphere, which is under intense study. The variability of the ionosphere at medium and long–term scales and its connection to solar and geomagnetic activity was studied using scaling analysis. Scaling analysis is shown as a relatively new method for ionospheric research yet it gives interesting results.

Wave–like oscillations in Es and connection to the neutral atmosphere

We studied the effects of planetary waves originating on the stratosphere to the area of the sporadic E–layer formation. Apart from the well known effect of diurnal tides on the Es formation, we found common oscillations at periods corresponding to PWs periodicities that are seen as regular quasiperiodic oscillations within stratosphere temperature time series. A significant influence of the stratospheric PWs on the Es layer formation can be detected in the Es layer data.

We present the following new results:

- Both temperature–hEs and temperature–foEs data show coherent wave–like oscillations at periods close to 2, 4, 8, and 16 days.
- Common periods of (T, hEs) and (T, foEs) detected in the area of planetary waves are located predominantly on periods corresponding to planetary eigen–periods (Rossby mode).
- The phase shift between stratospheric and ionospheric data is stable for diurnal periods, however it is variable for planetary–wave like periods even if we analyze one particular period. This later fact supports the idea of a non–linear connection between the stratospheric data and foEs and hEs at planetary wave modes.
- Planetary scale atmospheric waves are recognized as an important factor influencing the behaviour of sporadic E–layer formation and occurrence.

Medium and long–term behavior: Scaling analysis

We studied the scaling properties of critical frequencies foF2 from European ionospheric stations located at midlatitudes and high latitudes, and geomagnetic and solar data over several solar cycles. A comparison of ionospheric, solar and geomagnetic parameters according to a scaling function and mean value of Hölder exponent $\langle h \rangle$ shows a close relation between foF2 and Kp and AE, while the effect of solar activity (represented by F10.7) and geomagnetic activity (represented by Dst) on the chosen periods is more complicated. We detected the latitudinal dependence of $\langle h \rangle$ of the foF2 on the geographic and geomagnetic position of the ionospheric stations. Wavelet correlation coefficients of foF2 between the ionospheric stations, and between foF2 and geomagnetic and solar indices are very weakly dependent on the latitude of the stations.

We show these important new results:

- Multifractal behaviour of analyzed ionospheric, geomagnetic and solar data was detected.

- Values of $\langle h \rangle$ for Kp, AE and foF2 from all stations are at a relatively narrow interval [0.69, 0.89], which suggests a close relation between geomagnetic activity at midlatitudes and in the auroral zone and ionospheric processes at studied stations. The scaling factor $\langle h \rangle$ is dependent on latitude. A linear dependence exists between the geomagnetic/geographic latitudes of the stations and the structure of the foF2 dataset. More northern stations behave in a smoother manner to those located further south.

- We detected a characteristic dimension of 10° at which a break in the correlation coefficient exists. Below this value, the correlation coefficients are very high and the foF2 datasets behave in a quasi–collective manner. Below this value the correlation coefficients significantly decrease rapidly. The high correlation between the foF2 below a distance of 10° is probably the result of neutral atmosphere activity with such a dimension (gravity waves activity).

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References

Abry, P., Flandrin, P., Taqqu, M.S., Veitch, D., Wavelets for the analysis, estimation and synthesis of scaling data, *Self Similar Network Traffic Analysis and Performance Evaluation*, pp. 39–88, 2000.

Barenblatt, G.I., Scaling. *Cambridge Texts in Mathematics*, 2003.

Burlaga, L.F., Klein, L.W., Fractal Structure of the Interplanetary Magnetic Field. *Journal of Geophysical Research*, 91, A1, pp. 347–350, 1986.

Chainais, P., Abry, P., Veitch, D., Multifractal analysis and alpha–stable processes: A methodological contribution. In *Proceedings of the International Conference on Acoustic, Speech and Signal Processing*, 2000.

Consolini, G., Marcucci, M.F., Candidi, M., Multifractal structure and intermittence in the AE index time series. *Physical Review Letters*, 76, pp. 4082–4085, 1996.

Davis, A., Marshak, A., Wiscombe, W., Cahalan, R., Multifractal characterization of nonstationarity and intermittency in geophysical fields, observed, retrieved, or simulated. *Journal of Geophysical Research*, 99, pp. 8055–8072, 1994.

Davis, A., Marshak, A., Wiscombe, W., Cahalan, R., Scale Invariance of Liquid Water Distributions in Marine Stratocumulus. Part I: Spectral Properties and Stationarity Issues. *Journal of the Atmospheric Sciences*, Vol. 53, no 11, pp. 1538–1558, 1996.

Forbes, M.J., Tidal and Planetary waves. In: Johnson, R.M., Killeen, T.L. (Eds.). The Upper Mesosphere and Lower Thermosphere. A Review of Experiment and Theory.*Geophysical Monograph*, vol. 87, AGU, Washington, DC, pp. 67–87, 1994.

Grinsted, J., Moore, C., Jevrejeva, S., Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*, 11, pp. 561–566, 2004.

Haldoupis, C., Pancheva, D., Planetary waves and midlatitude sporadic E layers: Strong experimental evidence for a close relationship. *Journal of Geophysical Research*, 107(A6), 1078, 2002.

Haldoupis, C., Meek, C., Christakis, N., Pancheva, D., Bourdillon, A., Ionogram height–time–intensity observation of descending sporadic E layers at mid–latitude. *Journal of Atmospheric and Solar–Terrestrial Physics*, 68, pp. 539–557, 2006.

Hnat, B., Chapman, S.C., Rowlands, G., Watkins N.W., Freeman, M.P. Scaling in long term data sets of geomagnetic indices and solar wind as seen by WIND spacecraft, *Geophysical Research Letters*, 30, 22, 2003.

Laštovička, J., Forcing of the Ionosphere by Waves from Below. *Journal of Atmospheric and Solar–Terrestrial Physiscs* 68(3–5), pp. 479–497, 2006.

Lovejoy, S., Schertzer, D., Scale, Scaling and Multifractals in Geophysics: Twenty Years on. *Nonlinear Dynamics in Geosciences*, pp. 311–337, 2007.

Mandelbrot, B.B., How long is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension. *Science*, 156, 636, 1967.

Mikhailov, A.V., Mikhailov, V.V., Skoblin, M.G., Monthly median foF2 and M(3000)F2 ionospheric model over Europe. *Annali di Geofisica*, 4, pp. 791–805, 1996.

Muzy, J.F., Bacry, E., Arneodo, A., The multifractal formalism revisited with wavelets. *International Journal of Bifurcation and Chaos* 4, pp. 245–302, 1994.

Pancheva, D., Haldoupis, C., Meek, C.E., Manson, A.H., Mitchell, N.J., Evidence of a role for modulated atmospheric tides in the dependence of sporadic E layers on planetary waves. *Journal of Geophysical Research*, 108 (A5), 2003.

Tascioni, T.F., Introduction to the Space Environment, 2–nd Ed., Krieger Publishing Company. 1994.

Mathews, J. D., Sporadic E: current views and recent progress. *Journal of Atmospheric and Solar-Terrestrial Physics* 60(4), pp. 413–435, 1998.

Mošna, Z., Šauli, P., Georgieva, K., Kouba, D., Comparison of HSS and CME Influences on F2-layer based on Storms in October 2005. *Fundamental Space Research, Suplement of Comptes Rendus, Academy of Bulgarian Sciences*, pp. 97–99, 2009.

Mošna, Z., Šauli, P., Georgieva, K., Ionospheric response to the particular solar event as seen in the ionospheric vertical sounding. *WDS 2009 Proceedings of Contributed Papers, Part II*, pp. 68–73, 2009.

Mošna, Z., Koucká Knížová, P., Scaling analysis applied to Ionospheric, Solar, and Geomagnetic Data, *WDS 2011 Proceedings of Contributed Papers, Part II*, pp. 61–66, 2011.

Mošna, Z., Koucká Knížová, P., Analysis of wave–like oscillations in parameters of sporadic E layer and neutral atmosphere. *Journal of Atmospheric and Solar Terrestrial–Physics*, pp. 172–178, 2012.

Prölss, G.W., Ionospheric F–region storms, in Handbook of Atmospheric Electrodynamics, Volume II, pp. 195–248, 1995.

Reinisch, B. W., Huang, X., Galkin, I.A., Paznukhov, V., Kozlov, A., Recent advances in real-time analysis of ionograms and ionospheric drift measurements with digisondes, *Journal of Atmospheric and Solar–Terrestrial Physics*, 67, pp. 1054–1062, 2005.

Roux, S.G., Koucká Knížová, P., Mošna, Z., Abry, P., Ionosphere fluctuations and global indices: A scale dependent wavelet–based cross–correlation analysis. *Journal of Atmospheric and Solar Terrestrial–Physics*, pp. 186–197, 2012.

Šauli, P., Bourdillon, A., Height and Critical Frequency Variations of the Sporadic–E layer at midlatitudes. *Journal of Atmospheric and Solar–Terrestrial Physisc*, 70, pp. 1904–1910, 2008.

Torrence, C., Compo, G. P., A practical guide to wavelet analysis. *Bulletin of American Meteorological Society* 79, pp. 61–78, 1998.

Uppala, S.M., Kallberg, P.W., Simmons, A.J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M., Jenne, R., McNally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J., The ERA-40 re-analysis. *Quarterly Journal October 2005 Part B*, 131, pp. 2961–3012, 2005.

Vörös, Z., Jankovičová, D., Kovács, P., Scaling and singularity characteristics of solar wind and magnetospheric fluctuations. *Nonlinear Processes in Geophysics*, pp. 149–162, 2002.

Voiculescu, M., Haldoupis, C., Pancheva, D., Ignat, M., Schlegel, K., Shalimov, S., More evidence for a planetary wave link with midlatitude E region coherent backscatter and sporadic E layers. *Annales Geophysicae*, 18, pp. 1182–1196, 2000.

Whitehead, J.D., The formation fof the sporadic E layer in the temperate zones, *Journal of Atmospheric and Terrestrial Physics*, 20, pp. 49–58, 1961.

Whitehead, J.D., Recent work on mid-latitude and equatorial sporadic E. *Journal of Atmospheric and Terrestrial Physics*, 51, pp. 401–424, 1989.

Zolesi, B., Cander, B., Ionospheric Prediction for Radio Propagation Purposes. *Springer Geophysics*, pp. 123–146, In Press, 2014.

Publications

1. Šauli, P., Mošna, Z., Boška, J., Kouba, D., Laštovička, J., Altadill, D., Comparison of true–height electron density profiles derived by POLAN and NHPC methods. *Studia Geophysica et Geodetica*, 51, pp. 449–459, 2007.

2. Mošna, Z., Šauli, P., Georgieva, K., Kouba, D., Comparison of HSS and CME Influences on F2-layer based on Storms in October 2005. *Fundamental Space Research*, pp. 97–99, 2009a.

3. Mošna, Z., Šauli, P., Georgieva, K., Ionospheric response to the particular solar event as seen in the ionospheric vertical sounding, *WDS 2009 Proceedings of Contributed Papers, Part II*, pp. 68–73, 2009b.

4. Automatic visualization method of height–time development of ionospheric layers, *WDS 2010 Proceedings of Contributed Papers, Part II*, pp. 199–204, 2010.

5. Koucká Knížová, P., Mošna, Z., Acoustic–Gravity Waves in the Ionosphere During Solar Eclipse Events. *Acoustic Waves – From Microdevices to Helioseismology*, Marco G. Beghi (Ed.), InTech, 2011.

6. Mošna, Z., Koucká Knížová, P., Scaling analysis applied to Ionospheric, Solar, and Geomagnetic Data, *WDS 2011 Proceedings of Contributed Papers, Part II*, pp.61–66, 2011.

7. Roux, S.G., Koucká Knížová, P., Mošna, Z., Abry, P., Ionosphere fluctuations and global indices: A scale dependent wavelet–based cross–correlation analysis. *Journal of Atmospheric and Solar–Terrestrial Physics*, pp. 186–197, 2012.

8. Mošna, Z., Koucká Knížová, P., Analysis of wave–like oscillations in parameters of sporadic E layer and neutral atmosphere, *Journal of Atmospheric and Solar–Terrestrial Physics*, pp. 172–178, 2012.

9. Šindelářová, T., Mošna, Z., Burešová, D., Chum, J., McKinnel, L. – A., Athieno, R., Observation of wave activity in the ionosphere over South Africa in geomagnetically quiet and disturbed periods. *Advances in Space Research* 50, pp. 182–195, 2012.

10. Georgieva, K., Kirov, B., Koucká Knížová, P., Mošna, Z., Kouba, D., Asenovska, Y., Solar influences on atmospheric circulation. *Journal of Atmospheric and Solar–Terrestrial Physics*, pp. 15–25, 2012.