Semidiurnal tidal signature over Collm (51.3N, 13E) in sporadic E layer frequency obtained from FORMOSAT-3/COSMIC GPS radio occultation measurements

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Abstract

We present measurements of sporadic E (Es) layer occurrence frequency from FORMOSAT-3/COSMIC GPS radio occultation measurements at 50°-55°N and compare these with zonal wind shears measured by meteor radar at Collm. Both parameters are, on a diurnal time scale, dominated by a semidiurnal oscillation. According to theory, maximum Es occurrence is expected when the zonal wind shear is negative. This is confirmed by our measurements and analyses.

Zusammenfassung

Es werden Messungen sporadischer E-Schichten (Es) mit Hilfe von FORMOSAT-3/COSMIC GPS-Radiookkultationsmessungen bei 50°-55°N vorgestellt und mit Analysen des zonalen Windes aus Meteorradarmessungen verglichen. Auf einer Zeitskala bis zu einem Tag ist eine halbtägige Komponente das dominierende Muster. Nach allgemein anerkannter Theorie sollten sporadische E-Schichten bevorzugt bei negativer Scherung des Zonalwindes auftreten. Die hier gezeigten Analysen bestätigen dies.

Introduction

Sporadic E (Es) layers are thin structures of enhanced electron density in the lower ionospheric E region. Es layers have been detected by ionosondes, incoherent scatter radars, or other radio methods as backscatter radars (Haldoupis et al., 2006). According to theory, Es layers are produced through the V×B or "windshear" mechanism (Whitehead, 1960). Taking into account a northward directed magnetic field, this mechanism leads to an accumulation of ions if the vertical shear of the zonal ion drift is negative, under the usual convention that positive drift is directed eastward. Since in the lower E region the ion drift is mainly dominated by neutral atmosphere dynamics, Es layers thus are expected when negative neutral wind shear is given.

Available climatologies of Es show that at mid-latitudes these layers are clearly a summer phenomenon, with strong enhancement in the period May-August (e.g. Voiculescu et al., 2000). Since the background wind shear in the lower thermosphere is positive during summer, this raised the question of the origin of Es layers then. Correlation between Es and planetary wave activity leads to the assumption, that wind shears modulated by planetary waves are potential drivers of Es (e.g. Shalimov et al., 1999; Voiculescu et al., 2000). Recent analysis of meteor flux rates indicate, that ion production through meteor flux is an important factor at mid-latitudes, since meteor rates are much stronger during summer (Haldoupis et al., 2007).

As summarized in the review paper by Mathews (1998), the motion and variability of mid-latitude Es can be described by the semidiurnal and diurnal tides in the lower thermosphere, so that the downward moving structure of tides in the course of one day is reproduced in Es registrations (e.g. Haldoupis et al., 2006). Tides are by far the strongest signal within lower thermosphere dynamics. The major components are the diurnal tide at lower latitudes and lower mid-latitudes, and the semidiurnal tide (SDT) at middle an high latitudes (e.g. Pancheva et al., 2002). Their amplitudes may reach values of more than 40 m/s (Manson et al., 2002a; Jacobi and Hoffmann, 2008). Thus they produce much stronger shears than the background circulation, which is provided in available climatologies. This may indicate that the required negative wind shear to produce Es is provided by tides, and the tidal signature is then reproduced in Es.

Concomitant measurements of neutral atmospheric tides and Es signatures, however, are still sparse. This is mainly due to the fact that in most cases Es is detected by ground-based systems and neutral wind is not necessarily available there. A new and global method to detect Es, however, is using GPS (Global Positioning System) radio occultation (RO) measurements from Low-Earth-Orbiting (LEO) satellites (Hocke et al., 2001), and interpreting strong electron density fluctuations as Es (Wu et al., 2005). This method provides the altitude of a single Es layer measured during the duration and at the location of the respective RO, therefore a time series of Es occurrence at a single place is not available from these signals. However, from long-term RO measurements it is possible to derive mean occurrence rates of Es depending on altitude and local time as a statistical measure of Es on a global grid, and we are able to compare, e.g., mean height-time cross-sections of Es probability at a given latitude with ground-based radar tides.

In the following we present Es probability rates derived from FORMOSAT-3/COSMIC GPS RO measurements as a function of local time for a latitudinal range of 50-55°N. These data are compared with Collm meteor radar wind shears to detect a possible correlation between these two parameters.

Meteor radar wind measurements over Collm

At Collm Observatory (51.3°N, 13°E), a SKiYMET (Hocking et al., 2001) all-sky meteor radar is operated on 36.2 MHz since summer 2004 (Jacobi et al., 2005). The wind measurement principle is the Doppler shift detection of the reflected VHF radio waves from ionised meteor trails, which delivers radial wind velocity along the line of sight of the radio wave. An interferometer is used to detect azimuth and elevation angle from phase comparisons of individual receiver antenna pairs. Together with range measurements the meteor trail position is detected. The raw data collected consist of azimuth and elevation angle, wind velocity along the line of sight and meteor height. The data collection procedure is described in detail by Hocking et al. (2001).

The meteor trail reflection heights are varying roughly between 75 and 110 km, with a maximum meteor rate around 90 km. The data are binned in 6 different altitude intervals centred at 82, 85, 88, 91, 94, and 98 km. Individual radial winds calculated from the meteors are collected to form hourly mean values using a least squares fit of the horizontal wind components to the raw radial wind data under the assumption that vertical winds are small (Hocking et al., 2001). More detailed description of the data analysis procedure, a comparison with Collm low-frequency lower E region drift measurements, and presentation of background winds are given by Jacobi et al. (2005, 2007) and Jacobi and Hoffmann (2008).

Here we use monthly means of hourly winds depending on local time during 4 months (October 2006; January, April and July 2007). Monthly means of hourly zonal wind shears have been calculated from the zonal winds for each of the 6 altitude intervals.

FORMOSAT-3/COSMIC GPS radio occultation measurements and analysis

The FORMOSAT-3/COSMIC (FORMOsa SATellite mission-3/Constellation Observing System for Meteorology, Ionosphere and Climate) is a joint Taiwan-U.S. satellite project. The constellation was launched on April 14, 2006. It consists of 6 satellites. A lifetime of at least five years is expected (e.g., Schreiner et al., 2007). The main scientific instrument aboard each satellite is a state-of-the-art GPS receiver IGOR (Integrated GPS and Occultation Receiver, provided by Broad Reach Engineering), which applies the GPS radio occultation technique for vertical atmosphere sounding on a global scale (e.g., Kursinski et al., 1997). GPS RO is a limb sounding method, which originally was developed by the Jet Propulsion Laboratory (JPL) and Stanford University in the late 1960s to study planetary atmospheres (see, e.g., Yunck et al., 2000). The payload of the six spacecrafts is complemented by tiny ionospheric photometers and tri-band beacons. Data and analysis results are made freely available to the international scientific community in near real time (for more information, see, e.g., www.cosmic.ucar.edu). We note that the FORMOSAT-3/COSMIC data are complemented by measurements from additional GPS RO missions, e.g., from the German CHAMP (CHAllenging Minisatellite Payload) satellite. It was launched on July 15, 2000 and generates the first long-term set of GPS RO measurements (e.g., Wickert et al., 2008).

GPS radio occultation measurements from LEO satellites have already successfully been used to derive vertical profiles of ionospheric electron density (e.g., Hajj et al., 1998; Jakowski et al., 2002). In addition, layered structures of enhanced electron density in the lower ionosphere such as Es can be identified, since they cause strong fluctuations in the GPS RO phase and Signal-to-noise-ratio (SNR) signals (Wu et al., 2005). In the ionosphere the phase and SNR scintillations can be directly related to sharp electron density fluctuations. We use the SNR of the 50 Hz L1 occultation measurements to detect Es layers. If a disturbance exists in the lower E-region due to irregularities of the electron density, the SNR shows strong fluctuations in the concerned altitude range due to strong vertical refractivity gradients. In this case we register the existence of a sporadic E layer. More detailed description and initial results of the application of this technique are given by Viehweg et al. (2007) and Wickert et al. (2008).

Our current analysis procedure provides no information on the amplitude, thickness and critical frequency of the respective Es layer. Since we only measure the variation of the SNR for a specific occultation event at a certain time and location, no information on the temporal behaviour of the detected layer is available, if the resolution of the RO measurements in time and space is not sufficient. But the number of the FORMOSAT-3/COSMIC data is appropriate through sorting it into voxels, to obtain information on the mean occurrence rate or probability of Es for each latitude, longitude, and altitude, depending on season and local time.

We use mean occurrence rates of Es on a 5×5 degree grid with a 1 km height resolution on a data base of 3 months each. In order to obtain a sufficient data coverage, we calculated longitudinal means of Es occurrence rates, but sorted the RO results according to local time. Therefore we are able to present the signatures of “migrating tides” in Es. We use time intervals centred at the 4 months mentioned above for the wind SDT analysis. We analysed a total of 752,897 RO measurements, with 118,702 of them with Es, i.e. we found an Es occurrence rate of 15.8% on a global and annual average.

Results

The relative frequency of Es occurrence for different heights and latitudes for 4 seasons is shown in Figure 1. The figure shows the known features (e.g. Wu et al, 2005), i.e. that Es is mainly a summer phenomenon at middle latitudes, with maximum rates at about 40° latitude. Values for the Southern Hemisphere are smaller than for the Northern Hemisphere. During equinoxes, Es are mainly found at lower latitudes of both hemispheres, and the probability of occurrence is lower. The smallest values are found in Northern Hemisphere autumn. Maximum values of Es occurrence are found at altitudes between 100 and 105 km. Note that the Es frequencies are given in values of 1/1000, which means, that there is a relatively low probability of Es at a given time in a given height interval. Summing up over all Es events at all heights in a given a 5 degree latitude interval leads to Es frequencies of up to 38.5% in summer at mid-latitudes (Figure 2).

The major dynamical feature at altitudes between 80 and 100 km at mid-latitudes is the SDT. To illustrate this, monthly mean hourly winds as measured with the Collm meteor radar are shown in Figure 3 for 4 seasons and at 3 different levels. The SDT signal is clearly dominating. Maximum amplitudes are found in winter. In summer, large amplitudes are found only in the upper levels considered here. This behaviour is well known from climatologies (e.g. Manson et al., 2002b; Kürschner and Jacobi, 2005; Jacobi and Hoffmann, 2008). At times, negative zonal wind shear is visible during each month, however, in summer negative values are only found in the upper layers above about 90 km altitude.

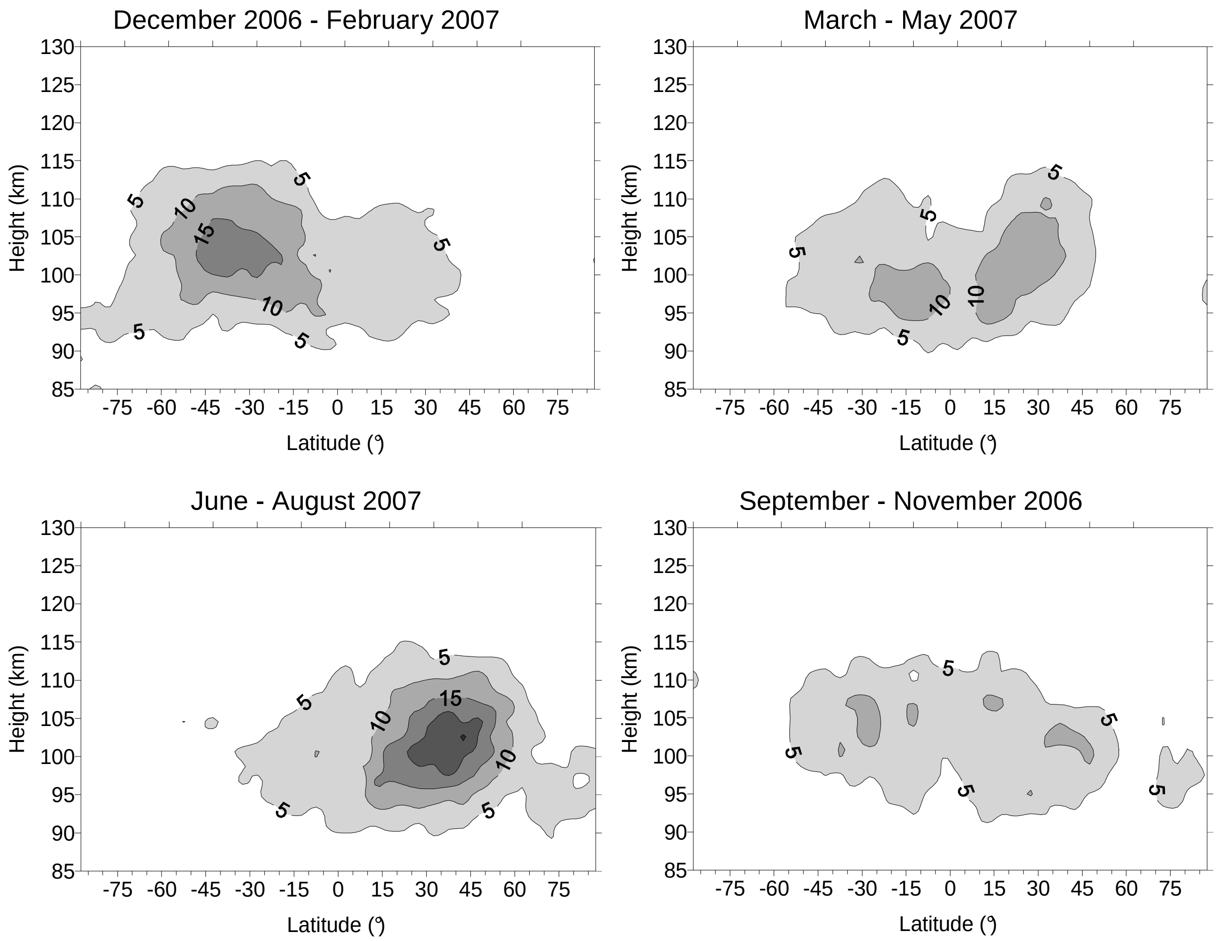

Figure 1: FORMOSAT-3/COSMIC RO daily mean relative Es occurrence rate for 4 seasons (3-monthly means). Values are given in 1/1000.

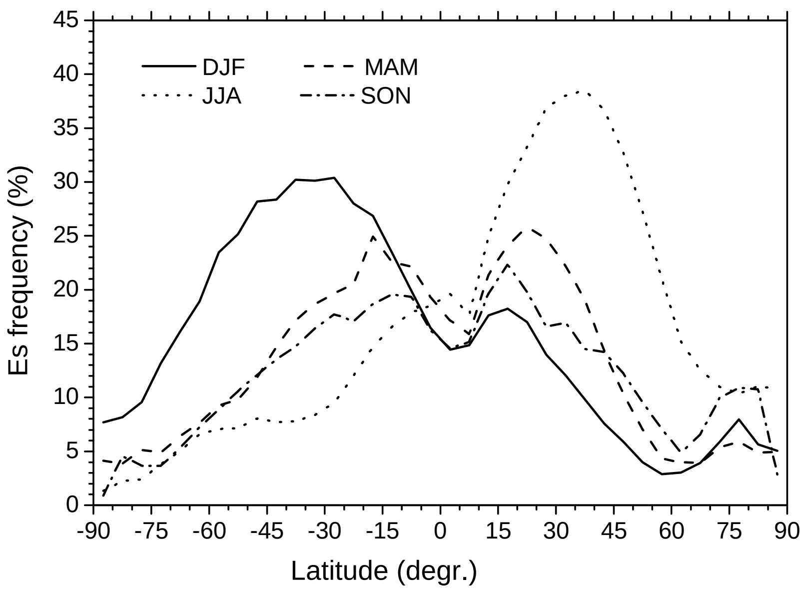

Figure 2: Total Es frequency of occurrence in a given latitude interval, for 4 different seasons.

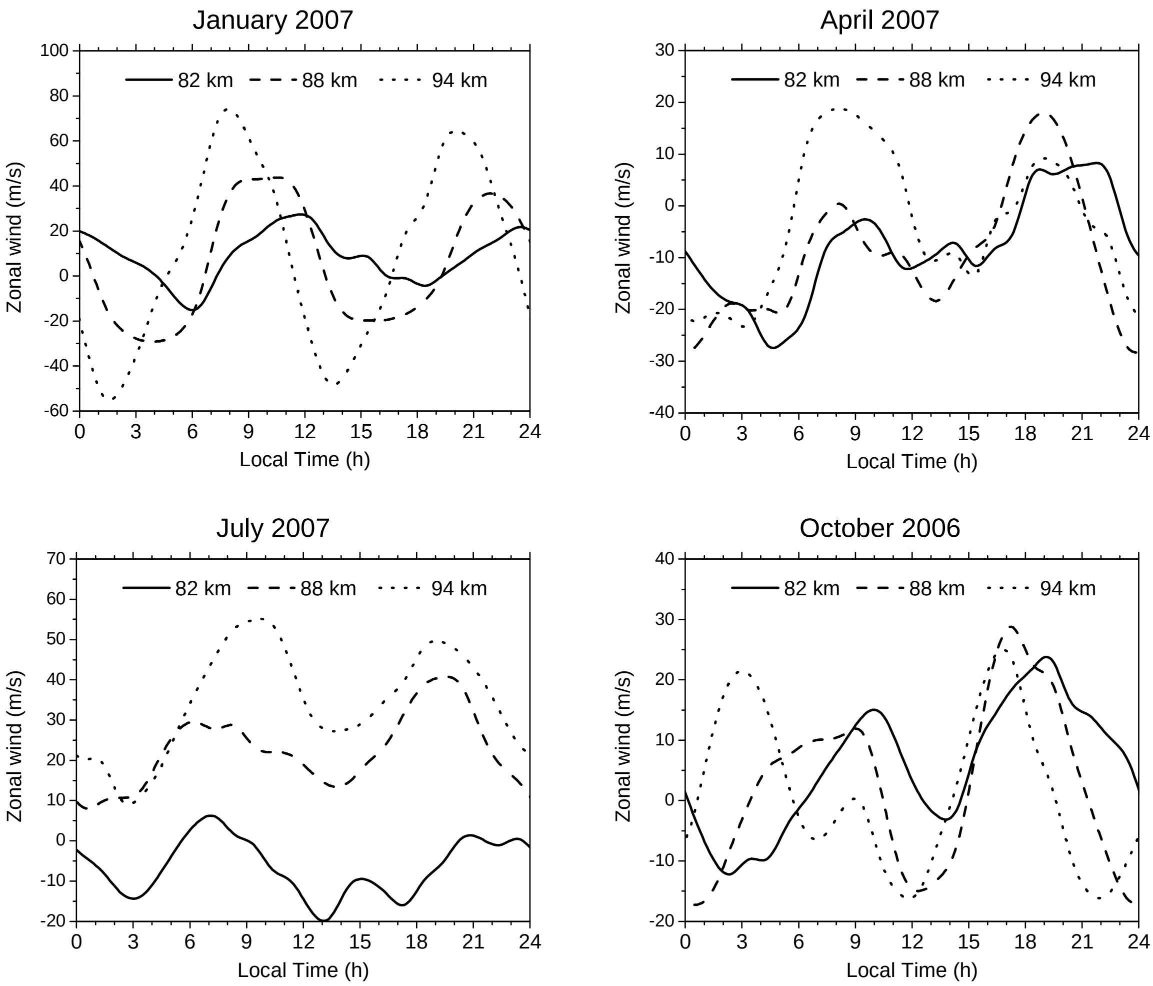

Figure 3: Monthly mean zonal winds at 3 different height gates, measured with meteor radar at Collm, for 4 seasons. Note the different scaling of the ordinate in the respective panels.

To analyse the influence of wind shear on Es formation, we calculated the shear from the meteor radar winds at the 6 height gates through simply calculating the wind difference between two adjacent gates. In addition, we binned the seasonal FORMOSAT-3/COSMIC Es occurrence frequencies for the latitude range 50°-55°N into hourly intervals of local time. In Figure 4 these data are shown as a height-local time cross section for 4 seasons, maximum values amount to about 4.5% in summer. Note that the numbers of each altitude level should be added up to obtain the overall frequency of Es occurrence. During each season the mean descending structure of Es probability with local time is visible, and there is a clear semidiurnal signal at altitudes of about 100-105 km. To show the correspondence with the zonal wind SDT, in the lower part of the panels the zonal wind shear derived from the meteor radar measurements are shown. Negative values, which are required for Es formation, are hatched. There is a striking correspondence between negative zonal wind shear and Es in each month.

Also added Figure 4 are phases of a least squares fit of a 12-hour sinusoidal oscillation to the Es and wind shear data. Note that the phase is defined here as the local time of maximum Es probability, but, in contrast to the usual convention, maximum negative zonal wind shear. The SDT is practically always significant in mid-latitude winds at mesopause region heights. For the Es oscillation, only those values are added that are significant according to a t-test. Especially at lower altitudes and in winter, when Es rates are low anyway, there is only a weak SDT signal, which is not necessarily the dominant oscillation. Therefore in January and October there is no clear overlapping height interval between the wind shear and Es phase profiles. However, if one linearly extrapolates the wind shear phases, this again fits well to those in Es.

In Figure 5 two examples of July Es probabilities at different altitudes are shown. At 85 km, only a weak SDT signal is visible, while at 105 km the signal is strong and dominating. Nevertheless, inspecting the SDT phase progression with height in both Es and zonal negative wind shear, a striking correspondence is visible even if insignificant Es phases are included into the visual inspection (Figure 6). Only in October at altitudes below 90 km the phases do not fit to each other, but it must be taken into account that the Es rates there and then are very small.

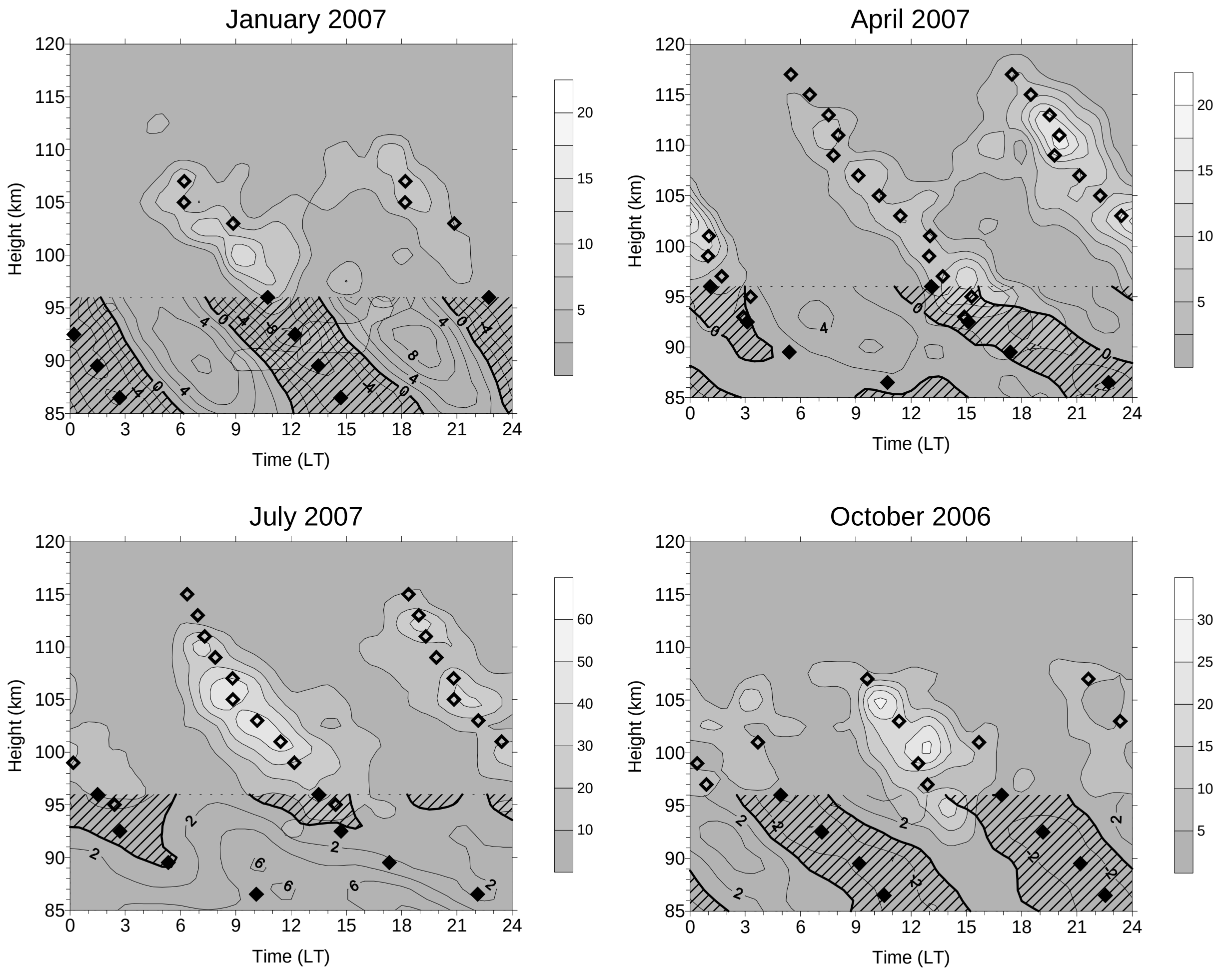

Figure 4: FORMOSAT-3/COSMIC relative Es layer occurrence (in 1/1000), for a latitude range from 50°-55°N (greyscaling). In the lower part are monthly mean wind shears, given in ms^{-1}km^{-1}, measured with the Collm meteor radar are shown as isolines. Negative shear values are hatched. Added are SDT phases of Es layer occurrence (open symbols) and wind shear (solid symbols, phase is defined as time of minimum shear).

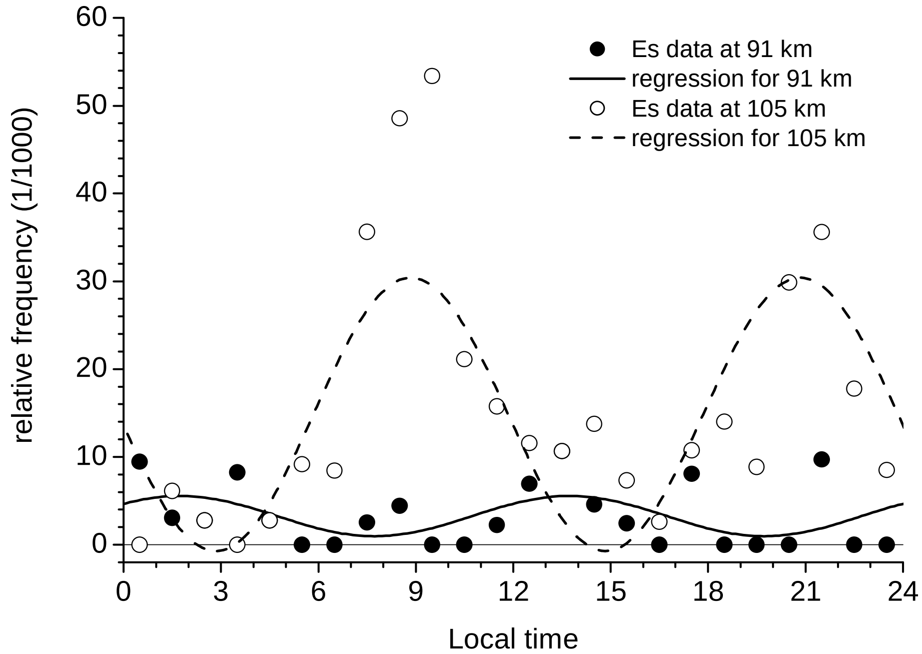

Figure 5: Examples for 2 summer mean time series of longitudinal mean Es occurrence frequency at 91 km and 105 km, together with results of a least squares fit.

Conclusions

We have shown from the FORMOSAT-3/COSMIC RO data together with Collm zonal wind shears a strong correlation of Es with the SDT in zonal wind shear, which clearly supports the theory that zonal wind shear produced by the SDT is a main driver of Es at mid-latitudes. Our results indicate that GPS RO observations have the potential to detect the SDT in Es, and thus, beyond their ionospheric aspects, may provide a measure on lower thermosphere dynamics at altitudes that are not accessible to most radar systems.

Since data on background ionisation are not considered here, at this stage we only can draw conclusions on the phase of Es occurrence, which is in remarkable correspondence with the zonal wind shear SDT. Since the GPS RO measurements are irregularly distributed in time and space over the globe, we also cannot detect the evolution of Es in time at a distinct point, but information on seasonal means or climatological behaviour of its occurrence can be derived.

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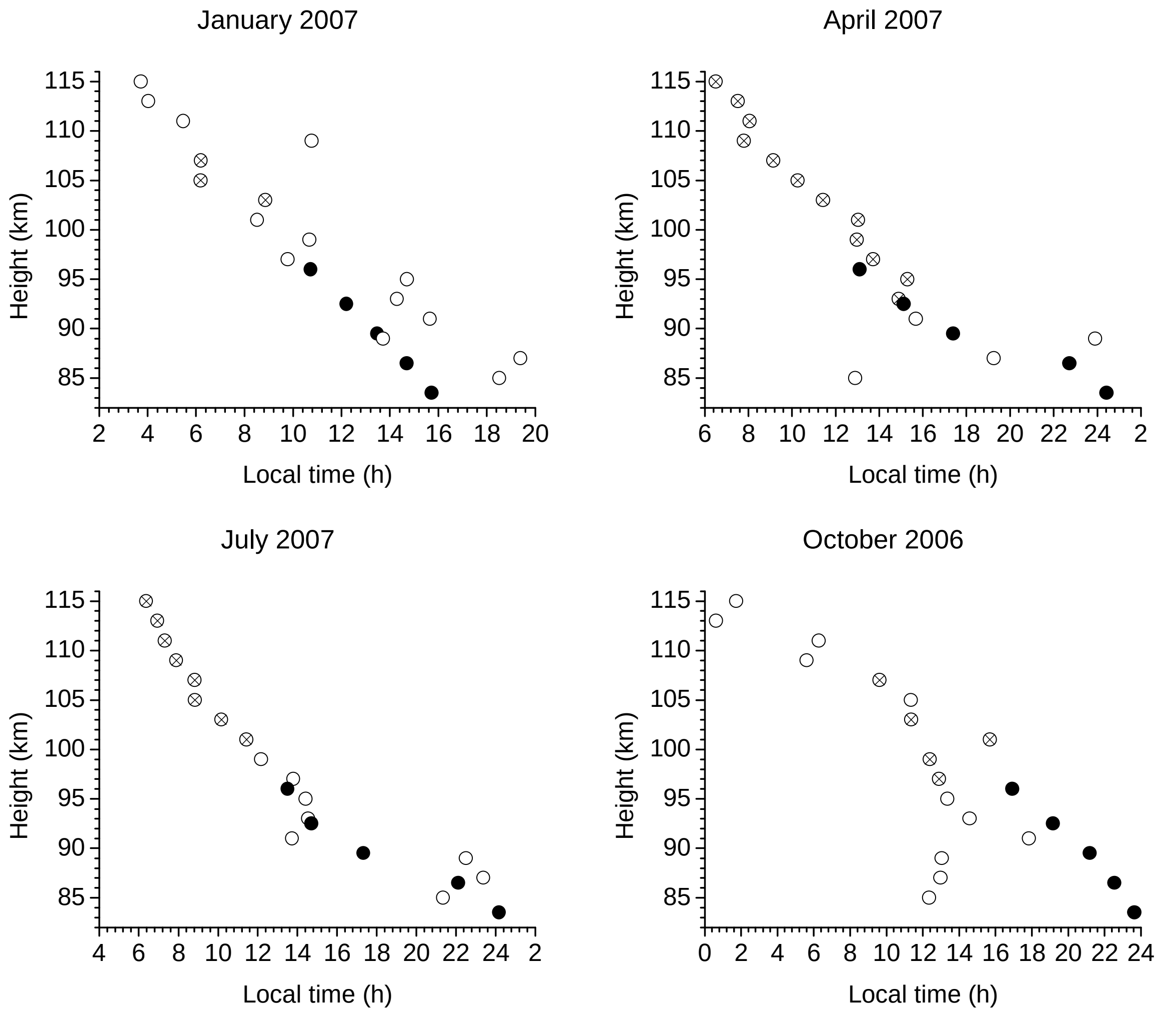

Figure 6: Semidiurnal phases of Collm meteor radar zonal wind shear, defined as time of minimum vertical shear (solid dots), and FORMOSAT-3/COSMIC relative Es layer occurrence (open circles), defined as time of maximum occurrence. Es phase values with statistical significant amplitudes are marked by a cross (X) inside the symbol.

References

Hajj, G. A., Romans, L.J., 1998: Ionospheric electron density profiles obtained with the Global Positioning System: Results from GPS/MET experiment. Radio Sci., 33, 175-190

Haldoupis, C., Meek, C., Christakis, N., Pancheva, D., Bourdillon, A., 2006: Ionogram height–time–intensity observations of descending sporadic E layers at mid-latitude. J. Atmos. Solar-Terr. Phys., 68, 539-557.

Haldoupis C., Pancheva, D., Singer, W., Meek, C., MacDougall, J., 2007: An explanation for the seasonal dependence of midlatitude sporadic E layers. J. Geophys. Res., 112, A06315, doi:10.1029/2007JA012322.

Hocke, K., Igarashi, K., Nakamura, M., Wilkinson, P., Wu, J., Pavleyev, A., Wickert, J., 2001: Global sounding of sporadic E layers by the GPS/MET radio occultation experiment. J. Atmos. Solar-Terr. Phys., 63, 1973-1980.

Hocking, W.K., Fuller, B., Vandepeer, B., 2001: Real-time determination of meteor-related parameters utilizing modern digital technology. J. Atmos. Solar-Terr. Phys., 63, 155-169.

Jacobi, Ch., Kürschner, D., Fröhlich, K., Arnold, K., Tetzlaff, G., 2005: Meteor radar wind and temperature measurements over Collm (51.3°N, 13°E) and comparison with co-located LF drift measurements during autumn 2004. Rep. Inst. Meteorol. Univ. Leipzig, 36, 98-112.

Jacobi, Ch., Fröhlich, K., Viehweg, C., Stober, G., Kürschner, D., 2007: Midlatitude mesosphere/lower thermosphere meridional winds and temperatures measured with Meteor Radar. Adv. Space Res., 39, 1278-1283

Jacobi, Ch., Hoffmann, P., 2008: Mean winds and tides over Collm (51.3N, 13E) in 2007 measured with meteor radar and the LF D1 method. Rep. Inst. Meteorol. Univ. Leipzig, this issue.

Jakowski, N., Wehrenpfennig, A., Heise, S., Reigber, Ch., Lühr, H., Grunwaldt, L., Meehan, T.K., 2002: GPS Radio Occultation Measurements of the Ionosphere from CHAMP: Early Results. Geophys. Res. Lett., 29, 1457, doi:10.1029/2001GL014364.

Kürschner, D., Jacobi, Ch., 2005: The mesopause region wind field over Central Europe in 2003 and comparison with a long-term climatology. Adv. Space Res., 35, 1981-1986.

Kursinski, E.R., Hajj, G.A., Hardy, K.R., Schofield, J.T., Linfield, R., 1997: Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System. J. Geophys. Res., 102, 23429-23465.

Manson, A.H., Luo, Y., Meek, C.E., 2002a: Global distributions of diurnal and semi-diurnal tides: observations from HRDI-UARS of the MLT region. Ann. Geophysicae, 20, 1877-1890.

Manson, A.H., Meek, C., Hagan, M., Koshyk, J., Franke, S., Fritts, D., Hall, C., Hocking, W., Igarashi, K., MacDougall, J., Riggin, D., Vincent, R., 2002b: Seasonal variations of the semi-diurnal and diurnal tides in the MLT: multi-year MF radar observations from 2-70° N, modelled tides (GSWM, CMAM). Ann. Geophysicae, 20, 661-677.

Mathews, J.D., 1998: Sporadic E: current views and recent progress. J. Atmos. Solar-Terr. Phys., 60, 413-435.

Pancheva, D., Merzlyakov, E., Mitchell, N.J., Portnyagin, Y., Manson, A.H., Jacobi, C., Meek, C.E., Luo, Y., Clark, R.R., Hocking, W.K., MacDougall, J., Muller, H.G., Kürschner, D., Jones, G.O.L., Vincent, R.A., Reid, I.M., Singer, W., Igarashi, K., Fraser, G.I., Fahrutdinova, A.N., Stepanov, A.M., Poole, L.M.G., Malinga, S.B., Kashcheyev, B.L., Oleynikov, A.N., 2002: Global-scale tidal variability during the PSMOS campaign of June-August 1999: interaction with planetary waves. J. Atmos. Solar-Terr. Phys., 64, 1865-1896.

Schreiner, C., Rocken, C., Sokolovskiy, S., Syndergaard, S., Hunt, D., 2007: Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission. Geophys. Res. Lett., 34, L04808, doi:10.1029/2006GL027557.

Shalimov, S., Haldoupis, C., Voiculescu, M., Schlegel, K., 1999: Midlatitude E region plasma accumulation driven by planetary wave horizontal wind shears. J. Geophys. Res., 104, 28207-28213.

Viehweg, C., Wickert, J., Heise, S., Jacobi, C., Beyerle, G., Schmidt, T., Rothacher, M., 2007: Global distribution of plasma irregularities in the lower ionosphere derived from GPS radio occultation data. EGU Vienna 2007, Geophysical Research Abstracts, 9, EGU2007-A-07823.

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

Whitehead, J.D., 1960: Formation of the sporadic E layer in the temperate zones. Nature, 188, 567-567.

Wickert, J., Michalak, G., Schmidt, T., Beyerle, G., Cheng, C.Z., Healy, S.B., Heise, S., Huang, C.Y., Jakowski, N., Köhler, W., Mayer, C., Offiler, D., Ozawa, E., Pavelyev, A.G., Rothacher, M., Tapley, B., Arras, C., 2008: GPS radio occultation: Results from CHAMP, GRACE and FORMOSAT-3/COSMIC. Terr. Atmos. and Oceanic Sci., in print.

Wu, D.L., Ao, C.O., Hajj, G.A., de la Torre Juarez, M., Mannucci, A.J., 2005 : Sporadic E morphology from GPS-CHAMP radio occultations. J. Geophys. Res., 110, A01306, doi: 10.1029/2004JA01701.

Yunck, T.P., Liu, C.H., Ware, R., 2000: A history of GPS sounding. Terr. Atmos. and Oceanic Sci., 11(1), 1-20.

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