Long-term predictions of space weather effects on the Earth's ionosphere

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Abstract

Certain limitations that have been identified in existing ionospheric prediction capabilities indicate that the deeper understanding and the accurate formulation of the ionospheric response to external forcing remain always high priority tasks for the research community. In this respect, this paper attempts a long-term investigation of the ionospheric disturbances from the solar minimum between the solar cycles 23 and 24 up to the solar maximum of solar cycle 24. The analysis is based on observations of the foF2 critical frequency and the hmF2 peak electron density height obtained in the European region, records of the Dst and AE indices, as well as measurements of energetic particle fluxes from NOAA/POES satellites fleet. The discussion of the ionospheric behavior in a wide range of geophysical conditions within the same solar cycle facilitates the determination of general trends in the ionospheric response to different faces of space weather driving. According to the evidence, the disturbances in the peak electron density reflect mainly the impact of geoeffective solar wind structures on the Earth's ionosphere. The intensity of the disturbances may be significant (greater than 20% with respect to normal conditions) in all cases, but the ionospheric response tends to have different characteristics between solar minimum and solar maximum conditions. In particular, in contrast to the situation in solar maximum, in solar minimum years the solar wind impact on the Earth's ionosphere is mainly built on the occurrence of ionization increases, which appear more frequent and intense than ionization depletions. The ionization enhancements are apparent in all local time sectors, but they peak in the afternoon hours, while a significant part of them seems not related with an F2 layer uplifting. Taking into account the main interplanetary drivers of the disturbances in each case, i.e. high speed streams (HSSs) and corotating interaction regions (CIRs) in solar minimum and coronal mass ejections (CME) in solar maximum, we argue that the identified tendency may be considered as evidence of the ionospheric response to different solar wind drivers.

1. Introduction

The transient changes imposed on the Earth's ionosphere by space weather events remain always one of the most fascinating but challenging topics for space weather purposes (e.g., Kutiev et al.,

2013; Bergeot et al., 2013; Liu et al., 2011). During disturbed space weather conditions, a variety of photochemical and chemical reactions, as well as dynamical and electrodynamical processes are activated in the magnetosphere-ionosphere-thermosphere system to drive exchange and transportation of mass, momentum and energy between the system's elements. As a result, the ionospheric structure is substantially altered.

Despite the apparent complexity, today there are several scenarios/models that attempt to describe the response of the upper atmosphere system to disturbed space weather conditions, comprehensively. A key element of this response is the disturbances in the peak electron density, in which we shall concentrate on here. The most dramatic changes, both increases and decreases in the peak electron density occur during geomagnetic storms to form the so called positive and negative storm effects, respectively. These variations are driven by highly variable solar wind and magnetospheric energy inputs to the Earth's upper atmosphere, mainly in the high latitudes [see for example the review articles presented by Rishbeth (1991), Prölss (1995), Buonsanto (1999), and Mendillo (2006)].

A widely accepted scenario for the development of the ionospheric storm time response is the Prölss phenomenological model (Prölss, 1993; Prölss, 1995) for the dependence of the F-layer disturbances on local time (LT). According to this model, positive storm effects are attributed to meridional winds, while negative ionospheric storm effects are attributed to changes in the neutral gas composition. The injection of solar wind energy to the polar upper atmosphere launches a wide spectrum of atmospheric gravity waves, which superimpose to form an impulse-like travelling atmospheric disturbance (TAD) that propagates with high velocity towards lower latitudes. An essential feature of such a TAD is that it carries along equatorward-directed winds of moderate magnitude that push the ionization upward. This results in the increase of the F2-layer ionization in daytime hours at middle latitudes. Concerning negative storm effects, the dissipation of the solar wind energy input generates a permanent composition disturbance zone at polar latitudes, which results in the decrease of the ionization at F2-layer heights. During disturbed conditions this zone expands towards middle latitudes in the post-midnight sector due to winds of moderate magnitude, designated as midnight surge. At the recovery of the geomagnetic activity the composition disturbance zone is simply rotated to the pre-noon sector following the Earth's rotation, and although they partially recover the perturbations are still large enough to produce daytime negative ionospheric storm effects. Any new intensification of the solar wind energy input results in the generation of a new disturbance zone in the ionosphere (Tsayouri et al. 2000). More generally, the mechanisms proposed in the literature for the explanation of the observed storm time effects include upwelling/downwelling of the gas due to storm-induced thermospheric circulation, penetration of electric fields of magnetospheric or interplanetary origin into the ionosphere [e.g., the super-fountain mechanism proposed by Tsurutani et al. (2008)] and plasma fluxes from the plasmasphere (Danilov, 2013). In general, the electron concentration at heights of the layer maximum tends to be more sensitive to changes in neutral composition, thermospheric gas temperature and horizontal winds, whereas electrodynamics (i.e., penetrating electric fields and plasma fluxes from the plasmasphere) is

more important in higher altitudes (400–800 km) (Danilov, 2013). Moreover, the ionospheric storm time response often displays seasonal and solar cycle variations.

In parallel with scientific advances, the operational requirements guided the development of relevant ionospheric forecasting models that are now available for various applications, such as for example the Geomagnetically Correlated Autoregression Model (GCAM - Muhtarov et al. 2002), the STORM model (Araujo-Pradere et al., 2002) and the Solar Wind driven autoregression model for Ionospheric Forecast (SWIF - Tsagouri and Belehaki, 2006; 2008; Tsagouri et al., 2009; Tsagouri, 2011). GCAM and SWIF have been implemented in the European Digital Upper Atmosphere Server (DIAS) to provide ionospheric forecasting products and services over Europe (<http://dias.space.noa.gr>), while STORM has been implemented in Space Weather Prediction Center (SWPC) in NOAA to nowcast the ionospheric storm activity level and it has been incorporated to the standard International Reference Ionosphere (IRI) to provide storm time corrections to the IRI climatological estimates (e.g., Bilitza, 2001) for ionospheric studies. The formulations of GCAM and STORM models are driven by the temporal evolution of geomagnetic activity indices, while SWIF applies an alternative approach, being driven by solar wind disturbances detected by ACE spacecraft at L1 point. SWIF's predictions for the local time dependence of the ionospheric storm time response are in compliance with Prölss phenomenological model (e.g., Tsagouri and Belehaki, 2008).

Nevertheless, there are certain limitations in our prediction capabilities that have been identified today to indicate that our knowledge on the ionospheric response to space weather forcing is far from complete and still offer new challenges for ionospheric researchers. Among others, one may report shortcomings in the models' prediction efficiency for ionospheric disturbances driven by corotating interaction region/high speed stream (CIR/HSS) driven storms. For instance, Tsagouri and Belehaki (2015) have shown that while ionospheric disturbances related with the occurrence of CME-driven storms in the ascending phases of the present and the previous solar cycle were successfully predicted by the SWIF model, the non-CME related ones were mainly missed by the model's alert detection algorithm. Also, Buresova et al. (2014) in an investigation of the ionospheric disturbances under the low solar activity conditions in 2008-2009, pointed out that STORM model did not give reliable predictions for the peak electron density during CIR-generated storms. Wang et al. (2011) reported that the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) model (e.g., Wang et al., 2004; 2008) was not sufficiently able to reproduce F2 peak electron density variations observed during the CIR events that occurred during the Whole Heliosphere Interval in 2008 (Day of Year 50 - 140). In general, current phenomenological and/or theoretical descriptions make no clear distinction between CME and non-CME events, and models have no explicit parameterizations for the different cases, but the results in practice suggest that we may need more sophisticated approaches in order to predict effectively the ionospheric response in all cases.

Based on the above, one may argue that it is important to clarify the role of the interplanetary drivers of the disturbances in the development of the ionospheric response and particularly, the

relevance of CIR/HSS, whose effects appear not well predicted. It should be noted that CIR and/or HSSs are related to mild geomagnetic disturbances compared to intense CME-driven events, but they last longer and therefore, they are still able to produce significant ionospheric disturbances in global scale. Taking also into account that we move towards the declining phase of the ongoing solar cycle, when the impact of CIR/HSSs is more frequent and evident, this issue becomes also an urgent request for the provision of reliable forecasting services. Relevant research questions that request for substantial progress include among others, whether there is a “typical” ionospheric response to high speed stream induced disturbances and what are the key physical drivers that determine this response (Mannucci et al., 2012). More generally, it has been suggested that substantial improvements in our prediction ability will be driven by the better understanding of what factors control electron density variations during disturbed space weather conditions, including neutral atmosphere composition, temperature and dynamics, ion-neutral coupling, solar EUV, particle precipitation, plasma transport, and ion chemistry (Schrijver et al., 2015).

In this framework, this paper attempts a long-term investigation of the ionospheric disturbances through the development of the present solar cycle 24. The aim is to analyze the ionospheric behavior in a wide range of geophysical conditions in order to determine specific features that may differentiate the ionospheric response to different faces of space weather driving. The analysis aims mainly at the morphology of the disturbances, but specific aspects of their control mechanisms are also considered. In this respect, the ultimate goal of this work is to help the better understanding and the more efficient modeling and prediction of the ionospheric structure during disturbed conditions. Evidently, such an investigation is better facilitated today due to the expansion of the observed data collections and the increased availability, accessibility, and sharing of space- and ground-based data that are available through data e-infrastructures. This work takes substantial advantage from new capabilities available through the Near-Earth Space Data Infrastructure for e-Science (ESPAS - <http://www.espas-fp7.eu/>).

2. Data presentation and analysis

2.1 Features of the ionospheric disturbances

The ionospheric observations, i.e. the foF2 and hmF2 records that are analysed here, were retrieved from the Global Ionosphere Radio Observatory (GIRO - <http://giro.uml.edu/>) data repository (Reinisch and Galkin, 2010). Quality control of the selected GIRO data has been a significant undertaking, given that over 90% of the acquired data were the result of the ionogram autoscaling (Galkin *et al.*, 2008) by an intelligent system for automatic interpretation of the visual signatures in ionograms. Although previous studies of the autoscaling quality suggest their excellent overall compatibility with the manual scaling at selected ionosonde stations (Galkin *et al.*, 2011), the autoscaled values may still occasionally be dramatically wrong, thus contributing errors to our point-by-point comparisons of the individual measurements to the quiet-time reference. In order to carefully evaluate the relative contribution of autoscaling errors in the

results obtained here, the analysis below includes special considerations regarding the quality of the autoscaled data. More precisely, this work takes substantial advantage from the confidence score (CS) (Galkin *et al.*, 2013), an automatic quality metric that GIRO assigns to the observations. Moreover, to address the potential quality concerns without any loss of valuable information, the analysis was performed twice: first, all available data were used in order to exploit all of the information, while in the second analysis phase only data of acceptable confidence (i.e., data marked with $CS \geq 50$) were included in order to avoid potential data artifacts and then evaluate sensitivity of the analysis approach to the input data noise.

In this investigation, the ionospheric disturbances are determined through the comparison of actual observations of the foF2 critical frequency with monthly median estimate, which aim to describe the normal ionospheric variation [i.e., the global ionospheric structure, supported by a balance between solar production, chemical loss, and transport that remains approximately constant over periods less than about a month (Forbes et al. 2000)]. To determine reliably the median conditions, we considered here only the cases for which median values were obtained by actual observations received in more than 17 days within each month. The monthly medians were esimated for each hour/month/year and the disturbances are quantified by the following metric: $DfoF2 \% = [(foF2_{obs} - foF2_{median}) / foF2_{median}] * 100$ in hourly basis. The present analysis is carried out for the middle latitude European region with data obtained over the ionospheric locations listed in Table 1 during the ascending phase of the present solar cycle 24: from the solar minimum years 2008-2009 up to the solar maximum in the second half of 2014. The evolution of the solar activity with time is shown in Fig. 1 in terms of the smoothed monthly solar sunspot number provided by the WDC-Sunspot Index and Long-Term Solar Observations (SILSO) in Royal Observatory of Belgium and the smoothed 10.7 cm radio flux provided by SWPC in NOAA.

Table 1: List of the ionospheric stations used in the present analysis and their geographic coordinates.

Station name	Geographic longitude (°E)	Geographic latitude (°N)
Chilton	359.4	51.5
Dourbes	4.6	50.1
Juliusruh	13.4	54.6
Pruhonice	14.6	50.0
Ebre	0.5	40.8
Rome	12.5	41.9
San Vito	17.8	40.6
Athens	23.5	38.0

Figure 1: The smoothed monthly solar sunspot number and 10.7 cm radio flux estimates for the interval 2008 -2014.

As a first step, it is useful to obtain an overview of the ionospheric activity level in annual basis in order to follow its temporal evolution through the solar cycle development. To this effect, we use the following two proxies: i) the annual mean of $|DfoF2|$ as a rough indicator of the intensity of the disturbances, and ii) the relative occurrence of the disturbances within a year. More precisely, concerning the latter the following metric was estimated: $D = (N_Disturbed / N) * 100$, where $N_Disturbed$ is the number of the disturbed cases (i.e., $|DfoF2|$ greater than 20%) and N is the total number of observations within a year. D values were estimated for each year of the analysis and for all stations. The results are presented in Fig. 2. One may argue that this approach reflects only roughly the ionospheric activity and its temporal evolution but, on the other hand it provides a clear view of the general trends and facilitates long term comparisons with solar, geomagnetic and magnetospheric activity proxies as it is discussed later in this section. As one may see in Fig. 2, the ionospheric activity follows the development of the solar activity up to the secondary peak in 2012, but then it recedes, recording more significant variance in relative occurrence: around 10% for 2008 to 2009, 35% for 2009 to 2012 and 25% for 2012 to 2014. As a point of special interest, one may note also the relatively high degree of activity in 2008 that surpasses the level of activity in 2010. The trends are evident in both datasets that are analyzed here, i.e. all data and data marked with $CS \geq 50$.

A more comprehensive view of the ionospheric conditions over Europe is attempted in Fig. 3, which presents the distributions of the $DfoF2$ values, separately for each year of the analysis in a box plot format for comparison purposes. This includes a box and whisker plot for each case. The box has lines at the lower quartile, median and upper quartile values. Whiskers extend from each end of the box to the adjacent values in the data, in our case to the most extreme values

within 1.5 times the interquartile range from the ends of the box. Outliers (i.e., data with values beyond the ends of the whiskers) are displayed with black crosses.

Figure 2: The annual mean of $|DfoF2|$ and the relative occurrence of significant ionospheric disturbances within a year as two indicators of the ionospheric disturbance level for each year of the analysis. More explanation on the definition of D is provided in the text.

Figure 3: The annual distributions of the DfoF2 estimates obtained over European locations for each year of the considered time period in a box plot format obtained through the analysis of all available data (top panel) and through the analysis of data marked with $CS \geq 50$ (bottom panel).

The results verify that significant ionospheric disturbances (greater than 20% with respect to normal conditions) are recorded during all years, even in extremely low solar activity conditions. Moreover, they make evident that there is a qualitative difference in the ionospheric activity between solar minimum and solar maximum years: the intensity of the positive disturbances (i.e., increases in the ionospheric ionization) is higher during the years of late declining phase and solar minimum (i.e., 2008 - 2010) compared to ascending phase and solar maximum (2012-2014), while they dominate numerically over the negative disturbances (i.e., decreases in the ionospheric ionization). Indeed, positive deviations characterize 65% of the disturbed cases in

2008-2009 and about 50% of them in 2012-2014 in all cases. The predominance of the ionization increases in solar minimum is apparent in all levels of significant ionospheric activity as it is shown in Fig. 4, where the distributions of positive and negative DfoF2s are provided with respect to the level of the activity (for $|DfoF2| > 20\%$). Nevertheless, it is strongly evident for disturbances greater than 30% in intensity. For this level of activity, the negative deviations decrease significantly and practically vanish for activity level greater than 50%.

Figure 4: The distributions of negative and positive DfoF2s in three levels of activity: (1) $20\% \leq |DfoF2| < 30\%$, (2) $30\% \leq |DfoF2| < 50\%$, and (3) $|DfoF2| \geq 50\%$ for each year of the considered time period obtained through the analysis of all available data (a) and through the analysis of data marked with $CS \geq 50$ (b). The results for $|DfoF2| < 20\%$ are not shown for visualization purposes, but for this case positive and negative deviations are almost equally apparent in all years of the analysis.

Figure 5: The variation of the relative occurrence of positive deviations with respect to the total disturbances versus the local time sector for each year of the analysis when all available data (top panel) and data marked with $CS \geq 50$ (bottom panel) are analysed.

As the next step, in Fig. 5 we investigate the LT distribution of the ionization increases. To this effect, we calculated the ratio $N_{\text{positive}}/N_{\text{disturbed}}$ for each year of the analysis and all stations. The results presented in Fig. 5 are grouped for each local time sector: morning (from 00 to 06 LT), pre-noon (from 06 to 12 LT), afternoon (from 12 to 18 LT) and evening (from 18 to 00 LT). The evidence in Fig. 5 verifies once again the predominance of positive deviations in solar minimum years (2008-2009), since the relative occurrence of positive deviations ranges to values greater than 60% in all local time sectors. Moreover, the relative occurrence of positive

deviations in 2008 increases from the morning to the prenoon sector and peaks (up to about 80%) in the afternoon sector. A similar peak in afternoon sector is also seen in 2009 and 2010. In contrary, positive and negative deviations are almost equally observed in most cases in 2012, while a shallow minimum is recorded in the afternoon sector for the occurrence of positive disturbances. It may be important to note here that the observations are almost equivalently distributed in all local time sectors (24% - 26%) and therefore, any relevant bias in the results is excluded.

Figure 6: The annual distributions of the Dhmf2 estimates obtained over European locations for each year of the considered time period in a box plot format: through the analysis of all available data (top panel) and through the analysis of data marked with $CS \geq 50$ (bottom panel).

Very often, the increases in peak electron density, especially when occurring in the daytime hours, are attributed to the uplifting of the F2 layer. To investigate the strength of this cause-effect relationship in the observed disturbances, we present in Fig. 6 the distributions of the deviations of peak electron density height, hmF2 from normal conditions (DhmF2) for each year of the analysis, also in a box plot format. The DhmF2 is defined as $DhmF2 \% = [(hmF2_{obs} - hmF2_{median}) / hmF2_{median}] * 100$ and it is calculated also in hourly basis. Once again, only the cases for which median values were obtained by actual observations received in more than 17 days within each month were considered. The results show that the DhmF2 ranges approximately in the same levels of activity in all cases. In addition, height increases and decreases are almost equally divided in all cases. Indeed, positive deviations in hmF2 characterize about 49% of the observations in each year of the analysis. If we concentrate in cases characterized by a significant increase in the ionospheric ionization (i.e., $DfoF2 \geq 20\%$), the general trends for the contribution of the hmF2 in the observed disturbances are captured in the results presented in Table 2: the height increase is related with 51% of the ionization increases in 2008 and with 57% of them in 2012 when the ionospheric activity is highest. This correspondence tends to be lower in solar minimum conditions in all cases, but significantly lower in the afternoon sector, where the occurrence of ionization enhancements is higher. In both years, 2008 and 2012, the correspondence is higher in the daytime hours.

Table 2: The percentage of the ionospheric disturbances ($DfoF2$ greater than 20%) that are accompanied by an increase in hmF2 in each local time sector during low (2008) and high (2012) solar activity years. The values in the parenthesis represent the results in case the analysis include only the observations marked with $CS \geq 50$.

	All	Morning	Pre-noon	Afternoon	Evening
2008	51%(51%)	45% (45%)	55% (55%)	63% (63%)	46% (47%)
2012	57%(57%)	51% (50%)	58% (58%)	84% (85%)	48% (48%)

In summary, significant ionospheric disturbances (greater than 20%) with respect to normal conditions are recorded during all years, even in low solar activity conditions. The ionospheric activity follows the development of the solar cycle up to the secondary maximum of 2012, while depicts an anti-correlation afterwards (2013-2014). The disturbances are dominated by ionization increases in late declining phase and solar minimum conditions, in both occurrence and intensity, while ionization decreases are mainly of moderate intensity (see for example Fig.4). The predominance of positive deviations in late declining phase and solar minimum conditions is clear in all local time sectors, but it peaks in the afternoon hours. Further, the ionization increases are not always related with enhancements in the F2 layer height. This is more evident during solar minimum, when about 40% of the ionization increases in the dayside hemisphere (pre-noon

and afternoon sectors) and 55% in nightside hemisphere are not accompanied by an increase in hmF2. In 2012, when the ionospheric activity is maximum the percentages count to about 30% and 50%, respectively. All the above may support the argument that the ionospheric disturbances tend to have different characteristics in late declining phase/solar minimum and solar maximum conditions and that they may be controlled by different processes in each case.

2.2 Geomagnetic and magnetospheric conditions

In this section, we investigate the general trends in the prevailing geomagnetic conditions measured by several proxies of solar wind energy dissipation in the inner magnetosphere and the ionosphere for the same time interval. These include the geomagnetic activity index Dst, which provides a rough indicator of the solar wind energy stored in the ring current and a good indicator of geomagnetic storm activity, and the auroral activity indices AE, AU, AL to provide an indication of the solar wind energy input dissipated as Joule heating in the auroral ionosphere. Dst and AE indices are provided by the World Data Center for Geomagnetism, Kyoto (<http://wdc.kugi.kyoto-u.ac.jp>).

Figure 7: The distributions of the Dst records for the years of the analysis in box plot format.

In Fig. 7 and Fig. 8 we present the distributions of the Dst records for the years of the analysis in box plot format and the variation of the Dst annual mean and standard deviation (STD), respectively. Fig. 7 clearly shows that the intensity of the geomagnetic disturbances is weak to moderate ($-100 \text{ nT} < \text{Dst} \leq -30 \text{ nT}$) in low solar activity years (2008 - 2010) and increases to intense conditions ($\text{Dst} \leq -100 \text{ nT}$) towards solar maximum. Both Fig. 7 and Fig. 8 demonstrate

the minimum of geomagnetic activity in 2009 (see also Tsurutani et al., 2011) and the maximum in 2012 for the interval of the present analysis. Further, in Fig. 9 we present the variation in the number of storm events that occurred in each year of the analysis in total, but also with respect to their interplanetary drivers. We count only moderate ($-100 \text{ nT} < \text{Dst} \leq -50 \text{ nT}$) and intense ($\text{Dst} \leq -100 \text{ nT}$) storm events and we distinguish two simple cases: storms related to CME-associated solar wind flows (e.g., sheath fields or the ejecta itself) in the near-Earth solar wind and storms not related to such structures (non-CME storms). The latter may be associated to other sources of disturbances, e.g., CIRs and pure HSSs. The different cases were distinguished through the examination of the list of interplanetary coronal mass ejections (ICMEs) that is available at <http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm> (Richardson and Cane, 2010). As an important input for the discussion of the results one may note that while the storm activity during solar minimum (i.e., 2008 and 2009) is related entirely with non-CME events, the storm activity towards the solar maximum is mainly driven by CMEs.

Figure 8: The annual mean (top panel) and STD (bottom panel) of the Dst records with time. The mean Dst values are appeared in absolute values, but they all come with a negative sign.

The auroral activity is then investigated through the variation of the annual averages of the AE, AU and AL records, which are shown in Fig. 10

Energetic particle fluxes are then analysed as an indicator of the solar wind energy that is dissipated in the magnetosphere-ionosphere system via particle precipitation. The MEPED (Medium Energy Proton Electron Detector) instrument onboard the NOAA/POES (Polar Orbiting Environmental Satellites) satellites fleet provides one of the longest datasets of magnetospheric energetic particle measurements. It includes two particle detector telescopes to measure the particle fluxes in two nearly orthogonal directions - along and perpendicular to the local vertical direction: the local vertical telescope, the so called 0° -telescope that is pointed almost to the Zenith and the 90° -telescope that is oriented roughly in the north-south direction. This orientation of the telescopes means that at high latitudes where the magnetic field lines near the Earth are nearly radial the 0° telescope measures roughly field aligned precipitating (or "untrapped") particles and the 90° telescope measures roughly locally trapped (or "quasi - trapped") particles. At low latitudes, the situation is opposite. Within the Near Earth Space data infrastructure for e-science (ESPAS) project (<http://www.espas-fp7.eu/>), the Space Physics group of the University of Oulu has made available the 1/4 orbit averages of energetic proton and electron fluxes obtained from NOAA-06, NOAA-07, NOAA-08, NOAA-10, NOAA-12, NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-19, and METOP-02 satellites. The 1/4 orbit averages describe energetic particle fluxes only roughly, but are ideal for long-term studies of space environment. The ESPAS data collections include both MEPED uncorrected and corrected data. The latter has been corrected for the following instrumental problems: degradation of proton detectors due to radiation damage, proton contamination of electron measurements, and non-ideal electron detector response (Asikainen et al., 2012; Asikainen and Mursula, 2011; Asikainen and Mursula, 2013). In Fig. 11 we analyse the annual mean values of the corrected electron fluxes from channels E1 (>30 keV) estimated from NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-19, and METOP-02 records. Particle flux averages for each 1/4 orbit segment are taken from L-shell region $L>2$, indicating that the 0° telescope mainly measures field aligned precipitating particles, while the 90° telescope mainly measures locally trapped particles (majority of which are in the drift loss cone). Note, however, that since the 0° telescope measures only a small fraction of the total precipitation, this may actually follow the values of the 90° telescope better on long timescales.

Figure 9: The number of storm events with time counting moderate and intense storm events. Also presented is the number of storms that are related to CME-associated solar wind flows in the near-Earth solar wind and storms not related to such structures (non CME storms).

Figure 10: The annual averages of the AE, AU and AL records with time.

Synthesizing an overview, one may argue that the ionospheric variance shares the same general trends apparent in the geomagnetic activity, the Joule heating and the particle precipitation pattern: it is relatively enhanced in 2008, minimized in 2009, peaks up in 2012 and recedes afterwards. Concerning the geomagnetic activity, it is important to note that the ionospheric activity correlates better with the variability of the Dst index as it is expressed by the STDs

presented in the bottom panel of Fig. 8, and consequently with the geomagnetic storm activity as it is expressed by the results in Fig. 9. The latter, is totally related with the occurrence of CIRs/HSSs in 2008-2009 (solar minimum) and it is mainly driven by CME impacts in solar maximum, although the contribution of non-CME events is evident and rather comparable in all years (exception for 2009). Other interesting points result from the inspection of the ionospheric activity and particle precipitation patterns: in both cases the activity level in 2008 is comparatively higher than the ones in 2010, 2013 and 2014.

Figure 11: The mean electron fluxes measured by POES satellite fleet in data channel E1 (>30 keV) from 0° (on the left) and 90° (on the right) telescopes.

3. Discussion and conclusions

In this paper we studied the long-term behavior of the ionospheric disturbances, from the solar minimum between the solar cycles 23 and 24 up to the maximum of solar cycle 24. The analysis was based on actual observations of the foF2 and hmF2 ionospheric characteristics obtained in Europe, resulting mainly from the automatic scaling of vertical sounding ionograms. However, special attention was paid also on the quality of the data. To this effect, the results were tested under two scenarios, one considering all available data and one considering data of acceptable quality to evaluate and mitigate the impact of the autoscaling errors in the identified trends. Remarkably, even though comparisons of two scenario outcomes reveal certain effects of excluding the potential data artifacts, both results are in a very good overall agreement, confirming that acquired measurements reflect observed phenomena reliably regardless of the data noise.

The confirmed outcomes demonstrate that the ionospheric disturbances follow the general patterns of the solar, geomagnetic and magnetospheric activity, which in turn indicates that they mainly come as manifestations of the space weather effects on the Earth's ionosphere. Taking also into account that the ionospheric disturbances were examined here in hourly resolution, which in practice exclude effects more evident in smaller temporal scales (e.g., the direct solar flare effects on the ionosphere), but most importantly the agreement that was evident between the ionospheric activity and the geomagnetic storm activity / Joule heating / particle precipitation (in overall, but also in specific terms), we argue that the ionospheric disturbances under consideration here capture mainly the impact of geoeffective solar wind structures in compliance with well accepted scenarios (e.g. Prölss, 1995; Lastovicka, 2002; Wilson et al., 2006).

The evidence indicate significant ionospheric activity even in extremely low solar activity conditions, but reveal differences in the characteristics of the ionospheric response between solar maximum and late declining phase/solar minimum conditions. In particular, it is shown that during solar minimum, the solar wind impact on the geospace environment favors particularly the occurrence of ionization increases, both in frequency and intensity. Ionization depletions are still present, but they mainly appear in moderate intensity, in contrast to the situation in solar maximum. The increases are apparent in all local time sectors, while they clearly dominate in the afternoon hours and they are accompanied only partially by an increase in the F2 layer peak electron density height (hmF2). This is in confirmation with the results of Buresova et al. (2014), who reported also mainly positive disturbances in terms of the peak electron density during storm events that occurred in the low solar activity years 2008-2009, with no significant changes in hmF2 in several cases. In addition, Cander and Ciraolo (2010) reported significant ionization increases between noon and dusk over Europe during the low solar activity years 2006-2007.

According to the results presented here, the above features in the ionospheric response are part of a more general solar cycle pattern: ionization increases are more intense in 2008, while they are gradually attenuated towards the solar maximum phase 2012 - 2014 (see for example Fig.4). Based on this, one may argue that they may be attributed to the solar cycle effect on the background conditions. For instance, it is known that the afternoon ionization enhancements observed during storm conditions, when portrayed as a percentage change, are inversely related to solar flux, simply because of the monthly median control curves having smaller magnitudes (Mendillo, 2006). Although this is an interesting point to be considered, one has to keep in mind that: i) there are significant differences in the occurrence rates of the ionization increases between different levels of solar activity, ii) their local time distribution in 2008 and in 2012-2014 tend to be anti-correlated, especially in the afternoon sector (see Fig. 5), when the ionospheric response tends to be characterized by opposite signs, and iii) there is no identified solar cycle effect in the distributions of Dhmf2: the positive and negative deviations in hmF2 characterize the 49% and 48% of the cases, respectively in all year of the analysis, while the general trends in their local time dependence appear to be the same (see Table 2). In this respect,

the net solar cycle effect may be not be sufficient enough to explain the observed features in the ionospheric response, which seems to be more complicated.

Another interesting point is that the geomagnetic response during high solar activity is mainly driven by CMEs, but CIR/HSSs are the dominant driver of the geomagnetic disturbances during low solar activity conditions in 2008-2009. In this respect, our findings may be considered as evidence of the ionospheric response to different solar wind drivers. In particular, taking advantage from the fact that the CIR/HSSs are the exclusive drivers of the activity in solar minimum, it is suggested that positive disturbances with strong afternoon component tend to be the main feature of the ionospheric response to their impact in ionospheric middle latitudes. Although the analysis of case studies is out of the scope of this paper, we present in Fig. 12 ionospheric observations from Dourbes for the time interval 26 - 30 March 2012 that is not related to ICME activity (<http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm>). The Dst index for this interval dropped below -50 nT indicating geomagnetic activity of moderate intensity. The ionospheric response starts with considerable positive effects on the main storm day on March 27 that turned to negative of moderate intensity on March 28 before it recovers. This picture is an interesting contrast to CME driven events: according to the results obtained by Tsagouri and Belehaki (2008) through superposed epoch analysis of the ionospheric response to a number of storm events that were occurred in solar cycle 23 and were driven mainly by CMEs, only ionization depletions are anticipated for latitudes greater than 45 °N regardless of the local time of the observation point at storm onset. To further explore this, we present in Fig. 13 the ionospheric response to the geomagnetic disturbances of moderate intensity recorded a few days earlier on 14-18 March 2012 (min Dst - 75nT). According to the list of ICMEs (<http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm>) this event is related with CME impact and the results verify that the ionospheric response is formulated by strong negative disturbances in all storm days. It may also be important to stress out that that the two storm examples presented above come with the same level of intensity and occur in the same year/month and therefore, under the same background conditions.

The results of this work are in agreement with the results of Buresova et al. (2014) obtained under the occurrence of CIR-generated storms as reported above. Also Burns et al. (2012) found positive effects of geomagnetic storms in the peak electron density of the ionospheric F2 layer in the day of storm during CIR/HSSs driven events. The close relationship between the positive ionospheric storms and recurrent geomagnetic activity is revealed by Dimitriev et al. (2013) and Verkhoglyadova et al. (2011; 2013). In addition, Belehaki and Tsagouri (2002) in an investigation of the ionospheric storm time response to five storm events that occurred in September and October 2000 observed nighttime ionization enhancements in peak electron density during weak to moderate geomagnetic activity. In particular, according to their findings the weaker the intensity of the storm is, according to the Dst index, the more likely it is that one will observe nighttime ionization enhancements in subauroral latitudes as well. Keeping in mind that intense storm events are usually driven by CME-associated solar wind flows (e.g.,

Richardson and Cane 2012; Zhang et al. 2007; Echer et al., 2008) and weak to moderate storms tend to be associated with CIRs and pure HSSs (e.g. Echer et al., 2013), the above result supports the argument that ionization increases are more likely to occur during coronal hole associated disturbances.

Figure 12: The Dst records and ionospheric observations ($foF2$, $DfoF2$ and $hmF2$, $DhmF2$) from Dourbes for the time interval 26 - 30 March 2012. Solid and dashed lines represent actual observations and monthly medians, respectively.

Figure 13: Same as Fig. 12 for the time interval 14 - 18 March 2012.

Typically, the increases in peak electron density, especially in daytime hours, may be attributed to the uplifting of the F2 layer caused by a vertical drift, since the upward displacement of the layer brings the ionization to areas where the ionization production rate dominates over loss rate. The F2-layer drift may be caused by two principal mechanisms: penetration of electric fields of magnetospheric origin and equatorward horizontal thermospheric circulation which lifts up the F2-layer plasma along the inclined geomagnetic field lines. The effect of neutral winds is more important in middle latitudes and F2 layer heights (Prölss, 1995; Danilov, 2013). Our results verify that height increases accompany the majority of the density increases in the dayside hemisphere (pre-noon and afternoon) and half of them in the nightside hemisphere in all cases. However, the evidence presented here indicate also that this cause-effect relationship attenuates during solar minimum. It is worthy to note that almost 85% of the ionization increases detected in the afternoon sector in 2012 are related with F2 layer uplifting, while in 2008 the corresponding percentage is decreased to 63%. In addition, in the example presented in Fig. 12, no considerable increase in hmF2 is observed over Dourbes.

All the above support the argument that both the characteristics of the ionospheric response and the relative contribution of the background mechanisms may differ between CME and non-CME driven disturbances. This may be expected, since recent results clearly demonstrate differences in the total energy deposition into the auroral atmosphere during CME and CIR/HSSs events (e.g., Kozyra et al. 2006; Turner et al. 2009; Verkhoglyadova et al. 2011) and the way this energy is distributed (e.g. Emery et al. 2009). This argument may be supported also by the enhanced energetic particle fluxes that were also evident here during late declining phase conditions following the HSSs/CIRs related activity. As another interesting point, one may also note the agreement in the relative response of the ionospheric activity (see Fig. 2) and the energetic particle fluxes (see Fig. 11) between low and high solar activity years: both have relatively high values in the late declining phase, while they recede below these values in 2013-2014. This is slightly different than the response of the ring current (i.e., Dst index) and the auroral (i.e., AE indices) activity, which although they partially recede in 2013 - 2014, they are still higher than in the late declining phase. This is rather expected since CME-driven (non-CME driven) events that dominate in solar maximum (minimum) years have a greater (less) influence over the ring current (e.g., Borovsky and Denton, 2006) and less (greater) in the auroral electron input (e.g., Emery et al. 2009). In that respect, one may speculate that particle precipitation may hold a crucial role in the development of the ionospheric response during CIR/HSSs driven disturbances as an energy source. For instance, one may keep in mind that although the resulting heating may create large-scale changes to the thermosphere composition, density and circulation (winds) in any case (e.g., Prölss, 2011; Mannucci et al. 2015), the rate of the energy deposition may differ between CME and non-CME cases. It has been reported that the main phase of CME driven events is characterized by intense but short-lived particle precipitation excursions, while the non-CME cases are characterized by prolonged periods of particle precipitation (Longden et al. 2008), which in turn may result in a gradual development of the disturbances in the latter case. On the other hand, gradually evolving storms may be characterized by the restricted development

of the neutral composition disturbance zone to higher latitudes. In this case, the extent of its equatorward boundary would depend on the intensity of the storm, giving advantage in plasmaspheric fluxes that dominate at middle to low latitudes as proposed by Belehaki and Tsagouri (2002). The interaction with the plasmasphere is able to explain also the enhancement of the ionization in the afternoon sector, as part of the so-called "dusk effect" (Mendillo, 2006).

4.Acknowledgements

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