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Summer tropospheric mesoscale situations with impact on the ionospheric plasma

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1. Abstract.

Coupling between distant regions of the atmosphere has been widely confirmed by theoretical and experimental studies. The tropospheric influence on the upper atmospheric ionosperic plasma is the primary focus of this report. As the troposphere warms, the absolute humidity and wind shear increase over the whole of Europe. This increase suggests that convective environments contributing to formation of summer thunderstorms will become more frequent.

Here we analyze and discuss the possible effects of cold fronts and thunderstorms and their influence on the upper atmosphere up to the ionospheric plasma. The state of the ionosphere is monitored by means of digisonde DPS 4D and continuous monitoring by Doppler sounder CDS. In coincidence with severe meteorological situations we have identified a variety of spread F echo on the ionograms and particular types of CDS spectrograms.

Keywords: Tropospheric weather systems; atmospheric gravity waves; ionospheric plasma irregularity

2. Introduction

The troposphere-ionosphere coupling is a hot topic. The atmosphere supports the propagation of a wide range of waves. Within the troposphere there are permanent sources of waves mostly tied to the orography [Hoffmann et al., 2013]. Other wave sources are more spread around the globe, locally less intense than orographic, however the integrated contribution of non-orographic waves can be comparable to that of orographic waves [Fritts and Alexander, 2003; Hertzog et al., 2008]. Their dissipation may act as a source of secondary waves with impacts in the thermosphere [Oyama and Watkins, 2012; Vadas and Azeem, 2021]. A large scientific community is convinced that the meteorologically induced effects should be taken into account in the energy balance of the ionosphere.

In our several previous case studies we have analyzed particular cases of synoptic-scale atmospheric fronts with significant pronounced effects on the ionosphere as detected by the ionosond [Boška and Šauli, 2001; Šauli and Boška, 2001]. As we have shown in some studies [Koucká Knížová et al., 2020; Koucká Knížová et al., 2023], significant disturbances in the ionosphere can also be related to tropospheric distortions of sub-synoptic scales and enhanced by local orographic features. Recently, we have been focusing on the summer tropospheric situations as manifested by tropospheric thunderstorms. Preliminary results (presented at international workshops and conferences) show more frequent occurrence of severe weather systems and consequent effects on ionospheric plasma. These results are in agreement with climatological studies [Rädler et al., 2019; Kolendowitz et al., 2017; Taszarek et al., 2019] highlighting high occurrence of severe tropospheric events. Temperature and moisture of mid-tropospheric summer days have increased in the last decade. Furthermore, according to the EURO-CORDEX climate model projections at 0.44° resolution, the probability of severe weather events will increase significantly across Europe. For example, under the most aggressive RCP8.5 climatic scenario, the occurrence of large hail (greater than or equal to 2 cm in diameter) is projected to become 40-80% more likely across central and eastern Europe by the end of the century [Rädler et al., 2019]. This is due to anthropogenic climate change, which is associated with a variety of changes in the troposphere. As the planet warms, absolute humidity and vertical wind shear increase in the troposphere over all Europe [Brooks, 2013]. In addition, there is increasing evidence that the polar jet stream has become more meandering as a result of Arctic amplification [Rädler et al., 2019]. Faster warming of the Arctic region compared to the mid-latitudes leads to a smaller temperature difference between northern and southern Europe, and thus to both a decrease in the speed of the zonal flow in the upper troposphere and a more pronounced meandering of the polar front.

This paper describes two typical tropospheric situations of the summer season. One of them is a late summer rapid transition of an extratropical frontal cyclone over Europe in the mid-latitudes. The other is the case of a summer storm within a tropical air mass extending over central Europe. In both cases, we analyze the pressure pattern structures and the associated flow at different heights in the troposphere. We also discuss the ionospheric disturbances associated with both events as they are seen on ionograms and Doppler spectrograms.

3. Troposphere

3.1. Frontal thunderstorms associated with a fast-moving extratropical cyclone Fabienne

The synoptic conditions, ground-level observations of the transition of a significant cold front associated with extratropical cyclone Fabienne, are described in detail in the paper [Koucká Knížová et al., 2020], so we report them briefly. The Fabienne case is used to compare the two different situations and to complete the view. In general, frontal extratropical cyclones typically occur in autumn and winter, and their movement from west to east is driven by a polar front that separates the colder polar air in the north from the tropical air in the south. (At the same time, there is a jet stream at the upper boundary of the troposphere.) The greater the horizontal temperature gradient, the more severe the extratropical cyclone is, which initially originates as a wave disturbance on the polar front. Moreover, the Central European region is characterized by a transition between the maritime Atlantic air and the continental Asian climate. The difference in temperature and moisture from the Atlantic gives energy and speed of motion to extratropical cyclones and associated fronts in the low and mid-troposphere. Cold fronts are often associated with thunderstorms (even in the cold season of the year, but not discussed here). Figure 1A plots the pseudoequivalent temperature (θ_{ep}) in the lower troposphere, at 850 hPa, which corresponds to a height of about 1.5 km above the surface. The θ_{ep} field is used by meteorologists to identify atmospheric fronts. It contains information about both the temperature and the humidity of the atmosphere. It is the theoretical temperature of the air mass, which we calculate by extracting both the water and water vapor in that air mass by condensation and precipitation and then increasing its temperature by the latent heat of condensation released. In Figure 1A, there are clearly visible narrow transformation zones with a strong gradient in θ_{ep} that separate the polar air mass from the tropical air mass. Physically, these are regions of a narrow boundary where the troposphere tries to quickly return to the equilibrium temperature homogeneous state and consequently the generation of waves that potentially propagate up to ionospheric heights.

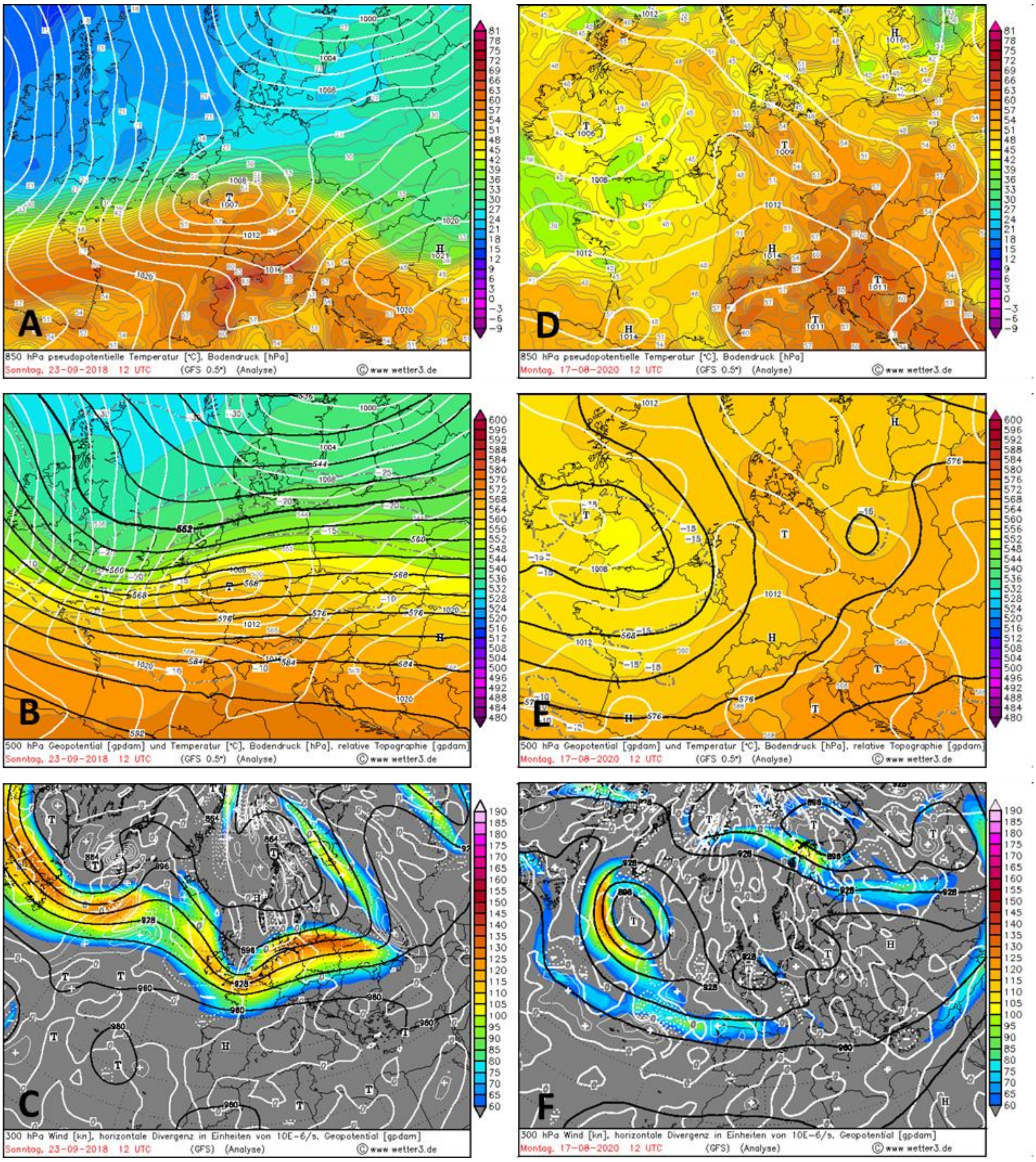

Figure 1. *The panels in the left column refer to the fast moving frontal cyclone Fabienne, passing the IAP observatory on 23 September 2018, and the panels in the right column refer to the air-mass thunderstorm on 17 August 2020. The analyses are valid for 12 UTC. Panels (A, D) show the pseudo-equivalent potential temperature at the 850 hPa pressure level (color scale) and the sea level pressure (white contours). Panels (B, E) show the geopotential height of the 500 hPa level (black contours, decameter), the sea level pressure (white contours), and the relative topography between 500 and 1,000 hPa (color scale)—this represents the vertical distance between the 1,000 hPa (surface) and 500 hPa (middle troposphere, about 5.5 km) levels and varies with temperature and moisture (it is a function of the mean virtual temperature). Thus, the color scale regions are directly related to the mean temperature and*

moisture of the middle troposphere (orange/red values indicate tropical air mass, and yellow/green indicate polar air mass). Panels (C, F) show geopotential height at the 300 hPa (black contours, decameter), wind speed (color scale) and horizontal divergence/convergence (white contours with "+"/"-").

All images are displayed from the GFS analysis. Archived from: https://www.wetter3.de/archiv_gfs_dt.html.

Figure 1B shows both the surface pressure field (white lines, T marks the center of cyclone Fabienne) and the pressure and temperature field in the mid-troposphere at about 5.5 km altitude (black lines and colored field). Figure 1B shows that low-level pressure pattern, including the Fabienne cyclone, moves very fast, as the 500 hPa height isolines are very close together. The atmosphere at 5.5 km is no longer under frictional influence from the surface, which is why the 500 hPa field is called the steering flow field in synoptic meteorology and is used to predict the speed and direction of movement of surface pressure patterns. The color field of the relative topography, indicating the thickness of the layer between the 1000 hPa and 500 hPa pressure levels, shows a strong gradient between the relatively thin and therefore cooler troposphere in the north and the vertically thicker and therefore warmer troposphere in the south.

Figure 1C shows the pressure field near the top of the troposphere at 300 hPa. The jet stream axis (maximum flow velocity indicated by the color scale) follows the polar front between the polar air mass and the tropical air masses. In the areas marked with a "+" sign, there is an horizontal divergence of the flow, which favors the formation of convective clouds and thunderstorms.

3.2. Air-mass thunderstorm 17 August. 2020

The second type of the meteorological situation associated with extreme weather events that we focus on is a thunderstorm within a homogeneous air mass. These events are accompanied by large hail, torrential rain, strong wind gusts, etc. They often occur in summer in very unstable warm and humid air masses of tropical origin, usually on the weak horizontal pressure gradient in the lower troposphere.

Figure 1D shows a pressure field near the ground at 2 m height (white lines) with a weak pressure trough extending from the Atlantic to central Europe (1010 hPa isobar) and a weak ridge from the Black Sea towards southern Scandinavia (1012 hPa isobar). Hot and humid tropical air was blown into the area between the trough and the ridge from the south. This is reflected in θ_{ep} values in the lower troposphere at about 1.5 km altitude, which reach up to 60°C. In the Czech Republic, values above 60°C at 850 hPa are very rare, occurring at most a few days per year.

Figure 1E shows that, in the mid-troposphere, central Europe is under the influence of a moderate flow from the southwest along a trough of low pressure, associated with the small upper-level cyclone that has formed over the Czech Republic and is slowly advancing towards northern Poland. The center of the upper-level cyclone, enclosing an area of local cold air minimum temperatures of -15°C, is over southern Poland at 12 UTC. The air below an upper-level cyclone is potentially unstable due to the rapid decrease in temperature with height, which supports convective motion and provides suitable conditions for the formation of cumulus clouds. It usually forms and breaks up within a few hours but can bring more persistent precipitation if it remains over an area for a longer period. However, unlike precipitation associated with atmospheric fronts, the intensity and duration of precipitation caused by an upper-level cyclone is generally difficult to predict.

The pressure field map near the upper tropospheric boundary also shows that Central Europe is under the influence of both the low pressure trough and the horizontal flow divergence, as is shown inFigure 1F. This means that convection occurs throughout the entire depth of the troposphere.

4. Ionosphere

4.1. Fabienne case

The case of Fabienne was in detail analyzed and discussed in paper Koucká Knížová et al. (2020). Here we only briefly summarize the observed effects.

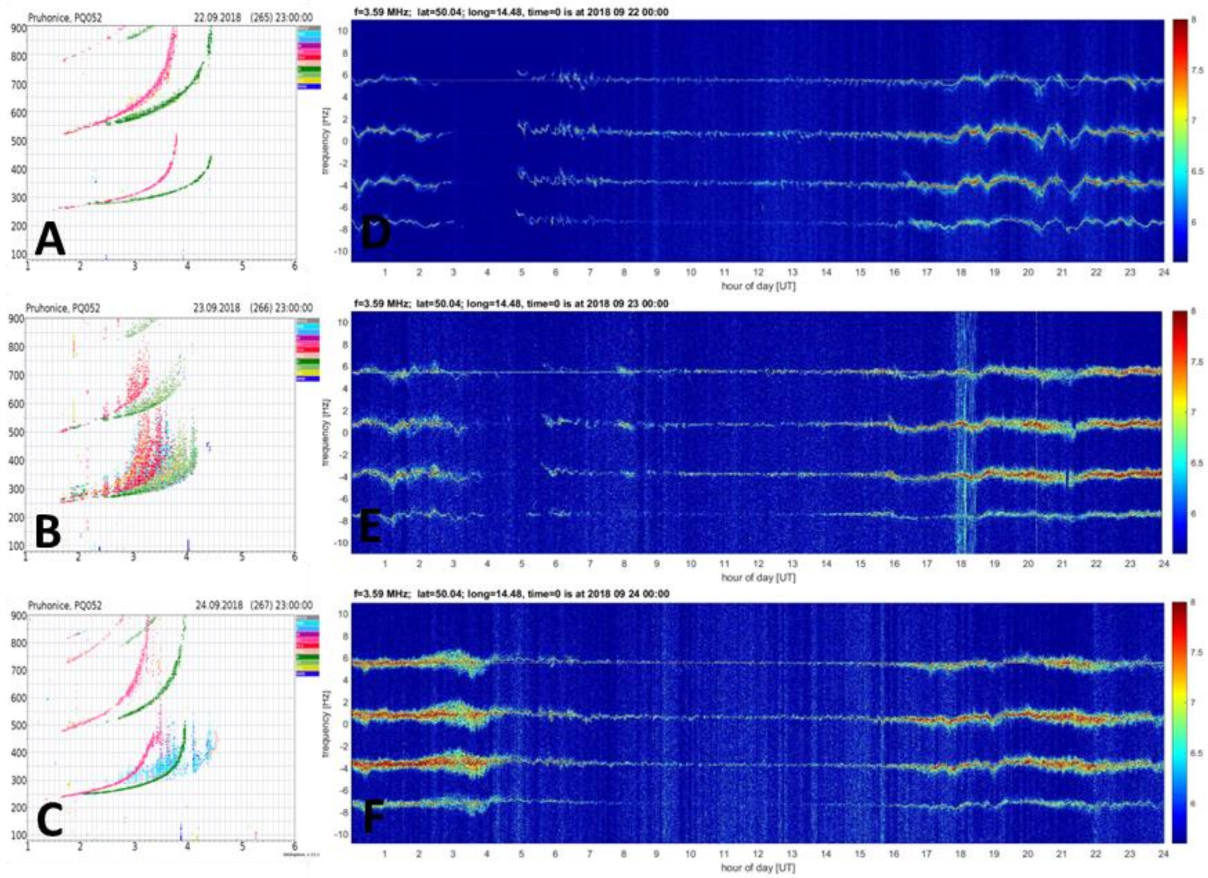

Figure 2. *Panels in the left column show the ionograms recorded by DPS 4D in Průhonice. Red color and green color denote ordinary and extraordinary reflection traces. Other colors denote off-vertical echoes registered by the antenna field. In particular, blue represents the north north-east direction of signal arrival.*

Panels in the right column show Continuous Doppler Sounder spectra measured during three consequent days. The quality of the spectra (width, oscillation of the central frequency) is changing.

Figures 2A,B,C show the sequence of ionograms recorded during three consecutive days around 23:00 UT at the Průhonice Ionospheric Observatory. Figure 2A shows a typical night time ionogram, recorded on 22 September, with a clear reflection trace of the ordinary and extraordinary electromagnetic waves. On the ionogram, one can observe typical quiet time reflection from the F2 region. No irregularities are apparent on the electron density profile. An important feature to point out is the presence of strong Spread F echo on ionograms on 23 September (Figure 2B) and slightly the following day of 24 September (Figure 2C). On both (middle and bottom) ionograms there are strong off-vertical echoes present. The ionogram on panel 2B is recorded on 23 September shortly after the passage of a cold front with strong storm activity. Spread F echo on ionograms is observed when the sounding frequency does not reflect on a horizontal plane, but it meets an undulated plane that causes reflected waves to scatter. Such a situation, departure from horizontal stratification, may be caused by presence of wave-like activity (propagating TIDs excited by geomagnetic activity, atmospheric waves from lower lying regions). In this particular case, the geomagnetic activity is rather low to moderate, hence we assume to attribute the effects to the propagating frontal system that effectively launches the atmospheric gravity waves (see details in the paper Koucká Knížová et al, 2020).

Figure 2D,E,F shows Continuous Doppler Sounder spectra for the consecutive days 22-24 September recorded for sounding frequency 3.59 MHz. Here on the plots, there are important features to comment on. The clear narrow echo is observed during the day with oscillations in the gravity wave band on Figure 2D. On the day of the Fabienne event on Figure 2E, there is a wide frequency noise, likely caused by the lightning in the vicinity of the receiver. With a delay of about two hours, we observe a spread spectrum that lasts till the following day on Figure 2F.

4.2. Air-mass thunderstorm case

Figures 3A, B, C show the sequence of ionograms recorded during three consecutive days around 23:00 UT recorded at the Průhonice Ionospheric Observatory by DPS 4D.

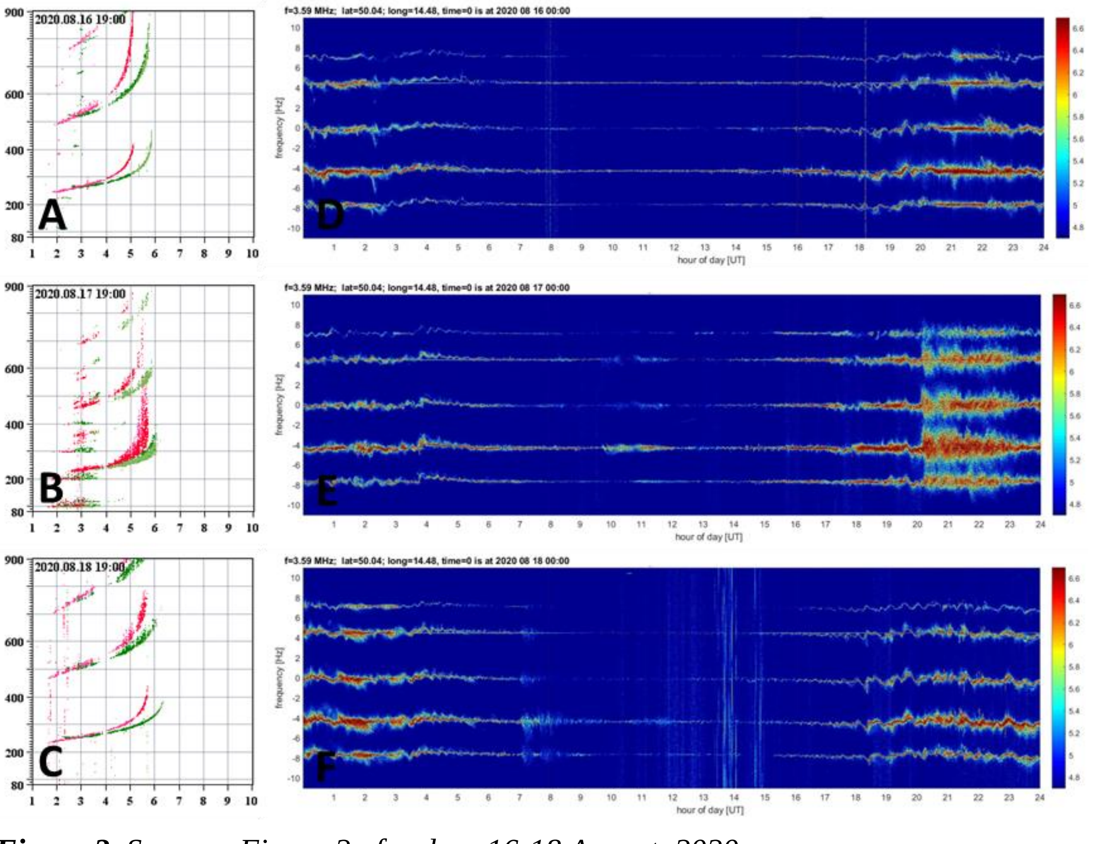

Figure 3. *Same as Figure 2., for days 16-18 August, 2020.*

Figure 3A shows the typical ionogram monitored before the event. The clear echoes of ordinary and extraordinary traces indicate a quiet regular ionosphere that is normally stratified. Hence the reflection happens on the horizontal planes. Figure 3B shows a rather strong spread F echo. Besides that, a strong Sporadic E layer is present. Also the Es echo shows the spread of the reflected signal. Figure 3C shows that the ionosphere at the F layer returns to a regular stratification and the traces are no longer spreaded. Figure 3C,D,E show CDS spectra for the three consecutive days. On 16 August (Figure 3A) clear or slightly spread spectra can be observed during night hours till the morning of the following day on Figure 3D. During the night hours, first a slight spread spectrum is observed till about 20 UT, after that exceptional strong spread appears on the signal. Following day, slight spread of the signal can be observed during the entire day (Figure 3E). As in the previous case, we suppose that spread F echo during the Air-mass thunderstorm event can be attributed to the atmospheric gravity waves of a tropospheric origin.

It is well known that geomagnetic disturbances strongly influence the ionosphere. The geomagnetic disturbances are due to two major solar activity drivers: coronal mass ejections (CMEs – clouds of solar coronal plasma with embedded magnetic fields ejected from the corona when enough energy has been stored there), and high speed solar wind streams (HSSs – emanating from unipolar solar magnetic regions, propagating and accelerating along the open magnetic field lines from the Sun far into the heliosphere). Both affect the ionosphere through electric fields, enhanced particle precipitation, Joule heating, ion drag, and composition changes (see e.g. Ren et al., 2020; Fagundes et al., 2023 among others). Two indices are mostly used to evaluate the level of geomagnetic disturbances: Dst which is more sensitive to CMEs, and Kp in which the effects of HSSs are more obvious. Figure 4 presents them for the two studied events. Fabien cyclone, September 23, 2018 (left panel) occurred after a minor disturbance characterized as "quiet to mild" according to Dst index which did not exceed -40 nT (geomagnetic disturbances are related to negative values of Dst) and "minor" according to Kp which did not exceed 5. During the passage of Fabien and the observed ionospheric effects on 23 and 24 September, the geomagnetic activity according to both indices had returned to "quiet". The air mass thunderstorm event on August 17, 2020 occurred during a prolonged period of very low geomagnetic activity. Before and during the thunderstorm Dst index was positive and Kp index was below 2, and after the event Dst did not reach -20 nT while Kp remained about 3, which, according to both indices, is defined as "quiet". Therefore, we can expect that the effects observed in the ionosphere in these particular cases are not related to geomagnetic activity but are mainly due to tropospheric processes.

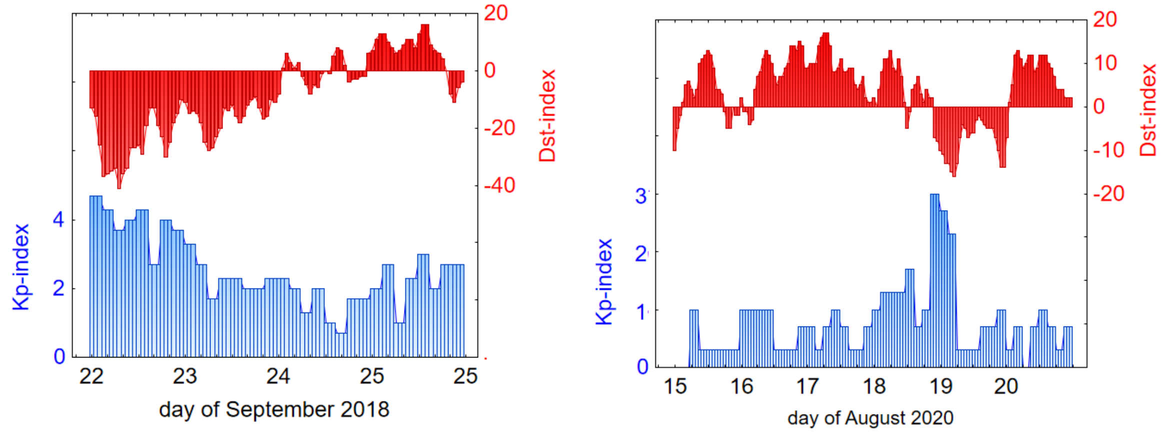

Figure 4. *Behavior of Kp-index (blue, left-sided scale) and Dst-index (red, right-sided scale) for the period 22-25 September 2018 (left panel) and 15-20 August 2020 (right panel).*

5. Conclusion

Our results highlight the importance of studying the meteorological influence on the upper atmosphere, in particular the ionosphere. Under favorable conditions (when the waves reach ionospheric heights in the form of primary and/or secondary waves), both described tropospheric situations can induce significant detectable changes up to ionospheric heights. At the same time, the response is not the same for both situations, but suggests some differences.

We observe long duration spread F echoes on ionograms during both discussed cases. As has been pointed out many times, the spread F echo indicates undulations of the reflection planes. These are very likely caused by the atmospheric waves propagating up to the ionosphere. This spread F on the ionograms measured in association with the frontal cyclone passage appears to be stronger, showing both range and frequency spread.

On the Continuous Doppler Sounding spectra we observe the increase of the spread of the Doppler shift in both analyzed cases. The observed frequency shift spread of the CDS spectra is larger in case of Air-mass thunderstorms. In case of the Fabienne storm we observe the echo from the F layer while in the air-mass thunderstorms event the echo of Doppler shift may come from the Sporadic E layer. However, in both cases we observe wave-like activity in the ionosphere.

Rather low geomagnetic activity allows us, as we suppose, to attribute the observed disturbance to the atmospheric gravity waves launched by the fast moving cyclone border Fabienne across Europe and to the air-mass thunderstorms.

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