

1 The authors would like to thank the editor and both anonymous reviewers for their valuable  
2 suggestions and comments that helped us to significantly improve the manuscript. All the  
3 changes are marked by yellow color in the text.

4 Sincerely,

5 Petra Koucka Knizova (on behalf of all the authors)

7 Answer to Reviewer 1 comments:

9 1. In the opinion of the reviewer, the absence of the analysis of these works in the introduction  
10 somewhat reduces the completeness of the approach used by the authors. Some of the methods  
11 used in the analysis of the ionospheric response to powerful tropical cyclones, and conclusions  
12 obtained from an analysis of the influence of tropical cyclones on the overlying layers, could be  
13 useful for this study. Perhaps the authors here are simply limited in size of manuscript.

14 *We agree with the reviewer comment that interesting results have been found based on the*  
15 *GPS-GLONASS monitoring. Very relevant papers have been published by Afraimovich et al.*  
16 *(2013), Ke et al. (2019), Yang and Liu (2016) and others dealing with tropical meteorological*  
17 *phenomena. Most of the papers address low latitude events, but we agree with the reviewer that*  
18 *these papers definitely have to be quoted in the review part of the paper. – Paragraf added on*  
19 *pg. 4*

21 GPS satellite measurements are promising tools for monitoring ionospheric changes  
22 connected with severe weather systems. Recently the analyses of scintillation S<sub>4</sub> index in  
23 relation to four tropical cyclones (Yasi in 2011, Marcia in 2015, Debbie in 2017 and Marcus in  
24 2018) were presented by Ke et al. (2019). They found intensification of scintillation effects  
25 mostly above the tropical cyclone path and attributed them to the electric field perturbation and  
26 consequent plasma bubble generation. Within COSMIC GPS data, Yang and Liu (2016) has  
27 found significant peak in radio occultation scintillation events during the passage of tropical  
28 cyclone Tembin (2012) during quiet geomagnetic or solar activity and attributed the observed  
29 effect to the gravity waves generated in the lower atmosphere by the cyclone. Afraimovich et  
30 al. (2013) published large review of GPS/GLONASS studies of the ionospheric response to  
31 natural and anthropogenic processes and phenomena. Paper focuses on wide range of ionospheric  
32 forcing and corresponding ionospheric variability detected in principle within Total Electron  
33 Content (TEC) and F<sub>2</sub> layer critical frequency foF<sub>2</sub>. In relation to tropical cyclones (Katrina,  
34 Rita and Wilma) occurring in 2005 they reported increase of wave-like activity in gravity-wave  
35 period range mainly in the range 20 to 60 minutes and intensification of TEC variations along  
36 the satellite path close cyclone. The zones of disturbances were found to form during hurricane  
37 stage of the cyclone (Afraimovich et al., 2013).

39 2. Illustrations are difficult to read.

41 Figures 6 and 7 according to the reanalysis of MERRA: it is not clear in what order they need  
42 to be analyzed (in rows or columns?), as the dates are difficult to distinguish even at high  
43 magnification, and in the captions of the figures and in the text itself there is no necessary  
44 explanation. In printed version this will be at all unreadable

45 *In the revised version of the paper we provide better explanation of the MERRA reanalyses*  
46 *results and improve results graphic representation (Figures 6 and 7) of the situation that*  
47 *capture time development of the situation before and after the storm passage over Europe.*

Figure 6a shows zonal wind at 1 hPa for Europe region from 20 September at 00 UT to 27 September at 18 UT. On the sequence there is well seen weak eastward wind in middle Europe and westward wind in south Europe which is typical situation for this period. Shortly before storm Fabienne (23 Sep 00 and 6 UT) easterly wind became stronger and replace westerly wind in the south (because of incoming waves from troposphere) and remain easterly for the following several days in whole studied area. At 0.1 hPa we can see changes from westerly to easterly wind shortly after Fabienne (24.9. 00 and 06 UT). We do not register any significant changes before because wave from the troposphere need some time to reach 0.1 hPa. Strong easterly wind remains in whole Europe again for several days after storm. The stratosphere needs some time for changing/restoration dynamics to normal situation because of wave disturbances which remains in inversion condition (temperature increase with altitude) much longer than in other layers. That is why we can observe strong eastward wind not only during the storm but for several days after storm in whole Europe as well.

Figure 8: I recommend in the caption to make an explanation of which direction of signal arrival corresponds to the color of the track on the ionogram. These inscriptions are not readable in the figures.

*Caption extended*

Particular color indicates direction of radio wave arrival. Vertical echo of ordinary wave is marked by red color, while green color stands extraordinary wave. Other colors represent non-vertical reflections. The strongest non-vertical echo comes from North-North-East direction (light blue color).

Figure 9: I recommend to give explanations about what is displayed on the directograms, what physical quantity is represented.

*Caption extended*

Directogram – direction of plasma motion above the observation site - recorded on 21–26 September presented in a standard DPS 4D format. Due to geometry of receiving antenna field, DPS 4D identifies direction of the wave arrival. The directograms are constructed from the raw ionograms. Each color correspond to particular antenna beam, hence the direction of the arrival of oblique echo from large scale irregularities. It is denoted by particular color on the left and right side of the diagram.

Figure10: Perhaps here you should give the Kp or Ap index, otherwise the explanations of the level of geomagnetic activity in the text do not look convincing.

*Kp added into Figure 10*

Figure13: There is no power scale. It is not clear where values are greater, where are less.

*Caption extended*

Wavelet Power Spectra of critical frequency foF2 for 21–27 September, 2018. WPS is normalized on each scale to corresponding scale maximum. Dark WPS areas exceed 0.95 significance level on each scale.

Figure 14: The plots indicate the day of the year, it is necessary, at least, in the caption to indicate the date. – Figure 14. The plots show the numbers of days of the year. It is necessary, at least, in the figure caption to specify dates.

*Caption extended*

Components of ionospheric plasma drift obtained by Digisonde DPS 4D during the studied event 20 September (top panel) – 27 September (bottom panel) – (a) vertical component; (b) North component; (c) East component presented in a standard DPS 4D format.

To improve perception, in all the figures it is desirable to indicate the moments of the front passage at the observation point.

*We have improved quality and caption of all the figures.*

Also there are a few comments to the references execution:

1. For the paper (Durand et al., 2004) (line 16 on page 5 and line 26 on page 9), the date of publication of the paper in the list of references is written 1989 (line 7-10 on page 17).

*Corrected*

2. Similarly, for the paper (Roux et al., 2012) (line 4 on page 3), the date of publication of the paper in the list of references is written 2002 (lines 36-38 on page 19).

*Corrected*

3. In the text there are links to articles (Hook, 1971a) and (Hook, 1971b) (lines 18, 22 on page 3). However, in the list of references letters "a" and "b" does not put on.

*Corrected*

4. For the paper "Sanders, F., 1986a..." (line 39 on page 19) it seems that the letter "a" should be removed and the year of publication should be moved to the end of the reference.

*Corrected*

5. The article McDonald's et al.... (line 46 on page 18) is not in alphabetical order in the reference list.

6. For the papers (Laštovička et al., 2012; Laštovička, 2012) (line 8 on page 3) there are no letters "a" and "b" both in the text of the paper and in the list of references (lines 5-8 on page 19).

*The papers differ in author teams, hence there is no letters "a" and "b" necessary in the references.*

Answer to Reviewer 2 comments:

General comments:

1. The authors give a very good review about the troposphere-upper atmosphere coupling in the introduction part. This very detailed summary/review could be complemented with a paragraph about the impact of the tropospheric events on the sporadic E layer because there are some very interesting papers which investigate and discuss this topic (e. g. Davis and Johnson 2005, Barta et al. 2017, Haldoupis 2018).

*Text added:*

Tropospheric convective systems are often connected with strong lightning. Possibility of thunderstorm influence on ionosphere has been already suggested by Bhar and Syam (1937). In general, two principal mechanisms are proposed. First mechanism presumes gravity waves generated by thunderstorm to propagate up to ionospheric heights. Second mechanism involves generation of electrical discharges in the E region above the storm. Applying superposed epoch analyses, Davis and Johnson (2005) reported statistically significant intensification and decent in altitude of midlatitude sporadic E layer directly above thunderstorm. Different observational result showing decrease of critical frequency of sporadic E has been reported by Barta et al. (2017). Mechanism involved in the coupling between thunderstorm lightning and ionosphere is very complicated and not well understood yet. The limitations of generally accepted mechanisms are discussed in detail in the paper Haldoupis (2018).

2. Page 8. line 17. "Around 15 UT the warm front brought light rain associated with stratiform clouds" It is not clear the date in this case for me.

*Text corrected:*

Around 15 UT on September 23, the warm front brought light rain associated with stratiform clouds.

3. Page 9. line 31-36: Please, discuss a little bit what we see on Fig. 5. and how it is related to the other observations.

*Text added:*

The accuracy is limited by the design of the instrument. In all the comparisons we consider this aspect. Single Doppler Wind Lidar is able to measure both Mie scattering from particles and aerosols, and Rayleigh scattering from the upper atmosphere molecules. This study uses the Rayleigh scattering measurement with random error ( $1\sigma$ ) is 1 m.sec<sup>-1</sup> at altitudes less than 2 km, 2 m.sec<sup>-1</sup> between 2 and 16 km. Systematic error ( $1\sigma$ ) is in this case smaller than 0.7 m.sec<sup>-1</sup> (Durand et al., 2004).

In the two upper panels of Figure 5a and 5b we may see situation before the storm on 22 September. At heights above 10 km there is area where the satellite registers opposite direction of the wind compare to surrounding regions (marked by blue color). Figure 5c represents situation of early morning of 23 September before the cyclone Fabienne has entered the area of measurement site. Calming of the windflow caused by temperature daily cycle is clearly visible. Figure 5d shows the post storm effect on 24 September. The area of opposite wind direction detected by satellite Rayleigh scattering is lifted up to heights of 15 km. The measurements at the time of Fabienne storm passage above the measurement site is not available due to satellite trajectory, however from the satellite records before and after the cyclone passage indicate extremely high speed changes within troposphere and lower stratosphere.

4. Page 12. line 6-9: "Both values agree well through the studied interval and their matching can be explained by dominant contribution of F2 layer's electron contribution to the TEC and much less contribution of E layer's variability during studied days, even during the Fabienne

event." Can you detail this explanation, please? Maybe it can be useful to show the variation of the foE parameter as well on Fig. 10.

*Text added:*

While TEC and foF2 show significant decrease in reaction to minor geomagnetic disturbance, there is no clear change in course and shape of critical frequency of E layer foE Figure 10 (middle panel) except of very short wave-like variability on 23 September before Fabienne storm passage above the observational site. On 23 September, maximum of foE reaches same values as on preceding and following days. Most of the variability is observable within time series of TEC and foF2 and both parameters agree well through the studied interval. Their matching can be explained by dominant contribution of F2 layer's electron content contribution to the TEC and much less contribution of E layer's variability during studied days, even during the Fabienne event.

*Figure 10 corrected*

5. Page 12. line 16-19.: "Geomagnetic disturbance started on 21 September at 21 UT. Frequency foF2 during night falls much faster than it is typical. Then foF2 oscillates and remain below 3.5 MHz till almost noon when rapidly increases." The second part is related to the variation on the night 22/23 September? Please, indicate the date, because it is not clear for me.

*Text corrected:*

Geomagnetic disturbance started on 21 September at 21 UT. Frequency foF2 during night falls much faster than it is typical. Then during night 22-23 September, critical frequency foF2 falls even faster, oscillates and remains below 3.5 MHz till almost noon when rapidly increases.

6. Page. 13. line 40-41: "The spectral content changed withtime and was different during the strong storm event compare to preceding and following day. " We can't see similar effect at 4.65 MHz. Can you give an explanation for that?

*Text enlarged:*

The spectral content changed with time and was different during the strong storm event compared to preceding and following day. During afternoon hours on 22 September, CDS registers clear sharp echo with wave-like fluctuations. On 23 September on both frequencies we have observed sudden increase of noise at 18 UT that could indicate arrival of acoustic wave packet from the frontal border. After that, stronger and blurred echo compared to 22 September is registered on both frequencies. Wave-like fluctuations are not detected within the signal on 3.59 MHz and 4.65 MHz. On both frequencies (better pronounced on 4.65 MHz on Figure 15 b), there are apparent coincidental drops in frequency at 18 UT. Blurred strong echo was observed until around 4 UT on 24 September. In the afternoon hours on 24 September, recorded CDS echo remains slightly blurred but it is significantly weaker. The occurrence of stronger echo on CDS sounding on 3.59 MHz in the interval 18 UT (23 September) till 4 UT (22 September) corresponds to the increased wave activity on directograms and detection of plasma flow on both North and East plasma drift components. The trace of 4.65 MHz is limited due to diurnal course of foF2. Hence the changes of in the CDS signal can be discussed only till 20 UT. Signal detected on 23 September is significantly stronger with respect to preceding and following days, especially in the part that corresponds to the frequency drop at 18 UT.

7. Page 14. line 30-32. "According to the evolution of Kp index and ionospheric plasma parameters (TEC and foF2) ionosphere was already in the recovery phase of the geomagnetic storm. Nevertheless, the observed disturbances are induced both by geomagnetic storm and convective activity in the lower laying atmosphere." Can you discuss in more details the convective activity effect on the TEC and/or foF2 and how it appears on Fig. 10.? I can not distinguish its impact from the geomagnetic storm in the case of these two parameters.

*Text added:*

*In the introduction part:*

Model study (Pedatella, 2018) demonstrated variability of the response of the atmosphere and ionosphere system to one particular storm when the internal variability characterized by the ensemble standard deviation is introduced. The study shows that implementation of arbitrary internal atmospheric variability leads to the geomagnetic storm occurring under a different, though climatically similar, atmospheric state for each ensemble member. The study has found that variability leads to uncertainty typically 20%–40% with localized regions exceeding 100%. It clearly shows that large-scale features of the storm are reproduced well and while small-scale characteristics of the response are dependent on lower atmosphere variability. Hence neglecting of the lower atmosphere may lead to significant complication in the geomagnetic storm interpretation.

*In the Discussion part:*

The observed variability of the parameters TEC, foF2 and foE on Figure 10 is caused jointly by the minor geomagnetic disturbance and atmospheric waves associated with Fabienne storm. It is practically impossible to distinguish what part of the variability belongs to the particular forcing. Ionospheric vertical sounding has, unfortunately, limitations and provides integral information about resulting behavior of the atmosphere. However, in addition to the time of flight of the electromagnetic wave the DPS 4D equipment recorded additional parameters of the reflected wave from ionosphere. Variability of critical frequency foF2 must be interpreted together with complete ionogram record. As it is demonstrated in the Figure 8, there is well seen change of the ionogram pattern through experiment. Ionograms recorded on 22 September (type on panel a) are usually recorded when the reflection plane is practically flat while ionograms recorded on 23 September (type on panel b) are measured when reflection planes are significantly undulated. Such situations occur in association with atmospheric wave activity. Hence, this additional information can be used to slightly untangle effects of the geomagnetic disturbance and convective activity. Taking into account the course of foF2 and TEC together with change of ionogram reflection patterns, we suppose, that dominant effect of the geomagnetic disturbance is pronounced as decrease of foF2 and TEC, while short term wave-like variability around mean course associated with spread echo occurrence on ionograms can be attributed to the convective activity in the lower atmosphere.

*In the conclusion part:*

Regarding results of model study (Pedatella, 2018) we attribute general decrease in foF2 and TEC to the geomagnetic forcing (longer-term, negative storm scenario) and significant increase in wave-like activity (short-term, wave-like activity) to the convective system forcing.

General comments to the Figures:



Unfortunately, it is very difficult to see the following figures (especially in print version): Fig. 3, Fig 6. and 7., Fig. 8, Fig. 14. Please, indicate the letters a, b, c etc. on the subplots where it is necessary. In some cases, when you show sequence of pictures it could help if you indicated the dates (in row e.g. on Fig 6 and 7) and the time (above the columns e.g. on Fig. 6 and 7)

*The authors hope that the Figures are corrected sufficiently*

Minor comments:

1. Sometimes the line spacing change in the manuscript: e.g. page 3. line ...7-8 / 9-10....; page 7. line ... 30-31 / 32-33

*Corrected*

2. Page 3. line 16. The effects of gravity waves on in the ionosphere: in should be deleted

*Corrected*

3. Page 4. line 1. On the longer term-term scale: one term should be deleted

*Corrected*

4. Page 6. line 25. Kouba et al. (2008)

*Corrected*

Editor's suggestion:

*We have added text in the Introduction part:*

Atmospheric vertical coupling via propagation of internal atmospheric waves was largely investigated by Yigit and Medvedev (2017). Their model study revealed significant impact of gravity waves on mean circulation and cooling the thermosphere down by up 12-18%. Further, they demonstrated influence of gravity waves on tides both direct and indirect. – pg.3

Detail insight into internal wave coupling processes in Earth's atmosphere comprising teoretical, model and experimental recent results can be found in Yigit and Medvedev (2015) and later in Yigit et al. (2016). – pg.4

*Conclusion part:*

As it has been pointed out, for instance in Yigit and Medvedev (2015, 2017), the gravity waves originating in the lower atmosphere are able to significantly alter processes up to the thermospheric heights and their impact is highly variable according to actual state of the background atmosphere.- pg. 17

# Evidence of vertical coupling: Meteorological storm Fabienne on 23 September 2018 and its related effects observed up to the ionosphere.

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**Abstract:** Severe meteorological storm system on the frontal border of cyclone Fabienne passing above Central Europe was observed on 23–24 September 2018. Large meteorological systems are considered to be important sources of the wave-like variability visible/detectable through the atmosphere and even up to ionosphere heights. Significant departures from regular courses of atmospheric and ionospheric parameters were detected in all analyzed data sets through atmospheric heights. Above Europe, stratospheric temperature and wind significantly changed in coincidence with fast frontal transition (100–110 km h<sup>-1</sup>). Zonal wind at 1 and 0.1 hPa changes from usual westward before storm to eastward after storm. With this changes are connected changes in temperature where at 1 hPa analyzed area is colder and at 0.1 hPa warmer. Within ionospheric parameters, we have detected significant wave-like activity occurring shortly after the cold front crossed the observational point. During the storm event, both by Digisonde DPS-4D and Continuous Doppler Sounding equipment, we have observed strong horizontal plasma flow shears and time-limited increase plasma flow in both North and West components of ionospheric drift. Vertical component of plasma flow during the storm event is smaller with respect to corresponding values on preceding days.

Analyzed event of exceptionally fast cold front of the cyclone Fabienne fell into the recovery phase of minor-moderate geomagnetic storm observed as a negative ionospheric storm in European Mid-latitudes. Hence, ionospheric observations consist of both disturbances induced by moderate geomagnetic storm and effects originated in convective activity in troposphere. Nevertheless, taking into account significant change in global circulation pattern in the stratosphere, we conclude that most of the observed wave-like oscillations in the ionosphere during night 23–24 September can be straight attributed to the propagation of atmospheric waves launched on the frontal border (cold front) of the cyclone Fabienne. Frontal system acted as an effective source of atmospheric waves propagating upward up to the ionosphere.





## 1      **1      Introduction - Variability of the ionosphere**

2  
3      The ionosphere is highly variable system that is influenced by solar and geomagnetic  
4 activity from above and lower-laying atmospheric phenomena from below. Ionospheric  
5 variability is observed on a wide-scale range from minutes, or even shorter, up to scales of solar  
6 cycle and secular variations of solar energy input. With no doubt, the most dominant driver of  
7 ionospheric variability is solar activity. Whole atmosphere and ionosphere react according to  
8 the level of solar energy input. The episodes of limited strongly enhanced dissipation of solar  
9 energy (solar flares, coronal mass ejections etc.) can affect only regions localized in high  
10 latitudes or can cover all the geosphere. During such event, the magnetosphere is affected first  
11 (see for instance Hargreaves, 1992). A large portion of solar energy is dissipated in the upper  
12 atmosphere and then in the ionosphere, thermosphere (Davies, 1990; Solomon and Qian, 2005).  
13 The perturbations can be detected at the ground level, for instance by magnetometers.  
14 Disturbances associated with such enhanced solar energy inputs are in general called  
15 geomagnetic storm (Gonzales et al., 1994, Buonsanto, 1999) or geospheric storms (Prölss,  
16 2004). Different types of solar agents that are mainly responsible for geomagnetic disturbances  
17 have been analyzed with respect to their geoeffectiveness by Kakad et al. (2019), Georgieva et  
18 al. (2006), Fenrich and Luhmann (1998), Leamon et al., (2002), Prölss (2004) and many others.  
19

20      Besides the solar and geomagnetic forcing the energy inputs from lower-laying  
21 atmospheric heights must be taken into account in the energy budget of the ionosphere. The  
22 lower laying atmosphere and its impact on the ionosphere have been largely studied during last  
23 exceptionally low solar cycle by mean of growing number of satellite measurements. Paper  
24 Anthes (2011) and more recent paper Liu et al. (2017) demonstrated effectivity of Radio  
25 Occultation (RO) sounding methods on board of satellites for systematic sounding of the  
26 atmosphere with respect to weather, climate and space weather.  
27

28      The ionosphere is weakly ionized plasma where both neutrals and ions play an important  
29 role. Ionization degree around maximum of electron concentration is less than  $10^{-2}$  and  
30 significantly smaller below the maximum in the F layer, except limited events of Sporadic E  
31 layer occurrence (Whitehead, 1961,1990; Mathews, 1998; Haldoupis, 2012). The impact of the  
32 collision processes on the ionospheric dynamics cannot be neglected especially in the lower  
33 ionosphere. During day time, due to incoming solar radiation, ionosphere is formed at height  
34 of mesosphere and thermosphere. Ionosphere is typically stratified into D, E and F layer, where  
35 the maximum electron concentration is usually located. The F layer is usually a region with  
36 maximum electron concentration. It can be split into two sub layers denoted F1 and F2 layers.  
37 In case of splitting into F1 and F2 layers, the maximum of electron concentration is located in  
38 F2 layer. During night time electron concentration decreases at all heights due to recombination  
39 processes and lack of ionizing radiation. It leads to practical disappearance of all ion pairs below  
40 F layer that remains present due to slow recombination processes at its height (Davies, 1990;  
41 Rishbeth, 1998; Prölss, 2004 among many others). As a measure of the ability of the Earth's  
42 atmosphere to absorb incoming solar radiation we can consider the maximum electron  
43 concentration NmF2 in the highest ionospheric level F or F2 if present. During solar cycle, we  
44 can observe clear link between incoming solar radiation and ionospheric ionization. With the

1 increasing solar activity we observe higher ionization. However, the relationship is not linear  
2 and is subject of large investigation. The link between ionospheric variability and both solar  
3 and geomagnetic indices were analyzed for instance by Clilverd et al., 2003; Cnossen et al.,  
4 2014; Forbes et al., 2000; Roux et al., 2012; Koucká Knížová et al., 2018, Perrone et al., 2017.  
5 Understanding of the relation between solar activity and corresponding ionospheric and/or  
6 atmospheric behavior is crucial for instance in the estimation of the trends and potential human  
7 impact on the atmosphere and ionosphere (Roininen et al., 2015; Laštovička et al., 2012;  
8 Laštovička, 2012; Georgieva et al., 2012).

9  
10 Ionosphere clearly reflects solar activity on all studied time-scales. Diurnal courses of  
11 the maximum concentration in the ionosphere clearly show the dominant solar influence,  
12 increase/decrease of the electron concentration with respect to solar zenith angle. During stable  
13 solar and geomagnetic situation, however, significant difference in the courses of ionospheric  
14 parameters is well seen on consequent days. Vertically propagating gravity waves are subject  
15 of large scientific interest since 1960s. A fundamental interpretation of atmospheric variability  
16 in terms of atmospheric gravity waves was provided by Hines (1960) and later by Hines (1963,  
17 1965, and 1968 among others). The effects of gravity waves on in the ionosphere up to F2  
18 region through photochemical and dynamical processes were discussed by Hooke (1970b).  
19 Garcia and Solomon (1985) reported GW importance on the chemical composition of the  
20 middle atmosphere. There, it has been already shown that the resulting effects of gravity waves  
21 depend not only on the wave properties but on the actual ionospheric situation and/or direction  
22 of propagation with respect to incoming solar radiation (Hooke, 1970a; 1971). It has been  
23 pointed out by Holton (1983) that gravity wave drag and diffusion are fundamental for the wind  
24 and temperature balance in the middle atmosphere. Fritts and Nastrom (1992) suggested that  
25 convective activity in the troposphere is as important source of gravity waves as topographic  
26 forcing. Model study of gravity wave generation and its observable signatures above deep  
27 convection is provided by Alexander et al. (1994). Tropospheric convective systems are often  
28 connected with strong lightning. Possibility of thunderstorm influence on ionosphere has been  
29 already suggested by Bhar and Syam (1937). In general, two principal mechanisms are  
30 proposed. First mechanism presumes gravity waves generated by thunderstorm to propagate up  
31 to ionospheric heights. Second mechanism involves generation of electrical discharges in the E  
32 region above the storm. Applying superposed epoch analyses, Davis and Johnson (2005)  
33 reported statistically significant intensification and decent in altitude of midlatitude sporadic E  
34 layer directly above thunderstorm. Different observational result showing decrease of critical  
35 frequency of sporadic E has been reported by Barta et al. (2017). Mechanism involved in the  
36 coupling between thunderstorm lightning and ionosphere is very complicated and not well  
37 understood yet. The limitations of generally accepted mechanisms are discussed in detail in the  
38 paper Haldoupis (2018).

39  
40 Later detail model studies of gravity wave propagation through the Earth's atmosphere  
41 simulations provided by Vadas and Fritts (2005), Vadas (2007), Vadas and Nicolls (2012)  
42 proved that gravity waves originating in the tropospheric convection can reach thermospheric  
43 heights and significantly affect wind and temperature profiles. Atmospheric waves propagate  
44 from lower laying atmosphere up to the thermosphere as primary waves or dissipate. The  
45 deposited momentum excites secondary waves (see for instance Vadas and Liu (2009) or Vadas  
46 et al. (2018)). Atmospheric vertical coupling via propagation of internal atmospheric waves was  
47 largely investigated by Yigit and Medvedev (2017). Their model study revealed significant  
48 impact of gravity waves on mean circulation and cooling the thermosphere down by up 12-  
49 18%. Further, they demonstrated influence of gravity waves on tides both direct and indirect.

1 The effects of GW on the atmosphere up to thermospheric heights are highly variable due to  
2 complexity of the system.

3  
4 Except model studies there are observational evidences of consequent ionospheric  
5 disturbances attributed to dynamical processes in the lower atmosphere. Chernigovskaya et al.  
6 (2018) provides an evidence of F2-layer ionospheric response to dynamic processes during the  
7 winter circumpolar vortex evolution in the strato-mesosphere. McDonald et al., (2018) reported  
8 an enhancement in total electron content in ionosphere, which coincides with the  
9 commencement of a stratospheric warming event. Goncharenko et al. (2010) observed  
10 persistent variations in the low-latitude ionosphere that occur several days after a sudden  
11 warming event in the high-latitude winter stratosphere. Enhancements of wave-like activity  
12 within ionospheric F layer with relation to meteorological events were reported by  
13 Chernigovskaya et al. (2015). Propagation of concentric gravity waves from source region in  
14 the troposphere related to tropospheric convective storm up to the ionosphere was reported by  
15 Azeem et al. (2015). Paper presents almost simultaneous observations of a gravity wave event  
16 in the stratosphere, mesosphere, and ionosphere. Suddenly increasing wave-like oscillations  
17 within ionospheric parameters after passing tropospheric cold front across observational point  
18 was reported by Boška and Šauli (2001) and Šauli and Boška (2001). On the longer term-term  
19 scale, the extremely high correlation between ionospheric measurements of the up to the 'break  
20 point' at 10 degrees in longitude and/or Earth's distance 1000 km is attributed to the mesoscale  
21 systems as proposed by Koucká Knížová et al. (2015). Infrasound waves excited by severe  
22 tropospheric storms (e.g. typhoons and strong storms) are discussed and analyzed. Chum et al.  
23 (2018) detected infrasound in the ionosphere from earthquakes and typhoons, by mean of  
24 Multipoint Continuous Doppler Sounding equipment. Authors give examples of observation by  
25 an international network of continuous Doppler sounders. The waves were observed at the  
26 height range from about 200 to 300 km by continuous Doppler sounder located in Taiwan  
27 (Chum et al., 2018). The infrasound was observed during several hours for strong storms events.

28  
29  
30 GPS satellite measurements are promising tools for monitoring ionospheric changes  
31 connected with severe weather systems. Recently the analyses of scintillation S<sub>4</sub> index in  
32 relation to four tropical cyclones (Yasi in 2011, Marcia in 2015, Debbie in 2017 and Marcus in  
33 2018) were presented by Ke et al. (2019). They found intensification of scintillation effects  
34 mostly above the tropical cyclone path and attributed them to the electric field perturbation and  
35 consequent plasma bubble generation. Within COSMIC GPS data, Yang and Liu (2016) has  
36 found significant peak in radio occultation scintillation events during the passage of tropical  
37 cyclone Tembin (2012) during quiet geomagnetic or solar activity and attributed the observed  
38 effect to the gravity waves generated in the lower atmosphere by the cyclone. Afraimovich et  
39 al. (2013) published large review of GPS/GLONASS studies of the ionospheric response to  
40 natural and antropogenic processes and phenomena. Paper focuses on wide range of ionospheric  
41 forcing and corresponding ionospheric variability detected in principle within Total Electron  
42 Content (TEC) and F2 layer critical frequency foF2. In relation to tropical cyclones (Katrina,  
43 Rita and Wilma) occurring in 2005 they reported increase of wave-like activity in gravity-wave  
44 period range mainly in the range 20 to 60 minutes and intensification of TEC variations along  
45 the satellite path close cyclone. The zones of disturbances were found to form during hurricane  
46 stage of the cyclone (Afraimovich et al., 2013).

47  
48 Review of lower atmosphere forcing was provided by Lastovička (2006). Detail insight  
49 into internal wave coupling processes in Earth's atmosphere comprising teoretical, model and  
50 experimental recent results can be found in Yigit and Medvedev (2015) and later in Yigit et al.

(2016). The importance of involvement of lower atmosphere into ionospheric variability study in order to accurately capture smaller-scale features of the upper atmosphere response even to the geomagnetic storms, is demonstrated by Pedatella and Liu (2018). The evidence of lower atmosphere forcing is clearly demonstrated on the day-to-day ionospheric variability (known as an ionospheric anomaly) during low and stable solar and geomagnetic activity during consequent days. Ionospheric parameters (e.g. electron concentration or height of ionospheric layers) on such scales are influenced by combination of meteorologic activity and solar/geomagnetic forcing. During geomagnetically quiet days the tropospheric forcing is more emphasized and relatively more important and is ruling the ionospheric dynamics, far more than the solar and geomagnetic energy inputs.

Model study (Pedatella, 2018) demonstrated variability of the response of the atmosphere and ionosphere system to one particular storm when the internal variability characterized by the ensemble standard deviation is introduced. The study shows that implementation of arbitrary internal atmospheric variability leads to the geomagnetic storm occurring under a different, though climatically similar, atmospheric state for each ensemble member. The study has found that variability leads to uncertainty typically 20%–40% with localized regions exceeding 100%. It clearly shows that large-scale features of the storm are reproduced well and while small-scale characteristics of the response are dependent on lower atmosphere variability. Hence neglecting of the lower atmosphere may lead to significant complication in the geomagnetic storm interpretation.

## 2 Data

For the description of cyclone Fabienne in the troposphere we use **meteorological** ground-based data (<https://www.ventusky.com/>, [www.wetterkontor.de](http://www.wetterkontor.de), <http://wetter3.de>, <http://www.ufa.cas.cz/institute-structure/departement-of-meteorology/present-weather-sporilov.html>) and Aeolus satellite measurements described in the following chapter 2.1. Behavior of the stratosphere is interpreted using **stratospheric** wind and temperature reanalysis MERRA 2 datasets (<https://disc.gsfc.nasa.gov/daac-bin/FTPSubset2.pl>) described in chapter 2.2. The ionosphere observation (details are provided in chapter 2.3) comes from two ground based vertical **ionospheric** sounding using the Digisonde DPS 4D (<http://giro.uml.edu/> and <http://digisonda.ufa.cas.cz/>) and oblique reflection using the multipoint Continuous Doppler Sounding (CDS) [http://www.ufa.cas.cz/files/OHA/M\\_Doppler\\_system.pdf](http://www.ufa.cas.cz/files/OHA/M_Doppler_system.pdf). Besides that we use satellite TEC measurement ([http://gnss.be/Atmospheric\\_Maps/ionospheric\\_maps.php](http://gnss.be/Atmospheric_Maps/ionospheric_maps.php)) for station Pruhonice. For geomagnetic situation description we use geomagnetic indices from Potsdam Data Center <https://www.gfz-potsdam.de/en/kp-index/>. The data used for interpretation of Fabienne event and related disturbances in stratospheric and ionospheric heights cover time interval 20–27 September 2018.

### 2.1 Meteorological data

In order to describe severe storm Fabienne we use ground-based meteorological monitoring combined with satellite observation. For determination of the synoptic condition in

the troposphere, surface and upper synoptic maps were used (available at <https://www.wetterkontor.de/> and <http://wetter3.de>). We also used meteorological ground-based radar observations taken from the <https://www.ventusky.com/>. In addition hourly averages meteorological data performed by automatic weather station located at the Institute of Atmospheric Physics IAP (50.04°N, 14.48°E) were used for determining the time of frontal passage (<http://www.ufa.cas.cz/institute-structure/department-of-meteorology/present-weather-sporilov.html>). Data are available for last 30 days, and then they are stored in the institute archive.

The Earth Explorer Atmospheric Dynamics Mission Aeolus yields data from global observations of wind profiles from space using the active Doppler Wind Lidar (DWL) method (Gompf, 2000). The DWL measurement is the unique method that has the potential to provide the required data on a global scale, from direct observation of wind. The DWL measures 100 wind profiles per hour using both Rayleigh and Mie scattering method (Durand et al., 2004). The global wind profiles (along a single line-of-sight) are measured up to an altitude of 30 km to an accuracy of 1 m s<sup>-1</sup> in the planetary boundary layer (up to an altitude of 2 km). The Aeolus mission was launched on 22 August 2018 and scientific measurement started on 12 September 2018.

## 2.2 Stratospheric Data

The MERRA2 (Modern-Era Retrospective analysis for Research and Applications, version 2 from <https://disc.gsfc.nasa.gov/daac-bin/FTPSubset2.pl>) with resolution 0.5° in latitude and 2/3° in longitude was used. The MERRA-2 is a global atmospheric reanalysis produced by the NASA Global Modelling and Assimilation Office (GMAO), details can be found in Gelaro et al. (2017). The MERRA2 is available up to 0.1 hPa from 1980 till present but we show only 1 and 0.1 hPa for period from 20 September 2018 to 27 September 2018 which is relevant for our studies. This reanalysis provides reliable time series in regular grid network. Temperature and zonal wind 6-hourly data (00, 06, 12 and 18 UT) in the stratosphere and lower mesosphere (from 30–80 km) were used. The MERRA 2 reanalysis has many advantages as reliable time series without gaps, regular grid network or high vertical resolution. Of course there are some disadvantages. Because the reanalysis includes many observations datasets from satellite, radiosondes or ground measurements they have to be assimilated into one dataset. That is why we can get biased dataset especially at higher altitudes. However, usage of MERRA 2 for our analysis is sufficient as the reanalysis provides us with clear description of the stratosphere situation during the studied interval.

## 2.3 Ionospheric Data

State of the ionosphere has been monitored globally on a regular base since setting of the network of ionosondes in frame of the International Geophysical Year in 1957–1958. Some of the ionospheric station are still operating and represent observatories with longest time series of ionospheric data available for research.



1 Vertical sounding of the ionosphere is based on the reflection of electromagnetic wave  
2 from ionospheric plasma. Sounding pulse is reflected from plasma unit when the sounding  
3 frequency is equal to its plasma frequency (see for instance Davies (1990)). Using typical  
4 sounding frequency range 1 MHz–20 MHz it is possible to monitor ionosphere from the E layer  
5 up to maximum electron concentration in the F region. With increasing frequency of the  
6 sounding wave, the pulse penetrates higher to the ionosphere. When the frequency of the  
7 sounding pulse exceeds plasma frequency of maximum, the pulse propagates through the  
8 ionosphere without reflection and no echo is registered in the receiver. Maximum frequency of  
9 the reflected wave from the particular layer is called critical frequency and is simply related to  
10 maximum plasma concentration of the layer. For the purpose of the analyses we use maximum  
11 of electron concentration NmF2 located in the F or F2 layer, and the corresponding plasma  
12 frequency called critical frequency and denoted foF2. Time series of foF2 are the longest data  
13 sets available for systematic study of ionospheric variability.

14  
15 In the Observatory Pruhonice (49.9°N, 14.6°E) located close to Prague, Digisonde DPS  
16 4D is used for regular ionospheric monitoring. Digisonde DPS 4D provides ionograms,  
17 directograms and skymaps for further evaluations and interpretations. Digisonde operates in the  
18 multi-beam sounding mode using six digitally synthesized off-vertical reception beams in  
19 addition to the vertical beam. For each frequency and height on a multi-beam ionogram, the  
20 raw data from the four receive antennas are collected and processed to form seven beams,  
21 separately for the O-mode and X-mode echoes (Reinisch, 1996; Reinisch et al., 2005). Detail  
22 description can be found also on web page <http://umlcar.uml.edu/digisonde.html>.

23  
24 All the data were manually checked and evaluated. Detail processing of the drift  
25 measurement and how the skymaps are controlled, is described by Kouba et al. (2008) and  
26 Kouba and Koucká Knížová (2012). High-rate sounding campaign partly overlaps our selected  
27 time span. The aim of the high-rate sounding measurement was to monitor short-term variability  
28 of the Es-layer. Hence, our data consists of data with 2-minutes (till 24 September at 6:30 UT)  
29 and 15-minutes repetition time. Ionospheric drift data are not yet widely used for description of  
30 ionospheric variability. Kouba and Koucká Knížová (2016) have provided first systematic  
31 study of regular course of vertical drift component in Mid-latitudes. The study was conducted  
32 during year 2006, i.e. during time interval described by low solar and geomagnetic activity. It  
33 shows diurnal and seasonal variability of the vertical plasma drift component and quantifies its  
34 characteristic values.

35  
36 Ionogram represents height-frequency characteristics of the ionosphere above the  
37 station. It displays virtual reflection height vs. sounding frequency. Using only vertical echo on  
38 the ionogram one can receive height profile of frequency or electron density (Davies, 1990 and  
39 many others). According to the receiving antenna field, multi-beam ionograms can be recorded.  
40 Digisonde can register off-vertical reflections in addition to the vertical one. The off-vertical  
41 signals are further processed to show characteristics of the oblique reflection caused by  
42 ionospheric irregularities. Directogram (see for more detail description  
43 <http://ulcar.uml.edu/directograms.html>) provides information about direction of the echoes  
44 received from irregularity. The central column between the panels corresponds to the vertical



1 reflection at zero zenith angle. Shades of blue in the directogram correspond to general direction  
2 of plasma-drift from west to east, and shades of red are used to represent drift in the opposite  
3 direction, i.e. from east to west.

4  
5 In addition to Digisonde DPS-4D, ionosphere is regularly monitored by a multi-point  
6 continuous Doppler (CDS) sounding portable system based on the measurements of the Doppler  
7 shift experienced by waves reflected from the ionosphere. The measurements are  
8 simultaneously performed on 3 to 5 frequencies with 4 Hz separation around the center  
9 frequency of 3594.5 kHz. Multipoint measurement makes it possible to investigate propagation  
10 of infrasonic waves or ionospheric oscillations caused by fluctuations of geomagnetic field etc.  
11 ([http://www.ufa.cas.cz/files/OHA/M\\_Doppler\\_system.pdf](http://www.ufa.cas.cz/files/OHA/M_Doppler_system.pdf)). Observation of wave propagation  
12 in the ionosphere is performed on the basis of multi-point and multi-frequency continuous  
13 Doppler sounding (CDS) in the Czech Republic. We used two multi-point CDS systems  
14 operating at frequencies of 3.59 and 4.65 MHz. Kouba and Chum (2018), demonstrated  
15 efficiency of Digisonde-based drift measurement together with Continuous Doppler Sounding  
16 on fixed frequency for study of dynamics of the ionosphere. Chum et al. (2018) detected  
17 infrasound waves generated by seven typhoons that passed over Taiwan or in its surroundings  
18 in period 2014–2016. The spectral characteristics of the ionospheric infrasound from convective  
19 storms are sensibly similar as for the cotyphoon infrasound. The highest spectral densities were  
20 observed during about 2–5 minutes (3.3–8.3 mHz).

21  
22 The ground-based ionospheric sounding was complemented by Total Electron Content  
23 (TEC) above station Pruhonice derived from satellite measurement  
24 ([http://gnss.be/Atmospheric\\_Maps/ionospheric\\_maps.php](http://gnss.be/Atmospheric_Maps/ionospheric_maps.php)). While the foF2 parameter  
25 describes local maxima of electron concentration, and thus the variation of foF2 can be  
26 attributed mostly to the ionization-recombination processes in the F2 region the TEC satellites  
27 measurement is a parameter representing integral of electron concentration from bottom to  
28 upper part of the ionosphere.

### 30 **3 Meteorological description of storm Fabienne**

31  
32 **Synoptic evolution:** On 20 September 2018 a short-wave travelled eastward from the  
33 British Isles towards Sweden and Poland and supports strengthening of a cyclone Elena over  
34 the North Sea. Anticyclonal warm late summer condition with weak southwest flow occurred  
35 in Central Europe. A strong frontal zone from the north Atlantic over the Central Europe  
36 separated cool Atlantic air from the hot continent. The unusually hot and dry weather in the  
37 Central Europe culminated September 21 afternoon and accelerate the movement of cold front  
38 around noon. Along the front there was forming squall line with thunderstorms in the evening.  
39 Recorded strong wind gusts were caused by both convective activity and a significant pressure  
40 gradient within the cyclone.

41  
42 During the following days, the low descent centre moved towards the northeast and  
43 formed a deep cyclone above Scandinavia. Because of the strong zonal flow along the lower  
44 edge of this cyclone another front system coupled with the Fabienne cyclone quickly moved to  
45 Central Europe. On 23 September the cyclone Fabienne deepened and passed through Central  
46 Europe to the east. Within the warm sector ahead of a cold front of the Fabienne humid low-

level air is advected northeastward from the subtropical North Atlantic. This resulted in evolving intense convection and formation squall line with thunderstorms along the very fast moving cold front. Synoptic time-evolution is demonstrated in the Figure 1.

**Surface data:** In Figure 2, there are average hourly data measured at Institute of Atmospheric Physics (IAP) meteorological station clearly show the cold front that passed over this station at 18 UT on 21 September, when ground level pressure reached a local minimum. Before the front, maximum air temperatures at 2m reached tropical values above 30 °C, behind the front the maximum daily temperature did not reach more than 20 °C. The average hour wind speed intensified before the front and during the rainfall associated with storm activity. After passing the front, the surface wind changed from southwest to northeast.

Around 15 UT on September 23, the warm front brought light rain associated with stratiform clouds. The temperature at 12 UT on September 23 was lower than in the afternoon when the area was temporarily in the warm sector of cyclone Fabienne. Lifetime of the warm sector was very short. The time-series of surface variables at IAP station show the warm front which is connected with slight direction windshift, but rapid rise in temperature until 18 UT on September 23. At this time the passage of the cold front connected with Fabienne occurred and brought a thunderstorm activity with heavy rain and wind shock. The surface pressure minimum was close to 1000 hPa, while the temperature reached local maximum and the wind direction changed from from west to north. The hourly mean wind speed rose rapidly up to midnight. On September 24 was cold, the maximum temperature reached only 12.8 °C. The strong cold northwest wind remained across the measurement point, the maximum averaged hourly values reached 7 m.s<sup>-1</sup> in the afternoon. Pressure continued to rise until midnight following day. Centre of the massive anticyclone Shorse (see Figure 1), which moved from the British Island over the Czech Republic in just 36 hours brought the pressure to a value of 1040 hPa.

Both the Europe surface pressure charts in Figure 1 and the ground level time series for IAP observatory in Figure 2 displays unusually fast passage of synoptic pressure patterns over the Central Europe. Cyclone Fabienne moved at around 25 m.s<sup>-1</sup>. It exceeds speeds of extratropical transition. Jones et al. (2003) described extratropical transition of tropical cyclones which can accelerate from a forward speed of 5 m.s<sup>-1</sup> in the Tropics to more than 20 m.s<sup>-1</sup> in the Mid-latitudes. Sanders (1986) noted mean surface cyclone speed of moving of about 18 m.s<sup>-1</sup> for cyclone originated in the west-central North Atlantic and deepened explosively. A manual in Czech language based on both empirical observations and classical synoptic meteorology states that the average cyclones speed over Europe is around 8 m.s<sup>-1</sup> to 11 m.s<sup>-1</sup> (Kopáček, Bednář, 2009)

The synoptic-scale windstorm connected with the cyclone Fabienne is an unusual event for the time of occurrence (23 September 2018) and for the storm moving velocity and intensity (Kašpar et al, 2017). The month of September in the Middle Europe is typically characterized by significant condition under high pressure, i.e. relatively weak wind sunny days. Figure 3 exhibited the fast moving of cyclone Fabienne in a strong zonal flow from Atlantic region across the Central Europe. Within the warm sector of the cyclone unstable wet air has been advected from subtropical Atlantic region to northest-ward perpendicular to the direction of cyclone moving. Follow-up strengthened baroclinity of the atmosphere at lower levels was the main cause of quick cyclone deepening (visible on surface pressure field - white lines) and generated storms at the head of the cold front.

The 500 hPa map shows the main flow regime of the troposphere. (The atmosphere at an altitude about 5.5 km is no longer under the influence of surface friction. In synoptic meteorology 500 hPa map is used to determine the speed and direction of synoptic patterns.) In the morning on 23 September the density of isohyps depicted at 4-decameters interval indicated a large pressure gradient between the warm southern and cold northern parts of Europe. At 12 UT the cyclone center is still located above Germany at 18 UT it is above the territory of the Czech Republic. On the 850 hPa pseudo-equivalent potential maps there are clearly visible narrow transformation zones with a strong gradient of pseudo-equivalent potential temperature. These “warm boundaries” are separated various homogenous air masses with different temperatures and locate the position of the fronts on the surface pressure field Kašpar (2003) (<http://www.met.wur.nl/education/atmospract/unit9/thetaw%20and%20fronts.pdf>). From radar images presented on Figure 4, the speed of the squall line can be estimated at 110 km/h. Impacts of the strong wind gusts associated with this squall line passage have been well documented on the European Severe Weather Database (<https://www.eswd.eu>).

**Satellite Aeolus observation provides** global wind profiles (along a single line-of-sight) up to an altitude of 30 km with an accuracy of  $1 \text{ m s}^{-1}$  in the planetary boundary layer (up to an altitude of 2 km). The Aeolus mission was launched on 22 August 2018 and scientific measurement started on 12 September 2018. All data outputs (including ALADIN instrument) have already been verified and their reliability verified for the examined period. The Earth Explorer Atmospheric Dynamics Mission Aeolus yields data from global observations of wind profiles from space using the active Doppler Wind Lidar (DWL) method (ESA, 1989; Durand et al., 2004). The DWL measurement is the unique method that provides data on a global scale from direct observation of wind. The Aeolus Doppler Wind Lidar measures 100 wind profiles per hour using both Rayleigh and Mie scattering method (for more information see <https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/aeolus>).

The graphs in Figure 5 display the wind profiles measured by Aeolus ESA satellite using ALADIN instrument working at 355 nm during the time period from 22–24 September 2018 (orbit numbers 481 to 520), geographical coordinates ranges:  $12^{\circ}$ – $19^{\circ}$  E,  $48^{\circ}$ – $51^{\circ}$  N; geomagnetic coordinates:  $97^{\circ}$  L,  $48^{\circ}$  F,  $-17^{\circ}$  Y. The vertical axes represent altitude of height bins, while the horizontal axes represent time of observation. Data catalogue is provided by ESA EO, from [http://aeolus-ds.eo.esa.int/socat/L1B\\_L2\\_Products](http://aeolus-ds.eo.esa.int/socat/L1B_L2_Products). The accuracy is limited by the design of the instrument. In all the comparisons we consider this aspect. Single Doppler Wind Lidar is able to measure both Mie scattering from particles and aerosols, and Rayleigh scattering from the upper atmosphere molecules. This study uses the Rayleigh scattering measurement with random error ( $1\sigma$ ) is  $1 \text{ m.sec}^{-1}$  at altitudes less than 2 km,  $2 \text{ m.sec}^{-1}$  between 2 and 16 km. Systematic error ( $1\sigma$ ) is in this case smaller than  $0.7 \text{ m.sec}^{-1}$  (Durand et al., 2004).

In the two upper panels of Figure 5a and 5b we may see situation before the storm on 22 September. At heights above 10 km there is area where the satellite registers opposite direction of the wind compare to surrounding regions (marked by blue color). Figure 5c represents situation of early morning of 23 September before the cyclone Fabienne has entered the area of measurement site. Calming of the windflow caused by temperature daily cycle is clearly visible. Figure 5d shows the post storm effect on 24 September. The area of opposite wind direction detected by satellite Rayleigh scattering is lifted up to heights of 15 km. The

measurements at the time of Fabienne storm passage above the measurement site is not available due to satellite trajectory, however from the satellite records before and after the cyclone passage indicate extremely high speed changes within troposphere and lower stratosphere.

#### 4 Stratospheric dynamics 20–27 September 2018

Stratosphere and its dynamics are very sensitive for wave activity in higher or lower layers (troposphere or mesosphere). That is why a strong storm Fabienne as a source of many different kind of waves should bring disturbance into regular dynamics. With changes in dynamics are connected changes in temperature and vice versa. Stratospheric wind and temperature for Europe region are presented for time span 20 September at 00 UT to September 27 at 18 UT (each day is represented by one row on the Figures). This period covers whole week (3 days before and 4 days after the Fabienne storm).

Figure 6a shows zonal wind at 1 hPa for Europe region from 20 September at 00 UT to 27 September at 18 UT. On the sequence there is well seen weak eastward wind in middle Europe and westward wind in south Europe which is typical situation for this period. Shortly before storm Fabienne (23 Sep 00 and 6 UT) easterly wind became stronger and replace westerly wind in the south (because of incoming waves from troposphere) and remain easterly for the following several days in whole studied area. At 0.1 hPa we can see changes from westerly to easterly wind shortly after Fabienne (24.9. 00 and 06 UT). We do not register any significant changes before because wave from the troposphere need some time to reach 0.1 hPa. Strong easterly wind remains in whole Europe again for several days after storm. The stratosphere needs some time for changing/restoration dynamics to normal situation because of wave disturbances which remains in inversion condition (temperature increase with altitude) much longer than in other layers. That is why we can observe strong eastward wind not only during the storm but for several days after storm in whole Europe as well.

The changes in the zonal wind, which mainly control stratospheric dynamics (meridional wind is much weaker but very important for Dobson-Brewer circulation), are usually connected with changes in temperature because strong zonal wind effectively block air mixing form different latitudes especially in higher latitudes. The temperature is observed directly so we can expect better approximation in reanalysis than for zonal wind which is derived parameter. The temperature fields at 1 hPa are presented on Figure 7a. We can find much colder air in middle and northern Europe shortly before and mainly after storm Fabienne (23 September 06 and 12 UT) because usual strong barrier (different winds between high and lower latitudes) are destroyed after Fabienne and much colder air from polar vortex can reach lower latitudes in our case middle and south Europe. Colder air in lower latitudes for several days after storm Fabienne could impact not only chemistry in higher stratosphere in autumn but mesosphere condition as well (i.e. the propagation of waves could be slower or faster than usual or they can be absorbed in the stratosphere). This change is well connected with change of zonal wind.

At 0.1 hPa (on the Figure 6b) the change of the zonal wind is even stronger than at 1 hPa (compare Figure 6a and b) because the wind in the mesosphere is usually stronger than in the stratosphere. As was pointed in wind results, several hours after storm (24 September 06 and 12 UT) zonal wind changes from westward or very weak eastward to strong eastward and remains without changes for several days. Meridional wind in mesosphere is stronger than in the stratosphere but still zonal wind plays major role in the dynamics changes. Temperature changes at this level, that corresponds to lower mesosphere, are opposite from pressure level 1 hPa. There is warmer air in higher latitudes so stronger eastward wind brings this warmer air to the lower latitudes (because it is not blocked by the westward wind) and affects the whole area of the middle Europe. The warmer air stays in analyzed area because we need to wait until the zonal wind reverses to his usual state (westward instead of eastward). We have to notice that 0.1 hPa is above stratosphere and the dynamics here could be affected by different processes (i.e. solar radiation, chemistry etc.) than at 1 hPa (almost stratopause).

Especially 0.1 hPa are on the top of the MERRA2 reanalysis so we should be very careful with interpretation of the results because the information from this level could be affected by border condition or problem with wave activity dissipation. But we need mainly qualitative description rather than quantitative description for our study so information from MERRA2 are sufficient.

## 5 Geomagnetic Situation – Preceding moderate storm

September 2018 was a period of rather low geomagnetic activity. On 4 September the geomagnetic activity increased for about 20 hours. Maximum registered Kp index was Kp = 6. The following period was characterized by low geomagnetic activity with Kp up to 3 till September 18 when the Kp index fall down to 0 and remain very low till September 21. On September 21 the geomagnetic activity increased again at 22:30 UT when Kp = 4+. Increased geomagnetic activity lasted for about 20 hours with maximum Kp = 5- on 23 September at 03 UT. The activity can be classified as a minor to moderate geomagnetic storm. On 23 September, the geomagnetic activity falls down again to values around Kp = 2 to 2+. In general, there was rather low geomagnetic activity with only short slightly enhanced events. However, the geomagnetic effects are responsible for part of the observed ionospheric variability and cannot be completely neglected. Geomagnetic indices were downloaded from Potsdam Data Center <https://www.gfz-potsdam.de/en/kp-index/>. Detail plot of geomagnetic Kp index for time span 21-26 September is provided as a part of Figure 10 (bottom panel).

## 6 Ionospheric dynamics and wave activity

An example of multi-beam ionograms measured by DPS-4D is shown in the Figure 8. There is a sequence of ionograms recorded during four consequent days around 23 UT. The receiving antenna system of the digisonde is able to identify the direction of the electromagnetic wave arrival. The information about the reflected wave arrival is included in the raw ionograms. Further, from sequence of raw ionograms the general plasma motion is constructed and presented as the directogram. Each color corresponds to particular antenna beam, hence the



direction of the arrival of oblique echo from large scale irregularities. Colors of echo indicate particular direction of arrival. It is clearly shown that echo changes significantly. Ionogram at 23 UT is selected to show changing dynamics of the ionospheric plasma. During night time, ionograms with clear echo are typically recorded. Antenna system registers practically only vertically reflected signal, as it is shown on panel (a) measured on 22 September and panel (d) recorded on 25 September. In comparison, qualitatively different pattern is detected on panels (b) and (c). The echo on panel (b), recorded on 23 September shortly after passage of the cold front with heavy storm activity, is called spread F situation. As it is indicated by color scheme on the right side of each ionogram, antenna system records echo from practically all sounding beams. Both vertical and off-vertical echoes are spread in height and frequency. It means that the ionosphere is full of irregularities and iso-contours of electron concentration are significantly undulated. On the panel (c) measured on 24 September, there is well recorded vertical echo and slightly higher oblique structure reflected from North-North-East direction. Such kind of echo is known as spur echo and may appear when ionospheric iso-contours are significantly tilted. In general, vertical echo on panel (c) corresponds to situation on panels (a) and (d). Spread F situation on panel (b) indicates significant wave-like activity within ionospheric plasma in the F-region.

Sequence of **directogram measurements** recorded by DPS-4D is shown in Figure 9. **There are two distinct episodes of increased activity.** On the directograms measured first two days 21–22 September, wave activity is rather low. Situation changes significantly on 23 September at 17 UT when strong echo is recorded till 24 September at 4 UT. Signal detected by the receiver varies significantly during night. An interesting fact is that DPS-4D instrument detects strong quickly changing plasma shears and reversal plasma motion with respect to zero zenith-angle. There is no prevailing or characteristic plasma flow for the event. During day-time, there is very low activity visible on the directogram till evening hours. Strong echo is recorded again from 24 September at 17 UT till 25 September at 4 UT. However, the echo is not as strong as the preceding night with smaller shears. Prevailing or dominant plasma motion during local night 24–25 September is in North-North-East direction.

On the plot of the diurnal course TEC in Figure 10 (**upper panel**), decrease can be observed on 23–24 September compared to previous day September 22<sup>nd</sup>. Similarly, in Figure 10 (**middle panel**), decrease in critical frequency foF2 was observed during 23–24 September. **While TEC and foF2 show significant decrease in reaction to minor geomagnetic disturbance, there is no clear change in course and shape of critical frequency of E layer foE Figure 10 (middle panel) except of very short wave-like variability on 23 September before Fabienne storm passage above the observational site. On 23 September, maximum of foE reaches same values as on preceding and following days. Most of the variability is observable within time series of TEC and foF2 and both parameters agree well through the studied interval. Their matching can be explained by dominant contribution of F2 layer's electron content contribution to the TEC and much less contribution of E layer's variability during studied days, even during the Fabienne event.** The effect of electron concentration decrease in the ionosphere can be attributed to the geomagnetic disturbance observed as a negative storm effect (Prölss, 2004) related to the decrease of the atomic oxygen leading to decrease of production of oxygen ions

1 and the increase of molecular nitrogen density leading to the increase of loss rate of ion species.  
2 Both processes lead to electron-ion concentration decrease. Values of critical frequencies foF2  
3 and TEC return to typical values of the season comparable with those preceding the observed  
4 geomagnetic storm event on 25 September (two days after the storm passage over Pruhonice  
5 station). Geomagnetic disturbance started on 21 September at 21 UT. Frequency foF2 during  
6 night falls much faster than it is typical. Then during night 22-23 September, critical frequency  
7 foF2 falls even faster, oscillates and remains below 3.5 MHz till almost noon when rapidly  
8 increases. During night 23–24 September, after sunset critical frequency foF2 decreases faster  
9 compared to nights 21–22 September and 25–26 September, when typical course of foF2 is  
10 registered.

11  
12 The observed variability of the parameters TEC, foF2 and foE on Figure 10 is caused  
13 jointly by the minor geomagnetic disturbance and atmospheric waves associated with Fabienne  
14 storm. It is practically impossible to distinguish what part of the variability belongs to the  
15 particular forcing. Ionospheric vertical sounding has, unfortunately, limitations and provides  
16 integral information about resulting behavior of the atmosphere. However, in addition to the  
17 time of flight of the electromagnetic wave the DPS 4D equipment recorded additional  
18 parameters of the reflected wave from ionosphere. Variability of critical frequency foF2 must  
19 be interpreted together with complete ionogram record. As it is demonstrated in the Figure 8,  
20 there is well seen change of the ionogram pattern through experiment. Ionograms recorded on  
21 22 September (type on panel a) are usually recorded when the reflection plane is practically flat  
22 while ionograms recorded on 23 September (type on panel b) are measured when reflection  
23 planes are significantly undulated. Such situations occur in association with atmospheric wave  
24 activity. Hence, this additional information can be used to slightly untangle effects of the  
25 geomagnetic disturbance and convective activity. Taking into account the course of foF2 and  
26 TEC together with change of ionogram reflection patterns, we suppose, that dominant effect of  
27 the geomagnetic disturbance is pronounced as decrease of foF2 and TEC, while short term  
28 wave-like variability around mean course associated with spread echo occurrence on ionograms  
29 can be attributed to the convective activity in the lower atmosphere.

30  
31 All ionograms were manually scaled and further used for determination of vertical  
32 profile of electron concentration (or frequency) with the use of NHPC inversion technique that  
33 is part of the digisonde software. Details and downloads are available on web page:  
34 <http://umlcar.uml.edu/digisonde.html>. In agreement with course of foF2 and TEC, analyses of  
35 entire electron density profiles reveal the same decrease on 23–24 September as a consequence  
36 of the preceding geomagnetic moderate storm. In order to illustrate well the electron  
37 concentration variability related to cold front effect we focus on profilograms for three  
38 consequent days 22–24 September.

39  
40 Due to geomagnetic disturbance electron concentration and corresponding plasma  
41 frequency decrease which leads to problematic representation of the situation for entire time-  
42 span 21–26 September. Figure 11 shows variations of reflection height of the sounding signal  
43 recorded on 22–24 September for selected range 2–6 MHz with 0.1 MHz step. Oscillations in  
44 heights clearly show strong wave-like activity within all ionospheric heights. Comparing



1 reflection heights at fixed frequencies for two consequent nights, there are shorter period  
2 oscillations visible during night on 22–23 September compared to night-time on 23–24  
3 September. Oscillations detected during both nights are coherent through all levels.

4  
5 Similar effects of oscillation **as observed** on Figure 11 are seen on the detail plot of  
6 profilograms Figure 12 composed from true-height profiles during all analyzed days. Deviation  
7 from regular course is well seen on profile thickness that is significantly smaller on 23  
8 September till 24 September about 6 UT, when the thickness of profiles increases again.

9  
10 Further we have analyzed critical frequency foF2 using continuous wavelet transform to obtain  
11 power content on particular periods. Wavelet Power Spectrum (WPS) for 21–26 September is  
12 presented on the Figure 13. Oscillations on shorter periods on 22 September compared to 23  
13 September are well seen in Figure 13. In the plot of WPS, there are high power domains of  
14 short-period oscillation in the range 5–30 minutes during day-time on 21 September and 22  
15 September. Less energy is detected during day-time on 23 September. Missing spectral content  
16 on periods below 30 minutes on 24–26 September is caused by change of sounding rate on 24  
17 September at 10 UT. As it has been explained in data section, high sampling rate campaign was  
18 switched till morning on 24 September for study of Sporadic-E phenomenon.

19  
20 Following three panels in Figure 14 show the ionospheric drift evolution 20 September–  
21 27 September. In the plots of North (panel b) and East (panel c) components, during several  
22 days preceding both geomagnetic and meteorological storm there are only rare situations where  
23 the ionospheric plasma motion was detected in a horizontal plane. Episode of longer duration  
24 of plasma flow in the horizontal plane is detected after sunset on 23 September when the storm  
25 Fabienne hit observation point. Characteristic value of plasma flow velocity is  $v_{North} \sim 40 \text{ m.s}^{-1}$   
26 and  $v_{East} \sim -30 \text{ m.s}^{-1}$ . Comparing North component of the plasma flow during night of the  
27 Fabienne storm (24 September, at 1 UT–4 UT) and corresponding time following days, it is  
28 important to point out that the flow is in opposite direction and practically same velocity  
29 magnitude.

30  
31 Vertical components in Figure 14 (a) show typical diurnal course with two minima, one  
32 located close to sunrise and one close to sunset (same as reported by Kouba and Koucká  
33 Knížová, 2016). Values of vertical drift before Fabienne storm event reached regularly larger  
34 values with respect to days after the event. For instance, magnitudes of sunrise negative velocity  
35 peaks are detected around  $\sim -50$  –  $\sim -30 \text{ m.s}^{-1}$ , while after the event sunrise peaks are not  
36 exceeding  $\sim -20 \text{ m.s}^{-1}$ . The abrupt change is seen on 23 September at 19 UT, soon after the  
37 cold front passing above the observation point. Characteristic values before storm are exceeding  
38  $v_v \sim 20 \text{ m.s}^{-1}$ , while after the storm they hardly reach  $v_v \sim 20 \text{ m.s}^{-1}$  and rather stay close  $v_v \sim 10$   
39  $\text{m.s}^{-1}$ . Change in plasma flow is well pronounced in all three drift velocity components shortly  
40 after the frontal passage above observational point at ground level.

41  
42 In the following Figure 15, we show Continuous Doppler Sounding (CDS) measurement  
43 on three consequent days 22–24 September on frequency 3.59 MHz (a) and 4.65 MHz (b).  
44 Beginning the storm Fabienne (or passage above observational point) is visible in the data as a

1 short-duration increase of noise across the CDS spectra on both frequencies, Qualitative change  
2 of the echo is evident for the first sight. Data were obtained from Continuous Doppler Sounding  
3 spectrogram archive IAP CAS, Prague, <http://datacenter.ufa.cas.cz/>. Spectrograms of the  
4 recorded infrasound during event Fabienne until 4 UT correspond to the reference time for this  
5 event.

6  
7 The spectral content changed with time and was different during the strong storm event  
8 compared to preceding and following day. During afternoon hours on 22 September, CDS  
9 registers clear sharp echo with wave-like fluctuations. On 23 September on both frequencies  
10 we have observed sudden increase of noise at 18 UT that could indicate arrival of acoustic wave  
11 packet from the frontal border. After that, stronger and blurred echo compared to 22 September  
12 is registered on both frequencies. Wave-like fluctuations are not detected within the signal on  
13 3.59 MHz and 4.65 MHz. On both frequencies (better pronounced on 4.65 MHz on Figure 15  
14 b), there are apparent coincidental drops in frequency at 18 UT. Blurred strong echo was  
15 observed until around 4 UT on 24 September. In the afternoon hours on 24 September, recorded  
16 CDS echo remains slightly blurred but it is significantly weaker. The occurrence of stronger  
17 echo on CDS sounding on 3.59 MHz in the interval 18 UT (23 September) till 4 UT (22  
18 September) corresponds to the increased wave activity on directograms and detection of plasma  
19 flow on both North and East plasma drift components. The trace of 4.65 MHz is limited due to  
20 diurnal course of foF2. Hence the changes of in the CDS signal can be discussed only till 20  
21 UT. Signal detected on 23 September is significantly stronger with respect to preceding and  
22 following days, especially in the part that corresponds to the frequency drop at 18 UT.

23  
24 According to our experience in Chum et al. (2018) we can conclude that we observe  
25 disturbances related to waves propagating from lower-laying atmosphere. It was shown that the  
26 cotyphoon infrasound waves were recorded in the spectral range from ~3.5 to 20 mHz with  
27 maximum of spectral density around 5 mHz (dominant periods between 3 and 4 minutes). The  
28 spectra revealed fine structures that were likely caused by modal resonances.

## 29 30 **7 Conclusion**

31  
32 We have analyzed atmospheric and ionospheric effects induced by fast transit of cold  
33 front with strong storm of the cyclone Fabienne. Cold front passed above Europe within 24  
34 hours with high speed reaching values  $30 \text{ m.s}^{-1}$  (approx.  $108 \text{ km.h}^{-1}$ ) on 23 September 2018.  
35 The synoptic-scale windstorm connected with the cyclone Fabienne was untypical in its time  
36 of occurrence, and velocity of storm moving activity highly exceeded standard values for the  
37 season. The temperature drop on frontal border of  $10^\circ\text{C}$  is also rather large. The major damages  
38 were caused by the storms on frontal border mainly on the territory of Germany, where the wind  
39 gusts reached extreme values  $45 \text{ m.s}^{-1}$  ( $162 \text{ km.h}^{-1}$ ). In the Czech Republic, the strongest wind  
40 gusts of about  $35 \text{ m.s}^{-1}$  ( $126 \text{ km.h}^{-1}$ ) were recorded mountains. Significant strong wind was  
41 observed in lowlands as well. For instance, in the meteo-station Karlov, located in Prague, wind  
42 gust reached values  $27 \text{ m.s}^{-1}$  ( $97 \text{ km.h}^{-1}$ ).  
43

1 We have detected significant change in the dynamical pattern in stratosphere followed  
2 immediately after storm both in wind and temperature. General circulation pattern above  
3 Europe at 0.1 hPa before the storm Fabienne event can be classified/characterized as part of the  
4 stratosphere in normal condition in September. Based on that, we attribute the overall change  
5 of the stratospheric circulation/dynamics to the strong wave-field that was launched upward  
6 from the fast moving mesoscale system.

7  
8 At the time of Fabienne event, ionosphere was slightly influenced by minor to moderate  
9 geomagnetic storm that occurred one day before. According to the evolution of Kp index and  
10 ionospheric plasma parameters (TEC and foF2) ionosphere was already in the recovery phase  
11 of the geomagnetic storm. Nevertheless, the observed disturbances are induced both by  
12 geomagnetic storm and convective activity in the lower laying atmosphere. Regarding results  
13 of model study (Pedatella, 2018) we attribute general decrease in foF2 and TEC to the  
14 geomagnetic forcing (longer-term, negative storm scenario) and significant increase in wave-  
15 like activity (short-term, wave-like activity) to the convective system forcing.

16  
17 We have found significant departures from typical values of ionospheric parameters  
18 shortly after transition of the cold front across the observation point. We have detected sudden  
19 strong increase of wave-like activity on the directograms and CDS records. Detected strong  
20 echo on directograms shows strong and rapid changes in the horizontal plasma motion. During  
21 the observation, there was no prevailing plasma motion direction. It rather accounts for  
22 turbulent flow within F-layer. In the strong echo in directograms attributed to the storm, there  
23 is no characteristic prevailing motion, but sudden changes in direction are observed through the  
24 event. Time-limited increase of plasma drift in North and East direction has been detected  
25 together with decrease of velocity of the vertical plasma flow. Wave-like oscillations are present  
26 within ionospheric plasma all the time. In the WPS spectra of critical frequency we have  
27 detected change of the spectral content during day of the Fabienne event compared to preceding  
28 day. We have noticed decrease of F layer thickness during day of the Fabienne event. Irregular  
29 stratification of the ionosphere is confirmed by spread-echo recorded by Digisonde during  
30 afternoon and night on 23 September till morning 24 September. CDS data show significant  
31 change in spectral content, shape and power of the registered signal corresponding to  
32 modulation by waves propagating from convective system. As it has been pointed out, for  
33 instance in Yigit and Medvedev (2015, 2017), the gravity waves originating in the lower  
34 atmosphere are able to significantly alter processes up to the thermospheric heights and their  
35 impact is highly variable according to actual state of the background atmosphere.

36  
37 On the above summarized results, we conclude that mesoscale system Fabienne is  
38 effective source of atmospheric disturbances that can reach ionospheric heights and  
39 significantly alter atmospheric and ionospheric conditions. Convective system Fabienne  
40 affected Earth's atmosphere on a continental scale and up to F-layer heights. Even during  
41 periods of geomagnetic disturbance, minor to moderate geomagnetic storm, the contribution of  
42 the lower atmosphere to the ionospheric dynamics cannot be neglected. Our experimental result  
43 is in agreement with theoretical study of Pedatella (2018) that internal atmosphere variability  
44 should be taken into account even during geomagnetic disturbances.

*Code availability*

<http://umlcar.uml.edu/digisonde.html>

*Data availability*

Data used for the paper can be downloaded via following sites:

<https://www.ventusky.com/>

<https://www.wetterkontor.de/>

<http://wetter3.de>,

<http://www.ufa.cas.cz/institute-structure/department-of-meteorology/present-weather-sporilov.html>

[http://aeolus-ds.eo.esa.int/socat/L1B\\_L2\\_Products](http://aeolus-ds.eo.esa.int/socat/L1B_L2_Products)

<https://disc.gsfc.nasa.gov/daac-bin/FTPSubset2.pl>

<http://giro.uml.edu/>

<http://digisonda.ufa.cas.cz/>

[http://www.ufa.cas.cz/files/OHA/M\\_Doppler\\_system.pdf](http://www.ufa.cas.cz/files/OHA/M_Doppler_system.pdf)

<http://datacenter.ufa.cas.cz/>

[http://gnss.be/Atmospheric\\_Maps/ionospheric\\_maps.php](http://gnss.be/Atmospheric_Maps/ionospheric_maps.php)

<https://www.gfz-potsdam.de/en/kp-index/>

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Kateřina Potužníková (KACA) – meteorology data preparation and interpretation

Daniel Kouba (DK) – DPS 4D settings, Drift data analyses

Zbyšek Mošna (ZM) - TEC data analyses and interpretation, figure preparation

Josef Boška (JB) - DPS 4D data interpretation

Michal Kozubek (MK) – stratospheric data analyzes and interpretation

*Competing interests.*

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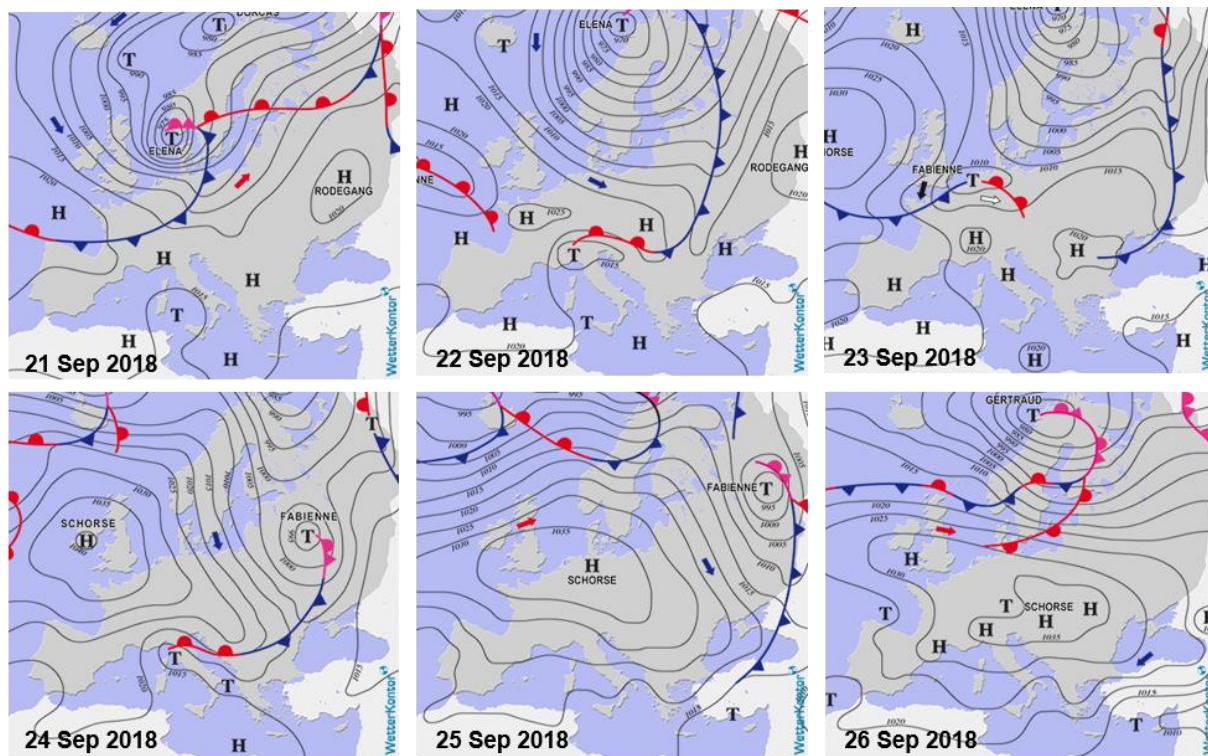
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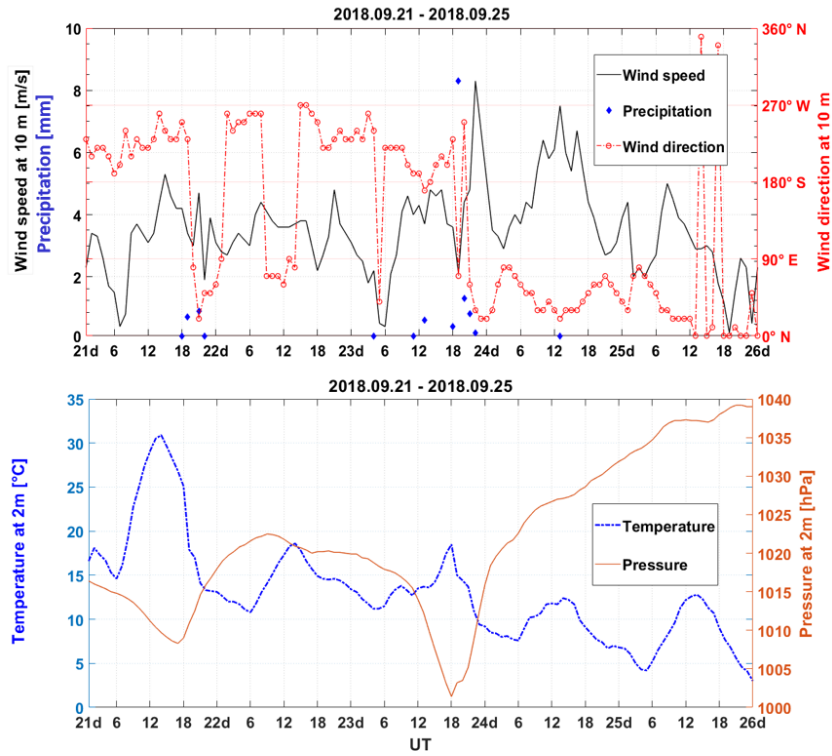
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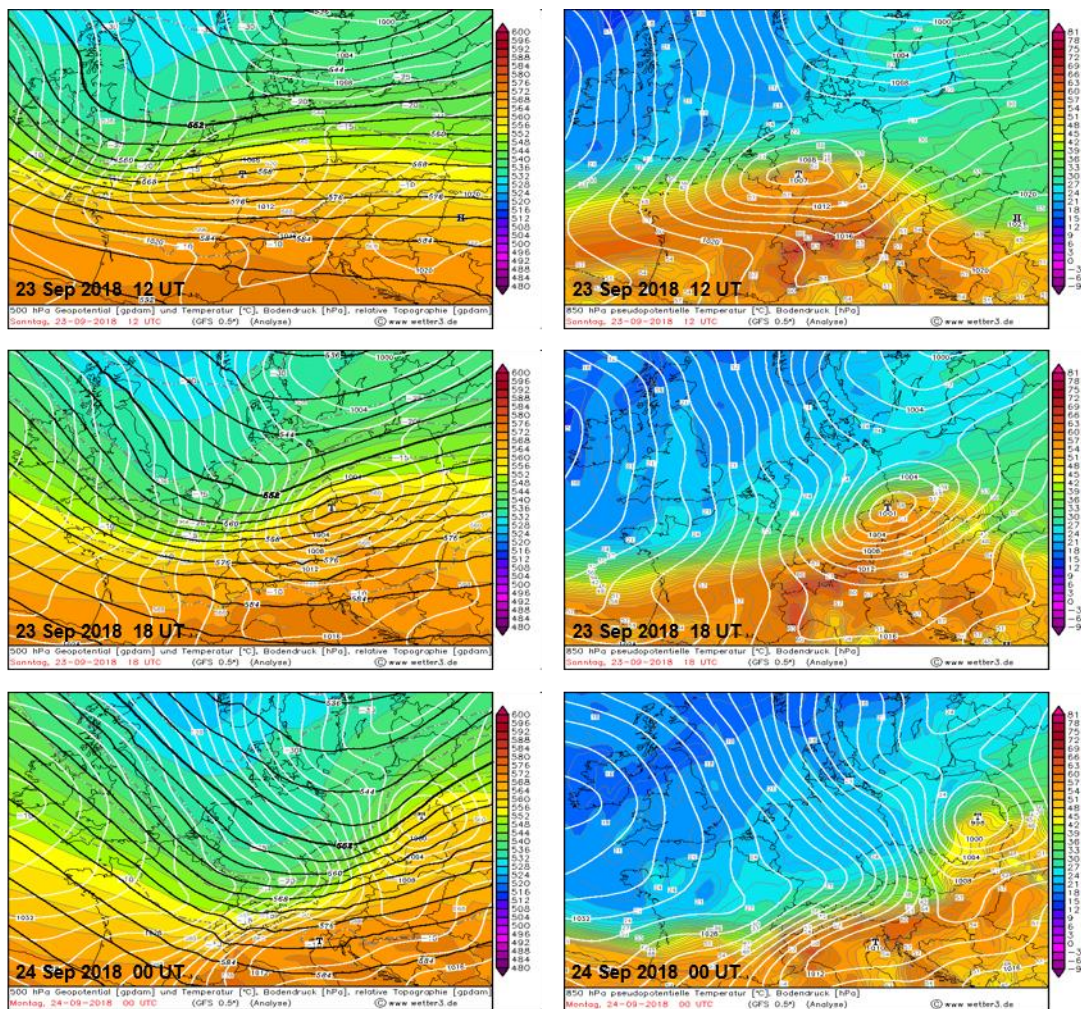


**Fig. 1.** Surface pressure maps provided by Wetterkontor, from [www.wetterkontor.de](http://www.wetterkontor.de). Surface pressure is plotted with solid lines with 5 hPa step. Atmospheric fronts (red curved lines with red semi-circles that point in the direction of warm front, blue curved line with blue triangles that point in the direction of cold front and purple line with alternating triangles and semi-circles pointing in the direction in the occluded front is moving), the location of the centres of high (H) and low (T) pressure systems are also presented.



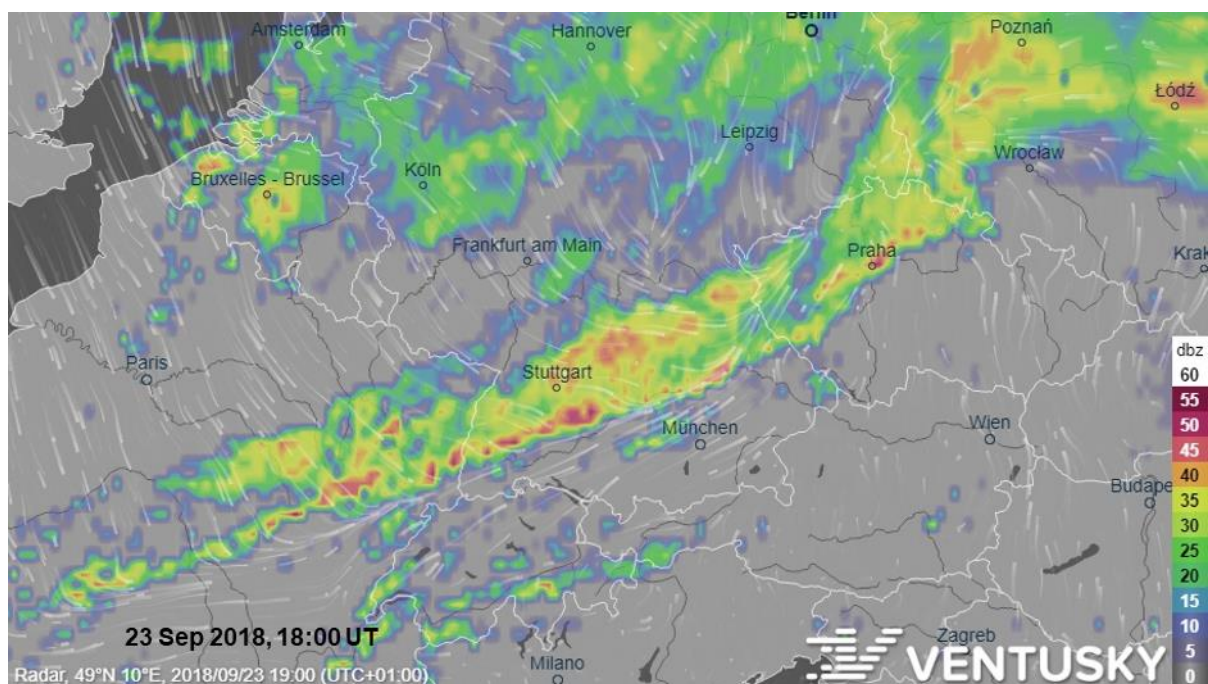
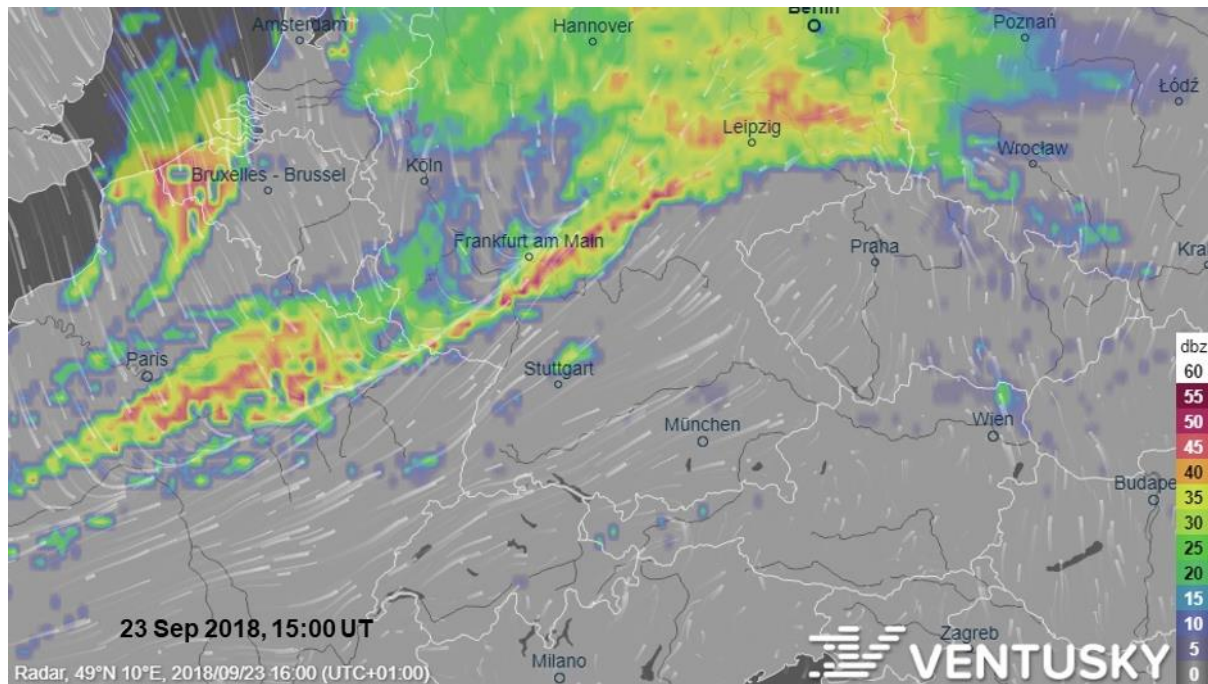
**Fig.2.** Hourly averages surface observations at IAP meteorological station. Atmospheric pressure, air temperature and precipitation amount are measured at 2 m height above the surface, wind speed and direction at 10 m height above the surface.



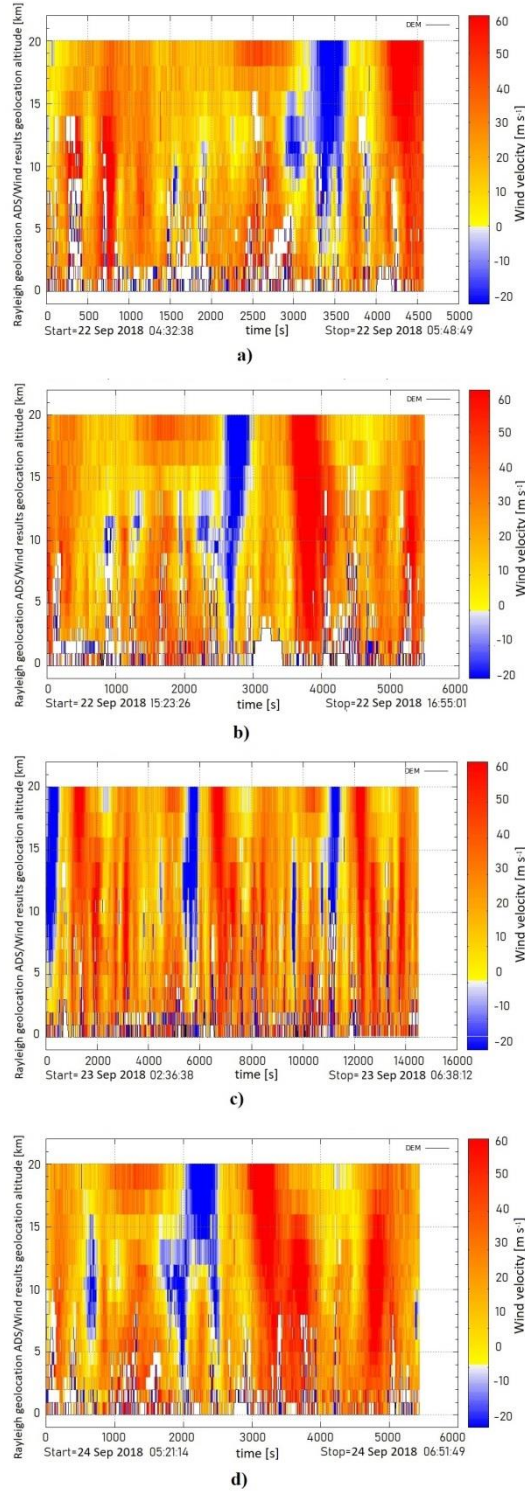


**Fig.3. Left panels:** Distribution of the geopotential field (black lines) and temperature (gray dashed lines) at level of 500 hPa, of the surface pressure field (white lines), and of relative topography 500–1000 hPa (color field). The 500 hPa is given in units of 10 geopotential decameter (gpdam), the temperature in °C, the surface pressure in hPa, and the 500/1000 hPa thickness in gpdam. Isohypsies and thickness are 4 gpdam apart, isobars 2 hPa and isotherms 5 °C. The thickness or difference in heights between the 1000 hPa (surface) and 500 hPa levels varies on temperature and moisture (is a function of average virtual temperature), thus the color field regions depicted the average temperature of the troposphere. (Orange/red values indicate warm tropical air, blue/indigo indicate arctic air.) **Right panels:** Analysis of pseudo-equivalent potential temperature in 850 hPa pressure level in °C (color field and isotherms - gray lines, 3 °C apart) and surface pressure field (isobars - white lines, 2 hPa apart). The pseudo-equivalent potential temperature is conservative in association with the moisture thus it allows to compare temperature of air masses in lower troposphere regardless of their humidity.



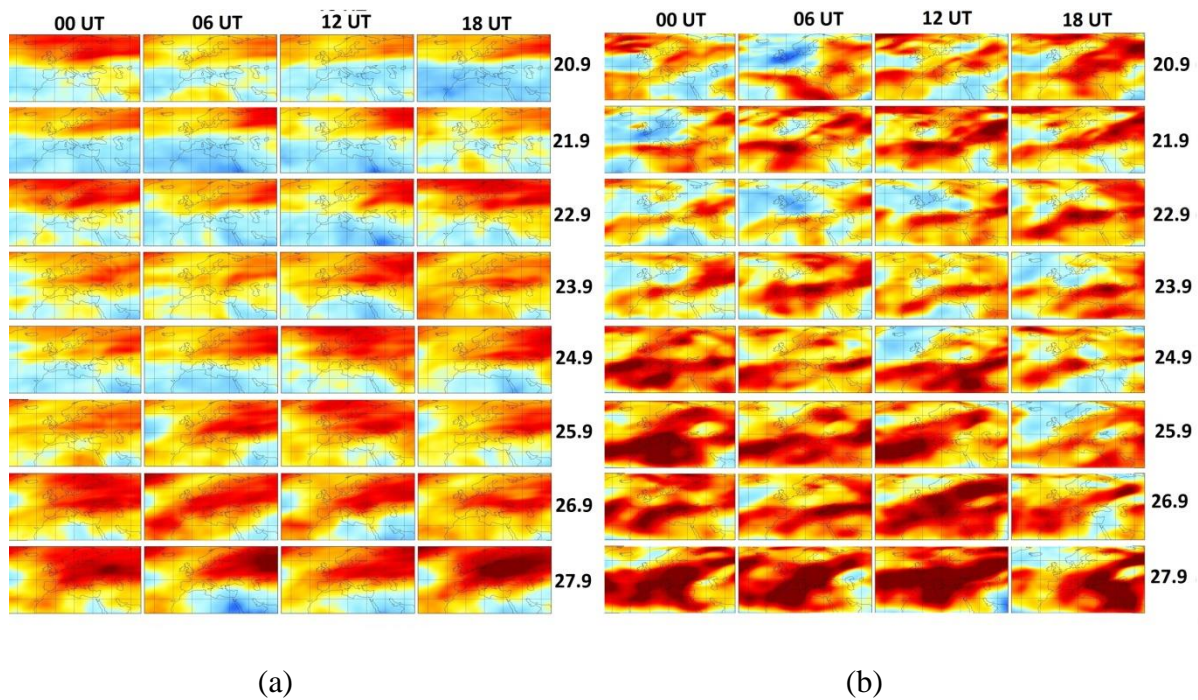


**Fig. 4.** Horizontal maximum projection of radar reflectivity from the European radar provided by VentuSky (<https://www.ventusky.com>). There is a rapid shift of the strong thunderstorms line (squall line) by 350 km per three hours. White lines illustrate the wind speed at ten meters above the ground. The colour scale indicates the radar reflectivity in 5 dBZ increments. The scale demonstrates exponential dependence of precipitation intensity [ $\text{mm h}^{-1}$ ] on radar reflectivity [dBZ]. The value of 55 dBZ (dark purple) corresponds to the instantaneous value of intensity of convective precipitation  $100 \text{ mm h}^{-1}$ .



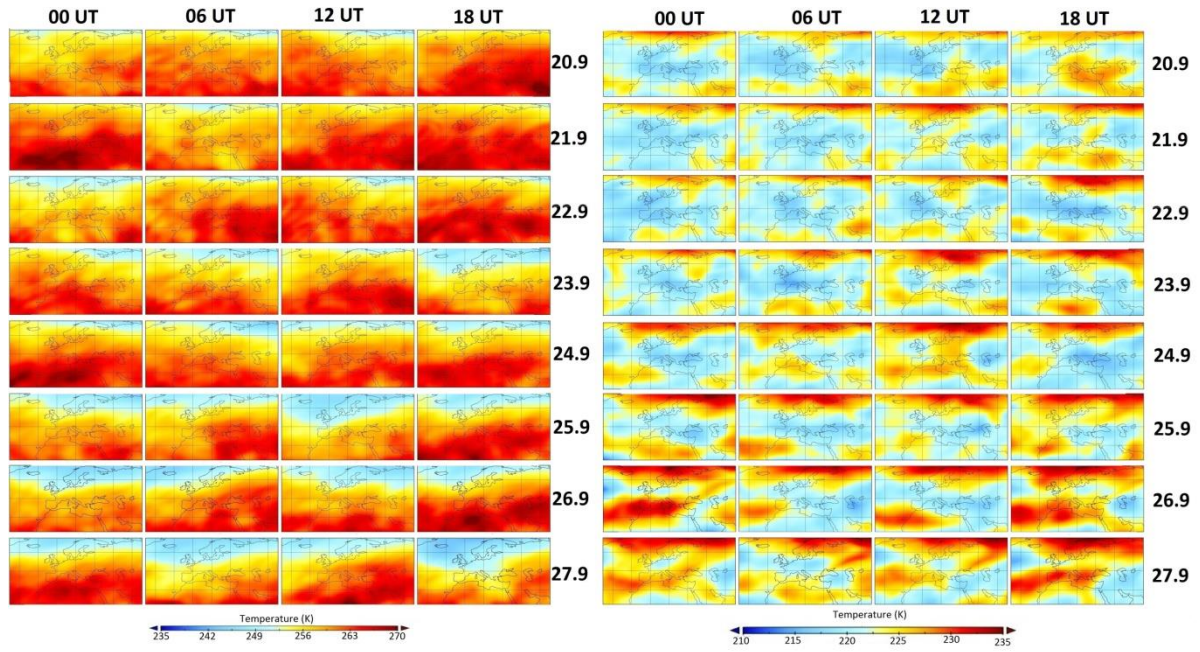
**Fig.5.** Aeolus Rayleigh scattering observations of wind profiles up to 20 km. The MDS wind profiles (positive towards the instrument) measured during the orbit numbers 513 and 514 on 22–24 September 2018 between 04:32 and 06:51 UTC using the MDS Rayleigh scattering. The blue areas indicate zones during which the wind speed variations introduced by the Rayleigh response fluctuations are negative. Random Error ( $1\sigma$ ) is  $1\text{ m}\cdot\text{sec}^{-1}$  at altitudes less than 2 km,  $2\text{ m}\cdot\text{sec}^{-1}$  between 2 and 16 km. Systematic Error ( $1\sigma$ ) is smaller than  $0.7\text{ m}\cdot\text{sec}^{-1}$ .





**Fig. 6.** Stratospheric wind above Europe at 1hPa (panel a), and at 0.1hPa (panel b). Red color represents eastward wind, blue represents westward wind.

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3

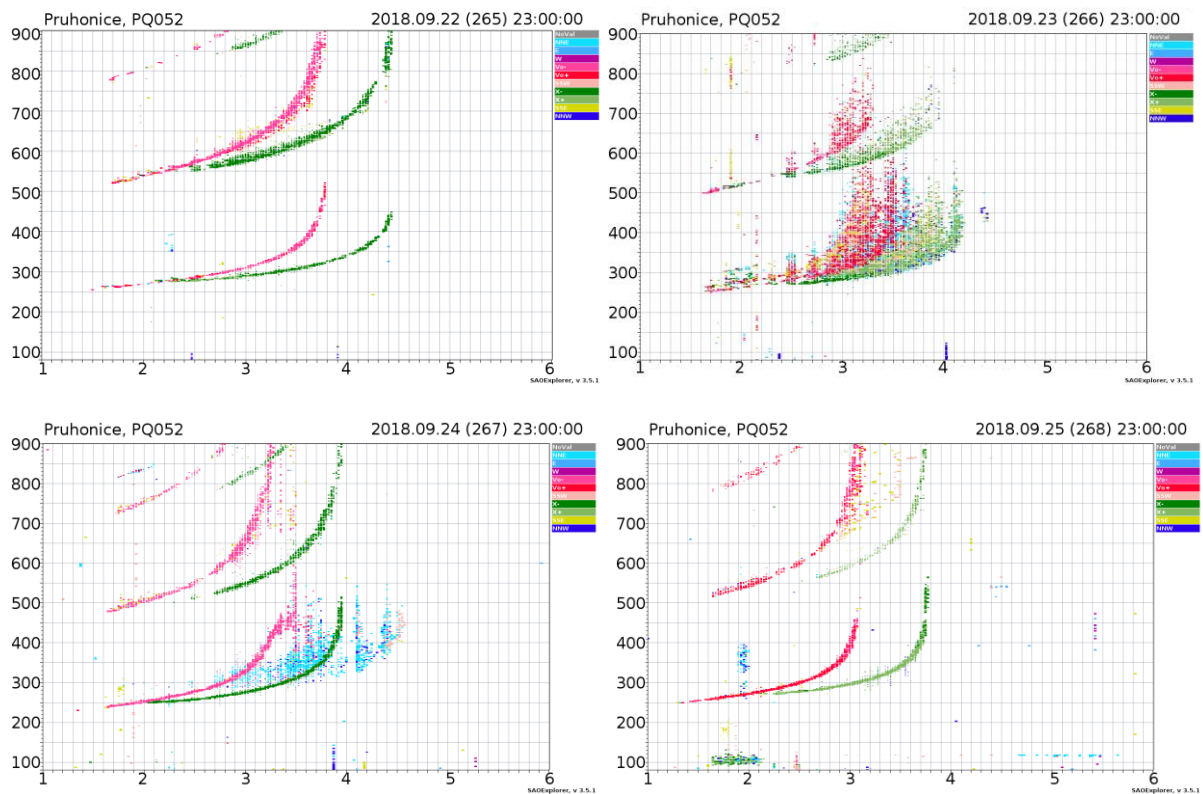


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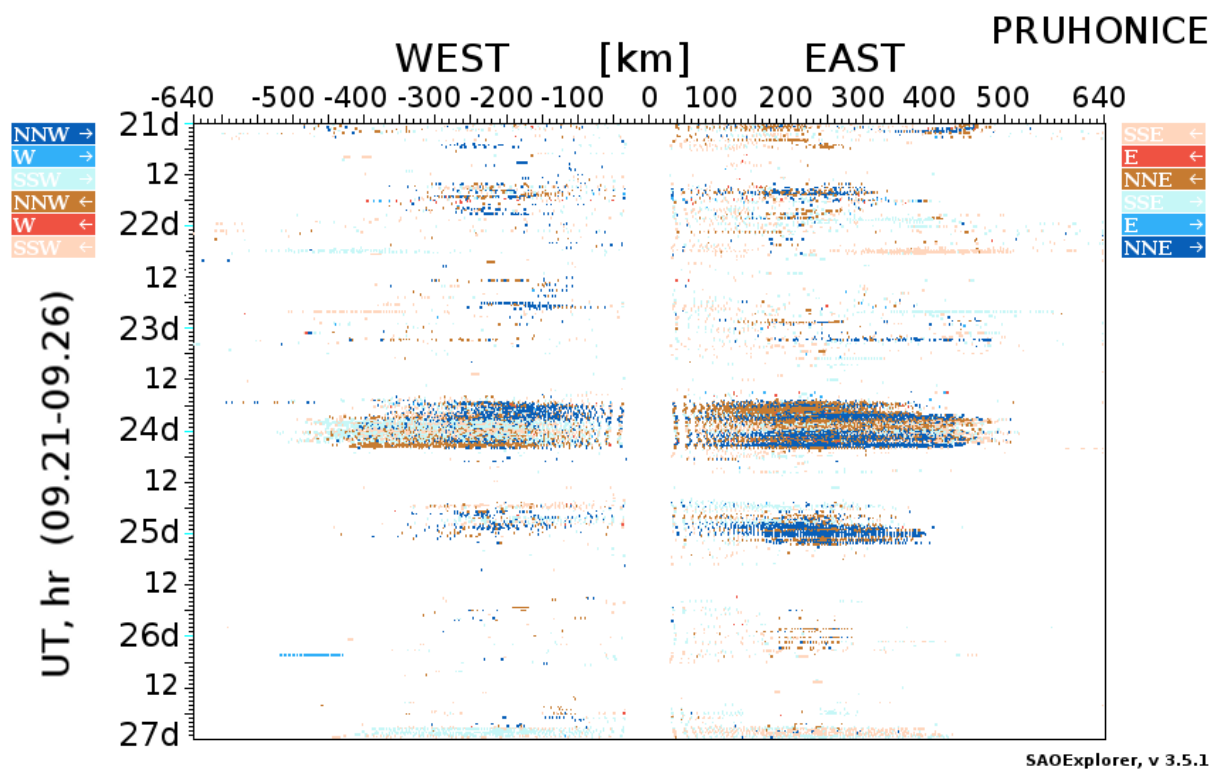
(a)

(b)

**Fig. 7.** Stratospheric temperature above Europe at 1hPa (panel a; temperature in the range 235 – 270 K) and at 0.1 hPa (panel b; temperature in the range 210 – 235 K).

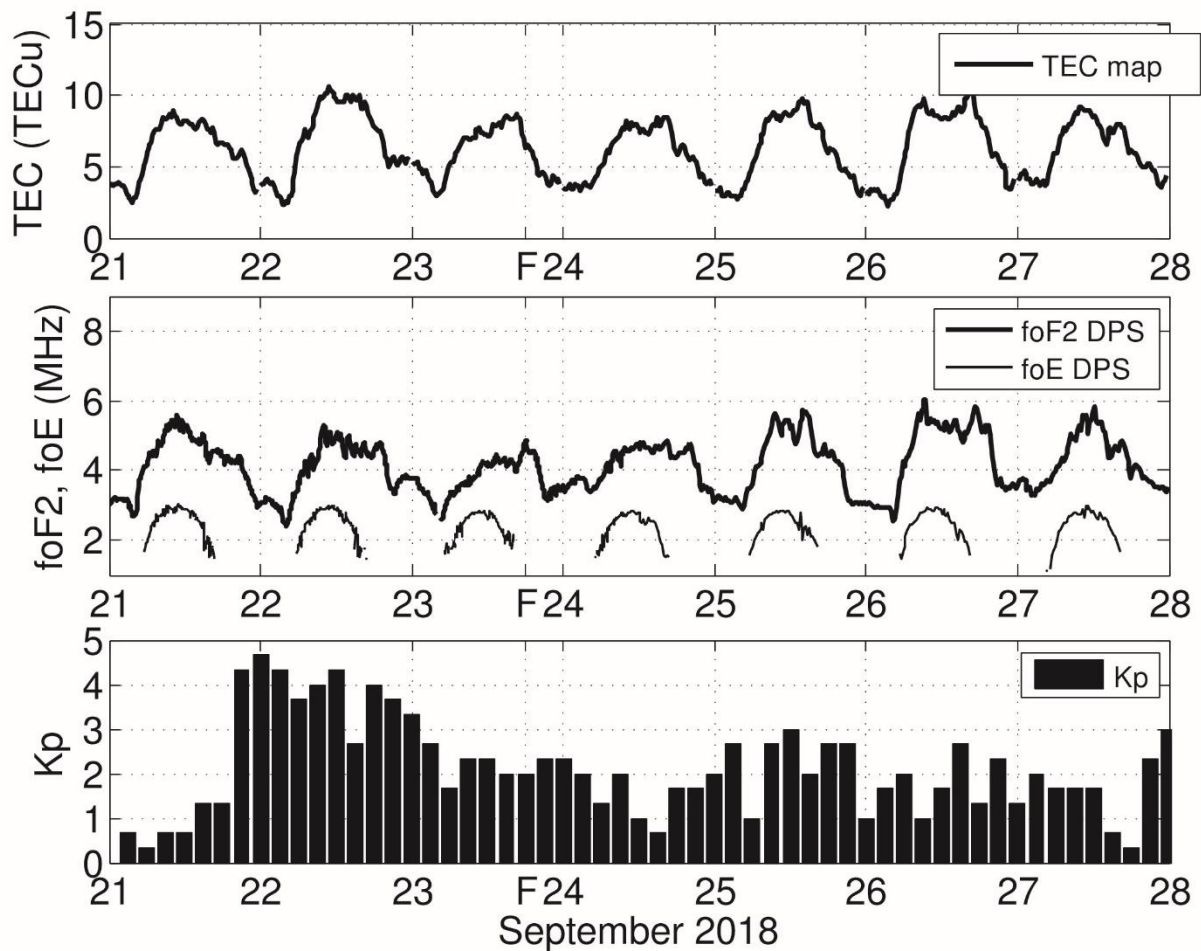


**Fig. 8.** Sequence of ionograms recorded during local night at around 23 UT presented in a standard DPS 4D format. Particular color indicates direction of radio wave arrival. Vertical echo of ordinary wave is marked by red color, while green color stands extraordinary wave. Other colors represent non-vertical reflections. The strongest non-vertical echo comes from North-North-East direction (light blue color).



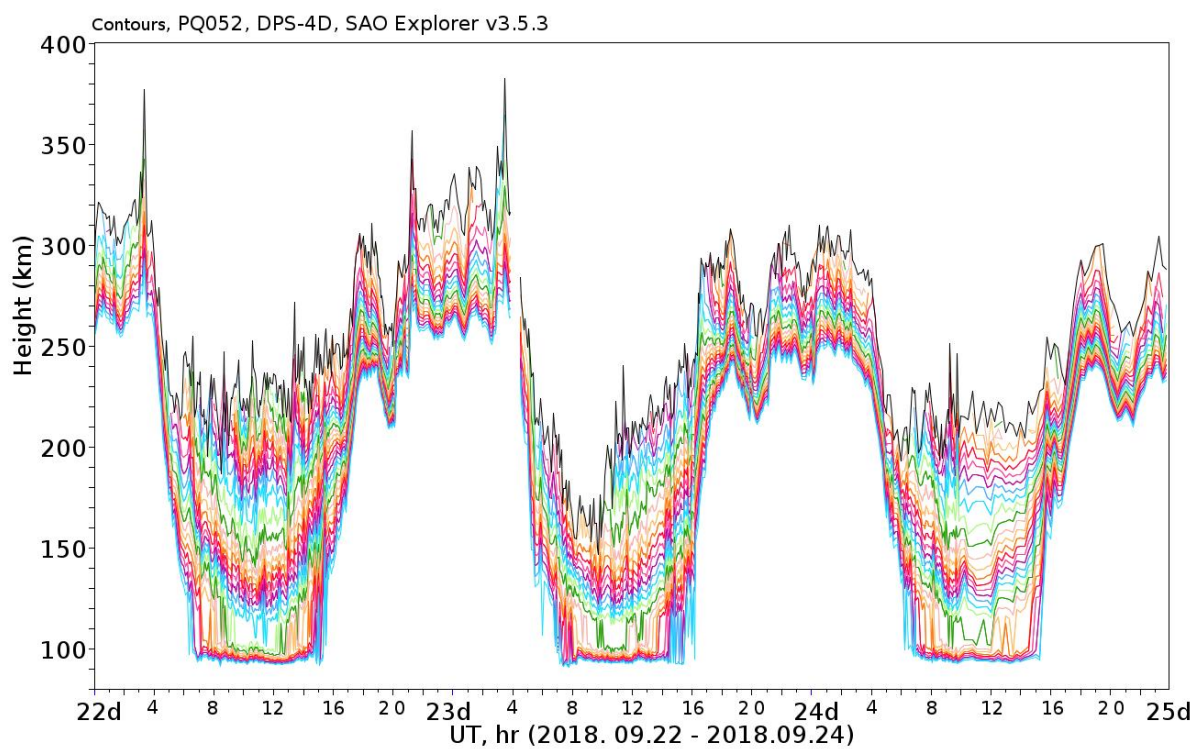
SAOExplorer, v 3.5.1

**Fig. 9.** Directogram – direction of plasma motion above the observation site - recorded on 21–26 September presented in a standard DPS 4D format. Due to geometry of receiving antenna field, DPS 4D identifies direction of the wave arrival. The directograms are constructed from the raw ionograms. Each color correspond to particular antenna beam, hence the direction of the arrival of oblique echo from large scale irregularities. It is denoted by particular color on the left and right side of the diagram.



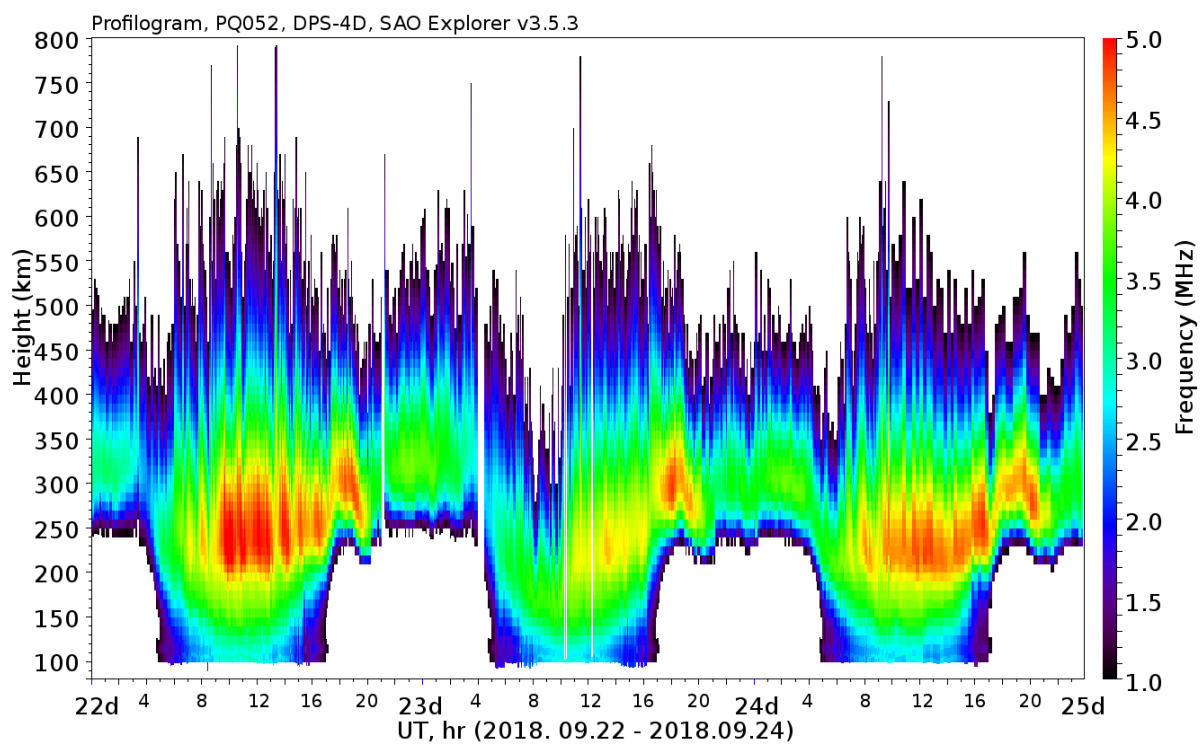
**Fig. 10.** Diurnal courses of Total Electron Content (upper panel), critical frequencies foF2 and foE (middle panel) above station Pruhonice ("F" denotes time of passage of the storm Fabienne over the station) and course of Kp index (bottom panel) during the observational period.



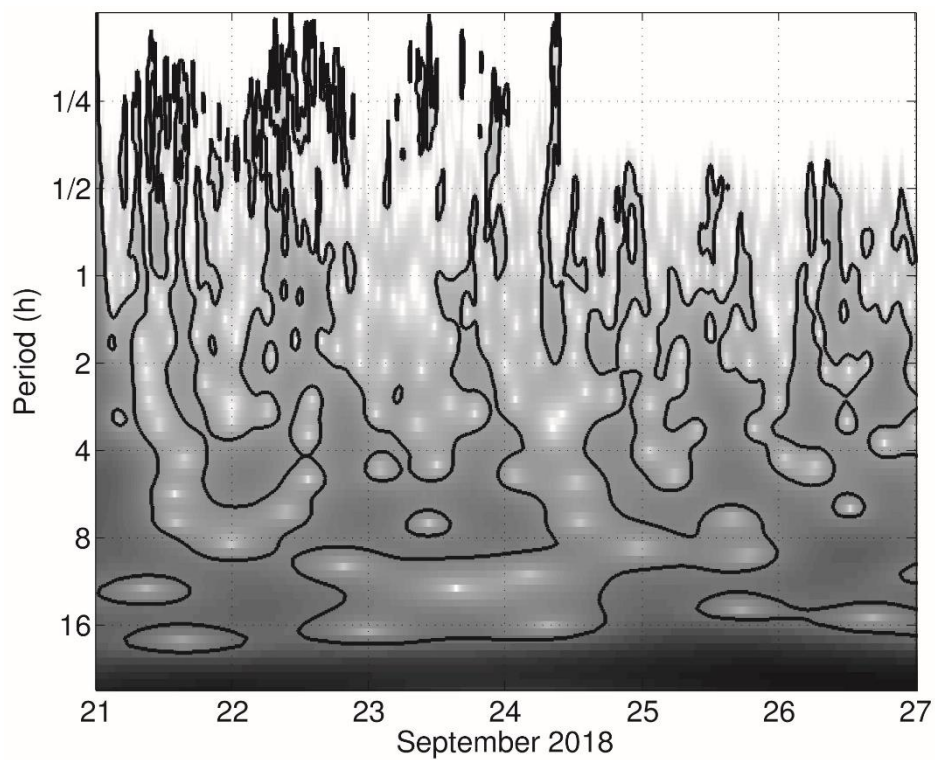


**Fig.11.** Variability of true-height reflection at fixed frequencies recorded during 22–24 September for frequency range 2–6 MHz with 0.1 MHz step, in a standard DPS 4D format.



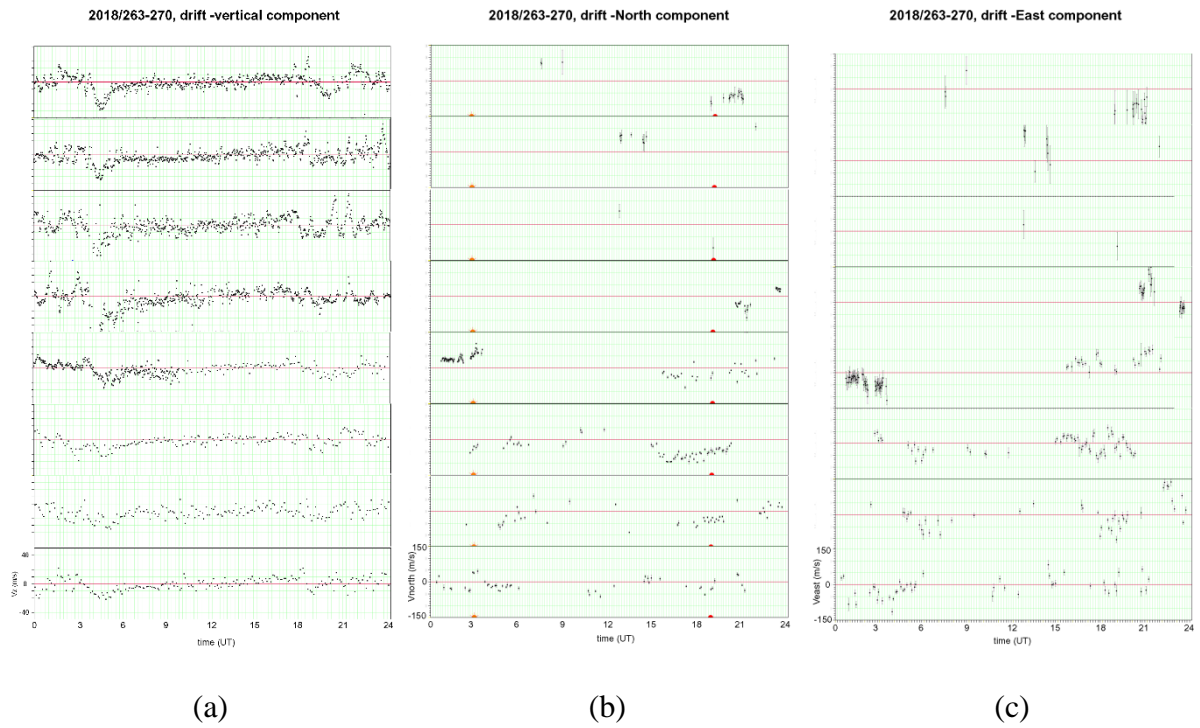


**Fig. 12.** Detail of profilograms in frequency – 22 September–24 September presented in a standard DPS 4D format.

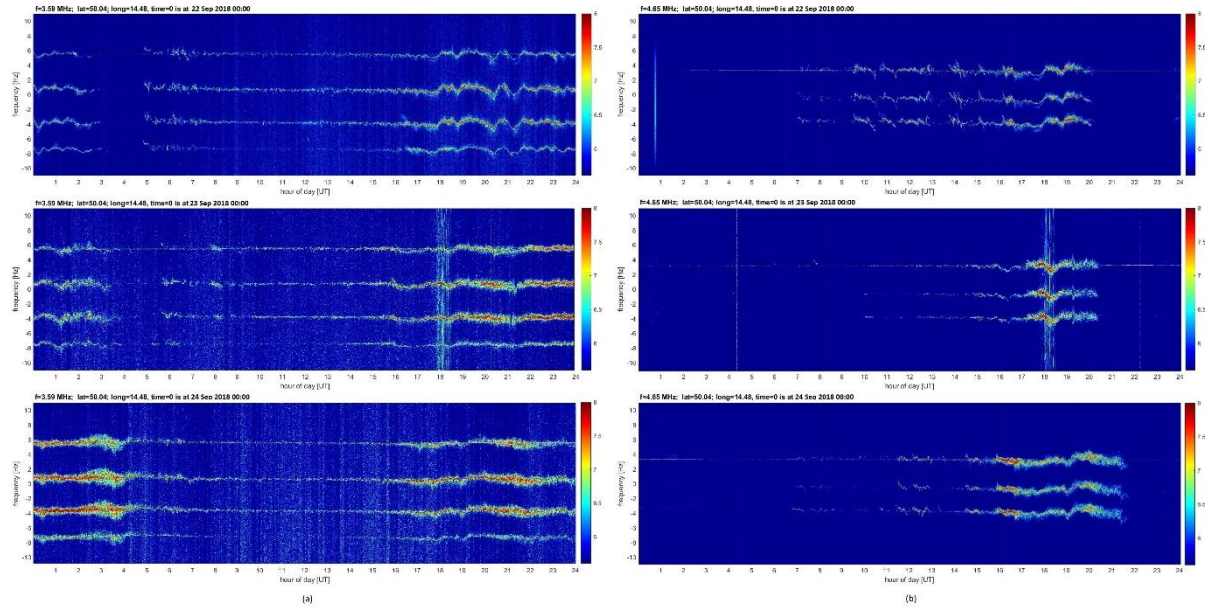


**Fig.13.** Wavelet Power Spectra of critical frequency foF2 for 21–27 September, 2018. WPS is normalized on each scale to corresponding scale maximum. Dark areas exceed 0.95 significance level on each scale.

1  
2



**Fig. 14.** Components of ionospheric plasma drift obtained by Digisonde DPS 4D during the studied event 20 September (top panel) – 27 September (bottom panel) – (a) vertical component; (b) North component; (c) East component presented in a standard DPS 4D format.



**Fig. 15.** Continuous Doppler Sounding measurement on three consequent days 22–24 September on frequency 3.59 MHz (a) and 4.65 MHz (b).