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Observation of Tropospheric Deep Convection in Mid-Latitudes with Potential Impact up to Ionospheric Heights

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Abstracts

Our case study investigates the coincidental occurrence of intense tropospheric convection and upper atmospheric variability. It focuses on the generation of gravity waves (GWs) at tropospheric heights and their potential impact on the ionosphere. Our analysis presents an organised mesoscale convective system (MCS) associated with a derecho event and air-mass severe thunderstorms with supercells occurring.

In both cases, sporadic ionospheric E layer was recorded. A significant reduction in electron density, which was expected after the passage of an extensive MCS, was also observed in the case of very intensive but spatially limited supercell thunderstorms.

1. Introduction

Sun and its changing activity are the most important factors influencing the state and variability of the neutral atmosphere and ionosphere. Changing solar flux and geomagnetic activity are reflected on broad time scales ranging from abrupt changes related for instance to geomagnetic storms up to secular solar variation. Apart from the solar and geomagnetic drivers, influence of the lower-lying atmospheric regions can contribute significantly to the resulting energy budget [Laštovička, 2006; Yigit et al., 2016; Koucká Knížová et al., 2018]. In the troposphere and lowermost stratosphere, convective storms represent important sources of atmospheric gravity waves (GWs), which can propagate upwards. Under favourable conditions defined by the neutral atmosphere dynamics, these waves may reach ionospheric heights and significantly influence the thermosphere and ionosphere up to the F2 layer.

In this study, we present ionospheric response on two different tropospheric convective sources of gravity waves over Central Europe and its: (i) a mesoscale convective system (MCS) with a derecho event, and (ii) a local-scale severe thunderstorms. Both meteorological cases emerged during periods of relatively quiet geomagnetic activity and stable solar forcing. Therefore, we further suppose that the observed disturbances in the ionosphere are primarily induced by GWs originated in the intense tropospheric convection.

2. Tropospheric observation

Strong updrafts in intense thunderstorms can penetrate the tropopause and extend a few kilometres into the lower stratosphere, where rising air parcels lose buoyancy, descend back to equilibrium level, and spread laterally to form extensive anvil clouds. These processes act as efficient sources of GWs that may propagate into the mesosphere and ionosphere. MCS is a cluster of storm cells with a roughly circular anvil several hundred kilometres across. MCSs typically form in the afternoon and may persist overnight due to radiative cooling of the anvil, which maintains sufficient lapse rate even without surface heating. With lifetimes often exceeding six hours, they represent long-lived sources of gravity waves comparable in cumulative impact to smaller tropical cyclones. In contrast, severe single-cell thunderstorms cover smaller areas. However, in some cases, they can develop into supercells with rotating updrafts whose intensity can locally equal or even exceed that of an MCS. In Central Europe, there are several mesoscale convective systems forming per year during the warm season (typically late May till early September). In addition, according to the European Severe Weather Database (ESWD), dozens of supercell thunderstorms occur annually in this region.

Figure 1 shows a MCS of the squall line type, formed in a very warm and humid air mass ahead of a cold front. The core of the storm, as indicated by both the overshooting tops visible on the satellite image (the sharp dark red spots) and the maximum reflectivity visible on the radar image, is arranged in a line along the German–Czech border. The southern part of the storm line is clearly bowed in the direction of its eastward movement. This indicates the intensification and subsequent acceleration of this part of the storm line. As the storm quickly moved across the Czech Republic, it was accompanied by destructive wind gusts at ground level that met the definition of a derecho (wind speeds greater than 25 m/s recorded over an area greater than 400 km).

At the end of May 2008, warm and moist air was advected northward into Germany from the Mediterranean region along large-scale upper-level trough, resulting in unstable atmospheric conditions favourable for deep convection. Figure 2 shows two independent supercells near the western border of the Czech Republic, each exhibiting cold rings and cold-U/V features ([Setvák, 2010] and summary of references herein), known as indirect indicators of potential storm severity. Throughout their existence, the storms generated a series of distinct overshooting tops that may have acted as sources of upward-propagating GWs. Compared to the previous MCS situation, the supercells have a smaller area of high reflectivity above 50 dBZ (an indicator of intense convection and dangerous phenomena such as hailstorms and torrential rain).

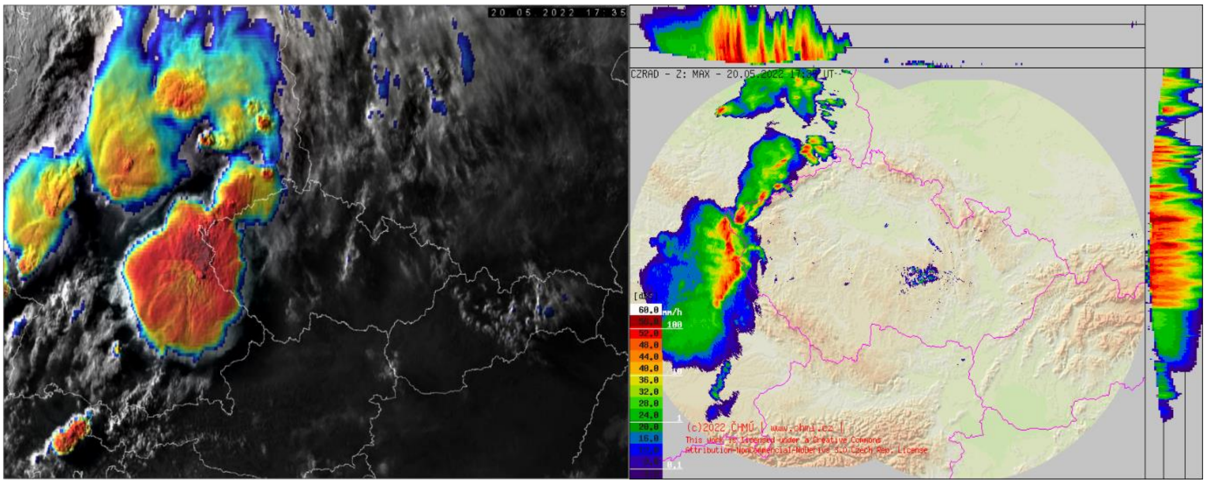

Figure 1. *MCS on 20 May 2022 at 17:35 UTC. Left panel: The Meteosat-10 (MSG3) sandwich product comprises VIS and colour-enhanced IR channels ranging from 200 K (dark red) to 240 K (blue). Source: EUMETSAT; CHMI. Right panel: CZRAD composite of maximum reflectivity (dBZ scale at bottom left) in pseudo 3D view, [Novak, 2007]. Source: CHMI.*

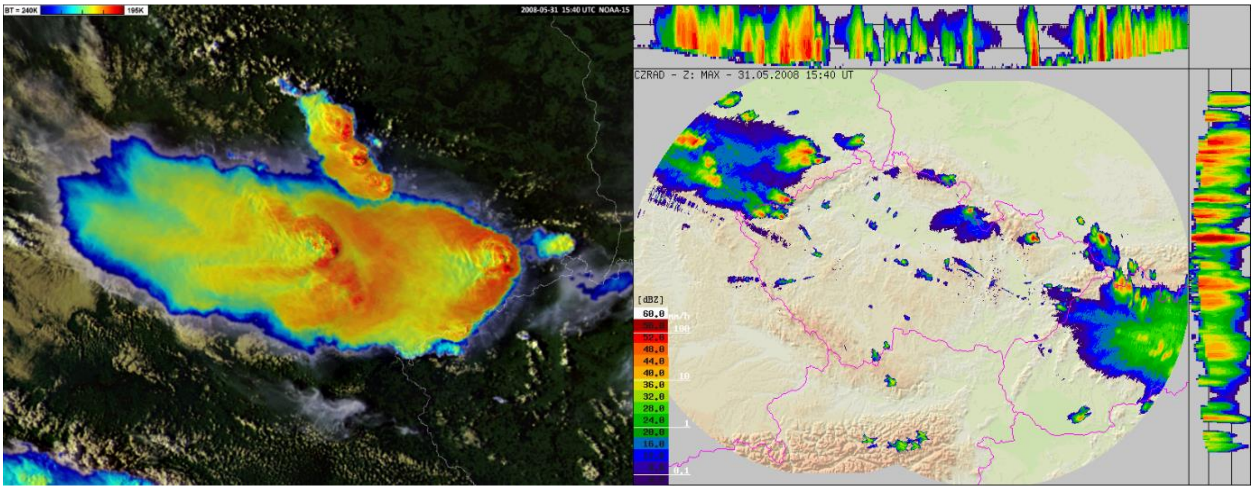

Figure 2. *Supercells on 31 May 2008 at 15:40 UTC. Left panel: NOAA-15 polar-orbiting satellite, sandwich product [Setvák et al., 2013]. Source: EUMETSAT; CHMI. Right panel: Same as the Right panel of Figure 1.*

3. Ionospheric response

Both analyzed events occurred during relatively similar conditions (low geomagnetic, stable solar forcing and season - spring before solstice) but in different Solar Cycles. Ionosphere is regularly monitored by digisonde DPS 4D with 5 and 15-minute cadence. Ionograms are manually scaled. Electron density profiles are inverted using the NHPC inversion technique. The Profilogram on Figure 3 represents the course of electron profiles for five consecutive days covering two days before and after the events. It shows variability of the entire electron density profiles. Wave-like variations in the electron concentration are well seen especially during daytime. In the case of MCS, a remarkable increase of electron concentration was seen one day before. Rather high electron concentration remains in the ionosphere during the day of the event. Afterwards, the fast depletion of the electron density is observed. The right panel on Figure 3 shows the profilogram observed during the supercell event. One can see less pronounced changes in the electron concentration compared to the MCS event. However, some depletion of electron density can still be observed during the day of the event that remains till the following day. The gaps in the profilograms are caused by the presence of a sporadic E layer, that especially in 2008 event is rather strong and is blanketing the ionosphere above. In Figure 4, the detailed analysis of the variability of critical frequency of the F2 layer (foF2) and corresponding maximum height (hmF2) reveals for both cases a slight decrease in foF2 (blue line) corresponding to the depletion seen on profilograms. While on the course of hmF2 (red lines) slight uplift is seen during the day of event followed by decrease on the consecutive days.

Our study confirms the observation of the electron concentration depletion in the whole profile shortly after the occurrence of a MCS and local scale supercell thunderstorms. Gravity waves launched by such tropospheric systems may alter the process of ionization, recombination and transport process so that it may lead to the decrease of electron concentration. Similar effects related to the organised tropospheric convection were reported in studies [Barta et al., 2025; Koucká Knížová et al., 2024; Koucká Knížová et al., 2023].

The wave-like activity in the gravity wave spectrum is well seen on the occurrence of particular types of the echo (split and spread echo) on ionograms recorded by digisonde DPS 4D (not shown here). Such types of the echo are observed when the reflection planes Spread F echo, often associated with atmospheric wave activity, occurs on several consequent ionograms before sunrise of the following day.

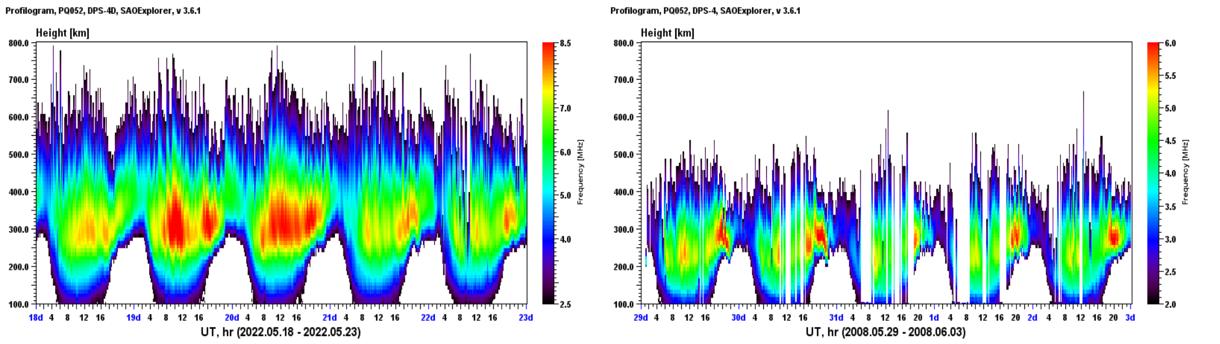

Figure 3. *Left panel: Profilogram from Průhonice observatory 18 - 22 May, 2022, displays variability of electron density profiles during five consecutive days covering day of MCS. Right panel: Same as the left panel for 29 May - 2 June, 2008 for the event of supercells.*

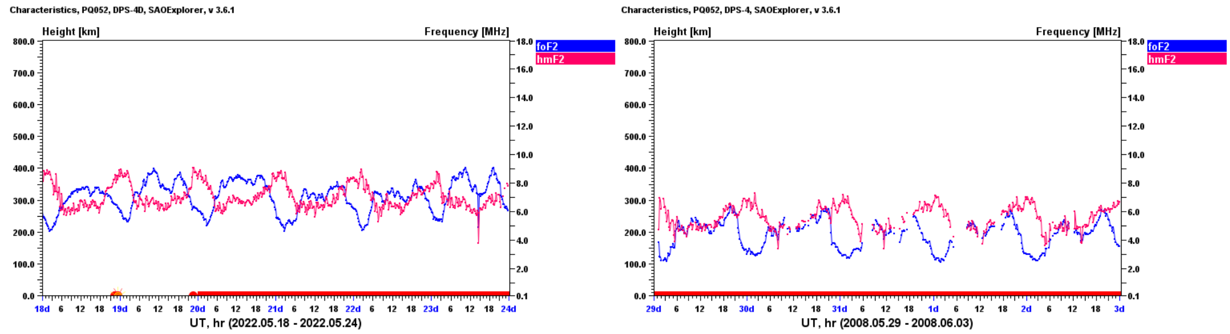

Figure 4. *Course of foF2 (blue line) and hmF2 (red line).*

4. Conclusion

This case study examined two meteorological events associated with severe convection. The first event was a MCS that developed ahead of a cold front. Based on records from meteorological surface stations and radar, this event was classified as a derecho, this event was classified as a derecho, confirming the mesosynoptic scale of the convection visible on satellite image. The second event was a severe air-mass (non-frontal) local-scale supercell thunderstorm. The vertical sounding measurement revealed similarity in the ionospheric response. The depletion of electron density was most pronounced feature. The uplift of the F2 layer maximum was registered shortly after the tropospheric situation occurrence close to sounding site. In both cases sporadic E was detected. In the derecho case, the sporadic E blanketed significantly the ionosphere above. Our preliminary results suggest that the effects of severe local-scale thunderstorms should not be overlooked in research on troposphere–ionosphere coupling.

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