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A statistical analysis on the relationship between thunderstorms and the sporadic E Layer over Rome

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Meteorological processes (cold fronts, mesoscale convective complexes, thunderstorms) in the troposphere can generate upward propagating waves in the neutral atmosphere affecting the behaviour of the ionosphere. One type of these waves are the internal atmospheric gravity waves (AGWs) which are often generated by thunderstorms. Davis & Johnson (2005) found in low pressure systems that a localized intensification of the sporadic E layer (Es) can be attributed to lightnings. To confirm this result, we have performed two different statistical analysis using the time series of the critical frequency (foEs), the virtual height of the sporadic E layer (h'Es), and meteorological observations (lightnings, Infrared maps) over the ionospheric station of Rome (41.9° N, 12.5° E). In the first statistical analysis, we separated the days of 2009 into two groups: stormy days and fair-weather days, then we studied the occurrence and the properties of the Es separately for the two different groups. No significant differences have been found. In the second case, a superposed epoch analysis (SEA) was used to study the behaviour of the critical frequency and virtual height 100 hours before and after the lightnings. The SEA shows a statistically significant decrease in the critical frequency after the time of the lightnings, which indicates a sudden decrease in the electron density of the sporadic E layer associated with lightnings.

1 Introduction

The first hypothesis that there could be a relationship between the thunderstorms and the ionosphere was predicted by Wilson (1925). Meteorological processes (cold fronts, mesoscale convective complexes, thunderstorms) in the lower atmosphere can affect the ionosphere mainly through two mechanisms: (i) electrical and electromagnetic phenomena (red sprites, blue jets etc.) and (ii) upward propagating waves in the neutral atmosphere (Laštovička 2006). One type of these waves are the internal atmospheric gravity waves (AGWs) which are generated by thunderstorms in the troposphere (Medeiros et al. 2004), but they are also generated by strong atmospheric fronts irrespectively of lightnings (Sauli & Boška 2001). According to the numerical simulations, the atmospheric gravity waves generated by convective systems in the troposphere break at mesopause heights, and they can excite upward propagating secondary waves that can be trapped in the upper mesosphere, and the lower thermosphere (Snively & Pasko 2003). The one-to-one correspondence between a meteorological phenomenon in the lower atmosphere and an AGW in the mesosphere is directly observable on the nighttime airglow images (Suzuki et al. 2007). The results of the model of Vadas & Liu (2011) showed that the velocities of the GWs can be higher than the velocities of the background tidal winds and can significantly affect the properties of the F-region.

Davis & Johnson (2005) revealed that the ionospheric sporadic E layer has a statistically significant intensification and a descent in the virtual altitude after thunderstorms, which have passed through over the ionospheric monitoring station at Chilton, UK. However, there was no response from the ionosphere in cases of low-pressure systems without electrical activity, consequently these changes in the properties of the sporadic E layer can be attributed to lightnings (Davis & Johnson 2005). Besides, a superposed epoch analysis (SEA) by Kumar et al. (2009) showed that the direction of the arrival of the thunderstorm is also very important. When the sources of the AGWs are in the opposite direction to the mean neutral wind flow, the effects of the thunderstorms on the ionosphere are dominant (Kumar et al. 2009). Furthermore, when they have used a longer time

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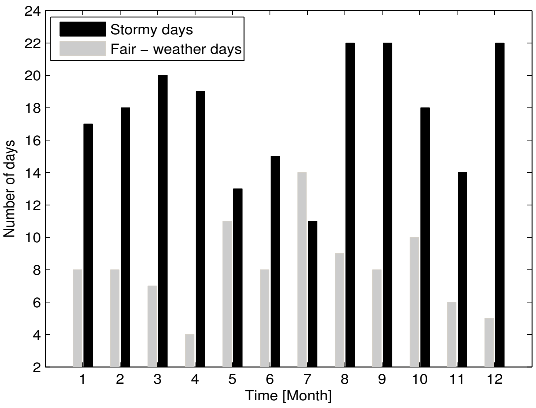

Fig. 1 Number of stormy days and fair-weather days in 2009.

window (50 hours on both sides of zero point of the SEA), the observed responses were stronger when thunderstorm onsets (instead of lightning times) were used as control (Kumar et al. 2009). Simultaneous images of sprites and OH airglow, modulated by gravity waves, were observed over a very active thunderstorm in Nebraska (Sentman et al. 2003). It is not clear whether the observed gravity waves were generated by the sprites, because an energy estimation based on the optical emission intensity of a sprite showed that the energy emitted by a sprite is not enough to produce a detectable perturbation in the OH emissions. On the other hand, there is evidence that the recorded AGWs were generated by the underlying thunderstorm which passed through below.

2 Data analysis

In this study, two different statistical analysis were performed using critical frequency (foEs), and virtual height (h'Es) of the sporadic E layer, as well as meteorological activity observations (lightnings, IR maps) within the 200 km range from the ionospheric station of Rome (41.9° N 12.5° E). In this way we evaluated troposphere-lower ionosphere coupling phenomena in the Mediterranean area. The territory under investigation was chosen because the magnitude of radius of the thunderstorm generated circular structured gravity waves is about 200 km at 85–96 km. Such radius has been determined on the basis of the airglow images (Suzuki et al. 2007). On the other hand, Davis & Johnson (2005) have found that the ionospheric response was insensitive within the 100 km range of the lightning, decreasing with distance beyond 100 km. World Wide Lightning Location Network (WWLLN) lightning data, METEOSAT-9 infrared images (downloaded from http://tropic.ssec.wisc.edu/archive/) and manually evaluated hourly data of foEs and hEs recorded in 2009 by the ionosonde (DPS-42) installed at the mid-latitude station of Rome are used in this work.

In the first statistical analysis using lightning data and infrared images, we separated the days of 2009 into two groups: stormy days (when basing on the lightning data and IR images, there was at least one thunderstorm in the area) and fair-weather days (when basing on the lightning data and IR images, there was not any convective system or cold front in the area). The number of the stormy days and fair-weather days in a month was very variable in 2009 (Fig. 1). Then we defined the stormy period and the fair-weather period, the latter is the same as the fair-weather days. Since the vertical component of the velocity of a gravity wave generated in the troposphere is typically 5 m s^{-1} (Liu et al. 1998), the propagation time is around 6 hours from the top of a cloud to the sporadic E layer. On the basis of this estimation, we defined the stormy period as a temporal interval from the first lightning to 12 hours after the last lightning of the thunderstorm. Then we performed a statistical analysis of the occurrence and the properties of the Es separately for the two different groups.

The SEA approach was used to study the differences of the foEs and hEs 100 hours before and after the lightning. The control time for the SEA was the time point of lightning strokes measured by WWLLN. The number of events (37096) was equal to the total number of lightning in 2009.

3 Results

3.1 The dependence of the sporadic E layer on thunderstorms

At first, the occurrence of the sporadic E layer was studied separately in the cases of thunderstorm and fair-weather periods. As shown in Fig. 2a) the occurrence of the two cases was different only in some months of the whole year; these differences, however, are not significant.

Figure 2b shows the average diurnal variation of foEs for the two cases. In both groups there is a strong maximum around noon, because the critical frequency is proportional to the maximum electron density of the sporadic E layer, obviously related to the photo-ionization effect of the solar radiation. Furthermore, the foEs is higher in the afternoon in the case of stormy periods, Hence the electron density increases in the afternoon in the case of storms, but this effect is not statistically significant.

Then we studied the annual variation of foEs and h'Es during 2009 for the two different cases. There is a maximum of the foEs in both cases in June (Fig. 2c). This can be easily understood, because the maximum electron density of the sporadic E layer is higher in the summer months in the northern hemisphere due to the ionization effect of the solar radiation. However, there is no statistically significant difference in the critical frequency (Fig. 2c) neither in the virtual height (Fig. 2d) nor during the stormy and the fair-weather periods.

3.2 Superposed epoch analysis

The SEA was used to study the behaviour of the critical frequency and virtual height 100 hours before and after the

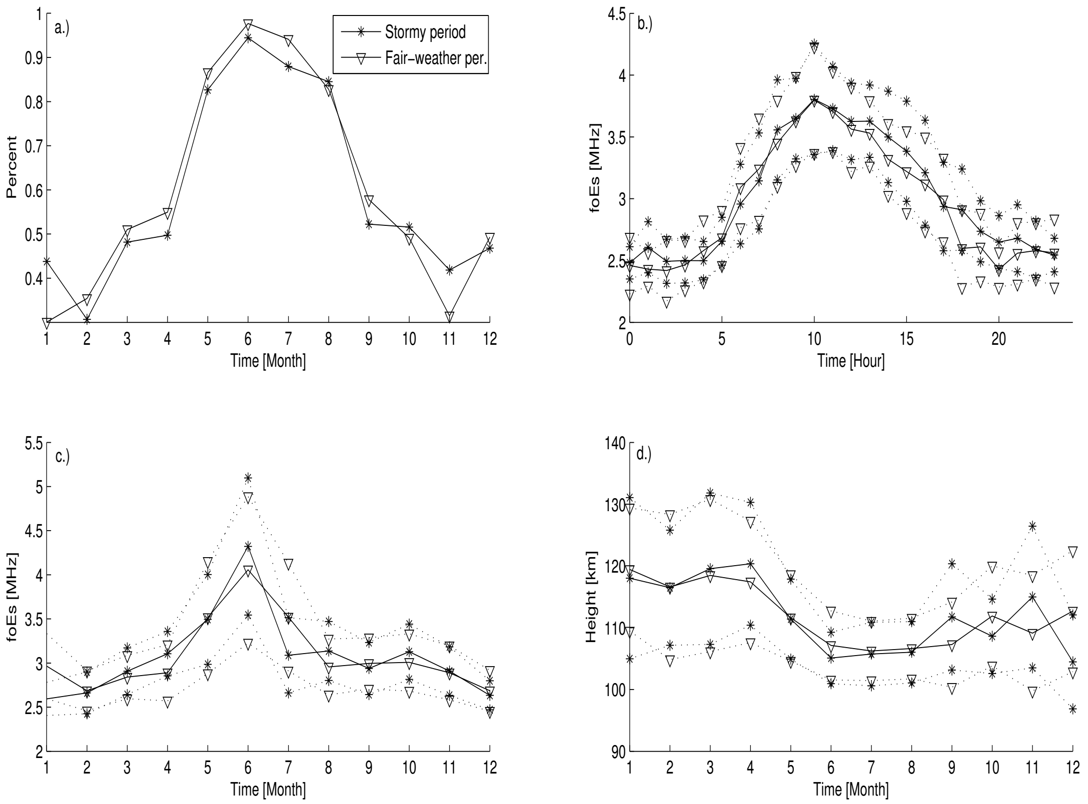

Fig. 2 (*a*) The annual variation of the occurrence of the sporadic E layer, (*b*) the average diurnal variation, (*c*) the annual variation of the critical frequency (foEs), and (*d*) the annual variation of the virtual height (h'Es). The dotted line indicates the standard deviation of the quantity in all cases.

lightning. Figure 3a shows the results of the SEA for the variation of the annual average of dfoEs (difference between any hourly value of foEs and the respective monthly mean for the same hour) in response to the lightning strokes in 2009. There is a statistically significant decrease just after the lightning i.e. $|$mean before zero hour $-$ mean after zero hour$| = 0.0877 >$ (standard deviation before zero hour $=$ 0.0809 *and* standard deviation after zero hour of $= 0.0493$).

A decrease is also shown in the annual average of dh'Es (difference between any hourly value of h'Es and the monthly mean value for that hour) (Fig. 3b), similar to the results obtained by Davis & Johnson (2005). However, this difference is not statistically significant i.e. $|$mean before zero hour mean after zero hour$| = 0.3084 <$ (standard deviation before zero hour $= 1.3074$ AND standard deviation after zero hour $= 1.3708$).

4 Conclusions

No significant differences of the occurrence and the properties (foEs, h'Es) of the sporadic E layer between the thunderstorms and the fair-weather periods have been found. These results showed that thunderstorms could not significantly affect the formation and the behavior of the sporadic E layer. The reason of the lack of a significant difference could be that we did not separate the huge thunderstorms from the little ones which are not big enough to affect the ionosphere and did not exclude the possibility of a physical relationship between thunderstorms and the sporadic E layer.

The SEA shows a statistically significant decrease in the dfoEs of the sporadic E layer after the time of the lightnings. This indicates a sudden decrease in the electron density of the sporadic E layer associated to lightnings. However, the physical explanation for this phenomenon has yet to be determined. There is also a decrease in the dh'Es similar to the results of Davis & Johnson (2005), but this difference is not statistically significant.

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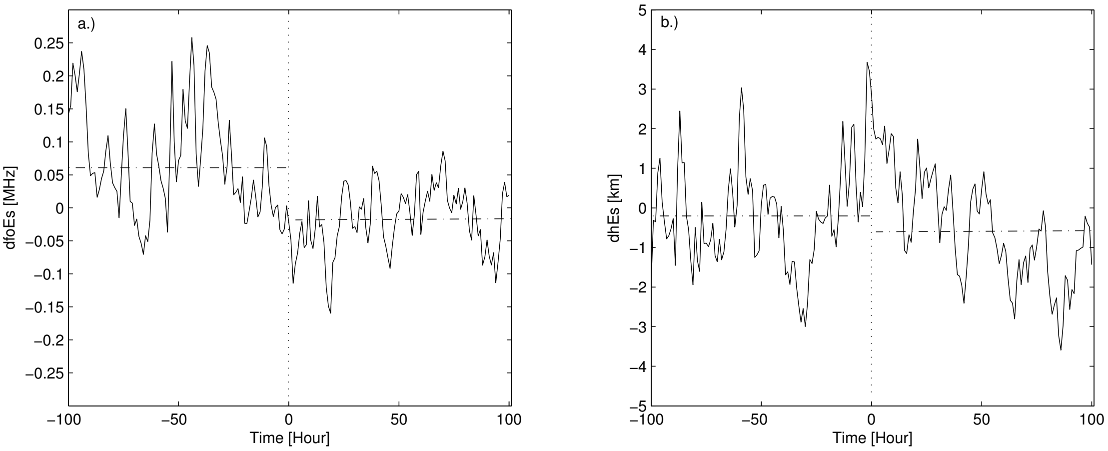

Fig. 3 (*a*) Superposed epoch analysis (SEA) for the annual average of dfoEs (difference between any hourly value of foEs and the respective monthly mean value for the same hour) and (*b*) the annual average of dh'Es (difference between any hourly value of h'Es and the respective monthly mean value for the same hour) in 2009. Horizontal dashed lines indicate the mean values of dfoEs and dh'Es before and after zero hour.

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