

Thunderstorm-related variations in the sporadic E layer around Rome

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Abstract Superposed epoch analysis (SEA) was used to study possibly statistically significant variations of the critical frequency (foEs) and virtual height (h'Es) of the sporadic E layer (Es) related to thunderstorm activity generated in the troposphere. The reference time for the SEA was the time of lightning strokes measured by the World Wide Lightning Location Network at the ionosonde station of Rome (41.9°N, 12.5°E) during the year 2009. The results obtained reveal that: (a) a statistically significant decrease of foEs after the time of lightnings has been found for time windows of ± 100 h; (b) the effects of thunderstorms on the ionosphere is larger when the thunderstorm approaches from the opposite direction to the mean neutral stratosphere–mesosphere wind flow; (c) a statistically significant decrease of foEs related to thunderstorms during nighttime was observed. No significant changes in foEs and hEs over the seasonal time scale as well as in the latter parameter in the three (a–c) cases related to thunderstorms.

Keywords Lightning discharge · Sporadic E layer · Thunderstorm–ionosphere coupling · Superposed epoch analysis

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1 Introduction

Thunderstorms developing in the troposphere can affect the ionosphere through electrodynamic and mechanical processes. The top of a thunderstorm can be coupled to the ionosphere by upward electrical discharges first predicted by Wilson (1925). Lightning discharges may deposit electromagnetic (EM) energy through quasi-electrostatic (QE) and EM fields to the middle atmosphere and lower ionosphere. These fields above thunderstorms can accelerate electrons causing energetic charged particles and Transient luminous events (TLEs, i.e. sprites, elves, blue jets). Intense lightning discharges and TLEs (especially sprites and elves) may also cause heating and extremely long-lasting changes in ionization in the upper D and lower E-region ionosphere (Taranenko et al. 1993; Füllekrug and Rycroft 2006; Haldoupis et al. 2012). ELF (3 Hz–3 kHz) and VLF (3–30 kHz) measurements in relationship to optical and other observations of ionospheric effects of lightning was summarized by Inan et al. (2010).

Mechanical coupling can be produced through upward propagating waves in the neutral atmosphere generated by the thunderstorm (Laštovička 2006). These waves may be of different types including internal atmospheric gravity waves (AGWs) (Sauli and Boška 2001; Medeiros et al. 2004). On the basis of numerical simulations, the atmospheric gravity waves generated by thunderstorms in the troposphere break at the mesopause height, and can excite upward propagating secondary waves, which can be trapped between the upper mesosphere and the lower thermosphere (Snively and Pasko 2003). Nighttime airglow images show a one-to-one correspondence between a meteorological phenomenon in the lower atmosphere and an AGW in the mesosphere (Suzuki et al. (2007)). Kumar et al. (2009) showed that the arrival direction of the thunderstorm could also be very important. The effects of the thunderstorms on the ionosphere are strongest when the sources of the AGWs, i.e. the thunderstorms, come from the opposite direction to the mean neutral thermospheric wind flow.

Localized patches with higher electron density than the background in the height of the ionospheric E layer (95–120 km) is called sporadic E layer (Es) (Whitehead 1961, 1989). An Es layer can be characterized by the critical frequency and the virtual height of the layer. The critical frequency, foEs, is the maximum frequency which is reflected from the layer. This value is related to the peak electron density ($f = 8.98(N_e)^{1/2}$, where f is the frequency of the sounding pulse in Hz and N_e is the electron concentration per cubic meter). The virtual height, h'Es, is estimated from the time-of-flight of the radio pulse. This is not the true height since the velocity of the radio pulse is not equal speed of light in vacuum due to the interaction with underlying ionization. The sporadic E layer was studied in the relation of thunderstorm by Davis and Johnson (2005), Johnson and Davis (2006) and Barta et al. (2013). Davis and Johnson (2005) showed a statistically significant increase in the critical frequency of the sporadic E layer (foEs) 6 h after the time of a thunderstorm. This could be related to the effect of AGWs generated by the thunderstorm. However, no significant ionospheric variations were noted in the case of meteorological events without any electrical activity. Consequently these changes in the frequency of the sporadic E layer can be attributed to lightning. Furthermore, they found a ~ 1 km decrease in the virtual height (h'Es) of the sporadic E layer after the time of the thunderstorm (Davis and Johnson 2005). Using the same data set, Johnson and Davis (2006) found that there are several locations where the effect of lightning on the ionosphere is most significant statistically, each producing different ionospheric responses'. They interpreted this that there are more mechanisms combining to produce the observed changes in the sporadic E layer. Superposed Epoch Analysis (SEA) had been used to study differences in foEs and h'Es values 100 h before and after a thunderstorm in the vicinity of Rome demonstrating a statistically significant decrease in the foEs of the sporadic E layer

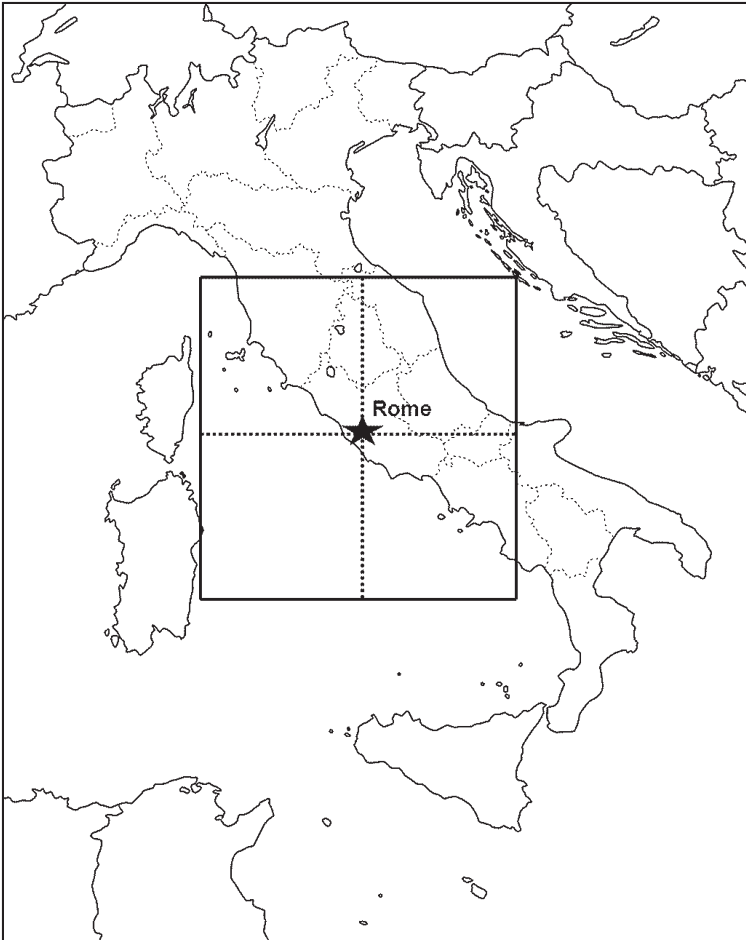


Fig. 1 The investigated territory (*bold line*) is located in the 200km range from the ionosonde station in Rome (41.9°N , 12.5°E). The total area was subdivided into four directional quadrants (*dotted line*) as follows: Northwest, Southwest, Northeast and Southeast areas

after the time of the lightning (Barta et al. 2013). This might be the indication of a decrease in the electron density of the sporadic E layer associated with lightning. A decrease in the $dh'Es$ similar to the results of Davis and Johnson (2005), but not statistically significant, was also observed. However, the physical explanation for this phenomenon has yet to be determined.

The aim of this paper is to further investigate the results of Barta et al. (2013). For this purpose, SEA was used to examine troposphere–lower ionosphere coupling in the Mediterranean area, and more precisely within a 200 km range of the ionosonde station in Rome (41.9°N , 12.5°E) as shown in Fig. 1. The reference times for the SEA were the occurrence times of lightning strokes measured in 2009 by the World Wide Lightning Location Network (WWLLN). Furthermore, manually evaluated hourly data for foEs and $h'Es$ recorded in 2009 by the Advanced Ionospheric Sounder produced by the National Institute of Geophysics and

Vulcanology (Zuccheretti et al. 2003), installed at the mid-latitude station in Rome, was also used in this work.

The next section describes the data analysis and defines the different statistical analyses carried out with the corresponding results, which are then discussed in Sect. 3.

2 Data analysis

In order to carry out the intended study, it is necessary to define a surface, the extent of which depends on the distance at which the effect of mechanical disturbances induced by thunderstorms can reasonably have an effect on the ionosphere. For this reason, an area of $1.6 \times 10^5 \text{ km}^2$ ($400 \text{ km} \times 400 \text{ km}$) centered on Rome was chosen for the investigation (Fig. 1), considering that on the basis of the airglow images (Suzuki et al. 2007), the radius of the circular structure thunderstorm generated atmospheric gravity waves is about 200 km at a height of 85–96 km. On the other hand, Davis and Johnson (2005) found that ionospheric response did not vary within a 100 km range of lightning and decreased with distance beyond 100 km.

Using SEA, the variations in the critical frequency and the virtual height of the sporadic E layer were studied before and after the time of lightning. All lightning strokes measured by the WWLLN in 2009 were considered and consequently the number of events was equal to the number of observed lightning strokes (37,096). In that year, maximum $365 \times 24 = 8,760$ Es data would be available in hourly time resolution. In those cases, when there was no sporadic E layer (no Es parameters) those values weren't considered in the SEA. The results of the data analysis using this method can be regarded as the cumulative effect of all lightning strokes on the ionosphere in a year, as if they were concentrated into a single "super" thunderstorm passing through the area studied. The "key-hour" can be considered when the 37,096 lightnings occurred. In this case, several portion of lightnings appears in the other hours, too, with decreasing trend around the "key-hour" (see lower panel in Fig. 2). The 25 % of lightnings still gets to the time interval of $\pm 25 \text{ h}$ around the "key-hour" consequently their possible influence on the sporadic E layer might be started earlier than the "key-hour". Based on this consideration, the interval of $\pm 25 \text{ h}$ as "the key-interval" was selected around the hour of the maximum activity of the huge virtual thunderstorm and the mean level of the sporadic E layer parameters were compared before the -25th hour and after the +25th hour in the SEA.

In the first step of the analysis, the hourly average foEs was calculated for the period of 15 days before and after the time of each lightning stroke to eliminate the daily and seasonal variations of the critical frequency. In the second step, the difference between any hourly value of foEs and the average value mentioned above was calculated for the same hour, determining the value of dfoEs. (For example if the second hour before the time of the lightning was at 4 pm, then the difference between the foEs at 4 pm and the average foEs at 4 pm was calculated, and so on.) These steps were carried out for each lightning stroke in order to study the effect of all lightning strokes simultaneously. This procedure was also repeated for the data of virtual height (dh'Es).

Four analyses have been carried out: In the first analysis, SEA with time window of $\pm 100 \text{ h}$ was used to study the variation in values of dfoEs and dh'Es before and after the time of the virtual "super" thunderstorm. In the second analysis, the SEA was performed for the four different seasons separately. In the third analysis, the territory was separated into four directional quadrants (Northwest, Southwest, Northeast and Southeast areas, see Fig. 1) and the SEA was carried out in each quadrant separately. In the fourth analysis, the daytime and

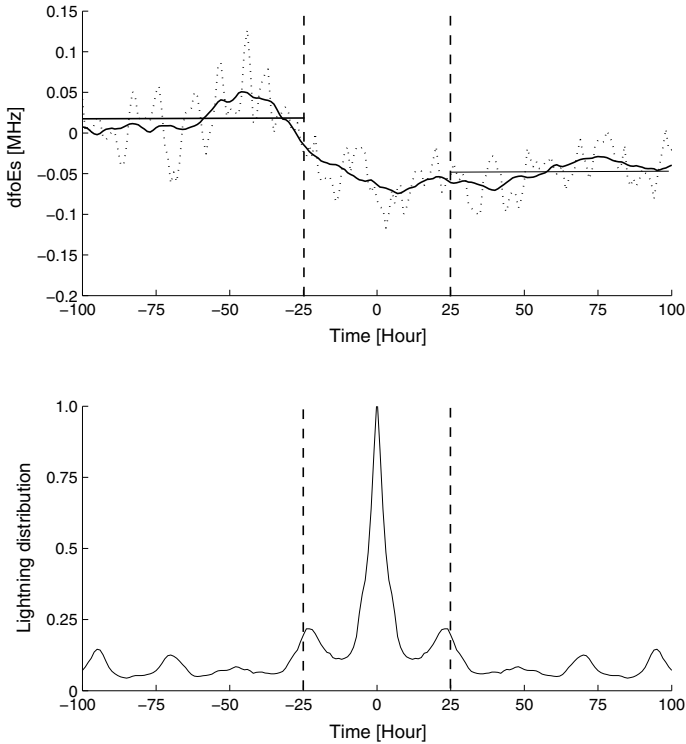


Fig. 2 Behaviour of dfoEs for ± 100 -hour time window (*upper plot*) and the lightning distribution (*lower plot*). The *upper plot* shows the change of the dfoEs (*dotted line*), the smoothed values (*solid line*, 10h running mean was used for smoothing) and the mean of the dfoEs before and after the key interval of ± 25 h

nighttime lightning strokes were separated and the SEA was performed on the two distinct cases.

2.1 Results of the SEA procedure for time window of ± 100 h

In the first analysis, SEA with time window of ± 100 h was used to study the variation in dfoEs and dh'Es values before and after the time of the virtual “super” thunderstorm.

Figure 2 shows the change of the dfoEs, the smoothed values of the dfoEs and the mean of the dfoEs before and after the “key interval” of ± 25 h (*upper plot*) and the lightning distribution (*lower plot*). The difference between the mean level of dfoEs before and after the “key-interval” is regarded as a statistically significant variation if its absolute value is larger than the standard deviation of dfoEs before and after the “key-interval”. The number of cases, N equals 37,096. On average, in the case of the ± 100 -hour time window, the result of the SEA showed a decrease in foEs already in the “key-interval” and a statistically significant decrease in foEs remained up to the end of the time window compared to the period before it.

Figure 3 relates to the behavior of the parameter dh'Es in the same time windows as in Fig. 2. In the ± 100 -hour time window, h'Es decreased about 1 km after the “key-interval” similar to the results of Davis and Johnson (2005), but it was not statistically significant.

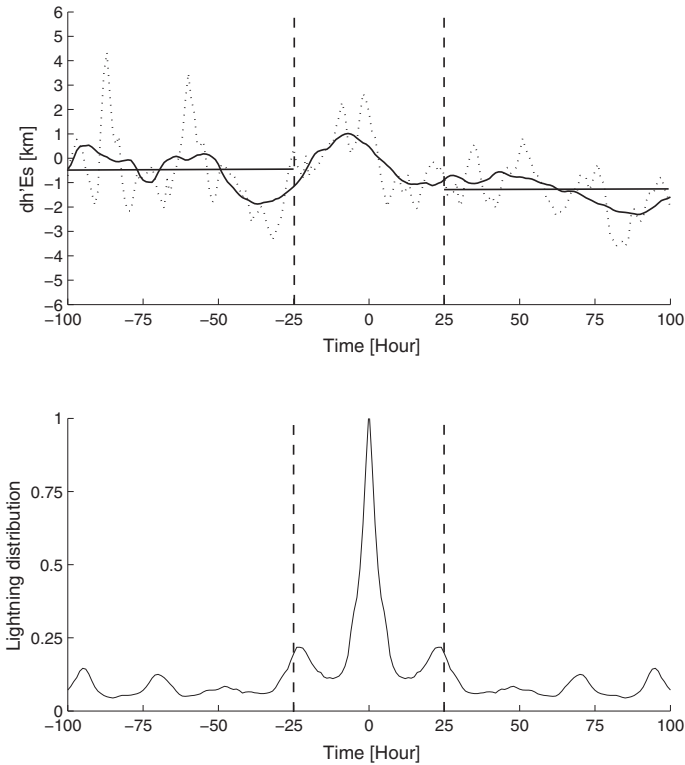


Fig. 3 Same as Fig. 2 but for $dh'Es$

2.2 Results of the SEA procedure for different seasons

There were no significant variations in $dfoEs$ and $dh'Es$ values in any seasons despite the fact that the sporadic E layer and the stratosphere–mesosphere wind systems which affect the propagation of the waves coming from the troposphere also have seasonal variations (Whitehead 1989; Brasseur and Solomon 1984; Mingalev et al. 2012). This might be attributed to the opposite seasonal distribution of the lightning and sporadic E layer as shown in Fig. 4. Lightning activity has a maximum in autumn and winter months in the Mediterranean region (Fig. 4a) while the occurrence of sporadic E layer is maximum in the mid-latitude region in summer months (Fig. 4b).

2.3 Results of the SEA in the case of different geographical location of thunderstorms

The results of the SEA carried out separately for the four directional quadrants (Northwest, Southwest, Northeast and Southeast areas, see Figs. 1) are shown in Fig. 5 and Fig. 6. According to Kumar et al. (2009), the wind-shear effect of the waves is probably higher if the arrival direction of the generated atmospheric gravity waves is opposite to the direction of the mean neutral wind in the stratosphere–mesosphere system, thus generating greater impact on the sporadic E layer.

According to the results of Mingalev et al. (2012), the direction of the stratosphere–mesosphere neutral wind in the Mediterranean area is northeast for most of the year.

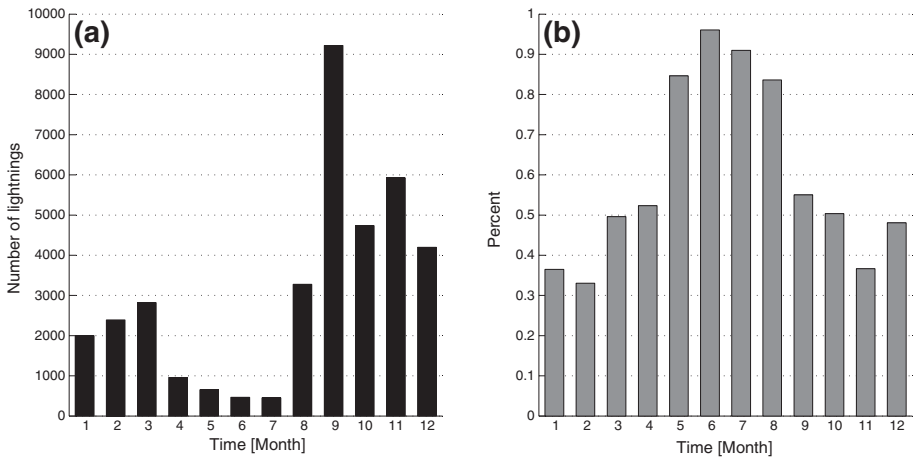


Fig. 4 **a** Annual distribution of lightning in the selected area around Rome in 2009 and **b** annual distribution of occurrence of the sporadic E layer observed from the ionosonde station at Rome in 2009. For example, this means that sporadic E layer was observable in 96 % of the hours in June

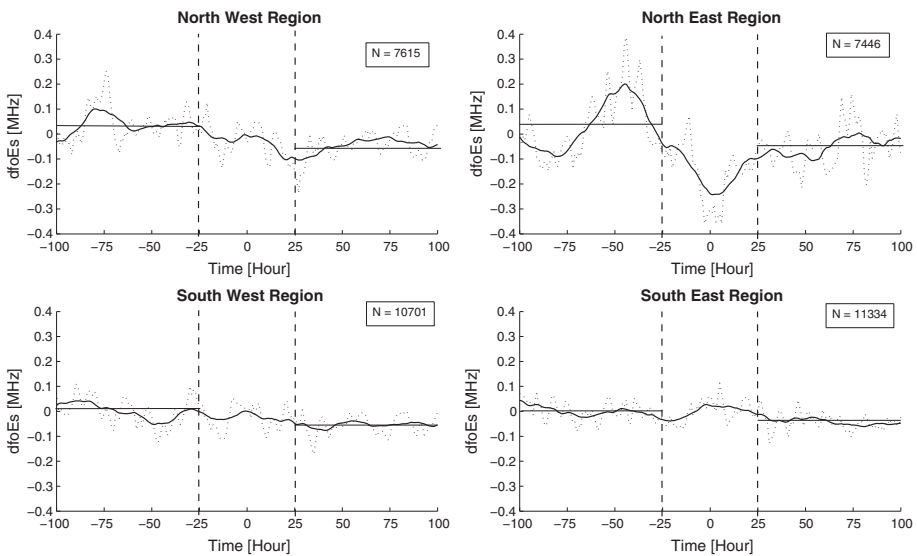


Fig. 5 Behaviour of dfoEs before and after the key-interval in the four quadrants related to the different directions

The results of the analysis show (Fig. 5) that variability of the critical frequency and its decrease were greatest when thunderstorms occurred in the Northeast quadrant for the parameter dfoEs (Fig. 5). On the basis of these findings it can be concluded that the effects of thunderstorms on the ionosphere are strongest when the thunderstorms come from the opposite direction to the mean neutral stratosphere–mesosphere wind flow, a result similar to that obtained by Kumar et al. (2009).

The variations of the virtual height, dh’Es were not significant in any quadrants (Fig. 6).

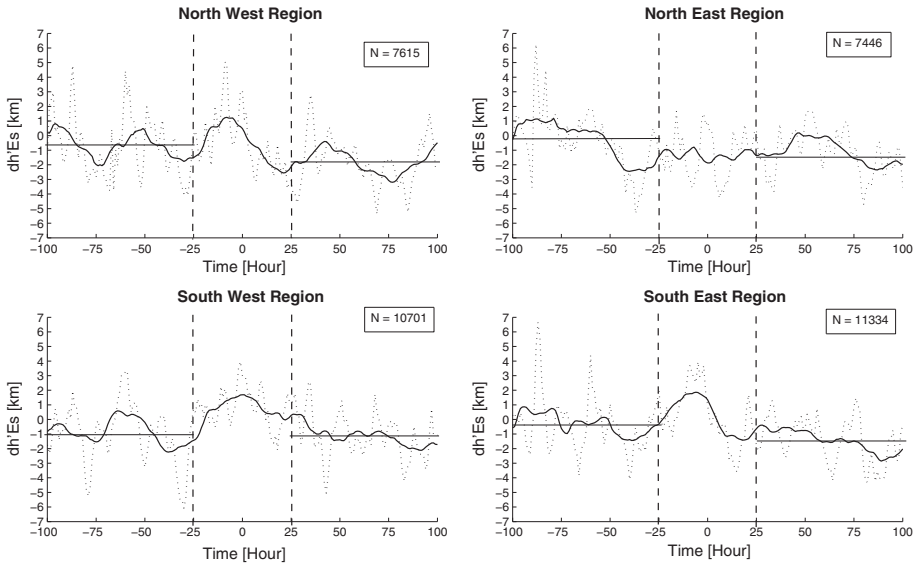


Fig. 6 Same as Fig. 5, but for $dh'Es$

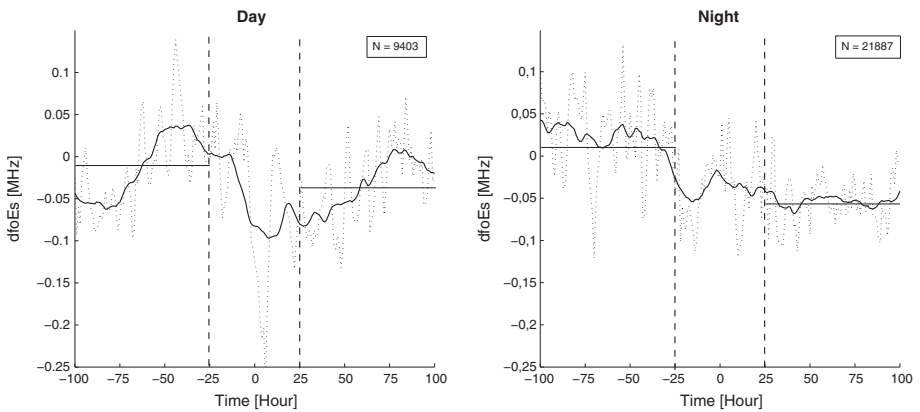


Fig. 7 Behaviour of $dfoEs$ 100h before and after the time of the lightning in the case of the daytime (*left panel*) and nighttime (*right panel*) lightnings

2.4 Results of the separate SEA procedures for daytime and nighttime lightning

The results of the SEA carried out separately for daytime and nighttime lightning strokes are shown in Fig. 7 and Fig. 8. A reduction was again found after the “key-interval” in these cases. The decrease in $dfoEs$ was statistically significant only in the nighttime period (Fig. 7). This means that the electromagnetic coupling between the thunderstorm and the sporadic E layer could be more pronounced during the night. The ionospheric D-region is well developed below the height of sporadic E layers during the daytime due to photoionization. It can therefore absorb the EM energy rising upwards from thunderstorms. It is thus assumed that EM coupling between a thunderstorm and a sporadic E layer is more likely during the nighttime when the ionospheric D-region is reduced.

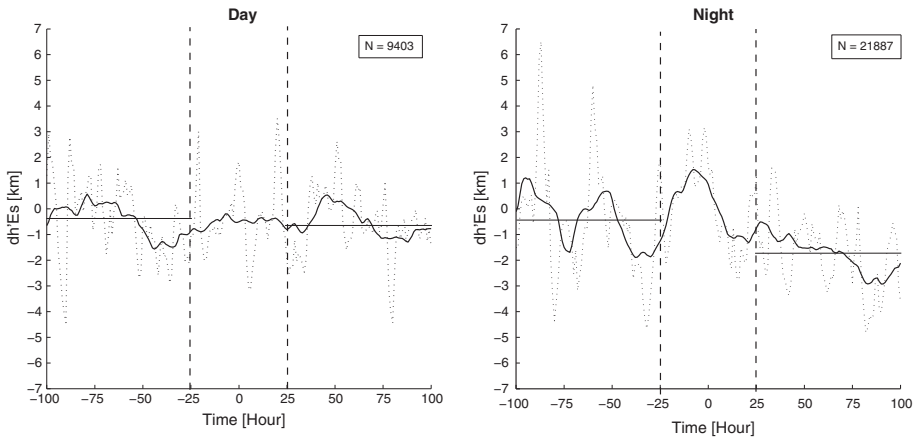


Fig. 8 Same as Fig. 7, but for $dh'Es$

In the case of virtual height, similar results were found, because the difference between the averages calculated before and after the key-interval was greater in the nighttime than in the daytime, but none of them was statistically significant (see Fig. 8).

3 Discussion and conclusions

In this study SEA was used to examine the behavior of the critical frequency and the virtual height of the sporadic E layer before and after the time of lightning to reveal troposphere–lower ionosphere coupling phenomena. The reference time for the SEA was the occurrence time of lightning strokes measured by the WWLLN in 2009 within a 200 km range of the ionosonde station in Rome (41.9°N, 12.5°E).

On average, in the case of the ± 100 -hour time window, the result of the SEA showed a decrease in foEs already in the “key-interval” and a statistically significant decrease in foEs remained up to the end of the time window compared to the period before it (Fig. 2). As regards this reduction in foEs, it can be assumed that the electron density is connected to the reduction in neutral density due to temporary heating produced by lightning-generated phenomena above thunderstorms. In the ± 100 -hour time window, h'Es decreased about 1 km after the “key-interval” similar to the results of Davis and Johnson (2005), but it was not statistically significant.

No significant variations in dfoEs and dh'Es values were noted in any season in spite of the fact that the sporadic E layer and the stratosphere–mesosphere wind systems which affect the propagation of the waves coming from the troposphere also have seasonal variations (Whitehead 1989; Brasseur and Solomon 1984; Mingalev et al. 2012).

According to the results of Mingalev et al. (2012), the direction of the stratosphere–mesosphere neutral wind is northeasterly for most of the year. The results of the analysis show (Fig. 5) that variability of the critical frequency and its decrease were greatest when thunderstorms occurred in the Northeast quadrant for the parameter dfoEs (Fig. 5). On the basis of these findings it can be concluded that the effects of thunderstorms on the ionosphere are strongest when the thunderstorms come from the opposite direction to the mean neutral stratosphere–mesosphere wind flow, a result similar to that obtained by Kumar et al. (2009).

SEA was also performed separately for daytime and nighttime lightning strokes. A reduction was again found after the “key-interval” in these cases. The decrease in df_oEs was statistically significant only in the nighttime period (Fig. 7). This suggests that the EM coupling between the thunderstorm and the sporadic E layer could be more pronounced during the night when the ionospheric D-region is reduced. In the case of virtual height, similar results were found, because the difference between the averages calculated before and after the “key-interval” was greater in the nighttime than in the daytime, but none of them were statistically significant (see Fig. 8).

Further studies of individual thunderstorms are needed, using high resolution (1–2 min) ionosonde measurements, to understand the coupling mechanisms between the thunderstorm/lightning activity and the sporadic E layer.

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