



A comparative sporadic-E layer study between two mid-latitude ionospheric stations

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Abstract

Hourly systematic measurements of the highest frequency reflected by the sporadic-E layer (f_oE_s) recorded from January 1976 to June 2009 at the ionospheric stations of Rome (Italy, 41.8°N, 12.5°E) and Gibilmanna (Italy, 37.9°N, 14.0°E) were considered to carry out a comparative study between the sporadic E layer (E_s) over Rome and Gibilmanna. Different statistical analysis were performed taking into account f_oE_s observations near the periods of minimum and maximum solar activity. The results reveal that: (1) independently from the solar activity, E_s develops concurrently over extended regions in space, instead of being a spatially limited layer which is transported horizontally by neutral winds over a larger area; especially during summer months, when an E_s layer is present at Rome, there is a high probability that an E_s layer is also present over Gibilmanna, and vice versa; (2) E_s layer lifetimes of 1–5 h were found; in particular, E_s layers with lifetimes of 5 h both over Gibilmanna and Rome are observed with highest percentages of occurrence in summer ranging between 80% and 90%, independently from the solar activity; (3) latitudinal effects on E_s layer occurrence emerge mostly for low solar activity during winter, equinoctial, and summer months, when E_s layers are detected more frequently over Gibilmanna rather than Rome; (4) when the presence of an E_s layer over Rome and Gibilmanna is not simultaneous, E_s layer appearance both over Rome and Gibilmanna confirms to be a locally confined event, because drifting phenomena from Rome to Gibilmanna or vice versa have not been emphasized.

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1. Introduction

The name sporadic-E (E_s) layer is a generic term that refers to values of ions and electrons confined within thin layers (0.6–2.0 km), which can reach much higher values than those occurring in the same height range (90–120 km) as normal daytime E region.

Sporadic-E layers can have serious effects on communications in the HF and low VHF range, also causing over-the horizon propagation for signals otherwise restricted to line-of-sight (Rice et al., 2011). At middle latitudes,

meter-scale magnetic field-aligned plasma irregularities have been observed and associated with sporadic E layers through coherent backscatter measurements (Haldoupis and Schlegel, 1993). Backscatter ionograms obtained with fixed frequency radar have been also used to study the spatial extension, motion and evolution through time of E_s layers: average lifetimes of 2 h were found by Harwood (1961); lifetimes of around 10 h in summer were found by Tanaka (1979). Sporadic-E “clouds” extending between 30° and 80° in azimuth and 150–800 km in range, with lifetimes of 1–4 h, have been detected by Houminer et al. (1996) analyzing several backscatter ionograms obtained simultaneously by propagation at different azimuth angles, using a backscatter sounder with a swept-frequency. Rice et al. (2011) have recently proposed a low-cost network

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based on software-controlled receivers that continuously watches for Es using oblique HF propagation from existing transmitters. Their observations showed that Es often develops quickly over regions of several hundred kilometers rather than gradually drifting across an area.

Unlike the others regular ionospheric layers, it is well known that Es layer cannot be explained by means of Chapman theory, and different alternative mechanisms were introduced to clarify Es formation. The variations in velocity and direction of the neutral winds (wind-shear), in conjunction with the Earth's magnetic field, are important factors to take into account for the formation mechanism of mid-latitude sporadic-E (Whitehead, 1960, 1970, 1989).

Several studies concerning the correlation of meteoric activity with the Es layers have been made (Chandra et al., 2001; Whitehead, 1970 and references therein). It is now clear that heavy meteoric shower activity produces long living metallic and molecular ions that constitute an important reservoir for the formation both of high and low intensive Es layers.

From a large number of studies carried out in the past, it has also emerged that meteorological processes, occurring in particular in the troposphere, can have an effect on the behavior of the ionosphere through upward propagating waves, and their modulation and modification, that can considerably affect the Es formation (Lastovicka, 2006). In fact, tidal waves, gravity waves and planetary waves (PW) have been found to play an important role in controlling the occurrence and strength of mid-latitude Es layer. Acting through their vertical wind shear, they “compel” the metallic and molecular ions into thin layers in the altitude range from 90 to 120 km. Significant long-term periodicities in the Es critical frequency (f_oEs) with periods in the PW range, suggest that Es layers can be affected by PW through non linear interaction and modulation of the atmospheric tides (Haldoupis et al., 2004). The occurrence of quasi-periodic radar echoes from mid-latitude Es was found to vary sinusoidally with a 5-day period, and this effect was clearly attributed to a PW identified through neutral-wind measurements made with a partial reflection drift radar (Tsunoda et al., 1998). The first confirmation of a relationship between PW and Es formation was found analyzing f_oEs measurements taken from a longitudinal chain of ionosondes during a significant PW event. A periodicity in f_oEs with a 7-day period was shown in all the stations concurrently with the 7 day period associated to PW revealed independently from ground radar and satellite wind measurements in the mesosphere – lower-thermosphere (Haldoupis and Pancheva, 2002).

As at middle latitudes, also at low latitudes the Es layer formation depends essentially on the vertical wind shear associated with the tidal winds, that seem to be almost always present between 100 and 160 km as inferred from incoherent scatter radar observations (Mathews, 1998). Gravity waves (GW) traveling in the lower ionosphere can have amplitudes and wind shears sufficiently large to

alter the regular tidal forcing of the Es forming process, and their interaction with tidal waves can give rise to an increase/decrease of plasma within the layer itself (Chimonas, 1971).

In addition, gravity waves propagating into the E region, may also cause layer disruption locally giving rise to sporadic E layers manifesting periodicities shorter than the typical dominant 12 and 24 h tidal periodicities. A circumstantial evidence of this comes from the wavelet analysis conducted on the time series of f_oEs , which revealed many short-lived spectral sequences corresponding to f_oEs variations with periods shorter than 6 h that quite well match with gravity wave periods, thus indicating a possible GW-Es association (Haldoupis, 2012).

It is known that Es morphology layer certainly depends on tides. Many investigations ascertained the fundamental role played by the diurnal and semidiurnal tides in the formation and variability of Es layers. MacDougall (1974), by analyzing the Es layers heights from a world-wide distribution of stations, proved the semidiurnal zonal wind pattern and its agreement with theoretical predictions. Diurnal and semidiurnal tidal modes have been also identified as the triggering mechanisms for Es layer formation by analyzing ionosonde data (Wilkinson et al., 1992; Szuszczewicz et al., 1995). Haldoupis et al. (2004), applying the spectral analysis to time series of f_oEs recorded at middle latitudes, clearly identified semidiurnal (12 h) and diurnal (24 h) periodicities and they associated them with atmospheric tides. Again, the existence of diurnal and semidiurnal periodicities in the formation of Es layer, as well as the corresponding descent rates (1.6–2.2 km/h for a nighttime layer, 0.8–1.5 km/h for a daytime layer), were revealed by Haldoupis et al. (2006) in a more recent work using the technique of ionogram height-time-intensity analysis.

It is now widely agreed that Es formation at middle latitudes, as well as its seasonal and global occurrence, are justifiable according to the wind shear mechanism, taking into account the geographic distribution of the horizontal magnetic field component, the tidal wind atmospheric dynamics, and the deposition of metallic ions of meteoric origin (Haldoupis, 2011). From some numerical simulations related to sporadic E layers observed during the Aladdin 1 rocket campaign, it has however emerged that the inclusion of an ad hoc small constant electric field at times can be important to mitigate the discrepancies between the modeled and experimental results (MacLeod et al., 1975). Moreover, the effects of the ambient electric field have been also proved important in producing a stable sporadic E-layer which otherwise by wind effects alone would be rapidly transported upwards to be dispersed by diffusion (Rees et al., 1976).

Numerous studies concerning the diurnal and seasonal variations of Es layers have been carried out in the past (e.g. see review by Whitehead (1989)). Among the others, the seasonal variations of Es occurrence were deeply studied by Baggaley (1985b). His investigation established the existence of a sharp summer maximum of Es appearance

around local midday and two minimums during the equinoctial months, this feature diminishing as the location of measuring approaches the magnetic equator. A more detailed study conducted to determine the seasonal characteristics of Es layers confirmed the existence of a maximum (minimum) occurrence in summer (equinoctial) months for different diurnal periods (Baggaley, 1986). Even though the work done by Triskova (1974) explains the presence of the maximum and minimum found by Baggaley (1986) in terms of the seasonal variation of zonal wind-shear, the belief now is that this behavior is completely inexplicable from wind-shear theory. Recently, Haldoupis et al. (2007) have found how the marked seasonal dependence of Es correlates well with the annual variation of meteor deposition in the upper atmosphere.

The influence of solar activity on Es occurrence has also been investigated by many authors over the last few decades. A decreasing general trend in Es occurrence relative to increasing solar activity was found by Kotadia (1969). In survey papers (Whitehead, 1970, 1989) positive, negative and no correlation of various Es layer parameters with solar activity level were reported. Baggaley (1984) analyzed *foEs* data over three solar cycles for two southern hemisphere stations and found that long-term *foEs* occurrence does not depend on the solar activity in all seasons. A further investigation conducted analyzing *foEs* data over two solar cycles during wintertime for day and night revealed increasingly dense Es relative to increasing sunspot number (Baggaley, 1985a). Both positive and negative correlations between the probability of appearance of Es layer and the solar activity cycle, depending upon layer intensity, have also been illustrated by Maksyutin and Sherstyukov (2005). Because of the different results emerging from existing literature, the subject of the influence of solar activity on the Es layer is still not completely resolved and further investigations are needed.

Worldwide patterns indicate that Es occurrence depends on latitude (Davies, 1990). At equatorial latitudes Es is essentially a daytime phenomenon depending very little on seasons; at high latitudes Es is mainly present at night again with a little seasonal variation; at middle latitudes, as already mentioned above, Es shows a clear diurnal and seasonal variation.

More recently, from a study conducted by Pietrella and Bianchi (2009), emerged that the most significant percentages of occurrence of Es layer over the ionospheric station of Rome (Italy, 41.8°N, 12.5°E) happen during daytime in summer months, with relatively low values before sunrise and after sunset in all seasons and without any significant dependence on solar and geomagnetic activity. As a continuation of this study, this new investigation, besides the hourly *foEs* measurements recorded at Rome, takes into account also the hourly *foEs* measurements made at Gibilmanna (Italy, 37.9°N, 14.0°E) to carry out a comparative study between the Es layers over these two sites.

Anyway, unlike the Pietrella and Bianchi (2009) investigation, this new work is not focused on the percentage of

occurrence of an Es layer for different intensity levels according to the hour of the day, the solar and the geomagnetic activity. This study wants primarily to highlight how the presence of an Es layer over Rome is possibly related to the presence of an Es layer over Gibilmanna and vice versa. Our main purpose is then to investigate whether Es layers are characterized by widespread “blooms”, borrowing this terminology from Rice et al. (2011), or by drifting phenomena covering a relatively large area.

Measurements of *foEs* recorded at both stations near the periods of minimum and maximum solar activity, over the years January 1976–June 2009, were considered to establish possible influences from solar activity. In this regard, different statistical analysis were performed and the percentages of occurrence for different patterns were calculated and analyzed in order to investigate Es lifetimes, possible latitudinal differences of the Es occurrence, as well as possible drifting phenomena between the Es layers appearing over Rome and Gibilmanna. Section 2 describes the data sets considered, and their corresponding organization. Section 3 defines the different statistical analysis carried out and illustrates the corresponding results, which are then discussed in Section 4. Concluding remarks and possible future developments are summarized in Section 5.

2. Data sets

In order to achieve statistical significance, this study analyzed more than three decades of ionosonde data. Hourly systematic measurements of *foEs*, recorded during the period January 1976–June 2009 at the Rome and Gibilmanna ionospheric stations, were downloaded from the electronic Space Weather upper atmosphere database (eSWua; <http://www.eswua.ingv.it/>) (Romano et al., 2008). Since the database includes 34 years of *foEs* measurements, it is suitable for investigating possible dependencies of the appearance of Es layer on the solar cycle. The periods considered in our analysis include 4 solar cycles with 4 minima and 3 maxima of solar activity: the solar cycle 21 started in June 1976 and peaked in December 1979; the solar cycle 22 started in September 1986 and peaked in July 1989; the solar cycle 23 started in May 1996 and peaked in April 2000; the solar cycle 24 started in January 2008 is an anomalous solar cycle because its minimum was reached in December 2008 (Table 1).

The procedure followed for the arrangement of data sets consists of two main steps: (1) the months of lowest and

Table 1
Months of lowest and highest solar activity for solar cycles 21, 22, 23, and 24 with the corresponding value of the solar index R_{12} .

Solar cycle	Lowest solar activity	Highest solar activity
21	Jun 1976 ($R_{12} = 12.2$)	Dec 1979 ($R_{12} = 164.5$)
22	Sep 1986 ($R_{12} = 12.3$)	Jul 1989 ($R_{12} = 158.5$)
23	May 1996 ($R_{12} = 8.0$)	Apr 2000 ($R_{12} = 120.9$)
24	Dec 2008 ($R_{12} = 1.7$)	

highest solar activity were identified for each of the four solar cycles considered (see Table 1); (2) the six months prior and following each month identified in step (1) were considered, and consequently seven groups of 13 months, four for low solar activity (LSA) and three for high solar activity (HSA), were formed (see Table 2).

Subsequently, foEs observations rearranged as in Table 2, were binned for any month differentiating between LSA and HSA (see Table 3). As the main purpose of this investigation is to carry out a comparative study between the Es layers over Rome and Gibilmanna, it is crucial for our study that measurements are contemporaneously present at the two ionospheric stations. The months for which foEs observations were simultaneously recorded at Rome and Gibilmanna are bolded in Table 3 and are those actually considered for the statistical analysis. Just to better clarify the question, in order to investigate possible links between Es layers over Rome and Gibilmanna in January for LSA (HSA), only foEs observations recorded in 1987 and 2009 (1980, 1989, and 1990) have been cumulated and used in the statistical analysis.

3. Data analysis and results

Different statistical analysis, were performed independently from the layer intensity and the hour of the day in order to find possible correlations between the Es layers over Rome and Gibilmanna for LSA and HSA.

As first step, the simultaneous occurrence of Es layer over Rome and Gibilmanna was investigated for each month. Assuming as favorable the event characterized by

the simultaneous presence of Es layer over Rome and Gibilmanna, indicated as “YesEsRom_AND_YesEsGib”, the percentage of simultaneous occurrence of Es layer over Rome and Gibilmanna for a given month *mm* was calculated using the following equation:

$$P_{\text{YesEsRom_AND_YesEsGib},mm} = \frac{N_{\text{YesEsRom_AND_YesEsGib},mm}}{N_{\text{TOT},mm}} \cdot 100 \quad (3.1)$$

where $N_{\text{YesEsRom_AND_YesEsGib},mm}$ is the total number of favorable events over the month considered, and $N_{\text{TOT},mm}$ is the total number of cases considered for the same month. Eq. (3.1) was applied for all the months, making a distinction between the months characterized by LSA and HSA, as shown in Table 3. The results are summarized in Fig. 1.

A further statistical analysis was performed to investigate the lifetimes of Es layers over Rome and Gibilmanna, assuming as favorable those events characterized by the presence of Es layer over Rome (Gibilmanna) at a given hour *hh* and Es layer over Gibilmanna (Rome) at the hours *hh* + 1, *hh* + 2, *hh* + 3, *hh* + 4, and *hh* + 5 (indicated respectively as “YesEsRom_ *hh*_AND_YesEsGib_ *hh* + *i*” and “YesEsGib_ *hh*_AND_YesEsRom_ *hh* + *i*”, with *i* varying from 1 to 5). The corresponding percentages of occurrence, for a given month *mm*, were then calculated using respectively the following equations:

$$P_{\text{YesEsRom_hh_AND_YesEsGib_hh+i},mm} = \frac{N_{\text{YesEsRom_hh_AND_YesEsGib_hh+i},mm}}{N_{\text{TOT},mm}} \cdot 100, \quad (3.2)$$

Table 2

Seven groups of 13 months, four for LSA and three for HSA, each of which is centered on the corresponding month of lowest and highest solar activity marked in bold (see Table 1). The symbol *** indicates that foEs observations are not available for December 1975.

Solar cycle 21	***	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LSA		1976	1976	1976	1976	1976	1976	1976	1976	1976	1976	1976	1976
<i>R</i> ₁₂	***	15.2	13.2	12.2	12.6	12.5	12.2	12.9	14.0	14.3	13.5	13.5	14.8
Solar cycle 21	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
HSA	1979	1979	1979	1979	1979	1979	1979	1980	1980	1980	1980	1980	1980
<i>R</i> ₁₂	153.0	155.0	155.4	155.7	157.8	162.3	164.5	163.9	162.6	160.9	158.7	156.3	154.7
Solar cycle 22	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
LSA	1986	1986	1986	1986	1986	1986	1986	1986	1986	1986	1987	1987	1987
<i>R</i> ₁₂	13.0	13.7	14.3	13.8	13.7	13.2	12.3	13.2	14.9	16.3	17.6	19.6	22.1
Solar cycle 22	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
HSA	1989	1989	1989	1989	1989	1989	1989	1989	1989	1989	1989	1989	1990
<i>R</i> ₁₂	141.9	144.9	149.6	153.4	156.8	158.3	158.5	157.6	156.5	157.3	157.5	153.5	150.6
Solar cycle 23	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
LSA	1995	1995	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996	1996
<i>R</i> ₁₂	11.4	10.8	10.4	10.1	9.7	8.5	8.0	8.5	8.4	8.3	8.4	8.8	9.8
Solar cycle 23	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
HSA	1999	1999	1999	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
<i>R</i> ₁₂	107.8	111.0	111.1	113.0	116.9	120.0	120.9	119.0	118.8	119.8	118.7	116.3	114.5
Solar cycle 24	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
LSA	2008	2008	2008	2008	2008	2008	2008	2009	2009	2009	2009	2009	2009
<i>R</i> ₁₂	3.2	2.7	2.6	2.2	1.8	1.7	1.7	1.8	1.9	2.0	2.2	2.3	2.7

Table 3

Database selected to study the behavior of the sporadic-E layer over Rome and Gibilmanna for LSA and HSA. The months for which *foEs* observations were simultaneously recorded at Rome and Gibilmanna are bolded and are those actually considered for the statistical analysis.

Low solar activity	High solar activity
Jan 1976 + Jan 1987 + Jan 1996 + Jan 2009	Jan 1980 + Jan 1989 + Jan 1990 + Jan 2000
Feb 1976 + Feb 1987 + Feb 1996 + Feb 2009	Feb 1980 + Feb 1989 + Feb 2000
Mar 1976 + Mar 1986 + Mar 1987 + Mar 1996 + Mar 2009	Mar 1980 + Mar 1989 + Mar 2000
Apr 1976 + Apr 1986 + Apr 1996 + Apr 2009	Apr 1980 + Apr 1989 + Apr 2000
May 1976 + May 1986 + May 1996 + May 2009	May 1980 + May 1989 + May 2000
Jun 1976 + Jun 1986 + Jun 1996 + Jun 2008 + Jun 2009	Jun 1979 + Jun 1980 + Jun 1989 + Jun 2000
Jul 1976 + Jul 1986 + Jul 1996 + Jul 2008	Jul 1979 + Jul 1989 + Jul 2000
Aug 1976 + Aug 1986 + Aug 1996 + Aug 2008	Aug 1979 + Aug 1989 + Aug 2000
Sep 1976 + Sep 1986 + Sep 1996 + Sep 2008	Sep 1979 + Sep 1989 + Sep 2000
Oct 1976 + Oct 1986 + Oct 1996 + Oct 2008	Oct 1979 + Oct 1989 + Oct 1999 + Oct 2000
Nov 1976 + Nov 1986 + Nov 1995 + Nov 1996 + Nov 2008	Nov 1979 + Nov 1989 + Nov 1999
Dec 1976 + Dec 1986 + Dec 1995 + Dec 2008	Dec 1979 + Dec 1989 + Dec 1999

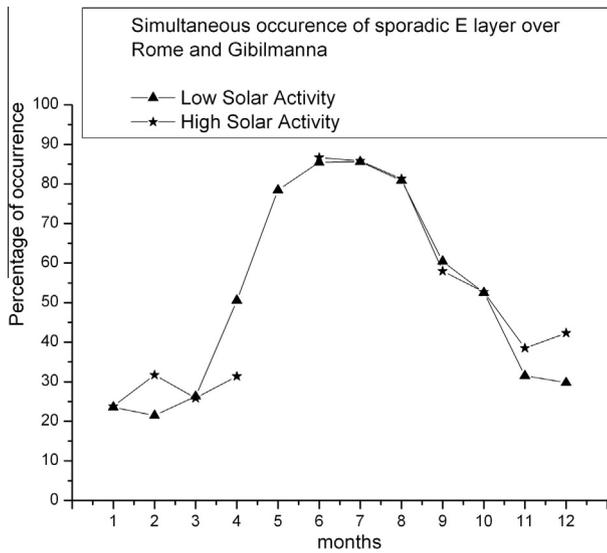


Fig. 1. Percentages of simultaneous occurrence of sporadic-E layer over Rome and Gibilmanna for each month, for LSA and HSA, calculated according to Eq. (3.1). In May the percentage is missing for HSA because *foEs* observations were not simultaneously available at Rome and Gibilmanna.

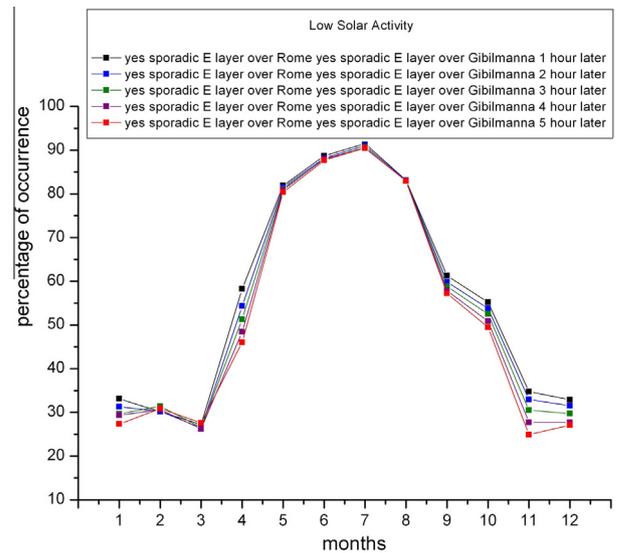


Fig. 2. Percentages of occurrence of sporadic-E layer for LSA in Rome at a given hour and Gibilmanna one (black plot), two (blue plot), three (green plot), four (purple plot), and five (red plot) hours later. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$P_{\text{YesEsGib}_{hh_AND_YesEsRom}_{hh+i,mm}} = \frac{N_{\text{YesEsGib}_{hh_AND_YesEsRom}_{hh+i,mm}}}{N_{\text{TOT},mm}} \cdot 100, \quad (3.3)$$

where $N_{\text{YesEsRom}_{hh_AND_YesEsGib}_{hh+i,mm}}$ ($N_{\text{YesEsGib}_{hh_AND_YesEsRom}_{hh+i,mm}}$) indicates the total number of favorable events characterized by the presence of Es layer over Rome (Gibilmanna) at the hour hh and Es layer over Gibilmanna (Rome) at the hour $hh + i$, and $N_{\text{TOT},mm}$ is the total number of cases relative to the considered month. Figs. 2–5 show the results obtained applying Eqs. (3.2) and (3.3) for all the LSA and HSA months according to Table 3.

Another investigation was also conducted in order to highlight possible latitudinal effects. The following two “patterns” were assumed as favorable events in the statistical analysis: (A) the cases with presence of Es layer over

Rome at a given hour hh and absence of Es layer over Gibilmanna at the same hour hh , indicated as “YesEsRom $_{hh_AND_NoEsGib}_{hh}$ ”; (B) the cases with presence of Es layer over Gibilmanna at a given hour hh and absence of Es layer over Rome at the same hour hh , indicated as “YesEsGib $_{hh_AND_NoEsRom}_{hh}$ ”. The corresponding percentages of occurrence were calculated using respectively the following equations:

$$P_{\text{YesEsRom}_{hh_AND_NoEsGib}_{hh,mm}} = \frac{N_{\text{YesEsRom}_{hh_AND_NoEsGib}_{hh,mm}}}{N_{\text{TOT},mm}} \cdot 100, \quad (3.4)$$

$$P_{\text{YesEsGib}_{hh_AND_NoEsRom}_{hh,mm}} = \frac{N_{\text{YesEsGib}_{hh_AND_NoEsRom}_{hh,mm}}}{N_{\text{TOT},mm}} \cdot 100, \quad (3.5)$$

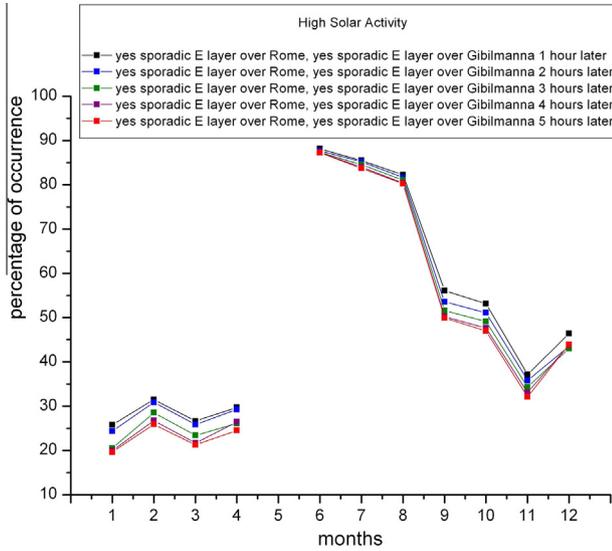


Fig. 3. Percentages of occurrence of sporadic-E layer for HSA in Rome at a given hour and Gibilmanna one (black plot), two (blue plot), three (green plot), four (purple plot), and five (red plot) hours later. In May the percentage is missing because *foEs* observations were not simultaneously available at Rome and Gibilmanna. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

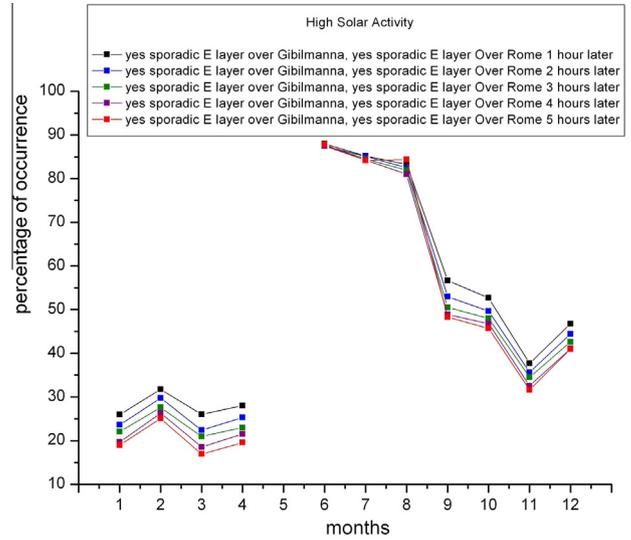


Fig. 5. Percentages of occurrence of sporadic-E layer for HSA in Gibilmanna at a given hour and Rome one (black plot), two (blue plot), three (green plot), four (purple plot), and five (red plot) hours later. In May the percentage is missing because *foEs* observations were not simultaneously available at Rome and Gibilmanna. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

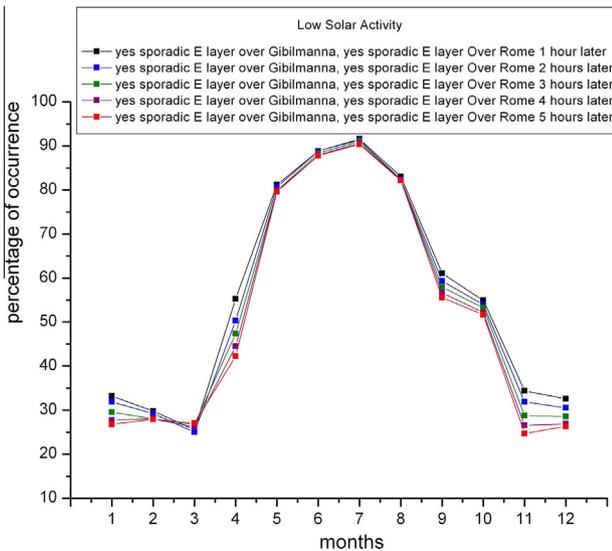


Fig. 4. Percentages of occurrence of sporadic-E layer for LSA in Gibilmanna at a given hour and Rome one (black plot), two (blue plot), three (green plot), four (purple plot), and five (red plot) hours later. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

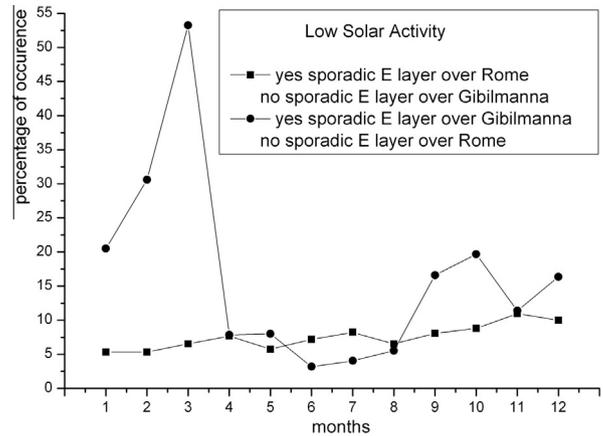


Fig. 6. Percentages of occurrence for the patterns (A) (black squares) and (B) (black circles) for each month for LSA.

where $N_{YesEsRom_hh_AND_NoEsGib_hh,mm}$ and $N_{YesEsGib_hh_AND_NoEsRom_hh,mm}$ indicate the total number of favorable events (A) and (B) respectively over the considered month mm , and $N_{TOT,mm}$ is the total number of cases relative to the same month. Eqs. (3.4) and (3.5) were applied for all the months discerning between the months characterized by LSA and HSA as shown in Table 3. The related results are summarized in Figs. 6 and 7.

Subsequently, to figure out whether the differences between the patterns A and B observed in case of LSA (Fig. 6) and HSA (Fig. 7) are statistically significant, a Student's *t*-test was carried out following a procedure similar to that elaborated by Pietrella and Bianchi (2009) to investigate if the magnetic activity significantly affects Es, specifically: (a) the percentage of occurrence for the patterns (A) and (B) was calculated for each hour from 00.00 to 23.00 local time and for each month; (b) the mean occurrence (arithmetical mean of the 24 hourly percentages of occurrence) for the pattern (A) and (B) was also calculated for all the months (Table 4); (c) the probability that the differences between the mean occurrence values for (A) and (B) patterns are not due to “chance” (null hypothesis), for a

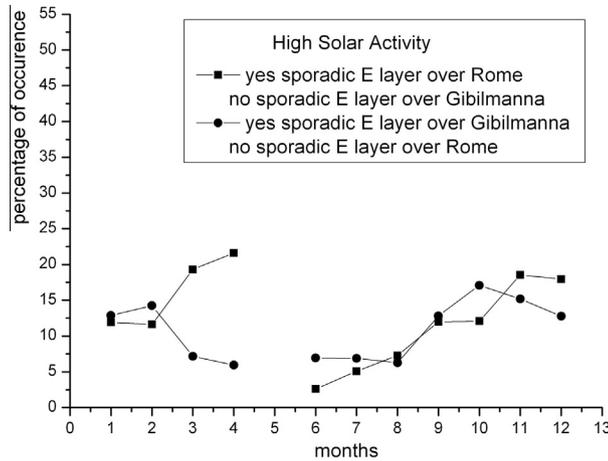


Fig. 7. Percentages of occurrence for the patterns (A) (black squares) and (B) (black circles) for each month for HSA. In May the percentage is missing because *f*oEs observations were not simultaneously available at Rome and Gibilmanna.

level of significance equal to 5%, was calculated with a Student’s *t*-test for all the cases in Table 4. The Student’s *t*-test results are reported in Fig. 8.

We have also tried to investigate the possibility that Es layer over Rome (Gibilmanna) could drift over Gibilmanna (Rome). Hence, the following four “patterns” were assumed as favorable events in the statistical analysis: (C) the cases characterized by the presence of Es layer over Rome and absence over Gibilmanna at a given hour *hh* and absence of Es layer over Rome but presence over Gibilmanna one hour later *hh* + 1, (indicated as [YesEsRom_ *hh*_ AND_ NoEsGib_ *hh*, NoEsRom_ *hh*_ + 1_ AND_ YesEsGib_ *hh*_ + 1]); (D) the cases characterized by the presence of Es layer over Rome and absence over Gibilmanna at a given hour *hh* and absence of Es layer over Rome but presence over Gibilmanna two hours later *hh* + 2, (indicated as [YesEsRom_ *hh*_ AND_ NoEsGib_ *hh*, NoEsRom_ *hh*_ + 2_ AND_ YesEsGib_ *hh*_ + 2]); (E) the cases characterized by the presence of Es layer over Gibilmanna and

Table 4

Mean occurrence values for the patterns (A) and (B) for LSA and HSA. In bold the cases in which the differences between the mean occurrence values for (A) and (B) pattern are statistically significant (see Fig. 8). In May, for HSA, the mean occurrence values are missing because *f*oEs observations were not simultaneously available at Rome and Gibilmanna.

Month	(A) Pattern LSA (%)	(B) Pattern LSA (%)	(A) Pattern HSA (%)	(B) Pattern HSA (%)
Jan	5.34	20.35	12.07	13.09
Feb	5.95	29.88	11.60	14.26
Mar	6.57	53.01	19.35	7.17
Apr	7.28	7.26	21.53	5.83
May	5.73	7.82	***	***
Jun	7.10	3.13	2.58	6.78
Jul	8.19	4.05	5.11	6.80
Aug	6.53	5.42	7.21	6.26
Sep	8.07	16.42	12.04	12.81
Oct	8.72	19.43	12.01	17.09
Nov	11.04	11.38	18.53	15.15
Dec	10.13	16.26	17.90	12.36

absence over Rome at a given hour *hh* and absence of Es layer over Gibilmanna but presence over Rome one hour later *hh* + 1 (indicated as [YesEsGib_ *hh*_ AND_ NoEsRom_ *hh*, NoEsGib_ *hh*_ + 1_ AND_ YesEsRom_ *hh*_ + 1]); (F) the cases characterized by the presence of Es layer over Gibilmanna and absence over Rome at a given hour *hh* and absence of Es layer over Gibilmanna but presence over Rome two hours later *hh* + 2, (indicated as [YesEsGib_ *hh*_ AND_ NoEsRom_ *hh*, NoEsGib_ *hh*_ + 2_ AND_ YesEsRom_ *hh*_ + 2]). The corresponding percentages of occurrence were calculated respectively with the following equations:

$$P_{[YesEsRom_hh_AND_NoEsGib_hh, NoEsRom_hh+i_AND_YesEsGib_hh+i],mm} = \frac{N_{[YesEsRom_hh_AND_NoEsGib_hh, NoEsRom_hh+i_AND_YesEsGib_hh+i],mm}}{N_{TOT,mm}} \cdot 100 \tag{3.6}$$

$$P_{[YesEsGib_hh_AND_NoEsRom_hh, NoEsGib_hh+i_AND_YesEsRom_hh+i],mm} = \frac{N_{[YesEsGib_hh_AND_NoEsRom_hh, NoEsGib_hh+i_AND_YesEsRom_hh+i],mm}}{N_{TOT,mm}} \cdot 100 \tag{3.7}$$

Table 5

Percentages of occurrence of sporadic-E layer for LSA and HSA for patterns (C), (D), (E), and (F). The symbol *** indicates that *f*oEs observations were not simultaneously available at Rome and Gibilmanna.

Month	(C) LSA	(C) HSA	(D) LSA	(D) HSA	(E) LSA	(E) HSA	(F) LSA	(F) HSA
January	2.05	1.97	1.76	2.41	1.02	1.97	1.76	1.77
February	0.99	1.19	2.40	2.00	1.85	1.27	2.40	2.17
March	0.29	1.93	1.01	1.80	1.57	1.04	2.30	0.75
April	0.40	0.43	0.63	0.44	0.60	1.29	0.63	3.06
May	0.28	***	0.45	***	0.55	***	0.56	***
June	0.33	0.33	0.45	0.17	0.38	0.33	0.11	0.34
July	0.20	0.28	0.21	0.43	0.33	0.28	0.21	0.57
August	0.39	0.46	0.11	0.62	0.11	0.15	0.28	0.00
September	0.95	1.29	1.18	0.72	1.05	1.15	0.70	1.30
October	0.76	1.80	1.12	1.12	0.65	2.07	1.01	2.52
November	1.09	1.02	2.15	2.38	1.16	1.89	1.57	2.82
December	1.32	3.15	1.67	2.46	0.93	1.86	1.71	2.46

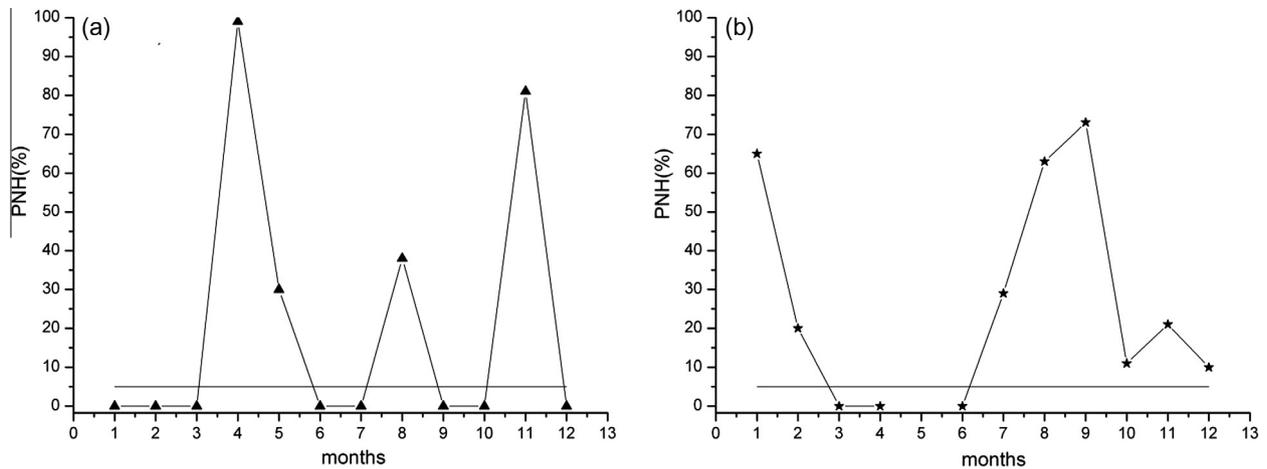


Fig. 8. Student's *t*-test results. Probability of null hypothesis (PNH, *y* axis) for (a) LSA and (b) HSA for each month. In May, for HSA, the percentage is missing because *foEs* observations were not simultaneously available at Rome and Gibilmanna. The horizontal line marks the level of significance (5%).

where $N_{[\text{YesEsRom}_{hh}\text{ AND NoEsGib}_{hh}, \text{ NoEsRom}_{hh+i}\text{ AND YesEsGib}_{hh+i}],mm}$ indicates the total number of favorable events (C), when *i* is equal to 1, and (D), when *i* is equal to 2, over the considered month *mm*; $N_{[\text{YesEsGib}_{hh}\text{ AND NoEsRom}_{hh}, \text{ NoEsGib}_{hh+i}\text{ AND YesEsRom}_{hh+i}],mm}$ indicates the total number of favorable events (E), when *i* is equal to 1, and (F), when *i* is equal to 2, over the considered month *mm*; $N_{\text{TOT},mm}$ represents the total number of cases for the considered month. The results attained applying Eqs. (3.6) and (3.7) are summarized in Table 5.

4. Discussion of the results

As it was already mentioned above, Es layer formation, its intensity and occurrence, depend mainly on the wind shear mechanism that involves mostly atmospheric tides, meteoric shower activity producing metallic ion densities, and the horizontal component of the magnetic field. For this reason it is not surprising that many authors have not found any significant correlation between the Es layer and the 11-year solar activity cycle (Baggaley, 1971, 1984; Whitehead, 1989; Pietrella and Bianchi, 2009). Nevertheless, in virtue of the fact that controversial results have also been found concerning a possible relationship between solar activity and the mid-latitude Es appearance (e.g. see Kotadia, 1969; Baggaley, 1985a; Maksyutin and Sherstyukov, 2005), the authors have also tried to investigate the influence of solar activity on Es occurrence, because the hourly systematic measurements of foEs manually validated at the Rome and Gibilmanna ionospheric observatories, covering 34 years and 3 solar cycles, represent a long reliable foEs data record that is very suitable to carry out analysis aimed to find out possible statistically significant connections between Es occurrence and solar activity.

Fig. 1 shows that, for LSA and HSA, the percentages of simultaneous occurrence of Es layer over Rome and Gibilmanna range respectively: between 78–86% and 81–87% in summer months (May, June, July, and August);

between 21–32% and 24–42% in winter months (January, February, November, and December); between 26–60% and 31–58% in equinoctial months (March, April, September, and October). These percentages are very similar to the percentages of occurrence of the Es layer itself (see Fig. 1 of Pietrella and Bianchi, 2009), and this means that Es layers can manifest themselves on a spatial scale of the order of ≈ 450 km, i.e. the distance Rome–Gibilmanna. This result is compatible with those found both by Houminer et al. (1996), who established the existence of Es “clouds” extending between 150 and 800 km in range, and by Rice et al. (2011), who inferred that Es layer develops more likely over regions of several hundred kilometres rather than to gradually drift across an area. The higher percentages of occurrence of sporadic E layers found during summer months can be explained with the meteoric deposition rates which, having a pronounced summer maximum, as observed by meteor radar measurements (Singer et al., 2004; Janches et al., 2004; Lau et al., 2006), determine a larger abundance of metallic ions during summer months which can consequently give rise to denser and longer living layers that are extended over large areas.

Moreover, Fig. 1 shows that the absolute maximum difference observed between the HSA and LSA percentages is about 1% in summer, about 13% in winter, and about 2% during equinoctial months (except April, for which the difference is 19%). These relatively small differences strengthen again the fact that Es is independent from the level of solar activity, as already stated by many authors (e.g. see Baggaley, 1971, 1984; Whitehead, 1989; Pietrella and Bianchi, 2009).

Figs. 2 and 4 show that, for LSA, the percentages of occurrence of Es layer over Rome (Gibilmanna) at a given hour, and Es layer over Gibilmanna (Rome) one, two, three, four, and five hours later the considered hour, remain more or less the same for all the months because their maximum variation is very small, about 6%, excluding the months of April ($\approx 13\%$) and November ($\approx 10\%$).

Figs. 3 and 5 show the same as Figs. 2 and 4, but for HSA, and also in this case the maximum variation is very small. Figs. 2–5 point out also three additional significant features: (a) independently from the season and the solar activity, Es layers over Rome and Gibilmanna are characterized by lifetimes of at least 5 h, and this finding agrees with lifetimes of 1–4 h detected from backscatter ionograms by Houminer et al. (1996). Hence, Figs. 2–5 reinforce what it is shown by Fig. 1; this means that over Rome and Gibilmanna Es layers manifest themselves as a very persistent phenomenon on a relatively large spatial scale. The independence from the solar activity is highlighted if we focus for instance on the percentages of occurrence calculated for $i = 5$ in Figs. 2–5. In fact, from Figs. 2 and 3 only two significant differences are revealed: in April when the percentage calculated for LSA is 22% higher than that observed for HSA, and in December when the percentage calculated for HSA is 17.0% higher than that observed for LSA. Similarly, from Figs. 4 and 5 only three significant differences emerge: in March and April when the percentages calculated for LSA are about 10% and 23% respectively higher than those observed for HSA, and in December when the percentage calculated for HSA is 15% higher than that observed for LSA. (b) Es layers with a persistence of 5 h over Gibilmanna (Rome) are observed during summer months with high percentages of occurrence ranging between 80% and 90%. The higher/lower percentages of occurrence during summer/winter and equinoctial months observed in Figs. 2–5, reflect very well the cause and effect relationship that exists between meteor count rates and foEs observations found by Haldoupis (2011) who demonstrated as the occurrence and intensity of sporadic Es layers is determined by meteoric deposition, that is abundance of metallic ions. In other words, the low percentages of occurrence of Es layers lifetimes of 1–5 h observed both at Rome and Gibilmanna in Figs. 2–5 during winter and equinoctial months, are likely due to a corresponding decrease of the meteoric shower activity (see Fig. 29.8 of Haldoupis (2011)); this gives rise to layers much weaker and short living, patchy and less extended in space, and more difficult to be detected by ionosondes. Vice versa, the higher percentages of occurrence of Es layers lifetimes of 1–5 h observed in summer, can be explained with a corresponding increase of metallic ions (see Fig. 29.8 of Haldoupis (2011)) which triggers denser and longer living layers. (c) Given the large spatial scale characterizing these Es layers, it is not surprising that if an Es layer is present at Rome an Es layer is also present over Gibilmanna and vice versa, as de facto happens with a very high probability during the summer months.

Figs. 6 and 7 also highlight interesting features. For LSA, the percentages of occurrence related to pattern (A) turn out to be much smaller than those relative to pattern (B), especially in winter and during the equinoctial months (see Fig. 6). In particular, (A) minus (B) differences between the two patterns of -15% , -25% , and -6% , in January, February, and December are respectively

observed, and the same trend occurs also in March, September and October when variations between the two patterns of -47% , -9% , and -11% are respectively detected.

As regards summer months, with the exception of May, a reversal of the trend can be noted in June, July, and August, but in these cases the differences between the two patterns are much less important, being their values equal to $+4\%$, $+4\%$, and $+1\%$ respectively. For HSA (see Fig. 7), the situation is much more ambiguous, the differences between the two patterns are much smaller than those observed for LSA, especially for winter and equinoctial months, and a clear trend does not emerge. (A) minus (B) differences between the percentages of occurrence of the two patterns of $+3\%$ and $+5\%$ are observed in November and December respectively, but in January and February a reversal of the trend is observed with differences of -1% and -3% respectively. Analogously, in March and April, the differences between the percentages of occurrence of the two patterns are $+12\%$ and $+16\%$ respectively, but a reversal trend occurs in September and October when differences of -1% and -5% are observed. During summer months, differences of -4% , -2% , and $+1\%$ are observed in June, July and August respectively.

By and large, the results shown in Figs. 6 and 7 indicate that for LSA a latitudinal effect can be observed between Rome and Gibilmanna. In particular, during winter and equinoctial months, the relatively large negative differences between the percentages of occurrence of patterns (A) and (B) emphasize that Es layer is a phenomenon that can be observed more frequently over Gibilmanna. This finding can be attributed to the fact that moving towards low latitudes, Es becomes more and more a phenomenon independent from seasons (Davies, 1990). This feature however seems to disappear for HSA, as shown by the very small negative/positive differences characterizing the trend of the two patterns plotted in Fig. 7.

With regard to this issue it could be argued that the observed LSA latitudinal effect could be due to a more sensitive ionosonde in Gibilmanna, or to a bias caused by different data reduction methods, or to the fact that Gibilmanna operates in an electromagnetic quieter site. The first two hypothesis can however be excluded because over the years both Rome and Gibilmanna operated with the same kind of ionosonde and the same data reduction method (same operators for the manually validated data). From the electromagnetic point of view, Gibilmanna site was always quieter than Rome, but it is difficult to assess how much this might have affected the statistics results illustrated in Figs. 6 and 7. Nevertheless, to verify the significance of the latitudinal effect highlighted by Figs. 6 and 7 a Student's t -test was performed and the corresponding results, reported in Fig. 8, seem to confirm that, in spite of the relatively small distance between Rome and Gibilmanna (≈ 450 km), a possible latitudinal effect there exists in winter (January, February, and December), equinoctial (March, September, and October), and summer (June, and July) months for LSA (Fig. 8a), and in equinoctial

(March, and April), and summer (June) months for HSA (Fig. 8b).

Finally, the percentages of occurrence of patterns (C), (D), (E), and (F) shown in Table 5, whose maximum value is around 3%, suggest that drifting phenomena of Es layers from Rome to Gibilmanna or vice versa are unlikely to happen, confirming again what was found by Houminer et al. (1996) and Rice et al. (2011), that is Es develops simultaneously over extended areas in space, rather than being a spatially restricted layer which is transported horizontally by neutral winds over a larger region.

5. Summary

A comparative study between the Es layers over the ionospheric stations of Rome and Gibilmanna conducted through a statistical analysis carried out over 34 years of foEs observations, has provided the following relevant features: (1) Es layers can manifest themselves on a relatively large spatial scale and no significant dependence on solar activity is observed, except for April when a moderately large difference is observed between LSA and HSA, but this result is probably due to a corresponding reduction of 67% of the available data, with respect to the other months, that somehow could have affected the significance of the statistical analysis in April for HSA; (2) Es layers with lifetimes of at least 1–5 h were found over Rome and Gibilmanna indicating that they can manifest themselves as a very persistent phenomenon on a relatively large temporal and spatial scale; (3) in particular, lifetimes of 5 h do not show significant differences between LSA and HSA except in March for Rome, and in April and December both for Gibilmanna and Rome; (4) the occurrence of Es layers with a persistence of 5 h over Gibilmanna (Rome) is much more probable in summer, ranging between 80% and 90%; (5) during summer months there is a very high probability that an Es layer occurs both over Rome and Gibilmanna; (6) overall, on the basis of Student's *t*-test results, likely latitudinal effects on Es layer occurrence emerge mostly for LSA during winter, equinoctial, and summer months, when Es is detected more frequently over Gibilmanna rather than Rome; for HSA, it is worth noting that the result for April shown in Fig. 8b could have been negatively affected by a decrease of 67% of the available data with respect to the other months. (7) Es drifting phenomena from Rome to Gibilmanna and vice versa are unlikely to occur.

With regard to future developments, similar investigations can be performed by taking into account foEs observations recorded in other ionospheric stations such as Athens (Greece), Tortosa and El Arenosillo (Spain), with the aim of getting possible noteworthy features characterizing the Es layer dynamics over the Mediterranean region.

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