Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 48 (2011) 2043–2052

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Statistical characterisation of spread F over South Africa

Emirant Bertillas Amabayo [a,b,*], Lee-Anne McKinnell [a,b], Pierre J. Cilliers [b]

[a] *Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa*
[b] *South African National Space Agency (SANSA) Space Science, P.O. Box 32, Hermanus 7200, South Africa*

Received 11 July 2011; received in revised form 16 August 2011; accepted 27 August 2011
Available online 5 September 2011

Abstract

The occurrence of mid-latitude spread F (SF) over South Africa has not been extensively studied since the installation of the DPS-4 digisondes in 1996 and 2000 at Grahamstown (33.32 °S, 26.50 °E) and Madimbo (22.38 °S, 30.88 °E) respectively. This study is intended to quantify the probability of occurrence of F region disturbances associated with SF over South Africa. A study was conducted using data for 8 years (2001–2008) over Madimbo (with a time resolution of 30 min) and Grahamstown (with a variable time resolution of 15 and 30 min). In this study, SF has been classified into frequency SF (FSF), range SF (RSF) and mixed SF (MSF). The SF events were identified by manually identifying ionograms showing SF and tabulating them according to type for further statistical analysis. The results show that the diurnal pattern of SF peaks strongly between 01:00 and 02:00 local time, LT (LT = UT + 2 h), where UT is the universal time. This pattern is true for all seasons and types of SF at Madimbo and Grahamstown in 2001 and 2005, except for RSF which had peaks during autumn and spring in 2001 at Madimbo. The probability of both MSF and FSF tends to increase with decreasing solar activity, with a peak in 2005 (a moderate solar activity period). The seasonal peaks of MSF and FSF are more frequent during winter months at both Madimbo and Grahamstown. In this study, SF was evident in ~0.03% and ~0.06% of the available ionograms at Madimbo and Grahamstown respectively during the 8 years.

Keywords: Mid-latitude spread F; Diurnal variation; Seasonal variation; Ionospheric irregularities

1. Introduction

Mid-latitude spread F (SF) has been investigated in a number of studies such as, e.g., Lambert (1988), Bowman (1991), Oliver et al. (1994), Hajkowicz (2007), Bhaneja et al. (2009), Earle et al. (2010) and Huang et al. (2011). This paper presents the development of a database of SF occurrence and its statistical characterisation for two South African ionosonde stations for the period 2001–2008. SF is a type of ionospheric phenomenon in which the pulses returned from the ionosphere are of a much greater duration than the transmitted pulses. SF can be observed by either radio techniques such as ionosonde, radar, and scintillation or optical techniques. This follows from previous reports that the use of HF radar (Cecile et al., 1996), scintillation data (Rao et al., 2005), ground-based optical measurements and satellite topside sounders may assist in creating a database that will unambiguously identify the different types of SF (McKinnell et al., 2010). However, for the work reported in this paper ionograms measured by ionosondes were used for detecting SF. Ionosondes use vertical sounding of radio waves to study the behaviour and structure of the ionosphere. In the F region of the ionosphere night-glow emissions can be observed optically by using conventional photometers or wide-angle imaging systems (Fagundes et al., 1999). SF affects radio communication and navigation systems utilising the Earth-space propagation environment. Although the probability of SF occurrence is small at mid-latitudes, there is still need to study the SF characteristics at mid-latitudes because of

---

* Corresponding author. Tel.: +27 (28) 312 1196; fax: +27 (28) 312 2039.

E-mail addresses: emirant.amabayo@gmail.com (E.B. Amabayo), LMcKinnell@sansa.org.za (L.-A. McKinnell), pjcilliers@sansa.org.za (P.J. Cilliers).

0273-1177/$36.00 © 2011 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2011.08.029

its strong influence on trans-ionospheric radio communication and satellite navigation. The mid-latitude ionosphere is highly dynamic and this makes it difficult to predict occurrence of ionospheric phenomenon such as SF. SF is also closely related to the scintillation of radio signals from satellites and radio stars (Davies, 1990), thus disrupting radio signals from astronomical sources, and possibly affecting radio astronomy studies (Fagundes et al., 1999). The probability of SF is an important parameter in the prediction and modelling of SF (McKinnell et al., 2010).

The occurrence of nighttime irregularities in the mid-latitude F region which produce SF originate from electron density perturbations, which in turn are believed to be caused by gravity waves (GWs) propagating in the F region (Abdu, 2001; Bhaneja et al., 2009; Hoang et al., 2010). Some parts of South Africa lie within the low mid-latitude region and hence can be affected by mechanisms that trigger irregularities in the equatorial region. Such irregularities can propagate to the mid-latitudes. SF echoes are apparently caused by spatial variations in the electron density of the ionosphere that scatters the signals. The development of SF may be enhanced when GWs raise the height of the F layer. The nighttime scintillation has been attributed to TIDs (Hajkowicz et al., 1981) or SF (Hajkowicz, 1977; Radicella and Ezquer, 2002) mainly in the F region, meanwhile the daytime events are attributed to the presence of sporadic E (Es) layer events. The F region of the nighttime mid-latitude ionosphere often exhibits irregular plasma structures that impose a dispersion on the delay and duration of returned echoes from the ionosphere. Echoes on the ionograms from multiple altitudes at the same incident frequency give rise to range SF (RSF). When the reflections occur at different frequencies from the same altitude, it is termed as frequency SF (FSF), and simultaneous occurrence of RSF and FSF yields mixed SF (MSF).

SF identification is usually independent of the physical mechanisms by which it forms. The presence of SF is identified in terms of the appearance of the ordinary (O) and extraordinary (X)-ray traces on the ionogram. An ionogram with no SF displays only two thin traces showing the O and X-ray traces. In the presence of SF, an ionogram displays a band of reflections on both the O and X-ray traces, which often merge as they spread either horizontally or vertically. Examples of the three classes of SF (i.e. FSF, RSF and MSF) are shown in Fig. 1. The classification is based on the classification described by several authors (e.g., Lambert, 1988; Davies, 1990; Wang et al., 2008). Besides the regular layers of the ionosphere, there are occasional irregular layers that affect the propagation of radio waves. The most significant of these is the sporadic E (Es) as shown in Fig. 1(d), which is outside the scope of this paper. Fig. 2. The FSF appearance is characterised by diffuse echoes near foF2, thus making this parameter undefinable (Davies, 1990; Wang et al., 2008, 2010). FSF occurs due to a range of densities at the same altitude that causes pulses of different carrier frequency to be reflected from that altitude. RSF is associated with the diffusiveness of the echoes near the horizontal part of the trace (Davies, 1990; Wang et al., 2008). The RSF is as a result of reflections from multiple altitudes at a given incident frequency (Bhaneja et al., 2009) during the period of observation. Lambert (1988) conducted the first South African mid-latitude seasonal statistical SF study by comparing data from two Kel IPS-4A pulse ionosondes located at Johannesburg (26.07 °S, 28.10 °E) and Hermanus (34.42 °S, 19.22 °E), South Africa. Lambert (1988) used ionosonde data at 5 min resolution from these two stations in order to resolve short period travelling ionospheric disturbances (TIDs). The study included data from a single solar minimum year (1985) for all seasons. Earlier low mid-latitude studies of SF was conducted by Singleton (1957) at Brisbane (lat. 275 °S, long. 1529 °E). Measurements done during the Singleton (1957, 1962) demonstrated that at equatorial and high latitude stations there is a strong correlation between vertical movement of the ionosphere and spread F, and that such movement was found to be independent of geomagnetic activity, time of day and season of the year. However, these results differ from what this study demonstrated at mid-latitudes.

The present study is an extension of the work done by Lambert (1988). Ionosonde data from Madimbo (22.38 °S, 30.88 °E) and Grahamstown (33.32 °S, 26.50 °E) were considered for an extended period ranging from the solar maximum year (2001) to the solar cycle minimum (2008). The SF data obtained were used to investigate diurnal, seasonal and solar activity patterns of SF over South Africa. Bowman (1991) stated clearly that the extent of range and frequency spread are controlled by the excess ranges to scattering regions displaced horizontally from the zenith position and the amount of excess ionisation in the small scale structures respectively. Further, Bowman (1991) expressed that atmospheric conditions associated with ionospheric F2 region heights and upper atmosphere neutral particle densities seem to favour the generation of frequency spread. In addition, Bowman (1991) also added that a horizontal gradient of maximum electron density is an additional requirement to create frequency spread.

The cause of mid-latitude SF has been investigated by several researchers such as, e.g., Kelley and Fukao (1991), Oliver et al. (1994) and Earle et al. (2010) and they have attributed SF with TIDs and GWs. According to these authors, TIDs and GWs could produce such structures and might also help to initiate development of the Perkins instability (Kelley, 2009). This instability has been preferred by some researchers for reconciling the low growth rate of GWs, with the sometimes abrupt appearance of SF at mid-latitudes (Bhaneja et al., 2009). Huang et al. (1994) also suggested that seeding by atmospheric GWs is pivotal in the generation of mid-latitude SF irregularities. The Perkins linear instability was shown to become significantly enhanced due to GWs seeding the mid-latitude ionosphere. However, the cause of mid-latitude SF has not yet been conclusively identified (Davies,

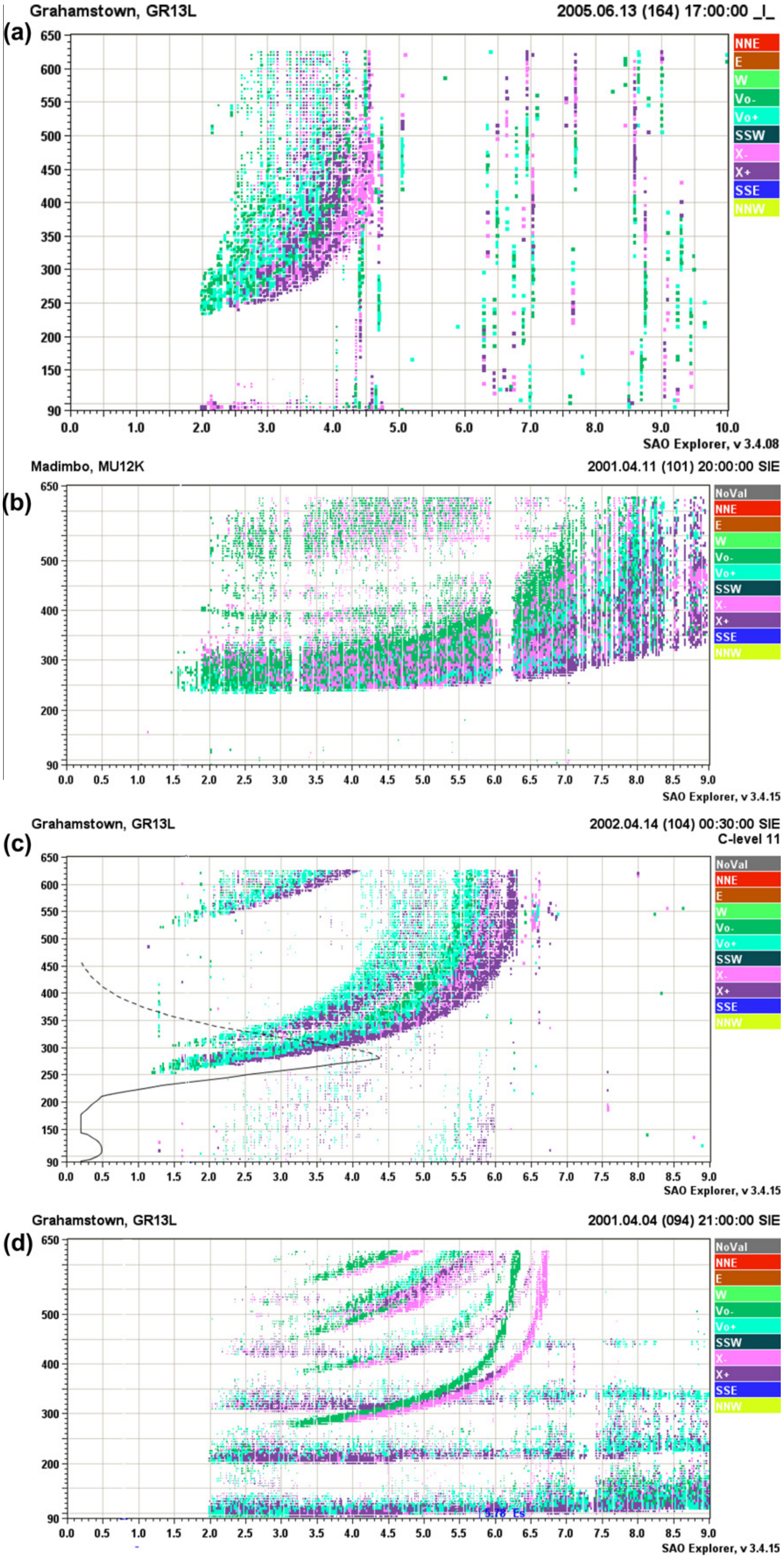

Fig. 1. Ionograms showing the appearance of the O and X-ray traces during (a) FSF, (b) RSF and (c) MSF. (d) Shows occurrence of normal reflected echoes and Es at lower virtual heights ∼(90–350 km).

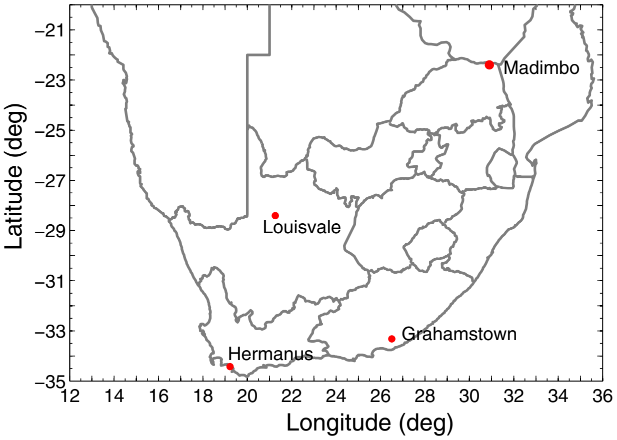

Fig. 2. Map of South Africa showing the four ionosonde stations. Data from only Madimbo and Grahamstown have been analysed in this study.

1990; Bhaneja et al., 2009). The study of the mid-latitude ionosphere by Kelley and Miller (1997) revealed the interconnections between GWs, TIDs, elongated bands of raised ionosphere density depletions and the turbulent upwelling of mid-latitude plasma (Hajkowicz, 2007). These phenomena have been extensively used to explain the causes of mid-latitude SF and scintillation irregularities in the F region. In a similar study, Bowman (1992) pointed out that mid-latitude SF is primarily caused by off-vertical reflections of radio waves from tilted isoionic surfaces produced by the passage of moderate scale TIDs (MSTIDs). Thus many different mechanisms have been proposed to contribute to SF occurrence at mid-latitudes, but this remains inconclusive. The study presented here does not explicitly address mechanisms of SF formation.

1.1. Data and methods

Much of today's understanding of the ionosphere has been derived from ionosonde studies, for example, e.g., Davies (1990), Reinisch et al. (2005) and McKinnell et al. (2010). About 17,500 ionograms from each station were viewed to identify SF events. Madimbo and Grahamstown ionosonde stations are separated by a distance of 1287 km (McNamara, 2009). The geographical and geomagnetic coordinates of the ionosonde stations used to obtain ionospheric SF information over South Africa are provided in Table 1. The magnetic coordinates of the stations shown in Table 1 are computed using a facility obtained from http://wdc.kugi.kyoto-.ao.jp/igrf/gggm/.

The SAO Explorer software (Reinisch et al., 2004) was used for the analysis of the ionosonde data. Both the raw and processed (SAO) data were loaded into the SAO Explorer software to display ionograms. The ionosonde measurements were recorded at 15 min intervals at Grahamstown in 2003 and 2006–2008. At all other times, the measurements at both stations were recorded at 30 min intervals. The number of the observed SF events at Madimbo and Grahamstown ionosonde stations were used to calculate the monthly probability of the three types of SF using Eq. (1). The calculation of the probability takes into account data gaps by only considering available ionograms in calculating the sums

$$\text{Probability} = \frac{\text{Sum of SF occurrences}}{\text{Total number of observed ionograms}} \times 100\% \tag{1}$$

Probability is consistently expressed as a percentage (%) in this study. The period of this study corresponds to the declining solar cycle 23. Diurnal variation of SF over South Africa was conducted for all seasons using data from the two ionosonde stations. The years 2001 (high solar activity) and 2005 (moderate solar activity) were chosen to present the diurnal pattern of SF for both Madimbo and Grahamstown. The number of SF events at a particular hour is obtained by adding all events sampled within that hour.

2. Results and discussion

The ionosonde database at Madimbo and Grahamstown stations enabled the analysis of the annual, diurnal, seasonal and solar cycle statistics of mid-latitude SF events over South Africa.

2.1. Annual SF statistics

This section presents the monthly probability of SF occurrence, which in turn constitutes the annual statistics of SF over Madimbo and Grahamstown. Huang et al. (2011) conducted SF study over Changchun (125.26 °E 43.83 °N) and Urumqi (87.63 °E 43.75 °N) both in China. They found out that the annual maxima of SF occurrence over the two stations are in summer and winter. The annual probability of the three types of SF and the availability of data are presented in Fig. 3. This analysis pro-

Table 1
Geophysical parameters of the ionosonde stations.

Station	Station code	Geographic coordinates long. (°E)	Lat. (°S)	Geomagnetic coordinates long. (°E)	Lat. (°S)
Grahamstown	GR13L	26.50	33.32	92.09	34.09
Madimbo	MU12K	30.88	22.38	98.89	24.16
Hermanus	HE13N	19.22	34.42	84.67	33.90
Louisvale	LV12P	21.24	28.51	88.04	28.48

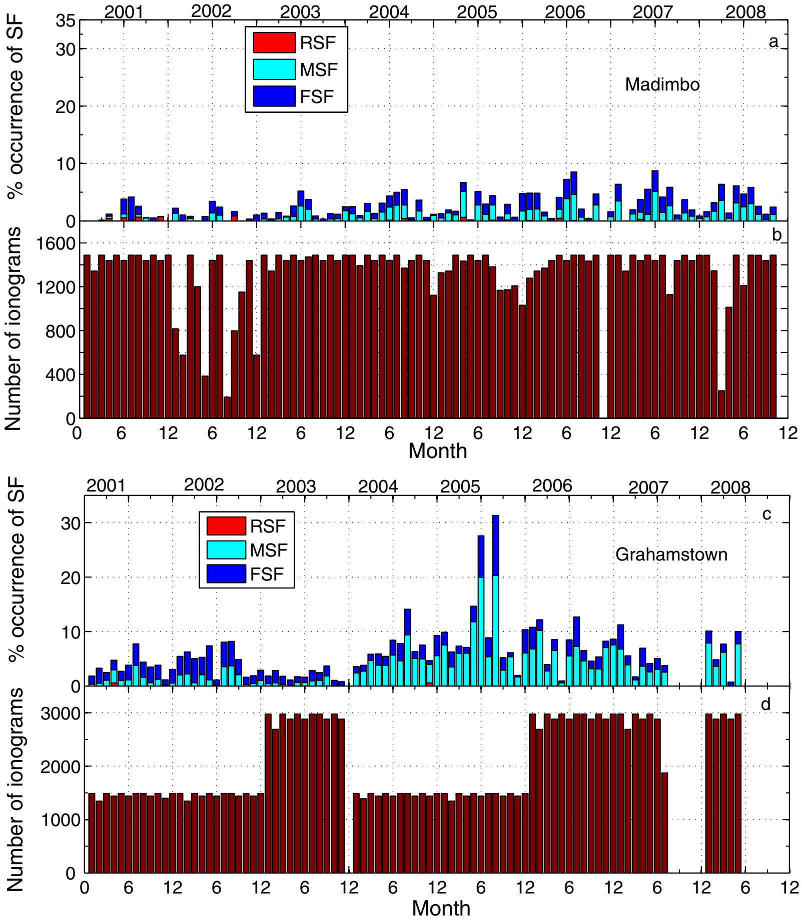

Fig. 3. Monthly probability of total SF from 2001 to 2008 with sub bars for each type of SF observed at (a) Madimbo and (c) Grahamstown. Monthly number of available ionograms observed at (b) Madimbo and (d) Grahamstown. The months are represented by numbers 1 (for January) up to 12 (for December).

vides the trend of monthly, seasonal and annual probability of SF.

Fig. 3(a) shows that RSF probability was very low for the observed period, but the peaks occurred in 2002 (September, ~0.88%) and 2001 (November, ~0.76% and August ~0.67%). The MSF peak probability were observed in 2007 (June, 5.14%) and 2005 (April, 4.53%), while the peaks for FSF occurred in 2007 (May, 4.37%) and 2001 (July, 4.03%). The annual peak of the probability of all types of SF at Madimbo was 4.0 % in 2001, increased from 2002 to the maximum value of ~8.0% in 2006 and 2007, and then decreased in 2008. On the other hand, Fig. 3(c) shows that RSF at Grahamstown station was observed only in 2001 (April, 0.56%) and 2004 (November, 0.56%). Both MSF and FSF attained their peak occurrences of 20.30% and 11.02%, and secondary peaks of 19.93% and 7.64% in the months of August and June respectively in 2005. The annual probability peak of all types of SF observed at Grahamstown is higher (August, 31.32%) in 2005. Meanwhile at Madimbo, it increased to the maximum value of ~8.0% in 2006 and 2007, and then further decreased in 2008. No SF events were observed during summer in 2001 at Madimbo as reflected in Fig. 3.

The important observation here is that MSF and FSF are the most dominant SF irregularities over South Africa, with much higher occurrences at Grahamstown compared to Madimbo. The difference in the SF probability at these two stations could be attributed to the difference in the levels of atmospheric GWs in the ionospheric F regions over the two stations. This may be further influenced by the latitude difference of the two stations, since SF is latitude dependent. Absence of SF occurrence in Fig. 3 means lack of data or unreliable data. This is evident in December 2006 at Madimbo in Fig. 3(b), December 2003, August to December 2007 and June to December 2008 at Grahamstown in Fig. 3(d).

Table 2 gives a summary of the annual probability results of SF for Madimbo and Grahamstown ionosonde stations. Table 2 shows that RSF occurs more rarely at Grahamstown than at Madimbo, although the probability is the same for the two stations in 2004. MSF and FSF occurred more at Grahamstown than Madimbo for all the observed years. The most important feature derived from this table is that MSF and FSF are the dominant forms of ionospheric SF irregularities over South Africa.

Table 2
The probability of the three types of SF for two ionosonde stations.

Madimbo					Grahamstown				
Year	RSF	MSF	FSF	Total	Year	RSF	MSF	FSF	Total
2001	0.22	0.18	0.75	1.15	2001	0.05	1.21	2.28	3.54
2002	0.75	0.47	0.06	1.28	2002	0.00	1.62	3.22	4.84
2003	0.00	0.83	0.99	1.82	2003	0.00	0.60	1.38	1.98
2004	0.05	1.35	1.27	2.67	2004	0.05	4.70	2.36	7.11
2005	0.08	1.45	1.25	2.78	2005	0.00	8.08	3.35	11.43
2006	0.06	1.63	1.86	3.55	2006	0.00	5.41	2.12	7.53
2007	0.02	1.61	2.01	3.64	2007	0.00	3.43	2.14	5.57
2008	0.00	1.64	1.69	3.33	2008	0.00	5.14	1.58	6.72

2.2. Diurnal variation of SF

The magnetic field lines at equatorial F region heights are known to be mapped to higher latitudes, including the mid-latitudes; and during the daytime, the high plasma conductivity of the E region suppresses any electric field, thereby inhibiting the development of the plasma instability (Wernik et al., 2004). However, after sunset, the E region conductivity drops considerably and the electric fields generated within the bottomside of the F region can develop plasma instabilities. The rapid post-sunset uplifting of the F region supports the onset of ionospheric plasma irregularities. Fluctuations in the ion drift velocity or plasma density caused by GWs or other large scale structures can initiate the generation of the initial perturbation (Davies, 1990). Throughout this study, no SF was observed during the daytime and hence the diurnal variation was limited to nighttime (20:00–06:45 LT) periods when events were present.

Ionospheric disturbances in the F region at two well separated mid-latitude stations were identified on ionograms by their spread echoes. The study of diurnal variation of mid-latitude SF over South Africa undertaken by Lambert (1988) revealed consistent minima in the probability of disturbance around sunrise and sunset. Disturbance probabilities were lowest during autumn and spring while the probability for winter exceeded the summer level. A similar investigation in this study presented in Fig. 4(a) shows that there is a gradual increase with hours in the probability of FSF. The peaks occur at 02:00 LT during winter and at 01:00 LT during autumn and spring in 2001 respectively. RSF and MSF occurrences remained low, although RSF occurrence dominates from 02:00 to 06:00 LT during spring in 2001. It's clear that FSF and MSF are the dominant nighttime SF irregularities observed at Madimbo, except from 03:00 to 06:00 LT (in spring) and at 00:00 LT (during autumn) when RSF shows the highest probability in 2001. Meanwhile, FSF and MSF were the dominant irregularity contributions during summer (0.40%) and spring (0.30%), with peaks at 00:00 LT and 01:00 LT respectively in 2001 and 2005 (see Fig. 4(b)).

The observations at Grahamstown in 2001 in Fig. 4(c) imply that FSF followed by MSF dominated the irregular plasma densities responsible for the generation of SF. The probability of both FSF and MSF increased steadily to a peak value at 01:00 LT and drops gradually towards 06:00 LT for all seasons (except during autumn where FSF peaks at 02:00 LT). The most prominent SF irregularity observed at Grahamstown in 2005 (see Fig. 4(d)) is the MSF followed by FSF. The highest probability of these two types of SF can be observed at 01:00 LT during winter and summer, and 02:00 LT during autumn and spring. It is evident from these observations that the SF diurnal peaks are highest in winter and occur at Grahamstown. Generally SF probability is highest between 01:00 and 02:00 LT for all seasons and types of SF in the 2 years chosen, except during autumn and spring (for RSF) in 2001 at Madimbo.

2.3. Seasonal variation of SF

For studying the seasonal variation, the SF observations have been grouped as follows: autumn (March–May), winter (June–August), spring (September–November) and summer (December–February). The probability of the three types of SF have been computed for each season. The results for Madimbo and Grahamstown ionosonde stations are presented in Fig. 4. The study by Lambert (1988) revealed a seasonal maximum in winter, equinoctial minima, and a secondary maximum in summer. Huang et al. (2011) also conducted SF study over Changchun (125.26 °E, 43.83 °N) and Urumqi (87.63 °E, 43.75 °N) both in China and found out that the annual maxima of SF occurrence over the two stations are in summer and winter.

Fig. 5(a) shows that, the seasonal peaks of RSF probability occur during winter in 2001 and spring in 2002 at Madimbo. Whereas RSF was only observed in 2001 during autumn and in 2004 during spring at Grahamstown as shown in Fig. 5(b). The probability of MSF is higher at Grahamstown than at Madimbo during this observation period. The seasonal probability of MSF peaks during winter at Madimbo for all the observed years, except in 2008 where the probability decreased to the same value for both autumn and winter. The seasonal probability of this particular SF irregularity at Grahamstown has a random pattern, with the highest occurrence during winter in 2005. The probability of FSF occurrence increases during winter from 2001 to 2007 and decreased in 2008 at Madimbo. The

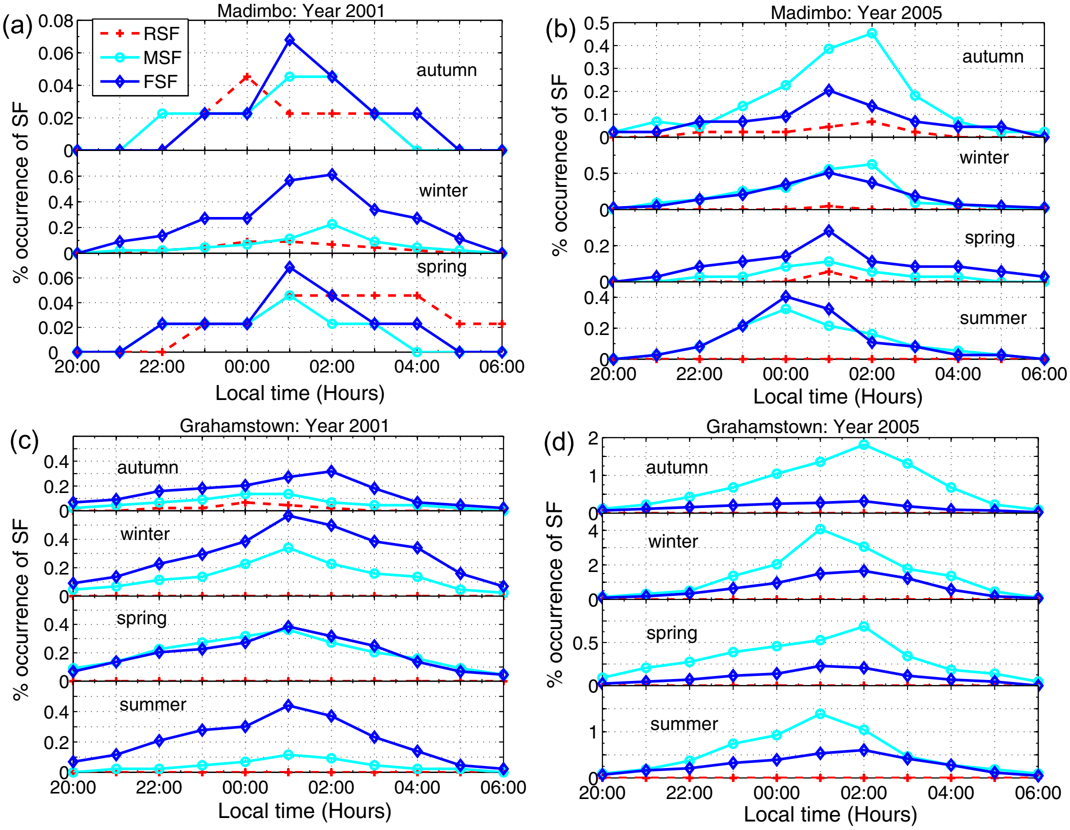

Fig. 4. Diurnal variation of SF over Madimbo station for (a) 2001 and (b) 2005. Diurnal variation of SF over Grahamstown for (c) 2001 and (d) 2005. There was no SF observed in 2001 in summer at Madimbo ionosonde station.

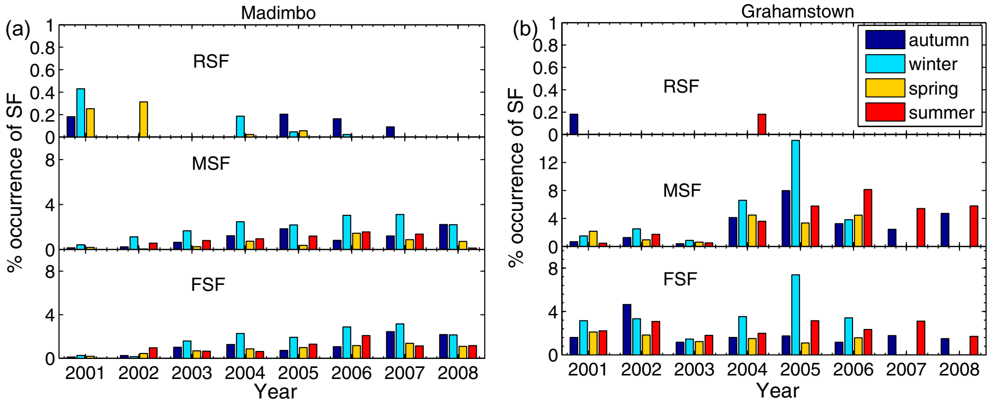

Fig. 5. The seasonal probability of the three types of SF from the peak of solar cycle 23 in 2001 to the minimum in 2008 observed at (a) Madimbo and (b) Grahamstown. The scale for RSF is different because it has small probability of occurrence.

probability of FSF is still higher at Grahamstown than at Madimbo, with the highest probability in 2005 during winter followed by a secondary summer peak in 2006. Therefore, MSF and FSF are the dominant seasonal SF irregularity structures observed from the two stations. The results of seasonal dependence of mid-latitude MSF and FSF in winter are consistent with the results obtained by Lambert (1988). These results are also consistent with the nighttime local winter maximum occurrence of topside SF at mid-latitudes studied by Dyson (1968).

2.4. SF dependence on sunspot number

Sunspot number (SSN) is a measure of solar activity and this study undertakes to investigate the relationship between this parameter and occurrence of SF. The monthly mean sunspot number (SSN) was used consistently to quantify the solar activity in this paper. Wang et al. (2010) carried out statistics of SF over Hainan station (geog. 19.5 °N, 109.1 °E, dip lat. 9.5 °N) in China during the declining solar cycle 23 from March 2002 to February

2008. Their statistical results show that MSF and strong SF (SSF) are the dominant irregularities in Hainan, with MSF occurring mainly during summer and low solar activity years. They found that SSF is dominant during equinoxes and high solar activity years, with FSF being independent of solar activity during each season. It can be observed that the probability of both MSF and FSF showed peaks in 2005 as shown in Fig. 6(b) and (c), during relatively low solar activity period. MSF and FSF are the dominant forms of SF irregularity observed over Madimbo and Grahamstown both during low and moderate solar activity. At Grahamstown, FSF shows higher probability up to 2004, which is the intermediate phase between high and moderate solar activity periods. After 2004, MSF became the most dominant irregularity with the peak phase in 2005, although a sharp anomalous decrease was observed in July 2005 at Grahamstown. Meanwhile at Madimbo, FSF and MSF showed very low but approximately the same pattern for all the years, except 2001 where anomalous peak in FSF was observed. It can be observed that higher FSF and MSF probabilities occurred during low solar activity than high solar activity periods. The results of SF pattern with solar activity for these two mid-latitude stations are consistent with those of, e.g., Wang et al. (2008, 2010).

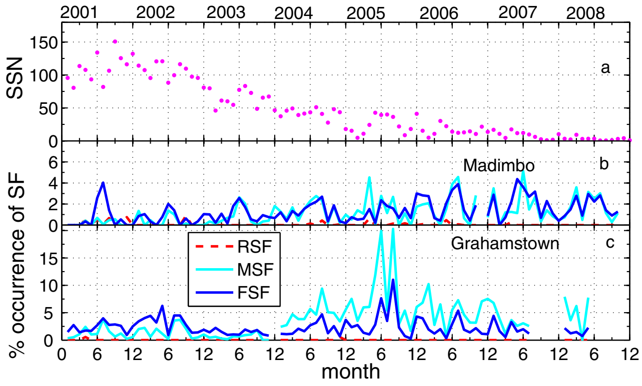

Fig. 6. (a) The average SSN for each month of a particular year. The probability of the three types of SF observed at (b) Madimbo and (c) Grahamstown stations. The months are represented by numbers 1 (for January) up to 12 (for December).

2.5. Scatter plots for SF occurrences

Correlation analysis done by Wang et al. (2010) showed that RSF and solar activity are positively correlated during equinoxes and summer and have no relationship during winter. However, they found significant dependence of MSF on solar activity during the summer and winter, but

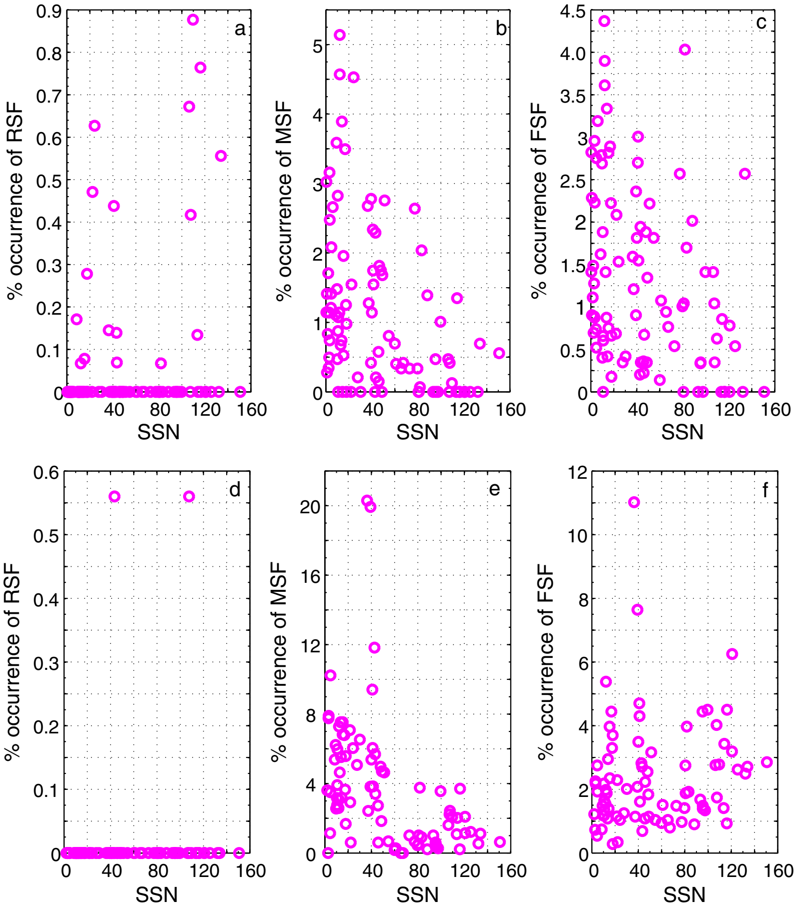

Fig. 7. Scatter diagram for (a) RSF, (b) MSF and (c) FSF observed at Madimbo station from 2001–2008. Scatter diagrams for (d) RSF, (e) MSF and (f) FSF observed at Grahamstown for the same period.

it does not relate to solar activity during the equinoxes. FSF was found to clearly increase with solar activity during equinoxes and summer, but independent of solar activity during the winter. The relationship between the three types of SF and solar activity in this particular study are shown in Fig. 7. The monthly SF statistics was combined for each type of SF for all the years to investigate the relationship between solar activity and SF. The scatter plots in Fig. 7(b) and (c) show that the probability of both MSF and FSF increases with decreasing solar activity, while in a few cases RSF occurrence increases with increasing solar activity (see Fig. 7(a)). On the other hand, there was almost no (except two cases) of RSF observed at Grahamstown (during the available period of data in this study, hence no conclusion about its pattern). The probability of MSF is observed to decrease with increasing solar activity, although a few anomalous cases were found between SSN of 30 and 50 (see Fig. 7(e)). It can also be observed in Fig. 7(f) that the probability of FSF as a function of solar activity is fairly random, with a few outlier cases between SSN values ranging from 30 to 50. Therefore, this study found out a weak negative relationship between solar activity and the probability of MSF at both stations. A weak positive relationship is also proposed between solar activity and RSF occurrence as observed for Madimbo station only. No relationship was found between FSF and solar activity for both Madimbo and Grahamstown stations.

2.6. Conclusions

The statistical features of SF observed in ionograms recorded by the ionosondes at Madimbo and Grahamstown stations during the 8 year period (2001–2008) have been analysed. SF occurrences were classified into three types (i.e. RSF, MSF and FSF). These types of SF show different characteristic patterns with some similarities. MSF and FSF are the most prevalent irregularities at Madimbo and Grahamstown stations, with both occurring mostly during winter and low solar activity years. RSF only reached levels above 0.40% in autumn (2001) at Madimbo. The diurnal peaks of SF occurrence were observed during the post-midnight stage (01:00–02:00 LT). The time of maximum diurnal occurrence of RSF is earlier in autumn than during spring. This time delay may be caused by the earlier sunset-linked reversal time of the E × B drift. MSF and FSF dependence on solar activity showed different patterns at the two stations. At Madimbo MSF and FSF has about the same probability irrespective of the SSN, while at Grahamstown (further south) the MSF probability was higher than the FSF probability during low SSN and vice versa during high SSN. The MSF probability has significant dependence on solar activity during moderate (2005) and low (2006–2008) solar activity years, while it does not relate so well to SSN during high solar activity. The difference in the diurnal, seasonal and solar activity patterns of SF at the two stations may be attributed to the latitude difference of the two stations.

Acknowledgements

This study was financially supported by the National Astrophysics and Space Science Programme (NASSP) of University of Cape Town and the South African National Space Agency (SANSA): Space Science. The authors acknowledge the management of Lowell DIDBase for providing ionosonde data. The authors also acknowledge the reviewers for their striking contributions towards improving the quality of this paper.

References

Abdu, M.A. Outstanding problems in the equatorial ionosphere–thermosphere electrodynamics relevant to spread F. Journal of Atmospheric and Solar-Terrestrial Physics 63, 869–884, 2001.

Bhaneja, P., Earle, G.D., Bishop, R.L., Bullett, T.W., Mabie, J., Redmon, R. A statistical study of midlatitude spread F at Wallops Island, Virginia. Journal of Geophysical Research, 114 (A04301), 2009. doi:10.1029/2008JA013212.

Bowman, G.G. Ionospheric frequency spread and its relationship with range spread in mid-latitude regions. Journal of Geophysical Research 96 (A6), 9745–9753, 1991.

Bowman, G.G. Upper atmosphere neutral-particle variations compared with spread-F occurrence rates at locations around the world. Annales Geophysicae 10, 676–682, 1992.

Cecile, J.F., Vila, P., Blanc, E. HF radar observations of equatorial spread-F over West Africa. Annales Geophysicae 14, 411–418, 1996.

Davies, K. Ionospheric Radio. Peter Peregrinus, London, 1990.

Dyson, P.L. Topside spread F at midlatitudes. Journal of Geophysical Research 73, 2441–2446, 1968.

Earle, G.D., Bhaneja, P., Roddy, P.A., Swenson, C.M., Barjatya, A., Bishop, R.L., Bullett, T.W., Crowley, G., Redmon, R., Groves, K., Cosgrove, R., Vadas, S.L. A comprehensive rocket and radar study of midlatitude spread F. Journal of Geophysical Research, 115 (A12339), 2010.

Fagundes, P.R., Sahai, Y., Batista, I.S., Abdu, M.A., Bittencourt, J.A., Takahashi, H. Observations of day-to-day variability in precursor signatures to equatorial F-region plasma depletions. Annales Geophysicae 17, 1053–1063, 1999.

Hajkowicz, L.A. Morphological and ionospheric aspects of quasiperiodic scintillations. Journal of Atmospheric and Terrestrial Physics 39, 833–841, 1977.

Hajkowicz, L.A. Morphology of quantified ionospheric range spread-F over a wide range of midlatitudes in the Australian longitudinal sector. Annales of Geophysics 25, 1125–1130, 2007.

Hajkowicz, L.A., Bramley, E.L., Browing, R. Drift analysis of random and quasiperiodic scintillations in the ionosphere. Journal of Atmospheric and Terrestrial Physics 43 (7), 723–733, 1981.

Hoang, T.L., Abdu, M., MacDougall, J., Batista, I.S. Longitudinal differences in the equatorial spread F characteristics between Vietnam and Brazil. Advances in Space Research 45, 351–360, 2010.

Huang, C.S., Miller, C.A., Kelley, M.C. Basic properties and gravity wave initiation of the midlatitude F-region instability. Radio Science 29, 395–405, 1994.

Huang, W.Q., Xiao, Z., Xiao, S.G., Zhang, D.H., Hao, Y.Q., Suo, Y.C. Case study of apparent longitudinal differences of spread F occurrence for two midlatitude stations. Radio Science 46, 2011.

Kelley, M., Miller, C. Mid-latitude thermospheric plasma physics and electrodynamics: a review. Journal of Atmospheric Terrestrial Physics 59 (13), 1643–1654, 1997.

Kelley, M.C. The Earth's Ionosphere: Plasma Physics and Electrodynamics, second ed Academic Press, Amsterdam, 2009.

Kelley, M.C., Fukao, S. Turbulent upwelling of the mid-latitude ionosphere. 2. Theoretical framework. Journal of Geophysical Research 96 (A3), 747–3753, 1991.

Lambert, S. Frequency and duration *f* disturbances in the mid-latitude F region of the ionosphere. Radio Science 23 (4), 693–707, 1988.

McKinnell, L., Paradza, M., Cilliers, P., Abdu, M., de Souza, J. Predicting the probability of occurrence of spread-F over Brazil using neural networks. Advances in Space Research 39, 1047–1054, 2010.

McNamara, L.F. Spatial correlations of foF2 deviations and their implications for global ionospheric models: 2. Digisondes in the United States, Europe, and South Africa. Radio Science, 44 (RS2017), 2009.

Oliver, W.L., Fukao, S., Yamamoto, Y., Takami, T., Yamanaka, M.D., Yamamoto, M., Nakamura, T., Tsuda, T. Middle and upper atmosphere radar observations of ionospheric density gradients produced by gravity wave packets. Journal of Geophysical Research 99 (A4), 6321–6329, 1994.

Radicella, B.F.S.M., Ezquer, R.G. A different approach to the analysis of GPS scintillation data. Annals of Geophysics 45 (3/4), 551–561, 2002.

Rao, P.V.S.R., Ram, S.T., Niranjan, K., Prasad, D.S.V.V.D., Krishna, S.G., Lakshmi, N.K.M. VHF and L-band scintillation characteristics over Indian low latitude station, Waltair (17.7 °N, 83.3 °E). Annales Geophysicae 23, 2457–2464, 2005.

Reinisch, B., Galkin, I.A., Khmyrov, G., Kozlov, A., Kitrosser, D.F. Automated collection and dissemination of ionospheric data from the digisonde network. Advances in Radio Science 2, 241–247, 2004.

Reinisch, B.W., Huang, X., Galkin, I.A., Paznukhov, V., Kozlov, A. Recent advances in realtime analysis of ionograms and ionosonde drift measurements with digisondes. Journal of Atmospheric and Solar Terrestrial Physics 67, 1054–1062, 2005.

Singleton, D. A study of spread-F ionospheric echoes at night at Brisbane. III. Frequency spreading. Australian Journal of Physics 10 (1), 60–76, 1957.

Singleton, D. Spread-F and the parameters of the F-layer of the ionosphere. III: Spread-F and the vertical movement of the F-layer. Journal of Atmospheric and Terrestrial Physics 24, 899–907, 1962.

Wang, G.J., Shi, J.K., Wang, X., Shang, S.P. Seasonal variation of spread-F observed in Hainan. Advances in Space Research 41, 639–644, 2008.

Wang, G.J., Shi, J.K., Wang, X., Shang, S.P., Zherebtsov, G., Pirog, O.M. The statistical properties of spread F observed at Hainan station during the declining period of the 23rd solar cycle. Annales of Geophysics 28, 1263–1271, 2010.

Wernik, A.W., Lucilla, A., Materassi, M. Ionospheric irregularities, scintillation and its effects on systems. Acta Geophysica Polonica 52 (2), 237–249, 2004.