Statistical Investigation of the relationship between the occurrences of AGW, ESF and ESF types in the American sector

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Abstract

Equatorial Spread F (ESF), a manifestation of nighttime irregularities in the equatorial ionosphere has been linked to Atmospheric Gravity Waves (AGW) by different authors. However, there have not been much study to ascertain the extent of the relationship between the occurrence of AGW and the generation and occurrence of ESF. This study investigates the correlation between AGW and ESF occurrences during the year 2016, using data obtained with the aid of satellite borne Atmospheric Infrared Sounder (AIRS) and ionogram obtained with the aid of Digisonde Portable Sounder (DPS-4) located at Jicamarca, (geog. Lat. 11.95, Long. 76.87 and geomagnetic Lat. 9.28, Long.-7.92), an equatorial station in the Peruvian sector. During this period, 72.9% of AGW occurrence was observed between 18:00UT and 00:00UT (post-sunset period) while the remaining 27.1% occurrence was observed between 00:00 and 04:00UT (post-midnight period) coinciding with the period of occurrence of ESF. Results from the study reveal that the occurrences of ESF and AGW are independent of each other. An insignificant correlation (0.39) was found between the days of occurrence of the two phenomena. While ESF occurrence is a regular daily occurrence with local time dependence, AGW propagation is not dependent on local time. For Jicamarca, we found that ESF occurrence is greater during the solstice months than equinox. The probability of AGW reaching the bottomside F-layer depends on the properties of the wave. In this study, AGW was able to penetrate ionospheric heights on only six occasions. The results also show that AGW occurrence can only influence the conditions that trigger ESF rather than triggering ESF altogether. The occurrence of AGW tends to influence the occurrence of MSF type of ESF which is predominantly a post sunset phenomenon in preference to the other two types. Coefficient of correlation between AGW and MSF ranged between

Tables

Table 1: Months and days of simultaneous occurrence of AGW and ESF during 2016 at Jicarmaca

S. N	**Days** (Nighttime) 18:00 – 04:00UT	No. of times **AGW** occurred	No. of ionograms with **ESF**	**%RSF**	**%MSF**	**%FSF**
1.	February 5 – 6	17	40	100	-	-
2.	April 20 – 21	15	8	-	100	-
3.	September 26 – 27	27	40	-	100	-
4.	September 28 – 29	9	18	-	83	17
5.	November 28 – 29	31	40	-	100	-

S. N	**Days** (Nighttime) 18:00 – 04:00UT	No. of times **AGW** occurred	No. of ionograms with **ESF**	**%RSF**	**%MSF**	**%FSF**
6.	December 20 – 21	17	40	-	75	25

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Abstract

Equatorial Spread F (ESF), a manifestation of nighttime irregularities in the equatorial ionosphere has been linked to Atmospheric Gravity Waves (AGW) by different authors. However, there have not been much study to ascertain the extent of the relationship between the occurrence of AGW and the generation and occurrence of ESF. This study investigates the correlation between AGW and ESF occurrences during the year 2016, using data obtained with the aid of satellite borne Atmospheric Infrared Sounder (AIRS) and ionogram obtained with the aid of Digisonde Portable Sounder (DPS-4) located at Jicamarca, (geog. Lat. 11.95, Long. 76.87 and geomagnetic Lat. 9.28, Long. -7.92), an equatorial station in the Peruvian sector. During this period, 72.9% of AGW occurrence was observed between 18:00UT and 00:00UT (post-sunset period) while the remaining 27.1% occurrence was observed between 00:00 and 04:00UT (post-midnight period) coinciding with the period of occurrence of ESF. Results from the study reveal that the occurrences of ESF and AGW are independent of each other. An insignificant correlation (0.39) was found between the days of occurrence of the two phenomena. While ESF occurrence is a regular daily occurrence with local time dependence, AGW propagation is not dependent on local time. For Jicamarca, we found that ESF occurrence is greater during the solstice months than equinox. The probability of AGW reaching the bottomside F-layer depends on the properties of the wave. In this study, AGW was able to penetrate ionospheric heights on only six occasions. The results also show that AGW occurrence can only influence the conditions that trigger ESF rather than triggering ESF altogether. The occurrence of AGW tends to influence the occurrence of MSF type of ESF which is predominantly a post sunset phenomenon in preference to the other two types. Coefficient of correlation between AGW and MSF ranged between

0.1 and 0.5, while for RSF and FSF it ranged between -0.2 and 0.2. These levels of correlations tend to confirm that AGW occurrence only do influence rather than outright triggering of ESF.

Keywords: Atmospheric gravity waves, Equatorial ionosphere, Equatorial spread F, Ionospheric irregularities,

1.0 Introduction

The earth atmosphere is a mixture of gases. The atmosphere has four main layers which are the troposphere below 10km, the stratosphere which ranges from 10 km to 50 km in altitude, the mesosphere (50 km to 60 km) and the thermosphere which is located above 60 km altitude. The coupling of the lower layers of the atmosphere with the upper layers has become a subject of interest to scientists in recent times as a result of the various studies (e.g. Chau et al., 2010) suggesting the possible interconnection between these two regions of the earth atmosphere. The dynamics of the lower atmosphere can be influenced by weather conditions leading to several activities among which are atmospheric gravity waves (AGW), the effects of which can be transferred to the upper atmosphere. Gravity waves are generated in fluid medium where buoyancy and gravity tend to attain equilibrium, propagating mesoscale disturbances which transport energy and momentum in fluid environments. Gravity waves have the ability to transport energy and momentum both horizontally and vertically far away from their sources and, upon breaking, deposit this energy and momentum into the mean flow, resulting in a drag force. AGW has been shown to penetrate to higher altitudes under suitable propagation conditions (Vadas *et al*., 2009a, and 2009b, Taylor *et al*., 2008; Wrasse *et al.,* 2008). Small amounts of gravity wave drag can significantly influence the thermal structure in the mesosphere and lower thermosphere (MLT) through downward control (Hindley, 2016). For instance, Takahashi *et al.*

(2008) noted a close correlation between AGW spatial scales in the Mesosphere and Lower Thermosphere (MLT) and plasma bubble scales seen in 6300 Å emissions at the F layer peak. Also, the airglow AGW momentum flux analysis by Vargas *et al*. (2009a) showed evidence of AGW spatial and temporal scales and amplitudes in the MLT and extending to the bottomside F layer. Studies by Hysell *et al.,* (2014) indicated that atmospheric gravity waves could induce plasma dynamics in the ionosphere directly by moving the plasma in the direction of the geomagnetic field and indirectly by driving electric dynamos, either in the F region or in the E region on common geomagnetic field lines. Vertical plasma drift could massively influence the height of equatorial F layer. The equatorial vertical plasma drift is, in general, upward during daytime and downward at night, and the reversal from upward to downward occurs around 20:00 LT. An important feature of the equatorial F region vertical plasma drift is the occurrence of a sharp increase of the upward velocity just before it reverses downward (Fejer *et al*., 2008). This Pre-Reversal Enhancement (PRE) of the vertical plasma drift is associated with an enhanced eastward electric field when the E region conductivity decreases rapidly immediately after sunset. Large PRE often occurs around equinox when the geomagnetic field lines are aligned with the sunset terminator, so the eastward polarization electric field becomes the strongest near the sharp horizontal gradient of conductivity (Tsunoda, 2005). Empirical patterns of the PRE depend on factors such as solar radio flux, season, longitude, and geomagnetic activity (Fejer *et al*., 2008). During the postsunset, PRE moves the equatorial F layer to high altitudes, and the bottomside of the F layer becomes steeper than that in the daytime because of non-existence of photo-ionization there, creating conditions conducive for the growth of the Rayleigh-Taylor instability. Atmospheric gravity waves of different scales and periodicity oscillating into the ionosphere are known to generate pre-reversal enhancement in drift velocity through the wind dynamo (Fesen *et al*., 2000; Abdu *et al*., 2006). According to Abdu, (2001), there are three processes that could lead to the formation of Equatorial Spread F namely: (i) the linear growth rate of the generalized Rayleigh–Taylor (R–T) instability process, (ii) flux tube integrated Pedersen conductivity that controls the nonlinear development, and (iii) density perturbations can serve as seeding sources. Rayleigh-Taylor (R-T) instability is believed to be the main physical mechanism responsible for the growth of equatorial spread F. The R-T instability is excited in the bottomside F region and evolves into a plasma instability that penetrates to the topside F region. According to Woodman, (2009), the generalized R-T instability mechanism was found to be too slow to explain the rapid development observed in ESF formation. AGW was therefore proposed as a seeding mechanism for the formation of the irregularity that results in ESF. This proposition was enhanced by the results obtained from studies carried out by Abdu *et al.,* (2006) and Takahashi *et al*., (2009) which show that AGW could cause PRE in the ionosphere, and that the short-term variability in the PRE vertical drift may arise from external forcing due to upward propagating atmospheric gravity waves.

The pre-reversal enhancement (PRE) vertical drift velocity responsible for the uplift of the F layer could trigger the R-T instability mechanism which is recognized as the basic drivers controlling the ESF morphology across different seasons and longitudes (Abdu, 2001; Dabas et al., 2003). The PRE rapidly elevates the ionosphere into a higher altitude region, where the collision frequency is lower and more conducive for further plasma depletion growth by the R-T instability mechanism (Afolayan *et al*., 2019). Haung, (2018) made extensive effort to identify the relationship between PRE and occurrence of ESF. Three distinct relationships were identified, which include (1) the requirement of threshold of PRE for ESF occurrence, (2) linear increase in PRE with the ESF occurrence probability, and (3) PRE serves as a function of continuous probability distribution of ESF.

ESF are observations of “spread” in the traces on ionogram at equatorial regions and are used to describe plasma instability phenomena that occur in the F-region of the equatorial ionosphere (Kelley, 1989). This phenomenon which was first observed by Booker and Wells (1938) was seen as “diffuse echoes” from the F region of the equatorial ionosphere over a wide range of wave frequency. The ionogram traces, rather than showing a thin line corresponding to the virtual height of the reflecting altitude, as the ionosonde frequency was changed, showed instead a range of virtual heights as if the echoing region were spread over a range of altitudes (range spread, RSF). At times, the spread showed only at the high frequency end and looked more like a spread in frequency for a given virtual height (frequency spread, FSF) (Woodman,2009). The diffuse echoes, suggested to be caused by irregularities in the ionospheric F region, were later named spread F. Consequently, three types of spread F have thus been identified namely range spread F (RSF), frequency spread F (FSF) and the mixed type of spread F (MSF). The aim of this paper is to investigate the relationship between the occurrence of AGW/- and the generation of nighttime ESF.

2.0 Data and Method

Gravity waves data in form of Brightness Temperature Perturbation (BTP) obtained with the aid of the Advanced Infrared Sounder (AIRS) on board Aqua satellites and ionograms recorded with the aid of digisonde located at Jicarmaca (Geog. Lat. 11.95, Long. 76.87 and Geom. Lat. -7.92, Long. 9.28) an equatorial station in the Peruvian sector for the year 2016. While the BTP data were retrieved from the AIR's data archive at http://data.pub.fz-juelich.de/slcs/airs/gravity.waves , ionospheric data were obtained from the Global Ionosphere Radio Observatory (GIRO) portal on (DIDbase) www.https://ulcar.uml.edu/DIDBase/ . The BTP data were used directly as proxy for the gravity wave data (although one may extract the gravity wave parameter from the BTP data by using a 4th order point polynomial filter e.g. see Wu 2004; Hoffmann and Alexander 2010). Since we are interested only in the nighttime, only BTP data during nighttime (18:00UT – 05:00UT) were considered. Nighttime ionograms covering the entire 2016 were extracted and manually inspected for the occurrence of ESF. Ionograms with ESF were further examined for the ESF type. Thus, ionograms with ESF were grouped into three: RSF, FSF and MSF. Equations (1) – (3) were used to determine the percentages of occurrence of ESF, types of ESF and AGW respectively. Corresponding number of BTP (values) percentage of occurrences were then correlated with the percentage of ESF occurrences in order to examine the relationship between gravity waves and ESF. The occurrence percentages (values) of BTP were also correlated with the types of ESF in order to examine the possible influence gravity waves played in the formation of the three types of ESF.

$$Percentage\, of\ Spread\, f\,(\%\,SF) = \frac{Total\, Number\ of\ spread\ F\,(TNSF)}{Total\, Number\ of\ Ionogram\,(TNI)} \times \frac{100}{1} \quad (1)$$

$$Percentage\, Type\, of\ Spread\ F\,(\%\,TSF) = \frac{\sum Type\, of\ Spread\ F\,(STSF)}{Total\, Number\ of\ Spread\ F\,(TNSF)} \times \frac{100}{1} \quad (2)$$

$$\%\, Frequency\ occurence\, of AGW\ per\ month = \frac{Total\ AGW\ occurence\ per\, month}{Total\, GW\, occurence \in 2016} \times \frac{100}{1} \quad (3)$$

3.0. Results and Discussion

3.1 AGW occurrence

Fig. 1 shows occurrence statistics of AGW (represented by BTP observations). The result shows that AGW occurrence was not regular during the period under review. BTP occurrence was observed 337 times spreading across (the nighttime) of only twenty-eight (28) out of the three hundred and sixty-five (365) days of the twelve months of the year 2016. Fig. 1 also shows the monthly occurrence percentage. The month of September is observed to have the highest percentage occurrence (21%) followed by July (18.7%). The month of December with percentage occurrence of 2.5% had the lowest. The occurrence percentage can thus be categorized according to the percentage BTP occurrence (%BTP) into high (%BTP > 15%); moderate 15% > %BTP < 8% and low %BTP < 8%. The months of February, July and September experienced high occurrence; April, Oct and November experienced moderate occurrence while the months of March, May and December had low occurrence. January and June did not experience any occurrence during the year under study. Fig. 1(b) is the plot showing number of days in each month with (nighttime i.e. 1800UT of one day to 0500UT of the other) AGW occurrence. The plot shows that AGW monthly occurrences were recorded only between two (one nighttime) and five days (two and half nighttimes). The month of October had the highest number of five days while February, April and September had occurrence of AGW on four days each. March, May, June and November experienced AGW on two days each while December had occurrence on three days within the month.

3.2. Equatorial Spread F Occurrence

Fig. 2(a) shows that unlike AGW, ESF is a regular occurrence. ESF was observed all through the twelve months of the year. The month of December recorded the highest number of days with occurrence. All the ionograms for the 31 days (i.e. nighttime) exhibit ESF. December was closely followed by June with ionograms for 28 out of the thirty days of the month having ESF occurrence. The month of August with 11 days has the least number of days of occurrence. Fig. 2(b) shows the seasonal plot of the number of days with ESF occurrence at Jicarmaca during the year 2016. ESF obviously shows seasonal dependence, (in accordance with the existing literature) with the solstice months showing predominance in number of days of ESF occurrence. December solstice with an average of 24 days has highest occurrence followed by June solstice with an average of 22 days. For the equinox months, March equinox with an average of 21 days of occurrence experienced ESF on more days than September equinox with barely 15 days with ESF. Fig. 2(c) shows the plot of relative occurrence of the three types of ESF. While MSF had occurrence every month of the year 2016, RSF was observed seven months of Feb., March, May, July, Aug., Nov., and Dec. FSF was observed eight months of the year, being absent in the months of Jan., May, June and August. A closer look at Fig. 2(c) reveals that RSF followed a trend, having higher number of days of occurrence during February and March (equinox) and November and December (solstice) while showing low occurrence during the middle of the year. Thus, a polynomial trend line through the plot shows that the monthly daily occurrence of RSF follows a polynomial of order two and correlation coefficient of 0.93.

3.3 Correlation between AGW and ESF

Fig. 3 is the plot showing the relative days of occurrence of AGW, ESF and the three types of ESF. The plot reveals that ESF and MSF in particular are regular occurrences as they are present throughout the months of the year. The months of January and June (solstice months) are observed to have recorded 100% of MSF, covering the 28 days for which ESF was observed. RSF is observed to have a maximum of seven days of occurrence and this occurred in the month of December. It is followed by the month of February with six days of occurrence of RSF. FSF is least in the number of days of occurrence during the year. A maximum of four days of occurrence is observed for each of the months of February and October. The month of October with the maximum of five days of AGW occurrence has the highest percentage of occurrence. The months of February, April and September had four days each with AGW occurrence. Fig 4 shows the correlation plots of days of occurrence of ESF (and ESF types) with AGW. The plots show that all except the days of occurrence of FSF were negatively correlated with the days of occurrence of AGW. The number of days of ESF occurrence shows a negative correlation with days of AGW occurrence with regression coefficient of 0.1513 (and correlation coefficient, R = 0.39). This suggests that the days of occurrence of ESF and AGW are not significantly related. Among the three types of ESF, only the days of FSF occurrence shows a positive relationship with the days of occurrence of AGW. A regression coefficient of 0.0068 (R = 0.08) is observed to exist between FSF and AGW. These results show that the day of ESF occurrence does not really depend on the occurrence of AGW. Although their days of occurrences are independent of each other, there is the possibility that, whenever the two phenomena occur simultaneously the presence of AGW may influence the conditions necessary for the onset of ESF (in cases where AGW generate enough momentum to reach ionospheric heights). Result from this study shows that during the entire 2016, simultaneous occurrences of AGW and ESF were recorded on only on six occasions (nighttime). Table 1 shows the months and days (18:00UT – 04:00UT) when the occurrence of the two phenomena coincide and their frequencies of occurrence. Simultaneous occurrence of ESF and

AGW were observed once each in February, April, November and December, and twice in September. A maximum of forty ionograms with ESF occurrences were observable between the hours of 18:00UT and 04:00UT (ionograms were recorded every fifteen minutes) while a maximum of thirty one AGW (BTP) occurrences were observable within the period. According to Takahashi et al., (2009) and Cabrera et al., (2010), where coincidence occurs, occurrence of AGW is expected to be connected to the occurrence of only two out of the three possible types of ESF, namely RSF and MSF. Fig. 5 shows scatter plots of the frequency of occurrence of the type of ESF prevailing on each of the days against the frequency of occurrence of AGW for the six days. The results show that the occurrence of MSF is more prevalent than RSF on the days of simultaneous occurrences of AGW and ESF. MSF occurrence was observed on five out of the six occasions. 100% of the ESF observed in April (20-21), September (26-27 and 28-29) and November (28-29) while 75% of December (20-21) were MSF. RSF occurrence (100%) was observed only on Feb (5-6). The implication of these results is that the occurrence of AGW tends to enhance the occurrence of MSF more than the other two types of ESF since the occurrence of MSF was predominant on days when there were coincidences in occurrences of AGW and ESF. Fig 5 shows the correlation plots of the frequency of occurrence of types of ESF and AGW on these days. The results show that, although the correlation between ESF types and AGW frequency of occurrence is positive for all the six except for 28-29 September, the correlation coefficients for all the days were very much less than unity, thus signifying that the degree of dependency of the two phenomena on each other is quite low. Correlation coefficient for February (5-6), April (20-21) and September (26-27) and December (20-21) are found to be 0.1, 0.2, 0.2 and 0.3 respectively while the correlation coefficient for September (28-29) and November are both ~0.5.

4.0 Summary and Discussion

A statistical study to investigate the relationship between the occurrence of AGW, a lower atmosphere phenomenon and ESF, a nighttime phenomenon characteristic of equatorial ionosphere has been carried out. We have used BTP obtained from AIRS as a proxy for AGW parameter, in conjunction with nighttime ionograms obtained with the aid DPS-4 at Jicarmaca, an equatorial station in the Peruvian sector during the year 2016, a year of low solar activity for the study. Results from the study shows that AGW occurrence is not a regular phenomenon when compared with the occurrence of ESF which a regular phenomenon emanating from the nighttime irregularity in the equatorial ionosphere. ESF has been shown to exhibit diurnal, seasonal, solar cycle, angle of dip and longitudinal dependence (e.g. Woodman, 2009; Li et al., 2008; Paznukhov et al., 2012; Adeniyi et al., 2017; Bolaji et al., 2018). Our study shows that ESF at Jicarmaca exhibits seasonal dependence being greater in occurrence in the solstice than equinox. Although AGW occurrence exhibits seasonal dependence, its propagation direction is not local time dependent (Ejiri et al., 2003). Its occurrence and extent depends solely on the level of atmospheric convection and other meteorological activities (Hoffmann and Alexander, 2010; Lane and Zhang, 2011; Vargas et al., 2016). Its direction of propagation is dictated by planetary waves which vary from one latitude to the other (Ejiri et al., 2003). Our result shows that AGW (nighttime) occurrence was recorded at Jicarmaca only on twenty eight out of the 365 days of the year under study compared to ESF which is a regular (nighttime) occurrence. Hence, the result further reveals that days of occurrence of the two phenomena show no reasonable correlation; their days of occurrences are independent one on the other. Coefficient of correlation for the days of occurrence of AGW and ESF was found to be 0.39. Furthermore, not all AGW propagating upward do get to the ionospheric heights. Depending on the wavelengths, AGW get absorbed at mesopause heights (Ejiri et al., 2003). We found that simultaneous occurrence of AGW and ESF can occur when their days and periods of occurrence coincide, and when gravity waves achieve large amplitudes enough to reach the bottomside F-layer heights (Fritts et al., 2008). Only six of such occasions were observed in this study. According to Fritts et al., (2008) AGW at bottomside F-layer altitudes will act to modulate the parameters that are responsible for the growth rates of plasma instability to varying degrees depending on the properties of AGW. Where AGW is able to reach the bottomside F-layer, it is expected to influence mainly MSF and RSF types of ESF (Takahashi et al., 2009;

Cabrera et al., 2010). Result of this study reveals that AGW occurrence at the bottomside F-layer influences the mechanisms that trigger MSF more than RSF types of ESF. MSF type of ESF was observed to predominate during the days of coincidental occurrences; with five of the six days having MSF occurrence. MSF is the type of ESF in which combines the attributes of the other two i.e. RSF and FSF. This implies that the influence of AGW at the bottomside F-layer heights is such that it enhances the conditions suitable for the triggering of MSF in preference to the other two types. Adeniyi et al., (2017) has shown that MSF is a post sunset phenomenon while RSF is predominant during post-midnight. Hence, the influence of AGW on ESF is predominant during post sunset periods.

5.0 Conclusion

A statistical analysis of the relationship between the occurrences of ESF and AGW has been carried out in this study. We have used AGW data in the form of BTP obtained using AIRS data and ionograms obtained with the aid of a digisonde located at Jicarmaca, an equatorial station within the Peruvian sector during 2016. Our results reveal that the occurrences of ESF and AGW are independent of each other. No significant correlation was found between the days of occurrence of the two phenomena. While ESF is a regular occurrence with seasonal dependence, AGW propagation is not dependent on local time. For Jicarmaca, we found that ESF occurrence is greater during the solstice months than equinox. The probability of AGW reaching the bottomside F-layer depends on the properties of the wave. In this study, AGW was able to reach ionospheric heights on only six occasions. When AGW has enough amplitude to reach ionospheric heights it influences the conditions that trigger rather than triggering it. We also found that AGW tend to influence the occurrence of MSF type of ESF which is predominantly a post sunset phenomenon. Coefficient of correlation between AGW and MSF ranged between 0.1 and 0.5. These levels of correlations tend to confirm the influence rather than outright triggering of ESF by AWG occurrences.

Footnote

This study is a statistical study of the correlation between AGW and ESF occurrences. We have used BTP as a proxy for AGW rather than extracting AGW parameter for the study. As a result, this study is limited to quantitative rather than qualitative analysis. We look forward to further studies which will examine qualitatively, the relationship existing between these phenomena.

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