3 COUNTER ELECTROJETS: LONG TERM TRENDS AND LUNAR INFLUENCES

3.1 Introduction

Equatorial eletrojet and counter eletrojet has been a topic of discussion for several decades. Though most of the theories related to equatorial electrojet are widely accepted, there are some points that are topics of controversies. According to one school of thought, quiet-time ionospheric current systems like the equatorial eletrojet (EEJ), field aligned currents and the low and mid latitude quiet-time currents that flow in the E – region ionosphere are all part of the Sq current system (Pedatella, Forbes, & Richmond, 2011; Rao, Rao, & Raja Rao, 1967) whereas, according to another school of thought, the EEJ is a separate current system with its own return currents (Onwumechili, 1997). Thus for a better understanding of the equatorial eletrojet and its occasional reversal called the counter eletrojet (CEJ), study on the long term variability is very important because it helps to delineate the various phenomena involved in the eletrojet currents. The intensity of electrojet varies depending on various factors like sunspot number, season, local solar hour of the day, latitude, longitude and geomagnetic activity to state a few. Several characteristics of eletrojet were brought out in the past using long term studies. The linear relationship between sunspot number and EEJ strength (Rao et al., 1967), the idea that EEJ is primarily due to the variations in the E region peak electron density (Chandra, Sinha, & Rastogi, 2000) and the observation that morning CEJ events are more frequent in equinoxes and afternoon CEJ events more frequent during the solstices (Barreto, 1992) are all outcomes of such studies.

The occasional reversal of equatorial electrojet called the equatorial counter electrojet is a special case of EEJ when the direction of eletrojet current reverses from eastward to westward direction. Detailed studies on the properties of counter eletrojet (CEJ) were first carried out by (Mayaud, 1977). The intensity, date and time of occurrence of CEJ depends on many factors that are not well understood. Therefore the exploration of possible drivers has become an interesting and challenging study. Lunar and solar semi – diurnal tides, sudden warming in the polar stratosphere (SSW) (Siddiqui et al., 2018; Yamazaki et al., 2012) and its aftermaths in the equatorial ionosphere and combination of certain tidal modes

(Gurubaran, 2002) are some global phenomena related with the occurrence of CEJ events. Local effects like meteor shower (Muralikrishna & Kulkarni, 2008), vertical winds (Raghavarao & Anandarao, 1980) and gravity waves (Vineeth et al., 2012) are also some proposed physical phenomenon related with equatorial counter electrojet events.

(Vichare & Rajaram, 2011) using Oersted satellite data retrieved the EEJ signatures and found that CEJ seen in satellite is always matching with CEJ observed at the Indian observatories. The study had also found wide longitudinal spread of CEJ events even more than 25^0 longitudinal separation. Highest occurrence of CEJ was found to occur in the Brazilian sector. Afternoon counter eletrojet (ACEJ) in the Indian sector was studied by (Rastogi, 1973) in detail and found that it is not seemed to be caused by lunar tide though their occurrence is modified by lunar age. The study also found seasonal variation in the CEJ peak time to be varying from 1530 in winter to 1600 in equinoxes to 1630 hours in summer. This time variation matches with the sun set time. Moreover, CEJ events are more frequent during low solar activity period and less frequent during high solar activity period.

Using EEJ data recorded at Kodaikanal (a station located at 0.5^0 geomagnetic latitude at that time) observatory during 1950 – '54, (Raja Rao, K. S. and Sivaraman, 1958) estimated lunar geomagnetic tides and found that the lunar geomagnetic tides is maximum when the angle between the Sun and the Moon is 135^0 indicating importance of studies related to the occurrence of CEJ events. Recently, (Zhou, Lühr, Xu, & Alken, 2018) analyzed CHAMP satellite magnetic data and found strong influences of lunar tides on the occurrences of CEJ events. They found that strongest lunar semi – diurnal (M2) tides occur around January month which is responsible for the high secondary occurrences in January. (Forbes &

Zhang, 2012) used SABER temperature data at 110 km altitude and density measurements from CHAMP and GRACE satellites and Global Scale Wave Model (GSWM) to bring out strong amplification in the lunar M2 tides during the January month of 2009 polar sudden stratospheric warming events.

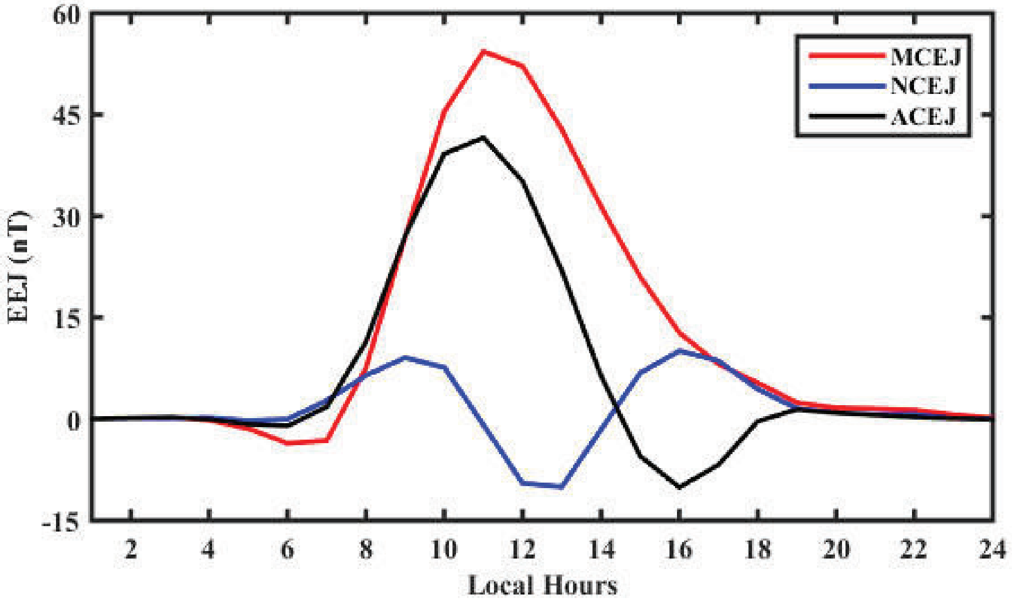

Figure 3.1 Average MCEJ and ACEJ trends at Tirunelveli for the period between 1993 and 2012.

Generally, the counter electrojet occurs during the morning or afternoon hours of the day with some occasional occurrences during the noon time. Figure 3.1depicts an average picture of all the three types of CEJ events as recorded at an Indian equatorial station, Tirunelveli during the period1993 - 2012. Clearly, the morning CEJs peak around 0600 – 0700 solar local hours, noon time CEJ events around 1200 – 0100 hours and afternoon CEJs around 1600 hours. The figure also demonstrates that increased CEJ amplitude is associated with decreased EEJ amplitude. Morning CEJ events are associated with the most intense eastward electrojets (EEJ) where as noon time CEJ events (NCEJ) are associated with the most weakest EEJ events. It is to be noted that statistical studies of one geographic area may not necessarily apply to other stations. This is because of the longitudinal variability in the occurrence of CEJ events. In a recent study using long term CHAMP satellite magnetic data, (Singh et al., 2018) has clearly established the relationship between diurnal eastward wave number 3 (DE3) tides and the longitudinal variability in the occurrence of afternoon CEJ events. The study also concluded that the seasonal variability of CEJ events is different for different longitudinal sectors.

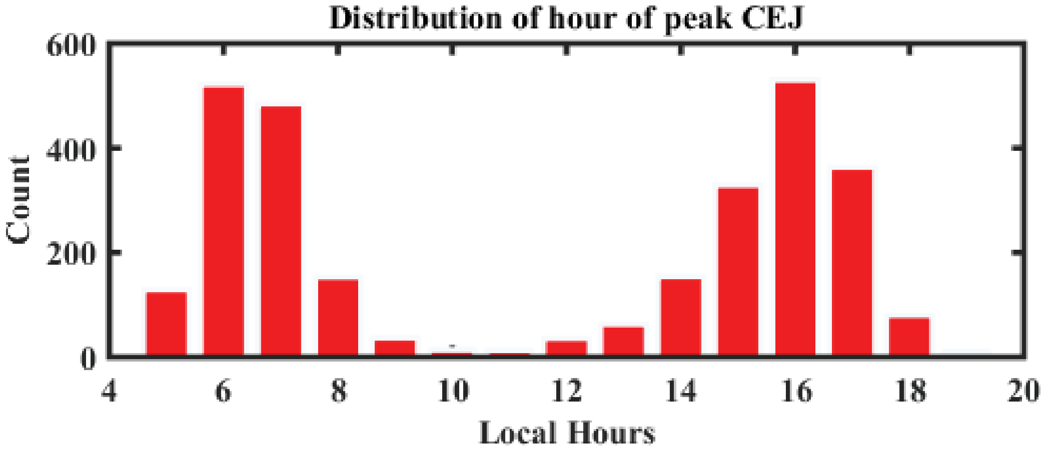

Figure 3.2 Bar graph showing number of days for each peak CEJ hour.

In this chapter we explore some important statistical characteristics in the occurrences of the equatorial electrojet in the Indian region for twenty years from 1993 to 2012. The average trends of ACEJ and MCEJ events have been shown in the Figure 3.1. One can see that in the Indian longitudinal sector, the afternoon CEJ events are more intense than the morning CEJ events. The average ACEJ intensity is three times more intense than the average MCEJ intensity. There is a proportionate decrease in the average intensity of eastward eletrojet

(EEJ) during ACEJ days than MCEJ days. EEJ intensity during MCEJ days are about 20% more than that during ACEJ days. On the other hand, the occurrence of MCEJ and ACEJ events are almost equal in the Indian sector; with ACEJ events a bit more than MCEJ events. The hour at which the peak CEJ occurs during the day time is considered for plotting the Figure 3.2. It shows that ACEJ events peak mostly at 1600 and MCEJ events at 0600 – 0700 local hours.

For the present statistical study, CEJ events are grouped into three different groups based on the local solar hour of peak CEJ (lowest value) during the given days. If a CEJ peak occur between the solar hours 0500 LT – 0900 LT, then such days are morning CEJ days (MCEJ days); if the same occurs during the local solar hours 1000 LT – 1300 LT, then such days are noon time CEJ days (NCEJ days) and if the time is between 1400 LT – 1900 LT then such days are afternoon CEJ days (ACEJ days). The lowest hourly EEJ value during the day should be < -3 nT to be considered a counter electrojet (CEJ) day. Only those days that satisfy the condition Ap <= 9 are considered to be quiet days. Moreover, if more than two hourly value is missing during the day time (between 0500 LT and 1900 LT), then such days are discarded. So there is a total of 4465 number of days. Out of these, 2918 CEJ days are split into 1325 MCEJ days, 126 NCEJ days and 1467 ACEJ days

The seasonal and solar cycle variability in the occurrences is consolidated in this chapter and the results are compared with the lunar tidal activities in the middle atmosphere over Tirunelveli during the same period. The lunar influence on CEJ events are tried to be explained in terms of position of the Moon relative to both the moon – earth – sun system and to the station separately.

3.2 Solar cycle variability in the occurrence rate of morning and afternoon counter electrojet

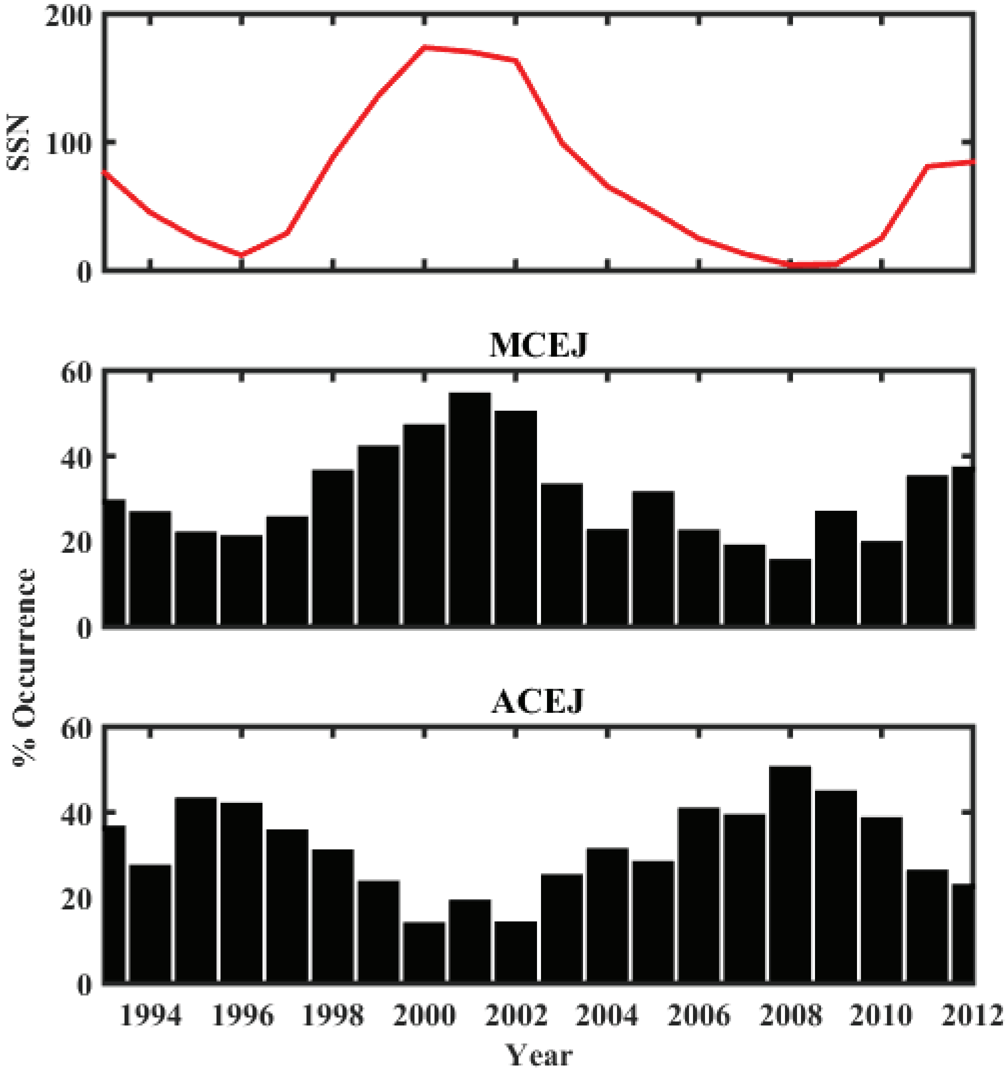

Figure 3.3 Inter annual variability in the percentage occurrence of ACEJ and MCEJ events. Top panel gives the annual mean sunspot number, the middle panel shows the percentage occurrence of ACEJ events and the bottom panel shows the percentage occurrence of MCEJ.

Figure 3.3 shows the percentage occurrence of afternoon CEJ (ACEJ – bottom panel) and morning CEJ (MCEJ – middle panel) events for the years from 1993 to 2012. The top panel shows the yearly average sunspot number for comparison. The percentage is calculated with respect to the total number of available quiet days in that year to avoid variations in the number of quiet days due to solar activity differences from year to year. The total number of quiet days in a year and total number of quiet time MCEJ are counted to calculate the percentage. Same is done for ACEJ events also to calculate ACEJ percentage occurrence. The yearly average sunspot number (available from http://www.sidc.be/silso/datafiles) is plotted in the top panel for comparison. From the bottom panel of the Figure 3.3, it is clear that the afternoon CEJ events (ACEJ) show a clear anti – correlation with the solar cycle. The highest percentage of occurrence in ACEJ events is during low solar activity years 1995 – 1996 and 2008- 2009 during solar minimum period. The occurrence rate is about 10% more in the year 2008 than in the year 1996. Even though 2009 saw more quiet days the occurrence rate was not proportionately high for ACEJ but that reduction can be seen compensated in the occurrence rate of MCEJ events as shown in the middle panel.

The inter – annual variability in the occurrence rate of morning CEJ events (MCEJ) show clear correlation with the sunspot number as can be seen from the middle panel of Figure 3.3. The solar maximum year 2001 show highest number of MCEJ events whereas the solar minimum years 1996 and 2008 show lowest numbers. 2009 was peculiar in that the occurrence rate increased for MCEJ and decreased for ACEJ events than expected though not very much remarkable.

3.3 Seasonal variability in the occurrence rate of morning and afternoon counter electrojet

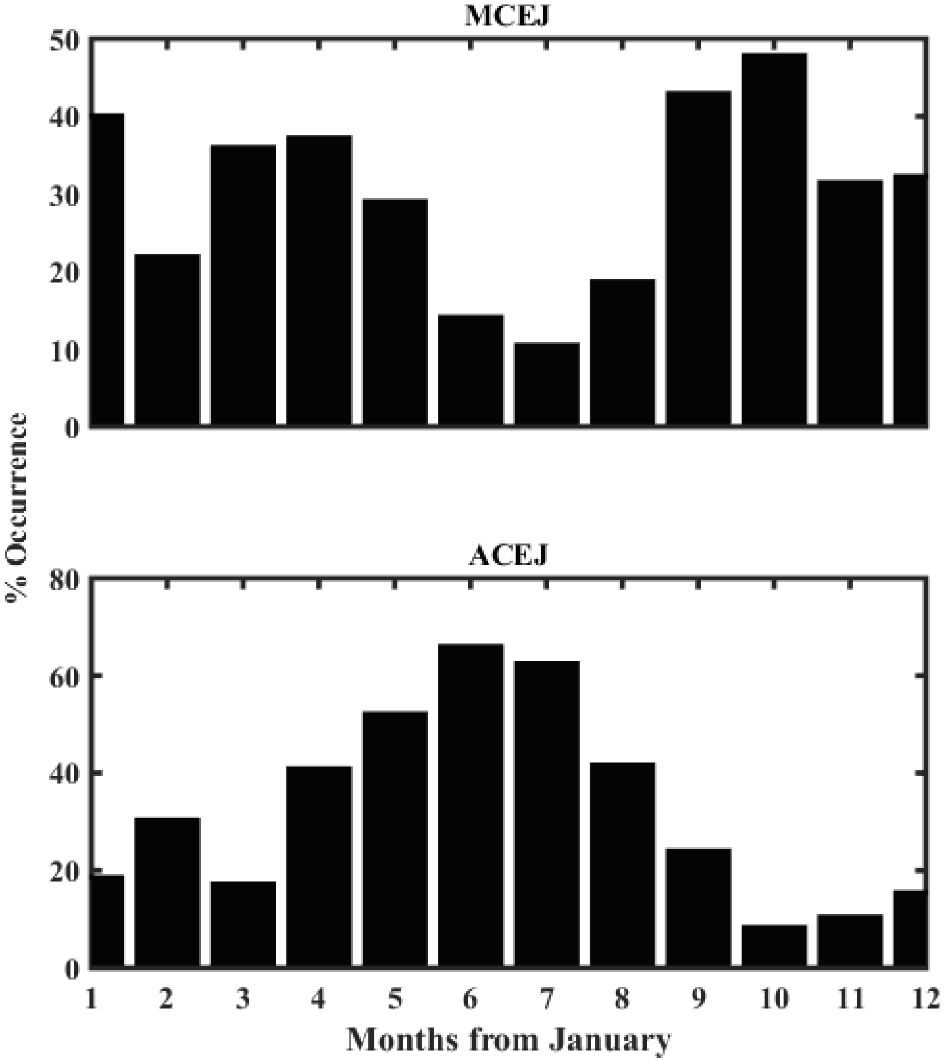

Figure 3.4 Seasonal variability in the occurrence rates of CEJ events. Top panel represents ACEJ events and the bottom panel represents MCEJ events.

The seasonal occurrence rate is calculated against the total number of available quiet days similar to the calculations of inter – annual variability. The percentage is calculated by first counting the number of quiet days in January month during the period of study and finding the number of CEJ days among them separately for ACEJ and MCEJ and for each month. Large seasonal variability is observed in the occurrence rate of counter eletrojet events, both ACEJ and MCEJ. Figure 3.4 shows the seasonal variability of counter eletrojet.

From the bottom panel of Figure 3.4 it is clear that the ACEJ events are more frequent during summer months and the highest occurrence is during June solstice (~ 64%). Lowest occurrence of ACEJ is during the month of October and throughout the winter months, occurrence of ACEJ is very less (between ~ 5% and ~ 20%).

The occurrence rate of morning CEJ events MCEJ) is in contrary to the case of afternoon CEJ events (ACEJ) as can be observed from the bottom panel of Figure 3.4. During summer solstice, the rate of MCEJ occurrence is the lowest. It can be attributed to the high occurrence of ACEJ during that season. The season is more favorable to ACEJ events. The highest occurrences in ACEJ are seen during equinoxes and from the figure it is also clear that there is large number of occurrences on MCEJ events during the winter month of January.

3.4 Seasonal variability in the solar local hours of peak CEJ

There is substantial seasonal variability in the occurrence rate of counter eletrojet events in the Indian longitudinal sector which is shown in the Figure 3.5. The seasonal variability is calculated against the total number of quiet days available for each month similar to the method adopted in the previous sections of seasonal and solar cycle variability. It has to be noted that all the panels have the same scale for both X and Y axes. Though the peak hour of MCEJ is during 0600 – 0700 hours for all the months, the occurrences at other morning hours vary substantially which can be inferred from the spread of the percentage occurrence during the morning hours from 0500 to 0900. During the equinoctial months March – April and September – October, the occurrence rate narrows down into 0600 and 0700 hours where as the occurrence rate starts to distribute itself considerably towards other local hours during summer (May to August) and winter (November – February) months.

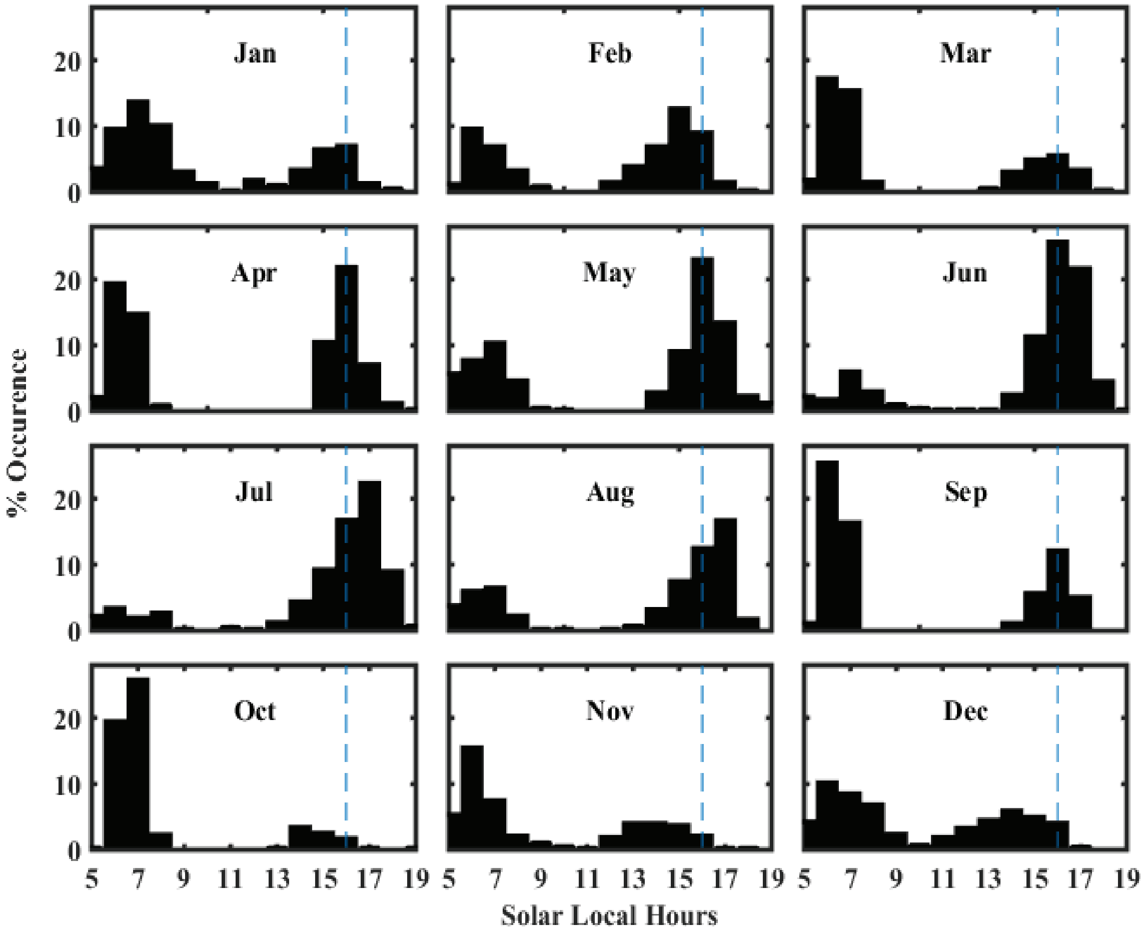

Figure 3.5 The month - wise plots showing distribution of occurrence rate of peak CEJ hour. The blue vertical dashed line denotes 1600 local hour.

For afternoon counter eletrojet (ACEJ) events, during summer solstice, the preferred time of peak CEJ is 1600 – 1700 local hours. During April, May and June, the peak occurrence hour is preferably 1600 LT where as in July and August, the preference shifts to 1700 hour. During other months the preference shifts to an earlier hour of the day. During October – December, the peak shifts to 14 hours, in January, the peak shift to 1600 hours and in February to 1500 hours.

The most preferred solar local hours for quiet time counter electrojet events in the Indian longitudinal sector are therefore 0600 – 0700 hours during equinoxes for MCEJ events and 1600 – 1700 hours during summer solstice for ACEJ events.

3.5 Variability with respect to lunar age and local lunar hour

Numerous studies in the past correlated the counter electrojet events with solar or lunar semi – diurnal tides. Lunar tides in the ionospheric currents were calculated by (Matsushita, 1968) and found that they are important in the eletrojet studies. The need to study the lunar semi – diurnal tides in the dynamo region was stressed also because of the simplicity of lunar tides against complex solar tides. We adopt a geometric approach to find the phase of lunar tide through hour angle as tidal phases denote the times at which lunar tides attain their highest amplitudes. It is important to note that tidal phase and lunar phase have different meanings. Lunar phases denote the relative position of moon with respect to the Sun – Earth line which complete one cycle in a lunar month (which is 29 days, 12 hours and 44 minutes or 29.5306 days) whereas lunar tidal phase denotes the phase of the semi – diurnal tides that completes one cycle in half a day at the given location on the earth.

3.5.1 Phases of the moon and CEJ occurrence

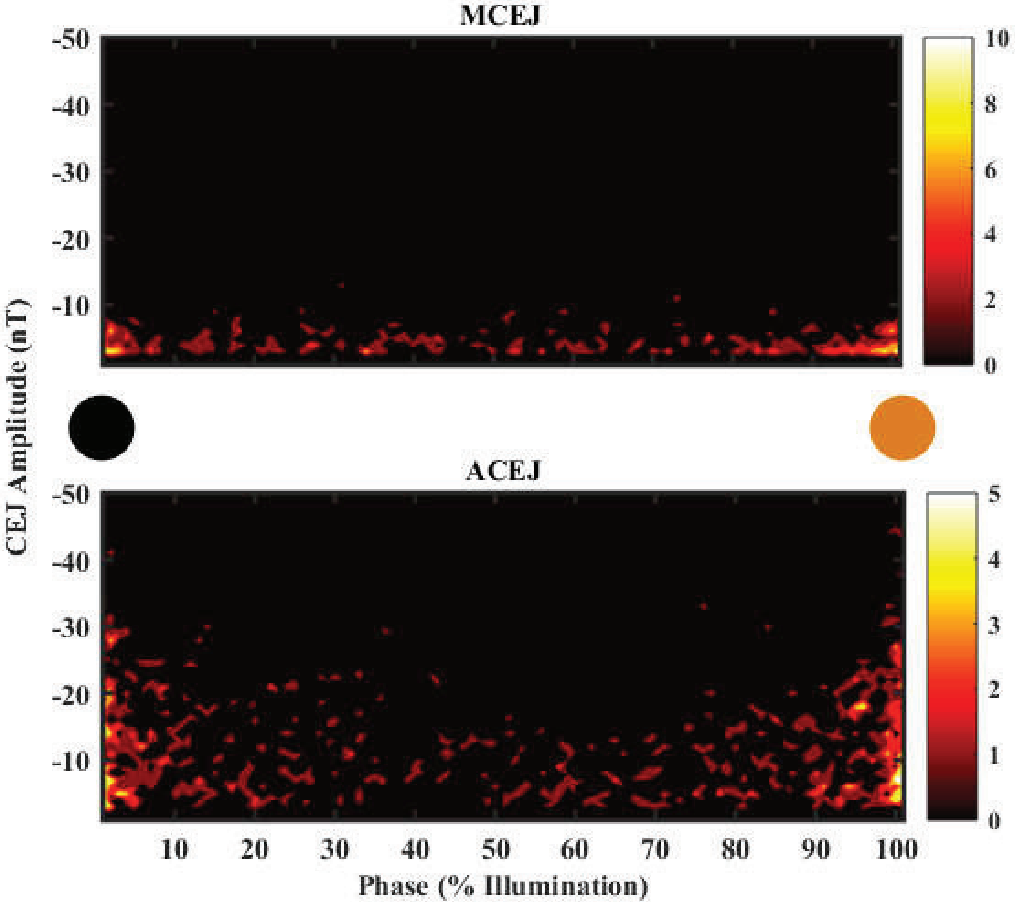

Figure 3.6 Variability in the occurrence rate of MCEJ (top) and ACEJ (bottom) events with respect to lunar phase and CEJ amplitude. ACEJ events have a high number of high amplitude CEJs where as MCEJs are generally not very intense.

Figure 3.6 shows the number of occurrences of CEJ events color coded according to the total number of events in each bin. The X axis shows the phase of the moon in percentage of illumination which is an indicator of the relative position of Moon with respect to the Sun – Earth line. The relative positions give an idea about the balancing between solar and lunar gravitational tidal forces. During full moon and new moon times the gravitational tides combine to produce an enhanced gravitational tidal effect. The Y axis shows the intensity of the CEJ events to get an idea about the relationship between gravitational tides (denoted as lunar phase) and CEJ events of different magnitudes. The color and corresponding number of events is given as a color bar at the right hand side of the figure.

During and around new moon and full moon there is a high number of occurrences of CEJ’s as suggested by (Rastogi, 1974). The top panel describes the morning CEJ events and the bottom panel describes the afternoon CEJ events. The black filled circle in between the panel indicates that phase is close to new moon in the left side of the figure and the orange color indicates the right side is close to full moon phase. The range of color bar is very much different. It is because in the case of MCEJ events, there is no much diversity in terms of the amplitudes of the CEJ whereas in the case of ACEJ, the amplitudes of ACEJ are much more diverse. In both the cases, much of the events are around either full moon days or around new moon days.

3.5.2 Lunar hour versus solar hour and occurrence of CEJ events

Figure 3.7 shows the distribution of CEJ peak hours with respect to lunar local hours and the solar local hours at which the CEJ of a given day reach its lowest value for all the CEJ events considered (2918 days). The maximum number of CEJ events occurs between the solar hours 0600 and 0700 LT (MCEJ) in the morning and between 15.00 LT and 17.00 LT (ACEJ) in the afternoon hours which shows slight changes from that discussed by (Rastogi, 1975) using Huancayo data for the period from 1948 to 1971 in which he showed that at

Huancayo, morning CEJ events peak around 0700 LT and afternoon CEJ events peak around 1500 – 1700 LT. He also showed that, the occurrence of ACEJ is maximum around lunar ages 1.4 and 13.4 or around lunar times 2.2 and 14.2 hours and that of MCEJ around lunar ages 4.8 and 16.8 or around lunar times 2.3 and 14.3 hours.

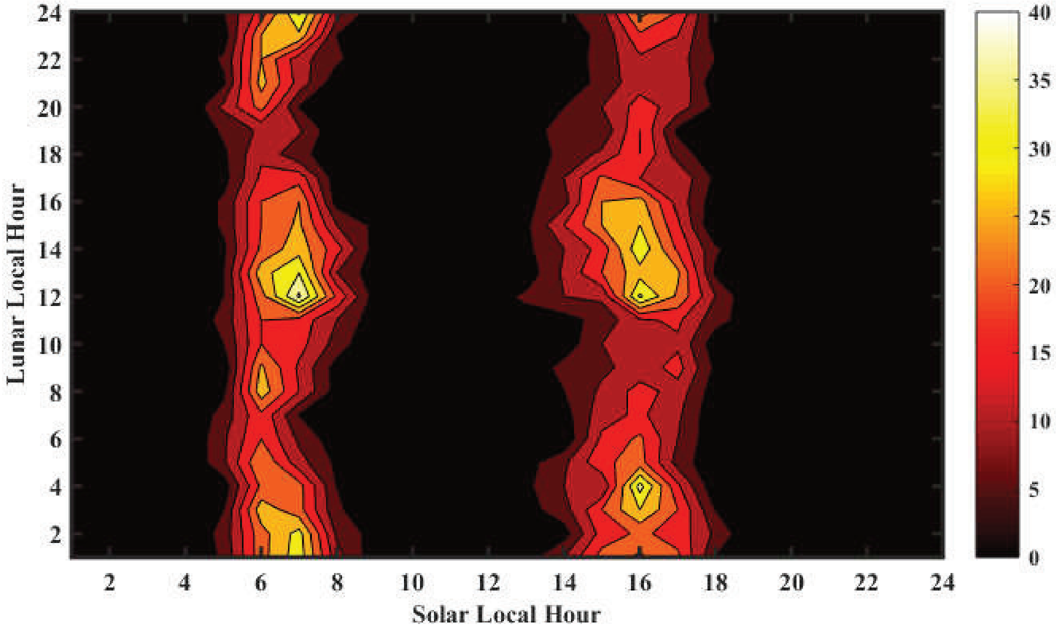

Figure 3.7 The distribution of CEJ events against solar and lunar local hours at Tirunelveli during 1993 - 2012. This includes all the three types of CEJ events namely, MCEJ, NCEJ and MCEJ events.

However in the present study it is shown that among the MCEJ events, those MCEJs that peaked at 0700 LT are found occur at 24.00 – 01.00 and 12.00 – 13.00 hours which again reaffirms the assumption of lunar tidal effects on the occurrence of such MCEJs. Again in case of ACEJs, where the highest number of ACEJs occurs at 1600 LT as shown in Figure 3.7, the highest number also occur at 1200 local lunar hours and secondarily high number at

0400 and 1400 local lunar hours. Though some CEJs show strong preferential occurrence during the hours at which the Moon is overhead or at the anti – pode, there are several examples for other cases also.

3.6 Summary and Conclusions

Present chapter describes detailed study of long term variability of equatorial counter eletrojet events observed at an Indian longitudinal equatorial station, Tirunelveli using the data during the years, 1993 – 2012. It is seen that counter eletrojet events show considerable inter – annual (or solar cycle), seasonal and lunar position dependent variability that has been delineated considering only geomagnetically quiet days.

Firstly, the classification of CEJ events is done based on the hour of peak CEJ value on the day. CEJ days are considered morning CEJ events (MCEJ) if the peak CEJ occur during the local hours 0500 – 0900 and afternoon CEJ events (ACEJ) if the peak CEJ occur during the local hours 1400 – 1900. The events that peak around the hours 1000 – 1300 are considered noontime CEJ events (NCEJ) that are only a few events therefore not included in the present chapter (average trends are shown in Figure 3.1). Then the distribution of CEJ peak hours is plotted to see the number of events in each hourly bin. It is found that at the highest number of CEJ events peak at 0600 - 0700 and 1600 hours Figure 3.2.

The solar cycle dependent variability is described in the subsequent section where the occurrence of both afternoon and morning events are studied in detail. It is found that the occurrence rates of ACEJ events anti – correlates with the solar cycle. The highest occurrence rate was during the low solar minimum periods 1995 – 1996 and 2008 - 2009 and the lowest occurrence rate during high solar activity year 2001. The occurrence rate of MCEJ events are found to correlate with sunspot number. The highest occurrence rate was during the year 2001 whereas the lowest rates were during 1996 and 2008. The occurrence rate in year 2009, a year of extended solar minimum, was slightly unexpected in which there was an increase in the occurrence rate for MCEJ and a decrease in the rate for ACEJ events.

The seasonal variability of CEJ events has many interesting features. The high occurrence rate of CEJ events in summer solstice is captured in the ACEJ events as shown in the bottom panel of Figure 3.4. The top panel shows seasonal variability of MCEJ events and shows a clear pattern of equinoctial maxima in addition to an exceptional maximum in the month of January. (Zhou et al., 2018) using ten years of CHAMP magnetic measurements had shown a secondary peak in January month. It is relevant to the result presented in this chapter because most of the CEJ events considered by them were MCEJ events. However, the most striking seasonal variability is the low occurrence rate of the MCEJ events and high occurrence rate of ACEJ events in the summer.

The seasonal variability of the hours at which MCEJ events attain their peak value exhibits peculiar features shown in Figure 3.5. Though the peak occurrence rate is at 0600 – 0700 hours on all months, there is substantial variability in the occurrence rates at other morning hours. During equinoctial months, the occurrence rate substantially narrows down into the hours 0600 – 0700 where as during other months; there is a better distribution of peak hours. The figure also shows variability in the hour for ACEJ events. The summer months April, May and June show high occurrence rates at 1600 local hours. During July – August, the preference shifts to a later local hour 1700. In September, the maximum occurrence hour again shifts back to 1600 hours. During October – December, the peak hour shifts to earlier hours 1400 but it is not very significant as their magnitudes are much less than summer and nearby equinoctial months (refer bottom panel of Figure 3.4). In January month, the peak hour again shifts to 1500 – 1600 hours and in February to 1500 hours. In March month the peak again reaches 1600 hours. The shift of peak occurrence rate maxima shows an annual pattern that maximizes at later hours around summer and earlier hours around winter months. This could be attributed to the shorter lengths of winter day times and longer lengths of summer day times.

There were a lot of studies on the lunar influences in the upper atmospheric tidal amplitude and geomagnetic variability in the past as well as in recent literature. The present chapter discuss occurrence of CEJ events in the light of lunar influences. The lunar age or alternatively, lunar phase has a significant effect on the occurrence of CEJ events which is discussed in the introductory part of this chapter. In section 3.5.1, the relationship between lunar phase and CEJ intensity is given. It is clear that there is a high occurrence rate of both MCEJ and ACEJ of all intensities during and around full moon and new moon phases. This phase relationship is shown in the Figure 3.6.

The next section discussed about the relationship of occurrence rate with respect to the solar and the lunar hours. The Figure 3.7 clearly shows a strong correlation for the MCEJ events, peaking at 0700 solar LT, with the lunar hours 240 – 0100 and 1200 – 1300; the hours at which the Moon reach overhead the station, Tirunelveli, or at its anti – pode, that is, the hours at which the lunar M2 tidal amplitude is maximum. The ACEJ events too show a high occurrence rate at 1200 lunar hours. A secondary high occurrence rate is seen at 0400 and

1400 local lunar hours for ACEJ events peaking at 1600 solar local hours. For other hours, the correlation is not remarkable as these cases.

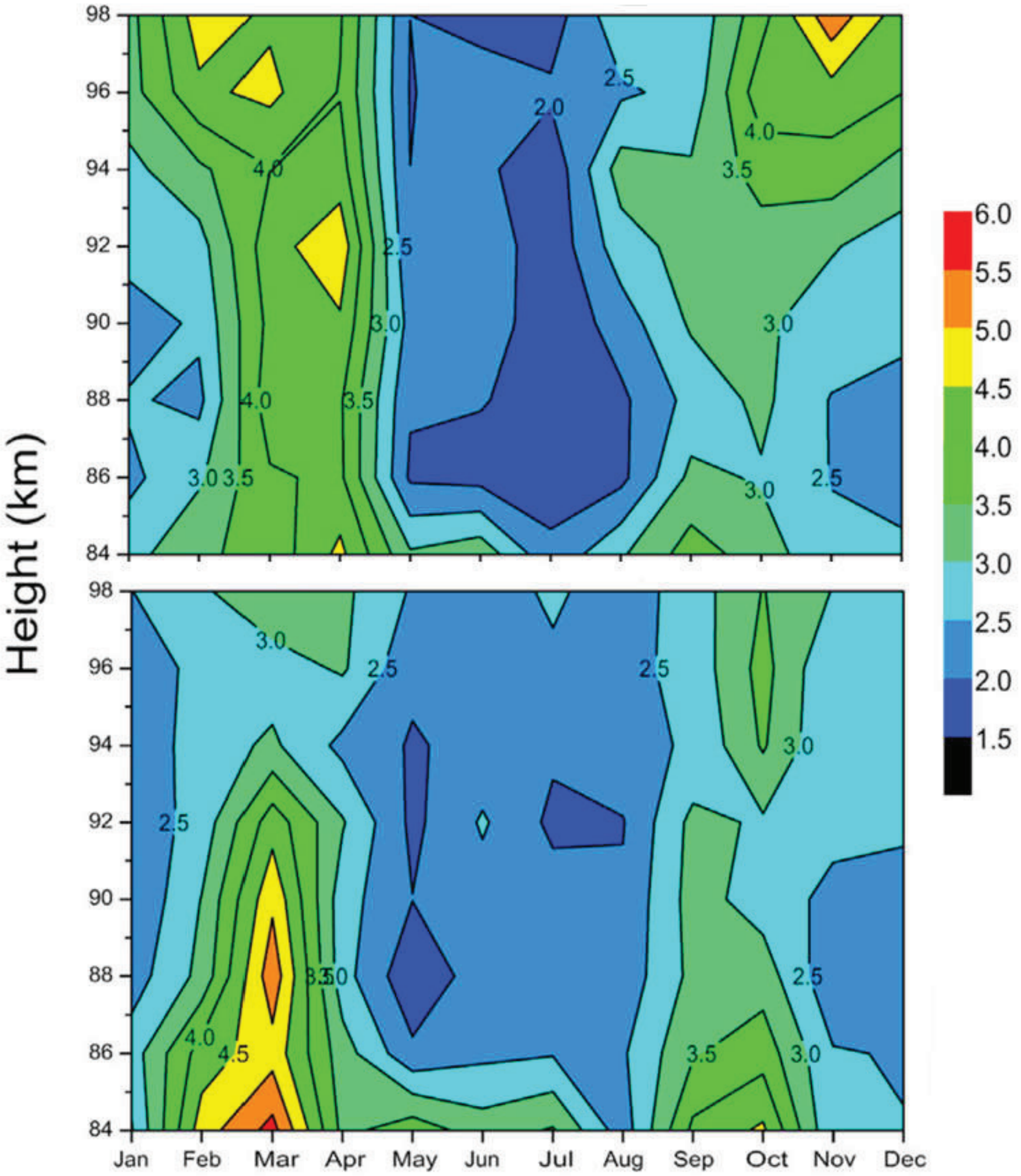

Figure 3.8 Seasonal variability of MLT winds over Tirunelveli during 1993 - 2012 years measured using M F radar. Top panel indicates lunar semi – diurnal tides in the zonal wind and the bottom panel indicates that in the meridional wind.

The facts that the most probable CEJ events (solar hours 0600 and 0700 for MCEJ and 1600 for ACEJ) are strongly most probable during lunar hours 2400 – 0100 and 1200 – 1300 clearly indicates the possibility of lunar influences on the occurrence of a huge number of CEJ events that match certain lunar conditions.

The calculations of lunar semi – diurnal tides in mesosphere – lower thermosphere (MLT) winds over Tirunelveli during the same period have been discussed in (Sathishkumar et al., 2017). It was shown that the tidal activities in zonal (east – west) as well as meridional (north south) winds exhibit similar seasonal behaviour. The calculated maximum amplitudes is about 5 m/s during the March equinox, and about 3 m/s during September. The minimum amplitudes are observed during the summer months from May to August as seen from Figure 3.8. This seasonal structure matches well with the results presented in the chapter for MCEJ events but does not match with ACEJ events. But the variability does not account for the January peak observed in MCEJ seasonal variability in Figure 3.4. Another important feature of lunar tides is that the maximum amplitudes in zonal winds appear at higher altitudes than that in meridional winds.

Changes in background wind and temperature and amplitude and height variations in zonal winds are some factors that influence tides. Various tidal modes can combine to produce considerable changes in the dynamic processes occuring in the dynamo region. The sharp dependencies of certain selected CEJ events (that coincidentally constitute the highest occurrence rates) on particular lunar positions indicates that certain phases of the lunar semi – diurnal tides could be matching with other tidal modes to generate the CEJ events at those times a lot.

Two very important aspects that need to be understood are; (i) the combination of lunar tidal modes with any other tidal modes and (ii) the possibility of exceptional amplification in the amplitudes of lunar tides during certain geophysical conditions, like that seen during polar sudden stratospheric warming events, with a phase that is positive to the effects.

The study by (Forbes & Zhang, 2012) discuss the amplification of lunar semi diurnal M2 (12.42 hr) and N2 (12.66) tides in January month of 2009 during a sudden stratospheric warming event (SSW) in the dynamo region between 100 km and 150 km using SABER temperature at 110 km and CHAMP density data and GSWM wind model generated values. The lunar tides were found enhanced during the times which were attributed to the shift of 'Pekeris resonance peak' from 12.81 on a day before SSW to 12.42 hrs during the peak of SSW in the GSWM model. The study put forward a theoretical basis for arguments that the lunar semi – diurnal tides amplify substantially during January months of several SSW years. (Pedatella, Liu, Richmond, Maute, & Fang, 2012) found large enhancements in the lunar semi diurnal amplitudes during winter SSW times and they are important in the low latitude electrodynamics during these times.

Full moon and new moon phases enhance the occurrence rate of both MCE and ACEJ which implies that the enhancement of lunar tides have a positive impact on both MCEJ and ACEJ occurrence. The greater lunar local hour dependence of MCEJ events compared with ACEJ events indicates that morning counter electrojets are prone to lunar influences more than the afternoon counter electrojets. The similarity of the seasonal pattern of lunar semi diurnal tides in the mesosphere – lower thermosphere (MLT) winds with the seasonal variability of MCEJ events confirms the lunar influences are more on MCEJ events that ACEJ events.