Chapter V
Mean winds and tidal components at equator during Counter Electrojet events

5.1. Introduction

Apart from the detailed morphological characteristics of Counter Electrojet (CEJ) events studied with the help of ground based magnetometer records, attempts have been made during the last two decades to understand the physical processes underlying the phenomenon of CEJ events. Theoretical investigations to explain the generation mechanism of CEJ events have proceeded mainly in two directions. In one approach it was suggested that the local interaction of height varying zonal winds with electrojet plasma can generate polarization electric fields which in turn can modify the latitudinal and height structure of electrojet current. (Richmond, 1973; Reddy and Devasia, 1981; Ananda Rao and Raghava Rao, 1987). The detailed computations of Reddy and Devasia (1981) and Ananda Rao and Raghava Rao (1987) have shown that CEJ current intensity (J) and the corresponding magnetic field variation (ΔH) on the ground near dip equator are very little affected by the local action of vertical shears of zonal wind. In a different approach, possible reversal of global eastward electrical field $E_y$ in the equatorial electrojet (EEJ) region due to abnormal combination of $S_1(1,2)$, $S_1(1,1)$, $S_2(2,2)$ and $S_2(2,4)$ tidal modes have been shown to produce CEJ event in the late evening hours.
(Forbes and Lindzen 1976 a, b; Marriott et al., 1979; Hanuise et al., 1983). This calls for an identification of the abnormal combination of the tidal modes and their variability which causes the CEJ event. Moreover, it is to be emphasised that the reversal of $E_y$ should produce CEJ events on a much larger latitude extent than the electrojet latitudes. However, the most interesting aspect of the CEJ events is that $E_y$ reverses only at electrojet latitudes and is observed at the same local time when it occurs in different longitude sectors. Further, reliability of the theoretical wind models used to predict the observed variations in the H component during CEJ events have not been tested in the past for want of wind measurements in the equatorial mesosphere and lower thermosphere. With the advent of meteor wind radar (Raghava Reddy et al., 1992, 1993), partial reflection radar (Vincent and Lesicar, 1991) and Meteor Detection and Collection (MEDAC) system operating with Stratosphere - Troposphere (ST) radar (Avery et al., 1990), we now have measurements of mesosphere and lower thermospheric winds at equatorial electrojet latitudes. This chapter presents experimental evidence on the behaviour of zonal winds, and the amplitude and phase variations of tidal wind components observed with a Meteor Wind Radar (MWR) operating at Trivandrum during CEJ events of January and June months of 1987.

5.2. Experimental details

The study has been carried out using observations obtained simultaneously with a Meteor Wind Radar (MWR), digital ionosonde and
fluxgate magnetometer operating at Trivandrum. The ionosonde and fluxgate magnetometer are operated on a round the clock basis. Quarter hourly ionograms are recorded on a magnetic tape and the fluxgate magnetometer records give the horizontal component of the earth’s magnetic field. The MWR was operated during January 19-31, 1987 and June 8-14, 1987 for recording the wind data. The details of the MWR are given elsewhere. (Raghava Reddy et al., 1992). The MWR operates at 54.95 MHz with a peak power of 40 KW and a selectable Pulse Repetition Frequency of 300/400/500 Hz. The transmitter pulse width is 280 µs phase coded by a 28 bit pseudo-random code of bit length 10µs which gives a range resolution of ± 0.75 km. By using interferometry base line of 1,3 and 10 wavelengths, the elevation and azimuthal angles of arrival of meteor echoes could be measured with an accuracy of ±1°. Consequently, the altitude of the meteor echoes could be measured with an accuracy of ±2 km. Identical five element Yagi-Uda antennas were used for both reception and transmission. The radar beam is oriented at an elevation angle of 45° and is switched alternately in NE and NW azimuthal directions for acquiring data from a preset number of meteors from each azimuthal direction. The data recorded on a computer compatible digital magnetic tape following the identification of the occurrence of a strong enough meteor trail are (a) echo amplitude for each of 184 successive transmitter pulses (b) Doppler waveform offset in frequency by -40 Hz sampled at the radar Pulse Repetition Frequency (PRF) for 256 transmitter pulses (c) the range of the echo for the first 16
successive transmitter pulses (d) phase difference between pairs of antenna elements of the interferometer sampled cyclically for the first 32 transmitter pulses (e) station data such as the PRF selected and the antenna orientation North East (NE) or North - West (NW) chosen and (f) time of occurrence of the meteor echo accurate to one second. The data recorded is processed off-line on CYBER 170/180 main frame computer in two stages. In the first stage of processing, the time variation of the echo amplitude is used to characterise the meteor trails as over dense or underdense. The underdense trails are further analysed to compute various parameters that characterise the trail such as the altitude of the echo, its Doppler frequency shift and the direction of arrival of the echo.

5.2.1. Determination of the Doppler Frequency

The ionized meteor trails move along with the surrounding atmosphere because of the strong collisional coupling between the ionized particles in the trail and the atmospheric particles. The radar data is collected after a delay of 3 echo pulses and this time delay of 6-10 millisecond is sufficient for the trail particles to come to equilibrium with the atmosphere. The movement of the trail produces a Doppler frequency shift of the radar carrier frequency \( f_c \) under the echo envelope. For a trail moving with a velocity \( V \) along the line joining the monostatic radar and the specular reflection point on the trail, the frequency \( f_R \) of the radar echo from the trail is given by
where 'c' in the velocity of light.

Since $c \gg V$, the above equation simplifies to

\[
f_R - f_c = \frac{2V}{c} f_c \tag{5.2}
\]

Thus, the line of sight velocity is directly related to the Doppler shift of the radar frequency. The Doppler frequency shift $f_D = f_R - f_c$ is positive for $V$ directed towards the radar and vice versa. In the case of a monostatic pulsed radar, the Doppler waveform is sampled at the radar PRF. Therefore, the maximum Doppler frequency that can be measured from the pulsed radar is equal to the Nyquist frequency equal to $PRF/2$. The Doppler shift corresponding to the line-of-sight velocity of the meteor trails almost never exceeds $\pm 40$ Hz (corresponding to $|V| \sim 110$ m/s). In order to measure the sense of the Doppler shift (positive or negative), the baseband frequency was shifted to $-40$ Hz instead of zero. Doppler waveform sampled at the radar PRF was spectrum analysed for the determination of Doppler frequency shift. As the desired accuracy in the Doppler frequency computed from the sampled values of the Doppler waveform is 1 Hz, Maximum Entropy
Method (MEM) (Burg, 1967) was used for the spectral analysis instead of the conventional Fast Fourier transform (FFT) technique.

5.2.2. Interferometer System to measure direction of arrival

The MWR has a full fledged radio interferometer system to measure the elevation and azimuth angles of arrival of meteor echoes. The interferometer configuration has three antennae mounted at the vertices of a right angled triangle, with the short arms oriented along NS and EW directions. If `d' is the separation between the corner (reference) antenna and the Northern (N) and Eastern (E) antennae then the difference between the phases of the signal received by the northern and the reference antenna \( \phi_N \) is related to the elevation (El) and Azimuth (Az) angles of arrival of the echo as

\[
\phi_N = \frac{2\pi d}{\lambda} \cos(El)\cos(Az) \quad (5.3)
\]

Similarly for Eastern antennae (E), it is given by

\[
\phi_E = \frac{2\pi d}{\lambda} \cos(El)\sin(Az) \quad (5.4)
\]

By measuring the values of \( \phi_N \) and \( \phi_E \) for each meteor trail and from the known values of 'd' and '\( \lambda \)' the direction of arrival (El, Az) of the echo can be obtained.
5.2.3. Computation of the altitude profiles of the Zonal and Meridional winds

The velocity determined from the Doppler frequency is the atmospheric wind velocity component along the line-of-sight between the receiving station and the reflecting point on the meteor trail, and hence will have contributions from the zonal, meridional and vertical wind components depending on the direction of arrival of the echo, and is given by

\[ \overline{V} = U \hat{l} + V \hat{m} + W \hat{n} \]  \hspace{1cm} (5.5)

where \( \overline{V} \) is the observed line-of-sight Doppler velocity, \( U, V \) and \( W \) are the zonal, meridional and vertical wind components respectively and \( l, m \) and \( n \) are the direction cosines of the echoing region of the trail. The above equation has three unknowns (\( U, V \) and \( W \)) and can be solved using atleast three independent observations, for which the time and height are same but occur at different elevation and azimuth angles. Different methods were used to compute the altitude profiles of the zonal and meridional wind components from MWR data (Manning et al., 1950; Elford, 1959 a, b; Groves, 1959; Salby, 1978).

For the present study, second version of the least squares fit method of Groves (1959) is adopted. In this method, the observations made during an interval of time are combined together to form a single
data set. The zonal and meridional wind components are assumed to be polynomial functions of height containing arbitrary parameters. These parameters are determined by least squares analysis of the data. The advantage of this method is that the altitude variation of the wind is taken into consideration explicitly. However, it is assumed that the temporal variation of wind fields within the time interval is small. This assumption is valid if the time period of the particular atmospheric phenomena being studied is far greater than the time interval of the data set, so that the wind fields do not change significantly within that interval. This algorithm computes the best fit altitude profiles of zonal and meridional winds. The author has used this algorithm for studies on the tidal wind fields and more details are given in Rajeev (1992) and Geetha Ramkumar (1994).

Here MWR data obtained during January 19-31, 1987 and June 8-11, 1987 have been analysed to obtain the mean zonal winds and tidal components. During this period, the variation in the horizontal component of earth's magnetic field ($\Delta H$) obtained from the fluxgate magnetometer operating at Trivandrum show counter electrojet events on 27-31, January 1987 as well as 8-11 June, 1987. The period from 19-26 January 1987 was found to be free from counter electrojet effects during afternoon hours and hence taken to represent the no-counter electrojet days for comparing with five CEJ days data during January months. For June 1987 we do not have the corresponding no-counter electrojet days
The time series data obtained from MWR at different altitudes is separated into three hourly intervals (00-03, 03-06,......21-24 IST) during all the CEJ days of January and June months and the second version of the least squares fit method of Groves (1959) is adopted to obtain the mean 3 hourly altitude profiles of zonal and meridional winds (Raghava Reddi et al., 1993). The zonal and meridional winds thus obtained were taken to represent the mean profiles corresponding to the three hourly interval of an "equivalent counter electrojet day". The eight 3 hourly profiles of NS and EW winds were Fourier analysed to obtain the mean wind and the amplitudes and phases of the diurnal, semidiurnal and ter-diurnal components at one kilometre interval in the height range of 80 - 105 km. By using the same methodology, the data obtained during 19-26 January, 1987 was analysed to obtain the mean winds and tidal components on the "equivalent no-CEJ day". Combining the data into three hourly bins was necessary because the occurrence rate of meteors is low in the evening hours when the CEJ events are in progress. Further, data from at least 70-80 meteors distributed in the altitude region 80 - 105 km are required to compute the wind profiles reliably. However, in the morning hours, number of meteors in the three hour bins are about 450. Computation of the amplitudes of the tidal oscillations from the three hourly average profiles results in underestimation of the diurnal component by 2%, semi-diurnal component by 5% and ter-diurnal component by 22.5% (Raghava Reddi et al., 1993). The phase of the tidal components obtained, however,
remains unchanged. It maybe mentioned that because of the altitude variation of the occurrence rate of meteor trails, the accuracy of the measured winds vary with altitude and is about $2 \text{ms}^{-1}$ in the altitude range of 85-105 km. The above limitations inherent, in general, in the meteor wind radar data analysis do not affect the main conclusions of the present study.

5.3. Results

The time variation of the horizontal component of the earth's magnetic field at Trivandrum during the CEJ days of January 1987 and June 1987 are shown in figures 5.1 and 5.2 respectively (solid curves). The dashed curves in the figures are the variations of $\Delta H$ on quiet days without any counter electrojet effects. For January month, average value of $\Delta H$ of 5-6 January, 1987 are taken to represent the quiet day and for the June month, $\Delta H$ value of 23 June, 1987 is taken. The night time baseline values for all the CEJ days and no-CEJ days were obtained by taking the average of the magnetic field values during 0000-0400 IST (IST is the Indian Standard Time corresponding to 82.5° East). The variations shown in the figures are above and below this baseline value. The necessary correction for $D_{st}$ variation is also applied before determining the nighttime baseline values. It is to be noted that on 28 and 29 January, 1987 (figure 5.1) the higher $A_p$ values indicate disturbance effects superimposed over the CEJ effects. There are some major differences between the $\Delta H$ variations during the CEJ days of
Figure 5.1: Time variation of the horizontal component of the earth's magnetic field ($\Delta H$) at Trivandrum during the five counter electrojet days of January, 1987 shown by full lines. The dashed curve shows the $\Delta H$ variations on the quiet days which represents the normal $S_q$ variations. Vertical arrow indicates the time of disappearance of $E_{sq}$ and inverted arrow indicates the time of reappearance of $E_{sq}$ irregularities.
Figure 5.2: Time variation of the horizontal component of the earth's magnetic field ($\Delta H$) at Trivandrum during the four counter electrojet days of June, 1987 shown by full lines. The dashed curve shows the $\Delta H$ variations on the quiet days which represents the normal $S_q$ variations.
January and June events (figure 5.1 and 5.2). This is seen more clearly in figure 5.3 which shows the behavior of CEJ events on 30 January, 1987 and 10 June, 1987. The interesting important points to be noted are:

(a) the intensity of the CEJ event defined as the maximum negative value below nighttime level varies from 10 to 50nT during January month whereas during June month it is about 10 to 20nT.

(b) in the month of January, on CEJ days, $\Delta H$ reaches its maximum value around 1000 IST whereas the maximum occurs around 1100-1200 IST during June month.

(c) the maximum intensity of the CEJ event reached at about 1400-1500 IST during the month of January shifts to 1600-1700 IST during June.

From a detailed examination of the quarter hourly ionograms recorded at Trivandrum, it was found that $E_{sq}$ echoes are present in the ionograms from 0700-1700 IST on no-CEJ days, whereas during CEJ days $E_{sq}$ echoes appear first around 0700 IST and then disappear and reappear at different times of the day. In figure 5.1 and 5.2 the disappearance and reappearance times of the $E_{sq}$ reflection in the quarter hourly ionograms recorded at Trivandrum are shown by an arrow and an inverted arrow respectively. It is seen that the disappearance of $E_{sq}$ irregularities occurs at least 30-60 minutes before the $\Delta H$ goes down below the nighttime level and the reappearance of $E_{sq}$
Figure 5.3: Comparison on the behaviour of $\Delta H$ variations during CEJ events of January and June months
irregularities is also observed to occur 30-60 minutes before the ΔH reaches its night time level.

Figure 5.4 and figure 5.5 depicts the altitude variation of the mean zonal winds as obtained from the MWR during CEJ (full line) and no-CEJ days (dashed line) for January and June months respectively. Eastward wind is taken as positive. The mean zonal winds in January are westward at all heights during CEJ days. During no-CEJ days they are eastward from 90-100 km and marginally westward above 100 km. However, during June, on CEJ days, the mean zonal winds are weak and westward below 85 km and eastward above 85 km.

The time variation of zonal winds at different altitudes during CEJ days and no-CEJ days are shown respectively by a full line and by a dashed line in figure 5.6 for January 1987. The most outstanding feature to be noted in the figure is that the zonal wind on CEJ days is westward at all heights from 0800-1800 IST, whereas, it is eastward from 1000-1600 IST on no-CEJ days. Further, in the morning hours of 0400-0800 IST, the zonal wind velocity is eastward on CEJ days up to 100 km and westward at all heights on no-CEJ days.

Another interesting feature is that westward zonal wind has a steady value of about 40-45 ms\(^{-1}\) from 1200 to 1400 IST, on CEJ event days. It is also to be noted that during 1400-1600 IST, when the CEJ
Figure 5.4: Height variation of the mean zonal winds observed during CEJ days (full line) and control days of January, 1987 (dotted line). Eastward wind velocities are positive.
Figure 5.5: Height variation of the mean zonal winds observed during CEJ days of June, 1987. Eastward wind velocities are positive.
Figure 5.6: Time variation of the zonal wind velocity observed at different altitudes shown by full line on CEJ days and dashed line on no-CEJ days of January, 1987. Eastward wind velocities are positive.
events are in progress, the westward zonal wind velocity changes from 10 ms\(^{-1}\) at 96 km to about 60 ms\(^{-1}\) at 102 km. In contrast, the time variation of zonal wind shown in figure 5.7 for CEJ days during June behaves in a different manner. The zonal winds are observed to be westward at all heights between 80-90 km during CEJ times (1500-1600 IST), whereas they are eastward between 90-95 km and become westward again at 100 km. Another interesting feature to be noted is that, in general, the magnitude of the zonal wind is smaller during June compared to January.

The altitude variations of the amplitude and phase (time of maximum eastward wind) of the diurnal, semi-diurnal and ter-diurnal wind components in zonal wind on CEJ days (full line) and no-CEJ days (dashed line) are shown in figure 5.8 for January 1987. The amplitudes and phases of all the tidal components on CEJ days are, in general, substantially different from those on the no-CEJ days. The remarkable feature to be noted is that the amplitude of the diurnal component is reduced on CEJ days compared to no-CEJ days (Somayajulu, 1988). The quasi sinusoidal variation in phase of the diurnal component on CEJ days [Figure 5.8 (a)] shows strong interference effects between two wave modes, possibly \(S_1(1,1)\) and \(S_1(1, -2)\) while on no-CEJ days, the interference effects are not clearly discernible. In contrast, the amplitude and phase of the semi-diurnal component, on no-CEJ days (figure 5.8 (b)) shows that the \(S_2(2,2)\) mode is dominant, whereas, on CEJ days the
Figure 5.7: Time variation of the zonal wind velocity observed at different altitudes on CEJ days of June, 1987. Eastward wind velocities are positive.
Figure 5.8: Altitude variation of the amplitude and phase of the diurnal (a), semi-diurnal (b) and ter-diurnal (c) winds in the meteor region over Trivandrum during CEJ evens (full line) in January, 1987 and no-CEJ days (dashed line).
rapid changes in phase with height and the corresponding amplitude minima at about 100 km clearly shows the presence of higher order modes.

The apparent increase of phase with altitude in some of the phase profiles does not necessarily mean that the wave energy is propagating from higher altitudes to lower attitudes. This is because when two wave modes with different vertical wavelengths propagate simultaneously upwards, the resultant phase of the two waves in a limited altitude region can appear to be increasing in the altitude (Raghava Reddi et al., 1992). The striking feature of figure 5.8 (c) is the significant amplitude of the ter-diurnal component observed during CEJ days. This may be due to the generation of the ter-diurnal component through the non-linear interaction between the diurnal and semi-diurnal components (Teitelbaum et al., 1989). The phase jump observed at 100 km and the corresponding amplitude minimum of the ter-diurnal component on CEJ days may be due to the presence of more than one mode of both the diurnal and semi-diurnal components on CEJ days. The non-linear interaction between the different diurnal and semi-diurnal tidal modes can result in the observed modulation in the amplitude and phase of the ter-diurnal component.

The amplitudes and phases of the diurnal, semi-diurnal and ter-diurnal components of zonal wind during CEJ days of June months are shown in figure 5.9. It is seen that the amplitude of the ter-diurnal
Figure 5.9: Altitude variation of the amplitude and phase of the diurnal (a), semi-diurnal (b) and ter-diurnal (c) winds in the meteor region over Trivandrum during CEJ events of June, 1987.
tidal component is larger compared to the diurnal and semi-diurnal components. However, at the westward maximum of the zonal wind in the evening hours of all the three tidal modes could be in the westward wind phase producing a weak CEJ event.

5.4. Discussion

It is generally believed that the dynamo region electric fields necessary to drive the global $S_q$ current system and the normal daytime equatorial electrojet current system responsible for the observed surface magnetic field variation during day time are produced by the first symmetric diurnal trapped mode $S_1(1,-2)$, the diurnal propagating mode $S_1(1,1)$ and the semi-diurnal $S_2(2,2)$ and $S_2(2,4)$ modes. (Schieldge et al., 1973; Forbes and Lindzen, 1976 a, b; Takeda and Maeda, 1980 and Takeda et al., 1986). However, during counter electrojet events, the reversal of the electrojet current as seen from the decrease of the horizontal component of the earth's magnetic field below the nighttime level and the decrease being confined only to electrojet latitudes have focused the attention on the possible large variabilities of mean winds and tidal wind components in the equatorial dynamo region as observed by MWR system. Forbes and Lindzen (1976 a,b) used a three dimensional treatment in which the local wind effects are included by considering the mean wind and a combination of certain tidal wind modes with characteristic latitudinal and height variations. They could...
CEJ event around 0600 LT and 1800 LT by assuming variations in the solar tidal wind fields of about 30-40% in amplitude and 1-2 hr in phase about their average values. Further, the effects of lunar semi-diurnal harmonic near full moon as predicted by Rastogi and Trivedi, 1970 and Rastogi (1974) were also included in their simulation, and concluded that the superposition of the lunar current variation on the equatorial $S_q$ variation cannot in itself account for negative excursions in $\Delta H$ greater than 10 nano tesla; rather the lunar effect is probably a modulation of solar effect. On the other hand, Marriot et al. (1979) with an unusual combination of tidal wind components have shown the possible reversal of the east-west electric fields ($E_y$) on a scale much larger than EEJ. Furthermore, the detailed analysis of Fambitakoye and Mayaud (1976 c) showed that the enhanced part of the equatorial electrojet current is westward during CEJ events where as the "background current density" is still eastward. Their results clearly show that the electric field reversal during CEJ events is confined essentially to electrojet latitudes and hence can be explained in terms of local mean winds and the behaviour of the tidal components at electrojet latitudes only.

The main observational results of the present study can be summerised as follows:

(a) The zonal mean winds are westward on CEJ days at altitudes of 90-105 km during January months and from 80-90 km during June months.
(b) The phases of the different tidal components in zonal winds are such that the maximum westward velocity occurs earlier (1400-1600 LT) during January months and later (1600-1800 LT) during June months.

(c) The amplitudes of the ter-diurnal components is considerably higher than what has been suspected hitherto.

It is reasonable to assume that the observed tidal wind fields during CEJ days and no-CEJ days (as far as January data is concerned) are of global scale in longitude. Further, theoretical studies have shown that the tidal wind fields are different from those observed at mid-latitudes and can be explained only by taking into account the mode coupling effects due to dissipation and latitudinal temperature gradients (Forbes and Hagen, 1988; Lindzen and Hong, 1974)

The zonal wind influence can be easily seen from the dynamo equation. A knowledge of the tidal wind fields permit us to calculate the eastward current density \( J_y \) which is given by

\[
J_y = \sigma_1 E_y + \sigma_2 \left[ E_z + W \times B \right]
\]

where \( \sigma_1 \) is the Pedersen conductivity, \( \sigma_2 \) is the Hall conductivity, \( E_y \) is the dynamo east-west electric field, \( E_z \) is the vertical polarisation field, \( W \) is the zonal wind and \( B \) is the geomagnetic field. The zonal wind
velocity of about \(-45\) to \(-50\text{ms}^{-1}\) with appropriate height gradient observed during the CEJ events can generate a local vertical polarisation field of about \(1.5 - 2.0\text{mVm}^{-1}\) directed downwards. (Richmond, 1973; Reddy and Devasia, 1981; Ananda Rao and Raghava Rao, 1987). The vertical polarisation field due to the global scale \(S_q\) field could be less in magnitude than the vertical polarisation field due to the local winds and directed upward. Consequently, the effective polarisation field could be directed downwards during an eastward current as indicated by \(\Delta H\) values reaching below night time level and the disappearance of the \(E_{sq}\) in the ionograms. Therefore we can conclude that a combination of global tidal wind fields which tend to weaken \(E_z\) in combination with local westward winds are necessary to produce the CEJ events.

The logical conclusion is that while it is probably true that the vertically trapped \(S_1(1, -2)\) diurnal mode in the mid latitudes is primarily responsible for the \(S_q\) and the equatorial electrojet current systems, our observations show that the semi-diurnal tidal component certainly influences the generation of CEJ event. This is corroborated by the pronounced semi-diurnal character of the \(\Delta H\) variation shown by the full line in figure 5.1 during CEJ days and nearly diurnal character of the quiet day (dashed line). It is to be noted that a correct quantitative apportionment of the contribution to the \(\Delta H\) variation from the global \(S_q\) current system and the local westward winds and the tidal wind components observed at equator is not possible unless information about
mid latitude winds that generate $S_q$ current system is available simultaneously. Nevertheless, model computations using the observed tidal wind field should be carried out in order to assess the role of observed local winds producing a CEJ event. In conclusion the observed features of the mean zonal winds and the amplitudes and the phases of the tidal wind components at low latitude represent the first direct evidence of the role played by tidal components during CEJ event observed at the equator.