Enhanced gravity wave activity over the equatorial MLT region during counter electrojet events

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This paper reports the evidence for an enhanced gravity wave activity of 1-2 hour periodicity in the equatorial mesopause temperature during the counter electrojet (CEJ) events. The analysis based on the data from a unique dayglow photometer and Proton Precession Magnetometer over a dip equatorial station Trivandrum (8.5°N, 77°E, dip latitude 0.5°N) clearly indicates that in general, the wave activity is high during CEJ events compared to a normal day. It is very interesting to note that the wave activity at mesopause region fades out during the period of the occurrence of CEJ when the mesospheric zonal wind shows a reversal from west to east. This indicates a possible upward penetration of the gravity waves from mesosphere to lower thermosphere during such events, thereby, reversing the vertical polarization field and hence the generation of CEJ. This study presents first direct evidence for such an enhancement in the wave activity in the upper mesospheric region during CEJ events, supporting the gravity hypothesis of Raghavarao & Anandarao [Raghvarao R & Anandarao B G, Vertical winds as a plausible cause for equatorial counter electrojet, Geophys Res Lett (USA), 7 (1980) pp 357–360].

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1 Introduction

The thermal and dynamical structures of the mesosphere-lower-thermosphere (MLT) region is primarily controlled by the wave forcing, like the tides, gravity waves and planetary waves, which are generated in the lower atmosphere and grow in amplitude as they propagate upward. At upper mesospheric altitudes, the impact of these dynamical forcing on the temperature, winds and density structure is very significant. In fact, a number of studies in the recent years indicate that the variability in the extent of these dynamical forcings higher above the dynamo region (90-120 km) also have important implications therein2,3. It has been shown that such waves affect the electrodynamical processes like the equatorial electrojet (EEJ) in the equatorial E-region and even lead to the reversal of EEJ called the counter equatorial electrojet (CEJ)2,3.

As of now, it is well understood that the EEJ and CEJ are primarily driven by the lower atmospheric wave forcing, especially by the solar tides. However, the tides themselves are vulnerable to the modulation by the waves of different time scales. Gravity waves play a major role in producing the short-scale variation in the tidal structure that in turn, gets reflected in the electrodynamics in the form of the occurrence of CEJ. The CEJ refers to the reversal of the EEJ current at occasions during morning and postnoo hours. Though different theories are proposed for explaining the CEJ, none of them could address the exact causative mechanism for its occurrence and day-to-day variability. Some of the theories proposed for the generation of CEJ are: (i) reversal of vertical polarization field by large vertical winds associated with the gravity waves1,4; (ii) formation of an additional current system by the interaction of altitude varying winds5; and (iii) reversal of the zonal electric field by appropriate phase combination of global scale tidal wind modes6,7.

On the whole, all studies related to the CEJ events in the past have highlighted the importance of dynamical features like winds, waves and tides in the MLT region. Recently, the vertical wind hypothesis postulated by Raghavarao & Anandarao1 got significant attention as more evidence for the existence of such winds has been brought out1,2. They showed that there exist a strong connection between mesopause and lower thermosphere during the CEJ events. The temporal variation of the daytime mesopause temperature was found to be exhibiting significant
cooling (10-20 K) on CEJ days in the afternoon hours during 1200-1600 hrs LT. The observation was found to be holding good even for partial CEJ days, where the magnetic field does not reach the mean night level. It was suggested that gravity wave, induced vertical wind, played a major role in such variabilities in the mesopause temperature and the EEJ. Similarly, in a recent study, Vineeth et al.2 have shown that not only the mesopause energetics but also the background wind exhibit a totally different pattern during the afternoon CEJ events. They observed a reversal in the zonal wind at 98 km from westward to eastward during the CEJ events.

Though, there were many studies related to the gravity wave hypothesis and CEJ, so far, no one has presented a direct evidence for such an enhanced gravity wave activity in the upper mesosphere region during CEJ, mainly because of the lack of measurements having high temporal resolution. In this context, the dayglow photometer developed in India provided high cadence measurements on daytime mesospheric airglow emissions in recent years. The measurements of daytime hydroxyl emission from the mesopause provided crucial information about the energetics/dynamics of this region8,9,10. In this paper, an attempt has been made to characterize the nature of the gravity wave oscillations in the upper mesospheric region using the optical emissions and the derived temperature therein. It has been observed that gravity wave activity of 1-2 h periodicity is enhanced in the intensities of OH emissions and mesopause temperature during the morning hours of the CEJ days, whereas it is absent or weak during a normal electrojet day. It is also interesting to note that the waves in the mesopause region either damps out or shows diminished amplitude during and after the time of occurrence of CEJ. This suggest a possible penetration of gravity waves to lower thermosphere from upper mesosphere as the zonal wind also showed a reversal from westward to eastward (or an eastward acceleration) during that time. Therefore, the present study, which deals with the vertical coupling between the mesosphere and lower thermosphere region would not only bring out the effect of lower atmospheric wave forcing in the energetics and dynamics of the mesopause region but also its manifestations in the lower thermospheric processes like the EEJ and CEJ.

2 Instrumentation
The daytime intensities of the OH (8-3) airglow emissions at wavelengths 731.6 and 740.2 nm have been measured using the Multiwavelength Dayglow Photometer (MWDPM) over Trivandrum (8.5°N, 77°E, 0.5° N dip latitude) in India. The details of the MWDPM have been already described11. The mesopause temperatures were estimated using the ratio method adopted by Meriwether12. The magnetic field strength at the surface was measured using a Proton Precession Magnetometer (PPM) located at Trivandrum and a Flux Gate Magnetometer located at Alibag (18.3°N, 72.6°E, 10.2°N dip latitude), an off equatorial station. The horizontal component of the Earth’s magnetic field over Alibag is subtracted from the total field over Trivandrum to obtain the EEJ induced field. Since Trivandrum is located right over the dip equator, the magnetic field lines are primarily horizontal and the PPM measurements represent the horizontal component of the field. It is widely believed that the induced field due to solar quiet (Sq) current system and magnetospheric currents are almost identical at Alibag and Trivandrum, which are separated only by a distance of ~1100 km. Therefore, the difference in field between Trivandrum and Alibag is related to purely ionospheric currents, which is primarily due to the EEJ during daytime. In the present analysis, a few cases of CEJ events during February-May 2005, where all the afore mentioned measurements were available, have been considered.

3 Observations
In order to characterize the nature of gravity waves during the CEJ events, seven CEJs of different extent of field reversal during the period February-May 2005 have been analyzed. To have a comparison, a normal electrojet (NEJ) is also considered. The night level subtracted EEJ induced magnetic field at surface (∆HTRV-∆HABG) during the considered days of study has been shown in Fig. 1. It is clear from the figure that 14 and 15 February; and 04 March 2005 are partial CEJ days while 03, 25 March; and 19, 20 May 2005 represent fully developed CEJs having field reversals of -10, -45, -30 and -25 nT, respectively. It must be mentioned that 25 March and 19 May were disturbed days with Ap values of 20 and 22, respectively. Though, these were disturbed days, the CEJ events of 25 March and 20 May exhibit all the classical features of quiet time CEJs (Ref. 2). In Fig. 1, 27 April 2005 represents a typical quiet time NEJ day. It is also clear that maximum strength of EEJ exhibits significant day-to-day variability.

In order to characterize the nature of gravity waves present at MLT altitude, the mesopause temperatures
at every one minute interval has been analyzed. Figure 2 represents the mesopause temperatures during the aforesaid days. It is clear from Fig. 2 that in general, the fluctuations present in both the parameters are more on CEJ days, and temperature on all the CEJ days exhibits a decreasing trend from morning to evening, whereas it shows an increasing trend during the NEJ day. Further, the amplitude of the oscillations present is considerably higher during the morning hours than in the evening and it shows a decreasing trend as time progresses. On 25 March 2005, a fully developed CEJ day, the amplitude of oscillation in both the temperature and $\Delta H$ are higher compared to the other two partial CEJ days. On the other hand, the amplitude of the oscillations is significantly smaller during the NEJ day compared to that of the CEJ days. On the other hand, the amplitude of the oscillations is significantly smaller during the NEJ day compared to that of the CEJ days. In order to find out the exact periodicity of the oscillations present, the fluctuations in the temperature are subjected to wavelet analysis\(^{13}\) and found that gravity wave of periodicity 1-2 h is dominant during all the CEJ days and it is much weaker during the NEJ day (Fig. 3). It is very interesting to note from figure that the oscillation is prominent during the morning hours of the CEJ days and dies out or shows weakened amplitudes during the afternoon hours. On 14 February 2005, a partial CEJ day, the wave seemed to be re-appearing during the afternoon hours immediately after the occurrence of CEJ. In general, the gravity wave activity of 1-2 h periodicity is found to be significantly enhanced in mesospheric temperature during the forenoon hours of CEJ days.

4 Results and Discussion

Atmospheric gravity waves play important roles in both the small and large scale dynamics of the MLT region through their vertical transport of horizontal momentum\(^{14,15}\). The dissipation of the waves in
this region causes turbulence and divergence of momentum flux, which leads to local heating, turbulent diffusion, and acceleration of the local mean flow. An extensive review of the generation, propagation and dissipation of the gravity wave is given by Fritts & Alexander. Most of the earlier studies regarding the gravity wave activity at mesopause region were based on radar measured wind and airglow intensity or lidar-derived density and wind data.

The response of the airglow emissions to the passage of the gravity waves has been a matter of intense research in the past. A link between rotational temperatures, hydroxyl intensity and the propagation of the gravity waves through the emission layers was first established by Krassovsky. Further, Walterscheid et al. modeled the wave-driven fluctuations in the OH nightglow and calculated the relative amplitudes and phases between the fluctuations in temperature and brightness as functions of the wave period. Another modeling study by Hecht et al. has suggested that there exists a simple relation between the variations of airglow intensity and gravity wave activity. They showed that the low wave activity in the mesopause region leads to low eddy diffusion and increased concentration of atomic oxygen and therefore, enhanced airglow brightness. So, airglow emissions are the perfect tracer of the ongoing dynamical activity of the MLT region.

Most of the studies related to the gravity waves at MLT region have been limited to the airglow intensity measurements during nighttime and had poor temporal coverage. In this context, the unique dayglow photometer developed in India, which is capable of measuring intensity of airglow emissions during daytime has overcome this limitation. One such photometer had been operated from Trivandrum (8.5°N; 77°E; dip latitude 0.5°N) since 2005 on a regular basis to study the energetics and dynamics of the mesosphere-thermosphere-ionosphere region. A number of new results pertaining to the daytime mesopause region have already been brought out.
using this unique photometer recently. In this context, the dayglow intensity measurements presented in this study provide crucial information about the behaviour of the gravity waves during the daytime electro dynamical phenomena like the CEJ.

The important result, presented in this paper, is the evidence for increased gravity wave activity in the upper mesospheric temperature and EEJ induced magnetic field during CEJ events. The reduced wave activity in the mesopause temperature during and after the occurrence of CEJ indicates a strong vertical coupling between the mesopause and the dynamo region through the gravity wave-associated vertical winds during such events. In fact, it provides an experimental confirmation for the gravity wave hypothesis for the occurrence of CEJ, originally proposed by Raghavarao & Anadarao and later on supported by Vineeth et al. While the former theoretically simulated the need for large vertical wind of magnitude 20-30 m s⁻¹, the latter inferred the existence of such vertical wind from the simultaneous cooling observed in the mesopause temperature during CEJ events. They suggested that the gravity wave-associated vertical winds at MLT region would oppose the downward diffusion of atomic oxygen form lower thermosphere leading to reduced exothermic reaction, which in turn manifest as cooling of the mesopause. In the meantime, the upward wind in the ionospheric dynamo region would either weaken or reverse the polarization field. The present study based on the spectral analysis of the mesospheric temperature provides a direct evidence for the presence of such waves in the equatorial MLT region during CEJ events. The signatures of gravity wave oscillations in the OH emission intensities (not shown here) further confirm the presence of such activity at mesosphere. As mentioned earlier, the wave activity at mesosphere either disappears or gets weakened during and after the CEJ events. This indicates the penetration of the waves from mesosphere to lower thermosphere as the background zonal wind also exhibited a reversal from westward to eastward on CEJ days when the field exhibits the reversal as reported by Vineeth et al.

5 Conclusions
This study provides the experimental confirmation for the existence of an enhanced gravity wave activity at MLT region during the afternoon equatorial counter electrojet events. The analysis based on the intensity measurements of the hydroxyl (OH) airglow emissions during daytime revealed that gravity waves of periodicity 1-2 h show intensification during the forenoon hours of CEJ days while on normal days the amplitude of the wave is found to be very weak. This study shows that there exists a strong dynamical coupling between mesosphere and lower thermosphere during the special electro dynamical event like the equatorial counter electrojet.

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