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On the role of horizontal wind shears in the generation of F0.5 layers over the dip equatorial location of Thiruvananthapuram: A numerical simulation study

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ABSTRACT

A numerical simulation is carried out to estimate the rate of convergence of ionization required to produce a F0.5 layer with peak plasma frequency (foF0.5) of 3.2 MHz from three different background layer densities, over Thiruvananthapuram (8.5°N; 77°E; dip latitude ~ 0.5°N), a dip equatorial station in India. Further the simulation study is extended to understand the convergences required by considering the seasonal mean peak F0.5 layer frequencies also. One possible mechanism by which this convergence can be produced is by a horizontal shear in the meridional wind. The corresponding shears required to generate the layer with the above convergence conditions are estimated. It is found that gravity waves are capable of generating wind shears, leading to the pooling of ionization and the generation of the layer over the dip equator. A meridional wind with the gravity wave induced wind shear is numerically estimated. Finally, the short scale gravity waves of periods around 3–23 min have been inferred to be more efficient in generating the wind shear when compared to large scale horizontal waves leading to the generation of F0.5 layer.

1. Introduction

Additional stratifications that are formed near the base of the F1 region and do not exhibit significant downward descent are referred to as the F0.5 layers. They are a class of Intermediate layers formed in the transition or valley region between E and F layers. The earliest of the observations on these layers have been of those induced by earthquake (Leonard and Barnes, 1965). Similar ionospheric layering was also observed during the severe earthquake of magnitude of 9.0 which occurred off the Pacific coast of Tohoku on March 11, 2011. In fact Maruyama et al. (2011) showed the occurrence of multiple cusp type traces indicating extra stratifications at Wakkanai and Yamagawa, which were ionosonde stations almost 1000 km away from the epicenter. Using other observations elsewhere Warrant et al. (2007) reported that during the strong geomagnetic storm on March 31, 2001, an F0.5 layer formed and tore off from the normal F layer and started descending with time and finally merged with the normal E layer about 2 h later. Though not particularly on F0.5 layers, several studies have been carried out on intermediate and descending layers over the low as well as mid latitude region (Osterman et al., 1995; Niranjan et al., 2010; Lee et al., 2003 and references therein).

The first study on Intermediate descending layers (IDL) was done by McNicol and Gipps (1951). Ionosonde observations were used to show the appearance of two distinct layers in the E region, one being in situ generated while second type formed at high altitudes and descended to the lower E region. Mac Dougall (1978) looked into the appearance of IDL in the ionograms and found that their occurrence periodicity is linked to long period tidal oscillations. Shen et al. (1976) reported a series of electron density profiles, illustrating the steady downward drift of IDL over period of several hours. Tong et al. (1988), using Incoherent Scatter Radar (ISR) data showed the presence of long period variations in IDL over Arecibo. Later Morton et al. (1993), during AIDA (Arecibo Initiative in Dynamics of the Atmosphere) campaign confirmed the regular quarter diurnal periodicities of the layers and postulated tidal influence as the causative agent for this periodicity. Arecibo radar provided measurements on IDL which otherwise were seldom visible in the Ionosonde for being mostly masked by high density sporadic layers. Numerical modeling studies of the layer processes in the upper E region have been carried out by Osterman et al. (1994) and their studies showed that the composition of IDL may be dominated by molecular ions at higher altitudes, progressively getting replaced by metallic ions as layers descend. In their study the formation of IDL in the valley region between E and F layers due to the effect of meridional winds have been studied. Heelis

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(1999) studied the ion composition of IDL above 130 km altitude using data obtained from retarding potential analyzer onboard Atmospheric Explorer C satellite and showed that both meridional and zonal winds may play a role in the field-aligned plasma transport that is primarily responsible for their formation. Recently Niranjan et al. (2010) discussed the drift aspects of IDL over a low latitude station of Waltair and found that the presence of 6 hourly tides in the lower thermospheric altitudes plays an important role in the generation and evolution of these layers. In this context Mridula et al. (2014) have reported the occurrence pattern as well as the properties of F0.5 layers observed over the dip equatorial location of Thiruvananthapuram. It was shown that during pre noon hours when the layer occurred earlier, the peak layer density foF0.5, was low and the layer base height h'F0.5 will be higher and vice versa. This study brought out and highlighted the role of chemistry in modulating the properties of F0.5 layer.

There are two prominent mechanisms that are based on wind shear theories used to explain the generation of IDL over low and mid latitudes. The first one involves vertical wind shear and is shown to be active at higher altitudes while the second one involving zonal wind shears is found to be dominant at altitudes, lower than 130 km. Osterman et al. (1995), proposed that a meridional wind profile with sinusoidal variation with altitude produces regions of alternate upward and downward field aligned ion drift at altitudes between 130 km and 200 km. Thus, a convergence/divergence in field aligned ion drift tends to produce regions of enhanced/depleted plasma density. Further, it was also shown that the downward motion of the IDL is consistent with the properties of a solar semidiurnal tide. Wilkinson et al. (1992), using the TIEGCM model showed the dominant role of zonal wind shears in the generation of IDL below 130 km.

However over the dip equatorial region, the vertical field aligned convergence is not active since the magnetic field lines are horizontal. In fact over this region only horizontal convergence of ions can lead to the accumulation of ionization resulting in the formation of an intermediate layer like F0.5. In the lower F region, both ions and electrons are highly gyrational and the zonal wind is not very efficient in moving ionization across the magnetic field causing an accumulation of ionization. Further, a zonal convergence can be followed by field aligned diffusion, hence reducing the effectiveness of convergence. The convergent meridional neutral wind however is capable of moving ionization along the magnetic field and lead to horizontal convergence of ionization. The region around the lower F region where production and loss due to dissociative recombination, transport and field aligned diffusion are active is rich in molecular ions like O_2^+. However, the loss due to transport and diffusion can be neglected as this is the transition region where ExB drift just begins. In this context, the mechanism proposed by Reddy and Devasia (1973) to explain the formation of blanketing Es layers in the dip equatorial E region on the basis of horizontal ion convergence due to meridional wind shears can be applied to lower F region heights, region which is the seat of F0.5 layer generation.

In recent years it has become very clear that the horizontal wind shears in the meridional winds can indeed be generated by short period gravity waves. An important source of short period gravity waves over low latitudes are tropical convective storms. The convectively generated gravity waves penetrate up to lower thermospheric altitudes and have been observed (Kherani et al., 2009) and the same have been demonstrated through numerical simulations (Alexander et al., 1995). Gravity waves with periods of 30–90 min have been detected in the mid-latitude thermosphere using the MU radar (Oliver et al., 1994). Realizing the importance of these layers in the ongoing electrodynamics over the dip equatorial region, the present study attempts to understand the role of meridional wind shear in the generation of the F0.5 layers over the dip equatorial region of Thiruvananthapuram using numerical simulation. The dominant role of gravity waves in generating this meridional wind shear is also discussed. Further the periods of gravity waves capable of producing meridional wind shears are also estimated.

2. Data used

The data from the digital Ionosonde located at Trivandrum (8.5° N, 77 ° E, 0.5 ° N dip lat.) have been used to investigate the formation of F0.5 layer. The KEL IPS-42 digital ionosonde has been operational at Trivandrum since 2001. KEL, a digital ionosonde, uses solid state technology and it operates in frequency sweep as well as pulsed modes. Frequency generation is done through a digital synthesizer. Operating frequency is varied between 1 and 22 MHz and one sweep time is 12 s. Two vertical crossed delta antennas have been used, one for transmitter and one for the receiver respectively. The ionograms recorded at every fifteen minutes during 2006 were analyzed, for identifying the formation of the F0.5 layer as well as inferring its peak ionization foF0.5. Days of Ap values >20 are avoided in the study. Ap index is obtained from SPDF OMNI website. A typical case on 23 April 2006 at 07 45 IST is considered in this study. The ground based magnetic field measurements are obtained from a collocated magnetometer details of which are given in Vineeth et al. (2009).

3. Simulation and discussions

In the current simulation study, first the convergence required to generate a layer of given electron density from a background ionosphere without layer is estimated assuming that this convergence is caused by a meridional wind shear over the dip equator with gravity waves as the source of these wind shears. Further perturbation amplitude in velocities which are capable of producing the meridional wind shears required to form the layer are estimated. The plasma density is taken to be equal to the number of ions Ni, which is again the number of electrons Ne. The continuity equation for ionization, neglecting transport and field aligned diffusion will be

$$\frac{\partial N}{\partial t} + \nabla.\ NV = P - L \tag{1}$$

Where N is the plasma density, V is the drift velocity, t is time and P and L are the production and loss terms. The background ionization without layer is taken as N_0 and if the peak of ion density of the layer is taken as N_m, and if quasi equilibrium condition is assumed, time derivative vanishes. Further the local production and loss are offset by convergence of ionization leading to the generation of the layer.

$$N\mathrm{m}\nabla.\ V = (P - L) \tag{2}$$

If we take -∇.V as convergence 'g', then based on the assumption that the additional ionization present in the layer over and above the background level is due to convergence,

$$g = -\frac{1}{Nm}[\alpha N0^2 - \alpha N\mathrm{m}^2] \tag{3}$$

On simplification, we find that

$$g = \alpha.\ N0.\left[\frac{\eta^2 - 1}{\eta}\right] \tag{4}$$

where $\eta = N\mathrm{m}/N_0$ (layer peak density /background density in the absence of layer).

This expression is obtained from the formulation expressed in Reddy and Devasia (1973). At the base of F region, i.e., around 160–170 km, the major ion source is still O_2^+ in addition to O^+ and hence the recombination rate can be taken as that of O_2^+, i.e. around 10^{-7}/cc/s (Prolls, 2004). Earlier studies have shown that as the layer descends, the molecular ions are replaced by metallic ions and this aspect is not considered here. The convergence g estimated here is ηg, involving the efficiency of convergence also.

In the present study only the convergence associated with molecular ions are considered, which is a limitation of the present