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A new insight into the vertical neutral-ion coupling between the mesopause and equatorial ionosphere F-region

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Abstract. This letter reports unique observations, illustrating the vertical coupling between the daytime mesopause and F-region of the ionosphere over the magnetic dip equatorial station Trivandrum (8.5° N, 76.5° E, 0.5° N dip lat.) in India. For the "first time", it has been shown that the temporal variations in the mean daytime mesopause temperatures (MPT), during geomagnetically quiet days corroborate well with that of the base height changes ($h'F$) of the ionospheric F-region. However, there exist some characteristic time delays between these two, which vary from 0 to 90 min. The MPTs are measured using the unique Multi-Wavelength Dayglow Photometer while the $h'F$s are derived using a co-located digital Ionosonde. The observed time delays are attributed to the intercompeting roles between the diffusion and wave-dynamical processes in modulating the transport of atomic oxygen at these altitudes.

Keywords. Atmospheric composition and structure (Middle atmosphere – composition and chemistry) – Ionosphere (Equatorial ionosphere; Ionosphere-atmosphere interactions)

1 Introduction

In recent years, the atmosphere-ionosphere coupling has emerged as an important area of research globally. Comprehension of the nature of this coupling requires an understanding of various neutral and plasma processes. As is known, the mesopause is a crucial transition region that facilitates the coupling between the neutral dynamics dominated atmosphere and the electro-dynamically controlled ionosphere above. In general, the day-to-day variability in this atmosphere-ionosphere system during geomagnetically quiet times are believed to be governed primarily by the dynamical forcings from below, like the tides, gravity and planetary waves and their interactions. It has also been shown that the aforesaid forcings induce significant changes in the mesopause energetics and dynamics (Smith, 2004). For instance, Vineeth et al. (2007a) have shown that the lower atmospheric forcing, like the gravity waves and tides, have significant manifestations in the equatorial electrojet. At the same time, the mesopause energetics responds to such forcings in the form of a lowering in the mesopause temperature simultaneous to the occurrence of counter electrojet (Vineeth et al., 2007b). By now, it is well understood that the investigation of the variability in the mesopause region vis-à-vis changes in the ionosphere can lead to a better understanding of the prevailing atmosphere-ionosphere coupling at any given time.

Recent investigations of quiet time atmosphere/ionosphere have revealed that the modulation in the lower atmospheric forcing is one of the major contributors to the ionospheric variability (Abdu et al., 2006; Vineeth et al., 2007a; Pedatella et al., 2008). The same has been found to be true even during specific transient events like the Sudden Stratospheric Warming (SSW). The impact of SSW, which is essentially a stratospheric process, has already been reported on various atmospheric and ionospheric parameters like equatorial mesopause temperature, electrojet strength and F-region vertical plasma drift (Chau et al., 2009; Sridharan et al., 2009; Goncharenko et al., 2010, and references therein).

However, it had been difficult to measure the neutral parameters like the temperature in the mesopause, more so during daytime, due to the relative inaccessibility of this region to the existing ground-based techniques. In recent years, the ground-based spectro/photometry of specific atmospheric emissions during both day and nighttime, has enabled measurement/estimation of key parameters representing the mesopause (e.g., the mesopause temperature) (e.g., Taylor et al., 2001; Vineeth et al., 2005, and references therein). In this

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context, the unique Multi-Wavelength Dayglow Photometer (MWDPM) developed in India had been successfully used for making daytime mesopause temperature measurements over the Indian longitudes in recent years (Sridharan et al., 1999; Pant et al., 2007; Vineeth et al., 2005). Presently, this dayglow photometer is operated from Trivandrum (8.5° N; 77° E; dip lat. 0.5° N), India to get the estimate and also the temporal variability of the mesopause temperature over the dip equator.

Using the measurements from MWDPM and collocated digital ionosonde, an attempt has been made to investigate the coupling, if any, between the mesopause and lower F-region of the equatorial ionosphere. Interestingly, it has been found that, during geomagnetically quiet days, the time evolution of the mean daytime mesopause temperature (MPT) significantly corroborates with that of the simultaneously measured mean bottomside ionospheric height ($h'F$), but with varying time delays. The present paper aims at reporting these first observations and exploring plausible physical mechanisms for explaining the same.

2 Experiments

The daytime mesopause temperatures were estimated using the OH Meinel (8-3) band dayglow intensities of rotational lines at 731.6 and 740.2 nm using the ratio method described by Meriwether (1975). The OH intensity measurements were made using the MWDPM over Trivandrum (8.5° N, 76.5° E, 0.5° N dip lat.), a geomagnetic dip equatorial station in India. The characteristics of the photometer and data analysis procedure had been published elsewhere (Sridharan et al., 1999). The measurements have already been validated/compared with the in situ WINDII satellite measured temperature and also collocated meteor radar measured temperature in the Indian region (Vineeth et al., 2005, and references therein). It has been found that the temperatures measured, using the aforementioned techniques, agree very well (within ± 20 K) with each other with all the variability coming out fairly well. The measurements at every $\sim$7 min intervals typically span $\sim$7–8 h during daytime between 09:00 to 17:00 h for the zenith sky. For the present study, the MWDPM observations of magnetically quiet days (Ap < 7) for the period 2005–2007 are considered, Ap being the index representing the planetary level of geomagnetic disturbance. Only those days when we have continuous observations of at least five hours, are included here. It must be mentioned here that Trivandrum being a tropical station, the optical measurements, like the present one, have limitations due to poor sky conditions. Hence, only those months which have the maximum number of observations during the magnetically quiet periods and cloud-free conditions during the period 2005–2007 are chosen for the present investigation. Simultaneous measurements on the F-region height variations ($h'F$) as scaled from the quarter hourly ionograms from the collocated digital ionosonde have been used for representing the ionospheric variability.

3 Observations

In order to find out the correlation between $h'F$ and MPT, the temporal evolutions of these parameters for eight different months during the period 2005–2007 are analysed. As mentioned earlier, only geomagnetically quiet days with clear sky viewing conditions have been considered for the analysis. In this context, each month represents the quiet time mean for about 15 days on an average, the minimum being 13 days and the maximum being 17 days. The exact time delays for each month have been estimated by carrying out the cross-correlation analysis. It was found that the time delays exhibit month-to-month variability. The results of this analysis for different months are depicted in Figs. 1 and 2. The red lines represent the time variation of the mean $h'F$ for the months mentioned in the panels, and the black lines the time shifted MPT. The scales of both MPT and $h'F$ are kept varying for different months, primarily to highlight the variability. The standard deviations (vertical bars), time delays (TD) and the correlation coefficients (r) for each month are marked in each panel. The positive time delay means that the $h'F$ precedes the MPT.

As evident from the figures, the correlation between $h'F$ and MPT are striking ($r > 0.6$) with a 90% confidence level for all the months. The correlation coefficient was found to be maximum during February 2006 ($r = 0.72$) and minimum during April 2006 ($r = 0.57$). As a result of the cross-correlation analysis, significant positive time delays were found for almost all months which are mentioned in each panel in Figs. 1 and 2, except for April 2006 when the time delay found was negative. Interestingly, during February 2006 (Fig. 1d), the cross-correlation analysis revealed no appreciable time delay between the $h'F$ and the MPT, nonetheless the correlation coefficient was found to be 0.72.

It can be seen in Figs. 1 and 2 that the mean MPT and $h'F$ exhibit short period ($\sim$30 min) modulations prevailing almost all the months, overriding an overall daytime trend. As is seen in the figures, these trends are quite significant. However, most of these modulations are small and less significant. It must be mentioned that even these modulations in MPT and $h'F$ correlate very well. At the same time, the noontime variability seen during May 2005 and March 2007 is significant as is evident from the involved standard deviations.

However, it must be mentioned here that the origin of this study is based on our observations which show that there are days when the daytime mesopause temperature variability correlates very well with the ionospheric changes after a time-delay. At the same time, we have observations when no such significant correlations are observed. These correlations (or absence of significant correlations on some days)

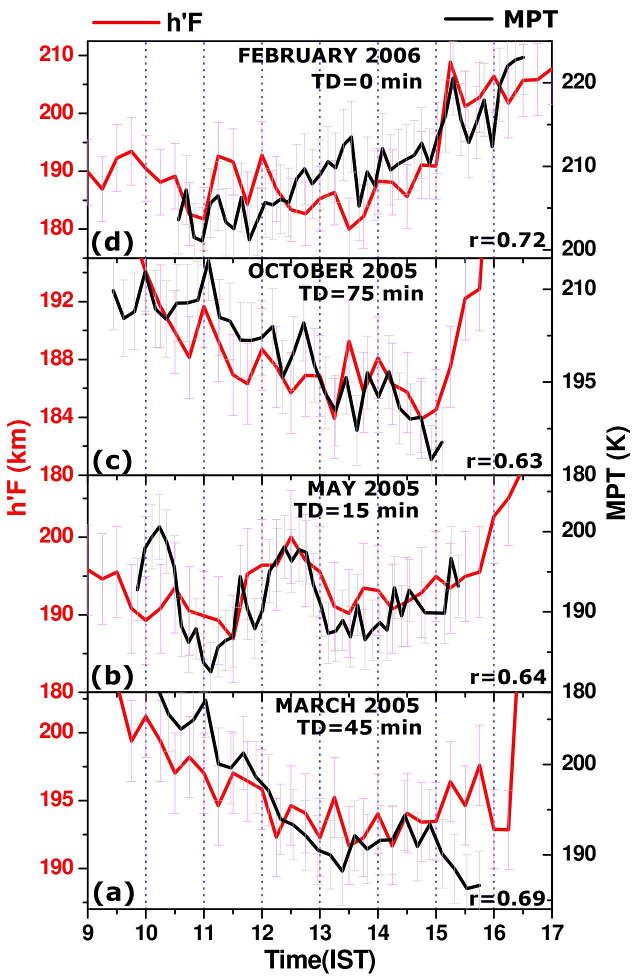

Fig. 1. Time variation of monthly mean $h'F$ variations and time delayed equatorial mesopause temperature (MPT) along with their standard deviations (SD) for different months during the years 2005–2006. The corresponding time delays (TD) and correlation coefficients (r) are also shown in each panel.

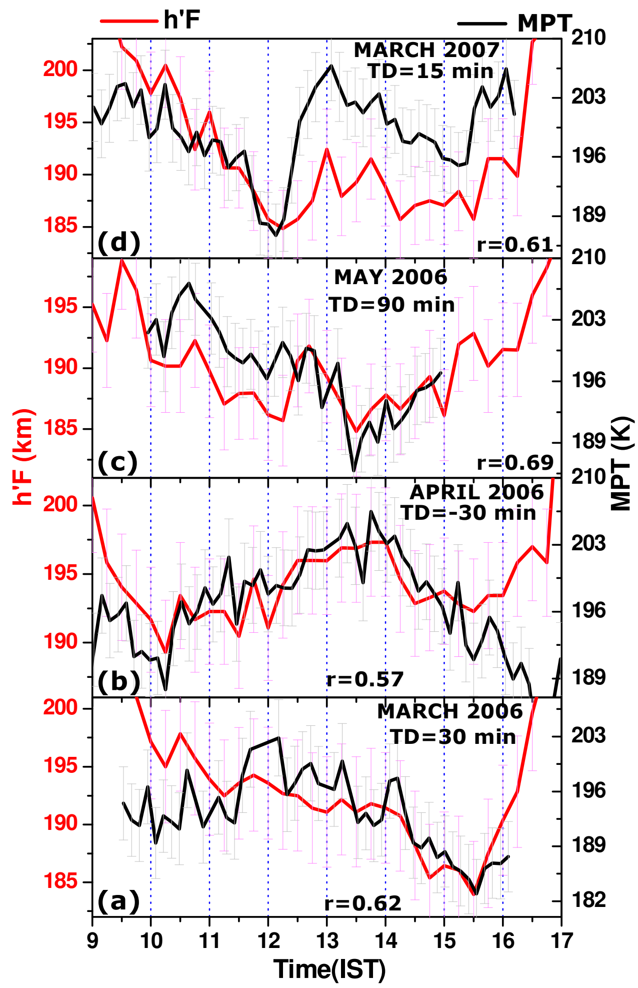

Fig. 2. Same as Fig. 1, but for different months during the years 2006–2007.

are due to the upward propagating waves which modulate the measurements pertaining to both the mesopause and the ionosphere depending upon the prevailing background conditions in the mesosphere-thermosphere-ionosphere region. On an average, 5 days in a month exhibit such uncorrelated behaviours. However, these days are also included in the present analysis. The reason behind taking the monthly average is to avoid the contribution from gravity waves. The rationale was that the variability due to short-period (∼2–3 h) waves will cancel out due to the averaging. As a consequence, there should not be any correlations seen in the averaged trends of the mesopause temperature and ionospheric height variability. On the contrary, as mentioned, we observed a much improved correlation between the two, clearly indicating that the cause of these correlated mesopause and ionospheric variability is not gravity wave induced.

4 Results and discussion

The observations showing the corroboration between the MPT and $h'F$ are very interesting. Typically, the $h'F$ over Trivandrum exhibits a decreasing trend from morning until noon and it gradually increases thereafter. During the morning hours, as the production of ionized species starts, the bottom side F-region gradually gets filled up which continues up to noon. This manifests as the lowering of $h'F$ in the morning hours. The converse happens in the evening hours i.e., as production decreases, bottomside density also decreases due to the increased recombination. This is observed as a rapid excursion in the $h'F$ in the evening hours. The other drivers, like wind or electric field, have a profound role in causing variability in this typical behaviour of $h'F$, other than the aforementioned variation due to the photochemistry. Over the dip equator, while the winds redistribute the ionization through horizontal transport, the electric field induces changes through vertical motion of ionization. During the evening hours, the $h'F$ may also show a sudden increase in height associated with the phenomenon of Pre-Reversal-Enhancement (PRE). On the other hand, the MPT shows considerable variability during the day, as it is controlled by many forcings like gravity waves, tides and planetary waves, and OH layer movement in addition to the chemistry and other transport processes, which are interdependent. Since a very good correlation ($r > 0.60$) exists in the monthly mean trends of these parameters, one can attribute these to the changes in the background variability which is not induced by the short period wave dynamics. At the same time, some of the MPT changes can be caused primarily by the OH layer movement. However, in the light of the above discussion, such modulations in MPT would lead to poor correlation with the variability in $h'F$. In this context, we conjecture that the vertical transport of the chemical species induced by the photochemistry at these altitudes is responsible for the observed coupling between the equatorial mesopause and F-region of the ionosphere.

It is known that during daytime the bottomside of the ionosphere (130–200 km) is "photochemically" governed, where photo dissociation of molecular oxygen in the Schumann-Runge continuum (135–175 nm) leads to the generation of atomic oxygen, which in turn leads to the formation of ionization. At the same time, the ionization loss processes are mainly controlled by the molecular Nitrogen through chemistry. As a result, the ratio [O]/[N_2] at any time is taken as a measure of the net ionization in the lower F-region (Forbes, 2007). Therefore, the modulations of the $h'F$, specifically during daytime, are taken to be the direct indicator of the ratio [O]/[N_2] in the bottomside ionosphere, since these measurements are actually the representative of the group retardation of the radio waves due to the presence of in situ generated ionization.

Since, the molecular diffusion coefficient grows rapidly with decreasing pressure and increasing temperature in thermosphere, its net effect in the lower thermosphere is always to increase the mixing ratio of [O]. As a consequence, in the lower thermosphere, there is always a significant downward diffusion of atomic oxygen (Smith, 2004). A part of this [O] diffuses into mesopause altitudes from its source region above. Near the mesopause, atomic oxygen has a mixing ratio that reaches 10^{-2}. The chemical lifetime for atomic oxygen increases with increasing altitude reaching 24 h near 85 km. As a result, below this altitude the [O] concentration has a strong diurnal variation, whereas above it, primarily the dynamics, rather than the chemistry, induces variability in the profile (Russell and Lowe, 2003). Recent results from SABER measurements showed that near the equator there exists a large diurnal variation of atomic oxygen at mesopause altitudes, ranging from a factor of 2 to more than a factor of 10 (Smith et al., 2010).

In this backdrop, it is suggested that during daytime the downward motion of [O] in the ionosphere reduces [O]/[N_2] ratio at F-region altitudes (i.e., net F-region bottomside ionization) which in turn manifests as a change (increase) in the ionosphere base height ($h'F$) as observed using the ground-based ionosonde. At the mesopause, this downward diffusion of [O] creates ozone maximum through three body recombination and subsequently increases the mesopause temperature through exothermic OH chemistry (Mlynczak and Solomon, 1993). In this process, there would be a time delay involved between the $h'F$ changes and the MPT modulations. While such a mechanism is plausible and consistent with the time-delays in the lower F-region, we realize that the time constants associated with such a transport process between the bottomside F-region and mesopause in terms of molecular diffusion would be very large and is of the order of hours to days (Garcia and Soloman, 1985). However, one factor which can help in the fast transport of [O] to the mesopause is the location of the turbopause. Below the turbopause altitude, which is typically around ∼90–120 km (Danilov and Kalgin, 1996; Offermann et al., 2007), the time scales of molecular diffusion are very large as mentioned above (Garcia and Soloman, 1985). Nevertheless, the eddy diffusion of the air parcels, of which vertical scale sizes are large, can create thorough mixing of species like atomic oxygen down to the mesopause. Apart from these, it must be kept in mind that the $h'F$ measurements described here correspond to the virtual height. The real heights will correspond to about 20–30 km lower than the virtual heights.

In view of the above, we believe that the downward transport of [O] from bottomside F-region to the turbopause is facilitated through the molecular diffusion and below eddy diffusion. Such a scenario can only create perturbations in MPT within the limits of the time delays observed here. Though the importance of eddy diffusion at lower thermosphere altitudes (90–130 km) had been reiterated in literature, it is largely uncertain ($K \sim 45$–$90\,\mathrm{m^2\,s^{-1}}$) and important to compute it correctly (Rishbeth et al., 2009). In view of this uncertainty in the eddy diffusion coefficient (K), the eddy diffusion time scale which is $\sim H^2/K$, H being the scale height, can vary from 1 day to a few hours. Eddy diffusion plays a large part in controlling the neutral gas composition – in particular the [O]/[N_2] ratio – by influencing the vertical motions (upwelling and down welling) of the neutral air. Increasing the eddy diffusion coefficient causes more [O] to be transported downward and more N_2 upward, thereby decreasing the ratio of [O] to [N_2] (Rishbeth et al., 2009). The transport processes induced by these turbulent motions produce fluxes of minor atmospheric constituents, heat and momentum and influence the atmospheric properties at and above these altitudes (Danilov and Kalgin, 1996). Recently, Kelley et al. (2009) proposed a two-dimension turbulence mechanism to explain the transport of energy to large scales in the lower thermosphere. They suggested that the molecular diffusion is too slow to account for the spreading of plumes as observed by them and concluded that the diffusion is inadequate because they neglected faster vertical flow that allows H atoms to spread out rapidly at higher altitudes where the atmosphere is thinner. In fact, the observations by Meier et al. (2010) reveal that atomic hydrogen, and by inference water vapour can transport over hemispherical-scale distances with speeds much faster than expected from models of thermospheric wind motions. In addition to this, processes such as heating of the upper mesosphere/lower thermosphere as well as upwelling can carry N_2-rich air to higher altitudes. This can also modulate the diffusive equilibrium state of the thermosphere, thereby influencing the [O]/[N_2] ratio especially in the lower ionosphere (Forbes, 2007).

Furthermore, we understand that the height variation of turbopause as well as the upward dynamical forcing like waves and tides would have a profound role in altering time scales of downward molecular diffusion/eddy mixing. The upward propagating waves and tides which have large vertical and horizontal velocity lead to advective transport of [O], thereby making its downward diffusion a slower process. It has also been shown that tidal impact is large at low latitudes and varies day to day, where the vertical velocity due to the diurnal tide is largest, though it also depends on the time of year (Deepa et al., 2006). During the month of March, the impact of tides is found to be significantly smaller than the impact of diffusion, where as calculations for April indicated a greater role of tides (Smith et al., 2003). It must be noted here that present observations also showed negative time delay (MPT precede $h'F$) during April 2006. It is due to this day-to-day variability in the lower atmospheric forcing like the tides and waves, and their competing roles in influencing the transport of [O], that the observed time-delays are found to be different for different months.

In this context, the trend of MPT preceding the trend for $h'F$ for the month of April 2006 could be due to the dominance of upward propagating tides/waves over the downward diffusion of [O] through molecular diffusion and eddy mixing. Larger vertical velocity can slow down the downward diffusion and even lead to accumulation of [O] at higher altitudes. In our view, in such a scenario the MPT may precede the changes in $h'F$ that could be the reason for the negative time delay observed during April 2006. However, it can't be said unambiguously.

At this juncture, it must be mentioned that the interplay between the diffusion and the dynamical processes still remains an aspect needing better clarity, and our proposition here is only qualitative at present. However, the observations presented are new and unique, and in our view, as discussed above, have significant implications in the present understanding of the equatorial Mesosphere-Ionosphere-Thermosphere system.

5 Conclusion

The present study reveals, for the "first time", that there exists a common cause influencing the $h'F$ and the mesopause temperature variability during daytime, at least for geomagnetically quiet days. The overall correlation between MPT and $h'F$ variations clearly reveals a strong coupling between the mesopause and bottom side F-region through [O]. The downward transport of atomic oxygen from thermosphere to mesopause through molecular diffusion and subsequent eddy mixing is proposed to be the plausible mechanism for the increase in both $h'F$ and MPT through chemistry and subsequent dynamics. The observed time delay is attributed to the time taken in the downward transport of atomic oxygen from the thermosphere to turbopause and thereafter to the mesopause through eddy mixing causing the exothermic chemical heating therein. The negative time delay observed during April 2006 is conjectured to be due to enhanced tidal/wave activity, which needs further investigation. Nonetheless, these observations are new and have significant implications in the understanding of the vertical coupling in the equatorial atmosphere-ionosphere system.

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