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Signature of midnight temperature maximum (MTM) using OI 630 nm airglow

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An anomalous behaviour of F-region neutral temperature at night, sometimes exceeding the maximum afternoon values has been recorded at equatorial latitudes. This feature is referred to as Midnight Temperature Maximum (MTM)[1]. The winds generated due to pressure bulge phenomena at the equator propagate polewards (northward) and its vertical component while propagating moves the F-region plasma downwards to a region of enhanced loss and airglow production. The optical signature of MTM phenomena (brightness wave) has been recorded at Kolhapur (16.8 °N, 74.2 °E; dip lat. 10.6 °N) in India using OI 630 nm night airglow during December 2002 to April 2003 showing peaks in intensity around 0200–0400 hrs LT. The structures were prominent for about two to three hours. The digital ionosonde data of Trivandrum (8.5 °N, 77.0 °E, dip ~ 0.6 °S), Sriharikota (13.7 °N, 80.2 °E; dip ~ 10.5 °N) and Visakhapatnam (17.67 °N, 83.32 °E; dip ~ 20 °N) stations show the descent of the F-layer at all the low latitude stations during MTM disturbance. The meridional winds estimated from *h*'F data of Trivandrum and Sriharikota showed generation of poleward winds and time delay of about one-and-a-half hours was observed between the observed time of the descent of the layer (*h*'F) at Sriharikota and the time of observations of the signature of MTM phenomena at Kolhapur.

Keywords: Meridional wind, Midnight temperature maximum, 630 nm airglow, Ionosphere collapse

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1 Introduction

A combination of *in-situ* satellite measurements and ground-based experiments in the last three decades has revealed an important feature of the equatorial ionosphere known as MTM phenomena[1,2], a region of anomalous temperature and density that is generally considered to be associated with atmospheric tidal interactions. This influences very strongly the neutral thermospheric dynamics and the neutral plasma. The first earth-based observations of an optical manifestation of the MTM phenomena were reported by Greenspan[3]. Using a photometer, regular occurrences of an enhancement in the OI 630 nm intensity near local midnight at equatorial latitudes were observed by Greenspan while traveling from North to South America by a US Naval ship. This was supported further by Nelson and Cogger[4] at Arecibo (18 °N) with a downward descent of the ionosphere by 50-100 km, which was called midnight collapse. They concluded that the F-region 6300 Å enhancement observed at Arecibo (18 °N) was due to decrease in F-region around midnight and found the descent occurred at later times with increasing geomagnetic latitude.

The descent was interpreted in terms of meridional wind variation using supporting data of incoherent scatter radar at Arecibo. The characteristics of MTM (such as shape, amplitude and the time of occurrence and the propagation) are highly variable. These events are prominent at the low latitude stations during the months of March and April around local midnight[5]. Using Atmosphere Explorer satellite data, Herrero and Spencer[6] generated temperature maps between latitudes 19.8 °S and 19.8 °N in the altitude range 250-370 km, which showed that the MTM phenomena occurred first at the geographic equator and had local time maximum in both Summer and Winter hemisphere.

While the MTM's generation mechanisms are not well understood, it is thought to be the result of the interaction between upward propagating tides from the lower atmosphere with those produced *in situ* in the thermosphere.[7] Using the routine all-sky imaging observations of 6300 Å airglow emissions at Arequipa, Peru (16.2 °S, 71.35 °W) from October 1993 to October 2000, Colerico *et al.*[8] reported on the persistent occurrence of an enhanced 6300 Å emission feature with an apparent north-south propagation through the field of view of the imager near local midnight. The authors referred to this feature as the midnight brightness wave (MBW). They concluded that the MBW was the airglow signature of the MTM phenomena as a result of the compressional heating of the thermosphere. A study of these effects was also carried out from the Arequipa Fabry-Perot measurements for the period 1996-2002. With the inclusion of 6300 Å all-sky observations from Tucuman (26.5 °S, 65.15 °W) and El Leoncito (31.8 °S, 69.0 °W), Argentina, Colerico and Mendillo[9] reported on the MBW's propagation through 39 °S in the American sector, suggesting that the MTM's influence on the upper atmosphere may extend to mid-latitudes.

The radar observations at Jicamarca (11.95 °S, 76.87 °W) show that the MTM assumes amplitudes in the range 40-200 K and occurs, on an average, about one hour after midnight in the local winter.[10] The time of the temperature enhancement over Kavalur, India on 18/19 and 23/24 Dec. 1992 was found to be consistent[11] with the MTM observation at Jicamarca, but the amplitude (280 K and 450 K), they found was much higher. The current knowledge of the global characteristics of MTM phenomena and the amount of investigation done is very much limited from Indian low latitude region.

The observations reported here were carried out using tilting-filter photometer at low latitude station, Kolhapur, in India to study the movement of MBWs caused due to MTM-induced winds propagating from equator to poles. Here, the preliminary results of the enhancement of OI 630 nm emission due to the signature of MTM have been presented. These results were complemented with digital ionosonde data from low latitude stations, Trivandrum, Sriharikota and Visakhapatnam showing abrupt change in the height of the F-layer coinciding with the present observations of MTM on most of the nights. The study provides a useful diagnostic of the night-to-night variation (both in night airglow and F-layer) of the MTM pattern itself and its source via tidal mode interactions.

2 Theory of tropical emission of OI 630 nm

The spectral line at OI 630 nm is indicative of the dissociative recombination involving O_2 molecules and electrons near 300 km altitude. The nighttime OI 630 nm emission originates mostly from the bottom side of the F-region in low- and mid-latitudes by the dissociative recombination process given by[12]

$$O_2^+ + e \rightarrow O + O^*(^1S, ^1D)$$
$$O^*(^1D) \rightarrow O + h\nu\ (630\ \text{nm})$$

The rate of this reaction is nearly proportional to the rate of recombination in the F2 layer.[13] The O_2^+ is produced from the charge transfer of O^+ with O_2 and the observed OI 630 nm emission is the column integral [$\int n(O^+)\, n(O_2)\, ds$] of the product of O^+ and O_2 concentration. Hence, any descent of plasma will promote higher recombination and corresponding enhanced airglow production.

3 Experimental set-up

The observations were made using a tilting-filter photometer[14] having one-degree field of view (overall) giving a cross-section of 5 km in the F-region height (250 km) looking at zenith. The interference filter (Barr Associates, USA) when kept at a temperature of 23 °C has a pass band centered at about 630 nm for normally incident light. The bandwidth of the filter is about 1 nm with 65 % transparency. The airglow intensity OI 630 nm emission is determined from the difference of the background with signal and background only.

4 OI 630 nm emission and F-layer during MTM

In this section we present the examples of the signature of midnight temperature maximum in OI 630 nm zenith photometer observations on clear moonless nights during the months of December 2002 and January-April 2003 at Kolhapur. We also use the ionosonde data of low latitude stations to study the movement of the F-layer at different latitudes and condition of the ionosphere during the period of observations. The local time variations of the OI 630 nm intensity are shown in Figs 1 and 2 in the upper panel. We also plot in the same figure the values of the ionospheric parameters (virtual height of the F-layer, $h'F$ (km) and square of the critical frequency of the F2 layer (f_oF2)) for the nearby station for the corresponding period on these nights. The square of the parameter (f_oF2) is proportional to the electron density at the peak of the F2 layer[15] and is given by $N_e(\text{max})\ \text{cm}^{-3} = 1.24 \times 10^{-4}\ [f_oF2\ (\text{MHz})]^2$. The figures also depict the complementary magnetic activity indices (Dst and Kp) for the corresponding nights. The enhancement of OI 630 nm emission with the corresponding lowering of the height of the F-layer as seen in their $h'F$ values are depicted in the figures on all the nights within the two vertical lines

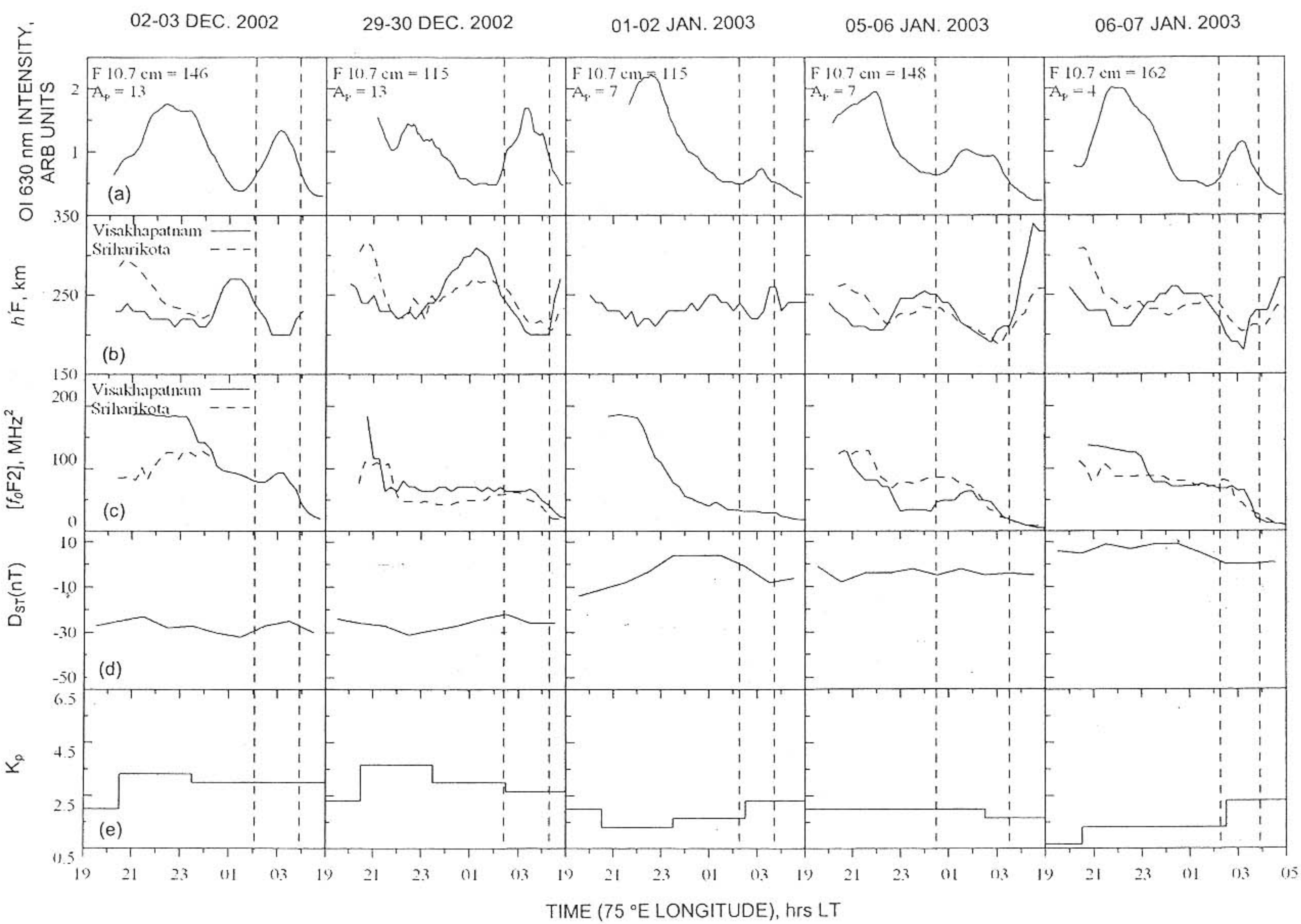

Fig. 1—Temporal variation of (b) *h*'F values at 15 min interval at Visakhapatnam and Sriharikota, (c) Temporal variation of $(f_oF2)^2$ values at 15 min interval at Visakhapatnam and Sriharikota, (d) *D*st and (e) *K*p values on the night of 2/3 and 29/30 Dec. 2004 and 1/2, 5/6, 6/7 Jan. 2003. The topmost panel (a) depicts the temporal variation of OI 630 nm intensity at Kolhapur on the above nights

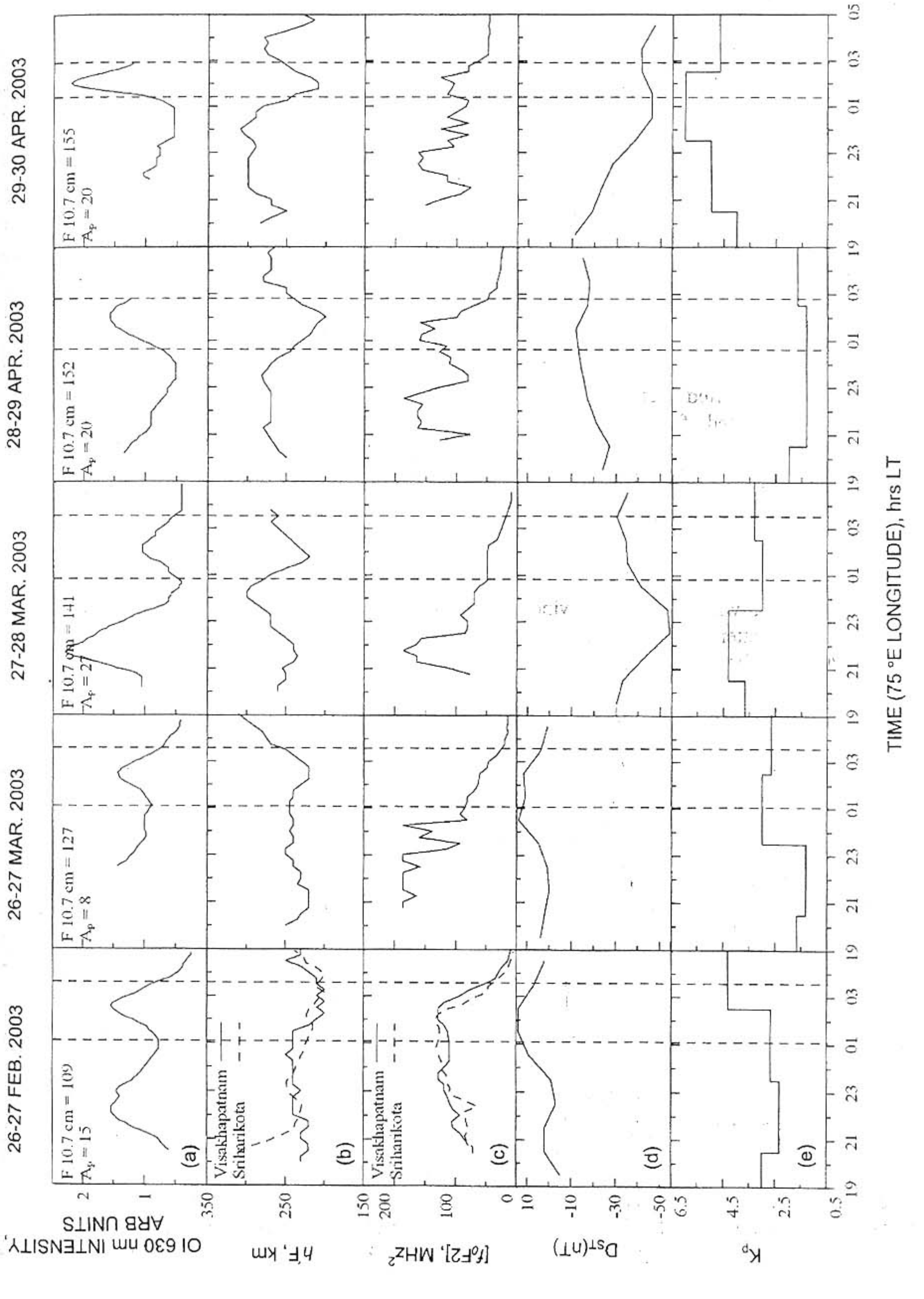

Fig. 2—Same as Fig.1 but for the nights of 26/27 Feb., 26/27 Mar., 27/28 Mar., 28/29 Apr. 29/30 April 2003

between 0100 and 0400 hrs LT. The enhancement of electron density at Visakhapatnam and Sriharikota was observed in five out of ten nights (Figs 1 and 2) during MTM events.

5 Meridional wind derived from ionosonde data

We have derived the nocturnal variation of meridional winds for the night of 29 Dec. 2003, using h'F data of Trivandrum and Sriharikota following the procedure given by Krishnamurthy *et al.*[16]. The basic assumption is that the F-region vertical drift at Trivandrum very close to the equator is affected solely by electric fields, while that at Sriharikota is controlled by electric fields, meridional winds and plasma diffusion. The method was validated by Sekar and Sridharan[17] and they reported that the ground based ionograms can be used for deriving the meridional winds during nighttime in the Indian longitude region. Miller *et al.*[18] also described a method for deriving the component of the neutral wind along a magnetic meridian from existing ground-based measurements of the height of the F2 layer at Arecibo. Good agreement was reached when the results were compared with meridional winds derived from incoherent-scatter radar measurements and measured directly by Fabry-Perot interferometer. In this report, the meridional wind component was calculated at 15-min intervals from the time derivatives of h'F at the two stations taking into account chemical loss and plasma diffusion effects.

Magnetic activity index Ap and solar F10.7-cm flux values are also shown in Fig. 3. In Fig. 3, we present the signature of enhancement of OI 630 nm airglow around 0200-0400 hrs LT due to MTM on the night of 29-30 Dec. 2002 at Kolhapur along with the height of the bottom side F-region (h'F) and its time rate of variation at stations Trivandrum and Sriharikota. Prominent changes in F-region height is seen at the stations Trivandrum (Fig. 3(e)) and Sriharikota (Fig 3(d)), though the decrease is more at the stations situated away from the equator. The off-equatorial stations are more influenced by the poleward winds and at Trivandrum station, the pattern of wind is controlled by electric field and hence decrease in h'F is less compared to Sriharikota station. In Fig. 3(c) we also plot the meriodinal wind derived from the ionosonde data of Trivandrum and Sriharikota.

It is evident that the amplitude and direction of wind are both variable and fluctuating up to middle of the night. Thereafter the wind blows poleward,

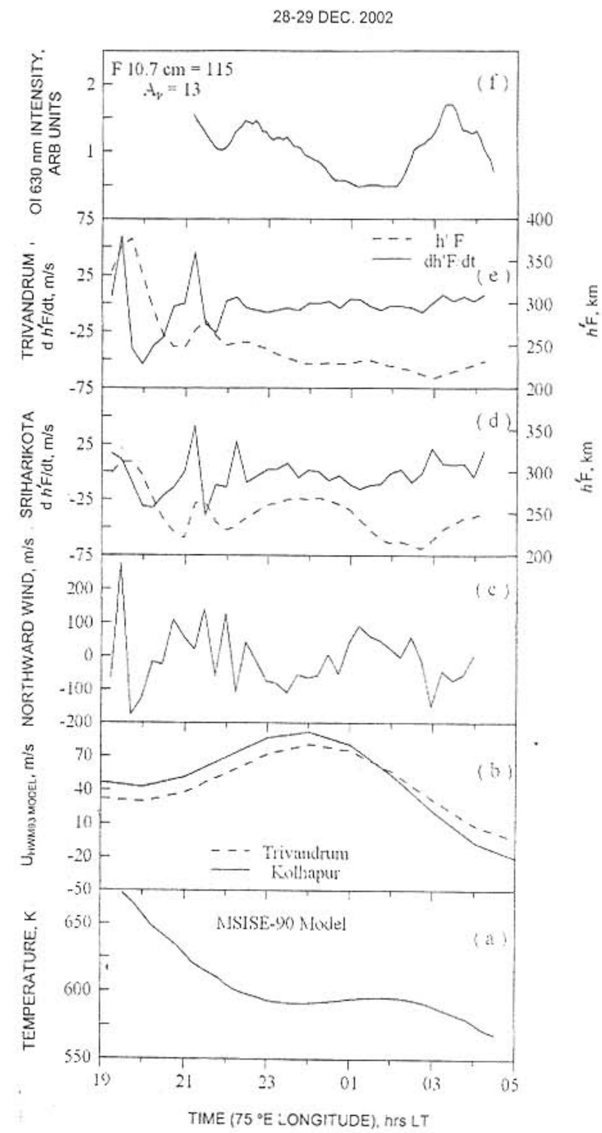

Fig. 3—Temporal variation of (e) h'F, d h'F/dt at Trivandrum (d) h'F, d h'F/dt at Sriharikota at 15 min interval (c) shows the variation of the meridional components of neutral winds derived from h'F data of Trivandrum and Sriharikota (b) variation of meridional components derived from HWM93 model at Trivandrum and Kolhapur on the night of 29/30 Dec. 2002. (a) temperature parameter computed from MSISE-90 model on the night of 29/30 Dec. 2002. The topmost panel (f) depicts the temporal variation of OI 630 nm intensity at Kolhapur on the same night.

reaching its maximum value around 0130 hrs LT. Figure 3(b) shows the variation of meridional component of wind velocity derived from HWM93 model[19] at Kolhapur and Trivandrum with appropriate parameters. The computed wind values from the model vary between 40 and – 20 m/s during the period of MTM disturbance. In the absence of measurement of F-region temperature at the place of observation, we compute the temperature (Fig. 3(a)) derived from MSISE-90 model[20] for the night of 29-30 Dec. 2000 at Kolhapur and Trivandrum for appropriate input parameters. The MSISE-90 model describes the neutral temperature and densities in Earth's atmosphere from ground to thermospheric heights. The thermospheric temperature computed at 250 km altitude during the period is 575 K and the model does not show any enhancement in F-region temperature.

F-region takes a certain time to respond to an imposed neutral wind field and this time constant for the Kolhapur is found to be about one-and-a-half hours. This time delay is seen between the time of minimum height reached at Sriharikota and maximum airglow intensity observed at Kolhapur is about one-and-a-half hours and this time constant for Ahmedabad is found[21] to be about 2 h. In Fig. 4 we depict the OI 630 nm variation on the previous night of 28/29 Dec. 2002, when the signature of MTM is not observed in the night airglow variation. We also plot the ionosonde data (h'F) from Trivandrum and Sriharikota stations. Instead of decreasing, the F-layer at low latitude stations was found to be increasing in the time interval 0100-0400 hrs LT. Also, the computed northward wind velocities were subdued during the above interval.

6 Comparison with servo model

In order to find the response of the vertical displacement of F2 peak at different wind speeds, the numerical values of h_{max} have been evaluated for the given thermospheric and ionospheric conditions. According to servo model, the F-layer peak height, h_{max}, is determined by diffusion and prevailing chemistry in that region, and is dependent on magnetic latitude and neutral temperature. Rishbeth and Edwards[22] provided the servo model to compute the meridional component of neutral wind velocity by the following equation:

$$\Delta h_{max} = H_i \ln (W/4H_i \beta) \qquad \ldots (1)$$

where $W = U_m \sin I \cos I$, and U_m is the meridional component of wind velocity, I = inclination angle, H_i = ion scale height and β = loss coefficient.

The wind causes the vertical ion drift (positive upwards), given by

$$W = U_m \sin I \cos I$$

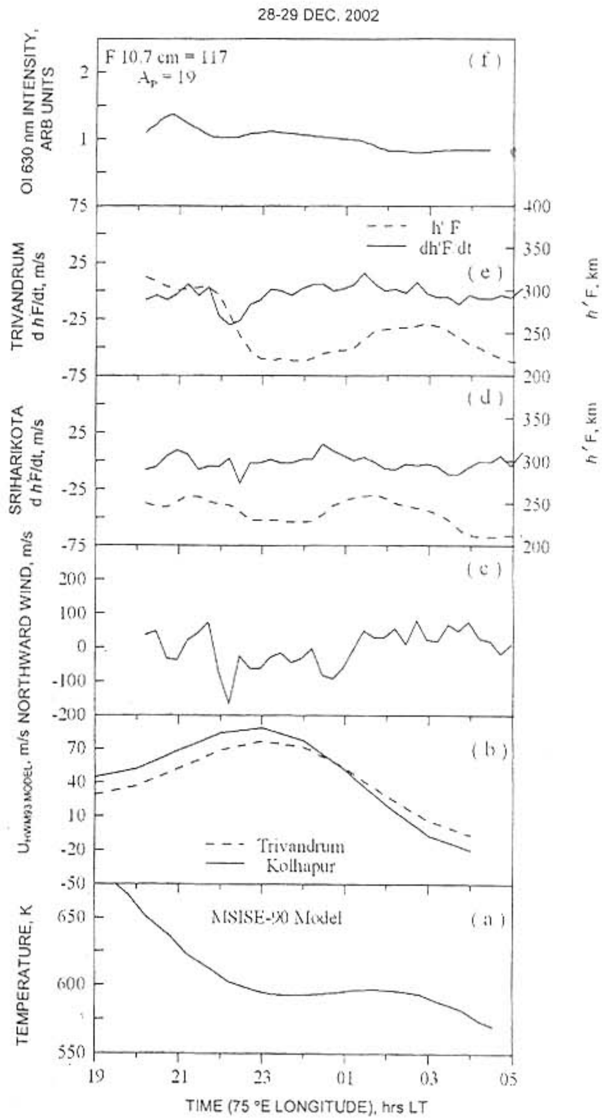

Fig. 4—Temporal variation of (e) h'F, d h'F/dt at Trivandrum (d) h'F, d h'F/dt at Sriharikota at 15 min interval (c) the variation of the meridional components of neutral winds derived from h'F data of Trivandrum and Sriharikota (b) variation of meridional components derived from HWM93 model at Trivandrum and Kolhapur (a) temperature parameter computed from MSISE-90 model on the night of 28/29 Dec. 2002. (f) The topmost panel depicts the temporal variation of OI 630 nm intensity at Kolhapur on the same night when MTM signature was not observed.

and the resulting shift in the height of the F2 peak, in the present case has been obtained from the observation at a station, Visakhapatnam situated at the same latitude as that of Kolhapur. To assess the effects of a meridional wind upon airglow production, the change in meridional wind velocity has been computed from the observed change in F-region height using Eq. (1). We have used the values of the change (Δh) in F-layer height at Visakhapatnam for the number of nights discussed in the report with appropriate parameters for Kolhapur (~ dip 20 °N). Since the response of the F-layer varies as $\sin^2 I$ (I being the dip angle), the model can be used to compute the meridional wind to locations with dip angles as low as 20°, below which it is not applicable[23]. The results are shown in Table 1. It is observed that the displacement (Δh) of the F-layer during MTM events is linearly proportional to the meridional component of the neutral wind.

7 Summary and conclusions

The simultaneous multi-station observations carried out at four low latitude stations in India with optical photometer and ionosonde techniques confirm the view that the pressure bulge pheomena associated with equatorial midnight temperature maximum (MTM) is responsible for the midnight poleward reversal of meridional winds which in turn leads to the post midnight collapse of the F-layer at low latitude locations situated almost on the same meridian.

The principal features of the present investigation are summarized below:

(a) The photometric data of OI 630 nm showed the enhancement in intensity around 0200-0400 hrs LT that may be due to signature of MTM. At the same time, the ionosonde data from Visakhapatnam, Sriharikota and Trivandrum showed decrease in height (h'F) of the F-region, which is known as the collapse of the F-layer. The decrease is more at Visakhapatnam station compared to other low latitude stations.

(b) The meridional component of wind velocity computed from Servo model at the station, Kolhapur during MTM events showed the values varying between 91 m/s and 201 m/s, which was more than the normally observed values at the low latitude regions[2]. This could be due to the effects of the observed neutral temperature, T_n, in altering the balance height, h_{max}, not included in the servo model calculation. The other uncertainties are the actual value of the ion-diffusion coefficient and the effects of the electric field in the determination of meridional winds from ionosonde data. It is reported that the F-layer height could vary by 11± 4 km for every 100 K change in T_n at low latitudes[24]. However, the meridional winds computed from the HWM model and the ionosonde data are smaller in comparison.

Table 1—Relationship between the observed change in height of the F-layer and the meridional wind using Servo model

Date	Δh (km)	Meridional wind U_m (m/s) (Servo model)
02-03 Dec. 2002	37.5	130
29-30 Dec. 2002	43.7	147
01-02 Jan. 2003	19.7	91
05-06 Jan. 2003	59.4	201
06-07 Jan. 2003	37.5	130
26-27 Feb. 2003	40.6	138
26-27 Mar. 2003	25.0	101
27-28 Mar. 2003	57.2	192
28-29 Apr. 2003	42.7	144
29-30 Apr. 2003	33.3	120

The meridional winds calculated from the time derivatives of h'F at the two stations, Trivandrum and Sriharikota on the night of 29-30 Dec. 2002 show short-term variations in the direction and amplitude of wind in the pre-midnight period before turning in to poleward direction at 0100 hrs LT and remained in that direction till 0230 hrs LT.

(c) We find the time delay of one-and-a-half hours between the minimum F-region height reached at Sriharikota and the time of maximum OI 630 nm intensity at Kolhapur as the representative of the response time of the F-region to the northward wind generated by MTM.

The off-equatorial station, Visakhapatnam shows a rapid descent in the F-layer and the enhancement of the electron density on number of nights during the MTM phenomena. Also, the poleward reversal of the meridional winds has been derived from equatorial ionosonde data. Hence, it may be concluded that the observed poleward (northward) wind enhancement probably caused by the MTM, pushed down the plasma in the F2 layer, subsequently resulting in enhancement of night airglow at off-equatorial station, Kolhapur.

$$\Delta U_m \rightarrow \Delta h_m \rightarrow \Delta I_{630\ nm}$$

The simultaneous measurement of the F-region temperature at night at equatorial region might have confirmed the present cause and effect relationship. Temperature parameter computed from MSISE-90 model does not show any enhancement during the period of MTM observation.

Based on FPI observations, Rao and Sastri[5] found clear evidence of enhancement in the night time temperature (MTM) on 19 nights during March-April 1992 at a low latitude station, Kavalur (12.5 °N, dip ~ 9.5 °N). Niranjan *et al.*[25] related MTM phenomena with the spread-F occurrences and showed that the seasonal variation and the probable onset times of the post midnight spread-F at a low latitude station, Waltair (17.7 °N, 83.3 °E) depend on the characteristics of the highly variable semi-permanent equatorial MTM. Using all-sky imaging observations of OI 630 nm at Kolhapur, Mukherjee[26] showed examples of the sudden enhancement in brightness that first appeared at the magnetic equatorial region in east-west direction and moved towards the north with a phase velocity 248 and 150 m/s. The structures were prominent for 2-3 h period during the post midnight period in March and April 1999. The day-to-day variability in the enhancement of temperature, meridional winds and OI 630 nm emission may be due to variability in the upward propagating semi-diurnal tides[7]. The semi-diurnal modal mix impinging on the lower thermosphere may vary on a day-to-day basis, depending on the background mean temperature and winds.

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