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The current state of investigations regarding the thermospheric midnight temperature maximum (MTM)

M.J. Colerico[a,*], M. Mendillo[b]

[a]Center for Space Physics, Boston University, 725 Commonwealth Avenue rm 506, Boston, MA 02215, USA
[b]Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA

Abstract

The thermospheric midnight temperature maximum (MTM) is an upper atmospheric effect found at low latitudes. It is accompanied by an increase in pressure and a signature poleward abatement or reversal in the meridional neutral winds. The MTM exhibits a poleward propagation away from the geographic equator with two secondary maxima developing at approximately $\pm 15^\circ$ latitude. In this paper, we review early works and recent efforts regarding the MTM. Outstanding questions dealing with seasonal and longitudinal dependencies of the MTM's basic characteristics are discussed. All-sky imaging systems at Arequipa and El Leoncito observed the propagation of 6300 Å airglow enhancements related to the MTM past 35°S latitude. This provides useful information on the upper latitude limit of the MTM. TIEGCM modeling efforts simulate the MTM through upward propagating semi-diurnal tides but have difficulty reproducing accurately its amplitude and occurrence time. It is suggested that the role of the terdiurnal tidal mode may be more important than previously thought. Recent comparative observation and modeling studies of MTM related 6300 Å emission proved unsuccessful. We report that the amplitude of the modeled MTM was not strong enough to instigate the 'midnight collapse' of the F-region needed to produce the airglow signature. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Midnight temperature maximum; Low-latitude ionospheric dynamics; Low-latitude thermospheric dynamics; Low-latitude midnight collapse

1. Introduction

Thermospheric dynamics consist of closely linked interactions between several upper atmospheric processes and parameters: neutral winds, tides, temperature, pressure, neutral density and F-region plasma. Modification of any one of these can effect the others. The MTM is a highly variable, large scale neutral temperature anomaly with wide spread influence on the nighttime behavior of the low-latitude thermosphere. This phenomenon and its signature in several ionospheric and thermospheric parameters have enjoyed a rich history in the literature, having been studied extensively by many groups using photometers, radars, satellites, Fabry–Perot Interferometers (FPI) and all-sky camera systems (Herrero et al., 1993). Even though much has been learned about the MTM's characteristics, its generation mechanism is not well understood. Modeling efforts to date have been only partially successful in reproducing the MTM's amplitude and occurrence pattern. In this paper, we will briefly visit these early observations before discussing recent findings and ongoing investigations regarding this important thermospheric phenomenon.

2. Observations

2.1. Early observations

Perhaps the first detection of an MTM related effect came through photometer measurements of 6300 Å emission enhancements from aboard the U.S.N.S. Croatan while traveling down the Pacific coast of South America (Greenspan, 1966). These airglow enhancements occurred near local

* Corresponding author. Tel.: +1-617-353-5611.
E-mail address: colerico@bu.edu (M.J. Colerico).

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midnight in the sampled geographic latitude range of 15°N–15°S. Without any additional correlated F-region parameter measurements, these enhancements were not linked to either a decent of the F-layer due to meridional neutral wind variations or an increase in neutral temperature. Nelson and Cogger (1971) used the Arecibo incoherent scatter radar (ISR) (18.3°N, 66.75°W) to report on the 'midnight descent' or 'collapse' of the F-layer correlated with an enhancement in 6300 Å airglow emission. Subsequently, Behnke and Harper (1973) attributed this midnight decent of the F-layer to a reversal of the meridional neutral wind from equatorward to poleward. This modification in the winds to a poleward direction serves to move plasma down magnetic field lines to altitudes where it can dissociatively recombine through the chemical reactions

$$O_2 + O^+ \rightarrow O_2^+ + O \quad (1)$$

and

$$O_2^+ + e^- \rightarrow O + O + h\nu \quad (2)$$

in order to produce 6300 Å airglow emission from the $O^*(^1D)$ state.

The first in situ measurements of the MTM were made by the neutral atmosphere temperature instrument (NATE) on board the Atmosphere Explorer-E (AE-E) satellite. The simultaneous neutral wind and temperature measurements made by NATE provided significant insights into the development and character of this phenomenon. NATE data analyzed by Spencer et al. (1979) revealed a recurrent enhancement in the neutral temperature accompanied by a poleward surge in the meridional neutral winds near local midnight. Occasionally, this nighttime increase in temperature exceeded its afternoon maximum value. Mayr et al. (1979) suggested that the MTM was the result of

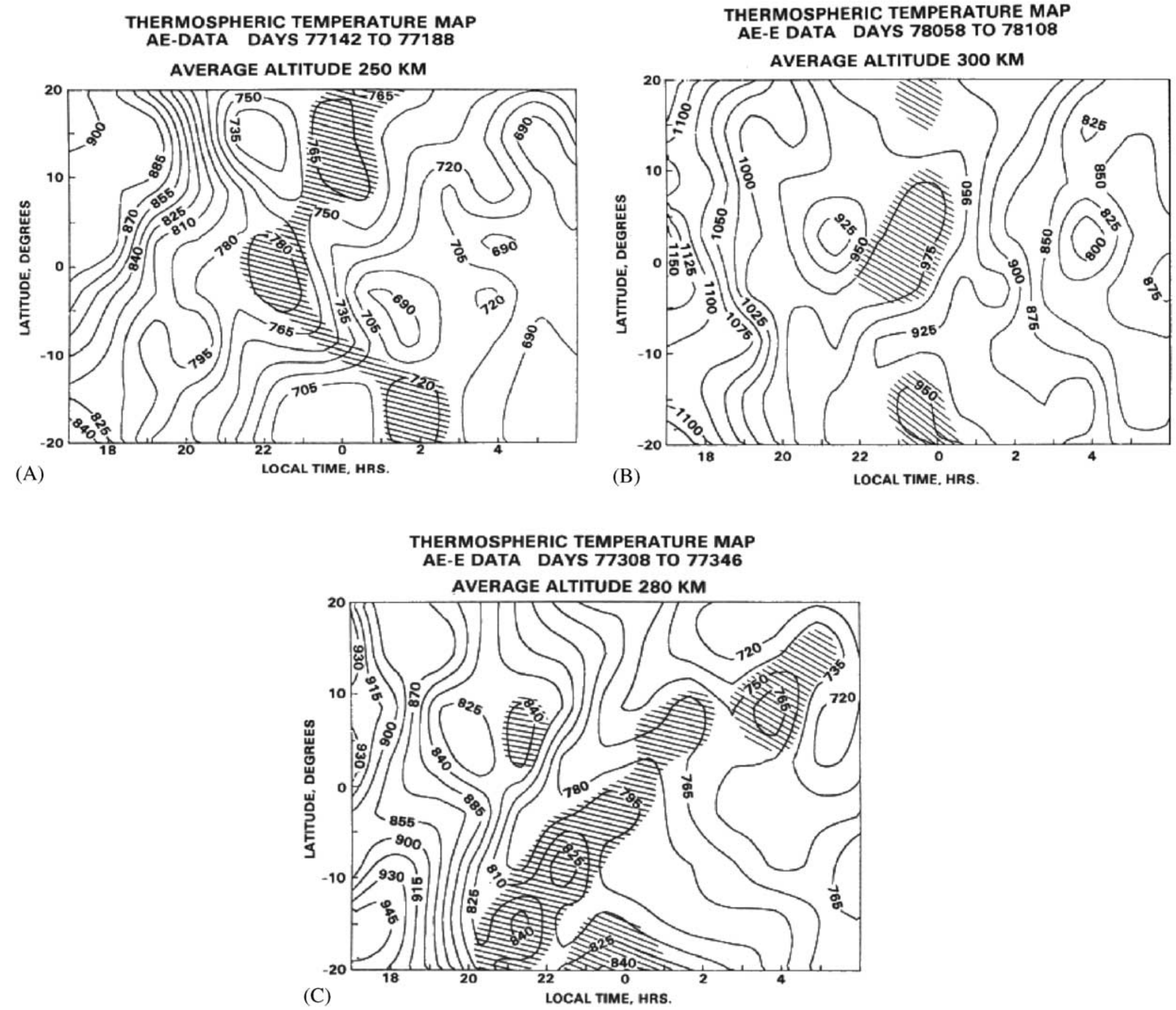

Fig. 1. NATE thermospheric temperature maps taken from Herrero and Spencer (1982). (A) Northern hemisphere summer. (B) Equinox. (C) Northern hemisphere winter. Contours give thermospheric temperature in K. Shaded area highlights the midnight temperature maxima.

interactions between upward propagating tides in the lower atmosphere produced by solar heating and semi-diurnal tides formed through ion-neutral momentum coupling in the thermosphere. This mechanism transports energy to the nightside where a local temperature maximum can form. This temperature enhancement is accompanied by a pressure increase which may modify the meridional neutral winds, altering its direction from equatorward to a poleward. The semi-diurnal component of lower atmospheric tides plays a dominant role in the formation of the MTM. Nevertheless, other tidal modes need to be examined. For example, Fourier analysis of NATE data by Mayr et al. (1979) showed that the observed temperature variations could be basically described with the first three tidal modes and accurately with the inclusion of up to the fifth. This suggests that these higher order tidal modes may play a small but significant role in development of the MTM.

Herrero and Spencer (1982) characterized the seasonal dependence and latitude distribution of the MTM using two-dimensional maps of averaged NATE neutral temperature data over a geographic latitude range of ±20°. Fig. 1 displays a set of these maps for northern hemisphere summer, equinox and northern hemisphere winter, respectively. They observed that, in general, the MTM initially forms at the geographic equator and propagates poleward. Two additional temperature maxima develop at approximately ±15° latitude with the summer hemisphere maximum occurring earlier with a larger amplitude. During equinox they are symmetric about the equator. Herrero et al. (1983) explained that the MTM's seasonal dependence was due to seasonal variations in the semidiurnal and terdiurnal components of the lower atmospheric tides. In the summer hemisphere, both tidal components are present and approximately equal in magnitude. These two modes reinforce each other and produce a strong MTM feature. In winter, the terdiurnal component is negligible. The weaker MTM in this hemisphere is mainly due to the dominant semidiurnal component.

Ground-based remote sensing of the MTM's signature in ISR temperature measurements and 6300 Å airglow has played a significant role in characterizing its behavioral patterns and day to day variabilities near 70°W in the American Sector. Fig. 2 shows the location of ISRs and optical instrumentation used in these investigations. Bamgboye and McClure (1982) used the Jicamarca Radar in Peru (12°S, 77°W, 1°N diplat) to examine the seasonal dependence of the MTM through electron and ion temperature measurements. Their results were consistent with the Herrero and Spencer (1982) findings.

Sobral et al. (1978) and Herrero and Meriwether (1980) used photometers to study 6300 Å airglow enhancements propagating from southeast to northwest over Arecibo near local midnight. These observed features were due to the meridional wind pattern associated with the passage of an MTM. Sobral et al. (1978) reported that these airglow enhancements passed over Arecibo within a 2–3 h span with

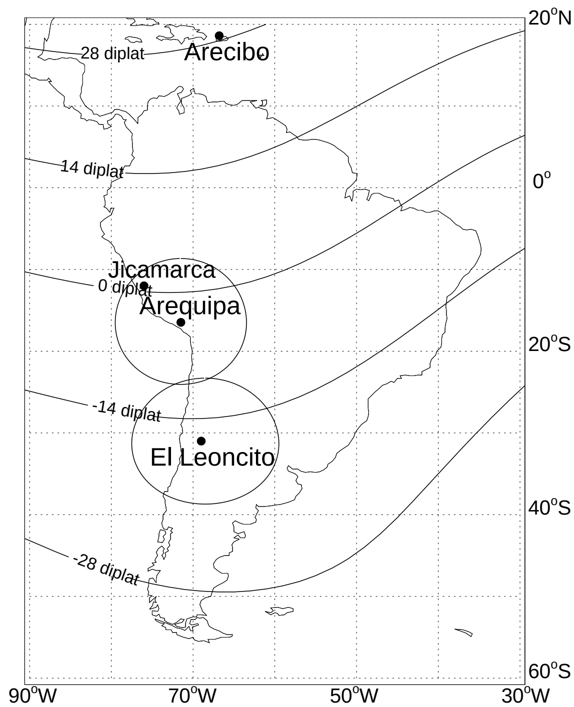

Fig. 2. The field of view of the Arequipa and El Leoncito all-sky imaging systems, as well as the Jicamarca and Arecibo radar sites. Notice the position of the magnetic equator north of Arequipa.

an average apparent phase velocity of 300 m/s. The propagation direction illustrates the movement of the MTM and its pressure bulge away from the equator. These results give rise to questions regarding the spatial extent of its poleward propagation track. The geographic latitude coverage of the Sobral et al. (1978) study ranged between 14°N and 24°N with the airglow enhancement observed exiting to the northwest. This indicates that the MTM and its effects extend past 24°N but supplies no information as to its upper limit. Therefore, it is conceivable that there may be mid-latitude consequences to this low-latitude phenomena. No 6300 Å airglow enhancements related to the MTM have been seen in all-sky imaging observations made at Millstone Hill (42°N). Extending the latitude range of MTM observations is necessary to define the latitude range.

2.2. Recent observations

Colerico et al. (1996) made the first two-dimensional ground based observations of the MTM through the 6300 Å airglow emission using an all-sky camera system installed at Arequipa, Peru (16.2°S, 71.35°W). The location of the imaging system and its field of view is shown in Fig. 2. They reported on a recurring enhanced 6300 Å airglow feature with an apparent northeast to southwest propagation through the imager's field of view near local midnight. These

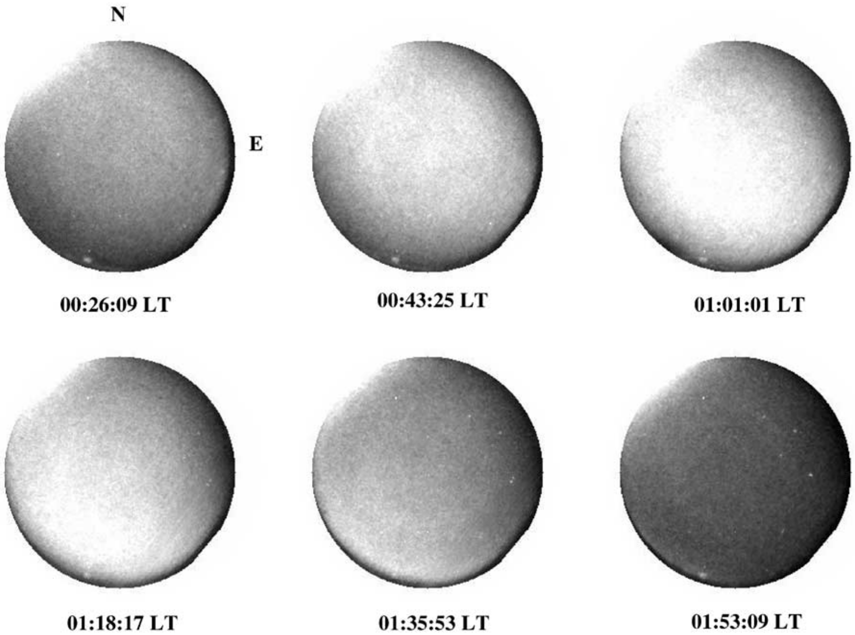

Fig. 3. A sequence of six images taken with the all-sky camera at Arequipa, Peru, on October 1, 1994, which illustrates an MBW event in the 6300 Å wavelength. Note that the stationary bright region at the northwest edge of the field of view is due to Arequipa city lights.

enhancements, though observed in all seasons, predominantly occurred during equinox months. The authors referred to this feature as the midnight brightness wave (MBW). Fig. 3 shows a sequence of six images taken by the Arequipa imager on October 1, 1994, which illustrates a typical example of an MBW occurrence. The MBW enters at 00:26:09 LT and exits at 01:35:53 LT. On average, these MBW events passed overhead within in a 2 h time window having a phase velocity between 200 and 400 m/s consistent with the earlier Sobral et al. (1978) findings. An FPI, collocated with the imaging system, provided simultaneous neutral winds and temperature measurements which revealed a strong correlation between the passage of an MBW event with neutral temperature enhancements between 100 and 200 K and poleward reversals/abatements in the meridional neutral wind. The authors concluded that the MBW was the result of a meridional wind induced 'midnight collapse' of the F-region associated with the MTM. This makes the MBW a useful proxy for two-dimensional MTM studies in the southern hemisphere.

In Fig. 3, the MBW does not enter from northeast edge of the field of view but brightens just north of zenith before it begins its apparent southwest propagation. This is due to the presence of the magnetic equator in the northern portion of the images as is shown in Fig. 2. At the equator, horizontal field lines prevent any downward motion of the F-layer due to neutral winds. The MBW's absence at the equator supports the theory that neutral winds play the dominant role in these events rather than electric fields. The MBW's exit to the southwest suggests that the MTM propagates past 26°S geographic latitude. An additional imaging system, recently installed south of Arequipa at El Leoncito (see Fig. 2), extended the latitude range of MBW observations in the southern hemisphere to 39°. Colerico et al. (2002) observed MBW events passing through the field of view of El Leoncito thus stretching the known upper latitude limit of the MTM's influence in the southern hemisphere.

Although Millstone Hill (42.6°N, 71.5°W) and El Leoncito (31.8°S, 69.0°W) have similar geographic longitudes, the MBW extends to higher latitudes in the southern hemisphere. This discrepancy in latitude extent may be due in part to differences in magnetic inclination angle (I) resulting from the offset of the magnetic and geographic equators. For these two stations, the magnetic equator is located approximately 12° south of the geographic equator. The inclination angle plays an important role in the meridional wind's effectiveness in moving plasma down field lines to lower altitudes where recombination occurs. The vertical plasma velocity is given by

$$V_{\text{plasma, vertical}} = U \sin(I)\cos(I) \quad (3)$$

with U being the horizontal neutral wind. At the southern edge of El Leoncito's field of view (39°S latitude) the inclination angle is 46° which yields a maximum value for $\sin(I)\cos(I)$ equal to 0.5. In this case, the poleward meridional winds can effectively transport plasma down field lines. In the northern hemisphere at Millstone Hill's latitude, 42°N, the inclination angle is 70° and $\sin(I)\cos(I)$

has a value of 0.32. The meridional wind is less effective in the vertical transport of plasma than at El Leoncito. Another interesting consideration for the northern hemisphere is the MTM's collocation with the Appleton Anomaly ionization crest. Ion-drag induced reduction in the meridional winds may result from the enhanced ionization. The combination of a smaller $\sin(I)\cos(I)$ term and reduced neutral winds may not provide sufficient downward motion of plasma necessary for producing the MBW at higher latitudes in the northern hemisphere. This suggests an interesting magnetic field dependence of the MTM's influence on upper atmospheric parameters which warrants future investigation.

Colerico et al. (1996) also reported on an additional enhanced airglow signature, referred to as the pre-midnight brightness wave (PMBW), which generally occurs between 20:00 and 21:00 LT. Its propagation direction is opposite that of the MBW passing from southwest to northeast through the field of view in a 1–2 h time span. Though not as frequent as MBW events, it is a regular feature in the Arequipa imaging data often occurring with, but not exclusively accompanied by, an MBW event. These PMBW events were often correlated with neutral wind and temperature effects similar to those found during the passage of an MTM. However, it is not clear whether these two airglow features are related. Colerico et al. (2002) addresses this question in detail.

The majority of ground based studies of the MTM phenomenon have been conducted in a limited longitude range in the American sector between 66 and 77°W. Measurements at other longitudes are needed to investigate possible longitude dependencies in the MTM's characteristics. Work done by Batista et al. (1997) investigated the effect of the MTM on neutral winds at Cachoeira Paulista (23°S, 45°W) using meridional winds derived from ionosonde measurements of h_{max}. The study found that during December solstice, normally equatorward neutral winds reversed to a poleward direction for a few hours between 22:00 and 1:00 LT. Data for June solstice revealed an additional poleward surge in the already poleward winds from 1:00 to 3:00 LT. The authors ascribed these observed seasonal variations in the expected global thermospheric circulation patterns to the MTM. No MTM related effects on the neutral winds were observed during equinox conditions. This is in contrast with the findings of Colerico et al. (1996) near 70°W in the American sector and Hari and Krishna Murthy (1995) in the Indian sector. Both observed reversals in the meridional winds to a poleward direction at local midnight during equinox conditions. Differences such as these suggest possible longitude dependent variations in the MTM's characteristics such as shape, amplitude, seasonal variation, and occurrence time.

Indian sector studies conducted by Sastri and Rao (1994) and Sastri et al. (1994) found the relationship between the MTM, meridional winds, and F-layer decent to be the same as in the Peruvian sector. Sastri and Rao (1994) concentrated on observations made during March/April 1992. They compared FPI neutral temperature measurements from Kavalur (12.5°N, 79°E) and h_{max} ionosonde data from Ahmedabad (23°N, 72°E) to correlate midnight temperature enhancements with a downward motion of the F-layer. Sastri et al. (1994) examined FPI temperature measurements and meridional winds derived from ionosonde data to relate MTM occurrences to poleward wind reversals during 1992 December solstice. Rao and Sastri (1994) presented a description of the MTM's intrinsic characteristics in the Indian sector. They noted a two hour seasonal shift in the MTM occurrence time between winter solstice (23:30–00:30 LT) and vernal equinox (00:00–02:00 LT). They also found the MTM's amplitude range in the Indian sector, between 80 and 570 K, to be much larger than in the Peruvian sector which have been reported in the range of 40–200 K. The authors suggested that this longitude difference in the MTM's amplitude may be due to variations in the in situ ion-drag resulting from F-region electron density dependence on the separation between the magnetic and geographic equators.

As we have seen in the different longitude sector observations, some MTM characteristics exhibit possible longitude variations such as neutral winds effects, seasonal occurrence patterns and amplitude. Since longitude dependencies in thermospheric/ionospheric parameters manifest themselves in their dynamical interactions, it follows that the MTM's signatures would vary with longitude as well. Continued monitoring and comparison of the MTM and affected F-region parameters in different longitude sectors is needed in order extend our understanding of this phenomena from a local to a global scale.

3. MTM and 6300 Å airglow modeling

Attempts at modeling the MTM began using the NCAR Thermospheric General Circulation Model (TGCM) described by Dickinson et al. (1981). Even though the model included ion-neutral momentum coupling and solar forcing, these efforts were unsuccessful until it included interactions between upward propagating lower atmospheric tides and semidiurnal tides generated in-situ in the thermosphere resulting from ion-neutral momentum coupling (Fesen et al., 1986). Fesen (1996) used the NCAR Thermosphere-Ionosphere-Electrodynamical General Circulation Model (TIEGCM) to study the MTM under equinox conditions in the American sector (70°W longitude). TIEGCM is a revised version of TGCM described as a self-consistent, first principles model of the coupled thermosphere-ionosphere system. The added electrodynamical component of the model includes the calculation of dynamo electric fields and currents (Richmond et al., 1992). The Fesen (1996) simulations included exhaustive combinations of tidal amplitude/phase pairings for the 2, 2 though 2, 6 semidiurnal modes. The results showed that the seasonal dependence of the MTM reported by Herrero and Spencer (1982) was due to the interaction of the 2, 2 and 2, 3 tidal modes since these two modes reinforce each other in summer and interfere with each other in winter. It was

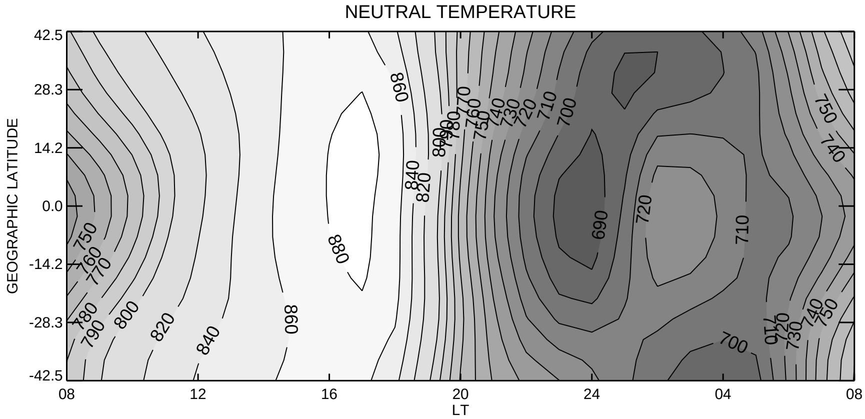

Fig. 4. TIEGCM modeled thermospheric neutral temperatures at an altitude of 300 km. The MTM develops at 3 LT centered on the geographic equator. The feature has an amplitude of 20 K with a maximum nighttime value of 720 K in comparison to the daytime peak of 880 K.

suggested that the day to day variations exhibited by the MTM were due to variability in the upward propagating tides. Even though TIEGCM could successfully generate a general MTM feature at the equator, it has difficulty reproducing important MTM characteristics such as amplitude and latitudinal extent. Fesen (1996) reported model amplitudes typically ~ 20 K. This is much smaller than reported American sector results ranging between 100 and 200 K (Sobral et al., 1978; Colerico et al., 1996). The model runs were also unable to reproduce the poleward propagation of the MTM away from the equator as shown in Fig. 1.

The state of the art version of TIEGCM, described by Fesen et al. (2000), simulates the MTM through upward propagating semidiurnal tidal modes that have been tuned to mimic UARS wind observations. Even with this revision, the current version has the same difficulties in modeling the MTM's basic characteristics as its predecessors. Fig. 4 (taken from Colerico et al. (2002)) shows the modeled neutral temperature results at 75°W longitude over a latitude range of $\pm 42.5°$. The geophysical specifics for this run were solar minimum, magnetically quiet, equinox conditions. The model run produced a weak MTM feature centered on the geographic equator near 3 LT. The development of the MTM at 3 LT is inconsistent with observations by Herrero and Spencer (1982) and Colerico et al. (1996) demonstrating that the MTM forms nearer to midnight during equinox. The amplitude of the modeled MTM is approximately 20 K. This is still at least a factor of five smaller then average observed values. The modeled results could not duplicate the two secondary temperature maxima symmetric about the equator as shown in Fig. 1b.

The upward propagation of the semidiurnal tide is essential to producing an MTM in TIEGCM. However, tuning this tidal mode to agree with observations could not reconcile differences with observed basic properties. This suggests that there are additional tidal modes or physical processes at work. An investigation into the terdiurnal tide in the lower atmosphere may prove useful. Tidal analysis studies of the MTM through NATE temperature data (Mayr et al., 1979; Herrero et al., 1983) indicated the importance of the first three tidal components in the production of the MTM. Herrero et al. (1983) suggested that the seasonal dependence of the MTM was due to the interaction of the semidiurnal and terdiurnal tidal components. The role of the terdiurnal tide in the lower atmosphere needs to be re-evaluated and its implementation within the model needs to be re-examined.

Colerico et al. (2002) conducted a modeling study of the MBW related to the MTM using a 6300 Å airglow modeling code developed at Boston University. This code employed the standard chemical reactions needed to produce the 6300 Å airglow emission. Its inputs were taken from the previously discussed Fesen et al. (2000) simulation. Fig. 5a, taken from Colerico et al. (2002), shows an averaged meridional intensity scan over 15 nights of data taken with the Arequipa imager in October 1996. A meridional intensity scan is constructed by taking a vertical slice through the zenith of each image over the course of an evening and stacking them in chronological order. In this case, individual meridional intensity scans for the 15 evenings were averaged together. This scan accentuates the average patterns of two reoccurring meridional propagation features present in the 6300 Å emission observations. The first is an example of a PMBW event which enters the imager's field of view from the south at 20:30 LT and exits to the north near 21:30 LT. The second is the MBW related to MTM which enters from the north at 01:00 LT and exits to the south at 2:00 LT. Correlated averaged FPI neutral temperature measurements exhibited an approximately 100 K enhancement during the passage of MBW events (Colerico et al., 2002), however, no temperature enhancement was observed for the PMBW case. This differs with the earlier results of Colerico et al. (1996) which found an average enhancement of 120 K for PMBW

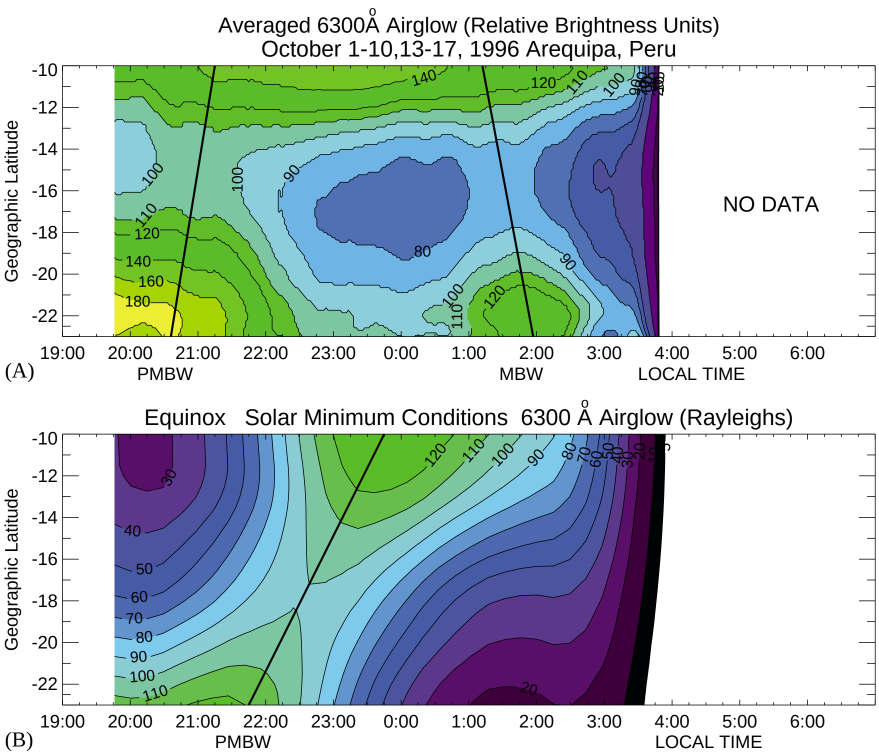

Fig. 5. (A) Averaged meridional intensity scan for 15 nights of 6300 Å emission observations from Arequipa, Peru, during October, 1996. The scan illustrates a PMBW event near 21:00 LT and an MBW event between 01:00 and 02:00 LT. (B) Modeled 6300 Å airglow highlighting a simulated PMBW event (21:30 LT–23:00 LT) and the lack of a modeled MBW event. In both panels, the black lines indicate the propagation paths of the PMBW and MBW events.

events which occurred under magnetically quiet conditions during October 1994. The geophysical conditions for October 1994 and 1996 were similar with the exception of solar flux having a value of 68.7 and 87.1, respectively. This suggests the possibility of a solar cycle dependent MTM contribution to PMBW development.

The fact that these features are prominent in the monthly average points to the temporal consistency and magnitude of these airglow signatures which we would expect to appear in the model results. The modeled airglow results, shown in Fig. 5b, successfully reproduced a feature similar in magnitude, direction, and occurrence time as the PMBW event. There are two differences to note between the PMBW averaged observations and model results. There is a 1 h shift in the PMBW occurrence time and a slower modeled propagation speed. While the average PMBW events for October 1996 occurred between 20:00 and 21:00 LT, other observations periods included events nearer to the model's occurrence time and propagation speed. Through the examination of additional TIEGCM modeled parameters, Colerico et al. (2002) suggested that the PMBW may predominantly result from the relaxation of the intertropical arcs due to the reversal of the electro-dynamically produced fountain effect. Model runs excluding the semidiurnal tides still reproduced the PMBW feature indicating that the tidally driven MTM contribution, if any, is minor. The model was unable to reproduce the MBW feature. A comparison between the TIEGCM modeled meridional winds and temperatures revealed the absence of the expected poleward reversal/abatement in the winds during the MTM occurrence. Colerico et al. (2002) concluded that the modeled MTM was not strong enough to modify the meridional winds and bring about the 'midnight collapse' of the F-region necessary to produce the MBW feature.

4. Conclusions

The history of the MTM in the literature spans over 30 years. In that time, investigations into its origins and influences were conducted using diverse instrumentation such as radars, satellites, ionosondes, photometers, FPIs, and all-sky camera systems. From these efforts we have constructed our present day understanding of this thermospheric phenomenon. The MTM is an enhancement in neutral temperature which occurs near local midnight at low latitudes. Its average amplitude is between 100–200 K in the American sector and 80–570 K in the Indian sector. This feature may be due to tidal interactions between the lower atmosphere and thermosphere. The MTM initially forms at the geographic equator and propagates towards the poles. Two additional temperature maxima form at low latitudes near 15°. The seasonal dependence of the secondary maxima is such that it occurs earlier and is stronger in the summer hemisphere. During equinox, these two maxima are symmetric about the equator. An MTM occurrence instigates a companion series of effects in other F-region parameters. The temperature enhancement is accompanied by a pressure increase which, in turn, can result in a reversal or abatement in the meridional winds from equatorward to poleward. This modification in the winds initiates the 'midnight collapse' of the F-layer which moves plasma to lower altitudes where it can dissociatively recombine and produce the observed enhancements in the 6300 Å emission.

There are still many outstanding questions regarding the MTM. First and foremost is its generation mechanism. The implementation of upward propagating semidiurnal tides in TIEGCM is critical in reproducing the MTM in simulations. This supports the theory that the MTM is a tidally driven phenomenon. Modeling efforts have fallen short in reproducing the MTM's basic characteristics, suggesting that other tidal modes or processes must contribute to its overall development. Studies by Mayr et al. (1979) and Herrero et al. (1983) suggest that the terdiurnal component may play a larger role than previously thought. Arduini et al. (1997) reported on the local time and altitude variations of the midnight density maximum (MDM) which accompanies the MTM. In Fourier analysis of the MDM, the third and fourth order harmonics were required in order to produce the MDM. These results point to the need to reexamine the terdiurnal component in future modeling efforts.

There are also issues to address regarding the spatial extent of the MTM. Up to now, the majority of MTM investigations have been conducted near 70°W. While this provides local detailed information about the MTM's characteristics, it leaves a gap in our understanding of the feature's global behavior and longitudinal dependencies. Since the MTM exerts widespread influence on important thermospheric/ionospheric parameters, it is important to characterize its effects over all longitudes. Studies conducted in Cachoeira Paulista (45°W) and the Indian sector (80°E) point to some possible longitudinal variations in the MTM's influence of the neutral winds (Batista et al., 1997) and amplitude (Rao and Sastri, 1994). Continuation of coordinated observations and new comparative studies over an extend longitude range is vital to completing our global view of this phenomenon. The limit on the latitude extent of the MTM's propagation away from the equator has yet to be determined. Using MBW observations as an indicator of the MTM's influence, Colerico et al. (1996) observed its propagation past 26° south geographic latitude. Recent observations from El Leoncito, Argentina, show that MTM effects may reach mid-latitudes before they dissipate.

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