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Daytime optical investigation of the equatorial mesopause energetics in the context of equatorial MLTI coupling: Recent results

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First experimental evidences for the mesopause energetic changes in context of (a) counter electrojet (CEJ); (b) solar flare; and (c) solar eclipse in the equatorial mesopause region using a daytime optical photometer are presented. The photometer has been operated in a scanning mode to probe the thermosphere and mesopause regions simultaneously in north-south direction over Trivandrum (8.5°N; 77°E; dip lat. 0.5°N). The striking features observed are (i) enhancement in the wave activity as seen in the mesopause temperature, during the eclipse, (ii) cooling of the mesopause during the equatorial electrojet (EEJ) reversal and (iii) decrease in mesopause temperature during a flare. These observations are discussed to highlight the vertical coupling of the mesopause with thermosphere-ionosphere region, mainly through neutral dynamics.

Keywords: Equatorial mesopause, Mesopause energetics, Equatorial electrojet, Counter electrojet, Mesosphere-lower thermosphere ionosphere (MLTI)

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1 Introduction

In recent years, technological systems like the GPS based navigation, has brought to the fore the need for better models to represent the terrestrial atmosphere in general, and earth's upper atmosphere (~ 90-400 km), also known as the thermosphere-ionosphere system, in particular. Comparison with the existing models has led to the revelation that the processes over the equatorial middle and upper atmosphere are yet to be properly comprehended. To understand and model this region in totality, several national and international programs, like the Middle Atmosphere Energy Programme (MAP) and the Solar Terrestrial Energy Programme (STEP) and a series of coordinated studies under the auspices of these programs, have been initiated in the recent past. Projects like the EPIC (Equatorial Process Including Coupling) and the PSMOS (Planetary Scale Mesopause Observing Systems) have focused on the complex problems pertaining to the middle and upper atmosphere, and their mutual coupling.

The knowledge gained through these earlier concerted efforts has led to a new international program called CAWSES, i.e. Climate And Weather of the Sun-Earth system that commenced in 2003. Under CAWSES, the scope of the earlier studies has been enlarged to encompass the climatic aspects of the Sun-Earth System. As is apparent, to achieve the objectives of such major programs in totality, one needs to probe the Sun-Earth system using a variety of techniques operating from ground and space. The optical techniques operating from the ground and space based platforms have played a very significant role in providing the much needed, important database in this context. Further, when it comes to the investigation of the morphology and aeronomy of the terrestrial atmosphere at various altitudes, the measurements of the atmospheric airglow have time and again proved to be of immense use.

As is known, the atmospheric energetics and dynamics, though primarily driven by the solar radiation absorbed at different altitude regions, significantly get modulated by a complex web of photochemical and dynamical processes. The photo-ionization of the atmospheric species and the consequent formation of ionosphere, release of the absorbed energy during recombination, variety of exothermic and endothermic reactions, large scale neutral and electrodynamic processes alter the energetics and overall dynamics of the upper atmosphere. Since these processes are altitude dependent, the conditions for the atmosphere to attain equilibrium differ significantly from one height region to another. As a result of these processes, etc., some atoms/molecules get excited and undergo specific spectral transitions, thereby playing an important role in overall energy balance. Atomic and molecular emissions occur as a consequence of these transitions. These emissions from the terrestrial atmosphere constitute the so-called `Airglow'.

The broad classification of airglow phenomenon is dayglow, nightglow or twilight-glow, depending on the time of the day it is being observed. These airglow emissions thus serve as a perfect tracer for the processes occurring in the altitude regions from which it emanates. As a consequence, systematic study of the airglow is capable of providing a wealth of information on various aspects of the physics and chemistry of the atmosphere at different altitudes. For instance, the columnar density of the airglow emitting species can be inferred directly by using a calibrated photometer to measure the airglow intensity. The high-resolution study of the emission line profile itself can provide an estimate of the Doppler temperature and line-of-sight winds. Using the vibration rotation spectra of airglow emitting molecules, one can estimate the rotational temperatures. Presence of the large-scale disturbance/wave propagating vertically can be unambiguously inferred by measuring the intensity of airglow originating at different altitudes.

The beginning of airglow studies in India could be linked contemporarily to the work done by Lord Rayleigh around 1925-27 elsewhere in the globe. A comprehensive description of these and various other earlier aeronomical studies done in India can be found in several reviews[1]. Traditionally the airglow measurements in India and elsewhere had been largely restricted to nighttimes since during daytime the solar radiation not only provides a large background continuum (10^6:1), the Fraunhofer lines present in the solar spectrum significantly alter the shape and intensity of the airglow emission features. However, innovative methods adopted in the measurement techniques in India[4] led to the development of the dayglow photometry two decades ago.

Using the airglow techniques both during day and nighttimes, several very important results having significant implications in the understanding of the aeronomy of the upper atmosphere over low and equatorial latitudes, have been obtained over the recent years. Some of these results are concerned with the understanding, modeling and forecasting the equatorial spread-F, a large scale nighttime equatorial process through ionosphere-thermosphere coupling, in addition to the overall energetic of the near earth space. The ESF basically represents a class of ionospheric irregularities that occur in the nighttime equatorial ionosphere. Nevertheless, a comprehensive understanding regarding both, the day and nighttime processes over the equatorial upper atmosphere emerged, as a result several of these studies in India and various others from across the globe [5-12]; the optical investigations have played significant roles in it.

Another significant development in recent years has been a growing understanding of how the thermosphere-ionosphere region is energetically/ dynamically coupled with the lower atmosphere. It is now very well realized that the processes originating in the mesosphere and lower atmosphere play an important role in modulating the dynamics/energetics of the thermosphere-ionosphere system. The lower part of thermosphere-ionosphere region is now commonly referred to as the mesosphere-lower thermosphere ionosphere (MLTI) region due to their constant interaction. In the MLTI region, the mesopause could be considered the transition region, which couples the neutral dynamically controlled mesosphere with the electro-dynamically controlled thermosphere/ionosphere region.

Recent studies have revealed that a part of the variability observed in the parameters representing the equatorial dynamo region is to be attributed to the prevailing coupling of this region with the lower atmosphere[13]. The nature of the MLTI processes and the atmosphere-ionosphere coupling through mesopause, tides and waves, etc., are the topics of intense global research in the recent years and our comprehension regarding them is not yet complete[14-18]. The relative inaccessibility of the altitude region around mesopause (~ 85 km) and slightly above, to the traditional atmospheric probing techniques has been the prime reason for it[19].

Nonetheless, it has been reported that very significant changes occur in MLTI parameters like the temperature and wind that vary over time scales ranging from a few hours to decades[20]. The day-to-day variability in the temperature and wind fields in the mesosphere is thought to be governed primarily by the dynamic forcings like the tides, gravity and planetary waves, which have sources mainly in the troposphere/stratosphere and these grow in amplitude as they propagate upward. However, the temperature and its variability at upper mesospheric altitudes, especially in the mesopause region, are difficult to measure. Most of the earlier measurements on the mesospheric temperature have come from the rocket, ground based radar experiments and optical experiments which were mainly restricted to nighttime clear sky condition.

Satellite borne experiments like the Wind Imaging Interferometer (WINDII) and the High Resolution Doppler Imager (HRDI) onboard the Upper Atmosphere Research Satellite (UARS) has provided the much needed global measurements on the mesospheric temperature in recent years[21]. The range of other ground based instruments like photometers, spectrometers and lidars have been enabling systematic measurements on the upper mesospheric temperature and its temporal variabilities over a number of locations on the globe[22-26]. However, owing to some inherent limitations in these techniques, getting estimates of temperatures, particularly during daytime, over a complete diurnal cycle for a given location had been difficult in the past. The daytime mesopause temperatures estimated using the mesospheric dayglow intensities, in India, are unique in this context. Selected emission lines of hydroxyl (OH) have been used for estimating the ambient temperature of the ~87 km altitude region, i.e. mesopause, from where the OH (hydroxyl) airglow emanates[27-19]. Important studies have been reported from Indian longitudes that involve these daytime measurements of the OH emission intensity and the estimated mesopause temperature using a ground based multi-wavelength dayglow photometer[23, 29-31].

A systematic investigation of the changes in the mesopause temperature from an Indian dip equatorial station, i.e. Trivandrum (8.5°N, 76.5°E, 0.5°dip), has led to a better comprehension of some hitherto less understood aspects/processes of the MLTI. In this context, this paper presents the optically estimated daytime mesopause temperature over Trivandrum, the dip equatorial station in India. To start with the day-to-day variations in the mesopause energetics, inferred through the daytime mesopause temperature for one month, i.e. March 2005 are presented and discussed. This paper further presents a convincing evidence for a significant vertical coupling between the mesopause and the E-region dynamo region during a CEJ event, when the surface magnetic field measurements exhibit large negative excursion; followed by a case study exhibiting significant changes in the temperatures during the solar flare event of 17 Jan. 2005. All these case studies demonstrate the potential and capability of daytime optical diagnostics of the coupling of the different atmospheric regions.

2 Measurements

The daytime airglow intensity measurements presented here were made using Multi Wavelength Dayglow PhotoMeter (MWDPM) on two rotational lines at 731.6 and 740.2 nm in the OH Meinel (8-3) band at Trivandrum. These daytime measurements were typically made between 0800 hrs IST and sunset, i.e., 1830 hrs IST and at various elevations between ± 30°, scanning from north to south along the meridian. The maximum horizontal distance covered for mesospheric measurements is ~ ± 150 km (~ 1.5° latitude) about the dip equator on either side, for the OH emission peak to be around ~ 87 km. The daytime OH emission intensity measurements at the wavelengths mentioned above were used to estimate the mesopause temperature[27]. These temperatures have already been validated/compared with the WINDII satellite measured temperature and also with the collocated meteor wind radar measured temperature from the Indian region[19]. The technical details of this photometer have been described elsewhere[28]. The EEJ induced magnetic field at the surface was measured using a collocated Proton Precision Magnetometer (PPM) at Trivandrum.

3 Results and discussion

3.1 Day-to-day variation of the daytime mesopause temperature

The daytime mesopause temperatures obtained from Trivandrum (8.5°N, 76.5°E, 0.5°dip) for the period of 01-31 Mar. 2005 are depicted in Fig. 1. The abscissa represents the time (Indian Standard Time) and ordinate represents the day number of the month. It is very well evident from Fig. 1 that the mesopause temperatures not only exhibit large temporal variations within a day, significant day-to-day variability is also seen therein. The temperature shows a gradually decreasing trend from 01 to 31 Mar. 2005, especially in the post-noon hours. Further after 15 March, significant small scale (~ 1-2 h) variability is seen in the forenoon hours.

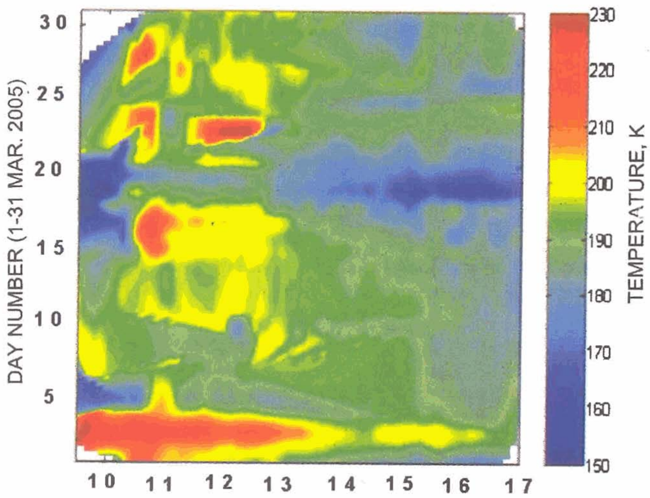

Fig. 1 — Day-to-day variation of mesopause temperature over Trivandrum during March 2005

Usually during the month of March, the mesospheric winds over the equatorial region undergo the transition associated with the Mesospheric Semi Annual Oscillation (MSAO). During this period, the mean zonal wind gradually turns westward, being primarily eastward before this. It has been shown that the dynamics in the stratosphere also simultaneously exhibits the semi-annual oscillation along with the MSAO but opposite in phase of the wind[32]. This has significant implication in the overall variability of the mesospheric energetics. The gravity and planetary waves which are generated in the lower atmosphere, mainly during the northern hemisphere winter are expected to propagate upwards through the stratosphere in this phase of stratospheric SAO; while the phase being opposite in the mesosphere, these waves would dissipate, transferring their energy and momentum to the background, thereby affecting the overall energetics of this region. In this context, the gradual decrease in the mesopause temperature during 1-31 Mar. 2005, as observed here, is ascribed to be due to the MSAO.

Though the presence of SAO in the mesopause dynamics is well observed, the same in the energetics, i.e. temperature has not been well understood so far[33]. In this context, Vineeth *et al.*[19] recently presented the measurements of the mesopause temperature to highlight the temperature variability, which varied from days to hours. This study also presented the first ever comparison of these daytime Mesopause OH rotational temperatures, as determined using Meinel (8-3) dayglow emissions with those obtained using the recently established and collocated, meteor radar (SKiYMET) over the magnetic equator in India. The temperatures estimated using these two very different and independent techniques revealed a consistency in magnitude of the temperature and also the variability involved therein.

As mentioned above, the temperature also shows the signatures of small scale (~1-2 h) oscillations, which are indicative of the presence of gravity waves. The dominant gravity wave periodicity is found to be ~ 1.5-2 h during this period. As is known, the primary sources of these gravity waves exist in the lower atmosphere[34]. Though the characterization of the gravity waves and their sources is extremely difficult, it has been observed that the gravity wave fluxes in the mesospheric region also exhibit a seasonal variability and are more dominant during the winter months than that during summer months, especially over mid-latitudes[35]. However, a similar understanding of the gravity wave climatology over the equatorial latitudes is yet to evolve. Over the Indian longitudes, some association between the measured gravity wave fluxes in the stratospheric altitudes and the convection\thunderstorm activity has been shown, which is known to be more during the months of March-April[36]. In this context, the enhanced small-scale oscillations could be the manifestation of the atmospheric weather activity in the lower atmosphere. However, simultaneous measurements of wind and temperature in all the three regions, i.e. troposphere, stratosphere and mesosphere are needed to establish the gravity wave sources unambiguously.

It is fairly well established that the gravity waves play a crucial rôle in providing the vertical coupling within the MLTI region. It has been conjectured that the vertical wind associated with the upward propagating gravity waves, though small, can have dramatic effects in the MLTI region especially in the dynamo region. The small magnitude (~ 5-10 m/s) of the vertical wind makes it difficult to measure it unambiguously. Nevertheless, its presence and manifestations in some of the MLTI processes had already been inferred indirectly through experiments and models[37]. One such MLTI process is the counter equatorial electrojet (CEJ), where the vertical winds associated with gravity waves are proposed to be playing a crucial role in its very generation[38]. Though model simulation has been carried out, there had been no direct observational evidence to substantiate this hypothesis. However, recent simultaneous measurements of mesopause temperature and the electrojet induced magnetic field on surface have clearly brought out a prevailing vertical coupling between the mesopause and the dynamo region, which can only be explained on the basis of vertical winds[31]. One such observation is presented here in the following section to highlight this aspect.

3.2 Mesopause energetics and the counter electrojet (CEJ)

Figure 2(a) and (b) show the spatial and temporal variation of the optically estimated mesopause temperature along the meridian on 2 and 17 Feb. 2006 respectively. Superimposed on Fig. 2(a) is the temporal variation of the EEJ induced magnetic field during the CEJ event of 2 Feb. 2005. The same on Fig. 2(b) is the magnetic field on 17 February, representing the control day. As is seen in Fig. 2(a), the mesopause exhibits a significant cooling (~ 20 K), when the induced magnetic field shows negative

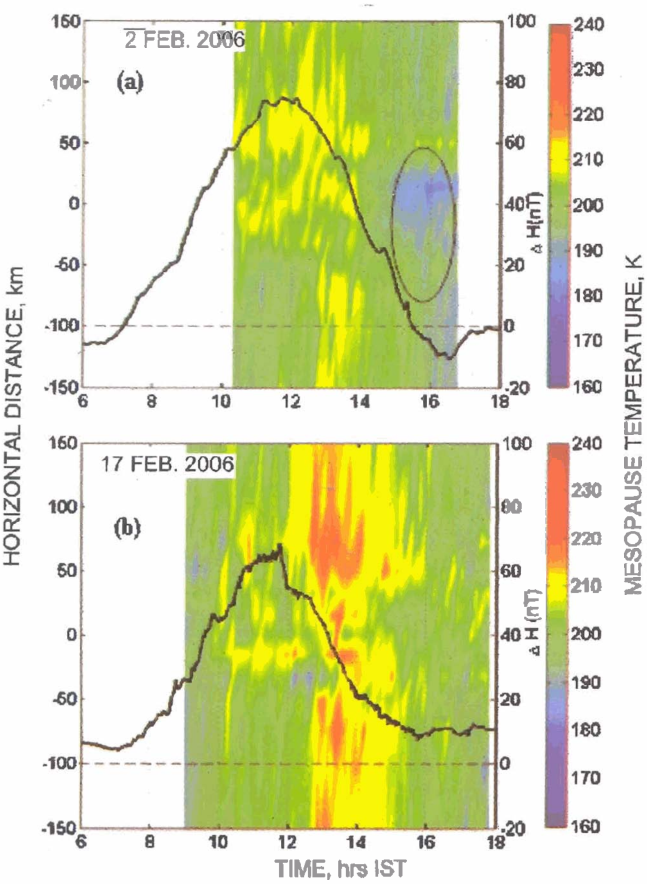

Fig. 2 — The time variation of magnetic field and spatio temporal variation of mesopause temperature on a CEJ day, i.e. (a) 02 Feb. 2006 and a normal electrojet day, i.e. (b) 17 Feb. 2006

excursion. The period of negative excursion of the magnetic field over the dip equator is the well known CEJ. The strength of the CEJ is about – 10 nT around 1630 hrs IST. Further, it is observed that the maximum cooling occurs almost simultaneous to the maximum negative excursion of the magnetic field, i.e. ~ 1630 hrs IST and the cooling is confined to a narrow region of ~ 100 km centered at around the magnetic dip equator. On 17 Feb. 2006, however, no such cooling *vis-à-vis* the magnetic field change is observed.

Though different theories have been proposed for explaining the CEJ, the exact causative mechanism of CEJ is not yet well established. However, some of the theories proposed for such a reversal of EEJ current are based on (i) the interaction of height varying winds[39]; (ii) gravity wave associated vertical wind[38] and (iii) appropriate phase combination of global scale tidal wind[40, 41]. On the whole, these and various other studies highlight the role and importance of winds in the generation of CEJ.

The authors' present observation suggests that there is a common forcing which is responsible for the simultaneous changes in the mesopause temperature and the reversal of EEJ. It is believed that the vertical wind hypothesis of Raghavarao and Anandarao[38] could explain both the observations. The rationale for the same is presented below.

It has been shown that chemistry plays a dominant role as far as the energy budget of the mesopause region is concerned. In a recent study, Mlynczack and Solomon[42] showed that the reaction involving H and O_3, which leads to the radiatively active vibrationally excited OH in the Meinel band, is also an important contributor to the chemical heating at the mesopause altitudes. It is known that the 3-body recombination of O and O_2 is the main source of O_3 in the mesopause region. The [O] is generated through the photolysis of O_2 in the lower thermosphere and brought to mesopause through downward diffusion or mean advection[43]. As a consequence, larger downward diffusion of [O] leads to larger concentration of O_3, which in turn could lead to larger temperature in the mesopause through the exothermic OH chemistry.

In this context, the gravity waves associated vertically upward wind would oppose the downward diffusion of [O]. This would cause a reduction in the O_3 concentration and OH emission rates in the mesopause region, which would in turn manifest as a lowering in the temperature. At the same time, the vertically upward wind in the ionospheric dynamo region would either weaken or reverse the vertical polarization field[38]. However, there could be a small time-delay between the temperature and magnetic field changes, which would depend upon the ongoing tidal mean interactions and the vertical propagation of gravity waves and vice versa. The present results of mesopause cooling associated with the reversal phase of the EEJ provide some evidence on the presence of vertical winds.

3.3 Effects of solar flares on mesospheric energetics

Other than dynamics, solar heating is also shown to have a direct control on the mesopause energetics[44-46]. A linear relation of mesopause temperature with F10.7 cm radio flux has been established by using nighttime hydroxyl measurements by Offerman *et al.*[46] At the same time however, the solar cycle effect on OH temperatures is not very clearly seen by Bittner *et al.*[45] As is known, the mesospheric ozone is the main source of solar heating in this region apart from molecular oxygen and the CO_2. The solar heating is dominated primarily by the absorption of solar UV radiation[42] by O_2 and O_3. Mlynczak *et al.*[47] made a thorough evaluation of solar ultraviolet heating by ozone in the mesosphere and showed it to be in good agreement with two-dimensional model calculations. However, the response of mesopause temperature to sudden surge of energy from the Sun is yet to be properly evaluated. The authors' observations, first of its kind, indicates that on occasions when there is a sudden change in the solar activity, there appears to be a mesopause response in the form of a decrease in the mesopause temperature, either immediately or after a few minutes. To highlight this aspect, presented here are the observations during the period 17-19 Jan. 2005 and the solar flare event on 17 January.

The sun was very active during the period 17-21 Jan. 2005, as a very large sunspot group (720) appeared on the solar surface and caused at least five M and X class flares during its evolution before going behind the solar disc on 21 January. The Solar region 720 (N13W27) produced the long duration (almost 4 h) X3.8 flare on 17 January. In fact, the LASCO (space based coronagraph) confirmed a full halo event showing that the associated mass ejection was earth directed and likely to be very geo-effective. The flux from this flare blinded the US ACE solar wind satellite due to the detector saturation. The same sunspot group produced another powerful X-class solar flare on 20 January at 0636 hrs UT, but it was not found to be very geo-effective due to the location of the sunspot on the solar disc, i.e. 61°W solar meridian.

Figures 3-5 (top panel) present the ground based mesopause temperature as measured over the dip

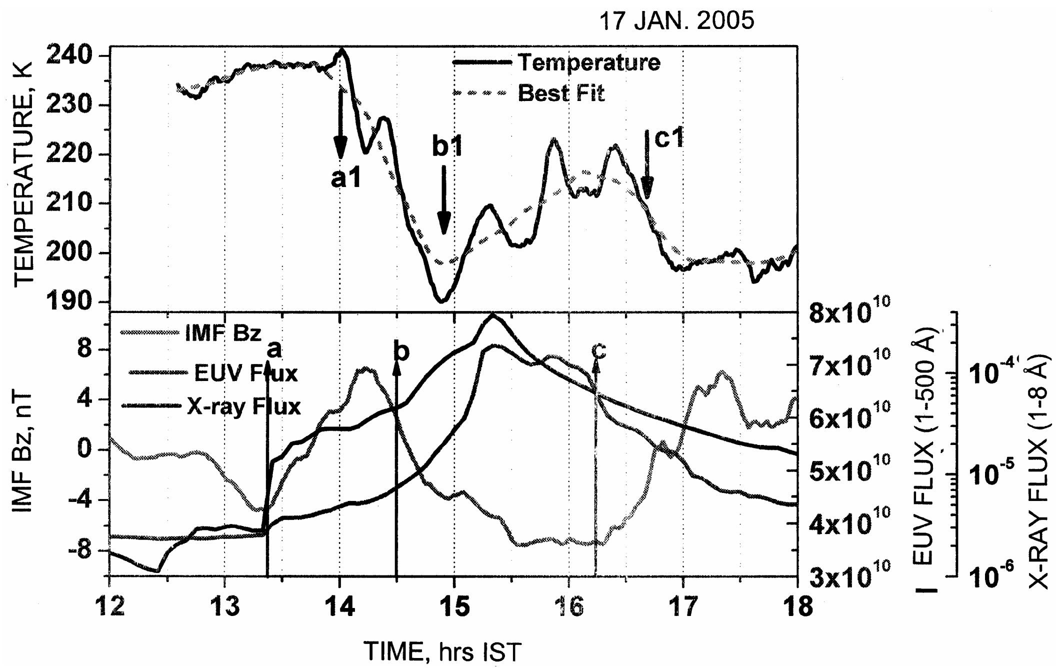

Fig. 3 — Time variation of mesopause temperature (top panel), IMF Bz, EUV Flux and X-Ray flux (bottom panel) for 17 Jan. 2005

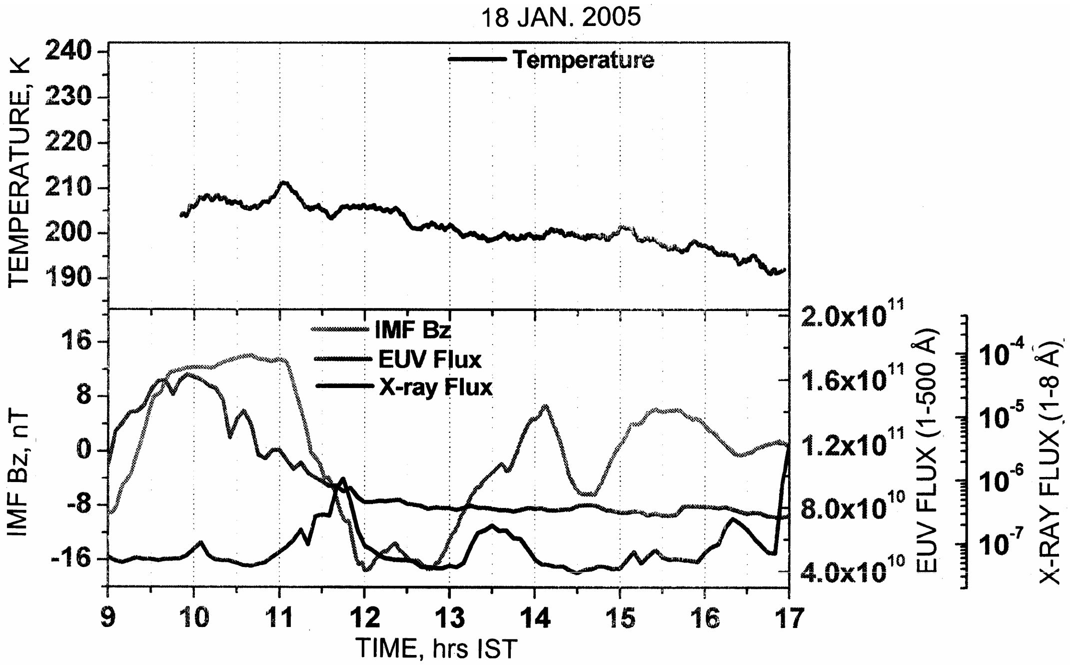

Fig. 4 — Same as Fig. 4 but for 18 Jan. 2005

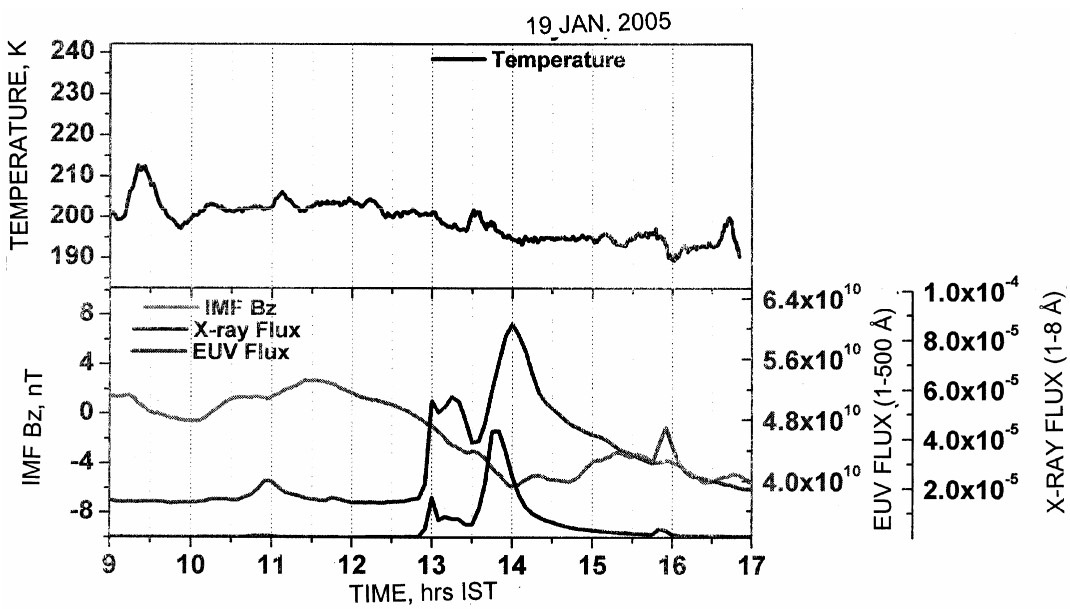

Fig. 5 — Same as Fig. 4 but for 19 Jan. 2005

equator on three days, i.e 17, 18, and 19 Jan. 2005. The temperature on 17 January, i.e. the day of first X-class solar flare exhibited a significant decrease associated with large wavelike modulations. The temperature showed a decrease from 240 to 190 K, 40 min after the beginning of the flare at 0950 hrs UT (1520 hrs IST). The temperature on other days did not show either the decrease or the modulations *vis-à-vis* the changes in the solar flux as seen on 17 January. It must also be mentioned that the overall temperature on 17 January was higher than the temperature on rest of the days.

The simultaneous variation of IMF Bz, satellite measured EUV flux (1-500 Å) and X-ray flux (1-8 Å) (http://www.ngdc.noaa.gov) on these days are presented in Figs 3-5 (bottom panel). As mentioned earlier, the mesopause temperature on 17 January responded to the changes of the radiation and IMF Bz after a time delay of about 40 min. To highlight this aspect, arrows are shown in Fig. 3. The times of change in temperature trend and irradiance are denoted by arrows numbered a1, b1, c1 and a, b, c, respectively. As can be seen from Fig. 4, the rise and fall of the radiation flux on 17 January is almost simultaneous, with the southward and northward turning of the interplanetary magnetic field respectively. The days 18 and 19 January remained geomagnetically active with no significant enhancement in the EUV and X-ray flux during the day. On 18 January, the EUV flux was more in the morning hours and remained low and nearly constant during the rest of the day. The mesopause temperature on 18 and 19 January exhibited a monotonically decreasing trend indicating that the ongoing storm activity has little influence on the mesopause energetics. However as mentioned earlier, the modulations in the mesopause temperature as seen on 17 January are ascribed to the flare induced changes in the MLTI region. The rationale for attributing the temperature changes on this day to be solar flare induced is as discussed below.

As is known, in the MLTI region during normal daytime conditions, the solar UV radiation below 310 nm would lead to the production of atomic oxygen ([O]) by the photolysis of O_3 and O_2. The [O] from the lower thermospheric heights would be brought to the mesopause through downward diffusion or mean advection[43]. The larger concentration of O_3 due to this downward diffusion of [O] would manifest as larger temperatures through the exothermic OH chemistry. Further, it is known that the ionization at heights of around 70 km is generally maintained mainly by direct Lyman-α radiation (121.6 nm) from the sun, which partially ionizes the minor neutral constituents therein (e.g. the nitric oxide). Under normal conditions, the solar X-ray flux is too small to be a significant source for ionization in this height region. However, during a solar flare, the enhanced X-rays below 1 nm would be able to penetrate down up to ~ 60-70 km. This increases the ionization rate and also influences the nature of chemistry therein, especially the ones involving nitrogen, oxygen and ozone[48-50]. For instance, the chemical channels involving odd-nitrogen NO_x and odd-hydrogen HO_x can get strengthened, which could subsequently lead to the depletion[50] of O_3. Further, the significantly enhanced XUV irradiation during the solar flare would produce energetic secondary photoelectrons, which are capable of photo-dissociating the O_2 in the lower thermosphere-ionosphere region through collisions[51].

In this context, on 17 January the initial increase in X-ray (region between arrows marked a and b in Fig. 3, where the EUV radiation increased only marginally) marking the beginning of the flare would lead to (i) overall depletion of O_3 in the mesosphere through the enhanced photolysis; (ii) depletion of O_3 in the mesosphere through reactions involving O_3 with the odd-nitrogen NO_x and odd-hydrogen HO_x. Further, this depletion in O_3 would lead to a decrease in the formation of vibrationally excited OH radicals, which in turn would cause significant cooling in the mesopause. The decrease in the mesopause temperature during 1400-1450 hrs IST (region between arrows marked a1 and b1) is attributed to this mechanism. However, it must be mentioned that there appears to be a time delay of ~ 40 min before the mesopause temperature responds to these ongoing changes in the mesosphere. In this context, ~ 40 min could be interpreted as the overall response time of the mesopause region.

After 1430 hrs IST, the solar X-ray as well as the XUV irradiance increased steeply, the fluxes increasing almost 2 and 1.5 times respectively, within 40-50 min. The X-ray irradiance increased and immediately started decreasing (i.e. region between arrows marked b and c) while the increase in XUV irradiance lasted about 40-50 min longer than that in X-rays. At this point, the generation of additional O through the photo-dissociation and photoelectron impact of O_2 will also begin in the lower thermosphere. This additional O would get transported downward to the mesopause region, which in turn would lead to the production of O_3 through three-body recombination; thus counteracting the ongoing depletion of O_3. As a consequence, this would manifest as an increase in the temperature. The mesopause temperature enhancement seen between 1500 and 1630 hrs IST, i.e. region between arrows marked b1 and c1 is proposed to be due to this sort of feedback mechanism.

Further as the XUV irradiance decreased beyond 1615 hrs IST, the production and subsequent downward diffusion of the additional O from thermosphere into the mesopause also would get lowered. At the same time, the chemistry in the mesosphere would slowly recover. The observed temperature trend beyond 1530 hrs IST clearly showed a decrease; followed by a marginal increase beyond 1630 hrs IST, when the X-ray flux almost assumed the pre-flare values and XUV flux still kept monotonically decreasing. It must be noted that the time-delay of ~ 40 min appears to be consistent throughout the day. This is believed to be a unique observation, exhibiting a clear response of the mesopause region to the ongoing solar flare activity. The response time appears to be ~ 40 min. However, it must be mentioned here that this could change with season and solar epoch. In this context, more quantification is required for providing the actual time constants involved in the MLTI processes.

3.4 Response of equatorial mesosphere to the partial solar eclipse of 29 Mar. 2006

It is well known that unique events like a solar eclipse can also cause changes in the dynamics, composition and energetics of the atmosphere under the moon's shadow. In fact, internal atmospheric gravity waves get generated due to the supersonic movement of the dark spot in the earth's atmosphere, produced by the fast moving moon's shadow during an eclipse[52, 53]. These waves usually build up as a wave front and propagate away from the source regions and manifest themselves in the temperature and wind measurements as modulations. The partial solar eclipse of 29 Mar. 2006, which was limited to the northern part of India presented an opportunity to observe this aspect of the eclipse related changes, if any, in the mesopause region over Trivandrum.

In the past, significant eclipse induced effects have been observed in the ionosphere and discussed in literature[54]. In the mesosphere, in the altitude range of 50-65 km, the eclipse effects have been observed to be manifesting as a lowering in temperature by as much as ~ 3-5 K and zonal wind speed by ~ 6 m/s during a partial solar eclipse[55]. Prominent gravity wave-like structures in the ionosphere at distances away from eclipse totality with periodicities varying from one to few hours after the maximum of solar occultation by the moon have been reported from mid-latitudes[56, 57]. However, the eclipse effects in the mesopause altitudes (~ 85-90 km) have not yet been well explored, primarily due to the lack of measurements in this region. In this context, the partial solar eclipse which occurred over Indian region on 29 Mar. 2006 provided a unique opportunity to study the eclipse related effect, especially the waves, on the mesopause energetics over Trivandrum, i.e. a place far away from the locations, where the eclipse was seen. As shown in Fig. 6, the partial solar eclipse occurred over India during the evening hours (1602-1830 hrs IST). In fact the path of the Moon's umbral shadow began in Brazil around 0836 hrs UT and extended across the Atlantic, northern Africa, and central Asia, where it ended around 1148 hrs UT; at sunset in northern Mongolia.

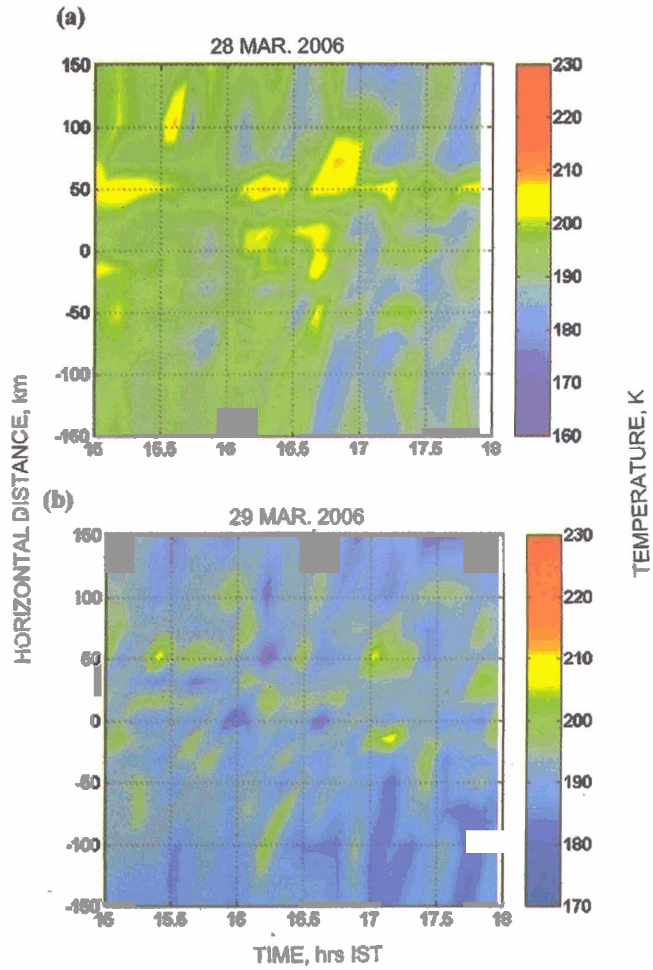

Fig. 6 — Spatio temporal variation of the mesopause temperature on (a) control day 28 Mar. 2006 and (b) the eclipse day 29 Mar. 2006

The maximum obscuration of ~ 100% was seen over Astana, (51°N, 71°E), Kazakhstan at 1141 hrs UT (i.e. 1711 hrs IST) while ~ 8% was observed at Nagpur (25°N, 85°E), India at 1153 hrs UT i.e. 1723 hrs IST. The path of the eclipse penumbra (eclipse shadow) was in the north-east direction as is shown in Fig. 7. The thick lines embedded with the circles shows the path of the totality. The percentage of the obscuration and corresponding time (in UT) is marked on the figure.

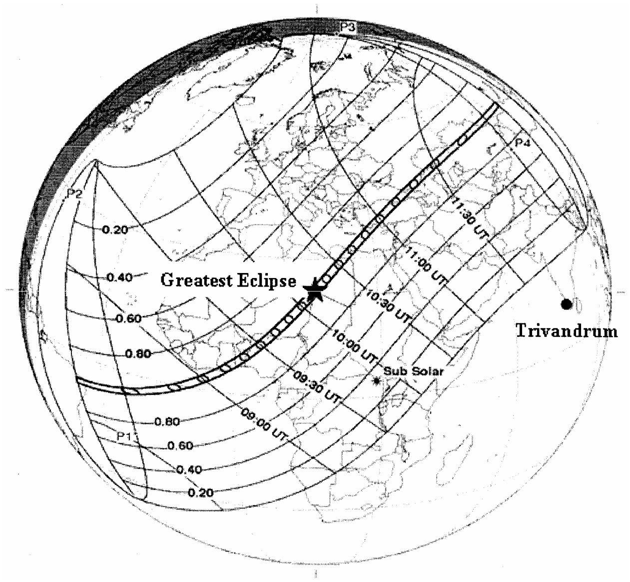

Fig. 7 — Path of the annular solar eclipse of 29 Mar. 2006 over the globe [The location of Trivandrum and the greatest eclipse is marked on the figure. Courtesy: Fred Espanak, NASA/GSFC (/Sun earth.gsfc.nasa.gov/eclipse/eclipse.html)]

The spatio-temporal variations of the mesopause temperature during the progression of the eclipse are shown in Fig. 6(b). The abscissa represents the time in IST and ordinate represents the horizontal distance from Trivandrum. Positive and negative Y-axis represents the northern and southern directions. To highlight the changes due to eclipse, the temperature variability for 28 March, taken to be the control day, is also presented in Fig. 6(a).

The mesopause temperature exhibited some remarkable features during the course of the eclipse. Overall on the eclipse day, the mesopause temperature did not exhibit any large change and varied between 185 and 210 K even during the progression of the eclipse. Nevertheless, it unambiguously exhibited a significant enhancement in the small scale perturbations having 0.5-1.0 temporal and 50-100 km spatial variability. It is to be noted that the similar extent of small scale oscillations are not seen on the 28 March, which suggests that these modulations could be generated due to the eclipse forcing. The spatial and temporal scales of these modulations corroborate well with the wavelength and period of internal gravity waves[57]. In this context, these modulations in the mesopause temperature are attributed to the internal atmospheric gravity wave, presumably generated and launched during the progression of the eclipse during earlier hours. This observation is considered unique and its importance lies in the fact that even if the path of totality is far away, the atmosphere, especially the mesopause could respond to it through enhanced gravity wave activity and subsequent changes in its energetics.

4 Conclusions

The results presented here clearly highlight the importance of the mesopause energetics in understanding the MLTI processes over the equatorial region. However, to understand its climatological variability, systematic long-term measurements of mesopause temperatures are needed. As mentioned in the text of this paper, the CAWSES – India program is currently on and it is envisaged that the measurements that are being made on a number of parameters representing terrestrial and solar atmosphere using variety of ground and space based instruments will lead to a better understanding of the sun-earth system in the coming years.

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