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Signature of the 27-day oscillation in the MLT tides and its relation with solar radiation at low latitudes

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Abstract

The modulation of the dominant atmospheric tides (i.e. diurnal, semidiurnal and terdiurnal) in the mesosphere and lower thermosphere (MLT) is investigated using long-term meteor wind database from three Southern hemispheric low-latitude locations, São João do Cariri (7.4° S, 36.5° W), Cachoeira Paulista (22.7° S, 45° W) and Santa Maria (29.7° S, 53.7° W). The spectral analysis reveals an evident and intermittent signature of a 27-day oscillation in the tidal amplitudes. Relationship between the 27-day tidal modulation in the MLT and solar rotation is looked into utilizing solar UV flux (Lyman-α) that indicates a conspicuous linkage of the tides with the solar short-term variability. The strong correlation between the solar variability and tidal modulation in the concerned period with positive lags at certain intervals may indicate predominate solar influence on the MLT tides. Potential involvement of the lower, middle and upper atmospheric dynamics and chemistry to support the observed oscillation feature is deemed plausible.

Keywords: 27-day oscillation, Tides in the MLT, Meteor radar observations

Introduction

Atmospheric tides are one of the most prominent dynamical entities that transfer significant amount of energy from the lower atmosphere to mesosphere and lower thermosphere (MLT) and modify the ambient dynamical condition considerably (Miyahara et al. 1993; Hagan and Forbes 2002). Periodic solar heating of the atmosphere is the prime reason for the generation of these tides containing periods of several subharmonics of a solar day, i.e. 24, 12, 8, 6 h and so on (Batista et al. 2004; Guharay et al. 2011, 2013a, 2015, 2018). In general, the amplitudes of the tides with higher periods tend to be very small and the dominant tidal manifestation in the atmosphere occurs in the periods, 24 h (diurnal), 12 h (semidiurnal) and 8 h (terdiurnal) tides. The diurnal tide generally dominates in the low latitudes and semidiurnal tide takes over the former in the mid and high latitudes

(Manson et al. 1989). Although the amplitude of the ter-diurnal tide is normally much smaller than the other two components, it can be significantly large at times (Thaya-paran 1997).

Since Sun is the major source of energy of the Earth, it has potential to control and modify various physical, chemical and dynamical processes occurring at various levels in the Earth atmosphere. The prominent signature of the variability of the solar UV irradiance can be observed in the atmosphere with periodicities, 11 years (solar cycle), 1 year (seasonal) and 27 days (Carrington rotation) as investigated by the past investigators from various locations over the globe (Suh and Lim 2006; Guharay et al. 2009, 2017, 2019 and references therein). A major portion of the solar UV flux is absorbed in the middle atmosphere. The short-term solar UV flux variability can be as large as 25% during solar active condition (Schanz et al. 2016). The solar 11-year oscillation was reported mostly in the stratospheric ozone as the photochemical processes associated to ozone production are very sensitive to the solar UV radiation (Chandra and McPeters 1994; Hood 1997).

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The evident feature of the solar 27-day oscillation was found in various atmospheric parameters, e.g. lightning activity (Füllekrug and Fraser-Smith 1996), ozone concentration (Hood, 1997; Ross and Walterscheid 1991), temperature (Hood 2016), wind (Huang et al. 2015; Guharay et al. 2017), ionospheric plasma (Pancheva et al. 1991; Ma et al. 2012; Ren et al. 2018), etc. The 27-day oscillation is most pronounced in the Lyman-α line (UV band) although it is present in the total solar irradiance. The evident signature of the 27-day oscillation was also reported in the long-period planetary wave activities in the stratosphere (Ebel et al. 1981; von Savigny et al. 2019).

Using Whole Atmosphere Community Climate Model (WACCM), Schanz et al. (2016) investigated the effect of solar irradiance on the zonal wind variability. They concluded that the solar short-term variability driven atmospheric perturbations might interact with atmospheric internal oscillation modes or background mean flow to cause associated changes in the ambient dynamical condition. With the help of space-based observations from the Solar Occultation for Ice Experiment (SOFIE) onboard Aeronomy of Ice in the Mesosphere (AIM) satellite, Thomas et al. (2015) found evident signature of the solar 27-day oscillation in the water vapor and temperature that could influence the chemistry of the polar mesospheric cloud (PMC) formation. Luo et al. (2001) studied the longer period (20–40 days) wind oscillation characteristics in the MLT using multi-station radar observations at mid and high latitudes in the Northern hemisphere and inferred that the 27-day periodicity in the wind was a manifestation of solar short-term variability.

As mentioned before, the 27-day oscillation was evident in various atmospheric quantities. However, relationship between the solar 27-day signal and the dominant atmospheric tides is not looked into extensively and hence our understanding regarding the underlying processes is very limited. Furthermore, different signatures of the 27-day signal in the MLT were obtained by the past investigators. Previous studies interpreted that the concerned oscillation in the middle atmosphere was (i) linked with the solar rotation (Pancheva et al. 1991; Luo et al. 2001; Guharay et al. 2017), (ii) a component of the lower atmospheric intraseasonal oscillations (Huang et al. 2015) and (iii) an inherent mode of the atmosphere (Schanz et al. 2016). In the present work, an extensive investigation related to the imprint of the 27-day signal on the dominant MLT tides and its relationship with the solar rotation is carried out using meteor radar wind observations from three low-latitude Southern hemispheric stations, São João do Cariri (7.4° S, 36.5° W) (CA), Cachoeira Paulista (22.7° S, 45° W) (CP) and Santa Maria (29.7° S, 53.7° W) (SM).

Instrument and data analysis
Meteor radar
The meteor radar systems in the current study are a SKiYMET type, operating at a frequency of 35.24 MHz. It uses peak power of 12 kW, pulse width of 13 μs and pulse repetition frequency of 2 kHz. It consists of a three-element transmitting antenna and five phase-coherent, two-element Yagi antennas aligned along two orthogonal baselines with a center antenna common to the both for detecting meteor echoes. Since both receiving and transmitting antennas have a large angle of acceptance, the radar records meteor echoes in all zenith and azimuth directions. The radar detects around 5000 meteor echoes per day to estimate angular position, range and radial velocity. Details of the radar operation and method of horizontal wind velocity estimation can be found in the past literature (Hocking et al. 2001).

In the present study, horizontal winds from the three radar systems are used with temporal resolution of 1 h and vertical resolution of 3 km in the MLT (80–100 km). The amplitude and phase of the dominant tidal components are estimated using least square fit method considering a data window of 4 days, which is progressively shifted by a day to estimate daily tidal parameters using Eq. 1.

$$Y(t) = Y_0 + \sum_{n=1,2,3} A_n \sin\left[\frac{2\pi n}{24}(t - \phi_n)\right] \qquad (1)$$

where $n = 1$, 2, 3 denote diurnal, semidiurnal and terdiurnal components, t is the time in hour, A is the amplitude of the tide, ϕ is the phase of the tide, Y_0 is the mean value within the fitting window and $Y(t)$ is the zonal/meridional wind. The tidal parameters are estimated for the cases where at least 48 data points (twice the period of the diurnal tide) are available. However, one should note that selection of 4-day window can give two or three consecutive ambiguous daily outputs depending on the pattern of the available and missing data. We have thoroughly checked the same with our observational intervals used for the present study and do not find any such case. Since the quasi-2-day wave was found to be very active at times over the present sites (Guharay et al. 2013b), it is removed from the original time series before estimating the tidal parameters.

The daily tidal amplitudes estimated from the available data spans, 2004–2008 (CA), 1999–2018 (CP), 2004–2010 (SM), are undergone wavelet analysis using Morlet as a mother wavelet (Torrence and Compo 1998) to obtain the spectra of the modulating periodicities. Utilizing the wavelet spectra of all three sites, intervals with evident 27-day modulation are identified and used for

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further analysis. The 27-day modulation is mostly found in the tidal amplitudes derived from the zonal wind and hence only zonal amplitudes are utilized in the present study. The interval window is restricted to 62 days (~ more than twice the period of interest) to avoid long data gaps and to maintain uniformity among the selected cases. The details of the selected intervals when 27-day modulations of the tidal amplitudes in the zonal wind are prominent are provided in Table 1. Overall, 3 cases at CA, 9 cases at CP and 3 cases at SM containing all the tidal components (diurnal, semidiurnal and terdiurnal) are identified and analyzed in the present work as illustrated in Table 1. The 27-day modulated amplitudes and corresponding phases in the tides are estimated by utilizing least square fit on the daily tidal amplitudes for each interval (window of 62 days) and tidal component independently.

Solar Lyman-*α* flux

To find out the solar linkage of the observed 27-day modulation in the tidal amplitudes obtained from the zonal wind in the MLT, solar Lyman-α flux (121.6 nm) data provided by the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado, corresponding to the selected intervals are analyzed. For the present purpose, the Lyman-α data with temporal resolution 1 day are utilized.

The dominant periodicities in the solar flux during the selected intervals are estimated using wavelet analysis. To determine the relationship between the solar flux and 27-day oscillations in the MLT tidal amplitudes in

the zonal wind, cross-correlation analysis is carried out. Before carrying out the cross-correlation analysis, both series are undergone a bandpass filter with cutoffs at 24 and 31 days to consider the quasi-27-day oscillation.
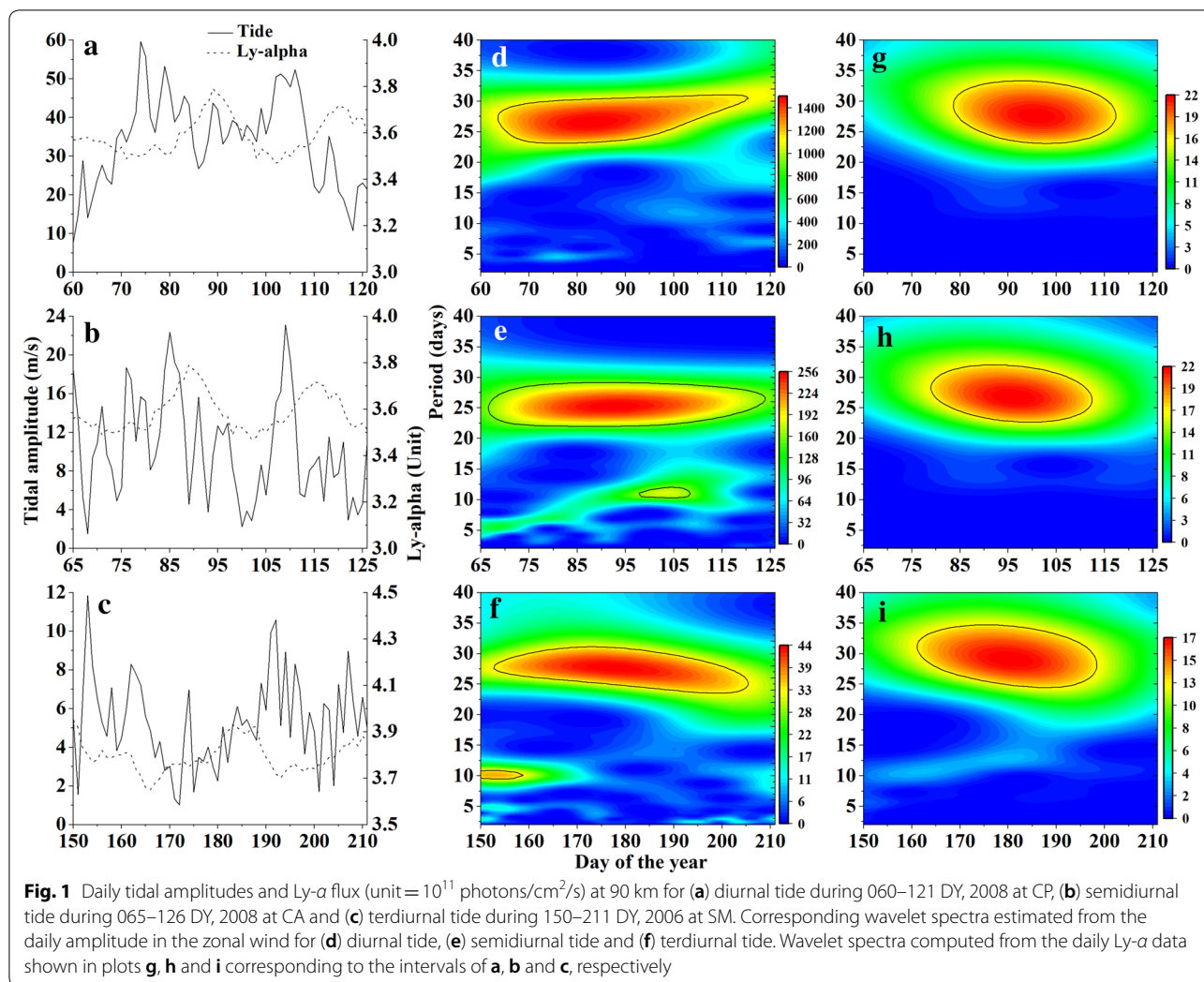
Results

The daily tidal amplitudes at 90 km and Ly-*α* flux (unit $= 10^{11}$ photons/cm^2/s) for the selected intervals, i.e. diurnal (060–121 DY, 2008) at CP, semidiurnal (065–126 DY, 2008) at CA and terdiurnal (150–211 DY, 2006) at SM, respectively (DY represents day of the year). In general, solar flux exhibits visually identifiable crests/troughs with approximate periodicity ~ 30 days. Tidal amplitudes show more fluctuations in the temporal profiles. Although diurnal tide exhibits less prominent ~ 30-day periodicity, such behavior is not very clear in other tidal components. To determine the exact periods, wavelet analysis is carried out. Figure 1d–f shows the wavelet power spectra of the tidal amplitudes in the zonal wind at 90 km for the corresponding intervals. The bold lines represent the 95% significance level. Evident from the plots is conspicuous periodicity near 27-day in all the spectra. In addition, smaller but significant patch of 10-day period is also present in the semidiurnal and terdiurnal components indicating a possible coupling with a 10-day planetary wave. However, since the theme of the present work is 27-day oscillation, we will not discuss any other waves/oscillations in the rest of the manuscript. One may note a slightly lesser periodicity in the tidal amplitudes as compared to the Ly-α. The small difference in the observed periods may be ascribed to direct bearing of the solar signature in case of solar flux and subsequent imprint on the atmospheric wind/tides (i.e. atmospheric response to the solar forcing). Figure 1g–i shows the wavelet power spectra estimated from the solar Lyman-α flux corresponding to the above-mentioned intervals. It is interesting to note that all the three solar spectra exhibit dominant power near 27-day consistent with the spectra of the tidal amplitudes in the zonal wind implying a possible link between them. However, during 150–211 DT, 2006, the period in the Lyman-α spectra is slightly higher than the same of the tidal spectrum in the zonal wind. Behavior of the 27-day oscillation in the tidal amplitudes and their association with the solar flux will be investigated in the following part of the paper.

Figure 2a–c shows the 27-day modulated amplitudes of diurnal tide at CA, CP and SM, respectively. Larger number of cases is visible at CP as compared to the other sites due to longer database. At CA, gradual increase of amplitude is visible although there is a saturation tendency at bottom and top altitudes. At CP, vertical behavior of the modulated amplitudes for the 4 years is not smooth unlike CA. Broadly, the variability can be considered as

Table 1 Details of the selected intervals showing evident signature of the 27-day modulation of the tidal amplitude in the zonal wind

Station	Tidal component	Interval (DY)	Year
São João do Cariri (7.4° S, 36.5° W)	Diurnal	220–281	2004
	Semidiurnal	065–126	2008
	Terdiurnal	160–221	2008
Cachoeira Paulista (22.7° S, 45° W)	Semidiurnal	110–171	2002
	Semidiurnal	110–171	2003
	Terdiurnal	140–201	2003
	Diurnal	235–296	2004
	Diurnal	060–121	2008
	Diurnal	250–311	2012
	Terdiurnal	250–311	2012
	Semidiurnal	260–321	2013
	Diurnal	210–271	2014
Santa Maria (29.7° S, 53.7° W)	Terdiurnal	155–216	2006
	Diurnal	240–301	2008
	Semidiurnal	105–166	2010

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Fig. 1 Daily tidal amplitudes and Ly-*α* flux (unit = 10^{11} photons/cm^2/s) at 90 km for (**a**) diurnal tide during 060–121 DY, 2008 at CP, (**b**) semidiurnal tide during 065–126 DY, 2008 at CA and (**c**) terdiurnal tide during 150–211 DY, 2006 at SM. Corresponding wavelet spectra estimated from the daily amplitude in the zonal wind for (**d**) diurnal tide, (**e**) semidiurnal tide and (**f**) terdiurnal tide. Wavelet spectra computed from the daily Ly-*α* data shown in plots **g**, **h** and **i** corresponding to the intervals of **a**, **b** and **c**, respectively

two types, (i) increasing trend with altitude (2004 and 2014) and (ii) peaking near 87–90 km and decreasing upward as well as downward (2008 and 2012). The maximum 27-day modulated tidal amplitude is observed in 2008 near 87–91 km. Except 2012, all the profiles exhibit decreasing amplitude with respect to altitude at the bottom. On the other hand, at SM a single profile shows alternate maxima and minima in the MLT with overall decreasing trend.

Figure 2d–f plots the 27-day corresponding phases of the diurnal tidal modulation at the three stations. The phase profiles over all the locations show relatively smoother behavior as compared to the amplitudes depicted before. It should be noted that the phases are basically estimated considering initial time similar to the method of Guharay et al. (2017), and hence, phase and oscillation propagation directions are similar. In general, the phase profile at CA shows slightly negative phase gradient indicating downward oscillation progression.

Overall, the phase profiles at CP exhibit upward phase/oscillation propagation except 2014, although the regions 81–84 and 87–100 km individually show upward phase/oscillation progression in 2014. At SM, the phase profile shows almost consistent upward phase/oscillation progression.

Similarly, the 27-day modulated amplitude and corresponding phase profiles of the semidiurnal tide are shown in Fig. 3. Although the amplitude shows monotonically increasing behavior in the MLT, it decreases sharply at the top. Interestingly, at CP all the profiles show two prominent troughs around 84–87 and 93–96 km and one crest within 90–93 km. The maximum modulated amplitude is observed at the top in 2003. The amplitude profile at SM shows "S" kind of feature with a crest at 84 km and trough at 93 km.

The corresponding 27-day semidiurnal phase profile at CA shows decreasing trend or downward phase/oscillation progression. However, at CP all the three

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Fig. 2 The 27-day modulated zonal diurnal tide amplitude at (**a**) CA, (**b**) CP and (**c**) SM. Corresponding phases of the 27-day amplitude modulation are shown at (**d**) CA, (**e**) CP and (**f**) SM

Fig. 3 Same as shown in Fig. 2, but here it is for the zonal semidiurnal tide
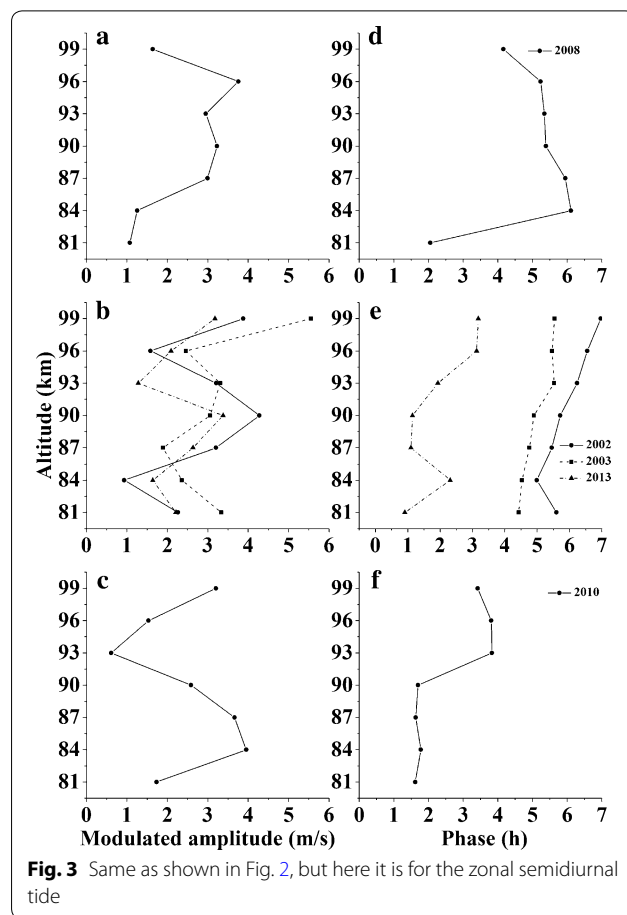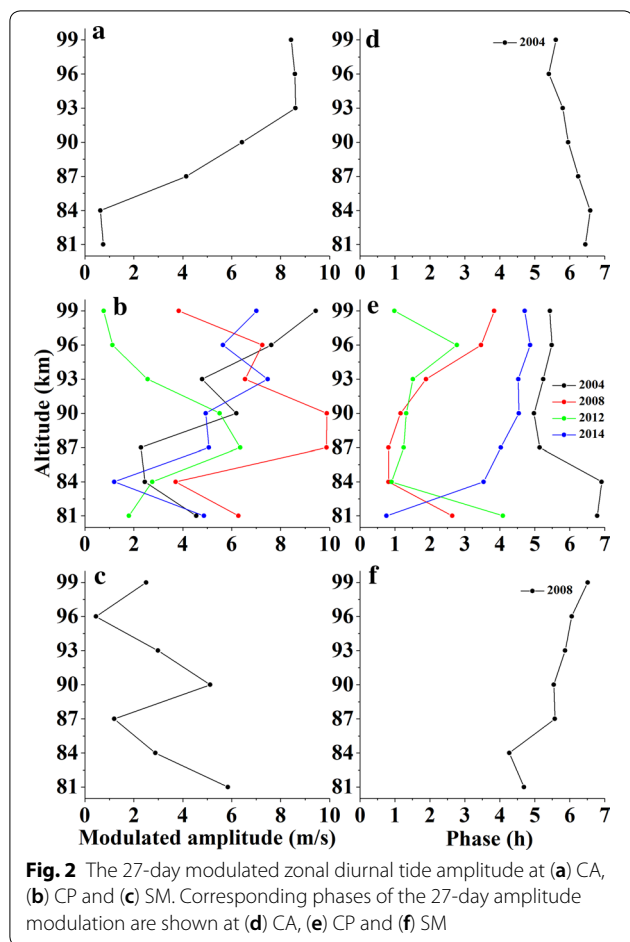
profiles exhibit upward phase/oscillation propagation. At SM, the phase behavior is different at upper and lower MLT as the phase gradient is slightly negative at upper altitudes and slightly positive at lower MLT with a sharp positive change around 90–93 km.

In a similar fashion, the 27-day modulated amplitudes and corresponding phases of the terdiurnal tide are plotted in Fig. 4. The amplitude at CA shows almost linear alternate increase and decrease with a peak at 87 km and dip at 93 km. At CP, the amplitude profiles are generally zig-zag in nature. However, the profile in 2003 shows overall increasing trend and no clear trend can be evinced in 2012. On the other hand, at SM almost linear increasing amplitude at lower MLT from 84 to 93 km and decreasing trend hereafter can be noted.
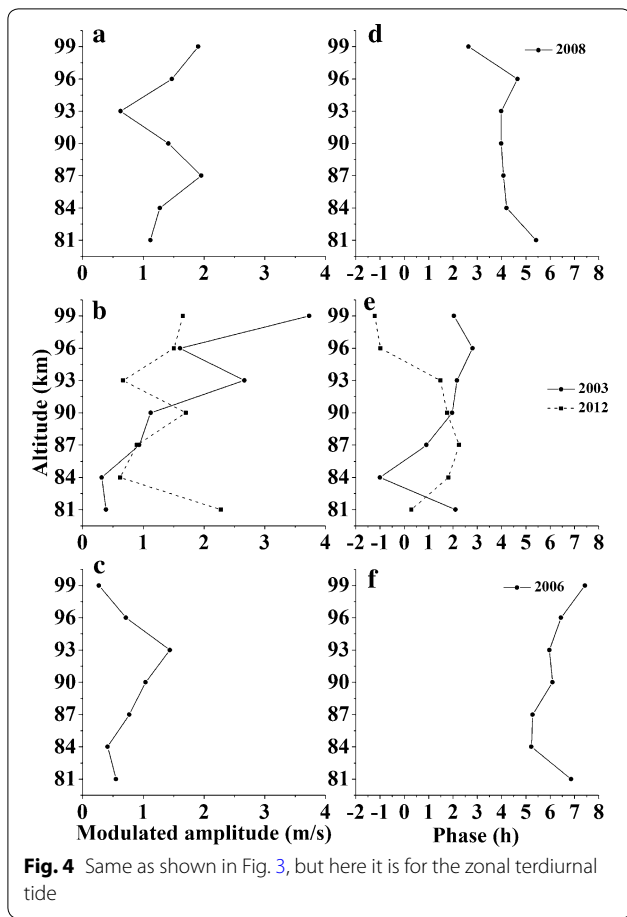
The phase variation at CA shows overall small negative gradient implying downward oscillation progression. The oscillation propagation direction at CP can be found to be upward from 84 km in 2003. However, in 2012 oscillation propagation is upward in the lower MLT and downward hereafter. At SM, small positive gradient of the

phase profile can be observed implying upward oscillation progression.

So far, the characteristic features of the 27-day modulation on the dominant tides in the MLT are investigated. To find out its link (if any) with the solar radiation, cross-correlation analysis is carried out and the results are presented in the subsequent paragraphs.

The cross-correlation coefficient (r) between the filtered solar Lyman-α flux and tidal amplitudes in the zonal wind is shown in Fig. 5a–c. The values of r greater than 0.5 (significant with $\alpha = 0.01$) are considered for existing relationship between the two variables. According to the r values, there exists a strong relation between the two variables as found at lower MLT at CA. Although r decreases at higher altitude, significant relationship exists in the MLT. At CP, almost constant and strong correlation is found in all the profiles over the whole range except at the bottom and top altitude bins. On the contrary, no evident correlation is found among the two variables except at 87 and 96 km at SM.

The corresponding cross-correlation lag profiles are shown in Fig. 5d–f. Here, the positive lag represents that the oscillation in the solar flux leads the same of the tidal

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Fig. 4 Same as shown in Fig. 3, but here it is for the zonal terdiurnal tide

Fig. 5 Cross-correlation coefficient estimated between the filtered solar flux and zonal diurnal tide amplitude at (**a**) CA, (**b**) CP and (**c**) SM. Cross-correlation lags are shown at (**d**) CA, (**e**) CP and (**f**) SM
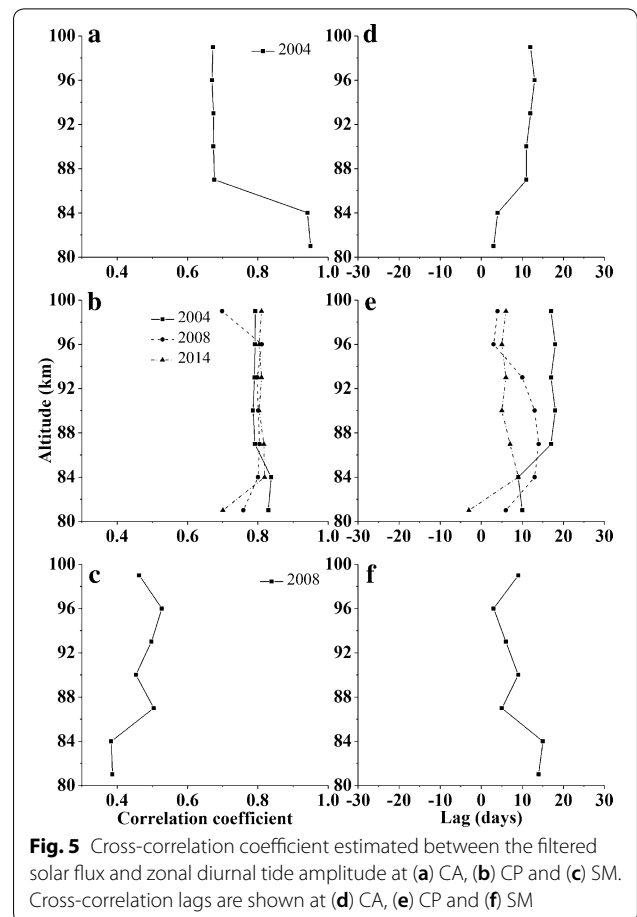
amplitude in the zonal wind and the negative value of the lag indicates the opposite. The positive lag (maximum 13 days) all over the MLT at CA may indicate influence of solar radiation toward the 27-day modulation of the diurnal tide. At CP, the lag profiles are mostly positive except at bottom in 2004. The observed range of the positive lag is 3–18 days indicating a possibility of wide range of response time of the MLT tides to the solar radiation. Although a positive lag profile is found at SM, small correlation values (*r*) are unable to ascertain any relationship between the solar flux and MLT tidal oscillation except at 87 and 96 km.

Similar to the previous plot, the *r* profiles for the semidiurnal tide are shown in Fig. 6a–c. Significantly large correlation (>0.8) is found at CA with a small positive gradient except at the top. At CP, strong correlation is found in 2003 and relatively weaker correlation is observed in 2013 at 84, 93, 96 and 99 km. However, in 2002 no evident correlation can be noted. At SM, appreciable correlation can be observed throughout the range.

The correlation lags corresponding to the semidiurnal tide are shown in Fig. 6d–f. At CA, the lag starts with negative values at the bottom and increases gradually

and finally turns to positive in the upper MLT. The large negative lag at lower altitude may indicate the presence of the 27-day modulation of the tides is most probably due to some other source/s that will be discussed in the next section. Notably, long (>20 days) lags are found in 2003 and 2013 indicating slow response of the MLT tides to the solar forcing. Since the correlation is found to be insignificant in 2002, implication of lag values cannot be conceived. At SM, consistent and short positive lags are visible except the upper range (96–100 km).

In a similar way, the *r* values for the terdiurnal tides are shown in Fig. 7a–c. High and almost constant correlation is observed all over the range except 81 km at CA in 2008. At CP, appreciable correlation can be found in the range 81–93 km with a very high correlation around 96–99 km. However, in 2003 no evident correlation is observed. Almost constant and large correlation throughout the range is evident in 2006 at SM.

Figure 7d–f shows the correlation lag profiles of the terdiurnal tide. Small positive lags are evident at mid and top altitudes at CA. At CP, mostly negative lags are present except at top altitudes (96–99 km) in 2012

Fig. 6 Same as shown in Fig. 5, but here it is for the zonal semidiurnal tide

Fig. 7 Same as shown in Fig. 6, but here it is for the zonal terdiurnal tide
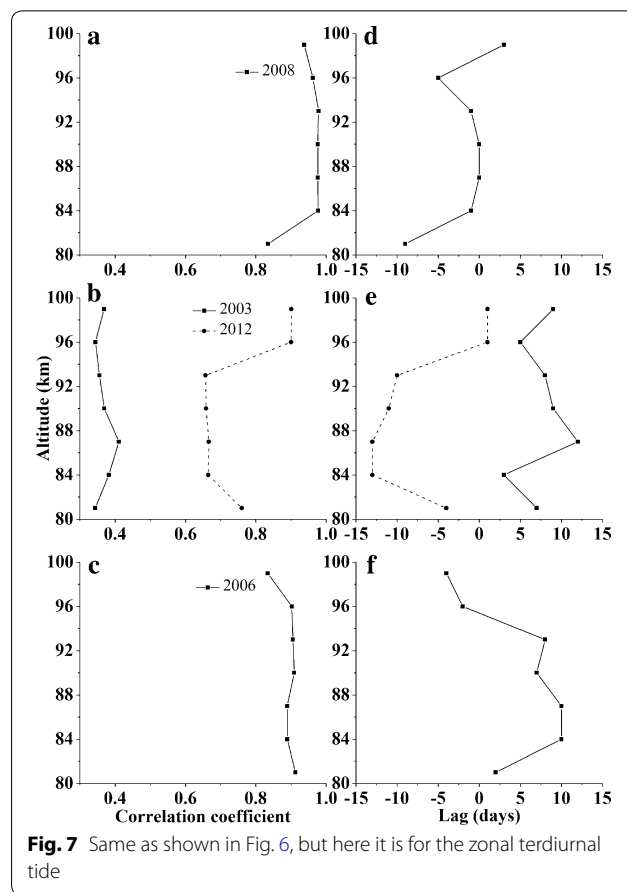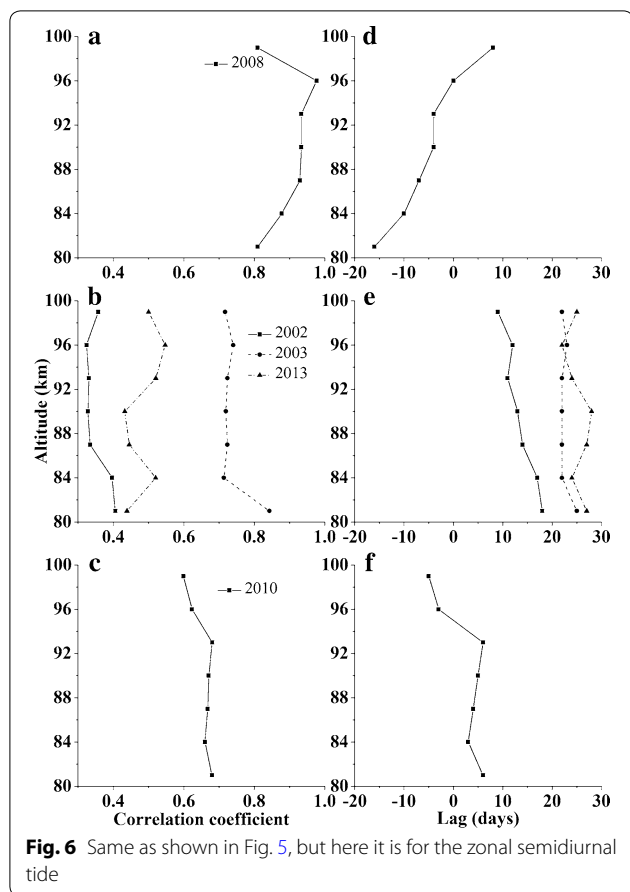
corresponding to high *r* values. On the other hand, sufficiently long positive lags are observed in 2003. However, solar association cannot be deemed herein due to small correlation values. At SM, lags are mostly positive with maximum value of 10 days, except at the top (96–99 km).

Discussions

A handful of cases of prominent signature of the 27-day modulation in the dominant atmospheric tides in the MLT are found in the long-term meteor wind database from three low-latitude Southern hemispheric stations. The modulation of the tides reveals significant variability in the MLT among various stations. The solar influence on the tidal modulation is investigated. At present, there is hardly any study available that extensively deals with the tidal modulation and solar relationship from the low-latitude region corroborating importance of the present work. Some interesting features as observed in the present study are discussed in view of the plausible mechanisms and agreement/disagreement with the available literatures.

As mentioned earlier, the 27-day oscillation is mostly observed in the tidal amplitudes in the zonal wind (weak

and infrequent appearance of the same in the meridional wind) that leads us to focus only on the tidal modulation in the zonal wind. In case of 27-day wind modulation, all the previous studies found strong activity of the concerned oscillation in the zonal wind (Luo et al. 2001; Huang et al. 2015; Guharay et al. 2017). Therefore, major impact of the solar flux variability can be conceived to be on the zonal circulation of the atmosphere and a similar imprint on the tidal amplitudes in the zonal wind can also be deciphered from the present findings.

From the results of the present study, one may note that the 27-day modulation does not take place in all the tidal components simultaneously although the atmospheric tides are primarily driven by the solar radiation due to absorption by the atmospheric species, e.g. water vapor, ozone, etc. The intervals of dominant 27-day modulation of the various tidal components in Table 1 may indicate independent relationship of the tides with the solar radiation which seems to be logically incongruous. The reason for such occurrence is the choice of the events based on the statistical significance of the concerned spectral component. Since the period of the concerned oscillation signature lies well within the intraseasonal oscillation (ISO)

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band, existence of dominant ISO components might suppress the period of our interest at times and as a result, all the three tides may not manifest the 27-day modulation simultaneously. Another reason could be the response mechanisms of the atmospheric species (water vapor, ozone, etc. responsible for tidal excitation) to the solar flux variability that may affect the final tidal response to the solar radiation indirectly.

Naturally, a question arises whether the periodicity is a manifestation of the ISO originating in the lower atmosphere that finally reaches the MLT through gravity waves, planetary waves and tides (Eckermann et al. 1997). Since some of the present cases (out of total 15 cases) exhibit strong correlation (with positive lag) between the solar short-term variability and tidal 27-day modulation, there is a strong implication of solar influence on the tidal variability. However, in the case of longer positive lags, indirect impact of the solar radiation, i.e. first lower atmospheric excitation, and subsequent propagation of the same to the MLT through tides also looks a viable mechanism in addition to the direct excitation. In this context, it should be mentioned that the observed 27-day modulation of the tides over the present sites is not a regular feature. It rather is intermittent appearing in the presence of congenial ambient condition and suitable forcing.

Furthermore, the prominent 27-day variability in the MLT zonal wind can be due to tropospheric convective activities (Huang et al. 2015) or a manifestation of a normal mode inherent in the atmosphere (Andrews et al. 1987; Schanz et al. 2016). In the present study, weak correlation between the solar UV flux variability and MLT tidal modulation is also found at certain intervals. In addition, in some cases, long negative lags (short negative lag to be discussed later) are observed although correlation may be strong. In such cases, it is unlikely that the concerned modulation is directly linked to the solar rotation and hence it could be of lower atmospheric origin as suggested by the previous investigators mentioned above. Utilizing model simulation, Schanz et al. (2016) argued that the 27-day periodicity in the atmosphere should not be linked with the solar rotation as the same could be masked by the dominant inherent mode of the atmosphere, although they admitted that the determination of the actual solar contribution toward this feature to be challenging. Furthermore, they also pointed out a possibility of considerable solar rotational influence on the mesospheric dynamics in winter that seems to be consistent with the present finding.

Recent study by Guharay et al. (2017) from the same locations found an intermittent 27-day feature in the long-term MLT zonal wind and concluded major linkage with the solar UV flux as compared to the lower

atmospheric convection. Therefore, from the above discussion, one can interpret that the contribution of the lower atmospheric dynamics cannot be ruled out even in the cases of strong correlation between the modulated tidal amplitudes and solar flux as found in the present work although the lower atmospheric processes are ultimately controlled/modified by the incoming solar radiation.

In a most recent study, Zhao et al. (2019) concluded a prominent manifestation of a Rossby normal mode with the periodicity ~ 28 days in winter at high/polar-latitudes and weak feature of the same at mid-latitudes. However, this finding does not seem to be related with the present results due to various reasons: (i) present study is based on low-latitude observations and (ii) the 27-day signature in the current study is found to exist over various seasons in multi-year observations. Ultimately, the previous study indicated a possible role of solar 27-day variability toward excitation of the suspected normal mode consistent with the discussed source mechanism of the present study.

The solar UV flux, utilized in the present study to investigate the solar influence on the tides in the MLT, has a major implication associated to the atmospheric tides. Since the solar UV radiation is effectively absorbed by the ozone in the stratosphere, it has potential to modify the amplitudes of the propagating tides (Ross and Walterscheid 1991). It was also argued that the solar irradiance might not directly modify the MLT dynamics, rather its effect reached there through absorption by the stratospheric ozone (Luo et al. 2001). Using meteor wind observations from a mid-latitude station, Pancheva et al. (2003) indicated a plausible link between the semidiurnal tide in the MLT and the stratospheric ozone in the perspective of the 27-day modulation. Therefore, all the above findings indicate a possible origin of the observed 27-day tidal modulation in the stratosphere due to ozone abundance that reach MLT through the upward progressing tides. Thus, the modulation in the MLT tidal amplitudes as observed in the present study can also be interpreted as an indirect effect of the solar flux via stratospheric excitation.

As mentioned earlier, a few cases in the present study reveal weak correlation between the solar UV flux and MLT tidal modulation that may underestimate the direct solar influence on the observed tidal variability. In addition to the lower atmospheric contribution mentioned before, another possibility for this phenomenon could be a considerable shift of the solar rotational period from the concerned 27-day as it was found to vary within a wide range of 19–33 days (Kane 2002). Furthermore, the corresponding 27-day phase directions show both upward and downward propagation. The upward progression of the phase/oscillation is consistent with the

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previously discussed stratospheric/lower atmospheric influence on the tides. The downward propagation of the corresponding phase may indicate a possible excitation of the concerned oscillation in the ionosphere above (Ma et al. 2012). In this context, it is relevant to mention that the ionospheric response to the solar 27-day variability is prompt enough with a delay as short as less than a day (Ren et al. 2018) supporting the plausibility of the observed lag of a few days in the MLT.

Earlier, Pancheva et al. (1991) inferred that the 27-day oscillation in the ionospheric D region was of direct origin provided the Lyman-α flux bore the same periodic variability. In the present study, the simultaneous existence of the concerned oscillation in both tidal amplitudes and solar Lyman-α flux with short positive lag is consistent with the interpretation of the previous study.

The 27-day modulated tidal amplitudes and corresponding phases exhibit large variability in the MLT. The complexity of such behavior actually depends on the tidal strength, background wind, thermal condition, ambient stability condition, solar flux variability and the associated atmospheric chemistry that could only be addressed through additional and extensive study and beyond the scope of the present work. As depicted before, a few cases of negative lags are observed corresponding to the high correlation. The short negative lags in the cross-correlation analysis may be attributed to the solar influence. In this context, it can be mentioned that Keating et al. (1987) explained the small negative lag (< 3 days) in the ozone variability in response to the solar short-term UV variability in presence of the temperature feedback mechanism. Although in the present work the investigated parameter is different (tidal amplitude), it may imply an analogous process. In this connection, further extensive study is required to obtain greater details regarding the underlying processes responsible for such peculiar behavior.

Summary

An evident signature of the intermittent 27-day modulation in the dominant tidal amplitudes (diurnal, semidiurnal and terdiurnal) is found in the MLT using long-term meteor wind data over three Southern hemispheric low-latitude stations. The influence of the solar rotation on the observed tidal modulation is studied using simultaneous solar Lyman-α flux. Prominent linkage between the tidal modulation and the solar UV radiation is found in a number of cases indicating predominate solar influence in controlling the tidal activities in the MLT. In addition to the direct solar radiation, lower atmospheric dynamics, convective activity, absorption by ozone in the stratosphere, ionospheric absorption of solar radiation, etc. are also surmised to influence the prominent tidal variability in the MLT at times. A few intricate issues, i.e. vertical variation behavior of the modulated tidal amplitude and corresponding phase, long negative lag in concert with high correlation coefficient, etc. as appear, require further coordinated study to improve our current understanding.

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