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Diurnal, monthly and seasonal variation of mean winds in the MLT region observed over Kolhapur using MF radar

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ABSTRACT

Medium Frequency (MF) radar located at Kolhapur (16.8°N, 74.2°E) has been upgraded in August 2013. Since then continuous measurements of zonal and meridional winds are obtained covering larger altitudes from the Mesosphere and Lower Thermosphere (MLT) region. Diurnal, monthly and seasonal variation of these mean winds is presented in this study using four years (2013–2017) of observations. The percentage occurrence of radar echoes show maximum between 80 and 105 km. The mean meridional wind shows Annual Oscillation (AO) between 80 and 90 km altitudes with pole-ward motion during December solstice and equatorial motion during June solstice. Quasi-biennial oscillation (QBO) with weaker amplitudes are also observed between 90 and 104 km. Zonal winds show semi-annual oscillation (SAO) with westward winds during equinoxes and eastward winds during solstices between 80 and 90 km. AO with eastward winds during December solstice and westward wind in the June solstice is also observed in the mean zonal wind between 100 and 110 km. These results match well with that reported from other latitudes within Indian region between 80 and 90 km. However, above 90 km the results presented here provide true mean background winds for the first time over Indian low latitude region as the present station is away from equatorial electro-jet and are not contaminated by ionospheric processes. Further, the results presented earlier with an old version of this radar are found contaminated due to unknown reasons and are corrected in the present work. This upgraded MF radar together with other MLT radars in the Indian region forms unique network to investigate the vertical and lateral coupling.

1. Introduction

Equatorial or low latitude atmosphere plays a key role in the global change of the Earth's environment due to predominant convective systems. Many dynamical processes take place at equatorial or low latitude middle mesosphere. Some of these processes are caused due to large solar insolation, relatively less Coriolis force yielding to the long-period wave modes in these regions (Hamilton, 1999; Rajaram and Gurubaran, 1998). Waves of this kind contribute significantly to the energy budget of the middle atmosphere through complex wave mean flow interactions (Eswaraiah et al., 2013) to some long period oscillations like Quasi-Biennial Oscillation (QBO) (Lindzen and Holton, 1968; Reed, 1965), Semi-Annual Oscillation (SAO) (Reed, 1965; Hirota, 1978; Dunkerton, 1979) and Annual Oscillation (AO) (Burrage et al., 1996; Garcia et al., 1997). Therefore, in recent years much attention has been paid to study the dynamics of the equatorial and low latitude mesosphere and lower thermosphere (MLT) region.

Medium frequency (MF) radars have been widely used to measure the MLT winds on continuous basis but more reliably above 80 km. MF radar measures echoes generated from mesospheric electrons which are dragged by the neutral air flow due to their high collision frequency. Partial reflection radars operating in the medium frequency range yields useful information of mean winds, tides, planetary waves and gravity waves in the MLT region (Rajaram and Gurubaran, 1998; Patil et al., 2007). It has been observed that planetary waves with various periods exist in the middle and upper atmosphere and they contribute to the variability of

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the atmospheric parameters in these regions (Kishore et al., 2004). The MF radars working at several places are useful in deriving the enormous information about the less understood MLT region. The formation of radar networks has advanced coordinated studies across the globe (Manson et al., 1999).

In the year 1999, Indian Institute of Geomagnetism has established MF radar at Kolhapur (16.8°N, 74.2°E). Using data from June 2000 to April 2003, Patil et al. (2007) have reported first results from this radar covering the altitudes 70–98 km. Sharma et al. (2010) made the comparative study of MLT mean winds (80–98 km) between Kolhapur and Tirunelveli (8.7°N, 77.8°E). They observed SAO in the meridional wind and AO in the zonal wind over Kolhapur but the opposite was noticed over Tirunelveli. Signatures of QBO were observed in zonal wind over Tirunelveli as well. However, it is found that the results presented by both the studies mentioned above are contaminated due to unknown reasons. These are corrected in the present communication using the upgraded version of this radar re-established in August 2013. The up-gradation has been done in the hardware section in the sense that earlier it was Analog transmitter and receiver. The new system contains *trans*-receiver that is similar to MF radar system at Tirunelveli. After up-gradation, the radar is functioning with full power and provides an excellent data quality. Rokade et al. (2012) reported the latitudinal behavior of intra-seasonal oscillations (ISO) in the zonal wind at low latitude MLT region and found that ISO activity is strong in the regions where convective activity is strong. They used data from the two stations mentioned above. Ratnam et al. (2001) and Kumar et al. (2008) compared various techniques (MF radar, Tirunelveli, High Resolution Doppler Imager (HRDI) onboard the Upper Atmospheric Research Satellite (UARS), and CIRA-86 model) with Mesosphere, Stratosphere and Troposphere (MST) radar located at Gadanki (13.5°N, 79.2°E). They observed SAO and QBO in the zonal wind and large inter-annual variability in the meridional wind. Ratnam et al. (2008) from the same station (Gadanki) showed the SAO and QBO in the lower mesospheric height (70–80 km) and studied the phase difference of these oscillations with stratospheric quasi-biennial oscillation (SQBO). Similarly, long term oscillations in MLT region are extensively studied by using different ground based observational techniques over low latitude and equatorial stations (Gadanki, Thumba (8.5°N, 77°E) and Tirunelveli) (Rajaram and Gurubaran, 1998; Sridharan et al., 2007; Kumar et al., 2008, 2014; Rao et al., 2012; Ratnam et al., 2013).

The main objective of the present communication is to provide results using upgraded MF radar that could resolve the previously reported errors. Further, altitude coverage is extended to 110 km to provide true background winds for the first time as the present location is away from the equatorial electro jet that is not contaminated by any ionospheric processes.

2. Data and methodology

The data used for the present study is collected from MF radar for the period August 2013 to July 2017 covering ~4 years of data. This radar is located at Shivaji University Campus, Kolhapur (16.8°N, 74.2°E) and has been installed by Indian Institute of Geomagnetism (IIG), Mumbai, in the year 1999 and has been upgraded in the year 2013. The system operates at 1.98 MHz with 32 kW peak power, 25 μs pulse duration and 2 km height resolution. It is fully phase coherent and determines the horizontal winds in the MLT region between 70 and 110 km with a time resolution of 1 min. The antennae are circularly polarized. Although the vertical resolution is 2 km, the actual height sampling is about 4–5 km. The pulse repetition frequency is 80 Hz (40 Hz) with 32 (16) point coherent integration during day (night) time, to avoid problems arising due to equatorial spread F (ESF). Another almost identical system (MF radar) is installed by IIG at equatorial station Tirunelveli (8.7°N, 77.8°E) with the only difference is that the antenna is linearly polarized. The typical MF radar setup is shown in Fig. 1. The set of receiving antenna are located at the vertices of an equilateral triangle with spacing of 180 m or 1λ. The transmitting antennas are in square shape with a spacing 75 m or λ/2 (Sharma et al., 2010). More details regarding the system are given in Vincent and Lesicar (1991).

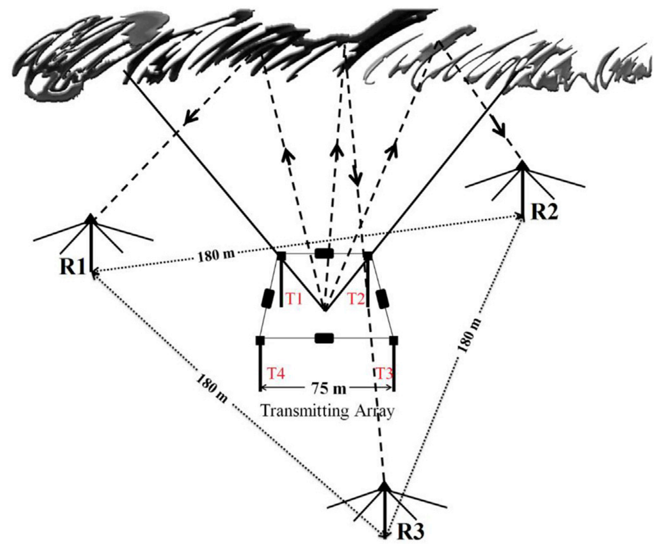

Fig. 1. Schematic layout of MF Radar system located at Kolhapur.

The map indicating the geographic location of the Kolhapur MF radar is depicted in Fig. 2 along with the locations of other MLT radars over the Indian region i.e., MF radar at Kolhapur, Meteor radar at Thumba, MF radar at Tirunelveli, MST radar at Gadanki and Meteor radar at Tirupati. The MST radar can be used to study the dynamics up to 80 km while using MF radar one can study above 80 km. The MF radar and meteor radar have consistency in measurement of winds below 90 km. Above this altitude, huge differences in the measurements is observed (Kumar et al., 2007; Rao et al., 2014). The earlier radar from the same location was able to measure the winds up to 98 km. After up-gradation of radar, now it is able to measure winds up to 110 km. Thus, additional information covering higher altitudes from this radar can be beneficial to understand the dynamics of low latitude MLT region.

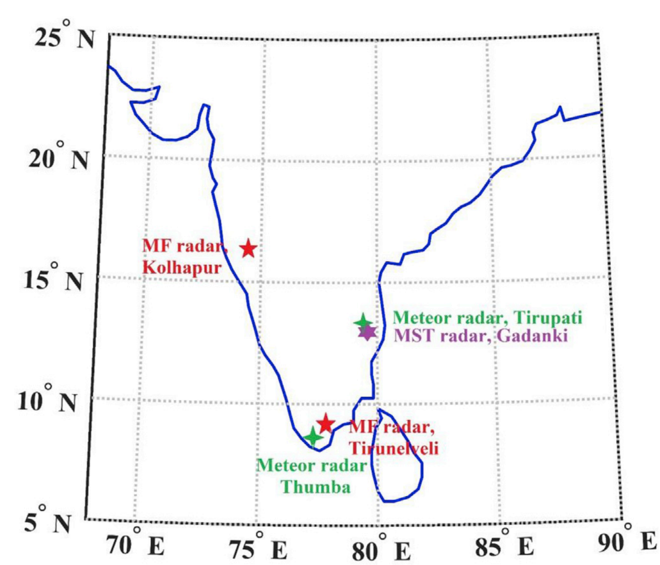

Fig. 2. Map showing the geographic locations of the MLT radars located in India along with Kolhapur MF radar.

3. Percentage occurrence (PO) of MF radar echoes

Before using data from this radar, it will be useful to check the percentage occurrence of echoes from different altitudes so as to assess the statistically significant results. The monthly mean percentage occurrence of MF radar echoes obtained during August 2013 to July 2017 is shown in Fig. 3(a). The composite monthly percentage occurrence is shown in Fig. 3(b). Composite mean diurnal variation observed during different seasons is shown in Fig. 4(a–d). Seasons are sorted as Northern Hemisphere (NH) summer (May–August), NH winter (November–February), spring equinox (March–April) and fall/autumn equinox (September–October). A large variability in the percentage occurrence of highly reflected echoes in both altitude wise and season wise can be noticed. The maximum occurrence (larger than 50%) is seen, in general, between 82 and 105 km, if we consider more than 50% of occurrence of echoes. Maximum percentage occurrence is observed between 85 km and 95 km. No big difference in the percentage occurrence of the echoes is seen between NH summer and NH winter. Between 80 and 90 km, less percentage is seen in NH summer than in NH winter particularly at 1 200 h. In both the seasons, occurrences larger than 60% are seen above 90 km altitude. The percentage occurrence of MF radar echoes during equinoxes lies between the occurrences during summer and winter. During the year 2015, the percentage occurrence of MF radar echoes were maximum in the fall equinoctial period followed by NH summer and NH winter. In general, there is no significant diurnal variation in the percentage occurrence of echoes during different seasons but spring equinox show less percentage than other seasons above 95 km altitude. The occurrence frequency goes on increasing up to 86–88 km and decay above this mainly due to the reasons mentioned below.

The Appleton-Hartree equation for the refractive index (RI) of plasma in the ionosphere is given by,

$$n^2 = 1 - \frac{\omega_N^2}{\omega^2\left(1 - i\frac{\vartheta}{\omega}\right)} \tag{1}$$

where n is the refractive index, ω_N is the natural frequency of the plasma, ω is probing frequency, i is $\sqrt{-1}$, ϑ is the electron collisional frequency (collision per second).

By Snell's law, when a wave encounters a region where the RI is zero, the wave is reflected. Hence a radio wave traveling up into the ionosphere is totally reflected only when it encounters a region where the frequency of the wave (ω) equals the plasma frequency (ω_N) of the region. Here the RI is complex and this leads to absorption. The absorption maximizes when collisional frequency (ϑ) approaches to the probing frequency (ω). This process is related to the electron density as well as neutral atmosphere density. The collisional frequency varies considerably with time and declines rapidly with altitude. As we go higher altitudes into the ionosphere, for example lower E-region, the collisional frequency can be ignored and refractive index becomes real. The real part of RI never reaches zero so total reflection never occurs, however strong reflection can only occur as the RI gets very small. Since the probing frequency is constant, the plasma frequency increases with height, the RI becomes smaller and smaller and we get stronger and stronger reflection with height. At particular height we get very small RI and very strong reflection. As we move further to higher altitudes, the plasma frequency goes on increasing; now again the Snell's law violates, the wave reflects but the strong reflection does not occur because of scattering/absorption of radio wave causes loss of energy of the wave (Brown, 1992).

Second reason is, percentage occurrence is essentially determined by the built in rejection criteria described in Full Correlation Analysis (FCA) for wind estimation. Among the rejection criteria, some consideration is given to the antenna and geometrical parameters as rejection of data results if the signal-to-noise ratio is too small, fading is too slow, time delays are too long and pattern analysis breaks down, this can happen when randomness associated with formation of irregularities is too strong (Gurubaran and Rajaram, 2001). As the percentage occurrence of MF radar echoes is very small below 80 km altitude due to insufficient ionization for the radar echoes to be detectable levels; hence for further analysis we only discuss the variability in the winds above 80 km though we show results from 70 km onwards.

4. Results and discussion

4.1. Composite diurnal variation in the mean winds during different seasons

To see the diurnal variation, hourly velocities are considered. Initially, hourly mean for each season in a year is made and then hourly average of the respective seasons for all years has been calculated. Finally, average of corresponding season in all years has been calculated in order to obtain composite diurnal variation. Composite diurnal variations of derived zonal and meridional winds (2014–2017) sorted according to the seasons are presented through contours in Fig. 5.

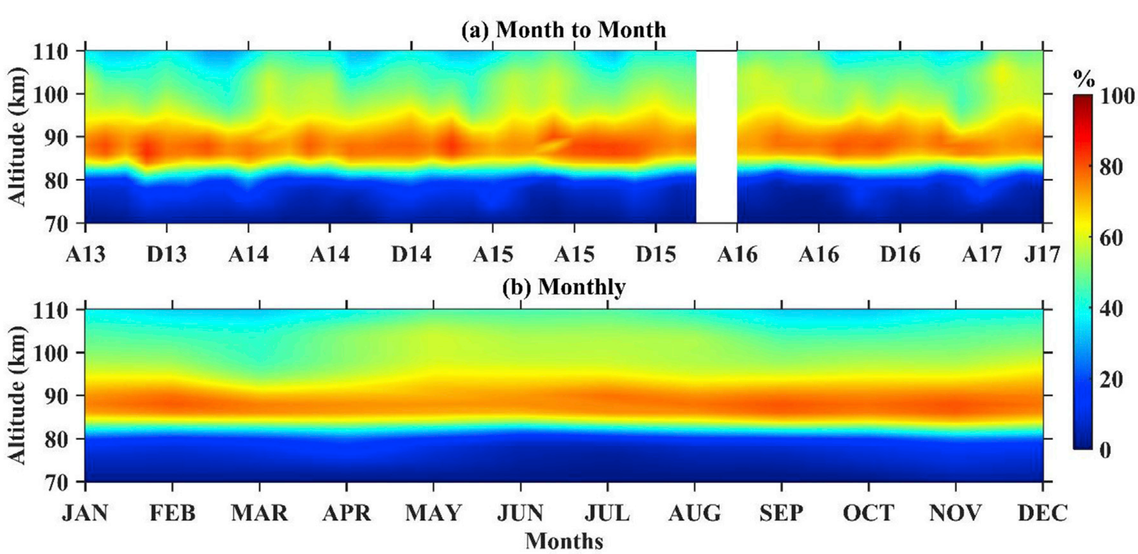

Fig. 3. (a) Monthly mean percentage occurrence of Kolhapur MF radar echoes observed during August 2013 to July 2017. (b) Composite monthly mean percentage occurrence echoes averaged during above mentioned period.

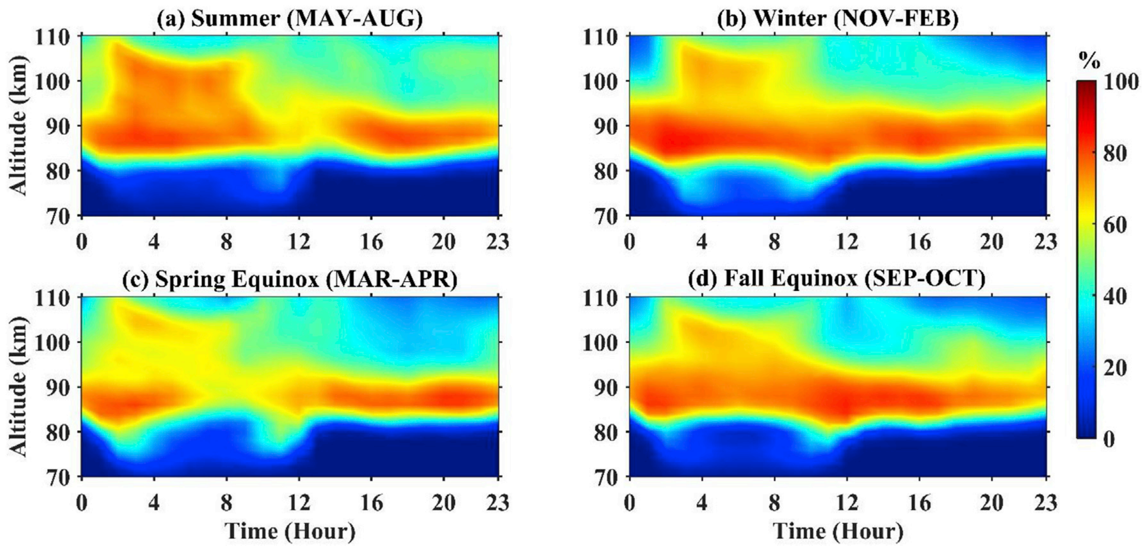

Fig. 4. Composite diurnal variation of percentage occurrence observed during (a) NH summer, (b) NH winter, (c) Spring and (d) Fall equinoxes averaged during above mentioned period.

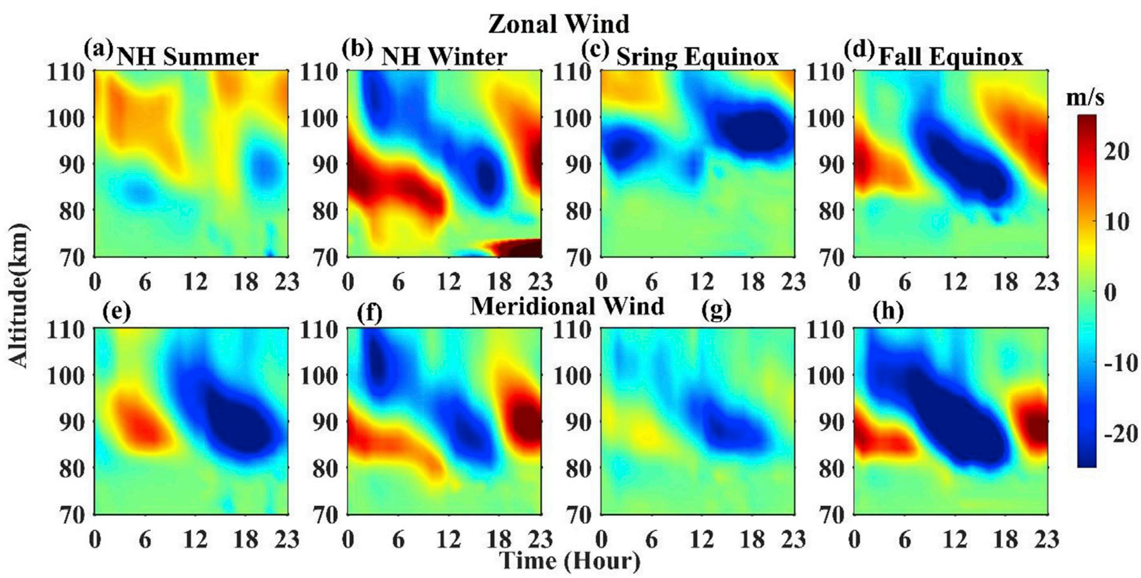

Fig. 5. Composite diurnal variation observed in the zonal wind during (a) NH summer, (b) NH winter, (c) Spring and (d) Fall equinoxes averaged during August 2013 to July 2017. (e) – (h) same as (a) – (d) but for meridional wind.

In NH summer season, zonal wind is eastward above 90 km whole day with velocity ~10–15 m/s while below 90 km the wind is westward at ~5 LT (Local Time) and ~20 LT. During NH winter season the zonal wind is strongly eastward (average velocity ~25 m/s) during night time and westward during the day time (average velocity ~20 m/s) in the upper mesospheric altitudes while reverse is the case of lower thermospheric altitudes is observed. The zonal wind is westward (average velocity ~25 m/s) during spring equinoctial period while at higher altitudes (104–110 km) the wind is eastward during night with very low winds. In fall equinoctial period the zonal wind is eastward during night while it is westward during the day. In general, the change in direction of wind takes place at dawn and dusk periods.

During NH summer season, the meridional wind is pole-ward (northward) during post-midnight period while during day and pre-midnight the wind flow is equator-ward (southward). The mean meridional wind is pole-ward during night while equator-ward in the upper mesospheric altitudes during NH winter season while reverse is found in the lower thermospheric altitudes. Similar, pattern is observed during spring and fall equinoctial periods but the wind speed is less during spring equinox and high in the fall equinox. These features reveal the well-documented structures of tides in both zonal and meridional winds (for example Deepa et al., 2006). In general, diurnal tides dominate in all the seasons though some component of semi-diurnal tides is also visible. Detailed study on the tidal variability is out of scope of present communication.

4.2. Day-to-day variation of zonal and meridional winds

In general, and as mentioned above, tidal amplitudes will be very strong in the MTL region and for obtaining the mean background winds these need to be removed. Thus, diurnal mean has been made first in order to obtained day-to-day variation in the background winds. Day-to-day variation observed in the zonal and meridional wind over Kolhapur during August 2013 to July 2017 is shown in Fig. 6. From this figure one can see alternating eastward and westward in the zonal wind during solstices and equinoxes, respectively, between 80 and 90 km. However,

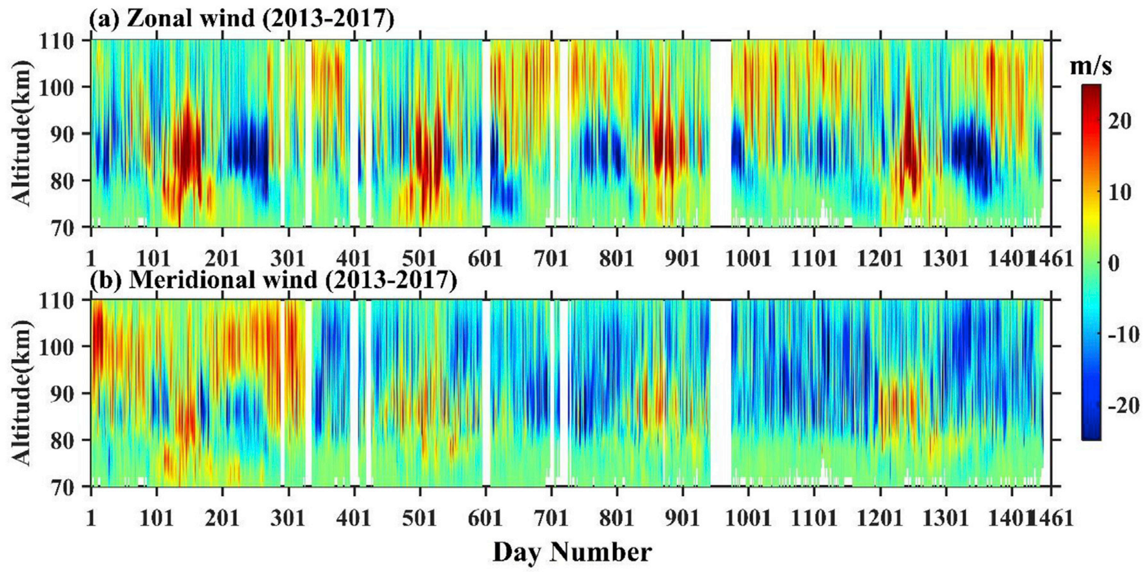

Fig. 6. Daily mean contours of (a) zonal wind and (b) meridional wind observed during August 2013 to July 2017. White gaps represents data gap.

eastward wind dominates above 90 km throughout the period. Meridional wind mostly shows southward between 80 and 90 km whereas it is slightly northward below. This data is used to study the monthly, seasonal and inter-annual variation in the mean winds.

4.3. Monthly variations of zonal and meridional winds

Contours of monthly mean winds of zonal and meridional winds averaged during August 2013 to July 2017 are shown in Fig. 7. Semi-annual oscillation is clearly seen in the zonal wind between 80 and 90 km with eastward winds during solstices and westward wind during equinoxes. The westward winds during spring equinox are stronger than that observed during the fall equinox. Thus, Mesopause SAO (MSAO) having westward winds occurs near the equinoctial periods similar to that well documented earlier from other locations within India (Rajaram and Gurubaran, 1998; Ratnam et al., 2008, 2013; Kumar et al., 2008). By April end the winds shift to weaker eastward flow maximizing in June at higher altitudes (above 90 km). This eastward flow separates the two westward flows occurred during equinoxes. This feature is consistent with AO in mean zonal winds at higher altitudes. Winds return to westward flow in the beginning of August and to eastward flow during the late November. The second westward phase of the tropical mesospheric mean winds begins in the month of August are smaller than that those seen during the first westward phase (February to May) of tropical mesospheric winds.

In general, meridional winds (Fig. 7b) are weak ranging between ± 10 m/s. The mean meridional wind shows AO with pole-ward motion during December solstice while equatorial motion during June solstice. Reversal in the direction of winds occurs during equinoctial months (Burrage et al., 1996; Garcia et al., 1997; Rao et al., 2012). In mean meridional flow, the cross equatorial circulation from summer to winter hemisphere is observed. Since the radar site is located in the northern hemisphere (Kolhapur), the cross equatorial flow is northward during winter and southward during summer. The contours of composite mean meridional wind reveals *trans*-equatorial flow with equator-ward during NH summer and pole-ward during NH winter. These features match well with those reported using MF radar located Tirunelveli (Rajaram and Gurubaran, 1998; Sridharan et al., 2007), meteor radar

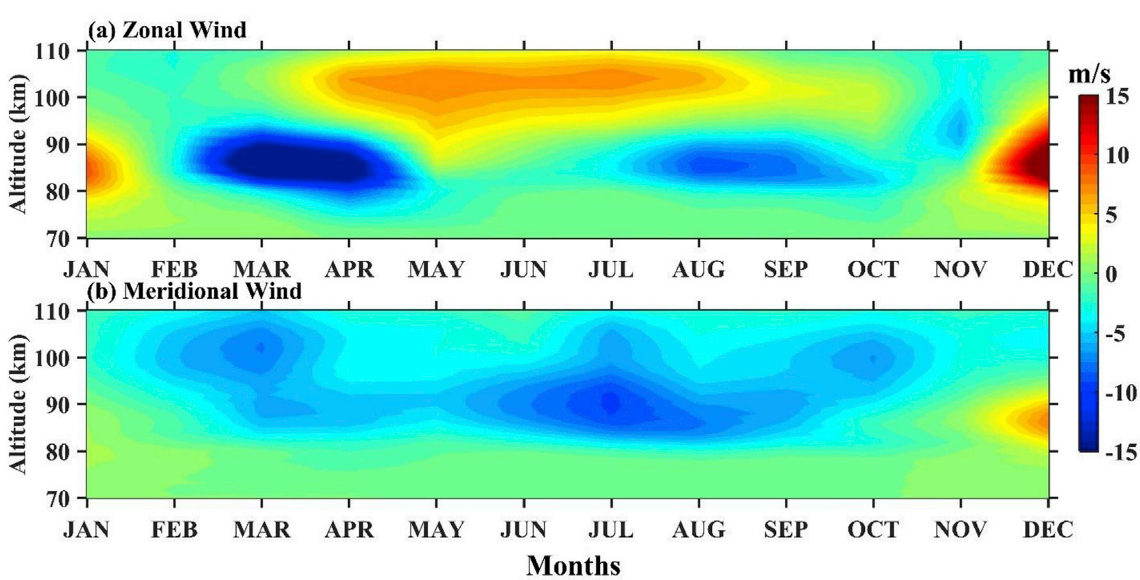

Fig. 7. Composite monthly mean variation observed in the (a) zonal wind and (b) meridional wind averaged during August 2013 to July 2017.

located at Thumba and MST radar located at Gadanki (Kumar et al., 2008).

4.4. Seasonal mean variation of zonal and meridional winds

Profiles of seasonal mean zonal winds observed during August 2013 to July 2017 individually in each year are shown in Fig. 8. Horizontal bars show standard deviation obtained while averaging the respective season. Though large inter-annual variability in the mean zonal winds is observed, the variation in the zonal wind is consistent in each season. The profiles of all years averaged (2013–2017) seasonal variation is also included. During NH summer (Fig. 8 (a)) the zonal wind is westward below 90 km while it is eastward above. In NH winter season (Fig. 8 (b)), a clear transition from eastward to westward is observed above 90 km in all the years. In the all year averaged winter season (2013–17), the transition occurred above 94 km. During spring equinox (Fig. 8 (c)) the zonal wind is westward below 92 km while it is eastward above it except in the equinoctial period of 2014 which is not included in this figure. In the year 2014 the zonal wind flows westward at all the altitudes. Similar trend is observed in all the years' average to that observed during 2015–2017 including the height at which direction reversal occurred. Maximum wind speed towards west were observed at 86 km in the years 2014 and 2017 having velocities 22.91 m/s and 26.67 m/s, respectively. During fall equinoctial period (Fig. 8(d)), large variability is observed between the years but the trend is similar in all the years except in the year 2013. During fall equinox of year 2013, net westward motion is observed in all the altitudes while in the remaining years the mean wind transit from west to east. In the year 2014, the zonal wind again turns towards west above 104 km altitude.

Profiles of seasonal mean meridional winds observed during August 2013 to July 2017 are shown in Fig. 9. Similar to that of zonal wind, good consistency in the height variation of meridional wind in each season can be noticed. In general, large inter-annual variation is also noticed in the meridional wind. During NH summer season the mean meridional wind is equator-ward (southward) in all the years (Fig. 9a). The maximum wind speed observed towards equator at 90 km is ~11, ~12 and ~10 m/s in the years 2015, 2016 and 2017, respectively. In NH winter season (Fig. 9b) the mean wind is equator-ward at all the altitudes except in between 76 and 90 km where within these altitudes the wind change-over to pole-ward (northward) in all the years. During spring equinoctial period (Fig. 9c), large inter-annual variability is observed though overall nature of the mean wind is same i.e., the mean meridional wind is equator-ward at all the altitudes. Maximum wind speed observed in spring equinoctial period is ~15 m/s at 102 km in the year 2017. During

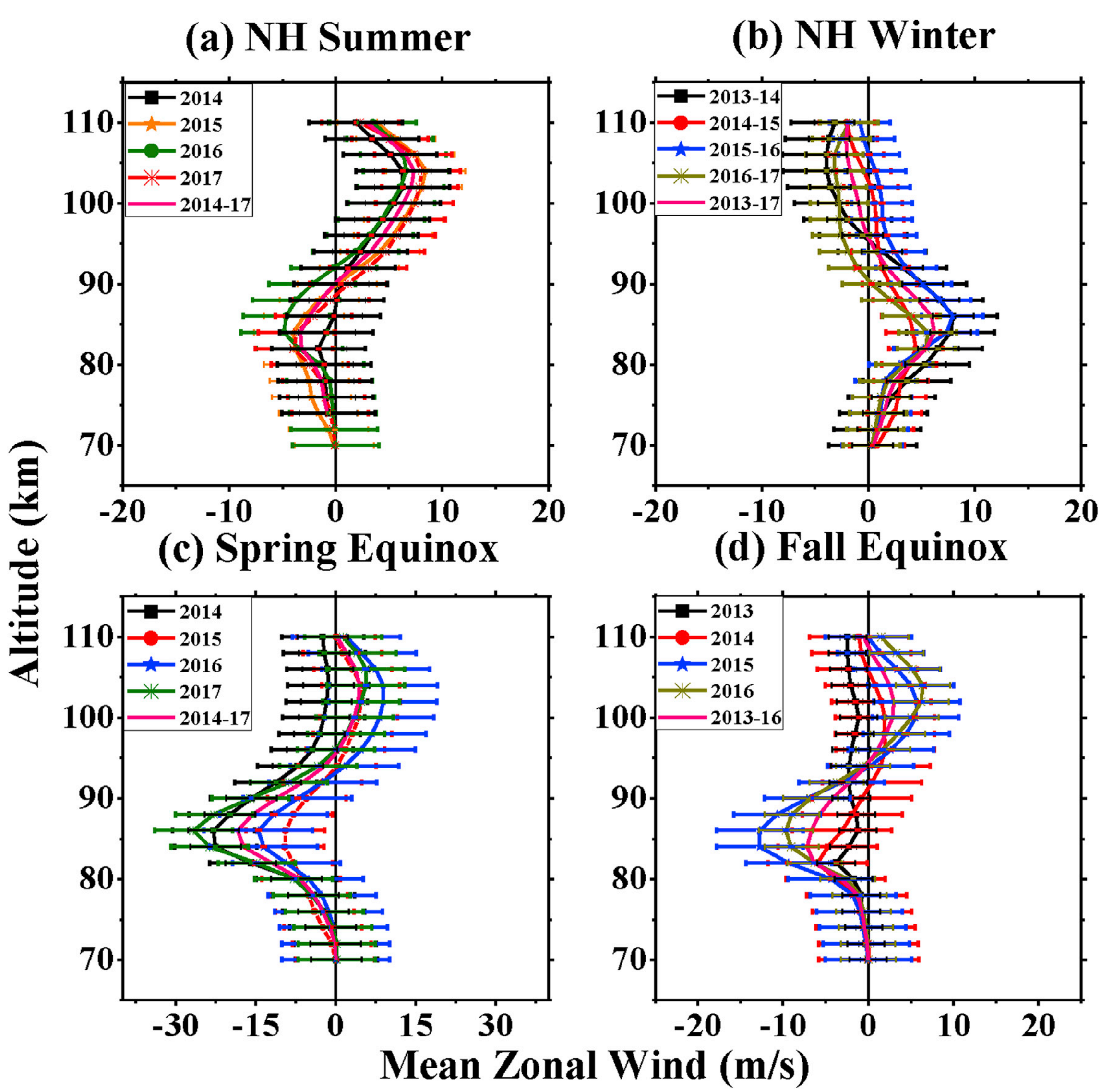

Fig. 8. Seasonal mean profiles of zonal wind observed during (a) NH summer (b) NH winter (c) Spring and (d) Fall equinoxes during different years.

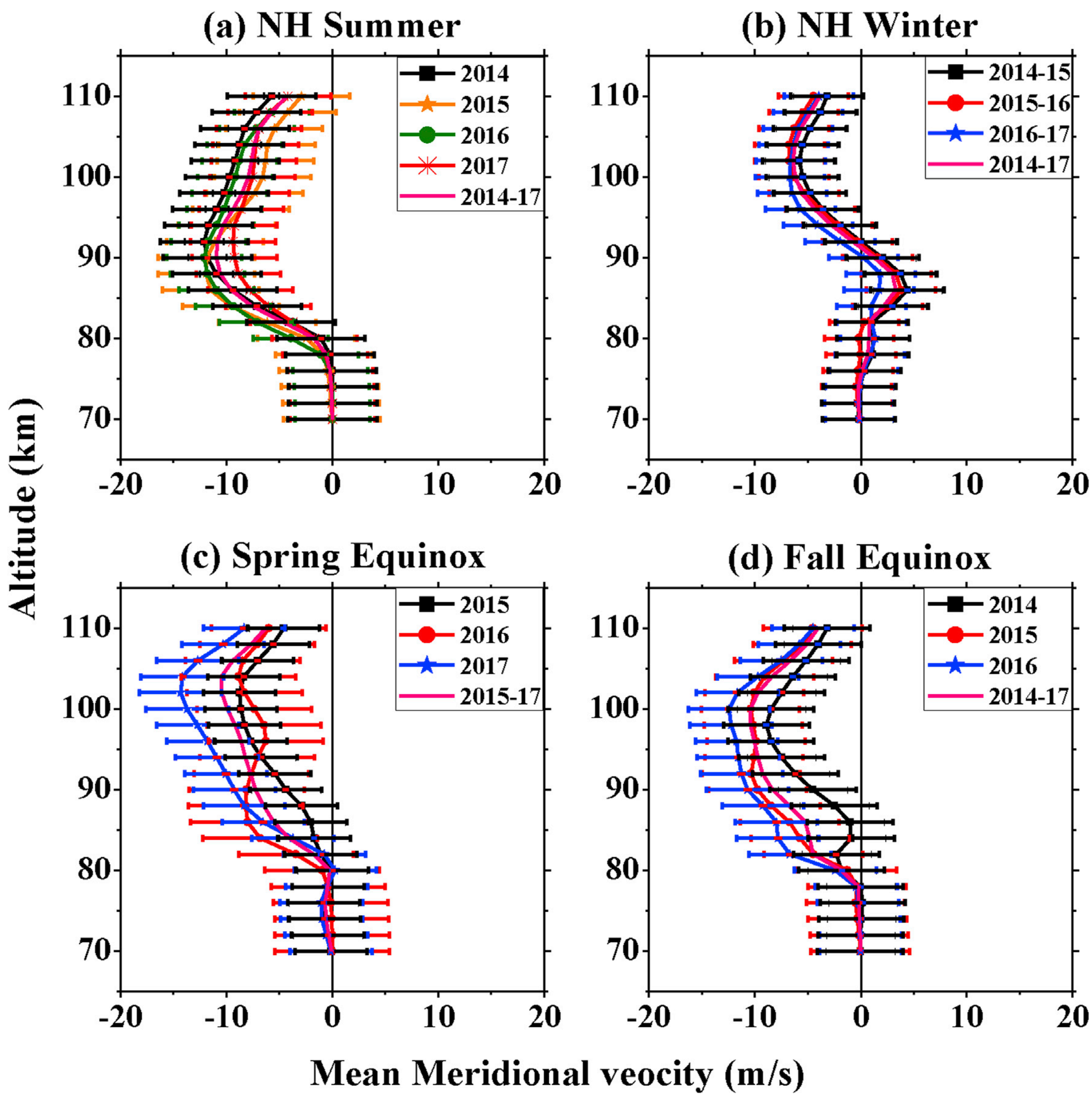

Fig. 9. Same as Fig. 8 but for meridional wind.

fall equinox (Fig. 9d), similar results were observed i.e., the mean meridional wind is equator-ward at all the heights. The maximum wind speed observed during fall equinox of year 2016 is ~12 m/s at 100 km height. Similar trend is observed in all years mean that was observed in the respective seasons.

4.5. Long period oscillations observed in zonal and meridional wind

To investigate the long period oscillations present in the background mean winds, Fast Fourier Transform (FFT) is applied to the daily mean data. Fig. 10(a) depicts the FFT of mean zonal wind. A clear signature of SAO near 180 days between 80 and 90 km altitudes with amplitude ~9 m/s is observed. AO near 360 days between 80 and 90 km and 100 and110 km altitude with amplitudes ~6 and ~5 m/s, respectively, are also observed. Similarly, FFT applied to the mean meridional wind is given in Fig. 10(b). In general, AO is observed in the meridional wind with very less amplitudes compared to the zonal winds. A weak SAO is observed between 80 and 90 km altitudes. Comparatively strong AO is observed with amplitude of ~6 m/s. QBO near 720 days with amplitude of ~5 m/s is also observed between 90 and 104 km altitudes. Since the data used in only for 4 years, there could be some bias in estimated QBO.

4.6. Amplitude and phase variation of SAO, AO and QBO in zonal and meridional wind

To determine the amplitude and phase of the SAO, AO and QBO, the monthly mean wind data were harmonically analyzed using time series constructed from day-mean values. Time series for zonal and meridional wind components were least square fitted with prevailing and 180-, 360- and 720-day harmonic components. Each wind component can be represented by a function of time by expression;

$$A(t) = a_0 + \sum_{m=1}^{3} A_m \cos\left(\frac{2\pi t}{T_m} + \varphi_m\right) \tag{2}$$

where a_0 is prevailing component, A_m and φ_m are the amplitude and phase of the mth harmonic component with period of T_m (Vincent et al., 1998).

Fig. 11 shows amplitude and phase variation of SAO, AO and QBO in the zonal and meridional wind. Similar to that shown in previous figures, zonal wind exhibit dominant SAO with maximum winds of ~13 m/s between 80 and 90 km. AO dominated at the same altitudes and with maximum velocities of 6 m/s. However, peak is observed at 105 km with amplitudes of 8 m/s. No significant QBO amplitude is noticed throughout

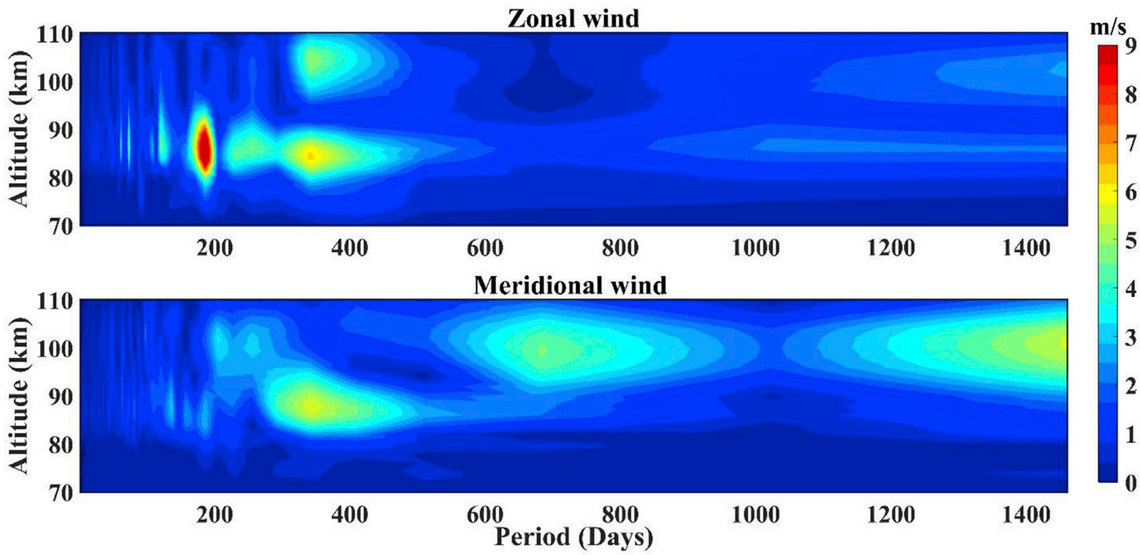

Fig. 10. Fast Fourier Transform analysis showing the dominant oscillations in (a) zonal wind and (b) meridional wind.

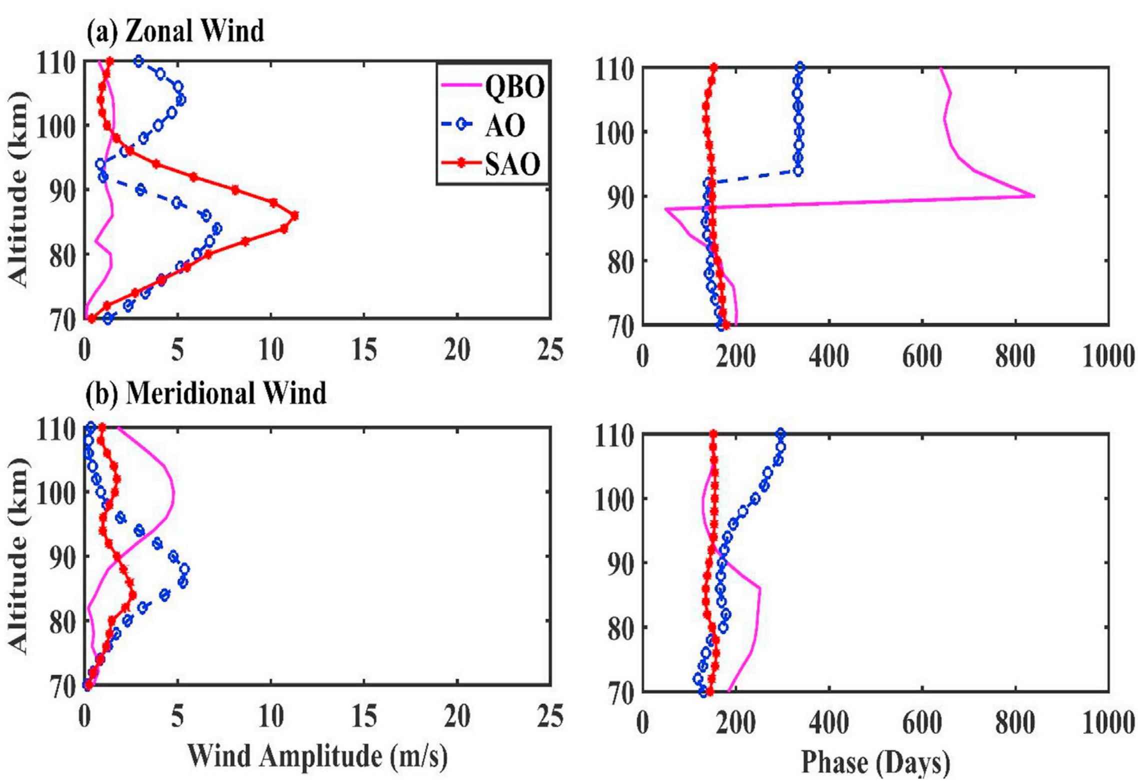

Fig. 11. Amplitude and phase profiles of QBO (Quasi Biennial Oscillation), AO (Annual Oscillation) and SAO (Semi Annual Oscillation) observed in the (a) zonal wind and (b) meridional wind.

the altitudes; perhaps more data is required for the detection of the QBO. No significant phase difference is observed in SAO between 70 and 110 km. However, significant phase difference in AO below and above 90 km is observed. Similarly significant phase difference blow and above 85 km is observed in QBO. In general, AO dominates in the meridional wind with peak amplitudes of ~6 m/s between 80 and 90 km followed with SAO (4 m/s) and minimum in QBO (2 m/s). Peak around 105 km appears in the QBO amplitudes. Phase did not show significant change throughout the altitudes in the meridional wind for all the dominant oscillations.

Rao et al. (2012) compared the SAO and AO amplitudes observed in zonal and meridional winds between various stations. Though SAO amplitudes in zonal winds reach as high as 25 m/s in 1990's, they are less than 10 m/s in recent decade at both nearby latitudinal stations, Tirunelveli (8.7°N, 77.8°E) and Kauai (22°N, 154°W). AO amplitudes reached as high as 15 m/s at Kauai but they are close to 10 m/s over Tirunelveli. SAO and AO amplitudes in the meridional wind are found to be close to 4 m/s and 8 m/s, respectively, at above mentioned two stations. Amplitudes of SAO and AO presented in the current communication match well with that reported earlier from other stations.

5. Summary and conclusions

The mesosphere and lower thermosphere (MLT) mean winds obtained by using newly upgraded MF radar over Kolhapur are presented in this paper. The data from August 2013 to July 2017 covering four years is used to investigate the diurnal, monthly, seasonal, annual and inter-annual variation in the mean background winds. The percentage occurrence of echo (>50%) shows peak between 80 and 105 km and occur less frequent below 80 km. Thus, results are discussed only when percentage occurrence of echoes are more than 50%. There exists strong diurnal variations in the mean winds in all seasons and is attributed to the presence of diurnal and semi-diurnal tides that are usually dominant in the MLT region.

Monthly variation in the zonal wind reveal strong semi-annual oscillation (SAO) with westward winds during equinoxes and eastward wind during solstices between 80 and 90 km. Above these altitudes, annual oscillation (AO) is seen dominant. These results are consistent with that reported (Rajaram and Gurubaran, 1998) from Tirunelveli using similar radar and also Indian MST radar located at Gadanki (Ratnam et al., 2002; Kumar et al., 2008). Thus, the present study re-iterates the similarity in the winds, that was observed from other locations within India, which was wrongly reported earlier by Patil et al. (2007) and Sharma et al. (2010). Meridional winds show dominant equator-ward motion above 80 km altitude irrespective of the season. However, there exists strong equator-ward motion during spring and fall equinoxes and July months. Below this altitude, pole-ward motion is seen though statistically not significant.

Monthly mean winds subjected to FFT analysis reveal existence of SAO, AO and QBO in both zonal and meridional winds. SAO in zonal wind show maximum amplitudes between 80 and 90 km with peak amplitude of 13 m/s followed by AO with amplitude of 6 m/s. There exists another peak around 105 km in the AO with similar amplitudes. QBO in zonal wind shows very small amplitudes and perhaps one more year data is required to get meaningful results on QBO features. In general, meridional wind shows weak magnitudes in all these oscillations with slightly higher magnitudes in AO followed by SAO and very weak QBO between 80 and 90 km.

Thus, the present study extends the altitude coverage of mean winds (up to 110 km) for the first time over Indian region through upgrading the system capabilities in addition to the existence of this location away from the equatorial electro jet. Additional information covering higher latitudes from this radar can be beneficial to understand the dynamics of low latitude MLT region. Further, errors in the previously reported results are rectified in the present work and could notice similar variability that was reported from other stations within Indian region. The present radar combined with other similar radars shown in Fig. 2 can form a unique regional network to investigate both short and long period waves and oscillations from equatorial latitudes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jastp.2018.01.028.

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