Studies on the variability of mean winds in the mesosphere and lower thermosphere region (MLT) over Kolhapur (16.8ºN, 74.2ºE)

G.P. Naniwadekar[1,2]*, S.Gurubaran[3],A.P.Jadhav[3], R.N.Ghodpage[4], P.T.Patil[4], D.S.Burud[5]
[1]Sou.S.M.Lohia Junior College, Kolhapur, India
[2]Physics Department, Shivaji University, Kolhapur, India
[3]Indian Institute of Geomagnetism, Navi Mumbai, India
[4]M.F. Radar Facility, Indian Institute of Geomagnetism, Shivaji University Campus, Kolhapur, India
[5]Sh. M. M. Patel Institute of Sciences and Research, KadiSarva Vishwavidyalaya, Gandhinagar, India
*Email: naniwadekargouri@gmail.com

(Received: 9th November 2022, Accepted in final form: 10 April 2023)

DOI: *https://doi.org/10.58825/jog.2023.17.1.78*

Abstract: We present the study of mesospheric winds in the 78–98 km height range using observations by a partial reflection radar station (MF–radar) situated at Kolhapur (16.8° N, 74.2° E), India. The sequential wind profiles over the period of 2014–2019 obtained from this radar operated at 1.98 MHz are used for this study. To delineate the behaviour of the winds in the mesosphere and lower thermosphere (MLT) region, we use wind data providing horizontal wind velocities averaged for an hour. Details of the seasonal, annual, and inter-annual variations and also the climatology of mean motion in zonal (East-West) and meridional (North-South) components in the MLT region over the aforementioned period are presented. The zonal wind below 90 km has been observed with eastward flow for the period of solstices and westward flow at equinoxes, showing strong semi-annual oscillations (SAO). While above 90 km, annual oscillations (AO) are seen to be dominant. Annual oscillations (AO) are observed in the mean meridional wind, with poleward motion during winter and equatorward motion during the remaining seasons. At higher altitudes (above 92 km), the poleward motion weakens and the equatorward wind flow becomes strong.

Keywords: Wind profiles, MF (medium frequency) radar, low latitude, MLT region, Annual Oscillation, Semi-annual Oscillation.

1. Introduction

The Earth's tilt with the ecliptic plane and its rotation about its axis are responsible for the unequal heating of the atmosphere between the poles and the equator, resulting in large-scale circulation. Due to this, the wind in the mesosphere-lower thermosphere region (MLT) is expected to flow northward during the day and southward during the night. Similarly, there is an inter-hemispheric flow with trans-equatorial motion from the summer hemisphere to the winter hemisphere at low to mid-latitudes (Patil et al. (2007), for example). The neutral wind flow represents zonal and meridional wind components in a three-dimensional trajectory along with the vertical component. These components can be observed by the MF radar using echoes from the MLT region. The MLT region extends from 60 to 110 kilometres and is part of the middle atmosphere. Atmospheric waves, tides, gravity waves, and planetary waves are well known to affect the dynamical structure of the MLT region (Gurubaran & Rajaram, 2000). Most of them are produced at tropospheric heights and propagate in the upper atmospheric region. As the wave propagates, its amplitudes rise in an exponential way with the falling atmospheric density (e.g., Andrews et al., 1987). Considering the dominating influence of waves in the MLT region, extensive averaging is used to revive the mean wind from the radar observations. As the Coriolis frequency is smaller at low latitudes, many long-period wave modes exist in the equatorial region. Complexities arise owing to the interactions such waves undergo with the mean flow.

Zonal winds in the MLT region exhibit certain dynamical features involving long term atmospheric oscillations like the quasi-biennial oscillations (QBO) with period of around 2 years and semi-annual oscillations (SAO) with period of 6 months (Veryard & Ebdon, 1961; Reed et al., 1965; Hirota, 1978; Andrews et al., 1987). In the equatorial region, the middle atmospheric part is found with long-period waves whose propagation mechanism is studied with the help of satellite data obtained from board Nimbus-7, the Microwave Limb Sounder (MLS), and the Limb Infrared Monitor of the Stratosphere (LIMS) as a part of the UARS (Upper Atmospheric Research Satellite) mission (Salby et al., 1984; Delisi & Dunkerton, 1988; Hitchmann & Leovy, 1986; Canziani et al., 1994). Ground based observations with high temporal resolution have been of great help in understanding the propagation mechanism of long-period oscillations has been studied using equatorial radar (Vincent, 1993; Rajaram & Gurubaran, 1998).

MF radars are known to provide information on the varaibilities of the MLT region with enhanced resolution in time and height (Woodman & Guillen, 1974; Vincent & Lesicar, 1991; Harris & Vincent, 1993; Palo & Avery, 1996). Continuous monitoring of the MLT winds with MF radars is possible at heights above 80 km (Ratnam et al., 2001). The medium-frequency (MF) radar facility in Kolhapur (16.8^0 N, 74.2^0 E) was established in 1999 and has been operated since then by the Indian Institute of Geomagnetism. The system was subsequently upgraded during 2013 with further enhancement of the altitude coverage and improved sensitivity and data quality. The operating frequency of radar systems installed at both the stations Kolhapur and Tirunelveli (8.7°N, 77.8°E) is 1.98 MHz (Rajaram & Gurubaran, 1998). The mode of operation and the experimental details of these systems are available in the literature (Vincent & Lesicar, 1991). This study is important to understand the various characteristics of wind motions across the MLT region over low latitudes and would contribute to the study of the overall dynamics of this low-to-mid latitude region at various temporal and spatial scales.

2. Observations and Data Analysis

The Kolhapur MF radar is a conventional spaced antenna arrangement that operates at 1.98 MHz and has 32 kW of ultimate power. The Spaced Antenna Technique is the most powerful and economical method for the study of neutral wind patterns, especially in the MLT region. The MF radar probes the most weakly ionised part of the atmosphere by transmitting and receiving radio waves vertically in the height range 70 to 98 km. The radio waves transmitted upward are partially reflected back to the ground due to the presence of an irregularity in the refractive index of the atmosphere. Thus, scattering and reflection processes are responsible for the radar signals returning from the atmosphere.

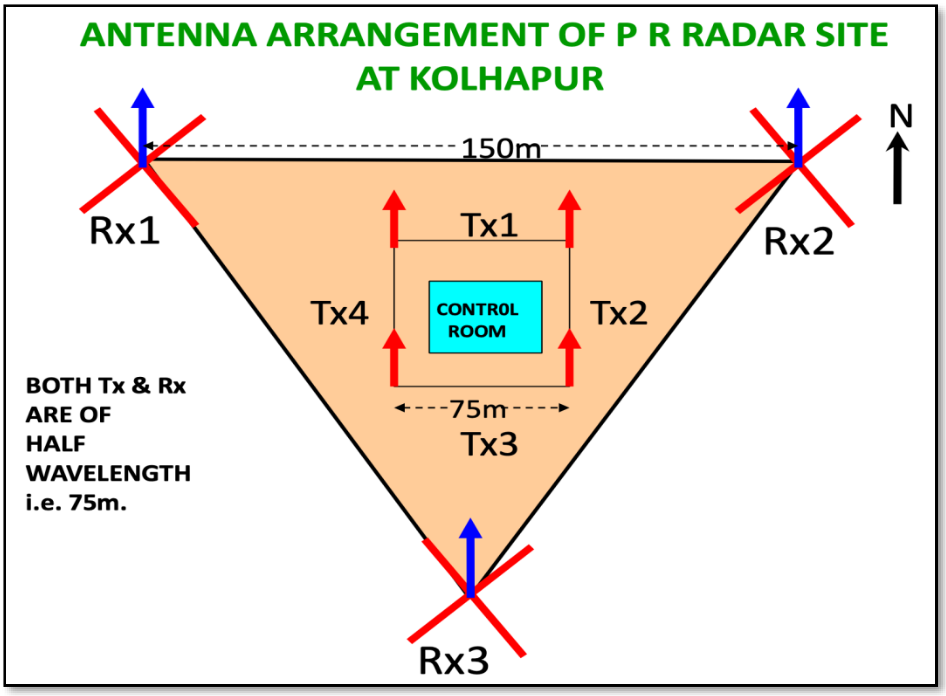

Figure 1. Schematic diagram of the medium-frequency radar system installed at Kolhapur

Figure 1 is the schematic representation of the MF radar system. The main parts of the system are the transmitter, the receiver, and the data acquisition system. The transmitting antenna array is consists of four centre-fed half-wave dipoles, each ~75 m in length, arranged in a square. The receiving antennas are placed in a form of equilateral triangle as shown in figure 1. The height of the transmitting antenna is 30 m, which is one-fourth of the transmitting wavelength above the ground plane. Three receiving antennas are positioned at the vertices of a regular triangle with 180-metre spaces and shaped as an inverted-V type. The radar system is monostatic because the transmitters and receivers are collocated. The operational frequency of the transmitter is 1.98 MHz and offers a constant phase difference. The transmitters are specified with 32 kW of power and a pulse length of 25 µs, along with a 4.5 km height resolution. The pulse repetition frequency is 80 Hz. The receiving and data acquisition system is controlled by the computer controller, which analyses the raw data. In the end, the data after analysis is stored in binary form by the computer controller.

The method of data retrieval is based on the movement of scatterers over the receivers. These movements are being characterized by the Full Correlation Analysis (FCA) method (Briggs et al., 1984). To estimate the background wind vector, three fading signals from the three receiving antennas with different time delays are used. For each of the three fading signals, the auto- correlation and cross-correlation functions were determined by applying the FCA method. This wind vector, known as apparent velocity, is produced without taking into account random variations in the pattern and generally overstates the background wind speed. To determine true velocity, it is adjusted for arbitrary variations in the diffraction pattern. This technique calculates the wind velocities using the ground diffraction pattern generated due to the scattering of transmitted radio signals.

The full correlation analysis of Briggs is adopted to derive various atmospheric parameters and retrieve information on the spatial and temporal characteristics of the ground diffraction pattern. This radar samples the two components of the horizontal wind between heights of 68 and 110 km with a spatial and temporal resolution of 2 km and 2 min, respectively. Hourly mean winds for each height are utilized in this work for further analysis. Sharma et al. (2018) presented the first results on mean winds observed over Kolhapur, but with limited data sets. For the present work, the height region is restricted to 78–98 km due to poor data quality below 80 km. Recently, Gaikwad et al. (2019) reported the day-to-day variability of the MLT region over Kolhapur caused by planetary-scale waves.

The data for the period July 2014–June 2019 were chosen for the present work. For the purpose of analysis, hourly wind observations are further averaged using the methodology adopted in Rajaram & Gurubaran (1998). The present study is restricted to examining the seasonal variation of mean MLT winds over Kolhapur. For the present purpose, the seasons are considered to be: Summer - from May to August, winter - from November to February; Spring equinox, March and April; Fall equinox, September and October.

3. Results

Mean winds are one of the parameters that are used to describe the state of the atmosphere and its dynamics. Here, we present results from the analysis of wind data obtained from the radar system in terms of mean zonal and Meridional wind components over the altitude of 78–98 km and for the period July 2014 to June 2019.

3.1 Mean Zonal Winds

3.1.1 Composite seasonal variations of mean zonal winds over Kolhapur:

Figure 2 depicts the time–height contours showing prevailing zonal wind patterns over the chosen period. For this analysis, we use the monthly mean wind velocities to represent the monthly variations over the five-year period**.**

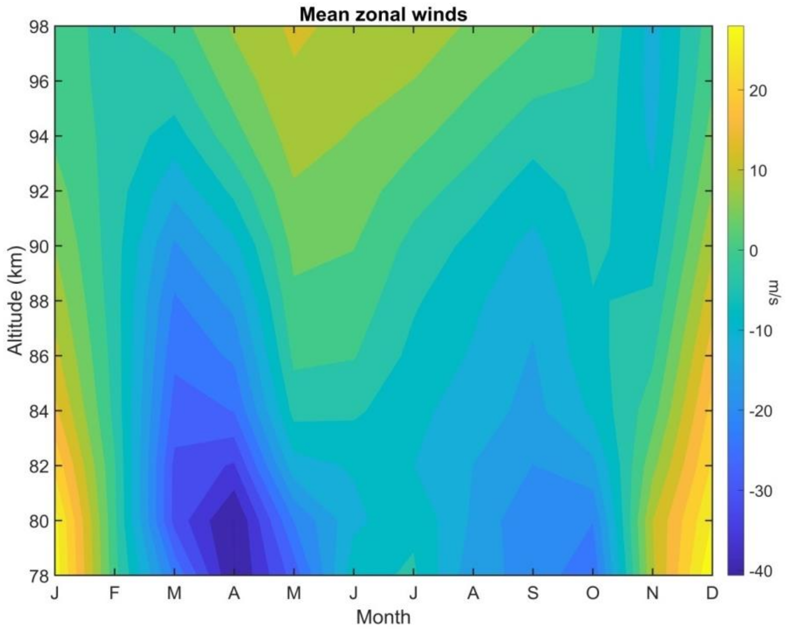

Figure 2. Composite seasonal behaviour of the zonal winds in the altitude 78 - 98 km over Kolhapur.

In Figure 2, the contours of the mean flow with positive values represent the eastward component of the zonal winds, while the negative values represent the westward component. The plots clearly highlight the altitude dependence of the mean zonal flow. The winds are largely westward during the equinoxes (March-April and September-October) at lower altitudes (86 km) and eastward during the solstice's months at higher altitudes (> 86 km). At lower altitudes, the flow is weaker during the summer months. Large eastward wind speeds exceeding 20 m/s are noticed during the winter months of December and January at altitudes below 84 km. The largest westward wind speeds are 35 m/s during the equinox months. In general, at lower altitudes, the westward wind flow is stronger than the eastward wind flow, while at higher altitudes, the eastward wind flow is stronger. An important feature to be noted is that at lower elevations, we observe a semi-annual type of variation, while at higher elevations (above 90 km), the variation is typically annual. Hereafter, we denote the semi-annual type of variation as SAO and the annual type as AO. At lower heights, SAO is stronger and becomes weaker with increasing altitude. The study emphasizes that AO is stronger at higher altitudes.

3.1.2 Averaged Seasonal Variations in Mean Zonal Wind over Kolhapur

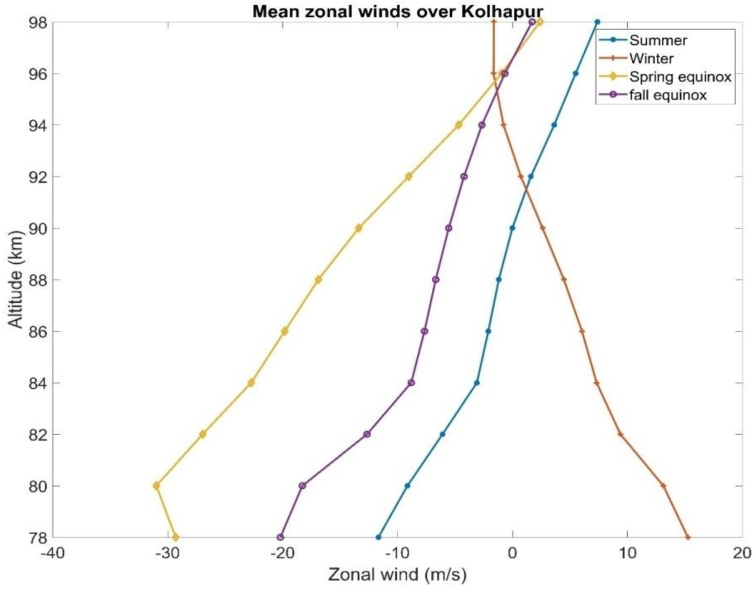

Figure 3. Seasonally averaged zonal wind over Kolhapur for the year 2014-2019

Figure 3 reveals the seasonal component of the zonal wind averaged over 5 years, i.e., July 2014 to June 2019. Altitude profiles clearly show the eastward and westward winds in winter and summer, respectively. Winds are stronger westward during the spring equinox compared to the fall equinox. The wind directions during different seasons are more distinct and clear at altitudes below 90 km. At higher altitudes, winds change direction and exhibit opposite behaviour to those at lower altitudes. The averaged wind velocities vary from -30 m/s to 15 m/s (Figure 4). The winds are larger in magnitude at lower altitudes, and a clear seasonal dependence of the wind velocities can be seen.

3.1.3 Long term variations in mean zonal wind

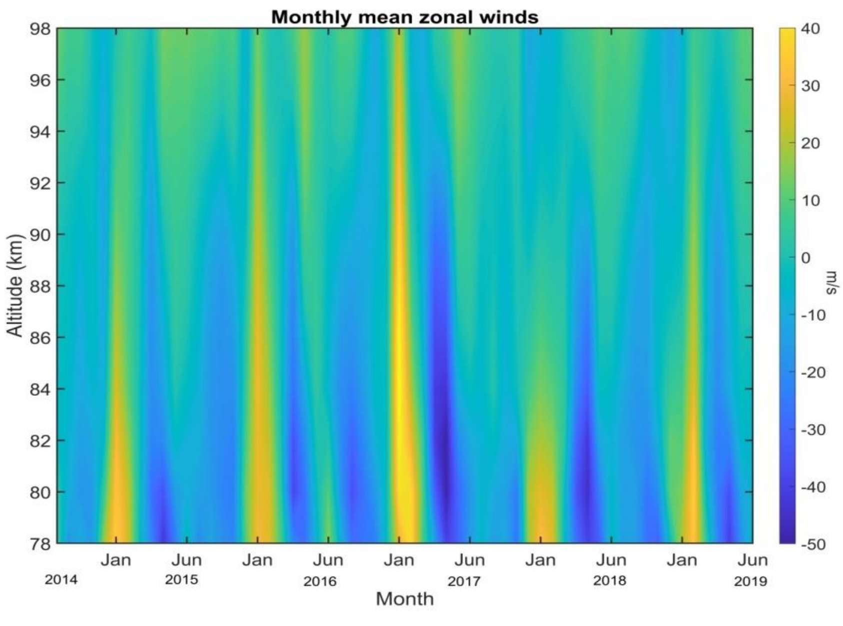

Figure 4. The time-height representation of monthly averaged zonal winds during 2014-2019 for heights 78-98 km

The monthly mean MLT wind over Kolhapur for the period 2014–2019 is presented in contour form with a time-height cross-section of monthly averaged zonal winds in the altitude range 78–98 km. The contour plot confirms the dominance of the SAO at a lower height and the AO at higher heights. There is an inter-annual variability superimposed on the wind fields on the annual and semi-annual time scales. Also, the westward maximum occurring in the Spring equinox (March-April) is stronger as compared to that occurring in the fall equinox (September-October). Similarly, the eastward motion observed during the December-January solstice period is stronger than that observed during the June-July summer solstice period. Largest eastward and westward wind speeds are observed during the December–January months of 2016–2017 and during the following spring equinox months of March–April, respectively. Considering the dominance of SAO at lower altitudes, the MLT region over Kolhapur behaves very much like a low latitude/equatorial site with its characteristic SAO. On the other hand, the motion at higher altitudes, with its characteristic annual oscillation, resembles that observed at mid-latitudes.

3.2 Mean Meridional winds

3.2.1 Composite seasonal variations of mean meridional winds over Kolhapur

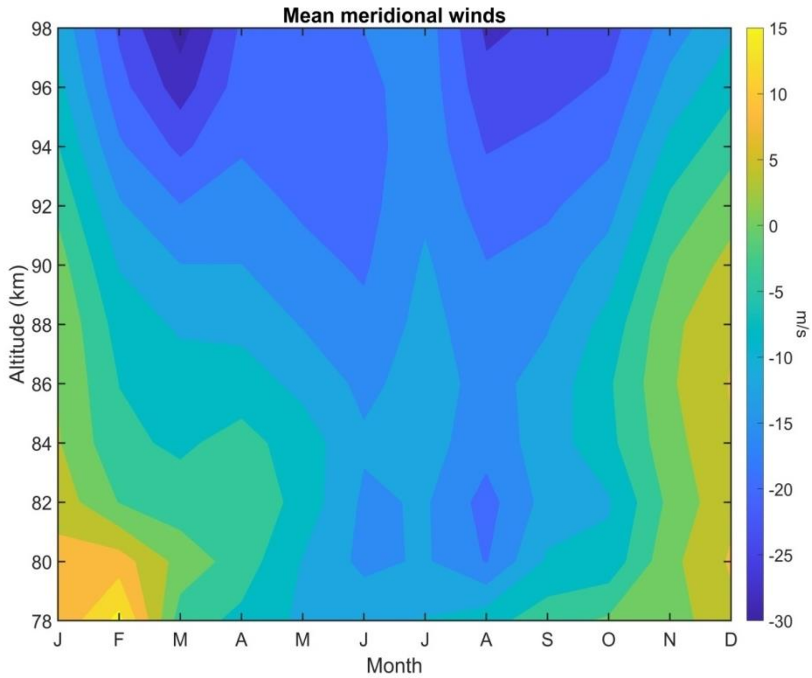

Figure 5. Composite seasonal behaviour of the Meridional winds in the altitude range of 78-98 km over Kolhapur

The monthly composite seasonal variations of mean meridian wind over Kolhapur in the altitude region of 78–98 km representing the chosen five-year period are plotted in Figure 5, with positive values representing northward motion and negative values representing southward motion. From this plot, it can be seen that at lower heights (90 km), the wind motion tends to reflect an annual variation, but at higher altitudes (> 90 km), the motion is largely southward (largest speeds in the range of 15–25 m/s) but for a weak northward (pole ward) motion (speeds in the range of 0–5 m/s) during the winter months. As was expected, the wind motion is northward during the winter, while during the summer, the wind flows in the opposite direction, as the radar site is situated in the Northern Hemisphere.

3.2.2 Averaged Seasonal Variations in Mean Meridional Wind over Kolhapur

Figure 6 plots the seasonal mean flow in the meridional direction for 5 years. Unlike zonal wind vertical profiles, meridional winds do not show much variation with respect to altitude. Seasonal variations have a considerable impact on wind magnitudes. The mean winds vary seasonally between -20 m/s and 5 m/s. The southward winds during the spring equinox become more southward as summer approaches and then turn northward during the winter. This shows the effect of seasons on the meridional component of winds and pole-to-pole circulation.

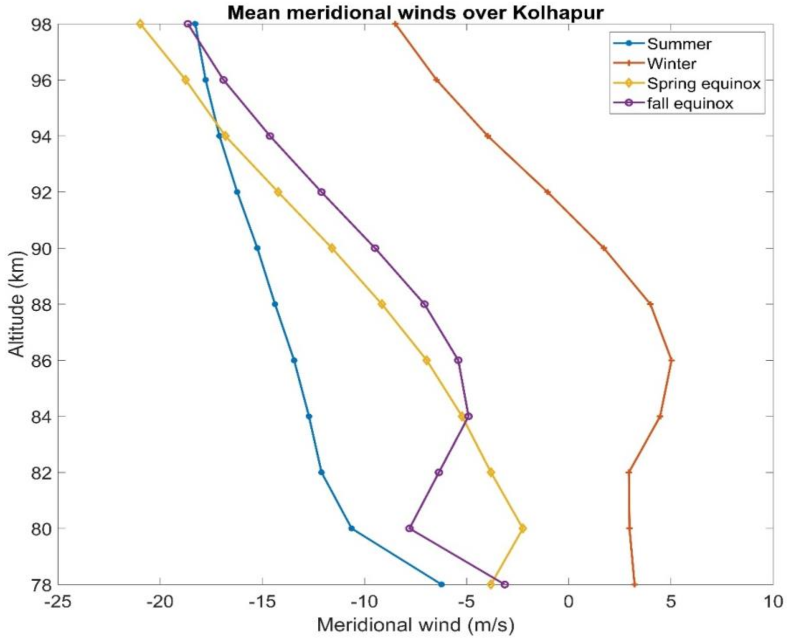

Figure 6. Seasonally averaged meridional wind over Kolhapur for the year 2014-2019

3.2.3 Long term variations in mean meridional winds

Figure 7 represents the monthly mean meridian winds across the altitude range of 78–98 km from July 2014 to June 2019. The contour plot depicted herein clearly shows the annual oscillation (AO) in the mean meridian wind during the chosen years. Throughout the winter, it has been noted that the meridional wind advances northward, and at nearly all other times, the wind motion is southward. Above 94 km in height, it is observed that the wind constantly flows in the southward direction. The largest southward motions are indeed observed at these heights. The wintertime northward wind speeds are in the range of 10-15 m/s, which are somewhat weaker than the 25–30 m/s southward wind speeds observed during the summer months on the monthly time scales. A persistent feature has been that during the month of January every year, a strong poleward wind motion occurs below 84 km. The northward motion seems to occur one month earlier at higher altitudes.

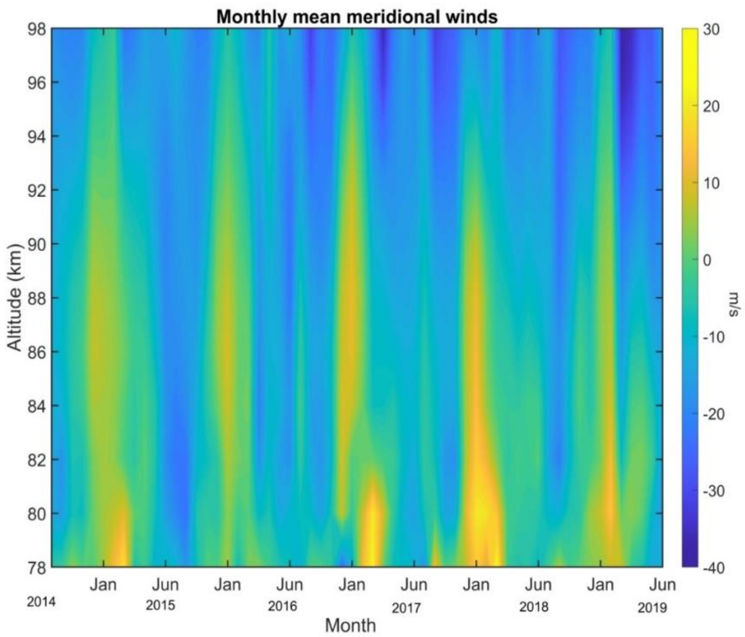

Figure 7. The time-height representation of monthly averaged meridional winds during 2014-2019 for heights 78-98 km

4. Discussion and Conclusion

Medium-frequency (MF) radars are among the powerful tools yielding valuable information about the dynamic processes occurring in the low-latitude and equatorial mesosphere. The data used in this work is from the MF radar operated at Kolhapur. The analysis carried out was for the period July 2014 to August 2019. The main goal of the current analysis was the study of mean wind variations and the seasonal variation over Kolhapur. In particular, MLT mean zonal and meridional winds are examined on monthly time scales, and the seasonal variations and the altitudinal dependence of the seasonal transitions in mean winds are brought out in this work.

The semi-annual variation in the mean zonal wind, especially at lower altitudes, is a distinct feature that is reported. The SAO is characterised by westward flow during equinoxes and eastward flow during solstices, a well-known feature reported from equatorial sites (Rajaram & Gurubaran, 1998, for example). On the other hand, at higher altitudes, an annual type of oscillation is observed. There is a tendency for interannual variability in the occurrence of SAO. For example, the westward motions during the April equinox period of 2017 and the eastward motions during the December/January winter solstice of 2016/2017 were more intense than during the previous and subsequent years. An interannual variation of this kind is a defining trait of the MLT zone near the equator. The seasonal asymmetry in SAO, for example, in the westward flow between the two equinoxes or in the eastward flow between the two solstices, is also a notable feature reported in this work.

The mean meridional wind flow, in contrast to the mean zonal wind, indicates the presence of inter-hemispheric flow that is caused by the uneven solar heating of the two hemispheres. A northward move in the winter and a southern motion at other times define the yearly cycle of meridional flow. In the annual meaning, there is also a separate time-mean flow. More crucially, as one rises in height, the southerly (equatorward) wind becomes stronger. It is clear that the meridian winds consistently rely on altitude over the course of all the years, with little inter-annual variation in this behaviour.

The seasonal variation in the monthly mean meridional wind component follows a consistent pattern year after year: northward motion during winter months and southward motion during summer months. These observations are similar to the previous outcomes reported from Tirunelveli by Rajaram & Gurubaran (1998) and from Gadanki by Ratnam et al. (2001). SAO in mesosphere as well as in stratosphere display seasonal variation and exhibit similar behaviour. The first cycle of the stratospheric SAO, which starts with the westward phase in the winter of the Northern Hemisphere, is more powerful than the second cycle, which starts with the westward phase in the winter of the Southern Hemisphere. Variations in extratropical planetary wave forcing, which are stronger in the northern winter than the southern winter, are the source of this asymmetrical behaviour (Hitchman & Leovy, 1986; Delisi & Dunkerton, 1988). Burrage et al. (1996) used data from the UARS (Upper Atmospheric Research Satellite) program to discover interannual variations for the first time. The current study provides compelling evidence supporting this conclusion. . With four years (1993-1996) of MF radar data, Rajaram & Gurubaran (1998) previously noticed this distinctive characteristic over Tirunelveli.

In summary, a comprehensive overview of mean winds over Kolhapur using a 5-year database is presented here with distinct features that resemble more of the behaviour reported for equatorial sites. Though this is the case for the zonal wind, the meridional wind over Kolhapur behaves like that over mid-latitude sites. In particular, the annual mean Meridional wind at the highest altitudes sampled by the radar reveals a large southward component and if this prevailing wind feature exists at mid-latitudes needs to be seen. With the help of a comparatively longer database, the present analysis brings out some supplementary structures.

Acknowledgements

The Indian Institute of Geomagnetism (IIG), Navi Mumbai, an autonomous organization under the Department of Science and Technology (DST), New Delhi, Government of India, provided assistance for the scientific effort detailed in this article. MF Radar observations were carried out as part of a scientific collaboration programme (MoU) between the IIG, Navi Mumbai, and Shivaji University, Kolhapur.

References

Andrews DG, JR Holton and CB Leovy (1987). Middle atmosphere dynamics, Academic Press.

Briggs BH (1984). The analysis of spaced sensor records by correlation techniques, Middle Atmosphere Program: Handbook for MAP., 13, 166-184.

Burrage MD, RA Vincent, HG Mayr, WR Skinner, NF Arnold and PB Hays (1996). Long-term variability in the equatorial middle atmosphere zonal wind, Journal of Geophysical Research: Atmospheres, 101(D8), 12847-12854.

Canziani PO, JR Holton, E Fishbein, L Froidevaux and JW Waters (1994). Equatorial Kelvin waves: a UARS-MLS view, Journal of the Atmospheric Sciences, 51(20), 3053-3076.

Delisi DP and TJ Dunkerton (1988). Seasonal Variation of the Semiannual Oscillation, Journal of the Atmospheric Sciences, 45(19), 2772–2787.

Gaikwad HP, AK Sharma, OB Gurav, GA Chavan, DP Nade, PT Patil, SS Nikte and GP Naniwadekar. (2019). Seasonal, annual and interannual variability in MLT Quasi Two Day Waves over low latitude region Kolhapur (16.8^{o} N; 74.2^{o} E), Advances in Space Research, 63(7), 2100-2117.

Gurubaran S and R Rajaram (2000). Signatures of equatorial electrojet in the mesospheric partial reflection drifts over magnetic equator, Geophysical Research Letters, 27(7), 943-946.

Harris TJ and RA Vincent (1993). The quasi-two-day wave observed in the equatorial middle atmosphere, Journal of Geophysical Research: Atmospheres, 98(D6), 10481-10490.

Hirota I (1978). Equatorial Waves in the Upper Stratosphere and Mesosphere in Relation to the Semiannual Oscillation of the Zonal Wind, Journal of the Atmospheric Sciences, 35(4), 714–722.

Hitchman MH and CB Leovy (1986). Evolution of the Zonal Mean State in the Equatorial Middle Atmosphere during October 1978-May 1979, Journal of the Atmospheric Sciences, 43(24), 3159-3176.

Palo SE and SK Avery (1996). Observations of the quasi-two-day wave in the middle and lower atmosphere over Christmas Island, Journal of Geophysical Research: Atmospheres, 101(D8), 12833-12846.

Patil PT, S Gurubaran, R Rajaram, AK Sharma and RV Bhonsle (2007). Mesospheric winds from 70 to 98 km altitude over low latitude station Kolhapur by a partial reflection radar, Bulletin of the Astronomical Society of India, 35, 561-568.

Rajaram R and S Gurubaran (1998). Seasonal variabilities of low-latitude mesospheric winds, Annales Geophysicae, 16, 197-204.

Ratnam MV, DN Rao, TN Rao, S Thulasiraman, JB Nee, S Gurubaran and R Rajaram (2001). Mean winds observed with Indian MST radar over tropical mesosphere and comparison with various techniques, Annales Geophysicae, 19(8), 1027–1038.

Reed RJ (1965). The quasi-biennial oscillation of the atmosphere between 30 and 50 km over Ascension Island, Journal of the Atmospheric Sciences, 22(3), 331-333.

Salby ML, DL Hartmann, PL Bailey and JC Gille (1984). Evidence for equatorial Kelvin modes in Nimbus 7 LIMS, Journal of the Atmospheric Sciences, 41(2), 220-235.

Sharma AK, HP Gaikwad, MV Ratnam, OB Gurav, L Ramanjaneyulu, GA Chavan and S Sathishkumar (2018). Diurnal, monthly and seasonal variation of mean winds in the MLT region observed over Kolhapur using MF radar, Journal of Atmospheric and Terrestrial Physics, 169, 91-100.

Veryard RG and RA Ebdon (1961). Fluctuations in tropical stratospheric winds, Meteorology Magazine, 90, 125-143.

Vincent RA (1993). Long-period motions in the equatorial middle atmosphere, Journal of Atmospheric and Terrestrial Physics, 55(7), 1067-1069, 1071-1080.

Vincent RA and D Lesicar (1991). Dynamics of the equatorial mesosphere: First results with a new generation partial reflection radar, Geophysical Research Letters, 18(5), 825-828.

Woodman R F and A Guillen (1974). Radar Observations of Winds and Turbulence in the Stratosphere and Mesosphere, Journal of the Atmospheric Sciences, 31(2), 493-505.