Planetary waves – major forcing agent in generating stratospheric and mesospheric quasi biennial oscillation

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Quasi Biennial Oscillation (QBO) and Semi Annual Oscillation (SAO) are dominant natural oscillations in the equatorial lower stratosphere and mesosphere and are believed to be generated by the wave-mean flow interaction. The characteristics of stratospheric QBO (SQBO) and mesospheric QBO (MQBO) and SAO are studied by making use of the monthly mean zonal and meridional winds derived from four decades of balloon (1970–2010) and rocket (1971–2007) flights and seven years of SKiYMET meteor radar (2004–2011) observations over an equatorial station Thiruvananthapuram. The year-to-year variation and interrelationships between these oscillations are also studied. The quantitative estimation of forcing towards the mean flow acceleration producing the maximum phase of SQBO during the four-decade period shows 70–80% contribution from planetary waves, while during minimum phase of SQBO the contribution is 30–35%. It is also found that the contribution by planetary waves towards the mean flow acceleration producing MQBO maximum during the seven-year period is around 30–90% and during MQBO minimum phase it is 30–60%. The vertical structure of these oscillations present over the equatorial station is also derived.

Keywords: Quasi biennial oscillation, mean flow acceleration, mesosphere, planetary waves, stratosphere.

THE presence of Quasi Biennial Oscillation (QBO) and Semi Annual Oscillation (SAO) in the atmosphere is widely recognized and it has generally been assumed that these oscillations in different atmospheric parameters present at different regions of the atmosphere are related in one or another. Within ±15° latitude, equatorial oscillations are observed in the zonal circulation, i.e. the SAO with a period of 6 months and QBO with a period around 2 years[1,2]. The QBO is so named because the average period of oscillation is slightly longer than 2 years, and the period is irregular, varying between 18 and 36 months. The amplitude and period of QBO in zonal wind are observed to vary from one cycle to the next[3–5]. The basic classical mechanism responsible for QBO is wave-mean flow interaction between gravity waves/equatorial Kelvin waves/mixed Rossby gravity (MRG) waves and the background zonal flow in the lower stratosphere[6,7]. The deposition of momentum in this region by Kelvin and MRG waves respectively, explains the downward propagating alternating westerly and easterly regimes of the lower stratospheric zonal winds. Later modifications to the theory take into account the secondary circulation of QBO[8] and the upwelling branch at the equator of the Brewer–Dobson circulation in affecting the descent rate and hence the period of QBO[9,10]. The results from these simple models agree in many respects with the observations. Several works followed and further elucidated the study of characteristics of QBO using two-dimensional[8] and three-dimensional models[11]. An important property of QBO is the observed confinement of the zonal winds to equatorial latitudes even with a wave source that is globally uniform. At the equator where the Coriolis force vanishes, the waves accelerate the zonal winds without generating a meridional circulation that would tend to redistribute and dissipate the flow momentum. The flow is thus essentially trapped around the equator, where the wave interaction is primarily balanced by eddy viscosity causing the QBO to propagate downwards. Away from the equator, irrespective of the wave source, the meridional circulation comes into play and dissipates the zonal flow[12]. Without the meridional circulation, the QBO zonal winds at the equator could be described for simplicity with a one-dimensional 'prototype model'[13].

Several studies have revealed the biennial-type signals in meteorological quantities in the troposphere and stratosphere[14–16]. Biennial oscillation is found in the rainfall over India and Indonesia[17]. One of the current problems associated with this biennial oscillation is the vertical coupling of QBO and SAO to the mesosphere and upwards, and the troposphere below and its influence on the tropospheric weather conditions. Even though it is well established that waves originating in the tropical and extra-tropical latitudes are the key forcing mechanisms in the generation of these oscillations, the relative contribution of these waves is poorly understood. The exact forcing mechanisms in different phases of these oscillations are yet to be substantially quantified. Quantifying the role of these waves still remains illusive until more complete

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knowledge is attained of momentum spectrum of these wave.

In this background, the scope of the present study is to characterize the oscillations in the equatorial stratospheric and mesospheric regions over the low-latitude station Thiruvananthapuram (8.5°N, 77°E) using a unique dataset available for almost 40 years from both radiosonde (1970–2010) and rocketsonde (1971–2007) and 7 years of data from meteor wind radar (2004–2011). The influence and interdependence of these oscillations and their propagation characteristics during typical phases of maximum and minimum activity are also studied. An attempt is also made to quantitatively estimate the forcing by planetary waves, towards the generation of stratospheric QBO (SQBO) and mesospheric QBO (MQBO).

Data and analysis method

In the present study, data on zonal and meridional winds obtained from balloon-borne/GPS radiosonde flights at Thumba Equatorial Rocket Launching Station (TERLS) in the height region from ground level to 30 km for a period of 41 years (January 1971–December 2010) are used to study the characteristics of SQBO. Due to lack of simultaneous and continuous data above 30 km, the present study on SQBO is limited to 30 km even though propagation characteristics of SQBO extend beyond that height. High-altitude balloons carrying radiosondes and radar targets are used for measuring altitude profiles of wind, temperature, humidity and pressure in the 0–35 km altitude region. The meteorological information from radiosonde is acquired and recorded at our station. The accuracy of radiosonde measured wind speeds of magnitude above 25 ms^{-1} is found to be 1–2 ms^{-1}. For wind direction the accuracy is about 10° for lower wind speeds and 5° for higher wind speeds (>25 ms^{-1}).

Rocketsonde flown by both M-100 and RH-200 rockets from TERLS measured zonal and meridional wind data from 35 to 60 km for a period of 37 years (January 1971–November 2007) and these are used to characterize stratospheric SAO (SSAO). Due to a gap in the rocket data during 1974–1975, 1992–2002 and 2007–2010, the zonal wind derived from ECMWF reanalysis data in the 35–50 km region is combined with available rocket data to obtain information on SSAO. RH-200 is a two-stage rocket, which uses chaff as a payload to measure winds in the 30–65 km altitude region. The chaff is released at the apogee point of the rocket trajectory and tracked by the ground-based radar to measure the wind velocity in the stratosphere as the chaff descends with time. The wind velocity is calculated from the radar measured position coordinates of the chaff (R, θ, ϕ) as a function of time, where R, θ and ϕ are the range, elevation and azimuth angles respectively. It is shown that the standard error involved in the RH-200 chaff-measured wind components is 2–2.7 ms^{-1} in the 20–50 km region and 3.8 ms^{-1} above 50 km region[18].

The zonal and meridional wind data collected in the 82–98 km height region from the meteor wind radar observations during 7 years starting from June 2004 to July 2011 are used for studying mesospheric SAO (MSAO) and MQBO. The altitude resolution of this radar is 3 km and it transmits 13.5 μs pulses. The radar system operates at a frequency of 35.25 MHz and uses an interferometric receiver antenna array. From the relative phases of the signals at the various antennas together with the echo range information, the position of the meteor is accurately located and the radial wind velocity is determined from reflected signal and Doppler shift, which is ultimately used to obtain zonal and meridional winds. Radial velocity can be measured with an accuracy of 5% or better and temperature with 10 K or better[19–23]. The radar operates continuously unattended, hence providing round-the-clock MLT-region wind measurements.

Monthly mean height profiles of the zonal and meridional winds are derived from the weekly balloon (0–30 km) and rocket (35–60 km) flights and hourly radar observations (82–98 km). There exists a gap region between 60 and 82 km, where enough data are not available for studying these long-period oscillations. There are few gaps in the data (maximum of 4 months), which are interpolated using spline interpolation method. The long-term mean removed fluctuations in zonal and meridional winds for each month is subjected to deseasoning to filter out the seasonal effect. Unlike the 6-month SAO and the 12-month AO that are closely tied to solar heating, the QBO which is characterized by periods, phases and amplitudes that are not exactly tied to the seasonal cycle can vary with space and time. This makes it difficult to describe the QBO in terms of Fourier series, which are characterized by fixed periods, amplitudes and phases. Since the period of QBO varies between 18 and 36 months, to filter out the components other than QBO, and in order to study the variability of QBO in both stratospheric and mesospheric region, a bandpass filtering technique is applied to the deseasoned monthly mean zonal wind fluctuations, in which all the spectral components except in the period range 18–36 months are removed[9]. Similarly, a bandpass filtering procedure is applied to extract the 6-month component in order to characterize SAO variability in both the stratospheric and mesospheric regions.

Results

Characteristics of SQBO in zonal winds

Figure 1 shows a detailed presentation of the observed QBO structure on decadal scales during the period 1970–2010. It has been already reported that the QBO phase propagates downwards[24], and the oscillation disappears

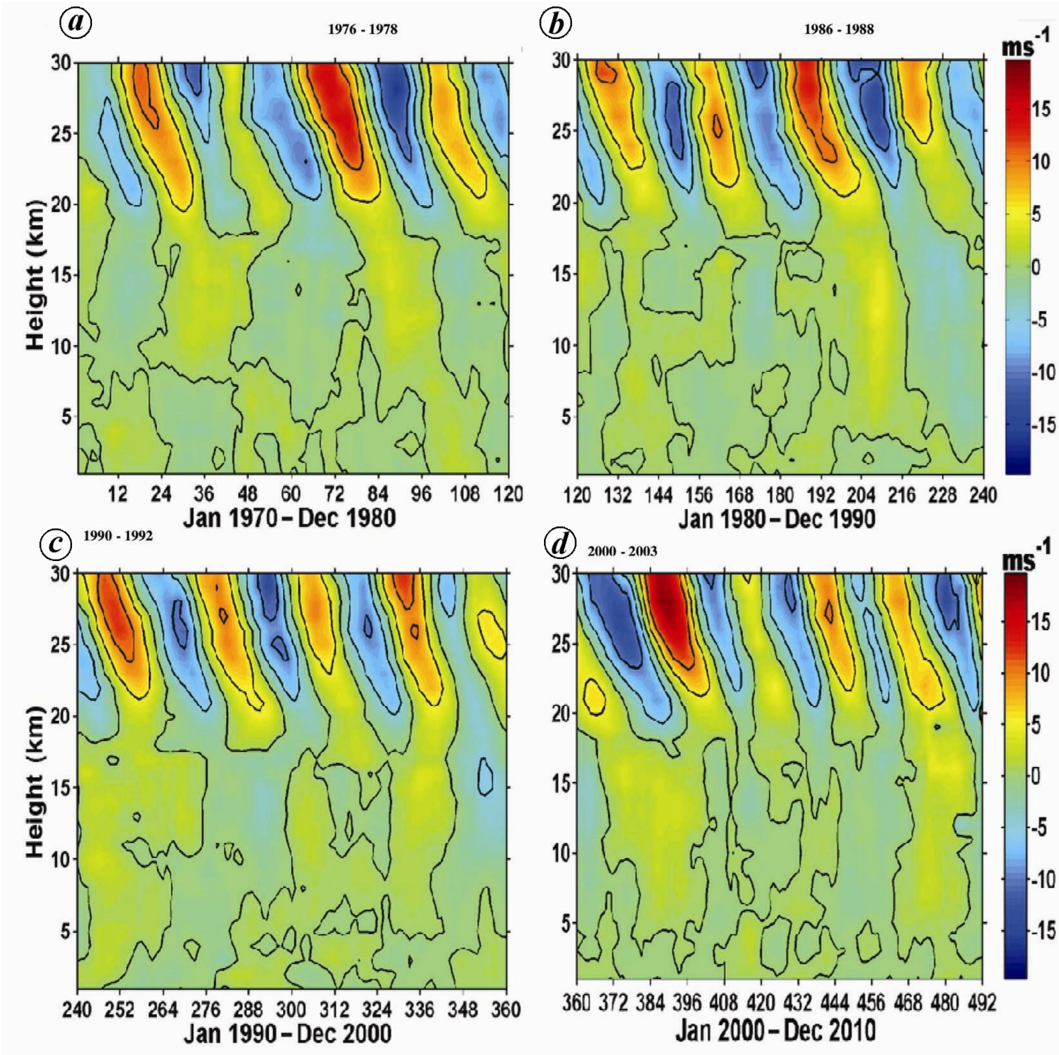

Figure 1. Time height section of Quasi Biennial Oscillation (QBO) in zonal wind for the period 1970–1980 (***a***), 1980–1990 (***b***), 1990–2000 (***c***) and 2000–2010 (***d***) derived from radiosonde data (1970–2010).

near the tropical tropopuase ~16 km. In the present study the downward propagation is noticeable till 18 km, after which it vanishes. The highest extent of the oscillation is found to be beyond 30 km and lowest extent is 18 km.

Over the four decades maximum amplitude of QBO activity is observed during 1976–1978 and 2000–2003, in addition to 1990–1992 and 1986–1988. Among these, during 2000–2003 the amplitude is found to be extremely large (18 ms^{-1}) compared to all other cycles.

The mean period of QBO has been calculated as the interval between successive occurrences of zero mean zonal wind. The period of the particular QBO cycle with very large amplitude is found to be ~36 months. There were studies which showed marginally longer QBO period of 28.4 months[25]. On an average the observed period of QBO is found to be about 28 months.

In general, eastward wind regimes propagate with time at a descent rate of 1.2 km/month, with maximum of 1.5 km/month during 1989 and minimum of 0.9 km/month during 1997. The average descend rate of westward regime is found to be 1 km/month, with maximum of 1.6 km/month during 2008 and minimum of 0.8 km/month during 1999.

Figure 2 represents the observed QBO winds at 28 km along with f10.7 solar flux during 1970–2010. It is clearly seen from the figure that both period and amplitude considerably vary from cycle to cycle. Although generated primarily by wave mean flow interaction, the amplitude and period of SQBO are also found to be affected by the seasonal cycle of solar forcing. Studies showed that the period of QBO is unambiguously lengthened as the solar flux increases[26]. Under low solar forcing, the QBO period is found to be about 24 months and QBO period jumps from 24 to 36 months when the solar forcing increases.

From our study it is observed that in only one out of three solar maximum cases (i.e. during 2002), the period is found to be large compared to all other cycles. Out of these events, maximum eastward amplitude of 18 ms^{-1} and maximum period of 36 months are observed during 2002–2004, coinciding with the solar maximum of 2002. From Figure 2, it is clearly seen that during three solar maximum events, viz. 1982, 1992, 2002 covering our observational period, QBO amplitude and period are found to be larger, which is in good agreement with the results of Salby and Callaghan[27]. During 1980–1982, magnitude of solar flux is ~200 units and the eastward and westward amplitudes of QBO is found to be 10 and 12 ms^{-1} respectively. During 1990–1992, the eastward amplitude of QBO is found to be 12 ms^{-1} and westward amplitude is 10 ms^{-1}; but they are comparable with that during solar minimum years. During 2000–2002, the magnitude of solar flux has decreased to 180 units, while the eastward amplitude of QBO is increased to 18 ms^{-1} and westward amplitude to 14 ms^{-1}. During 1975–1977, 1985–1987 and 2007–2009, when the solar flux is at minimum of ~70 units, a large westward amplitude of 15 ms^{-1} is observed. During the minima of 1996–1997, the westward amplitude is found to be less than 10 ms^{-1}. Hence out of four solar minimum events, three events coincide with maximum westward amplitude of QBO. Thus it is found that changes in QBO period in the stratosphere are generally correlated with the 11-year solar cycle, but there are exceptions as well. Salby and Callaghan[27] reported the possible mechanism in such a way that a stronger upwelling branch of the Brewer–Dobson circulation over the equator slows the descent of the QBO shear zone and thus extends the QBO period. A second mechanism is a radiative perturbation of the SAO–QBO transition region due to the ozone feedback.

Using 44 years of ERA-40 data during 1958–2001, spanning 18.5 QBO cycles, Pascoe *et al.*[25] arrived at a conclusion that the mean time for the easterly shear zone to descend from 20 to 44 hPa is 2 months less under solar maximum conditions than under solar minimum conditions. This rapid descent of the easterly shear zone cuts short the westerly phase of QBO in the lower stratosphere during solar max periods.

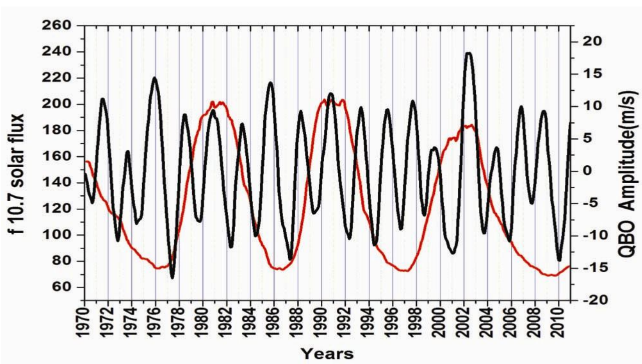

Figure 2. Observed QBO winds (zonal) at 28 km (black line) along with f10.7 solar flux (red line) during 1970–2010.

In the present study, we re-examined the possibility of a decadal solar cycle modulation of the period of QBO using an objective method and the longest record available from a low-latitude station. Figure 2 also showed that the duration of the eastward phase of QBO is more variable than the duration of the westward phase. There were reports that the duration of the westward phase of QBO in the lower stratosphere varies systematically with solar activity such that long (short) periods of equatorial westerlies were coincident with minima (maxima) in solar activity, which is not always true in our observations. As suggested by Hamilton[28], a conclusive answer establishing significant QBO–solar cycle relationship may need to await the availability of more solar cycles. Another possible mechanism to describe the decadal QBO modulation has been presented in a modelling study[29]. They showed that beat periods between 9 and 11 years could be generated by QBO as it interacts through gravity-wave filtering. It has also been suggested that the diabatic heating due to volcanic aerosols could be responsible for the occasional suspension of the downward propagation of QBO[30,31]. From our observations it can be noted that during 1991–1998 the three cycles of QBO have strong eastward and westward phases with almost equal amplitudes. It could be associated with the effects due to the Mount Pinatubo eruption in 1991. Marquadt[32] showed that the downward phase propagation of QBO can be blocked by forced diabatic heating when it is introduced in the westward shear zone, but found scarcely no change when the heating was introduced to eastward shear. What causes the variation of the QBO period in the lower stratosphere is a topic of current debate[25–28,33].

The deseasoned and filtered monthly mean zonal wind-observations from meteor radar are used to derive QBO characteristics in the 82–98 km height region. The band-pass filtered MQBO during 2004–2011 are presented

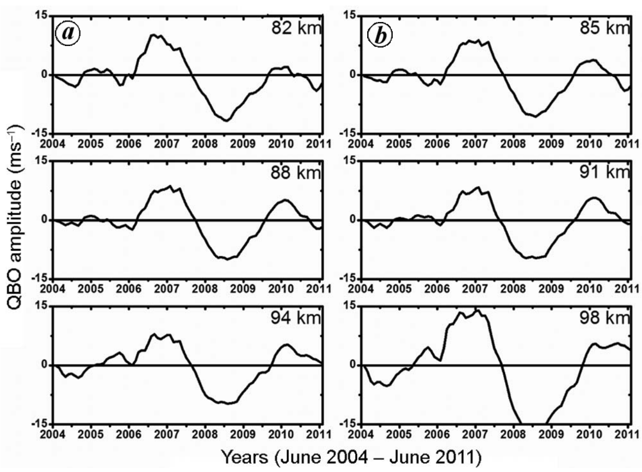

Figure 3. Time series of (***a***) MSAO and (***b***) MQBO in zonal wind during June 2004–June 2011 derived from meteor radar data at various levels.

in Figure 3. In MSAO, maximum eastward amplitude of 12 ms^{-1} and westward amplitude of 10 ms^{-1} are observed during 2006–2007 and minimum amplitude of 2 ms^{-1} in both westward and eastward phases is observed during 2008–2009. Since the data coverage is only 7 years, we could get hardly three cycles of QBO. During 2004–2006, the amplitude and period of MQBO are found to be extremely small. The maximum eastward amplitude of 15 ms^{-1} and westward amplitude of 18 ms^{-1} are observed during 2006–2009, which persisted for more than 34 months. It is also found that both SAO and QBO peak at around 98 km.

Inter-relationship among SQBO, SSAO, MQBO and MSAO

Over the present observational site, at equatorial latitude we have simultaneous measurements of stratospheric and mesospheric QBO and SAO. This provides an opportunity to look into their characteristics and inter-relationships among them. Figure 4 shows observed SQBO at 28 km and SSAO at 48 km respectively, along with MQBO and MSAO at 88 km. Though SQBO and SSAO characteristics are available over four decades, the intercomparison is restricted to 2004–2010 only, since the MQBO and MSAO characteristics from meteor radar observations are available only during this period.

The westward amplitude of SQBO during 2004–2006 is found to be large, whereas during the same period the amplitude of MQBO is found to be extremely small. During 2006–2009 the amplitude of MQBO is found to be large, but SQBO amplitude is small. During 2006–2008 the amplitude of SSAO is very small, whereas the amplitude of MSAO is large. The opposite trend is observed during 2009–2010. Thus it is clear that the waves which deposit their energy and momentum to the mean flow in the stratospheric region generate a large SAO/QBO amplitude over that particular region and the waves that are not depositing, propagate upwards and interact with the

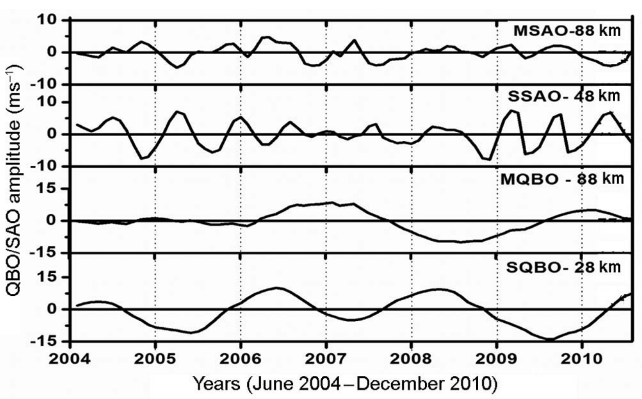

Figure 4. SQBO, MQBO, SSAO and MSAO in zonal winds during June 2004–December 2010 at representative altitudes.

mean flow thus generating SAO/QBO at mesospheric heights.

During strong westward phase of SQBO, both eastward and westward phases of SSAO are found to be equally strong. During weak westward phase of SQBO, both phases of SSAO are also found to be weak. Generally, the stronger westward phases of MSAO are associated with the phase transition of SQBO. Stronger eastward and westward phases of SSAO are associated with weaker phases of MQBO and vice versa. SSAO and MSAO are found to be exactly 180° out of phase[34]. Similarly, SQBO and MQBO also show an out-of-phase relationship in certain cases, but there exists some phase difference between these two, which depends on the strength and period of these oscillations. Ratnam *et al.*[35] reported that the out-of-phase relation between MQBO and SQBO fails whenever there is a strong and long-period SQBO. There were reports suggesting that the westward phase of MSAO is usually stronger only when deep westerlies are present in SQBO[36] (during 2007 and 2010), which is not seen from our observations. Mesospheric westerlies show marked inter annual variability and they do not correlate with SQBO. During 2008–2009, the MSAO amplitudes are found to be very small and SSAO amplitudes are found to be very large.

It is clearly understood that QBO period is controlled by a number of factors. Descending easterlies in particular, are quite erratic and strongly modulated by the seasonal cycle throughout their descent. The seasonal cycle affects QBO in the lower stratosphere[10,37] in a manner distinct from its effects in the middle atmosphere. The role of wave mean-flow interaction in generating these long-period oscillations is quite evident from the above discussion. Depending on the strength of source, propagation characteristics and the background flow, the momentum deposition by waves accelerates the mean-flow and thus through wave mean-flow interaction it generates SQBO in the 20–40 km region, SSAO in the 40–60 km region, and MSAO and MQBO in the 82–98 km region. There were reports using observations from MF radar Tirunelveli showing that at MLT heights strong westward winds are coinciding with eastward phases of SQBO. But from our analysis it is observed that it is not necessary that all the eastward phases of SQBO should accompanied by westward winds.

The easily observed QBO in the stratosphere can be used as a proxy for the behaviour of the zonal winds in the equatorial upper mesosphere. Our observations show that the mesospheric QBO is of sufficient amplitude to alternately block and allow the ducting of long-period planetary waves through generation of a critical level. The information is insufficient to predict how long this QBO cycle will last, or which year the new cycle will begin. To understand an entire QBO cycle it requires the knowledge of complete dynamical mechanisms relevant to the mean-flow evolution throughout the cycle.

Case studies of typical strongest (2000–2003)/ weakest (1973–1976) cycles of SQBO

To have detailed information on the propagation characteristics of the waves and mean flow, the strongest cycle of SQBO (2000–2003) during the observational period is considered as a case study. The time series of zonal wind data in the height region 0–40 km during 1998–2005, covering one cycle before and one after the maxima is spectrally analysed in order to study the height structure of amplitude and phase. Altitude variation of amplitude shows a sinusoidal structure with peak amplitude of 11 ms^{-1} at 28 km. Phase increases with increase in the 20–40 km region, indicating the downward propagation structure of QBO. From the phase structure we calculate the downward decend rate of QBO to be 0.8 km/month. During the same period the composite amplitude and phase structure of SSAO in the 35–50 km height shows that amplitude of SSAO reaches a maximum of 20 ms^{-1} at 48 km, and the phase remains constant throughout the region.

The time series of zonal wind data covering the weakest SQBO cycle during 1970–1977 (minimum being 1973–1975) is spectrally analysed to study the characteristics of SQBO, when the amplitude is minimum over the decades. At the time of minima throughout the entire height region the amplitude remains fairly constant and the value is found to be less than 2 ms^{-1}, while the phase varies drastically. Using the phase structure of QBO during the minimum phase, the calculated downward decend rate is found to be 1.2 km/month. At the same time the amplitude and phase of the SSAO remain almost constant and amplitude is roughly 2 ms^{-1}.

Forcing from planetary waves towards SQBO during strongest/weakest cycles

It is well known that the long-term variability of planetary waves is mainly governed by the underlying winds through which they propagate and the strength and efficiency of the wave excitation processes at various levels. Already established theories explain that gravity waves and planetary waves through wave mean-flow interaction accelerate the mean-flow, thus generating SQBO. Antonita *et al.*[38] have made an extensive study regarding the forcing by the gravity waves towards SQBO. An attempt is made here to quantify the forcing from the 2–16-day planetary waves towards SQBO during the strongest (2000–2003) and weakest (1973–1975) phases. The time series of zonal wind and temperature for a period of 20 days obtained from ECMWF reanalysis data in the height region 0–30 km during the change of SQBO phase from eastward to westward, is spectrally analysed to identify the prominently present periodicities (2–16 days) and then momentum fluxes corresponding to those periodicities are calculated using the method of cross spectra[39].

The mean-flow acceleration produced by the planetary waves in the 0–30 km height region is computed from momentum flux values using eq. (1) as follows

$$\frac{\partial \overline{u}}{\partial t} \approx -\frac{\mathrm{d}}{\mathrm{d}z}\langle \overline{u'w'} \rangle + \frac{\langle \overline{u'w'} \rangle}{H}, \tag{1}$$

which gives mean-flow acceleration resulting from the divergence of momentum flux of 2–16-day planetary waves. Here $u'w'$ is the vertical flux of zonal momentum and H is the scale height calculated from the mean temperature available from observations.

The wave momentum fluxes can also be estimated indirectly from the zonal wind u and temperature T. In the indirect method from cross spectra of T and u fluctuations, momentum flux can be calculated as

$$\overline{u'w'} = -\frac{g}{\overline{T}N^2}\int_{\omega_1}^{\omega_2} Q(\omega)\mathrm{d}\omega, \tag{2}$$

where g is the acceleration due to gravity, N the Brunt–Vaisala frequency, T the background temperature and ω_1 and ω_2 are lower and upper limits of the frequency range that we are interested in. Q is an integration of quadrature spectra over the same frequencies

$$Q(\omega) = -\frac{1}{\omega_0}\frac{\mathrm{d}T'}{\mathrm{d}t}u'. \tag{3}$$

The momentum fluxes computed by both the methods are compared and found to be in good agreement. Mean flow acceleration is estimated by taking the divergence of momentum flux and an attempt is made to quantify the forcing by the planetary waves towards the mean flow[39].

The change in mean zonal wind velocity in the 0–30 km region from the first half to the second half of the observational periods is estimated and thus the observed acceleration is also derived. It is found that the change in zonal mean flow is comparatively less during the SQBO minima, but during maxima the mean flow changes abruptly.

In order to estimate quantitatively the contribution of the planetary waves towards the generation of SQBO, the mean-flow acceleration produced by the divergence of momentum flux of these waves in the 0–30 km height region is compared with the observed zonal mean-flow acceleration as shown in Figure 5. The acceleration from momentum flux divergence towards the generation of SQBO during minimum phase is found to be eastward below 10 km and then changes to westward till 15 km, and again changes to eastward above that height. The observed acceleration remains more or less constant throughout the height region in both SQBO maximum

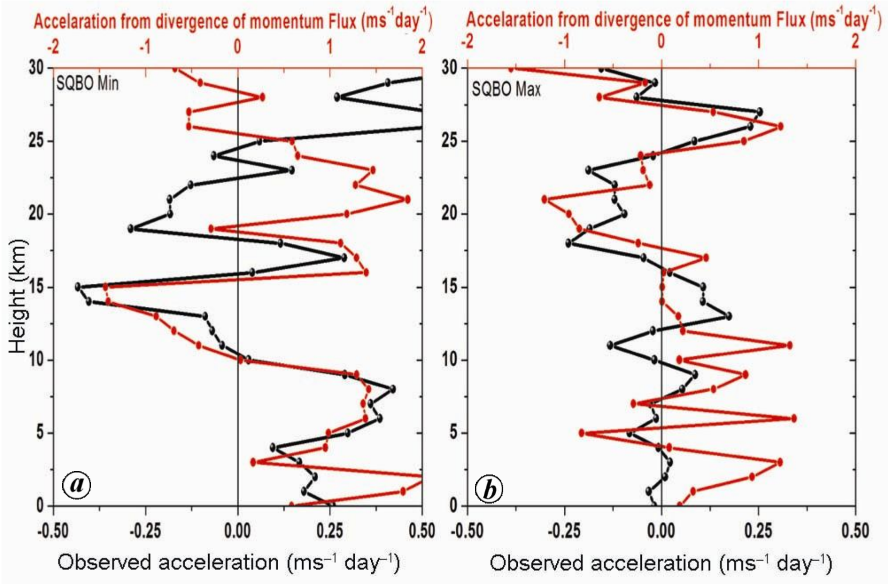

Figure 5. Observed zonal mean-flow acceleration (black line) compared with acceleration computed from momentum flux divergence of 2–16-day period planetary waves (red line) for (***a***) SQBO minimum and (***b***) SQBO maximum.

and minimum phases. During SQBO minimum phase, the planetary wave is imparting westward forcing around 15 km, above which it is imparting eastward forcing.

During SQBO maxima the planetary wave is imparting eastward forcing below 20 km, then a westward forcing in the 20–25 km height region and above 25 km again eastward forcing. Contribution from these planetary waves towards mean flow in producing SQBO is found to be more during SQBO maximum phase compared to the minimum phase. At 28 km, where the SQBO amplitude is found to be maximum, the contribution by the planetary waves is more during SQBO maximum phase, and comparably less in the QBO minimum phase, i.e. during SQBO maximum, the planetary waves contribute more than 70% towards the mean flow whereas during minimum it is found to be less than 30%. From the present observation it is can be summarized that in the QBO region (30–15 km) during minimum phase, the contribution by 2–16-day planetary waves is found to be very less, while during maximum phase it is found to be large. Thus, the quantitative estimation of forcing from 2–16-day period planetary waves towards the mean flow acceleration producing SQBO maximum show generally 70–80% contribution, while during SQBO minimum the contribution is 30–35%.

Forcing from planetary waves towards MQBO during strongest/weakest cycles

The contribution of the planetary waves towards MQBO maximum (2006–2009) and minimum (2004–2006) phases is estimated by calculating the mean-flow acceleration produced by the divergence of momentum flux of planetary waves in the 82–98 km height region and is compared with the observed zonal mean flow acceleration. The time series of zonal and vertical wind data from SKiYMET meteor wind radar during the change of MQBO phase from eastward to westward in the height region 82–98 km for a period of 20 days is spectrally analysed to identify the prominently present periodicities. The three-dimensional wind components derived from SKiYMET meteor wind radar located at an equatorial station Thiruvananthapuram (8.5°N, 77°E) are used to get daily zonal (u), meridional (v) and vertical wind (w) information in the 82–98 km height region and thus to derive the forcing towards MQBO.

The main problem associated with the previous observations of vertical flux of horizontal momentum involves the effective pointing angle of the radar beam used. We have taken this effect into account, and selected the zenith angles for the beams in an appropriate way, so that the vertical wind information will be relatively more accurate. In this study the radar observations are grouped in such a way that there will be sufficient number of meteor echoes to estimate meaningful winds. Meteor trails detected within the zenith angle 10–30° are utilized to derive three-dimensional winds, where enough number of meteors occur. Usually, 5–10 meteors are sufficient for wind estimation. Since the meteor count is found to be maximum during the early morning hours, we have selected five hours of data in the local morning. We are getting minimum of nine vector points per hour to derive the wind values. Thus, during five hours, minimum of 45 wind values are available for one day in the time series.

Thus daily averaged three-dimensional wind data for a period of 20 days are averaged for maximum and

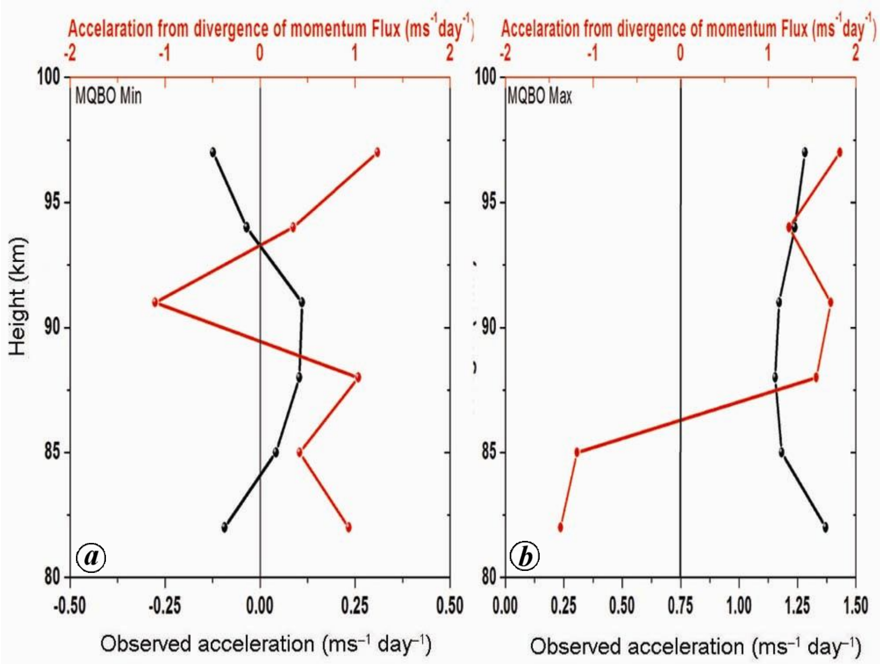

Figure 6. Observed zonal mean-flow acceleration (black line) compared with acceleration computed from momentum flux divergence of 2–16-day period planetary waves (red line) for (***a***) MQBO minimum and (***b***) MQBO maximum.

minimum MQBO phases and the mean removed fluctuation of these wind components is spectrally analysed to get the prominent periodicity bands. The 2–16-day bands are found to be prominent in all the wind components. This mean removal represents the planetary scale waves, removing the trend of tidal and other short-period oscillations. From the amplitudes (tidal component removed) and phases of the prominently present periodicities, the time series of perturbations in u, v, w are reconstructed and used to calculate the vertical flux of zonal momentum $(u'w)$[39].

As in the case of SQBO, here also it is noted that, the change in zonal mean flow is less during the MQBO minima, but during maxima the direction of mean flow itself changes drastically.

To estimate the contribution of the planetary waves towards MQBO maximum and minimum phases, the mean flow acceleration produced by the divergence of momentum flux of these waves in the 82–98 km height region is compared with the observed zonal mean-flow acceleration as discussed above. Figure 6 shows the comparison of the mean-flow acceleration produced by the divergence of momentum flux with the observed zonal mean-flow acceleration. The acceleration from momentum flux divergence in the MQBO minimum period is found to be eastward below 88 km and then changes to westward up to 94 km, and again changes to eastward. During maximum phase of MQBO it is found to be westward below 85 km and then changes to eastward. The observed acceleration in MQBO maximum phase is found to be eastward throughout the height region. During MQBO minima around 90 km, the planetary wave is imparting westward forcing. During MQBO maxima above 88 km, the planetary wave is imparting eastward forcing and below that height a westward forcing. Contribution from these planetary waves towards mean flow in producing MQBO is found to be more during MQBO maximum phase than the minimum phase. Generally, it is found that the contribution by planetary waves towards the mean flow producing MQBO maximum is around 90% above 88 km and 30% below it and during MQBO minimum phase it is around 60% above 88 km and 30% below it. Thus the quantitative estimation of forcing towards the mean flow acceleration producing MQBO maximum shows generally 30–90% contribution from planetary waves, while during SQBO minimum the contribution is 30–60%. The discrepancy between the estimated and observed acceleration could be due to the contribution from gravity waves, inertia gravity waves and tides. These waves may be contributing in the opposite direction to that of planetary waves whenever the estimated acceleration exceeds the observed acceleration. The forcing by short-period gravity waves towards the mesopause semi-annual oscillation over the same location has already been estimated to vary from 20% to 70% (ref. 39).

Vertical structure of QBO, AO and SAO for the study period

The height structure of amplitude of the various long-period equatorial oscillations in zonal wind derived from the long-term database (~ 40 years in 0–65 km region and 7 years in 82–98 km region) is summarized in Figure 7. Since the data are subjected to long-term mean removal and deseasoning procedure, the amplitude profiles are free from any contamination and seasonal variations. The SQBO shows a maximum of 12 ms^{-1} at about 28 km. Its amplitude in the troposphere is negligible. The annual cycle (black curve) is relatively small in both stratosphere and mesosphere (less than 5 ms^{-1}). Above 10 km, the AO amplitudes show three broad peaks: one around 20 km, another around 30 km and a third between 40 and 50 km. There are sharp minima: one is at 10 km, and another is at 35 km, which is close to the altitude of starting height of QBO. At 90 km, AO in zonal wind shows a sudden jump and the amplitude is around 4 ms^{-1}.

In the 40–60 km altitude region, the SAO has a broad peak with maximum amplitude exceeding 17 ms^{-1} at around 50 km. In the upper mesospheric region, both MSAO and MQBO show a peak near 98 km with amplitudes of 18 and 13 ms^{-1} respectively. Baldwin *et al.*[9] have shown the vertical distribution of amplitude of MQBO, MSAO, SSAO, SQBO and annual component at the equatorial belt. We have the advantage of simultaneous observations from a single station located near the equator. The height structure of these oscillations matches well with that reported by Baldwin *et al.*[9], but with a noticeable change in magnitude.

Summary

The characteristics of SQBO and MQBO are studied in detail, making use of the unique data available for almost 40 years from radiosonde, rocketsonde and that obtained from SKiYMET meteor wind radar observations for the low-latitude station over Thiruvananthapuram. The prominent features observed are the systematic change-over between eastward and westward anomalies in the QBO region and the downward propagating zonal wind regimes in the stratosphere having a variable periodicity of 18–36 months with an average period of 28 months. In the present analysis the downward propagation is noticeable till 18 km. The highest extent of the oscillation is found to be 38 km, and the lowest extent is 18 km. Maximum amplitudes of both phases are typically between 10 and 15 ms^{-1} and occur near 28 km. The QBO period is found to be lengthened during solar maxima. The inter-relationship among SQBO, SSAO, MSAO and MQBO is studied and the correlation between these oscillations is also reported. The propagation characteristics of SQBO during the strongest and weakest cycles are also studied and the variations are discussed. In order to estimate quantitatively the contribution of the 2–16-day planetary waves towards SQBO and MQBO strongest and weakest cycles, the mean-flow acceleration produced by the divergence of momentum flux of these waves in the 0–30 and 82–98 km height regions is compared with the observed zonal mean-flow acceleration. The quantitative estimation of forcing towards the mean-flow acceleration producing SQBO maximum shows 70–80% contribution from the 2–16-day planetary waves, while during SQBO minimum the contribution is 30–35%. Generally, it is found that the contribution by planetary waves towards the mean flow producing MQBO maximum is around 30–90% and during MQBO minimum phase it is 30–60%. To summarize, the height structure of the amplitudes of these long-period equatorial oscillations (AO, SAO and QBO) in zonal wind are derived from the available long-term database over the present observational site and compared with already reported results.

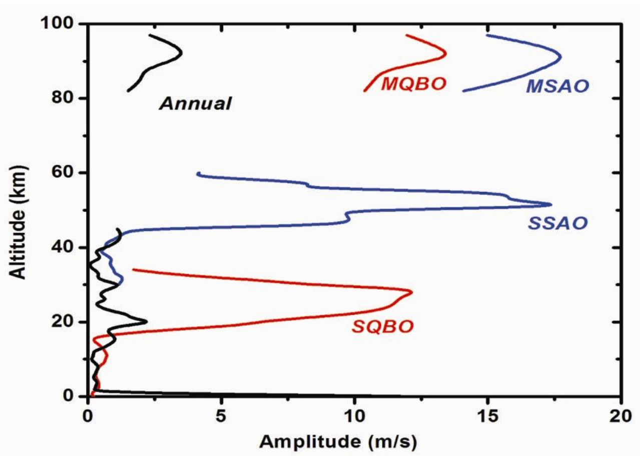

Figure 7. Vertical profile of the amplitude of MQBO, MSAO, SSAO, SQBO and annual component at Thiruvananthapuram.

1. Reed, R. J., The quasi biennial oscillation of the atmosphere between 30 and 50 km over Ascension Island. *J. Atmos. Sci.*, 1965b, **22**, 331–333.
2. Reed, R. J., Zonal wind behaviour in the equatorial stratosphere and lower mesosphere. *J. Geophys. Res.*, 1966, **71**, 4223–4233.
3. Angell, J. K., On the variation in period and amplitude of the quasi biennial oscillation in the equatorial stratosphere, 1951–85. *Mon. Weather Rev.*, 1986, **114**, 2272–2278.
4. Quiroz, R., Periodic modulation of the stratospheric quasi-biennial oscillation. *Mon. Weather Rev.*, 1981, **109**, 665–674.
5. Sasi, M. N., Murthy, B. V. K. and Ramkumar, G., A study of equatorial wave characteristics using rockets, balloons, lidar and radar. *Adv. Space Res.*, 2003, **32**, 813–818.
6. Holton, J. R. and Lindzen, R. S., An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, 1972, **29**, 1076–1080.
7. Lindzen, R. S. and Holton, J., A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, 1968, **25**, 1095–1107.
8. Plumb, R. A. and Bell, R. C., A model of the quasi-biennial oscillation on an equatorial beta-plane. *Q. J. R. Meteorol. Soc.*, 1982b, **108**, 335–352.
9. Baldwin, M. P., Gray, L. J., Dunkerton, T. J. and Hamilton, K., Quasi-biennial oscillation. *Rev. Geophys.*, 2001, **39**, 179–229.
10. Kinnersley, J. S. and Pawson, S., The descent rates of the shear zones of the equatorial QBO. *J. Atmos. Sci.*, 1996, **53**(14), 1937–1949.

11. Takahashi, M. and Boville, B. A., A three-dimensional simulation of the equatorial quasi-biennial oscillation. *J. Atmos. Sci.*, 1992, **49**, 1020–1035.
12. Haynes, P. H., The latitudinal structure of the quasi-biennial oscillation. *Q. J. R. Meteorol. Soc*., 1998, **124**, 2645–2670.
13. Holton, J. and Wehrbein, W. M., A numerical model of the zonal mean circulation of the middle atmosphere. *Pure Appl. Geophys*., 1980, **118**, 284–306.
14. Angell, J. K. and Korshover, J., Quasi-biennial variations in temperature, total ozone, and tropopause height. *J. Atmos. Sci*., 1964, **21**, 479–492.
15. Terray, P., Space–time structure of monsoons interannual variability. *J. Climate*, 1995, **8**, 2595–2619.
16. Trenberth, K. E., Atmospheric quasi biennial oscillation. *Mon. Weath. Rev*., 1980, **108**, 1370–1377.
17. Yasunari, T. and Suppiah, R., Some problems on the interannual variability of Indonesian monsoon rainfall. In *Tropical Rainfall Measurements* (eds Theon, J. S. and Fugono, N.), 1988, pp. 113–122.
18. Devarajan, M., Parameswaran, P. R., Reddy, C. A. and Reddy, C. R., Accuracy of stratospheric wind measurements using chaff releases from RH-200 rockets. *Indian J. Radio Space Phys*., 1984, **13**, 48–55.
19. Deepa, V., Ramkumar, G. and Krishna Murthy, B. V., Gravity waves observed from the equatorial wave studies (EWS) campaign during 1999 and 2000 and their role in the generation of stratospheric semiannual oscillations. *Ann. Geophys*., 2006a, **24**, 2481–2491.
20. Deepa, V., Ramkumar, G., Antonita, T. M., Kumar, K. K. and Sasi, M. N., Vertical propagation characteristics and seasonal variability of tidal wind oscillations in the MLT region over Trivandrum (8°N, 77°E). First results from SKiYMET meteor radar. *Ann. Geophys*., 2006, **24**, 1–13.
21. Hocking, W. K., Fuller, B. and Vandepeer, B., Real time determination of meteor-related parameters utilizing modern digital technology. *J. Atmos. Sol. Terr. Phys*., 2001, **63**, 155–169.
22. Kumar, K. K., Ramkumar, G. and Shelbi, S. T., Initial results from SKiYMET meteor radar at Thumba (8.5°N, 77°E), 1. Comparison of wind measurements with MF spaced antenna radar system. *Radio Sci.*, 2007a, **42**, RS6008; doi: 10.1029/2006RS003551.
23. Kumar, K. K., Antonita, T. M. and Shelbi, S. T., Initial results from SKiYMET meteor radar at Thumba (8.5°N, 77°E). 2. Gravity wave observations in the MLT region. *Radio Sci*., 2007b, **42**, RS6009; doi: 10.1029/2006RS003553.
24. Naujokat, B., An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci*., 1986, **43**, 1873–1877.
25. Pascoe, C. L., Gray, L. J., Crooks, S. A., Juckes, M. N. and Baldwin, M. P., The quasi-biennial oscillation. Analysis using ERA-40 data. *J. Geophys. Res*., 2005, **110**, D08105; doi: 10.1029/2004JD004941.
26. Fischer, P. and Tung, K. K., A re-examination of the QBO period modulation by the solar cycle. *J. Geophys. Res*., 2008, **113**, D07114; doi: 0.1029/2007JD008983.
27. Salby, M. and Callaghan, P. F., Connection between the solar cycle and the QBO. The missing link. *J. Climate*, 2000, **13**, 2652–2662.
28. Hamilton, K., On the quasi-decadal modulation of the stratospheric QBO period. *J. Climate*, 2002, **15**, 2562–2565.
29. Mayr, H. G., Mengel, J. G., Drob, D. P., Porter, H. S. and Chan, K. L., Modeling studies with QBO. I. Quasi-decadal oscillation. *J. Atmos. Sol. Terr. Phys*., 2003, **65**(8), 887–899.
30. Dunkerton, T. J., Theory of the mesopause semi-annual oscillation. *J. Atmos. Sci*., 1982a, **39**, 2681–2690.
31. Dunkerton, T. J., The evolution of latitudinal shear in Rossby gravity wave, mean flow interaction. *J. Geophys. Res*., 1983, **88**, 3836–3842.
32. Marquadt, C., The tropospheric QBO and dynamic process in the stratosphere, Ph.D. thesis, Meteorologische Abhandlungen, 1997, Series A, Band 9, Heft 4, Berlin, ISSN 0342-4324.
33. Soukharev, B. and Hood, L. L., Possible solar modulation of the equatorial quasi-biennial oscillation. Additional statistical evidence. *J. Geophys. Res*., 2001, **106**, 14855–14868.
34. Hirota, I., Equatorial waves in the upper stratosphere and mesosphere in relation to the semi annual oscillation of the zonal wind. *J. Atmos. Sci*., 1978, **35**, 714–722.
35. Ratnam, M. V. *et al.*, Long-term variability of the low latitude mesospheric SAO and QBO and their relation with stratospheric QBO. *Geophys. Res. Lett*., 2008, **35**, L21809; doi: 10.1029/2008GL035390.
36. Garcia, R. R., Dunkerton, T. J., Lieberman, R. S. and Vincent, R. A., Climatology of the semiannual oscillation of the tropical middle atmosphere. *J. Geophys. Res. D*, 1997, **102**, 26019–26032.
37. Dunkerton, T. J., Annual variation of deseasonalized mean flow acceleration in the equatorial lower stratosphere. *J. Meteorol. Soc. Jpn*, 1990, **68**, 499–508.
38. Antonita, T. M., Ramkumar, G., Kumar, K. K., Appu, K. S. and Nambhoodiri, K. V. S., A quantitative study on the role of gravity waves in driving the tropical Stratospheric Semiannual Oscillation. *J. Geophys. Res.*, 2007, **112**, D12115; doi: 10.1029/2006JD008250.
39. Babu, V. S., Ramkumar, G. and John, S. R., Seasonal variation of planetary wave momentum flux and the forcing towards mean flow acceleration in the MLT region. *J. Atmos. Sol. Terr. Phys*., 2012, **78–79**, 53–61.

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