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Long-term tendencies in the mesosphere/lower thermosphere mean winds and tides as observed by medium-frequency radar at Tirunelveli (8.7°N, 77.8°E)

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[1] The present study examines changes in monthly mean winds and tides observed by MF radar at Tirunelveli (8.7°N, 77.8°E) for the years 1993–2007 with respect to long-term variabilities, namely, the stratospheric quasi-biennial oscillation (QBO), the El Niño–Southern Oscillation (ENSO), the solar cycle (SC), and the long-term trends, using regression analysis. Both zonal and meridional winds show negative QBO response in the altitude region 84–94 km and negative ENSO response (~1 m s^{-1} per Southern Oscillation Index) above 90 km. However, only the latter show a notable positive SC response. The response of meridional diurnal tide is positive to ENSO (above 90 km) and stratospheric QBO and is negative to SC. The tides in both wind components show positive trends. The meridional winds show a significant negative trend (0.3 m s^{-1} yr^{-1}). Further, monthly variations of the responses of mean winds and tides to QBO, ENSO, and SC are presented and discussed.

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1. Introduction

[2] Most of the studies on long-term tendencies in mesosphere/lower thermosphere (MLT) winds are from midlatitudes and high latitudes. Several studies focusing on the relationship between solar cycle (SC) and MLT winds have found a negative correlation between solar activity and tidal amplitudes. *Sprenger and Schminder* [1969] investigated the SC dependence of midlatitude wind field using LF observations and found that both zonal and meridional wind fields showed positive correlation with solar activity and that semidiurnal tide showed negative correlation with solar activity. *Greisiger et al.* [1987] observed that both zonal wind and semidiurnal tidal amplitude showed negative correlation with solar activity and that there is no significant correlation between meridional wind and solar activity. *Fraser et al.* [1989] showed no correlation between tidal amplitude and solar activity. Though *Namboothiri et al.* [1993, 1994] obtained results similar to those of *Sprenger and Schminder* [1969], the correlation is weaker with a low confidence level. *Bremer et al.* [1997]'s results showed that both zonal wind and semidiurnal tide show weaker negative correlation with solar activity and that meridional wind and diurnal tide do not show any correlation with solar activity. *Portnyagin et al.* [2006] observed that the annual mean eastward (northward) wind decreases (increases) until the 1980s, but after that it does not have a significant trend. Their results showed that the tendencies are not the same during the time period of their measurements. Using MF radar observations over Scott Base (78°S, 167°E), *Baumgaertner et al.* [2005] found a negative correlation between amplitude of semidiurnal tide and solar activity and suggested that long-term changes in polar vortex (the location, strength, and duration of which affect the long-term variability of planetary wave amplitudes and the wave interaction with tides) could be important mechanisms for the long-term variability of tides. The breakdown of polar vortex and subsequent changes in the high-latitude dynamics influence low-latitude dynamics as well. The increase in gravity wave activity, decease in planetary wave activity, and change of poleward circulation to equatorial meridional circulation during major warming events have recently been reported over Tirunelveli (8.7°N, 77.8°E) [*Sridharan and Sathishkumar*, 2008; *Sathishkumar and Sridharan*, 2009]. Motivated by the lack of information on the long-term tendencies of low-latitude MLT neutral winds, the present study reports long-term trends in mean winds and tides in the altitude region 80–98 km over a low-latitude station, Tirunelveli, which is located at the southern tip of the Indian peninsula.

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2. Data Analysis

[3] The wind data analyzed were obtained from medium-frequency (MF) radar at Tirunelveli [*Rajaram and Gurubaran*,

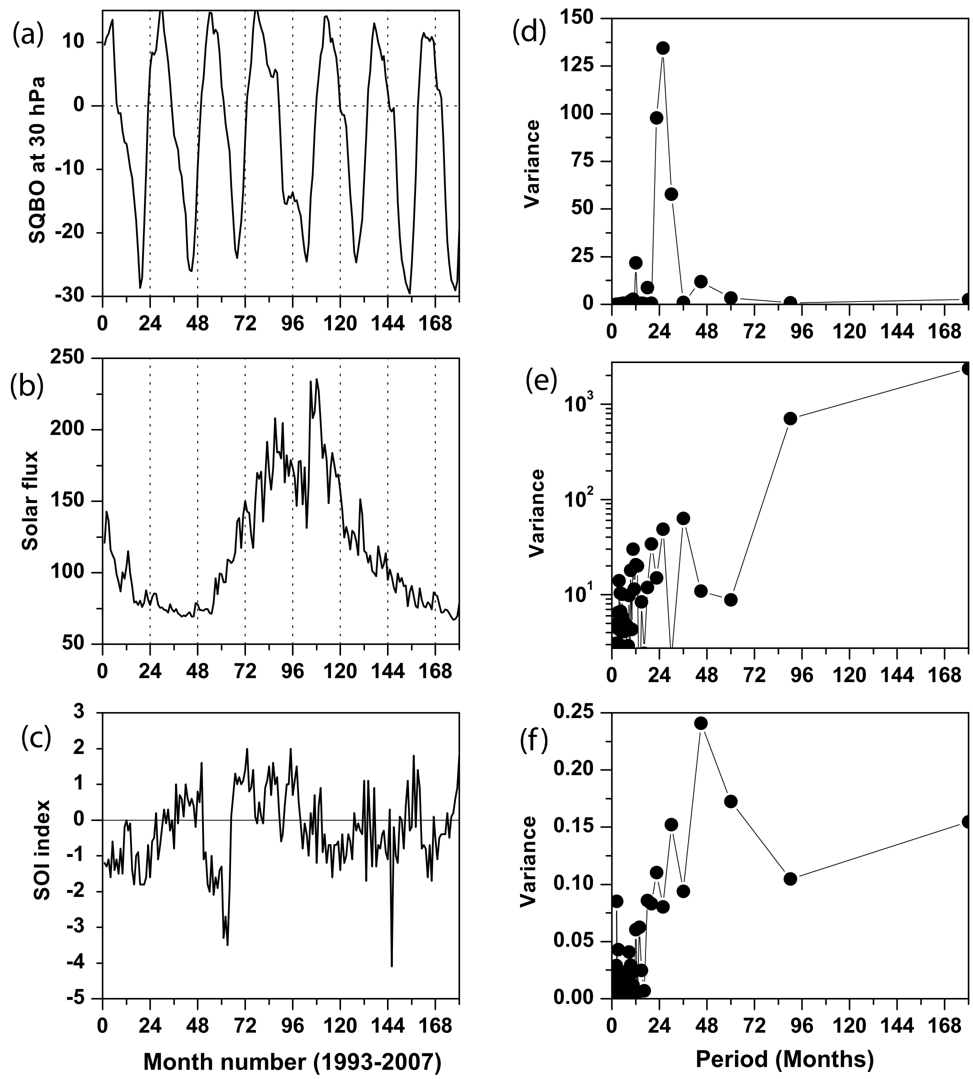

Figure 1. Monthly variation of (a) QBO at 30 hPa, (b) solar flux, and (c) SOI for January 1993 to December 2007. (d–f) The corresponding spectra.

1998] for the years 1993–2007. Although the time resolution of raw data is 2 min, we average for 1 h in this study. The hourly winds are averaged for a specific month according to time of day to obtain the hourly behavior of the wind during the composite day at specific altitudes. Then, monthly mean winds and tidal amplitudes and phases are determined by means of a least squares fitting on the composite data at each altitude. We put a criterion that each month should represent at least 10 days of data and the composite day should have at least 16 h of data to consider for extracting mean winds and tidal amplitudes. The present study focuses on the changes in the monthly mean winds and tidal components with respect to phenomena associated with multiyear periods (namely, the stratospheric quasi-biennial oscillation (QBO), El Niño–Southern Oscillation (ENSO), and the SC) and long-term trends.

[4] As the wind variation contains natural periodic signals, like the QBO, ENSO, and 11 year SC, a regression model is used to extract each signal quantitatively [*Randel and Cobb*, 1994]. The general expression for the regression model equation at each altitude is given by

$$T(t) = \alpha(t) + \beta(t)\cdot t + \gamma(t)\cdot QBO(t) + \delta(t)\cdot solar(t) + \varepsilon(t)\cdot Enso(t) + resid(t), \quad (1)$$

where $\alpha(t)$, $\beta(t)$, $\gamma(t)$, $\delta(t)$, and $\varepsilon(t)$ in equation (1) have the form

$$\alpha(t) = A_0 + \sum_{i=2}^{12} [A_i \times \mathrm{Cos}\omega_i t + B_i \times \mathrm{Sin}\omega_i t], \quad (2)$$

where $\omega_i = \frac{2\pi i}{24}$. The mean winds and tides are subjected to this linear regression model, and the coefficients α, β, γ, δ, and ε are determined in a least squares sense. The $\alpha(t)$ represents seasonal and intraseasonal variations. If S is the sum of the square of residuals, n is data length, and $p + 1$ is the number

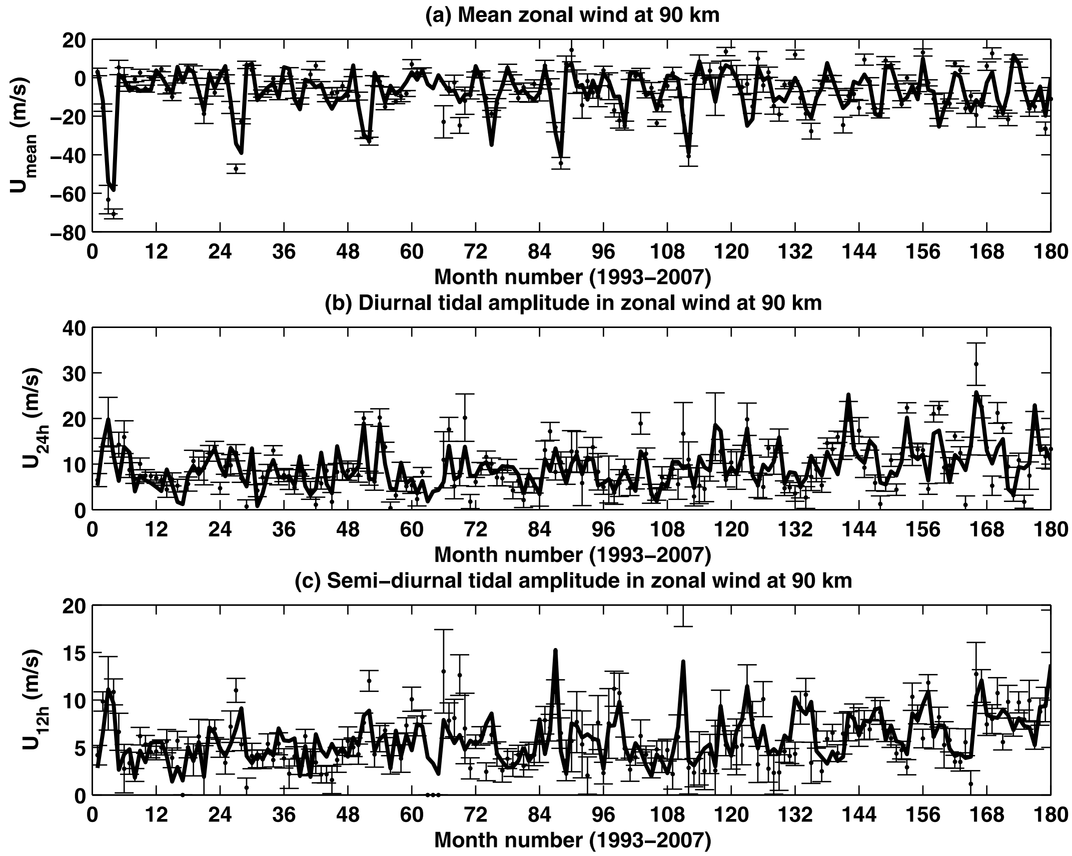

Figure 2. Monthly variation of (a) mean zonal winds, (b) diurnal tidal amplitude in zonal winds and (c) semi-diurnal tidal amplitude in zonal winds, plotted as dots with error bars. The fit from the regression model is the thick continuous curve.

of coefficients to be determined, then the error in the estimation of coefficients is given by

$$\sigma = \sqrt{\frac{S}{n-p-1}(X^T X)^{-1}}, \quad (3)$$

where X is the matrix of the regressors.

[5] We use Singapore monthly mean QBO zonal winds (m s^{-1}) at 30 hPa as a QBO proxy, F10.7 solar radio flux as solar proxy, and Southern Oscillation Index (SOI), which is the normalized Tahiti (18°S, 150°W) minus Darwin (13°S, 131°E) monthly mean sea level pressures (hPa), as ENSO proxy, corresponding to the months t. The QBO winds and SOI data were downloaded from the Web at http://www.cpc.ncep.noaa.gov/. The solar flux data were obtained from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/MONTHLY.OBS.

[6] Figure 1 shows the time series and their spectra of the monthly stratospheric QBO winds at 30 hPa (Figures 1a and 1d), F10.7 cm solar radio flux (Figures 1b and 1e), and SOI (Figures 1c and 1f). Though the dominant period of QBO is ~26 months, the period of QBO is extended to nearly 3 years during 2000–2001 [*Sridharan et al.*, 2007], which corresponds to solar maximum. Though the dominant period of ENSO is nearly 4 years, other shorter periods in the range of ~2–3 years can also be observed. The time series of QBO, ENSO, and SC are tested and found to be independent of each other, so that they can be used in regression analysis as regressors.

[7] Figure 2 shows the monthly variation of zonal winds (Figure 2a), diurnal tide in zonal winds (Figure 2b), and semidiurnal tide in zonal winds plotted as dots with error bars (Figure 2c). Figure 3 is the same as Figure 2, except that it is for meridional winds. The positive (negative) zonal and meridional winds denoted that the winds are directed eastward (westward) and northward (southward), respectively. The fits from the regression model (without the residuals) are the thick continuous curves. To measure how successful the fit is in explaining the variation of the data, the R-square method is used. The R-square is the square of the correlation between the response values and the predicted response values. It is also called the square of the multiple correlation coefficients and the coefficient of multiple determinations. R-square is defined as the ratio of the sum of squares of the regression (SSR) and the total sum of squares (SST). The fitted curves show 79%, 69%, 72%, 75%, 56%, and 68% of total variation of monthly values of mean zonal winds, mean meridional winds, diurnal tide in zonal winds, diurnal tide in meridional winds, semidiurnal

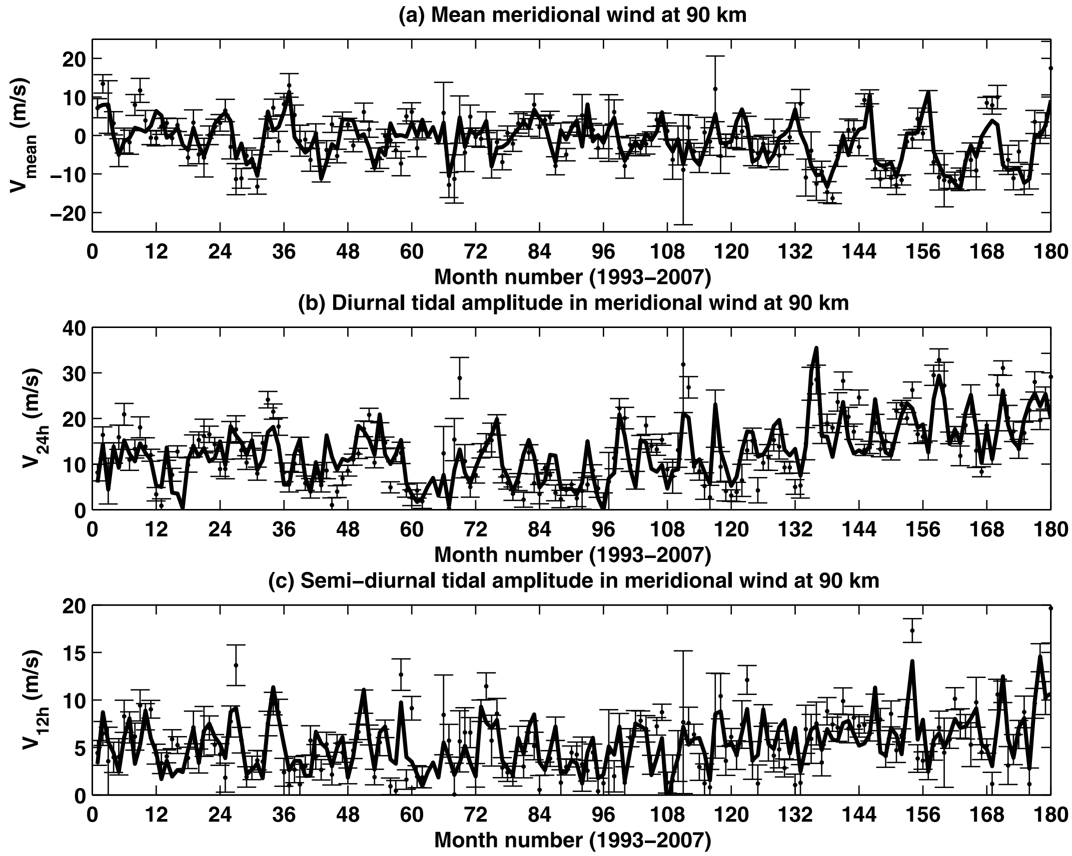

Figure 3. (a–c) Same as Figure 2 but for meridional winds.

tide in zonal winds, and semidiurnal tide in meridional winds, respectively.

3. Results

3.1. Mean Winds

[8] Figure 4 shows the altitude profiles of the annual mean response of mean zonal winds (Figures 4a–4d) and mean meridional winds (Figures 4e–4h) to QBO, SC, ENSO, and linear trend, respectively. The zonal wind response to QBO is negative with values in the range of ~0.1–0.2 m s^{-1} per QBO in the altitude region 84–90 km with the maximum of 0.25 ± 0.1 m s^{-1} per QBO at 86 km. The meridional winds show less of a negative response to QBO. They show a positive response to SC, and the response increases with altitude from 3 m s^{-1} per 100 solar flux units (sfu) at ~86 km to 5 (±1.5) m s^{-1} per 100 sfu at 94–98 km. The zonal wind response to SC is not significant. The ENSO response is negative in the altitude region 90–96 km (1 m s^{-1} per SOI) in both zonal and meridional winds. The meridional winds show a consistent negative trend of ~0.3 (±0.1) m s^{-1} at altitudes of 86–98 km, indicating a decreasing trend of northward winds, whereas the zonal winds show a large positive trend (0.4 m s^{-1} yr^{-1}) above 94 km and a negative trend (~0.5 m s^{-1} yr^{-1}) at 84 km.

3.2. Diurnal and Semidiurnal Tides

[9] Figure 5 is the same as Figure 4 but for monthly mean diurnal tide in zonal and meridional winds. The response of diurnal tide in meridional winds to QBO shows a positive maximum at 86 km (0.2 ± 0.07 m s^{-1} per QBO) and remains positive (>0.1 m s^{-1} per QBO) at altitudes of 84–88 km. Its response to SC is negative with a larger value of 8 m s^{-1} per 100 sfu at 86 km and is in the range of 5–8 m s^{-1} per 100 sfu at altitudes of 84–98 km. The zonal diurnal tide shows no noteworthy SC response except at altitudes 96 and 98 km, where it shows a relatively weaker positive response of 3–4 m s^{-1} per 100 sfu.

[10] Though diurnal tide in zonal wind does not show a notable response to ENSO, the same in meridional wind shows a positive response of ~1 m s^{-1} per SOI above 90 km. The latter shows a positive trend at the rate of 0.3–0.4 (±0.07) m s^{-1} yr^{-1} at heights of 88–94 km, and the former also shows a positive trend at that rate, the magnitude of which increases from 0.2 to 0.4 (±0.05) m s^{-1} yr^{-1} from 86 to 96 km.

[11] The semidiurnal tide in meridional winds shows a negative SC response with 1–2 (±0.06) m s^{-1} per 100 sfu at heights of 82–94 km (Figure 6) with a larger response at 86–90 km. Its QBO and ENSO responses are not so remarkable at most of the altitudes. Like diurnal tide, both zonal and meridional semidiurnal tides show a positive trend

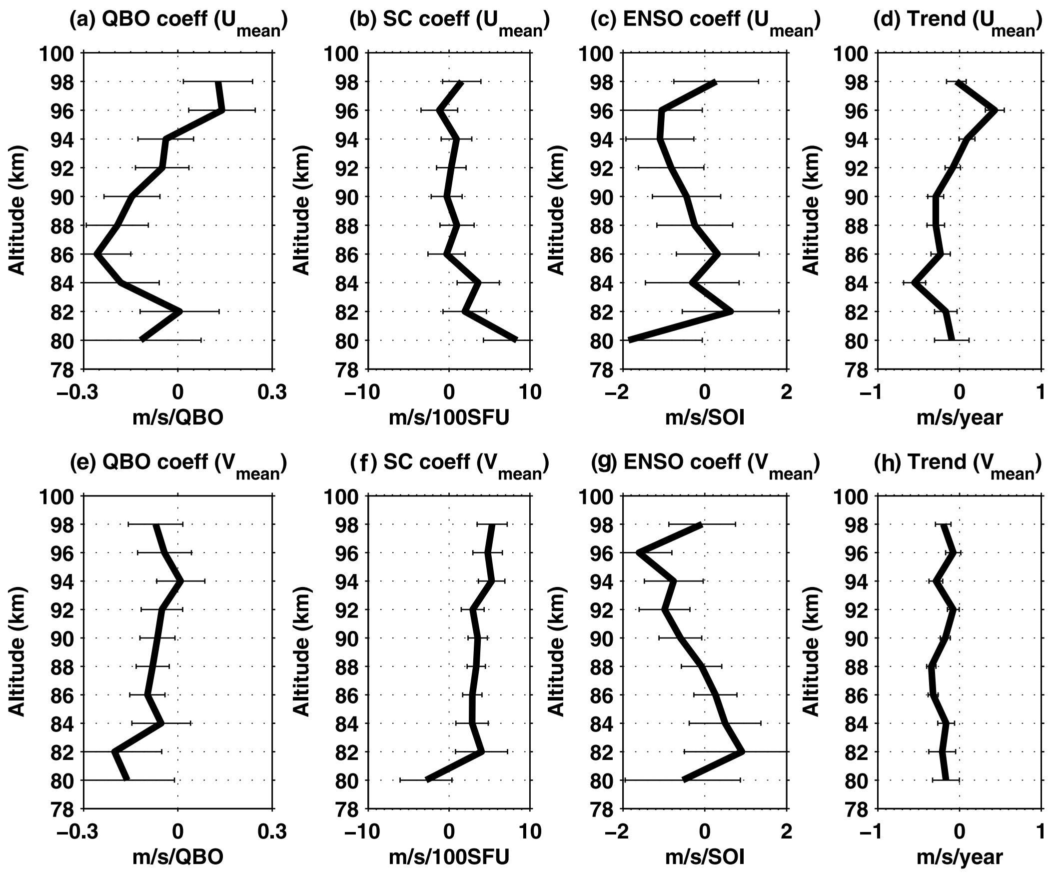

Figure 4. Altitude profiles of annual mean response to QBO, SC, ENSO, and linear trend for (a–d) mean zonal winds and (e–h) mean meridional winds.

(0.15–0.2 ± 0.04 m s^{-1} yr^{-1}), but it is weaker than that of diurnal tide.

4. Seasonal Variabilities in Trends

4.1. Mean Winds

[12] The values of monthly mean winds for different years are separated according to each month and are subjected to regression analysis with linear term, stratospheric QBO winds, SOI index, and sfu flux as regressors. The responses of the winds to QBO, ENSO, and SC as a function of altitude and month are plotted in Figure 7. A similar analysis is done for tides, and the results are shown in Figure 8. From Figure 7 we can infer a large negative response to QBO during March and a positive response during January in zonal wind. However, during other months, the response is not so notable. The meridional wind response to QBO is weakly positive (0.2 m s^{-1} per QBO) during all the months except during March–April, when it shows a weak negative response. The zonal wind response to SC is significant in April, October, and January with a negative response of 10–15 m s^{-1} per 100 sfu and 2–10 m s^{-1} per 100 sfu. Positive SC response (5–10 m s^{-1} per 100 sfu) is observed in February, August, and December. The meridional wind response to SC is positive during most of the months, with larger values during summer (6–10 m s^{-1} per 100 sfu) and spring equinox (10–20 m s^{-1} per F100.7 above 90 km), and negative (2–4 m s^{-1} per 100 sfu at altitudes of 86–90 km) during winter. During fall equinox months, the response is too weak at most of the altitudes. In zonal wind, the response to ENSO is negative during all the months except April and September, when it shows a weak positive response. In meridional wind, the response is negative during all the months except June and October, when it is positive at low altitudes (~84 km).

[13] There is a significant positive trend (0.5 m s^{-1} yr^{-1}) in zonal winds during spring equinox months. During winter and fall equinox months, it shows a maximum decreasing trend of 0.5–1 m s^{-1} yr^{-1} at heights below 90 km. The northward winds show no significant trend during winter; however, they show a decreasing trend (0.5–1 m s^{-1} yr^{-1}) during spring equinox and summer months and less than 0.5 m s^{-1} yr^{-1} during fall equinox months.

4.2. Diurnal Tide

[14] Referring to Figure 8, the response of diurnal tide to QBO is always positive with a larger response (~0.5 m s^{-1} per QBO) in March for the zonal component and in April for the meridional component. The ENSO response is negative during summer for both zonal and meridional components. The SC response is also negative during all the months for diurnal tide in zonal winds and relatively more negative for the same in meridional winds. The diurnal tide in meridional winds shows a larger positive trend in March–April and

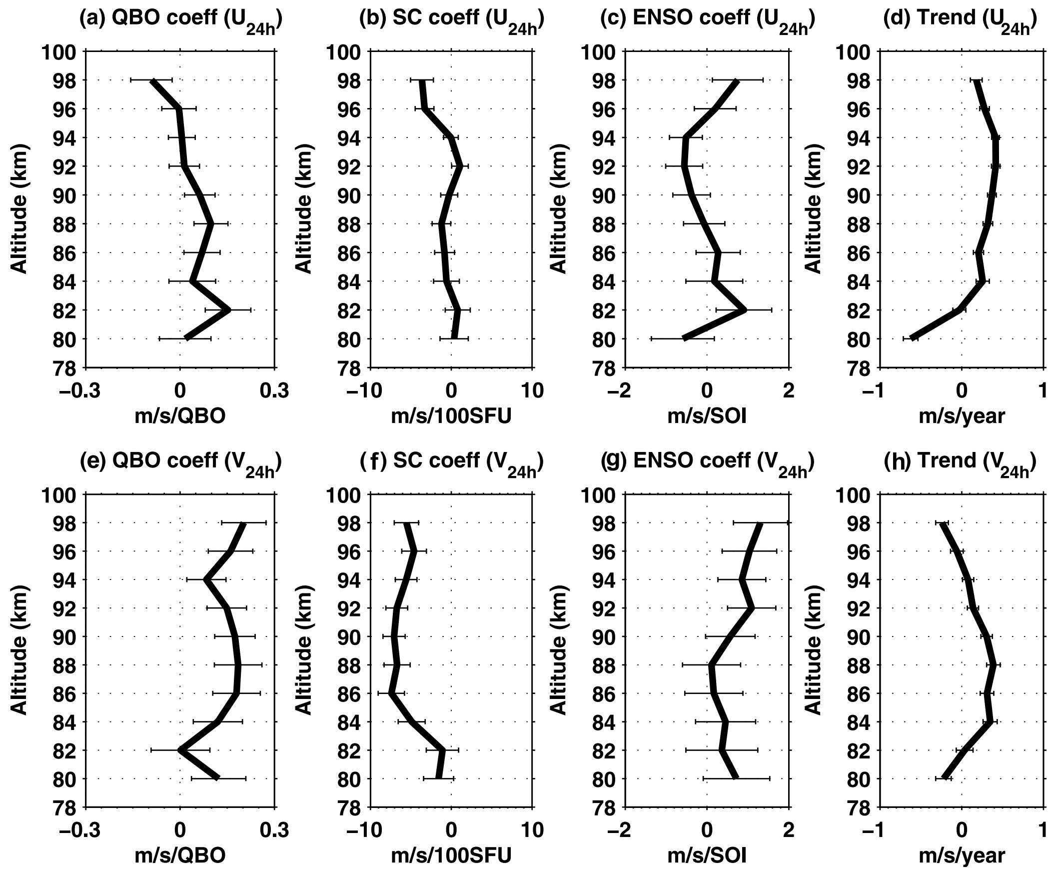

Figure 5. Same as Figure 4 but for monthly mean diurnal tidal amplitude in (a–d) zonal winds and (e–h) meridional winds.

August–September, whereas the same in zonal wind shows a positive trend during September–October.

5. Discussion

[15] The present study examines changes in winds and tides over Tirunelveli with respect to long-term oscillations, namely, QBO, ENSO, and SC, and long-term trends. The mean meridional winds show a negative trend (0.3 m s^{-1} yr^{-1}), indicating a decreasing trend of northward winds except during winter months. *Sridharan et al.* [2007] noted a decreasing trend in northward winds with more southward winds in recent years. The present study also shows that the annual mean response of meridional winds to SC is significantly positive. The monthly response of meridional winds to SC is also positive for most of the months with larger values during summer and spring equinox. Recent midlatitude observations also show that the response of mean meridional winds to SC is positive in summer and weaker in winter [*Keuer et al.*, 2007]. Though the zonal wind's annual mean response to SC is weaker, its monthly response is different in different months. It is significantly negative in April, October, and January and positive in February, August, and December. *Keuer et al.* [2007] noted a negative correlation with SC in summer and a positive correlation in winter. Those authors suggested that increasing solar activity amplifies mesospheric wind field by an enhancement of the westward winds in summer and eastward winds during winter. Our results over a low-latitude site reveal that westward winds increase during mid-equinox and midwinter months and eastward winds amplify during early equinox and early winter months.

[16] The response of both wind components to ENSO is negative above 90 km (~0.8–1.2 m s^{-1} per SOI). Recently, *Sridharan et al.* [2008] found a significant positive response in lower mesospheric temperatures over Gadanki (13.5°N, 79.2°E). *Li et al.* [2008] also reported an ENSO signature in the mesospheric temperature over Hawaii (19.5°N, 155.6°W). Model simulations suggest that an ENSO signature could be produced in winds and temperature at mesospheric altitudes by anomalous upward propagating planetary waves or gravity waves [*Sassi et al.*, 2004].

[17] The response of meridional diurnal tide is significantly positive to stratospheric QBO and negative to SC. The tides in both wind components show a positive trend. Similar to the midlatitude MLT observations, the semidiurnal tidal amplitude shows a negative response to SC. *Baumgaertner et al.* [2005] proposed several possible mechanisms for the relationship between SC and tidal amplitudes and their long-term trends. As they observed that the long-term changes in planetary wave amplitudes are similar to those observed in the semidiurnal tide, they suggested that nonlinear interaction between tides and planetary waves could cause tidal variabilities. *Labitzke*

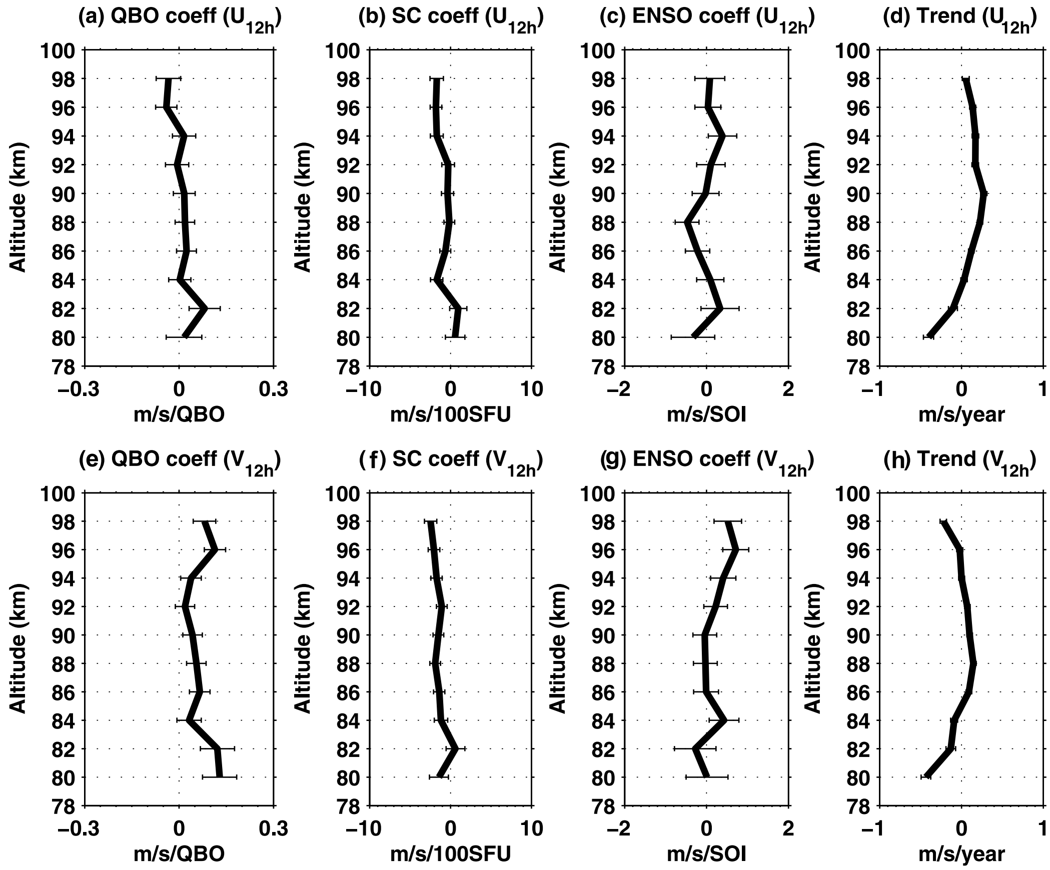

Figure 6. Same as Figure 4 but for monthly mean semidiurnal tidal amplitude in (a–d) zonal winds and (e–h) meridional winds.

[2004] found a negative correlation between polar vortex and SC during the eastward phase of QBO, when the planetary waves propagate upward from the troposphere and upon breaking distort the otherwise circular vortex, literally tearing away polar air from the edges of the vortex and stirring it into the midlatitudes [*McIntyre and Palmer*, 1983]. Earlier, *Labitzke* [1987] noted that more midwinter polar vortex disturbances occurred when QBO is in an eastward phase, while when QBO is in a westward phase, they occurred only during sunspot maxima.

[18] Long-term changes in polar vortex location, strength, and duration could affect the timing and strength of the tidal amplitude peaks. For example, *Jacobi et al.* [1999] noted that the interannual variability in the semidiurnal tidal amplitudes was correlated with that of stratospheric polar vortex. *Yamashita et al.* [2002] suggested cross-equatorial propagation of semidiurnal tide, which was excited in the winter hemisphere, up to equatorial MLT heights. It is possible that during high solar activity, the weaker vortex commences later in the year and breakup occurs earlier. The vortex disturbances are associated with stratospheric warmings. In the most dramatic cases, stratospheric temperatures can rise by ~50 K, and the mean eastward wind flow can reverse direction to westward. *Hoffmann et al.* [2007] observed a reduction in planetary wave activity associated with the onset of a major, sudden stratospheric warming event at high-latitude stratosphere. The reduction in the planetary wave activity continued even several days after the end of the major warming event. The weakening and reversal of the eastward stratospheric jet allow increasing amounts of eastward propagating gravity waves. The reduction of planetary wave activity even in the low-latitude middle atmosphere was reported recently by *Sathishkumar and Sridharan* [2009]. *Sridharan and Sathishkumar* [2008] observed an enhancement in monthly averaged gravity wave perturbations in meridional winds over Tirunelveli during most of late winter and early spring equinox, which follows midwinter major SSW events. *Liu and Roble* [2002] model results show that eastward gravity wave forcing in the winter hemisphere induces a southward and upward flow at low-latitude upper mesospheric heights and downward flow above. Before 1990, major warmings occurred about once every 2 years [*Labitzke*, 1982; *Naujokat and Labitzke*, 1993, and references therein]. No major warming occurred in nine consecutive winters from 1989 to 1990 through 1997–1998. In contrast to this previous behavior, there has been at least one major warming event in every alternate year beginning with 1998–1999 with two each in 1998–1999 and 2001–2002 [*Manney et al.*, 2005]. It is suggested that the decreasing tendency of northward winds is probably due to the frequent occurrence of the major warming events.

[19] The diurnal tidal amplitude over Tirunelveli shows a larger positive response to ENSO. As the diurnal tide carries momentum and energy from the troposphere to the MLT

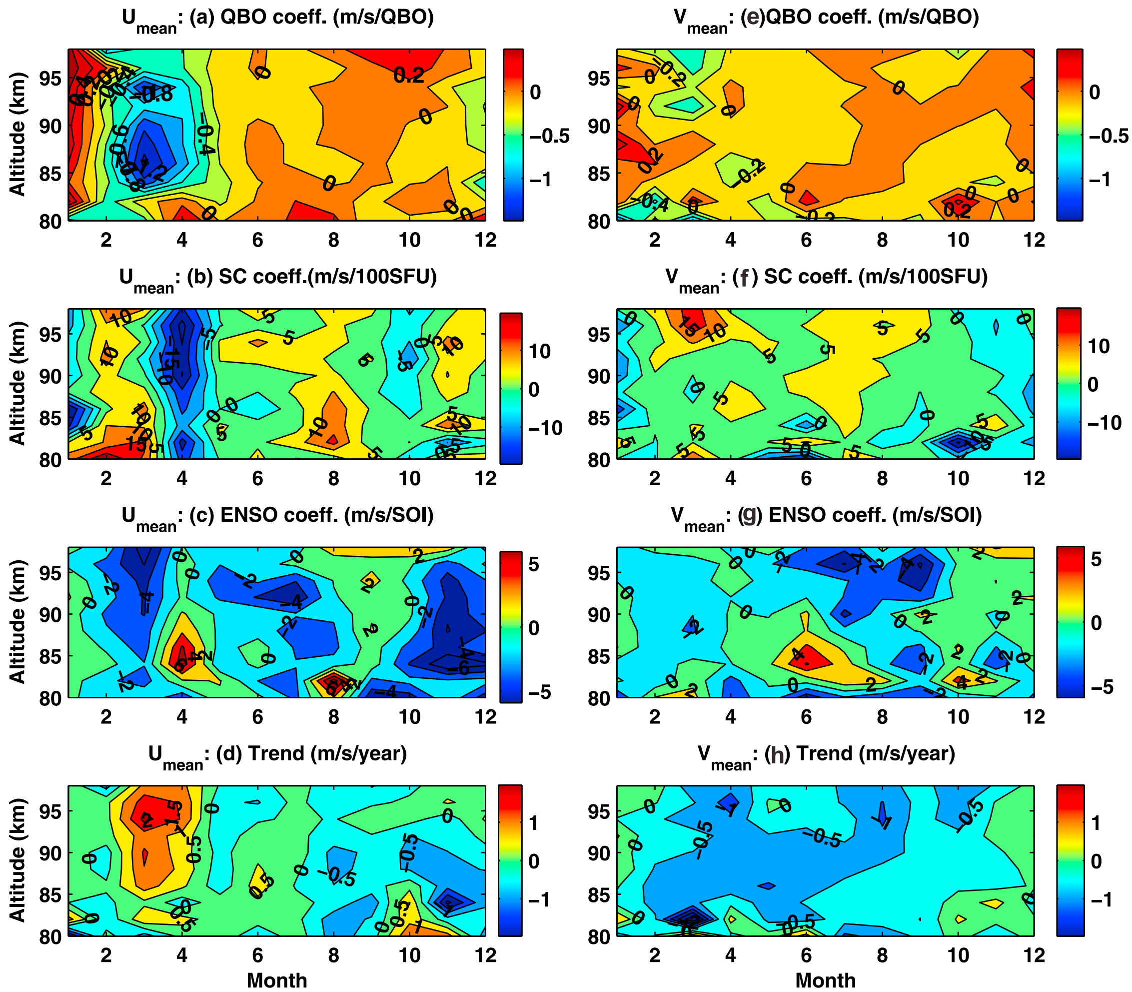

Figure 7. Seasonal variation of (a) QBO, (b) SC, (c) ENSO, and (d) linear trend coefficients, obtained from regression analysis applied to mean zonal winds for the altitudes of 80–98 km. (e–h) Same as Figures 7a–7d except for mean meridional winds.

region, the consequences of its modulation by ENSO and QBO for this latter region are important and should be investigated. *Hamilton and Garcia* [1984] demonstrated a QBO-like modulation of semidiurnal surface pressure fluctuations at Batavia (6°S, 107°E) (now, Jakarta), while *Vial et al.* [1994] reported a correlation between diurnal pressure variations and the ENSO phenomenon. According to *Vial et al.* [1994], during the warm phase of ENSO (El Niño), the atmosphere above Indonesia is drier and less cloudy, which means that more solar radiation is able to reach the ground and to warm it; hence, the diurnal temperature cycle at ground level should be larger. Using long-term MF radar observations of horizontal winds over Jakarta for the years 1993–1999, *Gurubaran et al.* [2005] noted that the interannual variability of diurnal tide in meridional winds at 86 km over Jakarta was influenced by ENSO, as they observed reduced diurnal tidal amplitudes in meridional winds during El Niño periods. According to them, the large-scale convective activity originating in the western Pacific as a response to ENSO facilitates excitation of nonmigrating tides, which compete with the dominant migrating tide and possibly induce interannual variability in diurnal tidal amplitudes. The positive response to ENSO obtained in the present study is consistent with the results obtained by *Gurubaran et al.* [2005]. Earlier, *Gurubaran and Rajaram* [1999] and *Vincent et al.* [1998] reported that the long-term variability in tidal amplitudes in zonal winds is linked to the stratospheric QBO. The present study reveals the positive response of diurnal tide in both zonal and meridional winds over Tirunelveli to stratospheric QBO at heights below 92 km.

[20] Midlatitude observations showed a decreasing trend in semidiurnal tidal amplitude [*Bremer et al.*, 1997; *Jacobi et al.*, 2005]. *Portnyagin et al.* [1993] suggested that the secular change of the forcing by ozone insolation absorption could be a reason for the decreased trend in the semidiurnal tidal amplitude. Our results show that both diurnal and semidiurnal tides show an increasing trend. Recently, *Keuer et al.* [2007] also noted an increasing trend in semidiurnal tidal amplitude. The ozone depletion, which started in the late 1970s, appears to have attained a maximum level in the year 1996, and there appears to be a recovery thereafter up to 2003. However, in the succeeding years, the ozone shows again a decreasing trend. The positive trend after the year

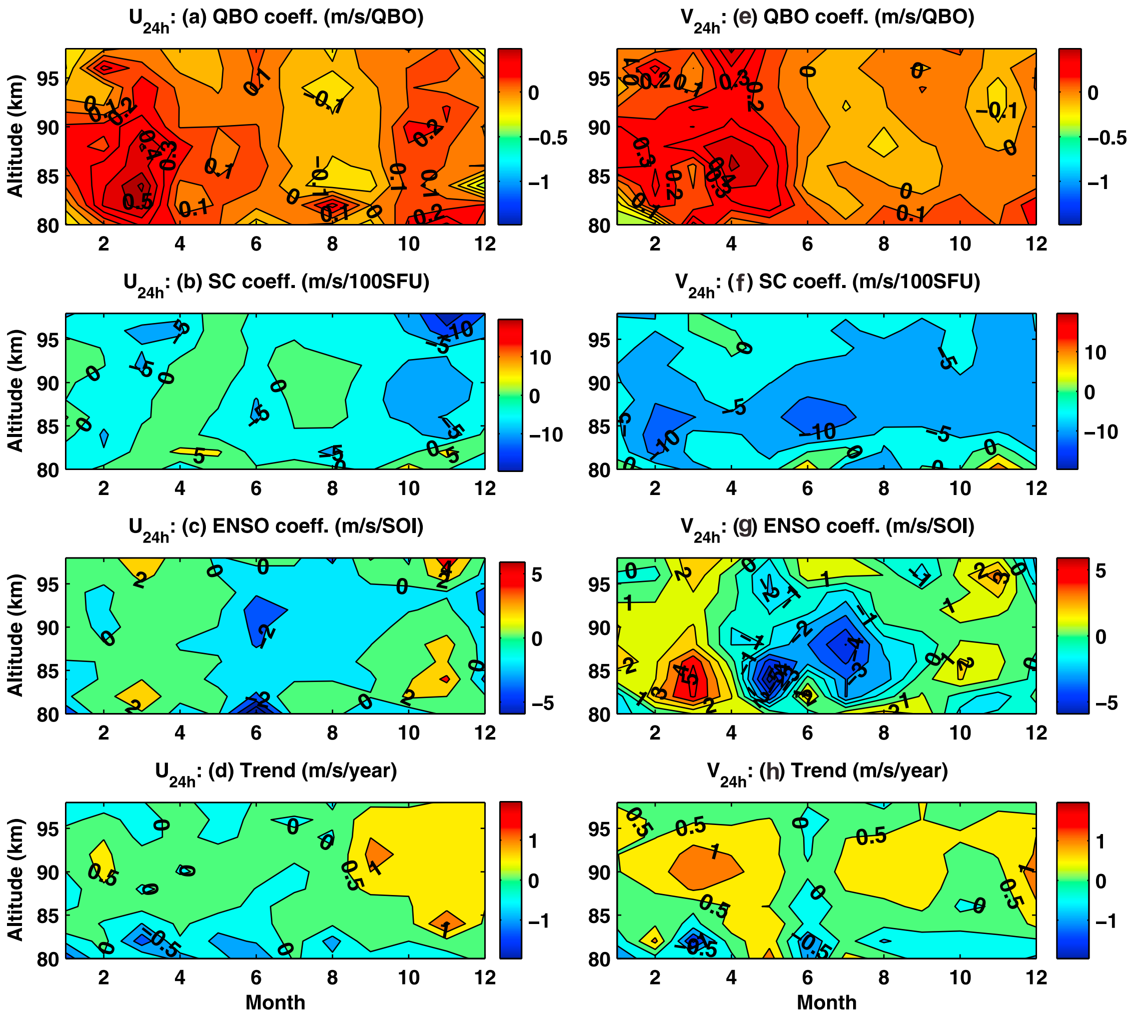

Figure 8. Seasonal variation of (a) QBO, (b) SC, (c) ENSO, and (d) linear trend coefficients, obtained from regression analysis applied to diurnal tide in zonal winds for the altitudes of 80–98 km. (e–h) Same as Figures 8a–8d except for diurnal tide in meridional winds.

1996 and weak negative trend after the year 2003 exhibited by ozone could be the reason for the small positive trend observed in semidiurnal tidal amplitudes.

[21] **Acknowledgments.** The medium-frequency radar at Tirunelveli was operated by the Indian Institute of Geomagnetism, Department of Science and Technology, Government of India. The QBO winds and SOI data used in the present study were downloaded from the Web at http://www.cpc.ncep.noaa.gov. The solar flux data were obtained from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/MONTHLY.OBS.

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