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Long-term variability of mean winds in the mesosphere and lower thermosphere at low latitudes

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[1] Long-term variations of monthly mean zonal and meridional winds in the Mesosphere and Lower Thermosphere (MLT) at low-latitudes are analyzed using four medium frequency (MF) radars and three meteor radars located in the Asia-Oceania region. Radar data taken at close-by latitudes are appended to construct long-term data sets. With this, we have long-term data from five distinct latitudes within ±22° (viz., 22°N, ∼9°N, 0–2°N, 6–7°S and 21°S). The data length varies at different latitudes and spans a maximum of two decades during 1990–2010. The zonal winds show semiannual oscillation (SAO) at all locations with westward (eastward) winds during equinoxes (solstices). The month height pattern of SAO is similar within ±9° and is different at ±22°. The westward winds in the March equinox were enhanced every two or three years during 1990–2002. We define this phenomenon as Mesospheric Quasi-Biennial Enhancement (MQBE). Such signature is not clear after 2002. The meridional winds show annual oscillation (AO), with northward and southward winds during the December and June solstices, respectively. However, the timing at which the wind direction changes does not coincide at all latitudes. The amplitude of the AO is enhanced after 2004 and 2008 at ∼9°N and ∼7°S, respectively. Orthogonal components of SAO and AO are detected with persistent phase relation, which suggests that the zonal and meridional winds are coupled. The meridional winds show long-term trends at latitudes of ∼9°N and ∼6–7°S, but not at other latitudes . The zonal winds do not show significant long-term trends.

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1. Introduction

[2] The long-term variability of atmospheric parameters in the Mesosphere and Lower Thermosphere (MLT) region has been studied for many years by employing various ground-based and satellite observations, and they have been discussed in terms of natural variabilities such as decadal variations, global warming effects and solar activity. Long-term temperature studies reported a cooling of a few degrees per decade in the MLT region [e.g., *Beig et al.*, 2008; *Li et al.*, 2011]. Long-term trends in winds [e.g., *Sridharan et al.*, 2007; *Merzlyakov et al.*, 2009; *Jacobi et al.*, 2012] and tides [e.g., *Vincent et al.*, 1998; *Tsuda et al.*, 1999; *Hagan and Forbes*, 2002; *Oberheide et al.*, 2009] are found to vary with location and period of observation. Long-term studies of gravity wave activity show inter-annual variability [e.g., *Tsuda et al.*, 2002] and increasing trend [*Offermann et al.*, 2011; *Hoffmann et al.*, 2011]. Recent studies attempt to summarize decadal variability and trends of the atmospheric parameters in order to get a comprehensive global picture [e.g., *Beig et al.*, 2008]. However, analyses of long-term variations in MLT winds on global scales are less comprehensive compared to those for temperature.

[3] Long-term studies of winds from mid- and high-latitudes reveal different long-term trends [e.g., *Bremer et al.*, 1997; *Portnyagin et al.*, 2006; *Keuer et al.*, 2007; *Merzlyakov et al.*, 2009; *Jacobi et al.*, 2012]. *Merzlyakov et al.* [2009] reported the wind measurements from Molodezhnaya (45.9°E, 67.7°S), Mawson (62.9°E, 67.6°S), and Davis (78.0°E, 68.6°S), Antarctica, from 1970 to 2006. In their study the zonal winds in summer show a negative trend up to 1993 and the westward wind decreases after 1993. This study also shows a positive trend of southward winds during winter. In another study *Portnyagin et al.* [2006] found that the annual mean zonal wind shows a decreasing trend until

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1980s while the meridional wind shows an increasing trend until 1990s. For the equatorial and low-latitude regions, long-term studies of MLT winds are very limited. *Sridharan et al.* [2007] studied the long-term variability of MLT winds using Tirunelveli (8.7°N, 77.8°E) MF radar observations and reported that the meridional winds show a decreasing trend. However, these long-term trends are not constant with height as reported by *Keuer et al.* [2007]. Thus, the long-term trends of winds vary with location and altitude.

[4] Zonal winds in the middle atmosphere in the equatorial and low-latitude regions exhibit prominent oscillations, the most important of these being semiannual and quasi-biennial oscillations (SAO and QBO, respectively) [*Hirota*, 1978; *Baldwin et al.*, 2001]. Zonal winds are known to exhibit two distinct SAO, each with nearly similar amplitude of 30 ms^{-1}, one near the stratopause and the other in the MLT region, with a node in between at ~65 km [*Reed*, 1966; *Hirota*, 1978]. Accordingly these two oscillations are called the stratospheric SAO (SSAO) and mesospheric SAO (MSAO), respectively. The oscillations are approximately in anti-phase with each other with the SSAO (MSAO) being eastward (westward) during the equinoxes and westward (eastward) during the solstices. *Dunkerton* [1982] proposed that the selective absorption and subsequent filtering of small-scale gravity waves by the SSAO is responsible for the existence of the MSAO and can explain the anti-phase relation between the two oscillations. Recent experimental studies also show a good correlation between the MSAO and short period gravity waves [e.g., *Venkateswara Rao et al.*, 2012].

[5] To a large extent, the characteristics of the MSAO have been studied through satellite and ground based observations [*Burrage et al.*, 1996; *Garcia et al.*, 1997; *Venkateswara Rao et al.*, 2012]. In satellite observations of High Resolution Doppler Imager (HRDI) on the Upper Atmosphere Research Satellite (UARS), the MSAO is seen to extend to latitudes of 20–30° in both hemispheres without any obvious asymmetry about the equator [*Burrage et al.*, 1996]. Outside the tropics an annual variation is apparent, which shows a 180° phase difference between the two hemispheres. *Garcia et al.* [1997] showed that the westward phase of the MSAO is more equatorially confined and more nearly symmetric about the equator, while the eastward phase appears as extensions of the midlatitude winter eastward winds. Furthermore, the eastward wind maxima in solstices are weaker by at least a factor of two than the westward wind maxima at the equinoxes [*Burrage et al.*, 1996]. It is worth mentioning that the amplitude of MSAO is found to be smaller in MF radar observations than in HRDI observations [*Burrage et al.*, 1996; *Garcia et al.*, 1997].

[6] The zonal winds in the tropical stratosphere exhibit a quasiperiodic oscillation with alternating eastward and westward winds at a period of 22 to 36 months, known as Stratospheric QBO (SQBO) or simply QBO [*Baldwin et al.*, 2001, and references therein]. In this oscillation the alternating wind regimes develop at the top of the lower stratosphere and propagate downward at a rate of 1 km/month until they are dissipated at the tropopause. *Pascoe et al.* [2005] showed that when annual and semiannual cycles are removed in the ERA-40 reanalysis data, the QBO signal appears at altitudes as high as 1 hPa, although its amplitude is reduced to about 5–10 ms^{-1}. *Burrage et al.* [1996], using multi-instrument measurement observations, reported the counterpart of this SQBO in the MLT region and named it as Mesospheric QBO (MQBO). In satellite observations, the amplitude of the MQBO is observed to be ~30 ms^{-1}, which is comparable to that of MSAO. The MQBO is also observed in radar measurements which showed the same phase and same peak altitude as those in satellite observations, but the amplitude is only about half that found in satellite observations [*Burrage et al.*, 1996].

[7] Meridional winds in the MLT region are known to exhibit a distinct annual oscillation (AO) with northward winds during December solstice and southward winds during June solstice [*Burrage et al.*, 1996; *Garcia et al.*, 1997; *Sridharan et al.*, 2007]. Satellite measurements show that the mean meridional winds in the mesosphere are generally in the range of -10 to 10 ms^{-1} (at an altitude of 82.5 km) and is characterized by an annual variation with a cross equatorial flow directed from the summer hemisphere to the winter hemisphere [*Burrage et al.*, 1996].

[8] Previous satellite observations by *Burrage et al.* [1996] and *Garcia et al.* [1997] cover a few years of observations only. Most of the ground-based studies so far are confined to a single latitude, so there is a lack of studies which reveal long-term variability in a wide latitude belt, especially at low-latitudes. This poses substantial limitations in understanding the long-term variability of winds globally and the trends remain uncertain. There are, however, a few MF and meteor radars in Indian and Pacific regions that have been operating for many years and for which data are available for nearly two decades. In the present study we use these data sets and study the long-term variability of mean zonal and meridional winds and their important oscillations in the equatorial and low-latitude MLT region.

2. Radar Locations and Data

[9] We use long-term observations of zonal and meridional winds obtained by MF radar observations from Kauai (22°N, 154°W), Tirunelveli (8.7°N, 77.8°E) (hereafter TIR), Christmas Island (2°N, 157°W) (hereafter CI), and Pameungpeuk (7.4°S, 107.4°E) (hereafter PPK) and meteor radar observations from Koto Tabang (0.2°S, 100.3°E) (hereafter KOT), Jakarta (6°S, 107°E), and Rarotonga (21.2°S, 159.7°W) (hereafter RTG). The locations of these radars are shown in Figure 1. Descriptions of these radars can be found elsewhere (see *Vincent and Lesicar* [1991] for TIR and CI MF radars; *Fritts and Isler* [1992] for Kauai MF radar; *Tsuda et al.* [1999] for Jakarta meteor radar; e.g., *Venkateswara Rao et al.* [2011] for PPK MF radar and KOT Meteor radar). The TIR observations presented in this paper are an extension of a study by *Sridharan et al.* [2007].

[10] Kauai, CI, and RTG are located at nearby longitudes. Similarly, KOT, Jakarta and PPK are located in Indonesia at nearby longitudes. Thus, there are longitudinal differences between some radars. In the present study, radars located at similar latitudes (although differing in longitude) are treated as one set. That is, data from CI and KOT are considered as one set (hereafter referred as CI_KOT) and the data from Jakarta and PPK are considered as another set (hereafter referred as JKT_PPK), as shown on the right hand side of

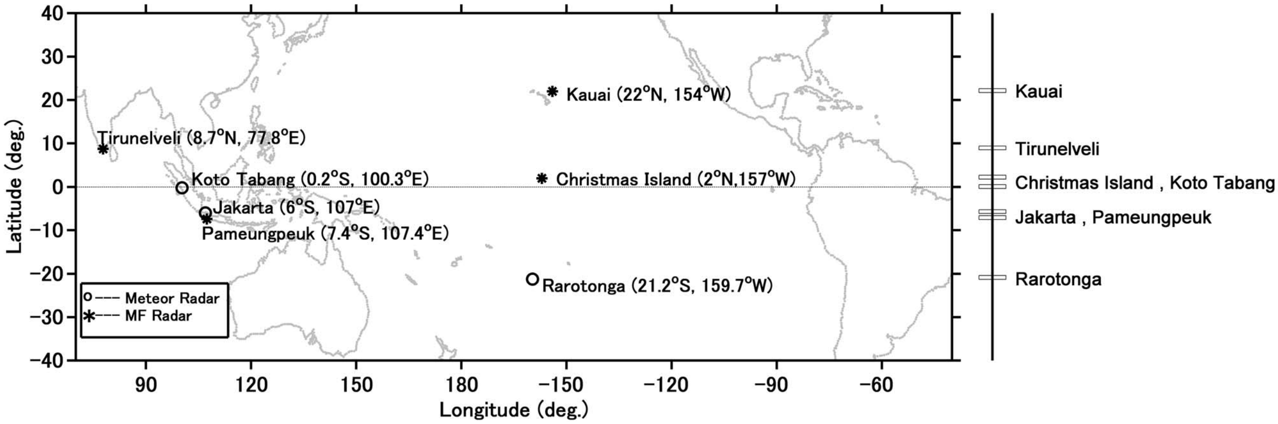

Figure 1. Map showing the location of radar sites used in the present study. Open circles and asterisks represent meteor and MF radars, respectively. The right hand side shows the latitudinal separation of radars, ignoring their longitudinal differences.

Figure 1. At other latitudes, long-term data come from single radars. Thus, the present study examines long-term variations in winds over five distinct latitudes (derived from seven radars). Table 1 summarizes the radar locations and data availability at each location. As noted from Table 1, long-term data are available at all locations, except at RTG where data are available from 2003 to 2008 (note that the data from CI and KOT are considered as one set and similarly the data from Jakarta and PPK are considered as another set).

[11] Error estimates are one of the most important issues in studies using observational data, especially when results from different data sets are compared. The error can be separated into "precision" and "accuracy." The accuracy of wind measurements by MF and meteor radars were validated in a few cases. *Murayama et al.* [1999] compared the Yamagawa MF radar observations with a foil chaff technique by a sounding rocket. They reported a discrepancy (accuracy) of about 2 ms^{-1}. However, such comparisons are not available for all the radars in the present study. *Hasebe et al.* [1997] compared the winds measured by Jakarta meteor radar and the High-Resolution Doppler Imager (HRDI) on board the Upper-Atmosphere Research Satellite (UARS), in which the HRDI observations are larger than that of meteor radar winds. *Garcia et al.* [1997] also noted that the HRDI winds are larger than that of CI radar winds. In the present study, we compared the CI and KOT radar observations and also Jakarta and PPK radar observations. The difference of CI and KOT mean winds is 2.4 ms^{-1} and 1.5 ms^{-1} for the zonal and meridional components, respectively. For Jakarta and PPK, these differences are 2 ms^{-1} and 3.8 ms^{-1}. We also calculated the standard variation as a function of height. The r. m. s values were <2 ms^{-1} and <1 ms^{-1} for the zonal and meridional components, respectively and does not show much height variation between 88 and 98 km. Below 88 km, these values increase slightly as the height goes lower. Furthermore, the radars' winds are compared with that from UARS (Upper Atmosphere Research Satellite) Reference Atmosphere Project (URAP) and will be discussed at the end of section 4.1.

[12] All the MF and meteor radars used in the present study have wind observations at 2 km height intervals, except the one at RTG, which has a height resolution of 3 km due to the low meteor count rate. With respect to time resolution, meteor radars provide hourly values of horizontal winds, while MF radars can provide winds with ~2 min time resolution. To homogenize the data sets, 2-min wind values are averaged to provide hourly winds, centered on each hour. Using these hourly winds we created a 24 h monthly composite data set by averaging the wind observations at each hour of a day over a month. Thus, we created one diurnal cycle (24 h) of hourly winds (zonal and meridional components separately) for each month. To remove tidal contributions, each 24 h composite data set was subjected to a least square fitting of the mean wind and tidal components (diurnal, semidiurnal, and terdiurnal) (similar to the procedure done by *Venkateswara Rao et al.* [2011]), so that mean winds, and tidal amplitudes and their phases are obtained for each month. This analysis shows that the tides contribute a major part of the wind variability. However, this contribution

Table 1. Location of Radars and Data Availability

Location	Attributes	Latitude	Longitude	Data Availability	Person in Charge of Data
Kauai	MF[a]	22°N	154°W	1990–2006	D. M. Riggin
Tirunelveli	MF	8.7°N	77.8°E	1993–2009	S. Gurubaran
Christmas Island	MF	2°N	157°W	1990–1997	R. A. Vincent
Koto Tabang	Meteor	0.2°S	100.3°E	2003–2010	T. Tsuda
Jakarta	Meteor	6°S	107°E	1993–1999	T. Tsuda
Pameungpeuk	MF	7.4°S	107.4°E	2004–2010	T. Tsuda
Rarotonga	Meteor	21.2°S	159.7°W	2003–2008	D. M. Riggin

[a]MF, medium frequency.

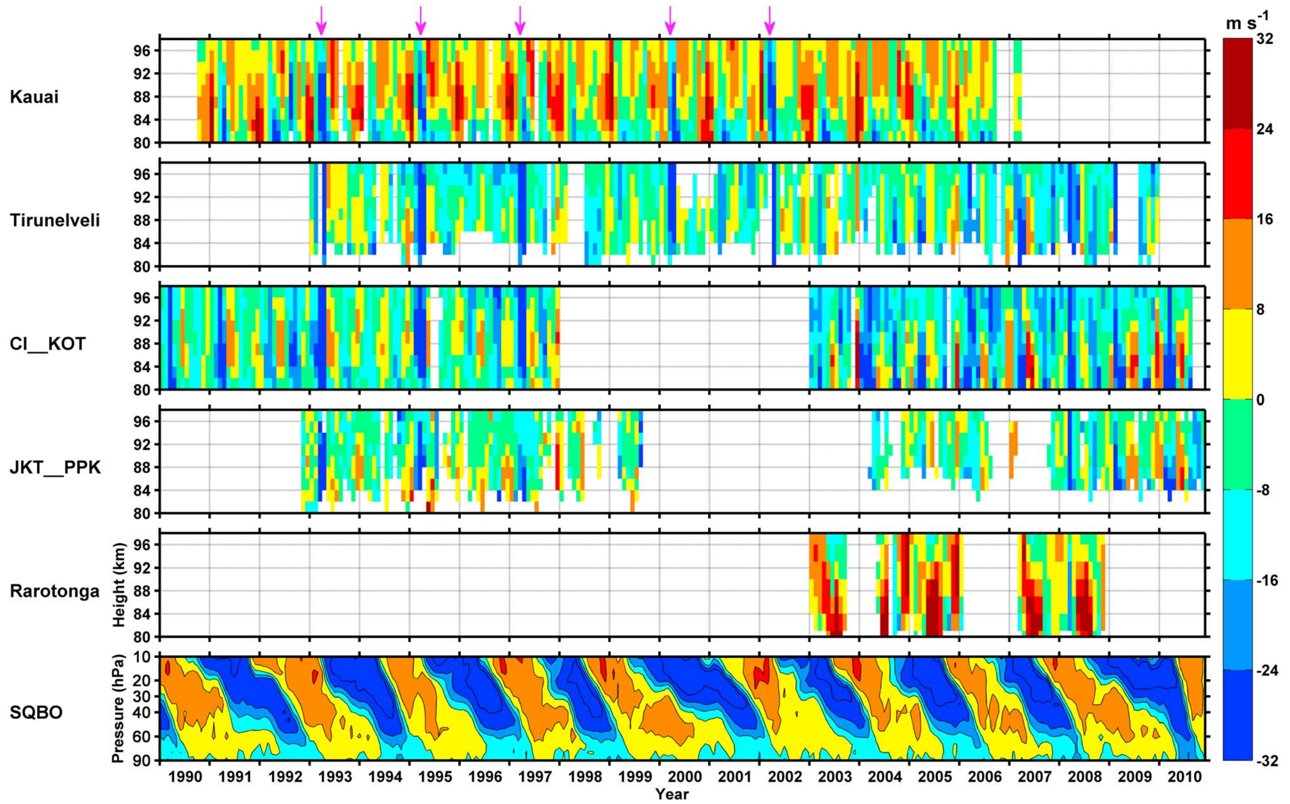

Figure 2. Height-month contours of monthly mean zonal winds for Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga (first through fifth panels). The sixth panel shows the monthly winds associated with stratospheric quasi biennial oscillation (SQBO).

varies with location, time and height. In general, removal of tides lead to a change of standard deviation in the zonal (meridional) winds by 40–60% (40–50%) at Kauai, 45–60% (45–55%) at TIR, 40–65% (40–50%) at CI, 50–65% (55–65%) at KOT, 45–65% (50–60%) at Jakarta, 45–65% (50–60%) at PPK, and 45–65% (50–65%) at RTG. In the present study we use the monthly mean winds. Positive values correspond to eastward/northward flow. Similar observations at locations other than Kauai and RTG are hereafter referred to as 'within ±9°', although they are between 8.7°N and 7.4°S. Occasionally, CI_KOT is referred to as 'the equator'. Note that all seasons mentioned in this paper correspond to Northern Hemisphere.

3. Results

3.1. Zonal Winds

3.1.1. Long-Term Variability of Mean Zonal Winds

[13] Figure 2 shows the long-term variability of monthly mean zonal winds through month-height contours for (top to bottom) Kauai, TIR, CI_KOT, JKT_PPK, and RTG. White space in the contours represent data gaps because radars were not operated or sufficient number of data points did not exist to construct monthly mean values. As can be noted from Figure 2, the zonal winds at all locations and all heights show a distinct semiannual oscillation (SAO), with westward winds during the equinoxes and eastward winds during the solstices. At the lowest latitudes, (within ±9°) westward winds are stronger than eastward winds, whereas at ±22°, eastward winds are stronger than westward winds. Thus, the annual mean winds are westward within ±9° and are eastward at ±22°.

[14] In Figure 2 we show long-term wind variations near the equator by combining the data from the CI MF radar in 1990–1997 and the KOT meteor radar in 2003–2010. These radars' data show a clear semi-annual oscillation, which becomes maximum at about 86 km at CI and at 82–83 km at KOT. Thus, the time-height pattern of MSAO seems to be shifted with its core being lower at KOT by ∼3–4 km. Similar comparison is investigated between the Jakarta meteor radar and the PPK MF radar, which, however, does not show any clear difference in the height change of MSAO structure. Note that CI and KOT are separated by ∼100 degrees in longitude, but Jakarta and PPK are located at nearly the same longitudes. This may suggest that discrepancy between CI and KOT could be attributed to longitude variations of the wind system. A semiannual pattern of the zonal wind at Kauai, which is a good reference because of continuous data records, seems to be more consistent with that at CI rather than KOT. We should not exclude a possibility that the observation height coordinates may need to be adjusted between the two different radars at CI and KOT. We will discuss this later in more details referring to satellite data of UARS.

[15] A striking feature in Figure 2 is that westward winds during the March equinox show inter-annual variability,

with larger values in 1993, 1995, and 1997 observed at all locations and at all heights. In previous studies these large westward winds were interpreted as a manifestation of a MQBO [*Burrage et al.*, 1996; *Garcia et al.*, 1997; *Ratnam et al.*, 2008]. It is important to note that, unlike the SQBO, the so-called MQBO is observed mostly in the westward phase of the MSAO in the March equinox [*Sridharan et al.*, 2007]. The eastward phase of MSAO, in general, do not show such enhancement. In other words, the SQBO is a quasi sinusoidal oscillation and the MQBO is a seasonally locked impulsive phenomenon that occurs only in March equinox. In all previous studies enhancement of westward winds during March equinox, which happens every 2 or 3 years, was called MQBO. However, the term MQBO may not be relevant as the corresponding wind variability in the MLT region may not be an oscillation. It is rather the enhancement of westward winds during March equinox with an interval of 2 or 3 years. Hence, the term mesospheric quasi-biennial enhancement (MQBE) may be more appropriate to describe the westward wind enhancement of MSAO. Accordingly, throughout this paper we use MQBE, instead of MQBO, to describe this phenomenon.

[16] In Figure 2 we observe clear MQBE during 1993, 1995, and 1997 at all locations and all heights. Such a MQBE signature can also be observed during 1991 at Kauai and CI_KOT; and during 2000 and 2002 at Kauai and TIR (shown through arrows in the first panel of Figure 2). Large westward winds are also observed during the March equinoxes of 2004 at CI_KOT; 2006, 2008 at TIR, CI_KOT; and in 2010 at CI_KOT and JKT_PPK. Thus, zonal winds at all locations (except RTG) show a clear MQBE signature. *Sridharan et al.* [2007] studied such large westward winds at TIR. The MQBE signature is weaker after 2002 at all locations. Large westward winds during March equinoxes are observed nearly every two years except after 1997, when the period is extended to three years and observed again in 2000. Thus, the MQBE is in fact a biennial enhancement during 1990–2002, except one triennial (3 year) enhancement.

[17] To compare the MQBE signature with that of the SQBO, we show the winds associated with the SQBO in the sixth panel of Figure 2, taken from http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/singapore.dat. Figure 2 shows that the peak westward winds during the March equinoxes in the MLT region (MQBE) occur during the eastward phase of the SQBO (at all altitudes below 10 hPa) during all years except in 1991 and 2000, where they occur when the SQBO winds are westward above 30 hPa and eastward below. It is also important to note that, while the SQBO winds show a downward phase progression, the MQBE is constant with height without any phase progression. Moreover, while the MQBE is weaker after 2002, the SQBO does not show any such drastic change.

[18] Figure 3 shows monthly mean zonal winds for (top to bottom) Kauai, TIR, CI_KOT, JKT_PPK, and RTG for a height of 88 km. Vertical bars (green color) in the middle of each panel correspond to standard deviation of the mean winds after removal of the tides. The standard deviations are generally in the range of 2–8 ms^{-1}, except at Jakarta where the values are slightly larger with a maximum of 10 ms^{-1}. The SAO features described in Figure 2 can be clearly noted in Figure 3 also. Within $\pm 9°$ the winds are westward biased and they are eastward biased at Kauai and RTG, with almost westward winds in some years (e.g., in 2004 at TIR) and almost eastward in some years at Kauai and RTG (e.g., in 1996 at Kauai and 2005 at RTG).

[19] Figure 3 reveals that, in general, the first westward cycle of MSAO in each year is stronger than the second at all locations. However, exceptions to this behavior are observed during some years when the first westward cycle is either smaller than (e.g., in 1992 and 2001 at Kauai; 1992 and 1996 at CI; 1996 at Jakarta) or nearly equal to the second one (e.g., in 1999 and 2004 at Kauai; 1996 and 2007 at TIR; 1994, 2004 and 2007 at CI_KOT). Figure 2 depicts that there is seasonal asymmetry in the eastward phase of the MSAO also, with the winter eastward cycle being stronger than in summer at Kauai. Such a seasonal asymmetry is also observed at other locations.

[20] The MQBE signature shown in Figure 2 can also be noted in Figure 3 at 88 km. The largest westward winds during March equinoxes of 1993, 1995, 1997, 2000, and 2002 are shown in Table 2 for the four locations. As is evident from Figure 3 and Table 2, the westward winds in 1993 are larger than those in 1995, which are again larger than those in 1997 at all locations, except at CI_KOT. At CI_KOT the peak westward winds in 1995 are larger than those in 1993. At Kauai, the peak westward winds in 2000 and 2002 are nearly equal. At TIR, the peak westward winds during 2002 are larger than in 2000. The peak westward winds are strongest at TIR during 1993 and 1997 and at CI_KOT in 1995 and decrease at other latitudes. Thus, the MQBE is maximum over the equator in 1995 and over TIR in 1993 and 1997 and decreases off from the maximum latitude.

3.1.2. Long-Term Variability of SAO and AO in Zonal Winds

[21] Figures 4a and 4b show the long-term variability of the amplitudes of the SAO and AO, respectively, for mean zonal winds at heights of 84 km, 88 km, and 92 km. Although it is well established that the zonal winds show a SAO, we tried to see if there is an AO signal in the zonal winds as well. The SAO and AO amplitudes are obtained by least squares fitting of 6 and 12 month period harmonic functions to the mean zonal winds (shown in Figure 2). The SAO and AO amplitudes are not computed for RTG as the length of the data is too small, with several intermittent gaps. The typical errors in the estimation of the SAO and AO amplitudes are 4–7 ms^{-1} and 2–3.5 ms^{-1}, respectively and these errors decrease with increasing altitude. The relative errors are between 0.2 and 0.5.

[22] Figure 4 demonstrates that SAO is the dominant mode of variability in the zonal winds at all locations. However, the zonal winds at Kauai also display significant AO amplitudes. The AO at Kauai shows a height variation where the amplitude decreases with increasing height. The maximum amplitude of the SAO is 25 ms^{-1} and that of the AO is 15 ms^{-1}. In accordance with the MQBE, the amplitude of the SAO also enhanced in 1993, 1995, and 1997 at all four locations. Such an enhancement is also observed in 2000 and 2002 at Kauai and TIR. The amplitude of the SAO at Kauai shows a negative linear trend with time at 84 km and 88 km. At TIR also the SAO amplitude shows decreasing tendency up to 1998. At CI-KOT the amplitude of the SAO decreases with height during 2003–2009 and

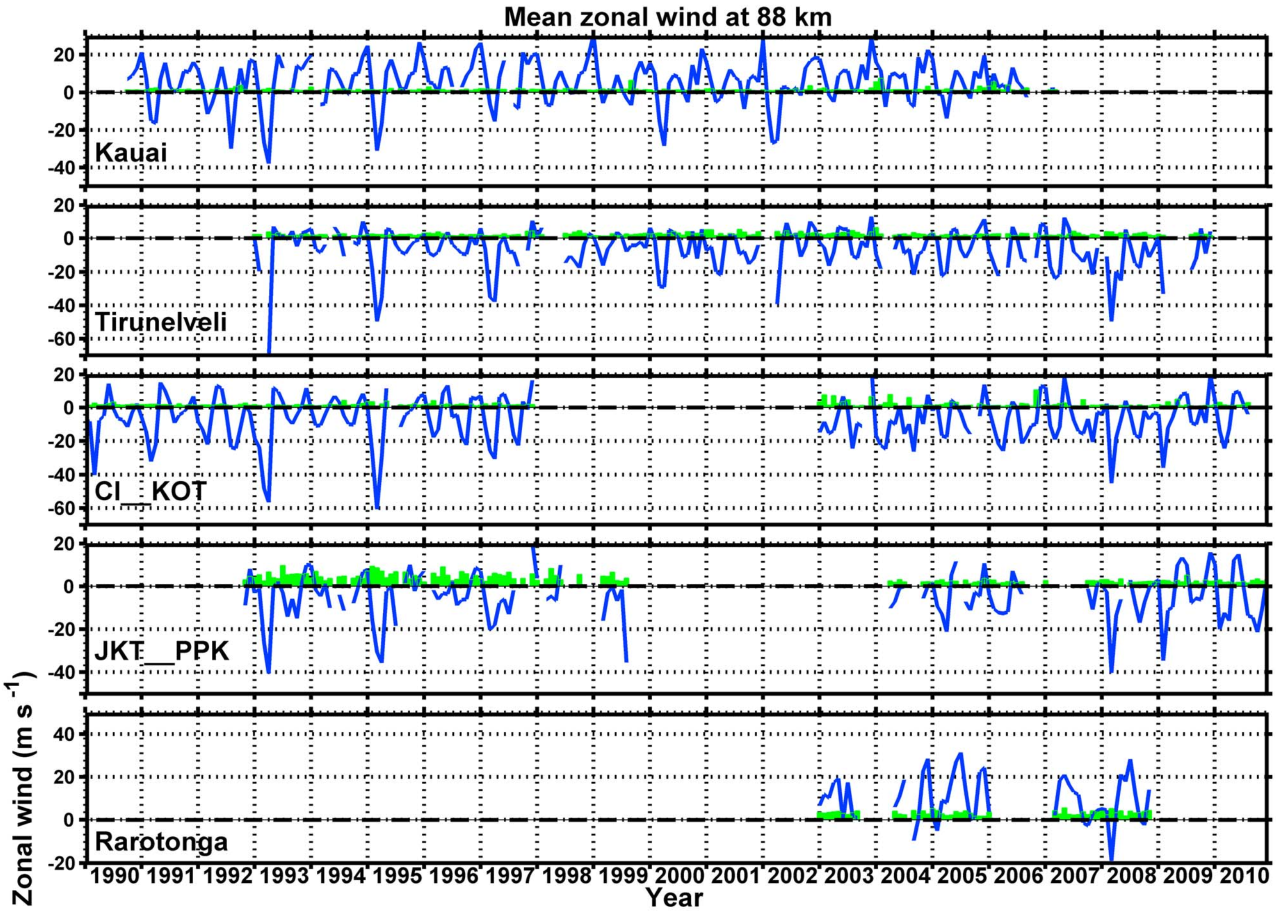

Figure 3. Temporal variation of monthly mean zonal winds for a height of 88 km observed at (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga. Vertical (green color) bars in the middle of each panel correspond to standard deviation of the mean winds.

shows a slight increase with time at 84 km. The amplitude of the AO at Kauai decreases with height. The amplitude of the AO does not show any significant systematic long-term variability at any location, though inter-annual variability is observed. It is important to note that the amplitude of the AO in the zonal wind is smallest over the equator and increases away from the equator.

3.1.3. Seasonal Variation of Mean Zonal Winds

[23] By averaging mean winds in each month (considering all available data at each location), a composite seasonal variation of zonal winds at 88 km is shown in Figure 5a for all locations. The percentage relative errors of these winds (calculated from standard deviations of Figure 3 and using law of propagation of errors) are 2.4, 2.8 2.5, 7.6, 5.2 for Kauai, TIR, CI_KOT, JKT_PPK, and RTG, respectively. The smaller values of relative errors indicate the reliability of the composite monthly zonal winds. The zonal winds in Figure 5a display a clear semiannual variation at all locations with westward winds during equinoxes and eastward winds during solstices. But, within ±9° latitude, the westward winds are larger and persist for many months longer than the eastward winds. The westward winds during the March equinox are larger than those in September equinox. At Kauai, the eastward winds are slightly larger than the westward winds. At RTG, the winds are almost eastward throughout the year, partly due to smaller data set (2003–2008).

[24] In order to study the seasonal variation at all heights, we show month-height contours of composite zonal winds in Figure 5b. These winds are calculated in a similar way to that of Figure 5a. The zonal winds show a clear SAO at all

Table 2. Peak Westward Winds (Monthly Mean) Observed During March Equinox of Various Years at Different Locations

Location/Year	1993 (ms^{-1})	1995 (ms^{-1})	1997 (ms^{-1})	2000 (ms^{-1})	2002 (ms^{-1})
Kauai	−38	−31	−15	−28	−27
Tirunelveli	−74	−50	−38	−29	−40
CI_KOT	−57	−61	−31		
JKT_PPK	−40	−35	−20		

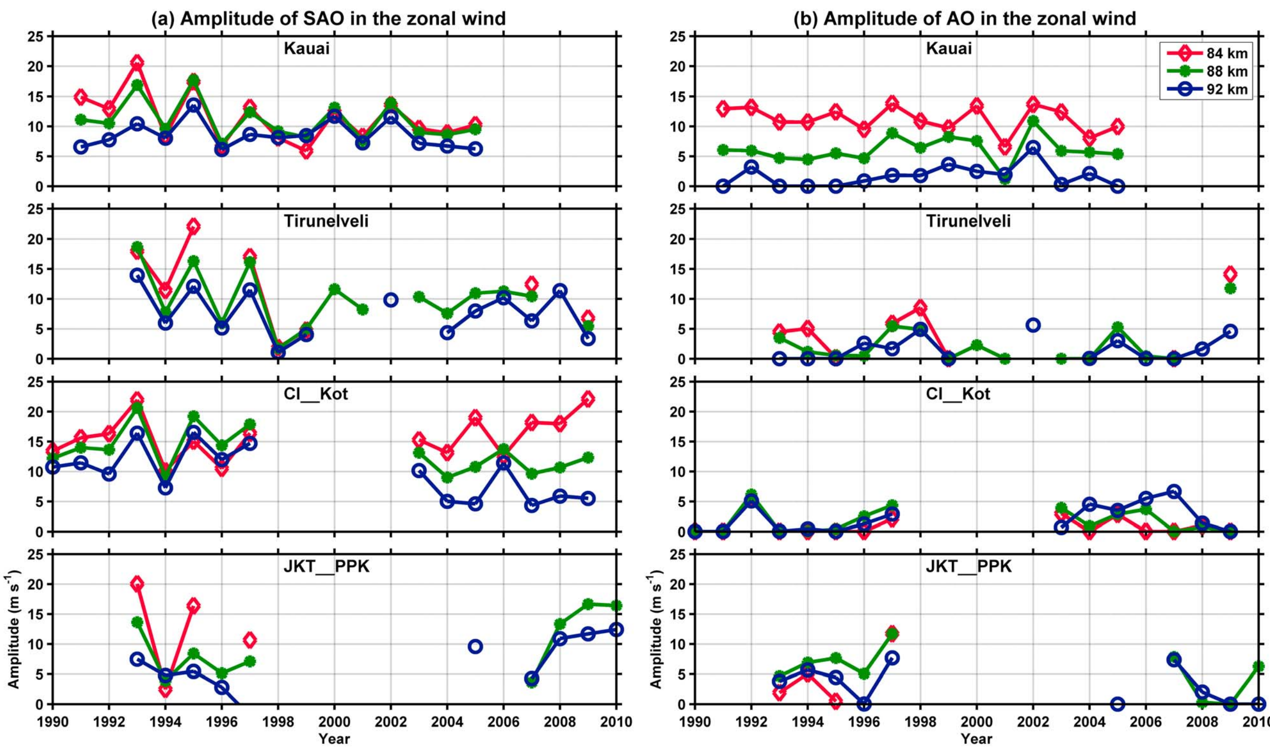

Figure 4. Temporal variation of amplitudes of (a) semiannual oscillation (SAO), and (b) annual oscillation (AO) in the zonal wind for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), and Jakarta and Pameungpeuk (JKT_PPK) at heights of 84 km, 88 km, and 92 km.

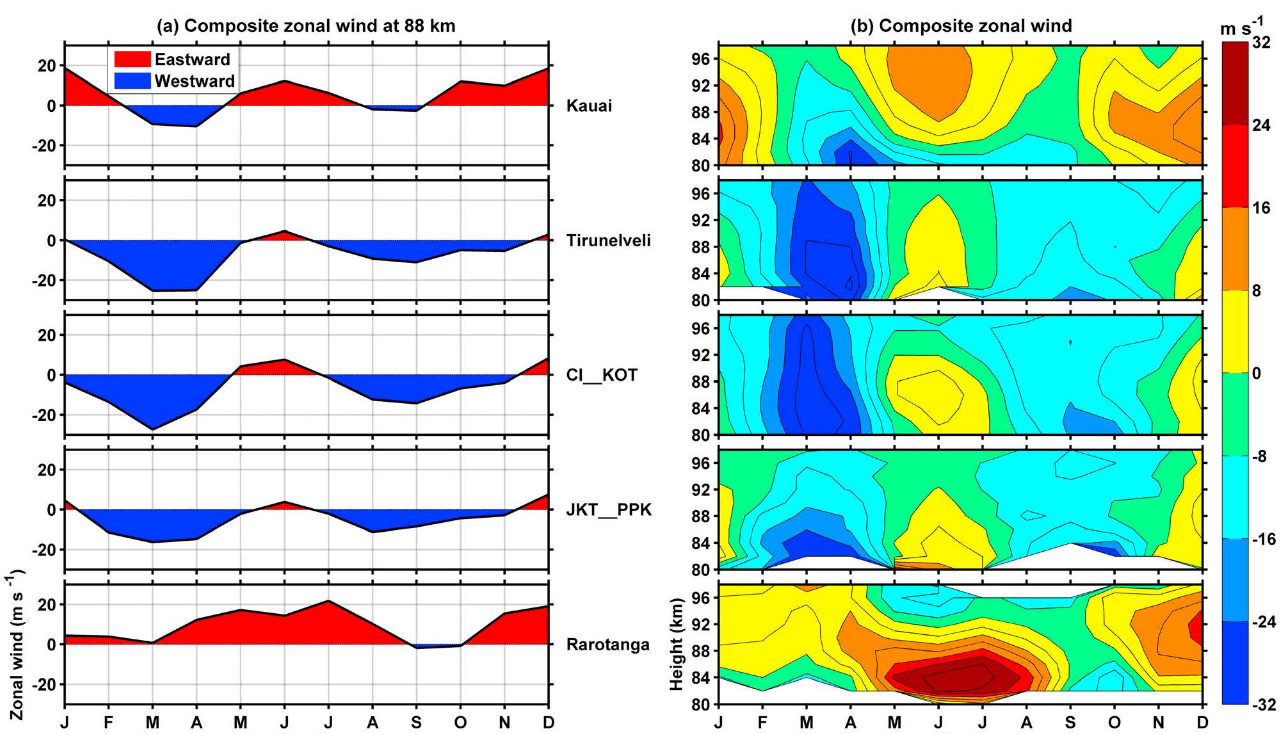

Figure 5. Composite (calculated using all available data at each location) seasonal variation of monthly zonal winds for (a) a height of 88 km and (b) for all heights between 80 and 98 km for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga.

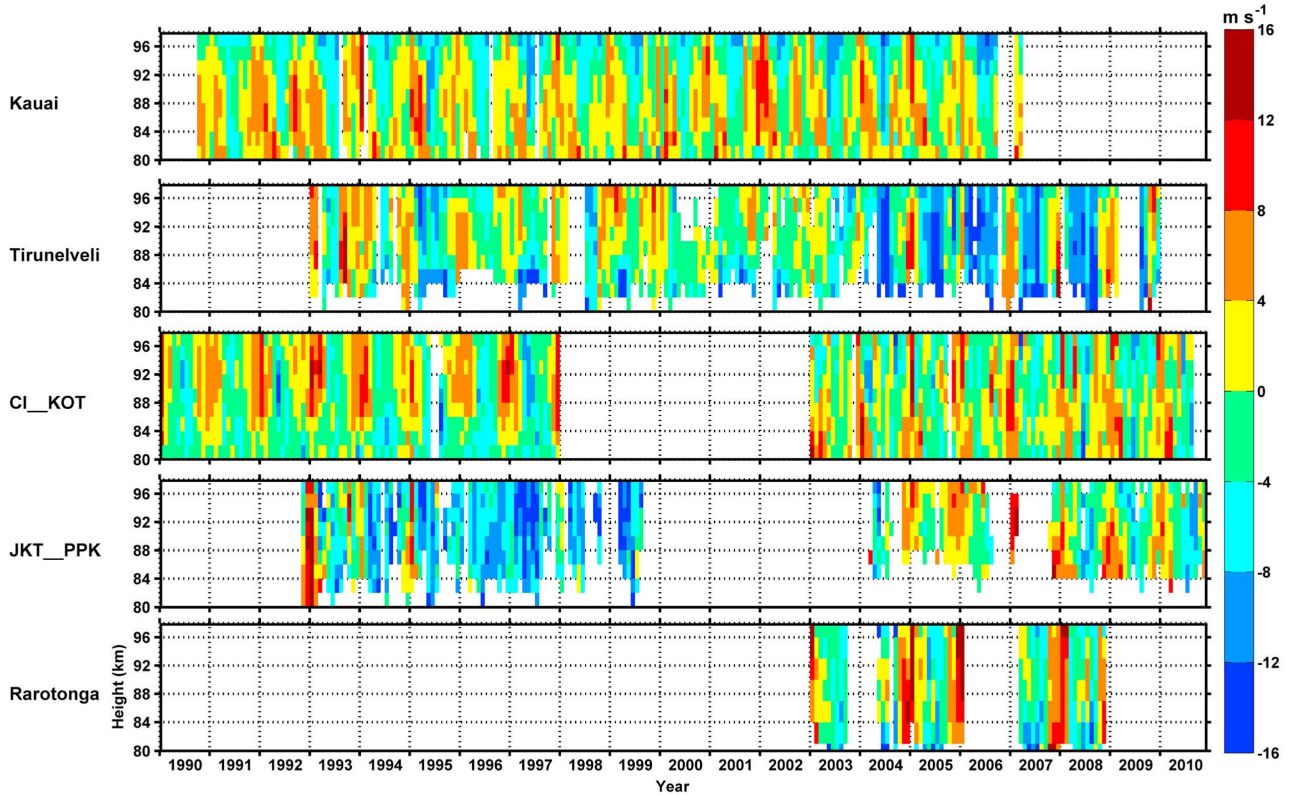

Figure 6. Height-month contours of monthly mean meridional winds for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga.

heights and all locations, except at RTG. At RTG semiannual variation is not very clear at high altitudes which is possibly due to the smaller data set with intermittent gaps. At Kauai, the SAO is clearly evident above 84 km, while the AO is observed below 84 km with eastward winds at the December solstice and westward winds at the June solstice. Moreover, the westward winds are larger in April below 84 km. Within $\pm 9°$ the westward winds during equinoxes are larger than the eastward winds during solstices. The westward winds during March equinox are larger than those in September equinox. Near $\pm 22°$, the eastward winds during solstices are larger than the westward winds during equinoxes. At RTG the winds are largely eastward throughout the year (except in September–October), despite SAO. The SAO do not vary much with height at TIR, CI_KOT, and JKT_PPK. Moreover, the month-height pattern is similar at these three locations. At Kauai and RTG, the SAO vary with height, but the month-height pattern of winds at Kauai is different from that at RTG. At Kauai the SAO is clearer at higher altitudes and at RTG the SAO is clearer at lower altitudes. Thus, there is a height difference of the SAO pattern at Kauai and RTG.

3.2. Meridional Winds

3.2.1. Long-Term Variability of Mean Meridional Winds

[25] Figures 6 shows the month-height contours of monthly mean meridional winds. The meridional winds at all locations consistently show an AO, with northward (southward) winds at the December (June) solstice. Over the equator, the AO is clearer at CI than at KOT and there is a tendency that the wind core appeared at slightly higher altitude at CI that at KOT. It is noted that the amplitude of AO at TIR increases after 2004.

[26] The winds at Kauai and CI_KOT do not show significant long-term variability. The meridional winds at TIR show long-term variability, changing from more northward to more southward from 1993 to 2009, despite AO. The winds at JKT_PPK also show long-term variability with the winds being more southward during 1993–1999 and northward after 2004. Due to the short data set, it is difficult to deduce long-term variability at RTG. Maximum northward winds during December solstices are nearly similar at all latitudes, except during the period when the winds become more southward at TIR and JKT_PPK.

[27] Figures 7 shows the long-term variability of monthly mean meridional winds for (top to bottom) Kauai, TIR, CI_KOT, JKT_PPK, and RTG at a height of 88 km. As in Figure 3, the vertical bars (green color) in the middle of each panel correspond to standard deviation of the mean winds after removal of the tides. The standard deviations are generally in the range of 2–6 ms^{-1}. The meridional winds at all locations show a distinct AO with northward winds during December solstice and southward winds during June solstice. This is in accordance with the residual mean meridional circulation in the mesopause region, which is from the summer to winter pole [*Andrews et al.*, 1987]. However, this is not strictly true as the winds sometimes show more than two peaks a year. For instance, three northward peaks a year can be noted in 1992, 1994, and 2002 at Kauai and in 2006 at

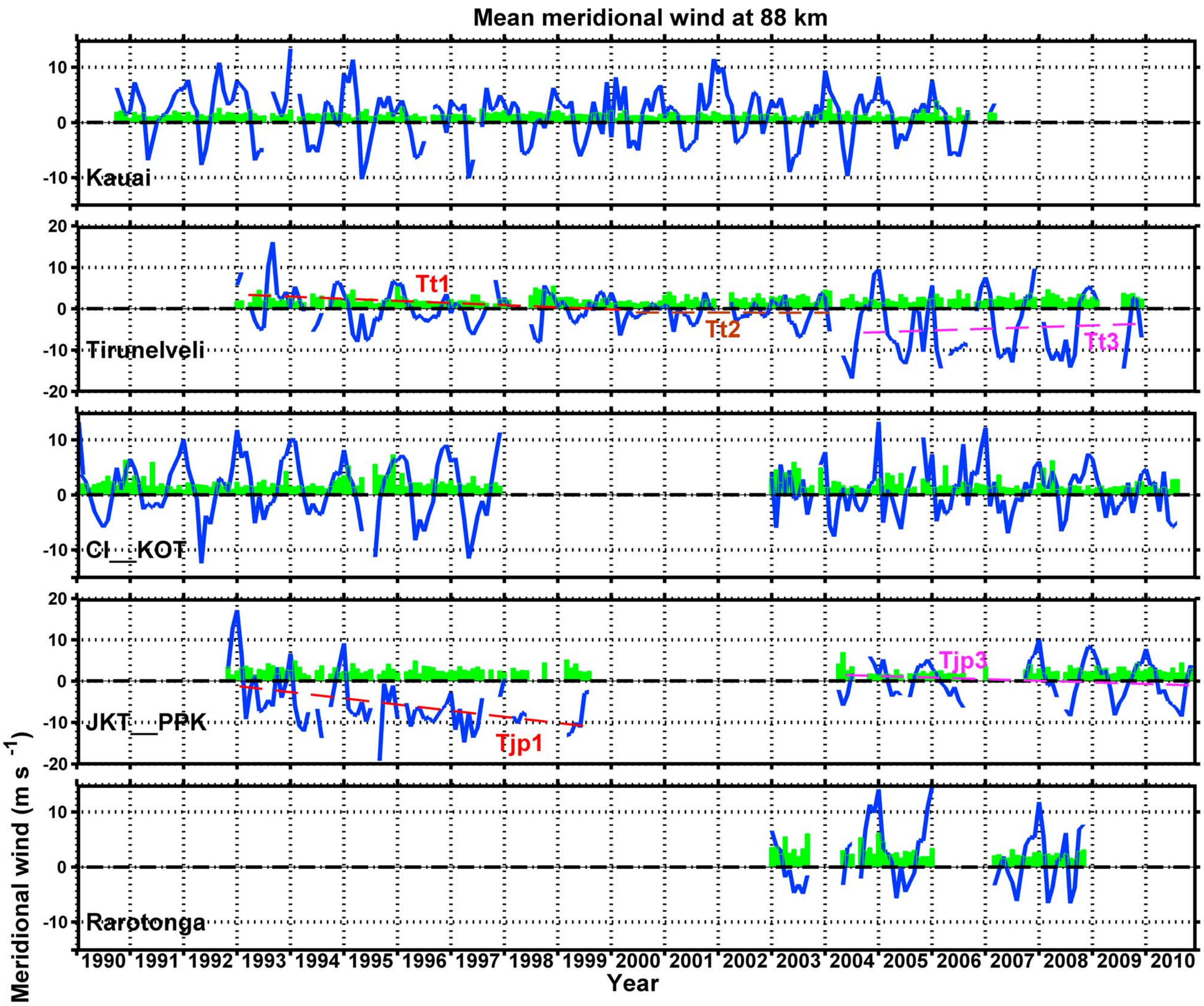

Figure 7. Temporal variation of monthly mean meridional winds for a height of 88 km at (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga. Vertical (green color) bars in the middle of each panel correspond to standard deviation of the mean winds. The trends at Tirunelveli are Tt1 = -0.5 m s^{-1} (for 1993–1999); Tt2 = -0.02 m s^{-1} (for 2000–2003); and Tt3 = 0.4 m s^{-1} (for 2004–2009). The trends at JKT_PPK are Tjp1 = -1.45 m s^{-1} (for 1993–1999) and Tjp3 = -0.38 m s^{-1} (for 2004–2009).

CI_KOT. Occasionally, the winds show much more irregular behavior and display more than three peaks a year (e.g., during 1999–2000 at Kauai; during 2003, 2004, 2008, and 2009 at CI_KOT; during 1993 at JKT_PPK). Thus, apart from the distinct AO the meridional winds seem to display variability at higher frequencies as well.

[28] The meridional winds at Kauai and over the equator do not show any pronounced long-term variability, but some longer-term variability is evident at TIR and JKT_PPK. The meridional winds at TIR change from more northward to more southward from 1993 to 2009. i.e., there is a linear trend. Further, the wind amplitudes are smaller during 2000–2003. The winds show larger amplitudes after 2004. The winds at JKT_PPK are southward during 1994–1999. After 2004, the annual mean winds are close to zero with larger winds after 2008. Thus, larger winds, with increased AO, are consistent between TIR and PPK after 2008. Over the equator, the winds show a clear AO with fewer fluctuations during 1990–1997 at CI and more fluctuations during 2004–2010 at KOT.

[29] As noted above, Figures 6 and 7 clearly demonstrate that the meridional winds at TIR and JKT_PPK show distinct long-term trends. Here, we further study this long-term variability by computing the trends through least squares fitting. It is important to note that the absolute value of trends may depend on the start and end points and the length of data. The winds at TIR (second panel) show three discrete trends during 1993–1999 (Tt1), during 2000–2003 (Tt2), and during 2004–2009 (Tt3) with slopes of -0.5 (±0.02) ms^{-1}/year, -0.02 (±0.01) ms^{-1}/ year, and 0.4 (±0.02) ms^{-1}/year, respectively. Thus, between 2000 and 2003 the winds do not show much trend, while they show opposite trend between 1993 and 1999 and 2004–2009. At JKT_PPK (fourth panel) two distinct trends are observed during 1993–1999 (Tjp1)

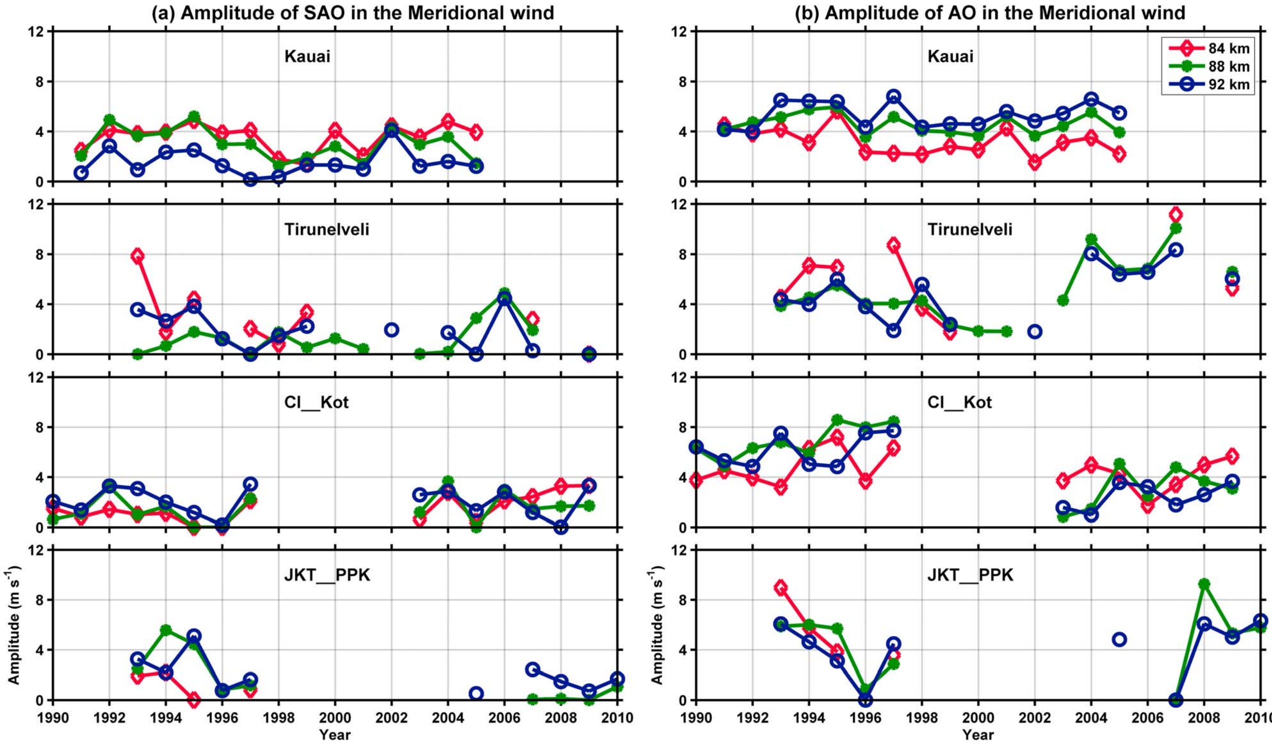

Figure 8. Temporal variation of amplitudes of (a) semiannual oscillation (SAO), and (b) annual oscillation (AO) in the meridional wind for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), and Jakarta and Pameungpeuk (JKT_PPK) at heights of 84 km, 88 km, and 92 km.

and 2004–2010 (Tjp3) with trends of -1.45 (± 0.05) ms^{-1}/year and -0.38 (± 0.05) ms^{-1}/year, respectively. During 2000–2003, data are not available at JKT_PPK to get trends. This shows that the winds at TIR and JKT_PPK during 1993–1999 show negative trend with the trend at JKT_PPK being larger. During 2004–2009, the trend at these locations is opposite. The trend difference between the two locations during 1993–1999 (Tt1-Tjp1 = 0.95) and during 2004–2009 (Tt3-Tjp3 = 0.75) is nearly same. Thus, the trends at both the locations undergo similar change.

3.2.2. Long-Term Variability of SAO and AO of Meridional Winds

[30] Figures 8a and 8b show the amplitudes of the SAO and AO, respectively, for meridional winds. These amplitudes are obtained in a similar way as those for zonal winds in Figure 4. Although it is well known that the meridional winds show an AO, we fitted a 6-month period to see if there is any SAO feature in the meridional direction. The typical errors in the estimation of the SAO and AO amplitudes are 1–2 ms^{-1} and 1.5–3 ms^{-1}, respectively and these errors vary slightly with altitude with the errors being more at lower altitudes. The relative errors are between 0.25 and 0.6. Figure 8 shows that while the AO is the dominant mode of variability in meridional winds at all locations, they also display significant SAO amplitudes. The maximum amplitudes of the SAO and AO at any location are 5 and 11 ms^{-1}, respectively (except one value of the SAO in 1993 at TIR). At Kauai, the amplitude of the SAO decreases with increasing height, while that of AO increases. The amplitude of the SAO is lower during 1998, 1999, and 2001, while the amplitude of the AO does not display significant interannual variability. At TIR the amplitude of the SAO is little larger during 1995 and 2006 compared to other years. The AO shows long-term variability with smaller values during 1999–2003 compared to other years. At CI_KOT, the amplitude of the AO is larger during 1990–1997 compared to 2003–2009. This could be due to either longitudinal difference between the two locations or a realistic long-term change. At JKT_PPK, the amplitude of the AO decreases from 1993 to 1996. Finally, it is important to note that the amplitudes of the SAO in the meridional wind are smallest over the equator and increase slightly with latitude.

3.2.3. Seasonal Variation of the Meridional Winds

[31] Figure 9a depicts the composite seasonal variation of mean meridional winds for 88 km. These winds are calculated in a similar way as the composite zonal winds in Figure 5. The percentage relative errors of these winds (calculated from standard deviations of Figure 7 and using law of propagation of errors) are 9.0, 11.4, 18.7, 8.8, and 36.5 for Kauai, TIR, CI_KOT, JKT_PPK, and RTG, respectively. These relative errors are large and hence care should be taken in interpreting the results. Figure 9a clearly demonstrates the AO of the meridional winds at all locations with northward (southward) winds at the December (June) solstice. However, the AO is not uniform at all locations. The time at which the wind direction changes from north to south or south to north is not the same at all the locations. Thus, the meridional winds during the solstices are in the same direction at all locations. During equinoxes, however, the winds are not in the same direction at all latitudes. This may partly be due to the large relative errors in the composite meridional winds. Further, the larger southward winds at

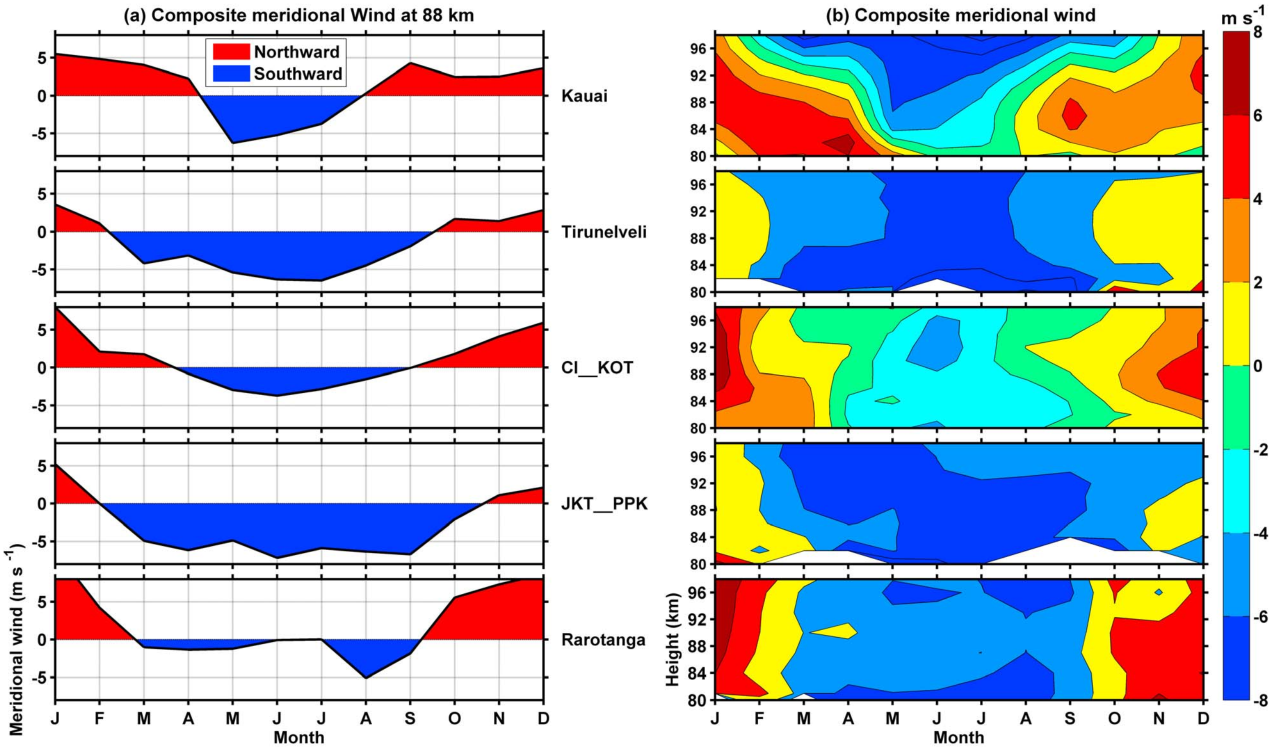

Figure 9. Composite (calculated using all available data at each location) seasonal variation of monthly meridional winds for (a) a height of 88 km and (b) all heights between 80 and 98 km for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), Jakarta and Pameungpeuk (JKT_PPK), and Rarotonga.

TIR and JKT_PPK are mainly due to the large southward winds observed during 2004–2009 at TIR and during 1993–1999 at JKT_PPK.

[32] In order to study the seasonal variation at all heights, we show month-height contours of meridional winds in Figure 9b. The meridional winds display a clear AO at all locations. The AO at Kauai shows a large variation with height, with southward winds during May–August at 80 km to February–November at 98 km. At TIR, the winds are southward from February until the middle of September at all heights. The AO of the meridional component over the equator changes little with height; the winds are southward from the middle of March to the middle of September and is northward for the northward rest of the time. At JKT_PPK, the winds are southward in February and November at all heights and northward during rest of the time. At RTG also the winds are southward during March to middle of September and show some variability with height. Thus, the time during which the winds blow southward and northward is different at different latitudes. At a given location the direction of the winds is nearly same at all heights, except at Kauai where the meridional wind direction changes with height.

4. Discussion

4.1. MSAO Structure and Its Long-Term Variability

[33] The MSAO structure of the zonal winds (with westward winds at the equinoxes and eastward winds at the solstices) in the equatorial and low-latitude MLT region is a well-established feature and has been studied by both satellite and ground based observations [e.g., *Burrage et al.*, 1996; *Garcia et al.*, 1997; *Sridharan et al.*, 2007; *Venkateswara Rao et al.*, 2012]. *Burrage et al.* [1996] from satellite observations showed that the SAO is the dominant mode of oscillation in the MLT region with a maximum over the equator and extending symmetrically to 20–30° in both hemispheres. The present results are consistent with these observations. However, the maximum amplitude of the MSAO here is 25 ms^{-1}, which is smaller than satellite and rocket results [*Hirota*, 1978; *Burrage et al.*, 1996; *Garcia et al.*, 1997]. The present study also shows that westward winds during equinoxes are larger than the eastward winds during solstices. Again, this is consistent with previous studies using multi-instrument observations [*Burrage et al.*, 1996; *Garcia et al.*, 1997].

[34] Here we find a seasonal asymmetry of the MSAO, with the first westward cycle being stronger than the second one in every year. Such a seasonal asymmetry was previously observed in SSAO structure, with first westward cycle in winter being stronger than the second one that occurs in summer, and was explained in terms of wave forcing due to strong planetary wave activity in the Northern Hemisphere winter [e.g., *Delisi and Dunkerton*, 1988]. *Garcia and Clancy* [1990] extended this mechanism to account for a similar behavior with the MSAO. Furthermore, the seasonal asymmetry of MSAO was attributed to a combination of an MSAO with different annual variations in the two hemispheres. However, *Burrage et al.* [1996] cautioned that the

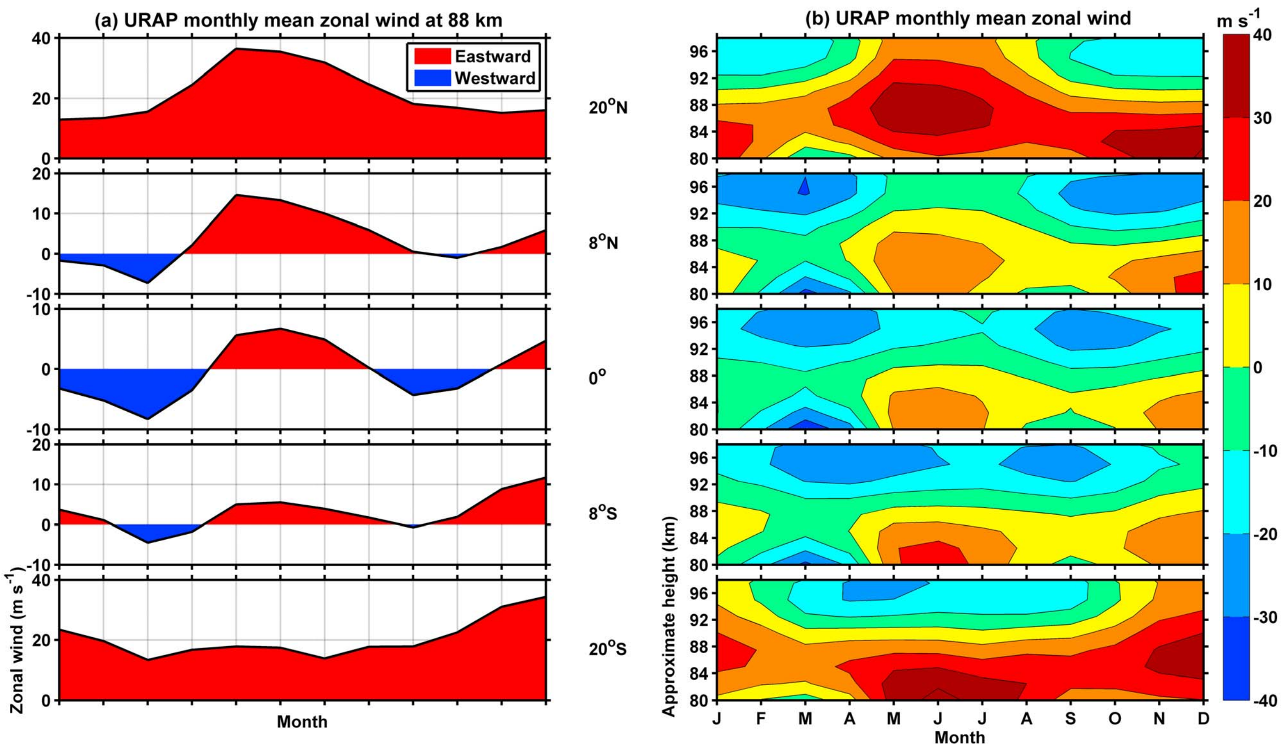

Figure 10. Seasonal variation of URAP monthly zonal winds for (a) a height of 88 km and (b) all heights between 80 and 98 km for (top to bottom) 22°N, 8°N, 0°, 8°S, and 22°S.

seasonal asymmetry may also arise from a combination of MSAO with the MQBO if the time series is not sampled long enough. The high resolution and long-term observations in the present study also show a clear seasonal asymmetry of the MSAO.

[35] The present observations also show that the zonal winds are eastward biased near ±22° and are westward biased at other locations, despite the SAO. i.e., the eastward (westward) winds of SAO are larger than the westward (eastward) winds near ±22° (at other locations). This is a new result and is evident throughout the observation period at each location during 1990–2010, which suggests that this a general feature. The winds in the lower thermosphere at equatorial locations are westward overall likely due to westward momentum deposited by the diurnal tide [e.g., *Lieberman and Hays*, 1994].

[36] In this paper, we evaluated the precision by calculating standard deviation of the wind velocity determinations for individual radars. However, as we are combining data from two different radars in order to construct a long-term data sets, it is important to estimate the accuracy (bias) of the wind velocity measurements, the height coordinate determinations, and so on. *Hasebe et al.* [1997] made such a comparison study and found that the HRDI winds are larger than the Jakarta meteor radar. Here we also compare the radars' winds in the present study with that from UARS Reference Atmosphere Project (URAP) [*Swinbank and Ortland*, 2003]. In Figures 10a and 10b, we show the seasonal variation of the MLT winds from URAP. The URAP data are obtained from http://uars.gsfc.nasa.gov/Public/Analysis/UARS/urap/zonal_wind_u_base_stand_hrdi-ukmo.html and chosen for latitudes that are closest to the radar locations. A comparison of Figure 5 (radar observations) and Figure 10 (URAP results) shows that the seasonal variation of zonal winds, in general, compare well between the two. Within ±9°, the SAO is apparent in both the winds, but the radar westward winds are larger than the URAP westward winds and the URAP eastward winds are larger than the radar eastward winds. Moreover, the time at which wind direction changes is different in radar and URAP observations. Near ±22° (±20° for URAP), the radar winds at 88 km (Figure 5a) show SAO behavior, especially at Kauai. The URAP winds, on the other hand, are completely eastward at ±20° at 88 km (Figure 10a).

[37] However, URAP eastward winds are much larger than that of radar winds. In general, a westward shift of URAP winds by 15–25 ms^{-1} for Kauai and by 5–15 ms^{-1} for TIR, CI_KOT, JKT_PPK would bring them to be in reasonable agreement with the radar winds. At higher altitudes, however, the URAP winds need to be shifted eastward by 5–10 ms^{-1} to agree with the radar winds. Furthermore, we separately compared the CI and KOT radar's data with that of URAP (not shown in this paper). This comparison shows that the peak eastward winds occur at same height in URAP and KOT and at 3–4 km higher at CI. However, a study by *Garcia et al.* [1997] (which used CI radar data from January 1990 to April 1995 and HRDI data from August 1992 to April 1995) shows that the maximum eastward winds occur at the same height both in CI MF radar and UARS. Such comparisons are also done for JKT and PPK in which the peak eastward winds occur at the same height as that of URAP. The larger relative error of

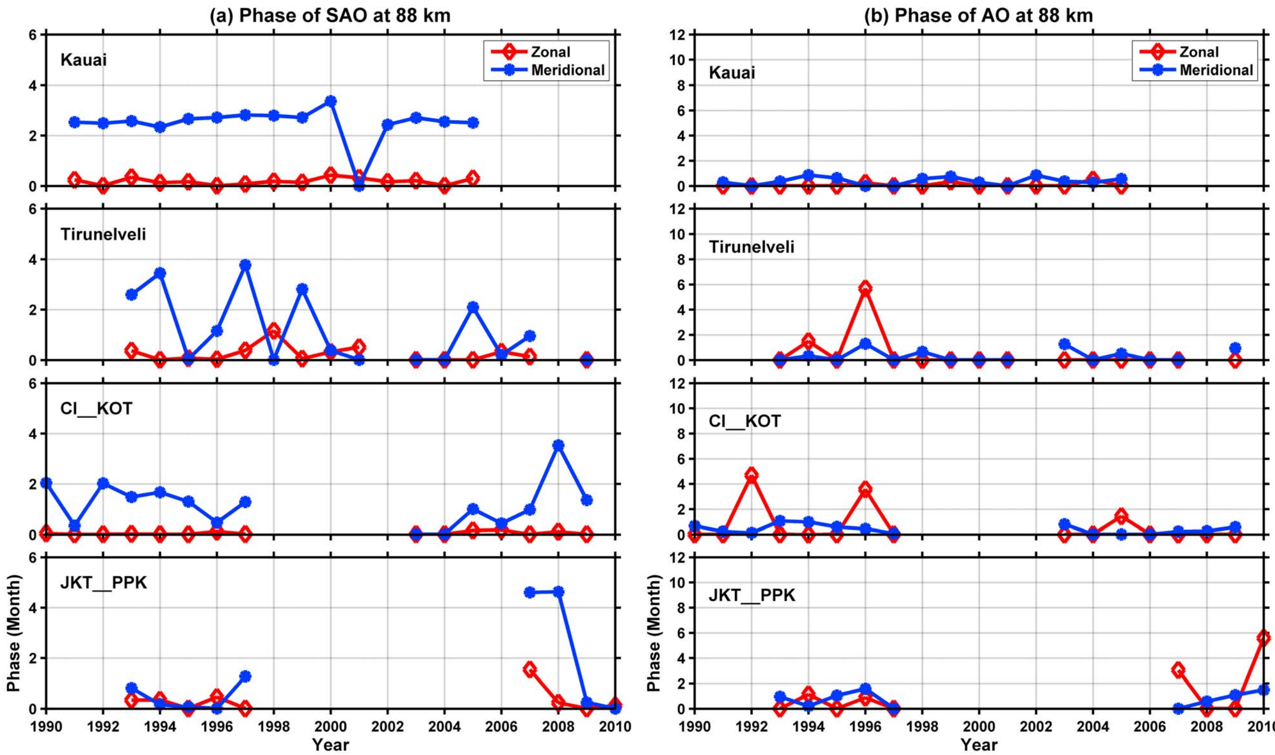

Figure 11. Temporal variation of phase of (a) semiannual oscillation (SAO) and (b) annual oscillation (AO) of zonal (red) and meridional (blue) winds for a height of 88 km for (top to bottom) Kauai, Tirunelveli, Christmas Island and Koto Tabang (CI_KOT), and Jakarta and Pameungpeuk (JKT_PPK).

radar winds at RTG (Figure 5) makes the comparison with URAP winds to be difficult.

4.2. Orthogonal Components of SAO and AO

[38] The SAO of the zonal winds and AO of the meridional winds is a well-established feature of the circulation in the tropical MLT. In addition, in the present study we noted an AO in the zonal winds and a SAO in the meridional winds. Such behavior of zonal and meridional winds is intriguing and needs a more detailed investigation. From Figures 4b and 8a we note that the amplitudes of these oscillations (AO of zonal and SAO of meridional winds) are smallest over the equator and that they increase with latitude. The Coriolis force also has a similar latitudinal variation, with a minimum over the equator and an increase in magnitude with latitude. This suggests that there could be a relation between the above mentioned oscillations and the Coriolis force.

[39] One way to check this possibility is to examine the phases of SAO and AO of the zonal and meridional winds, which are shown in Figure 11. Here phase is defined as the month when the eastward/northward wind reaches its first maximum. Coriolis force causes moving objects on the Earth to veer to the right (w. r. t. direction of motion) in the Northern Hemisphere and to the left in the Southern Hemisphere. Considering this effect, we anticipate a component of the SAO of zonal wind to appear in the meridional direction. The Coriolis force makes the eastward wind to deflect southwards in the Northern Hemisphere and northward in the Southern Hemisphere. Accordingly, the SAO of the meridional wind will lag behind that of zonal component by 3 months in the Northern Hemisphere and be in-phase in the Southern Hemisphere. From Figure 11a, we note that such a relation in fact holds good on many occasions. The phase of the zonal SAO occurs in December–January while that of the meridional SAO lags by 2–4 months (except in some years) in the northern hemisphere. This feature is much clearer at Kauai. At JKT_PPK, the phases occur nearly in the same months (except in 2007 and 2008).

[40] Similarly, considering the Coriolis effect, we expect the AO of the meridional wind to appear in the zonal direction. Since a northward wind veers eastward in the Northern Hemisphere and westward in the Southern Hemisphere, the AO of the meridional and zonal winds will be in-phase in the Northern Hemisphere and in anti-phase in the Southern Hemisphere. This relation seems to hold well as can be seen in Figure 11b which shows that the phases of AO in the meridional and zonal winds occur in December–January (except in 1996 at TIR). This relation, however, does not seem to hold for JKT_PPK. Again, this feature is much clearer at Kauai. Thus the presence of orthogonal components of AO and SAO suggests that the winds are coupled off from the equator and the coupling is stronger at higher latitudes. However, it can be noted that the zonal winds at mid- and high-latitudes display AO which can be observed at latitudes as low as tropics [e.g., *Burrage et al.*, 1996]. Thus, in addition to the Coriolis effect, it is also possible that the larger AO amplitudes in the zonal wind at Kauai are partly due to the actual AO of the midlatitude zonal winds that extend to tropics.

4.3. The Mesospheric Quasi Biennial Enhancement (MQBE)

[41] One of the important results of the present study is clear evidence of a MQBE signature in the zonal winds at all low-latitude sites, except RTG. The MQBE is a seasonally locked phenomenon that occurs primarily in the westward phase during the March equinox. In the case of stratospheric SAO, the westward phase is unaffected by the QBO while the eastward winds show an apparent QBO modulation [*Garcia et al.*, 1997].

[42] The MQBE shows evidence for long-term variability, with clear westward enhancements before 2002 at all low-latitude sites. After 2002, the MQBE is weaker. A comparison of MQBE with SQBO shows that large westward winds in the MLT in 1993, 1995, 1997, and 2002 are observed when the winds in the stratosphere are eastward. However, exceptions to this rule are observed during 1991 and 2000. During these years large westward winds are observed in the MLT region but the winds in the stratosphere are westward above ~30 hPa and eastward below. From CI MF radar observations, *Garcia et al.* [1997] noted this behavior for winds in 1991. In the present study we observed MQBE signals up to a latitude of 22°N, consistent with satellite observations, wherein the MQBE (it was called MQBO) is seen to extend to ±30°. Thus, the present study shows a clear MQBE signature at all low-latitudes before 2002, whereas the MQBE signature is absent/weaker thereafter.

[43] In previous studies it was suggested that the selective filtering of upward propagating short period gravity waves by the SQBO will produce a similar oscillation in the mesosphere, the so-called MQBO. However, in the mesosphere no such oscillation is observed and only the westward winds during March equinox are enhanced every 2 or 3 years (MQBE). If wind filtering of upward propagating gravity waves by the underlying wind systems (such as SQBO and SSAO) is responsible for the existence of MQBE, then it is important to understand what causes the wind enhancement only in March equinox and why such enhancement is not observed in other seasons. *Sridharan et al.* [2007] argued that eastward winds prevailing at all heights in the stratosphere during March equinox provide favorable conditions for the westward propagating waves to reach MLT heights and drive large westward winds there. However, it should be realized that such conditions can also persist during the September equinox and during eastward phases of the SSAO and SQBO, but the MQBE is observed only during March equinoxes and no significant wind enhancements at other seasons.

[44] The present study also raises several other questions regarding relation between the MQBE and SQBO. Particularly, what causes the MQBE period to change from two years to three years during 1997–2000 is not clear. *Sridharan et al.* [2007] argue that the period of the SQBO also increased from 2 to 3 years during that time. This is not entirely consistent, as the MQBE westward winds in 2000 takes place during the westward phase of the SQBO (above 30 hPa). For the wind filtering to be more effective to produce large westward winds in the mesosphere, we expect the SQBO to be in eastward phase. Moreover, whereas the SQBO wind regimes show a downward phase progression, the westward winds associated with MQBE do not show any phase progression.

4.4. Residual Meridional Circulation

[45] The present study reveals an interesting feature of the AO in meridional winds. The direction of flow of meridional winds is nearly the same at all latitudes during the solstices, i.e., the winds blow northward (southward) during December (June) solstice. This is consistent with the residual mean circulation due to radiative heating and gravity wave breaking at high latitudes [*Andrews et al.*, 1987]. This circulation consists of rising motion near the summer pole, a meridional drift into the winter hemisphere, and sinking near the winter pole. At the equinoxes, however, the diabatic circulation is weaker and consists of a rising motion at the equator and pole ward drift in both the spring and autumn hemispheres. The present observations also suggest that the winds during equinoxes are smaller. However, during equinoxes the meridional winds are not blowing in the same direction at all latitudes. i.e., in a given month the winds at different latitudes are not in the same direction. Thus, the time at which the winds change their direction from north to south or from south to north is not same at all latitudes. This may be due to the fact that radiative heating alone is not driving the diabatic circulation, but that eddy forcing plays a primary role [*Andrews et al.*, 1987].

4.5. Long-Term Trends of Meridional Winds

[46] The meridional winds at TIR and JKT_PPK show interesting long-term trends. During 1993–1999 the meridional winds at TIR and JKT_PPK show a southward trend, with the trend being larger at JKT_PPK (-1.45 ms^{-1}/year) than at TIR (-0.5 ms^{-1}/year). During 2000–2003 the meridional winds at TIR shows almost no trend. After 2004, the trend at TIR reverses to that during 1993–1999. At JKT-PPK, the trend is smaller during 2004–2010 compared to 1993–1999, but in the same direction. Although the trend direction is same during 1993–1999 and 2004–2010 at JKT_PPK, there is a change of winds from southward in 1999 to northward in 2004. We do not know whether such a change is continuous and real and what causes such a change.

[47] Several factors have been proposed to explain the long term trends of MLT winds. These include the 11-year solar cycle, the effects of sudden stratospheric warmings (SSW), climate change effects due to greenhouse gases such as CO_2 and changes in ozone. However, the response of the MLT winds to any of these factors is not clear. Thus, it is important to model and quantify the response of the MLT winds to the above factors, especially in an atmosphere when all of the above factors interactively drive the mean flow. The present study also emphasizes the importance of long-term observations of MLT winds globally to better understand the coupling between lower and middle atmosphere and to examine the behavior of the MLT region in the light of climate change and solar activity.

5. Summary and Conclusions

[48] In this paper we studied the long-term variabilities of monthly mean zonal and meridional winds in the mesosphere and lower thermosphere (MLT) at low-latitudes using medium frequency (MF) radar observations at Kauai (22°N, 154°W), TIR (8.7°N, 77.8°E), CI (2°N, 157°W), and PPK

(7.4°S, 107.4°E) as well as meteor radar observations at KOT (0.2°S, 100.3°E), Jakarta (6°S, 107°E), and RTG (21.2°S, 159.7°W). Important findings in this study are:

[49] 1. The zonal winds at all latitudes show a distinct SAO with westward winds during equinoxes and eastward winds during solstices. Within ±9° latitude the westward winds during the equinoxes are larger and persist for longer time than the eastward winds during solstices. The westward winds during the March equinox are larger than in September equinox. The SAO does not vary much with height at TIR, CI_KOT, and JKT_PPK and varies at Kauai and RTG. However, the month-height pattern is similar at TIR, CI_KOT, and JKT_PPK, which is different from that at Kauai and RTG. The month-height pattern of winds at Kauai is different from that at RTG.

[50] 2. Large enhancements of westward winds are observed in March equinoxes of 1991, 1993, 1995, 1997, 2000 and in 2002 at all locations. As this is a seasonal locked and impulsive phenomenon occurring only in March equinox, we define it as Mesospheric Quasi-Biennial Enhancement (MQBE), instead of MQBO. The MQBE is weaker/absent after 2002. A clear understanding of this phenomenon requires multi-instrument experiments that provide information about background winds from troposphere to MLT heights and upward propagating wave properties like phase velocities, horizontal wavelengths etc.

[51] 3. The meridional winds at all locations consistently show an AO with northward winds during the December solstice and southward winds during the June solstice. The amplitude of the AO increases after 2004 at TIR. Such an increase is also observed after 2008 at PPK. The meridional winds blow in the same direction at all latitudes during the solstices. However, during the equinoxes the timing for wind direction change did not coincide at all latitudes. The timing varies with height at Kauai and did not vary at other latitudes.

[52] 4. The meridional winds also show a SAO component and the zonal winds show an AO component. The amplitudes of these oscillations are minimum over the equator and increases with latitude. This shows that the zonal and meridional winds are coupled off the equator, probably through Coriolis effect. The coupling is much clearer at Kauai with persistent phase relation.

[53] 5. Winds show distinct long-term trends at conjugate latitudes of TIR and JKT_PPK. The trends at TIR at 88 km are -0.5 ms^{-1}/year during 1993–1999, -0.02 ms^{-1}/year during 2000–2003, and 0.4 ms^{-1}/year during 2004–2009. For JKT_PPK, the trends are -1.45 ms^{-1}/year during 1993–1999 and -0.38 ms^{-1}/year during 2004–2010. No significant trends are observed at other latitudes. This is an interesting feature and needs to be studied further in terms of potential driving factors such as climate change, decadal variability and solar cycle effects. In fact, a combination of several factors may be more important in accounting the long-term variability. If the long-term trends in the present study are related to climate change, then monitoring the MLT region may be more useful for climate change or global warming as the magnitude of variability is larger in the MLT region.

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