The Semiannual Oscillation of the Tropical Zonal Wind in the Middle Atmosphere Derived from Satellite Geopotential Height Retrievals

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ABSTRACT

The dominant mode of seasonal variability in the global tropical upper-stratosphere and mesosphere zonal wind is the semiannual oscillation (SAO). However, it is notoriously difficult to measure winds at these heights from satellite or ground-based remote sensing. Here, the balance wind relationship is used to derive monthly and zonally averaged zonal winds in the tropics from satellite retrievals of geopotential height. Data from the Aura Microwave Limb Sounder (MLS) cover about 12.5 yr, and those from the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) Sounding of the Atmosphere Using Broadband Emission Radiometry (SABER) cover almost 15 yr. The derived winds agree with direct wind observations below 10 hPa and above 80 km; there are no direct wind observations for validation in the intervening layers of the middle atmosphere. The derived winds show the following prominent peaks associated with the SAO: easterly maxima near the solstices at 1.0 hPa, westerly maxima near the equinoxes at 0.1 hPa, and easterly maxima near the equinoxes at 0.01 hPa. The magnitudes of these three wind maxima are stronger during the first cycle (January at 1.0 hPa and March at 0.1 and 0.01 hPa). The month and pressure level of the wind maxima shift depending on the phase of the quasi-biennial oscillation (QBO) at 10 hPa. During easterly QBO, the westerly maxima are shifted upward, are about 10 m s$^{-1}$ stronger, and occur approximately 1 month later than those during the westerly QBO phase.

1. Introduction

The semiannual oscillation (SAO) in zonal wind is the dominant mode of seasonal variability in the tropical middle atmosphere between the middle stratosphere and the upper mesosphere. The current picture of the SAO is constructed from combining various historical and more recent sets of in situ and remote observations. Rocket wind measurements (e.g., Hirota 1980; Garcia et al. 1997) and analyses of conventional meteorological data (Baldwin and Gray 2005; Rienecker et al. 2011) show an SAO in the upper stratosphere. However, there are substantial differences in the tropical winds in the upper stratosphere between several commonly used climatologies (Randel et al. 2004). Wind observations from satellite (Garcia et al. 1997) and radar (e.g., Venkateswara Rao et al. 2012; Davis et al. 2013) also show an SAO in tropical zonal winds in the upper mesosphere.

Several decades of observations by research satellites have greatly increased the knowledge and understanding of the middle atmosphere. Satellite observations have the benefits of near-global coverage and good continuity in time. Middle atmosphere winds were observed by the High Resolution Doppler Imager (HRDI) on the Upper Atmosphere Research Satellite (UARS) in the stratosphere and mesosphere. Garcia et al. (1997) and Ray et al. (1998) show the SAO from these data over the altitude range 10–40 km; Garcia et al. (1997) also include HRDI observations at 65–110 km. More recently, on the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED), the TIMED Doppler Interferometer (TIDI) measured winds for altitudes above 60 km; TIDI data have been used mainly to investigate wave phenomena rather than...
zonally averaged winds because of uncertainty in quantifying spacecraft effects that impact the determination of the absolute geophysical wind (Niciejewski et al. 2006).

Satellite direct wind measurements have never been available in the upper stratosphere and lower to middle mesosphere. With such a gap, the connection between the SAO in the mean winds at the stratopause and that in the upper mesosphere has not been well constrained by observations. In addition, there has been little observational investigation of the variation of the SAO in relation to other dynamical phenomena such as the quasi-biennial oscillation (QBO) and extratropical dynamical variability. With the increasing awareness of coupling of atmospheric dynamical processes across different vertical levels and latitudinal regions, there is a need for studies that characterize the SAO and its variability.

In this study, we present tropical mesospheric winds derived from the temperature measurements made by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the TIMED satellite and the Microwave Limb Sounder (MLS) instrument on the Aura satellite, and we assess their reliability in the lower stratosphere and upper mesosphere. Although observed profiles from both instruments span the entire middle atmosphere and SABER profiles even extend into the lower thermosphere, the range investigated here is limited to altitudes below about 84 km (0.004 hPa); at higher altitudes, the limited vertical resolution of MLS and potential contamination by the diurnal tide for both instruments make determination of zonal-mean zonal winds problematic. The long duration of the measurement records, which currently exceeds 12 yr for MLS and approaches 15 yr for SABER, allows us to investigate the interannual variability of the SAO and the relationship between it and the QBO.

2. Data and processing

a. TIMED/SABER geopotential height data

Temperature profiles are retrieved from SABER, version 2.0, measurements of CO₂ emissions. Remsberg et al. (2008) describe the temperature retrieval and uncertainties from version 1.07. Updated uncertainty information for version 2.0 is available online (from http://saber.gats-inc.com/temp_errors.php). The uncertainty due to precision of single temperature profiles over the altitude range 20–80 km is less than 1.8 K. For the standard data products, temperature profiles are integrated using the hydrostatic relation to determine geopotential height thicknesses; heights are then assigned by tying onto daily National Centers for Environmental Prediction (NCEP) analyses at 10 hPa. In this study, we use the altitude and pressure data from the SABER level 2A, version 2.0, files for the period 25 January 2002–31 December 2016 (available from http://saber.gats-inc.com).

Level 2A SABER profiles are obtained from observations made at variable latitudes along the tangent path of the observations over a range of pressure. For the analysis carried out here, the data are sorted into bins with a width of 4° in latitude. All profiles along one leg of an orbit that fall into a latitude bin are averaged to produce a mean profile for that bin; the profile coordinates are then the average longitude and time of the profiles included in the average. The effective vertical resolution of the SABER data is 0.3 scale heights; the scale height is the ratio ln(p₀/p), where p₀ is a reference pressure. A vertical resolution of 0.3 scale heights is equivalent to 2.1 km, assuming a mean scale height H = 7 km for the middle atmosphere. The lower limit of the analysis is 70 hPa; below this level, increasing noise and data gaps make the results less reliable.

Because of the precession of the TIMED satellite, the local time of SABER observations shifts from day to day. For any given day, the local times sampled have two narrow ranges that, at the equator, are about 8.8 h apart. The TIMED satellite executes a yaw maneuver about every 60–65 days on an annually repeating schedule. Near-complete local time coverage is obtained during each yaw cycle. A gap in local time coverage occurs near noon at all latitudes and times of the year; at the equator the gap extends for about 2 h.

b. Aura/MLS geopotential height data

Schwartz et al. (2008) describe the retrieval and validation of MLS geopotential height data. Geopotential height profiles from MLS, version 4.2, are available online (from http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/MLS/index.shtml). See Livesey et al. (2017) for an updated discussion of the data quality, screening recommendations, and uncertainties in the geopotential height data. The available data from 2 August 2004 to 31 December 2016 are used in the present study. The thicknesses of atmospheric layers are determined from the temperature and then tied to the height at 100 hPa determined from spacecraft pointing information.

The MLS data are given at fixed pressure levels with resolution that varies with altitude: 12 pressure levels from 100 to 10 hPa and from 10 to 1 hPa; 6 pressure levels from 1 to 0.1 hPa; and 3 pressure levels from 0.1 to 0.01 hPa. Geopotential height data above 0.01 hPa are not recommended for use; data at 0.01 hPa proved to be too noisy for wind calculations at the equator and are
not used in the present analysis. The data at the MLS geopotential height levels are used with no additional interpolation in pressure. Sampling in latitude is regular and is approximately every 1.5° in latitude in the tropical and subtropical region. The latitude bins used in the analysis here conform to this natural resolution and are at 1.5° intervals.

After screening for data quality, precision, data status, and data convergence, as described in the MLS documentation, outliers were still found that perturbed the wind calculations. Additional screening removed points that were outside the normal height-dependent range; the approximate quantity of data points removed was 0.01%.

c. Time series analysis

In the upper mesosphere, tidal amplitudes become large, so special care is needed to separate the migrating diurnal tide from the SAO. The amplitude of this tide has large semiannual variations (e.g., Burrage et al. 1995a; Wu et al. 2008; Davis et al. 2013). Since SABER and MLS geopotential height data are available twice per day and have very low rates of missing profiles, the asynoptic mapping method described by Salby (1982a,b) can be used to separate the diurnal tidal variations from the variations in the background.

In principle, the asynoptic sampling analysis technique applied to SABER profiles can give a clean separation of the diurnal tidal period of 1 day and the SAO period of about 183 days [see discussion and verification by Salby (1982a)]. However, as noted above, the sampling of SABER profiles is not uniform; there is a small shift to the track of limb viewing points about every 60–65 days as TIMED executes a yaw maneuver. In our analysis, we shift the coordinates of the profiles slightly to conform to a regular sampling pattern that is midway between the profile locations for the left-viewing and right-viewing periods. Tests with synthetic data show that this shift causes the diurnal tide to contaminate the zonal-mean time-mean geopotential height and hence also the calculated zonal wind. At higher altitudes where the amplitude of the tide in temperature and geopotential height is large, this introduces a bias in the time-mean wind. Comparison of the SABER winds derived in this study with radar observations indicates systematic differences that are small but not negligible at 80 km (~0.01 hPa) and grow with altitude. The biases fit the characteristics of tidal contamination found in our tests with synthetic data and appear to be confined to the long-term-average background mean wind, as predicted by these tests. Note that the amplitude of the migrating semidiurnal tide also grows in the upper mesosphere (e.g., Burrage et al. 1995b; Pancheva et al. 2009), but it is not expected to reach large enough amplitude to have a major impact on the tropical wind calculations over the height range considered here.

Aura is in a sun-synchronous orbit and the MLS data sampling is regular in longitude and time. The asynoptic sampling is therefore applied to the MLS profiles without any need for adjusting the locations and times of the profiles. The MLS analysis allows us to isolate fields at frequencies lower than 1 day that are free from contamination by the diurnal tide (Salby 1982a). In other words, the diurnal tide and its variability should not cause any contamination of the MLS zonal and time-mean geopotential heights. The amplitudes of the semidiurnal tide and other tidal frequencies are not large enough to affect the analysis in the equatorial lower and middle mesosphere.

Because of the tidal contamination, we restrict SABER analysis to altitudes below 0.004 hPa (about 84 km). As discussed below, the zonally averaged zonal winds at this cutoff altitude agree well with observations if the multi-year time-mean wind is removed.

d. Determining winds from geopotential height

The relationship between large-scale zonal wind and geopotential can be determined from the meridional momentum equation:

\[
\frac{\partial \nu}{\partial t} + \frac{u}{a \cos \phi} \frac{\partial \nu}{\partial \lambda} + \frac{v}{a} \frac{\partial \nu}{\partial \phi} + w \frac{\partial \nu}{\partial z} + fu + \frac{u^2}{a} \tan \phi = -\frac{1}{a} \frac{\partial \Phi}{\partial \phi}
\]

(1)

where \(u\), \(v\), and \(w\) are zonal, meridional, and vertical wind components, respectively; \(\lambda\) and \(\phi\) are longitude and latitude, respectively; \(z\) is log-pressure altitude; \(f\) is the Coriolis parameter; \(a\) is Earth’s radius; and \(\Phi\) is the geopotential. Taking the zonal mean (overbar), expressing eddy quantities (primed) in flux form, and neglecting zonal-mean \(v\) and \(w\) gives

\[
\overline{\nu}^2 + \frac{\overline{u}^2}{a} \tan \phi + f \overline{u} + \frac{1}{a} \frac{\partial \overline{\Phi}}{\partial \phi} + \left( \frac{1}{a \cos \phi} \frac{\partial \overline{\nu'} \nu'}{\partial \phi} + \frac{1}{a} \frac{\partial \overline{\rho\nu'w'}}{\partial z} \right) = 0.
\]

(2)

D. Ortland (2017, personal communication) found that the eddy flux terms in parentheses could not be neglected in the tropical upper mesosphere where the migrating diurnal tide reaches large amplitude. This is another reason why we do not extend the current analysis into the upper mesosphere. Lower in the middle atmosphere, where the tidal meridional winds can be neglected, Eq. (2) reduces to
\[ \frac{\pi^2}{a} \tan \phi + f \pi + \frac{1}{a} \frac{\partial \Phi}{\partial \phi} = 0. \] (3)

Randel (1987) showed that Eq. (3) gave good results for middle-atmosphere zonal-mean zonal wind; this is the formula we use in this study. In practice, the first term is quite small near the equator, so, in effect, solving Eq. (3) yields geostrophic winds there. The geopotential is obtained from the geopotential height data simply by multiplying by the acceleration of gravity \( g \), which we take to be equal to its value at sea level.

The main limiting factor of applying Eq. (3) close to the equator is that even small errors in the geopotential height data can introduce large errors in the zonal wind. This is because the meridional variation of \( \Phi \) is very slight near the equator, so its gradient is a small difference of two large numbers. On the other hand, errors in the data are random, such that their contribution to the calculated geopotential gradient becomes increasingly larger relative to the true gradient as the equator is approached. Observations from both SABER and MLS have very few data gaps. Sampling in a specified latitude interval includes about 30 profiles per day and 900 profiles per month. The excellent precision and large number of profiles of both of the satellite datasets means that noise is manageable in the calculations except very close to the equator, as discussed below.

For both datasets, we compute the spectra of geopotential height using the asynoptic sampling method over the entire time period: almost 15 yr for SABER and more than 12 yr for MLS. We then synthesize the spectral results for low-frequency variations (periods from 100 days to infinity) to get daily geopotential height profiles at each latitude band and day. These are averaged for each month. The monthly geopotential height data for MLS are smoothed in latitude using a five-point averaging. Because of the smoothing inherent in the binning of profiles that are irregularly spaced in latitude, no additional latitudinal smoothing is used for the SABER geopotential heights. The zonal wind values at all latitudes, but those very close to the equator come from Eq. (3).

For the results shown here, the equatorial and near-equatorial winds were estimated by cubic spline interpolation of the balance winds obtained from Eq. (3) at and poleward of latitudes of \( \pm 8^\circ \) for SABER and \( \pm 6^\circ \) for MLS. We experimented with many options before settling on these choices of how much latitudinal smoothing to apply to each dataset and how close to the equator to carry the balance wind calculations. The basic magnitude and structure of the wind was not highly sensitive to the details of the calculations. The method used gave the best overall agreement of the equatorial winds derived from MLS and SABER with each other and with the correlative data presented below.

Figure 1 shows the background time-mean wind calculated from SABER and MLS. The two agree very well up to 0.04 hPa. One exception is at 1 hPa, where the SABER analysis indicates the wind is weak easterly while the MLS analysis gives a weak westerly wind. The large magnitudes in the SABER mean wind above 0.01 hPa are consistent with tidal aliasing, as discussed above. Although tidal aliasing could contribute to the discrepancy between the SABER and MLS wind estimates above 0.06 hPa, it is also possible that a portion of the discrepancy is due to the coarser vertical resolution and increasing noise in the MLS observations.

In all subsequent figures that show SABER winds, the multiyear time-average wind is removed above 0.03 hPa. This pressure cutoff is chosen for three reasons: 1) it is approximately the level where the migrating diurnal tide becomes sufficiently large to contaminate the zonal mean wind, 2) the winds estimated from SABER and MLS increasingly diverge above this level, and 3) the SABER estimate for the time-average wind is small at this pressure level, so removal of the mean does not introduce a discontinuity in the vertical dimension.

e. Comparison with direct wind measurements from radiosonde

As noted in the introduction, the vertical range for which there are direct wind observations in the tropical middle atmosphere is limited. For validation of the
SABER and MLS wind analyses, we are particularly interested in long-term observations since February 2002. Here, we compare the satellite winds with two available datasets: one in the lower stratosphere and the other in the upper mesosphere.

The monthly mean radiosonde winds at Singapore (1°N; 104°E) in the lower stratosphere are included in a widely used dataset made available by the Free University of Berlin (available online at http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/) [see Naujokat (1986) for a description of the data]. The variability of the stratospheric equatorial wind on monthly or longer time scales is dominated by the QBO. Figure 2 shows a comparison of the Singapore winds at levels near 10, 20, 30, and 45 hPa with the monthly averaged zonal-mean winds at the same or nearby pressures determined from SABER and MLS. SABER winds are not shown at 10 hPa because this is the geopotential height tie-on level; geopotential heights at 10 hPa in the SABER data come from the NCEP analysis.

The winds from both satellite analyses follow the phase of the QBO quite well, but there are some differences that stand out. SABER winds indicate a similar QBO magnitude to the radiosonde winds and to the winds derived from MLS at 30 and 45 hPa, but the westerly maxima are systematically weaker at 20 hPa. This may be due to the coarser latitudinal resolution of the SABER data since the westerly phase of the QBO is narrowly confined to the deep tropics. The month-to-month variability does not always agree. The satellite winds show more month-to-month variability during periods of strong westerly wind; both the satellite and Singapore winds are variable during periods of strong easterly wind. There could also be a systematic discrepancy between zonally averaged satellite winds and single-longitude radiosonde winds arising from zonal asymmetries in the QBO (e.g., Hamilton et al. 2004; Kawatani et al. 2016) that are not captured in the Singapore observations.

**f. Comparison with direct wind measurements from meteor radar**

Wind data spanning 2002–07, with some gaps, were taken by a meteor radar at Ascension Island (8°S; 14°W) and are described by Davis et al. (2013) and Moss et al. (2016). The Ascension Island meteor radar is a commercially produced standard All-Sky Interferometric Meteor Radar (SKiYMET) system and operated in an all-sky configuration with a peak power of 12 kW up until 2007, transmitting at a frequency of 43.5 MHz. The data used in this study cover the period January 2002–December 2007.

Mesospheric winds were calculated from these data in the same way as previous studies (e.g., Davis et al. 2013; Moss et al. 2016). To calculate the atmospheric mean winds, the data are binned into six height gates at 78–83, 83–86, 86–89, 89–92, 92–95, and 95–100 km. The lowermost and uppermost height gates are wider to allow enough meteor observations to make accurate measurements. Coverage over all local times allows for the separation of tidal winds from the background daily means. A least squares method is used to determine the magnitude and direction of the mean wind, which is then split into zonal and meridional components. Low-pass filtering is applied to produce the 31-day monthly mean wind estimates.

Figure 3 compares the monthly mean winds from Ascension Island with the SABER-derived zonal-mean winds at 8°S for the same period. MLS winds are not shown because these altitudes are above the recommended pressure range of MLS geopotential height data. For these comparisons, the SABER wind values were interpolated onto altitude levels.
As noted above, diurnal tides can alias into the time-mean wind in the SABER analysis. The altitude levels shown in Fig. 3 are above 0.03 hPa, so the time mean has been removed from the SABER winds, as discussed in section 2d. At the lowest level shown (81 km), the magnitude, timing, and interannual variability of the SABER wind variations agree fairly well with the radar. Variations are also similar at the next higher level (84 km). For both datasets, the dominant period of variability is semiannual. At levels above 84 km, major discrepancies appear. For this reason, we limit the further analysis of SABER winds to levels below 0.004 hPa, approximately 84 km.

3. Climatological SAO

Figure 4 shows the climatological monthly average zonal-mean zonal wind from SABER and MLS at the equator for February 2002–May 2016. The tropical SAO near the stratopause (1 hPa, 50 km) is characterized by easterly wind maxima at the solstices. The easterly peaks are stronger in NH winter (December and January). Following both solstice periods, the SAO easterly winds descend downward to about 10 hPa, where the QBO also has large amplitude (not apparent in the multiyear average, which effectively removes the QBO). The timing and magnitudes of the wind variations are similar in the analyses from the two datasets, but there are some differences. One difference is that the MLS winds at all levels are more westerly during June–August (weaker easterlies at 1 hPa and stronger westerlies at 0.1 hPa). The difference in the time-mean wind at 1 hPa (see Fig. 1) is associated with stronger westerly winds in April and May and weaker easterly winds in July and August in the MLS analysis.
Holton and Wehrbein (1980) proposed that the solstice easterly winds of the SAO at the stratopause could be attributed in part to the advection of zonal-mean easterly momentum across the equator by the Brewer–Dobson circulation. The upper branch of this circulation flows from the summer to winter hemisphere and is strong in the upper stratosphere, giving two periods of easterly acceleration, as easterly zonal-mean zonal winds are advected from the summer to the winter hemisphere during the Northern and Southern Hemisphere summers. The easterlies could also have contributions from momentum transfer by planetary waves in the winter hemisphere (Hopkins 1975). The presence of westerly winds during equinox periods indicates wave driving of the zonal wind; angular momentum conservation dictates that these winds cannot be caused by advection by the mean meridional circulation. The westerly winds appear to propagate downward from 0.1 to about 3 hPa.

The SAO dominates the seasonal variability of equatorial winds from the upper stratosphere to the upper mesosphere. Above the stratopause, the SAO signal is defined by equinocial maxima of westerly winds peaking near 0.1 hPa and easterly winds peaking near 0.01 hPa. Dunkerton (1982) proposed that the SAO winds near the stratopause would selectively filter eastward or westward gravity waves that would then drive an SAO of opposite phase when they dissipated in the upper mesosphere.

Figure 5 shows latitude–month cross sections of the winds at 0.9–1.0, 0.15, and 0.014 hPa, which correspond to the easterly and westerly SAO peaks in the lower mesosphere in Fig. 4 and the easterly peak in the upper mesosphere (SABER only). The wind cross sections from MLS and SABER at 0.9–1.0 hPa are very similar to each other. The wind pattern is qualitatively consistent with the generation of the SAO easterly phase by advection; easterly winds in the summer hemisphere extend into the tropics. On the other hand, westerly winds are evident during the equinox season, which suggests wave forcing at that time. The pattern at 0.15 hPa (middle row; the level of the westerly wind SAO maxima) is similar in structure to that at the stratopause (bottom row). However, note that the equatorial time-mean wind at this level is westerly. The downward propagation of the westerly maxima seen in Fig. 4 is consistent with a feature driven by waves interacting with the mean zonal wind. The MLS–SABER difference during June–August noted in the discussion of Fig. 4 can also be seen in Fig. 5.

The SAO easterly wind peaks at 0.014 hPa in Fig. 5 are qualitatively somewhat different from those below. They show a connection to easterly features at higher latitudes of either hemisphere, in common with the appearance at lower levels. However, they also show maxima confined to low latitudes. Easterly winds appear near the equator in March and April, disappear during the solstice months, and then weaker easterly winds reappear in September and October. Dunkerton (1982) proposed that critical-level filtering of gravity waves by the winds in the stratopause SAO would affect the waves reaching the upper mesosphere. When these gravity waves dissipate, they would drive an SAO that was out of phase with that below. The wind results shown in Figs. 4 and 5 are somewhat consistent with this explanation. However, instead of seeing alternating easterly and westerly wind maxima at the stratopause (~1.0 hPa), as assumed by Dunkerton (1982), the westerly wind maxima occur at a higher altitude.

4. Variability of the SAO and its relationship to the QBO

Figures 6 and 7 show time series of the equatorial wind for the entire period derived from SABER and MLS, respectively. It is evident that there is substantial variability in the magnitudes of the wind extremes and the altitudes and months at which the minima and maxima occur. For most cycles, the MLS and SABER winds show similar behavior in the magnitude, timing, and pressure of the wind features. The agreement between these analyses gives greater confidence in the ability to characterize year-to-year variability in the winds.

There are a number of periods during which there is an apparent connection (downward descent) between the easterly wind maximum around 0.01 hPa during
equinox and the easterly wind maximum at 1 hPa at the following solstice. For example, see September–December 2003, March–June 2006, and a series of cycles beginning September 2012. For other periods, there is no evidence of a connection between the features at these two altitudes. Without further investigation into the processes driving the wind oscillation, it is not possible to determine whether this apparent spatial–temporal connection represents actual downward propagation.

Moss et al. (2016) found that the SAO winds at and above 81.5 km during March and April 2002 were much stronger than in the other years they observed. Figure 6 shows that the unusually strong winds are also seen in the winds derived from SABER around 0.01–0.004 hPa. The altitude of the easterly wind maximum is higher than average but not outside the range seen in other years. However, the combination of higher location of the easterly peak and strong maximum wind in the altitude range that can be observed by meteor radar sets this month apart. Winds at other levels during this period do not show any marked differences that would indicate that this perturbation is a response to unusual winds in the middle atmosphere below.

Previous observational studies (Burrage et al. 1996; Venkateswara Rao et al. 2012; de Wit et al. 2013) have
noted that the magnitude of the SAO in the upper mesosphere has a strong variation in phase with the QBO in the stratosphere, although there has been some debate about whether this modulation occurs only around the vernal equinox or throughout the year. The link between the phase of the QBO and the interannual variations in the satellite wind estimates in the upper stratosphere and mesosphere can be summarized by comparing the climatological winds for months with easterly and westerly phases of the QBO, as shown in Fig. 8. The phase of the QBO is identified by the Singapore wind at 10 hPa and is evaluated for each month independently. As a result, the data in sequential months are not necessarily from the same sets of years.

The bottom panel of Fig. 8 indicates where the differences are significant at the 95% level according to the Student’s t test. Note that the significance is determined independently for each calendar month and pressure level. Overall, the differences in magnitude are more likely to be significant during the periods after equinox (May–June and October–November), which are periods of rapid change. The displacement in altitude of the westerly equinox maxima (near 0.1 hPa during years when the QBO is westerly and near 0.2 hPa during years when the QBO is easterly) is a prominent feature of the difference plot. Using analysis from 4 years of wind observations, Ray et al. (1998) noted several interannual variations in the stratopause SAO that followed the phase of the QBO: weaker SAO westerlies and stronger SAO easterlies during the westerly QBO phase and deeper descent of SAO westerly winds during the easterly QBO phase. The current results (see also Figs. 6 and 7) confirm these differences.

The stronger westerly winds near 0.1 hPa during the easterly QBO suggest stronger wave driving by gravity waves and/or Kelvin waves. The westerly peaks are also more clearly centered on the equinox periods during easterly QBO. Similar results are obtained with the MLS dataset (not shown).
Figure 8 indicates that there is a relationship between the SAO and QBO but does not indicate causality. It is most easily understood how the QBO could affect the SAO through filtering of the waves that then dissipate and drive mean winds (Ray et al. 1998; Garcia and Sassi 1999; Peña-Ortiz et al. 2010). However, examination of the month-by-month equatorial winds derived here does not lead to a straightforward explanation. For any given month, the QBO winds between the levels of 70 and 3 hPa include both easterly and westerly winds that cover similar ranges of values (roughly peak easterly winds from $-20$ to $-30$ m s$^{-1}$ and peak westerly winds from 10 to 15 m s$^{-1}$). We were not able to identify a clear QBO dependence of the predicted critical-level filtering based on the peak winds encountered in a vertical column in the lower to middle stratosphere. It may be, as suggested by wave calculations by Ray et al. (1998) and simulations by Peña-Ortiz et al. (2010), that the key differences in wave forcing occur away from the equator.

It is also possible that the causality is in the opposite direction; that is, the SAO, especially at its lower reaches in the upper stratosphere, has an impact on the QBO. For example, the stronger easterly winds near the stratopause in the westerly phase of the QBO can contribute to seeding the wind shear in the upper stratosphere that is associated with the shift from the westerly to the easterly phase of the QBO. This mechanism is also not straightforward because of the time delay of several months needed for the QBO to propagate downward from the lower limit of the SAO to the 10-hPa level. The slow downward propagation of the QBO would imply a lag in the signal between the upper stratosphere SAO and the 10-hPa QBO, but no lag was used in assigning the winds in Fig. 8 to easterly or westerly QBO phases.

5. Conclusions

This study shows the climatology and interannual variability of the SAO in the middle-atmosphere zonal
The winds are derived from almost 15 yr of geopotential height data from TIMED/SABER and more than 12 yr of data from Aura/MLS. This analysis fills in the current gap in continuous equatorial wind measurements between 10 and 0.01 hPa; equatorial winds calculated in current reanalysis products (e.g., Rienecker et al. 2011; Coy et al. 2016) cover only part of this range. Comparisons of the zonally averaged winds with observed radiosonde winds at Singapore (1°N, 90–10 hPa) and with meteor radar winds at Ascension Island (8°S, 81.5–84 km) indicate that winds derived from both satellite datasets capture the mean and the seasonal and interannual variability.

The primary contributions that these satellite wind analyses can make to the investigation of the SAO are 1) long data records with no gaps in coverage and 2) continuous vertical coverage through the depth of the middle atmosphere. The vertical range covers the transition from QBO dominance in the lower to middle stratosphere to SAO dominance in the upper stratosphere and the transition from the stratopause SAO to the mesopause SAO. As discussed in section 2, a primary concern is possible contamination of the SABER time-mean zonal-mean fields by the migrating diurnal tide near the mesopause. Although not considered in the present study, both SABER and MLS can also give information about waves that have large-enough horizontal and vertical scales to be resolved in the observations; these include fast Kelvin waves, a subset of gravity waves and, for SABER, tides with diurnal periods.

Another aspect of the SAO that can be seen in these wind derivations is its latitudinal structure. Through most of the mesosphere, the latitude structure of the SAO does not show maxima at the equator but rather indicates that the tropical winds during both easterly and westerly phases are part of a large-scale structure with downward descent in time.

Earlier investigations (Burrage et al. 1996; de Wit et al. 2013) found that there is a large variation of the SAO in the upper mesosphere with the phase of the QBO in stratospheric winds. Note that the satellite analyses of Burrage et al. (1996), which used daytime-only data, may have some contamination from the large semiannual and QBO variations in the amplitude of the migrating diurnal tide. The results presented here greatly expand the information available by showing the SAO over a broad vertical range using two long continuous data records that have day and night observations. These show convincingly that the equatorial mesospheric winds at all times of year vary depending on the QBO phase.

Although an observed relationship between the QBO and the SAO has been seen previously, the explanation is still incomplete. Peña-Ortiz et al. (2010) showed that a comprehensive whole-atmosphere model with an interactively generated QBO could reproduce a link between the QBO and the mesospheric SAO. They found that forcing by both small-scale (parameterized) gravity waves and resolved waves contributed to the variability. The extent to which the SAO varied with the phase of the QBO was larger in their model simulations than in the current observational analysis.

There are several mechanisms by which the QBO could alter the SAO forcing in the mesosphere. Possibilities are 1) the QBO winds selectively filter and absorb upward-propagating large-scale equatorial waves, such as Kelvin waves (Garcia and Sassi 1999); 2) the QBO filters small-scale gravity waves in the tropical region; or 3) the QBO winds affect midlatitude dynamics in the winter hemisphere that then affect the driving of the SAO winds by large-scale advection. These mechanisms are not independent because of the
interaction of wave propagation and dissipation with the background wind. Although details and mechanisms involved in the interaction between the QBO and SAO are still not resolved, the middle-atmosphere winds derived here provide a powerful new set of observations that can be used for guiding further investigation.

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NASA supports the TIMED and Aura satellites and their instruments; retrieved profile data are freely available. Version 2.0 profile data from TIMED/SABER are available from the SABER website (http://saber.gats-inc.com). Version 4.2 geopotential height profile data from MLS are available from GES DISC (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/MLS/index.shtml).

Monthly averaged radiosonde zonal wind data measured at Singapore have been compiled by the Freie Universität Berlin and are available online (http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/).

Data for the monthly mean zonal wind estimates presented in this paper can be obtained from the lead author.

REFERENCES


