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**QBO and annual
variations in ozone
from SHADOZ and
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Interactive Discussion

The Quasi-biennial Oscillation and annual variations in tropical ozone from SHADOZ and HALOE

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QBO and annual variations in ozone from SHADOZ and HALOE

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Abstract

We examine the tropical ozone mixing ratio perturbation fields generated from a monthly ozone climatology using 1998 to 2006 ozonesonde data from the Southern Hemisphere Additional Ozonesondes (SHADOZ) network and the 13 year satellite record from 1993 to 2005 obtained from the Halogen Occultation Experiment (HALOE). The lengthy time series and high vertical resolution of the ozone and temperature profiles from the SHADOZ sondes coupled with good tropical coverage north and south of the equator gives a detailed picture of the ozone structure in the lowermost stratosphere down through the tropopause where the picture obtained from HALOE measurements is blurred by coarse vertical resolution. Ozone perturbations respond to annual variations in the Brewer-Dobson Circulation (BDC) in the region just above the cold-point tropopause to around 20 km. Strong annual signals of alternating positive and negative ozone anomalies are observed and correlate well with temperature anomalies. Above 20 km, ozone and temperature perturbations are dominated by the Quasi-biennial Oscillation (QBO). Both satellite and sonde records show good agreement between positive and negative ozone mixing ratio anomalies and alternating QBO easterly and westerly wind shears from the Singapore rawinsondes with a mean periodicity of 26 months for SHADOZ and 25 months for HALOE. There is a temporal offset of one to three months with the ozone QBO preceding the wind shear. Horizontal length scales for the annual cycle and the QBO, obtained using the temperature anomalies and wind shears in the thermal wind equation, compare well with theoretical calculations.

1 Introduction

One of the principal sources of interannual variability of the ozone distribution in the tropical mid-stratosphere is the quasi-biennial oscillation of the zonal wind (QBO). The QBO is characterized by downward propagation of alternating westerly and easterly

wind regimes with a period varying from 20 months to 30 months (Reed et al., 1961). The QBO arises from the interaction of vertically propagating equatorial waves acting on the zonal mean flow (e.g., Baldwin et al., 2001 and references therein). The effect of the QBO can be seen on trace gases and temperature, both of which vary with the phase of the wind shear.

The tropical stratospheric circulation is also influenced by the Brewer-Dobson Circulation (BDC). The BDC is characterized by rising motion in the tropics from the troposphere into the stratosphere with poleward transport and descending motion in the stratosphere at middle and polar latitudes (Brewer, 1949; Dobson, 1956). The BDC varies annually and is stronger during northern hemisphere winter.

We use the SHADOZ temperature profiles to develop a high vertical resolution tropical temperature perturbation time series. The mean temperature increases with height from the tropopause up to the stratopause in response to radiative heating from ozone UV absorption. It follows that changes in the mean temperature field induced by the strong QBO and the BDC signals affect the radiative heating rates, which in turn determine the strength of the residual circulation. Using in-situ temperature data we can establish observed meridional length scales of the QBO and BDC that have been previously calculated by theoretical models.

Previous work by Logan et al. (2003) used individual tropical ozone data from the SHADOZ network to map the changes in the shape of the ozone profiles induced by the QBO winds. Using almost four years of SHADOZ sounding data (late 1997 to early 2001) from three southern hemisphere stations, they showed a coherent relationship between the zonal winds and observed tropical ozone. Logan et al. (2003) expanded their study to examine the sub-tropical morphology of the QBO signal outside 20° of the equator and the strong El Nino Southern Oscillation (ENSO) event in 1997–1998. At the time of the Logan et al. (2003) study, only four years of ozonesonde data had been archived from the southern equatorial region and the goal was to study two complete QBO cycles where one cycle could be effected by the ENSO signal. The present study considers all SHADOZ stations within 10 degrees north and south of the equator. At

present, there are nine years of ozonesonde data allowing us to capture roughly four complete QBOs and nine annual cycles. In addition, we analyze stratospheric ozone profiles from 1993–2005 obtained from the Halogen Occultation Experiment (HALOE), one of the sensors on the Upper Atmosphere Research Satellite (Reber et al., 1993).

In this study, the data are described in the following section. The analysis given in Sect. 3 includes three components: the morphology of the ozone and temperature anomalies in the QBO regime (3.1); the annual variations of ozone and temperature (3.2); and estimates of the length scales of the annual cycle and the QBO using the power spectrum of temperature and wind shear (3.3). A summary follows in Sect. 4.

2 Data

All SHADOZ stations use balloon-borne Electrochemical Concentration Cell (ECC) ozonesondes (Komhyr, 1995), except Watukosek-Java which had used Meisei RSII-KC79D soundings prior to August 1999 (Kobayashi et al., 1966). The ozonesonde instrument is coupled with a radiosonde that measures pressure, temperature and relative humidity at 1 to 10 s intervals. The ECC ozonesonde measures ozone up to 33 km with 5% instrument precision and vertical resolution between 5 and 50 m, allowing us to resolve features in tropical ozone variability related to climate and dynamics. Detailed precision and performance assessments are given by Johnson et al. (2002) and Smit et al. (2007) and references therein.

The ozone and temperature perturbation fields have been generated from nine years of SHADOZ data (1998 to 2006) confined to stations located within a 10° N–10° S latitude range. The ozone QBO signal is narrowly confined to the same equatorial region (e.g. Baldwin et al., 2001; Dunkerton, 2001); the results of the analyses do not change when we further limit the dataset to within five degrees of the equator. Table 1 lists the nine tropical sites from the SHADOZ record used in this study where over 2000 profiles were used. Thompson et al. (2003, 2007) provides documentation of each station's instrumentation and launch procedures.

Ozone profiles from the Halogen Occultation Experiment (HALOE) complement the SHADOZ ozone record. This study analyzes 13 years of the HALOE ozone record from 1993–2005 (Russell et al., 1993; Brühl et al., 1996) using zonal monthly means at the equator that have been constructed by Schoeberl et al. (2008) at a vertical resolution close to 2 km. HALOE is a solar occultation instrument viewing, on average, 15 sunrises and sunsets daily over a narrow latitudinal range. Global sampling requires approximately 30 days.

Time series of the monthly mean ozone and temperature perturbations are produced by subtracting monthly averaged profiles from the monthly average for all nine years of data. The ozonesonde profiles have been averaged and interpolated to a uniform 0.25 km vertical grid. Gaps in the HALOE record have been linearly interpolated using adjacent values. The perturbation fields from SHADOZ have no gaps in time and altitude, and thus no additional interpolation is required.

In the analysis section below, the ozone and temperature perturbation fields are compared with the monthly zonal mean wind shear calculated from the Singapore raw-insonde wind fields (Naujokat, 1986). Wind observations from 50 hPa (19 km) to 15 hPa (30 km) are used.

3 Analysis

3.1 QBO morphology of ozone and temperature

Figure 1 shows a time-height section of monthly mean perturbation ozone mixing ratio for HALOE (top panel) and SHADOZ (bottom panel). Superimposed is the zonal mean wind shear component of the Singapore winds. The satellite/sonde reference profiles of ozone are shown in Fig. 2 and represent the mean of all profiles within the SHADOZ time period. Above 22 km the ozone reference profiles are in close agreement when the sonde vertical resolution is degraded to 2 km (solid red circle) to match HALOE. Otherwise, HALOE apparently underestimates the sondes at the higher vertical resolution

(black solid circle) by as much as 1 ppmv. HALOE and SHADOZ ozone time series at various altitudes from 1998–2005 are in qualitative agreement (Fig. 3). At the heights of interest, the two records track each other despite the differing measurement resolutions and interpolation in the HALOE record for missing months (see gaps in vertical
5   bar symbols in Fig.1).

Both records in Fig. 1 show the effect of a strong QBO signal on the ozone field above 20 km as descending positive and negative ozone anomalies exhibit similar patterns as the wind shear (white contours). The ozone perturbation maximizes around 25–27 km with gradual attenuation of the signal as it descends to 20 km and transitions to a
10   strong annually varying cycle. The ozone anomalies range ±1.4 ppmv in the vicinity of the maximum perturbations. In the vertical, the locations of the maximum zonal wind shear tend to be co-located with the highest ozone concentrations. However, the maxima are not contemporaneous. Linear correlation coefficients of ozone anomalies and wind shear were computed at heights within the dominant QBO regime (within
15   20 km to 30 km) for a range of time lags from −5 to +5 months. The best fits are summarized in Table 2, where a positive lag indicates that the ozone precedes the winds. These correlations reveal that the ozone QBO anomaly precedes the zonal wind shear by one to three months. Using Fig. 1 as a visual guide, we can interpret the temporal variability in ozone concentrations as increasing (decreasing) after the
20   passage of the maximum easterly (westerly) shear. The exception is at 27.5 km, where Table 2 shows the lag switching sign with the wind shear preceding the HALOE ozone by one month. There is a slight tendency for the QBO wind shear and ozone to be synchronized with height as the lags decrease with increasing height (Table 2) and the timing of descent of the shear zone coincides with the largest ozone anomalies (Fig. 1).
25   At this level and above, the ozone concentrations reach peak values and respond more rapidly to shifts in the wind field (see Fig. 2).

A strong ENSO event peaked in the latter half of 1997 and continued through early 1998. Logan et al. (2003) attributed the influence of the ENSO to an apparent anti-correlation between the QBO wind shear and ozone anomalies from the Nairobi

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ozonesondes and SAGE II data below 40 hPa (∼22 km). The ozone anomalies from our tropical climatology below 22 km do not show this relationship in 1998 or any other year. The zonal averaging of the SHADOZ data apparently diminishes any ENSO signal that is known to be very weak compared to the QBO and annual cycles (Hamilton et al., 2003). HALOE does not retrieve data at a high enough vertical resolution to isolate such an effect. In addition, there is a time lag between both ozone datasets and the QBO winds that might explain the anti-correlation as merely a temporal shift between the wind shear zones and the localized ozone anomalies. The ENSO signal is not considered further in this study.

The time evolution of the SHADOZ temperature perturbation field is shown in Fig. 4 with contours of wind shear superimposed. The structure of the temperature perturbation time series closely resembles that of the ozone anomalies seen in Fig. 1, and the temperature and wind shear are closely synchronized as expected from the thermal wind balance relationship (see Andrews et al., 1987, Eq. 8.2.2; Randel et al., 1999; Baldwin et al., 2001). In the QBO region between 20 km and 30 km, the zones of westerly (easterly) wind shear correspond to regions of warmer (colder) temperature anomalies. The maximum anomaly in the temperature signal is between 25 km and 27 km, similar to the location of the maximum ozone anomaly. The amplitude of the temperature anomaly is ±6 K. The exception is in the latter half of 2005 into 2006 where the maximum amplitudes of the zonal wind shear and temperature anomaly above 25 km are not well-aligned. We attempted to resolve this offset by removing the linear trend in the temperature anomaly but the result showed only a marginal improvement in the agreement with the QBO wind shear. However, correlation estimates summarized in Table 3 show no apparent lag above 25 km. Below 25 km the temperature phase change precedes the QBO wind shear phase change by two months.

3.2 Annual cycles in ozone and temperature

At 20 km and below the SHADOZ record captures well-defined annual variations in ozone (Fig. 1, bottom panel) and temperature (Fig. 4) related to the annual variations

in the BDC. The ozonesondes resolve fine structures in the ozone profiles that are not resolved by HALOE. When we degrade the vertical resolution of the SHADOZ profiles to 2 km, and recalculate the ozone anomaly time series, the resulting morphology below 20 km is similar to that of HALOE (not shown). Here, the advantage of using ozonesonde data is that we can resolve vertical structures that cannot be seen by remote sensing techniques.

Between 15 km and 20 km the ozone anomaly concentrations range from −0.17 ppmv to +0.66 ppmv in the SHADOZ record, with slightly smaller amplitudes from HALOE. The annual signal in the temperature anomaly field is slightly stronger than the QBO signal with amplitudes ranging ±8 K. The cold-point tropopause heights (Fig. 4, filled circles) typically occur within 16 km and 17.5 km and undulate along the base of the annual signal at levels where the gradients of the temperature anomalies start to amplify. Below the tropopause, located on average at around 16 km, the annual amplitudes of the ozone and temperature perturbations weaken rapidly. Using the SHADOZ sondes Randel et al. (2008) pointed out that annual variations in tropopause ozone are more likely to be caused by the annual variations in the BDC acting on the time mean ozone gradient rather than annual variations in convective lofting (Folkins et al., 2006). Figures 1 and 4 support the BDC forcing idea since convective lofting would not produce larger anomalies at 16 km than below.

In the transition region from 16 km to 20 km, Figs. 1 and 4 show the interaction between the annual variations in the BDC and the QBO acting on the ozone and temperature concentrations. The BDC upwelling is stronger during the Northern Hemisphere winter due to stratospheric wave driving (Haynes et al., 1991; Waugh, 1993; Randel et al., 1993; Schoeberl et al., 2008). In the case where the QBO and the BDC are in phase, the QBO signal appears to descend to the tropopause, as positive ozone anomalies of both systems merge, as previously noted by Gray and Dunkerton (1990). When the QBO easterly wind regime (Figs. 1 and 4, negative dashed contours) descends, negative ozone anomalies (blue contours) are met by the BDC positive ozone anomalies splitting the QBO feature. Interestingly, during the SHADOZ time period we

observe an unusually large cell of positive ozone and temperature anomalies in the region of the annual cycle that extends from 1999 into 2000 in Figs. 1 and 4. Figure 5 reveals a broad region of persistent QBO westerly winds modifying the annual cycle by sustaining warmer temperatures, allowing the ozone anomaly to grow and be maintained over the two year period.

3.3 Ozone periodicity, and length scales

The SHADOZ and HALOE ozone power spectrum in Figs. 6a and 6b, respectively, reveal a broad maximum range of amplitude in the QBO signal which peaks between 25 km and 27 km with a periodicity centered around 26 months for SHADOZ and 25 months for HALOE. There is a secondary QBO peak above 33 km measured in both records; however, there is less certainty about the ozone measurement accuracy at those levels. The modest ozone annual cycle at twelve months is also seen with a small peak extending from 17 km to 21 km in the SHADOZ record. The peak above the annual signal in the HALOE record may be an extension of the QBO signal. Also evident is the semi-annual oscillation above 30 km. A similar frequency distribution in the temperature spectrum is shown in Fig. 6c where the annual cycle is particularly prominent compared to the QBO signal which is similarly broad but weaker in amplitude.

From Fig. 4 we observe a coherent relationship between the temperature anomalies and the zonal mean wind shear. Quantitatively, this close relationship can be represented by the thermal wind equation where we assume latitudinal symmetry about the equator. Using notation from Baldwin et al. (2001), the thermal wind equation in the tropics can expressed as $\frac{\partial \bar{u}}{\partial z} = \frac{R\bar{T}}{H\beta L^2}$ where $\partial \bar{u}/\partial z$ is the zonal mean wind shear (m/s/km), R is the dry air gas constant, $\bar{T}$ is the zonal mean temperature anomaly, L is the length scale, H is the scale height ($\sim$7 km), and β is the latitudinal derivative of the Coriolis parameter at the equator. The zonal mean wind shear and temperature are used to estimate the length scales based on the QBO and BDC cycles. Figure 7

shows the profiles of the QBO and BDC length scales, respectively. Where the QBO temperature anomaly is largest (~27 km), our analysis shows that the QBO width is between 1000 km and 1200 km, as also found by Randel et al. (1999). The BDC length scales derived here vary from 1150 km at 21 km to near 1000 km at 29 km. Plumb and
5 Eluszkiewicz (1999) modeled upwelling length scales of the BDC about the equator and estimate a theoretical length scale of roughly 1100 km between 15 km and 25 km, similar to the range we derive from observations.

4   Summary

Our study takes advantage of the long-term ozone and temperature record from the
10 SHADOZ ozonesonde network and ozone retrievals from HALOE along the tropical band to construct a time series of ozone and temperature anomalies. With the high vertical resolution in-situ sounding data in the tropics we developed a detailed picture of the ozone vertical anomalies near the equator at resolutions greater than satellite retrievals. The SHADOZ observations show that below 35 km most of the variability
15 in tropical ozone and temperature are due to the QBO-induced circulation that sits atop the annual variations in the BDC. Below 20 km to the tropopause, variations in ozone and temperature are controlled by the annual signature in the BDC. Use of an ozonesonde dataset improves the agreement between the ozone anomalies and the zonal wind shear compared with what can be obtained using HALOE profiles, and the
20 structure of the annual variations in ozone and temperature below 20 km are more refined. The annual signals in the ozone fields maximize at the tropopause implying that convection alone cannot produce the large annual tropopause anomalies in ozone, as noted by Randel et al. (2008). Rather we observe that the ozone and temperature anomalies are controlled primarily by the wave mean-flow interactions of the BDC an-
25 nual cycles.

Correlations between the ozone and temperature tracer fields with the QBO winds show close agreement with maximum amplitudes between 25 km and 27 km. The

temporal offset is one to three months with the QBO ozone and temperature changing sign after the passage of the shear zones. The periodicity is similar to other studies at 25 to 26 months. The periodic irregularity indicates that the QBO behavior is primarily driven by internal wave dynamics rather than other periodic oscillations, such as seasonal or solar cycles. The interaction between the QBO and annually varying BDC signals is evident in the transition zone between the tropopause and the lowermost stratosphere (16 km–20 km). When the QBO and Brewer-Dobson anomalies are in phase the positive ozone anomaly extends past the tropopause (∼16 km). Conversely, when out-of-phase it is the QBO-induced negative ozone anomalies associated with the easterly regime that extends to the tropopause.

The meridional width of the QBO component is in good agreement with results by Randel et al. (1999). The QBO length scale increases with height and is approximately 1200 km about the equator in the mid-stratosphere. For the first time, we can also assess the latitudinal extent of the annual BDC cycle based on observations from ozonesondes across the tropics by isolating the observed temperature and wind fields at 12 months. The results show a mean length scale close to 1000 km, consistent with earlier estimates by Plumb and Eluszkiewicz (1999).

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Table 1. SHADOZ ozonesonde sites used in the study.

Tropical Sites	Lon (deg)	Lat (deg)	Study Years
Ascension Island	−14.4	−8.0	1999–2006
Heredia, Costa Rica	−84.1	10.0	2005–2006
Kuala Lumpur, Malaysia	101.7	2.73	1998–2006
Malindi, Kenya	40.2	−3.0	1999–2006
Nairobi, Kenya	36.8	−1.3	1998–2006
Natal, Brazil	−35.4	−5.4	1999–2006
Paramaribo, Surinam	−55.2	5.8	1999–2006
San Cristóbal, Equador	−89.6	−0.9	1998–2006
Watukosek-Java, Indonesia	112.7	−7.6	1998–2006

Table 2. Correlation coefficients (r^2) and lag offset in months between the zonal mean wind shear and the SHADOZ and HALOE ozone perturbations.

Altitude	r^2		Lag (Months)	
	SHADOZ	HALOE	SHADOZ	HALOE
22.5 km	0.67	0.70	+3	+2
24.5 km	0.81	0.84	+3	+1
27.5 km	0.79	0.73	+1	−1

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Table 3. Same as Table 2 except wind shear is correlated with the SHADOZ temperature perturbations.

Altitude	r^2	Lag (Months)
22.5 km	0.57	+2
25.5 km	0.70	+2
27.5 km	0.73	0

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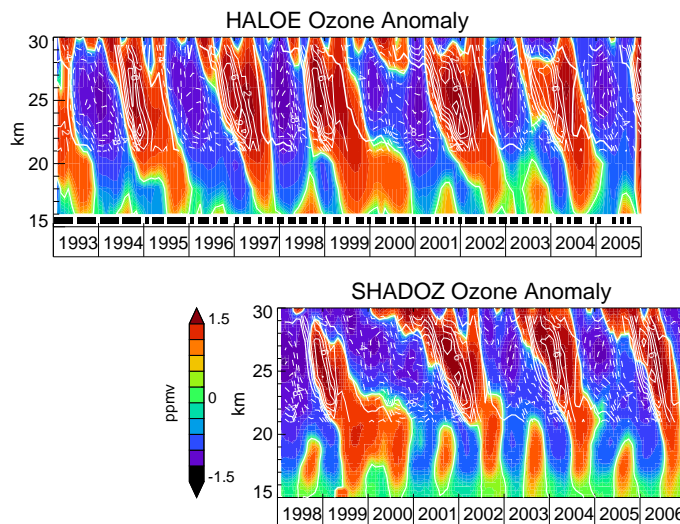
Fig. 1. Time series curtain plot of ozone mixing ratio anomalies (ppmv) using HALOE (top panel) and SHADOZ (bottom panel) data records. Bold white contour indicates the zero level between positive anomalies (red) and negative anomalies (blue). Overlaid are white lined contours of the QBO wind shear (m/s/km). Solid lines indicate positive (westerly) wind regime and dashed lines indicate negative (easterly) wind regime. The zero contour of the wind shear data is plotted as the extra-thick white line. Vertical black bars in the top panel for HALOE indicate where data is available.

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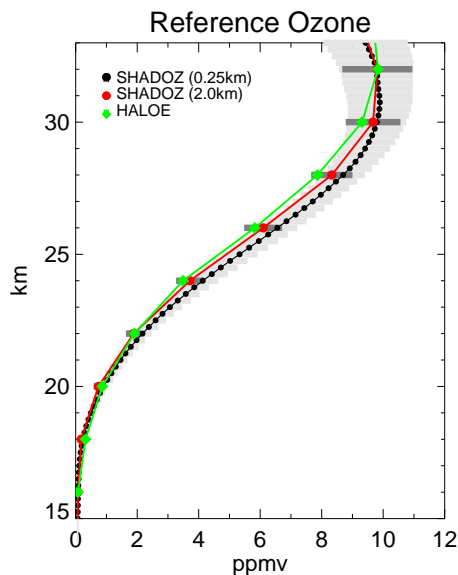
Fig. 2. SHADOZ and HALOE reference profiles of ozone mixing ratio (ppmv). SHADOZ profiles are plotted at vertical resolutions of 2.0 km (solid red circle) to match HALOE (solid green diamond) and 0.25 km (solid black circle). The gray shading indicates the 1-sigma from the 2.0 km (dark gray) and 0.25 km (light gray) mean. The HALOE reference profile is calculated from 1998 to 2005 to match the SHADOZ years.
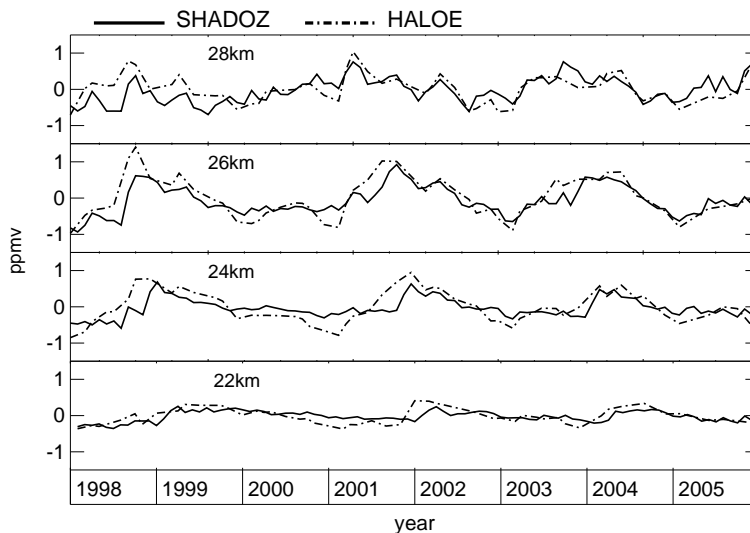
Fig. 3. Monthly time series of ozone mixing ratio (ppmv) for SHADOZ (solid) and HALOE (dashed) at various altitude levels that are limited to the HALOE vertical resolution (2 km).
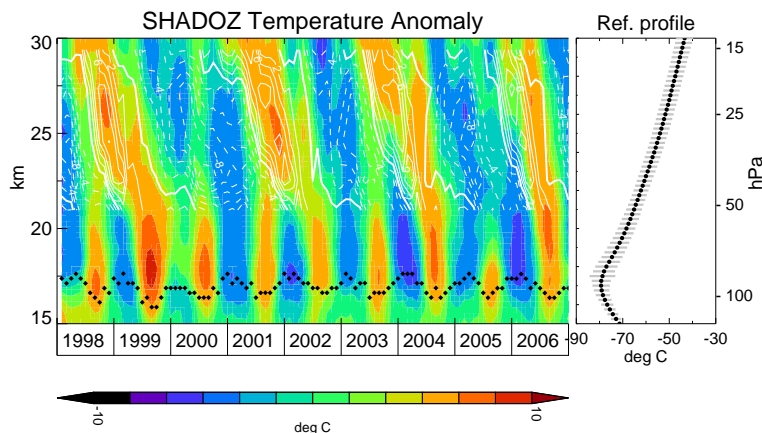
Fig. 4. Monthly time series curtain plot of ozonesonde temperature anomalies (°C) with overlaid lined contours of QBO wind shear (m/s/km) in white, as in Fig. 1. Filled black diamonds are the mean monthly cold point tropopause heights. Right panel is a plot of the reference temperature profile. Gray shading indicates the one sigma deviation from the mean.
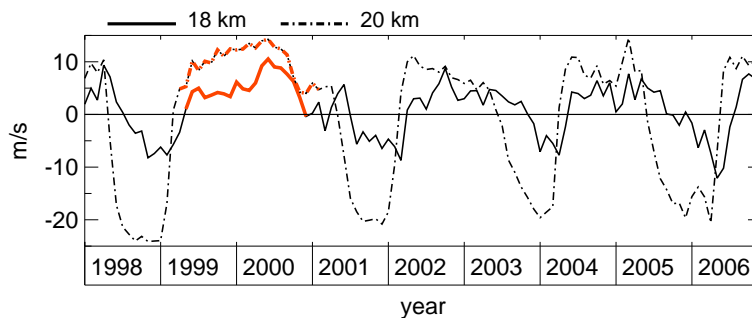
Fig. 5. QBO zonal mean winds (m/s) at 18 km (solid) and 20 km (dashed). Red lines highlight the lengthy time period where positive westerly wind shear sustains positive ozone and temperature anomalies.
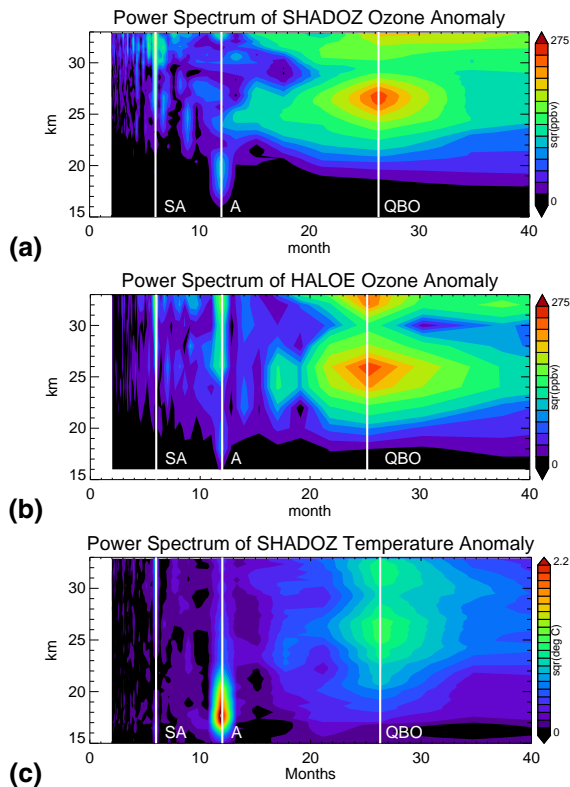
Fig. 6. Power spectrum of **(a)** SHADOZ and **(b)** HALOE tropical ozone mixing ratio anomaly field (ppbv^2) versus period in months, and **(c)** SHADOZ temperature anomaly (C^2). White vertical lines mark the semi-annual, annual, and the QBO periods and are notated by "SA", "A", and "QBO", respectively.
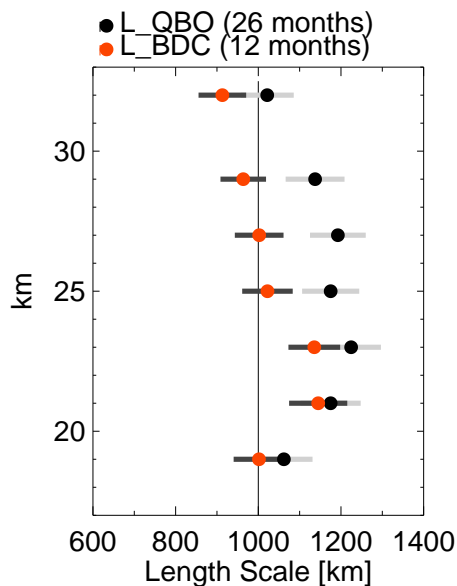
Fig. 7. QBO (black circles) and BDC annual (red squares) length scales at the vertical resolution the QBO winds. The 1000 km length scale is marked. A parametric bootstrap technique estimates the standard deviation of the length scales (gray lines) using a 5% instrument error in the ozonesonde temperature measurements and rawinsondes wind measurements.