Structure and Dynamics of the Quasi-Biennial Oscillation in MERRA-2

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ABSTRACT

The structure, dynamics, and ozone signal of the quasi-biennial oscillation (QBO) produced by the 35-yr NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), are examined based on monthly mean output. Along with the analysis of the QBO in assimilation winds and ozone, the QBO forcings created by assimilated observations, dynamics, parameterized gravity wave drag (GWD), and ozone chemistry parameterization are examined and compared with the original MERRA system. Results show that MERRA-2 produces a realistic QBO in the zonal winds, mean meridional circulation, and ozone over the 1980–2015 time period. In particular, the MERRA-2 zonal winds show improved representation of the QBO 50-hPa westerly phase amplitude at Singapore when compared to MERRA. The use of limb ozone observations creates improved vertical structure and realistic downward propagation of the ozone QBO signal during times when the MLS ozone limb observations are available (from October 2004 to present). The increased equatorial GWD in MERRA-2 has reduced the zonal wind data analysis contribution compared to MERRA so that the QBO mean meridional circulation can be expected to be more physically forced and therefore more physically consistent. This can be important for applications in which MERRA-2 winds are used to drive transport experiments.

1. Introduction

The quasi-biennial oscillation (QBO) is the major source of interannual variability in the equatorial stratosphere, influencing winds, temperatures, and the transport of trace gases and aerosol. The QBO consists of alternating descending westerly and easterly zonal winds in the equatorial stratosphere (~100–1 hPa) along with dynamically consistent temperature anomalies and meridional circulations. Forced by momentum transferred from the troposphere by vertically propagating waves, the approximately 28-month period of the QBO depends on the amplitude, phase speed, and spatial scale of these waves and is not a harmonic of the annual cycle. A detailed characterization of the QBO, including vertical and latitudinal zonal wind and temperature variability, meridional circulations, trace gas effects, and a description of the dynamics, can be found in Baldwin et al. (2001).

Multidecadal reanalyses, based on an unchanging data assimilation system (DAS), provide global gridded analyses that are especially appropriate for QBO studies, as reanalyses lack the possibly disruptive upgrades of archived operational numerical weather prediction systems. Since the observations are not uniformly distributed in the stratosphere, improvements in the model dynamics to better represent the QBO along with improved algorithms for weighting and blending observations should lead to improved equatorial zonal mean winds and temperatures. Another consideration when using reanalyses to study the QBO is that, while the equatorial zonal mean winds and temperatures can be
measured and assimilated directly into data assimilation systems, the smaller-amplitude mean meridional circulations associated with the changing QBO structure result from a complex interaction between the model physics [first investigated by Plumb and Bell (1982)] and the assimilated observations. Thus, these secondary meridional circulations can be difficult to capture accurately.

While not a reanalysis, the Met Office assimilation for the *Upper Atmosphere Research Satellite* (UARS) was one of the first data assimilation systems to obtain a dynamically consistent (complete meteorological winds and temperatures available) QBO (Swinbank and O’Neill 1994). The relatively short (2 yr) data record at the time of publication allowed only for the characterization of the QBO equatorial wind field and not for the more sensitive QBO meridional circulation. Later, Randel et al. (1999) were able to characterize the meridional circulation in a longer record (1992–99) of the Met Office assimilation for UARS, though the vertical component of the circulation was scaled by a factor of 1.4 to account for the underestimate of the QBO temperature signal in the assimilation system. Pawson and Fiorino (1998) examined the QBO in the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses and European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA). They found good agreement with Singapore (1°N, 104°E) radiosonde winds at 30 hPa and below, though westerlies were generally weak; however, both systems disagreed with the radiosonde observations at higher altitudes, especially at 10 hPa. In addition, their QBO meridional circulations were found to be either too weak (NCEP–NCAR reanalyses) or contaminated by noise (ERA). A subsequent study of the NCEP–NCAR reanalyses (Ribera et al. 2004) was able to discern coherent QBO meridional circulations using singular vector decomposition. These QBO meridional circulation cells resembled the expected pattern of downward equatorial motion associated with westerly shear regions (Plumb and Bell 1982) with the circulation cells extending out to mid-latitudes. The cells were found to be slightly weaker in the Southern Hemisphere. Using ERA-40, Pascoe et al. (2005) noted that the QBO winds can sometimes contain three vertical jet regions as the upper winds begin to increase before the lowest jet has vanished. They also reported connections between QBO frequency modulations and the solar cycle.

As air enters the stratosphere through the equatorial tropopause, the QBO-induced meridional circulation modifies the equator-to-pole Brewer–Dobson circulation, producing a QBO variation in ozone and other trace gases not only in the equatorial region (Choi et al. 2002; Logan et al. 2003; Schoeberl et al. 2008) but also out to midlatitudes (Randel and Wu 1996). The QBO influences the distribution of aerosol as well (Hitchman et al. 1994). This QBO-induced meridional circulation and its effects on stratospheric trace gases and aerosol has been included and analyzed in a number of modeling studies (see, e.g., Fleming et al. 2002; Tian et al. 2006; Hurwitz et al. 2013; Oman and Douglass 2014). The QBO ozone signal, in particular, is complicated by photochemistry in the upper regions of the QBO domain (Hasebe 1994; Randel and Wu 1996; Politowicz and Hitchman 1997); however, in the lower equatorial stratosphere the QBO ozone signal is anticorrelated with QBO vertical motion indicative of advection of the mean vertical ozone gradient (Schoeberl et al. 2008). Thus, the ozone QBO signal differs in phase with respect to the QBO zonal wind signature depending on altitude.

Here we examine the QBO in zonal wind, meridional circulation, and ozone using the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), system. The goal is not only to characterize the basic QBO structure in MERRA-2 but also to determine how the zonal momentum and ozone forcing terms interact with the data assimilation process in producing the reanalysis QBO signature. For comparison we also examine the earlier NASA MERRA system. In particular, Politowicz and Hitchman (1997) explored QBO forcing in terms of a two-dimensional model and found differences in the QBO response depending on which model term applied the forcing. Using two reanalyses provides additional insight into how modeling and assimilation development can affect the balance between physical forcing mechanisms and the observations in producing the QBO.

The plan of the paper is as follows: First, section 2 introduces the MERRA-2 system and the methods used to isolate the QBO signal in the reanalysis. Next, in section 3, the QBO circulations are shown, followed in section 4 by the results showing the QBO signal as seen in the zonal momentum and ozone forcing terms. Finally, section 5 has a brief results summary and some conclusions.

### 2. Data and methodology

The new MERRA-2 improves on and augments the original MERRA (Rienecker et al. 2011). The purpose of multidecadal reanalyses is to provide analyzed meteorological fields based on an unchanging analysis system, unlike archived analyses based on operational systems that undergo continual improvements.
Although using a fixed analysis system (both model and data assimilation components) removes the DAS itself as a source of variability in multidecadal output fields, the input observations and instrumentation still change with time and their effects still require consideration when examining reanalysis output (see, e.g., Punge and Giorgetta 2007). The MERRA system is not capable of incorporating the latest satellite instrument platforms, and as older platforms retire MERRA continues to lose input observations, hence the need for an updated system, MERRA-2. Along with the ability to use recent satellite observations, the MERRA-2 model incorporates improvements in the MERRA atmospheric circulation model (Molod et al. 2015). A description of the MERRA-2 system and initial evaluation is presented in Bosilovich et al. (2015a,b).

The most relevant change from MERRA to MERRA-2 for the QBO is the model retuning of the gravity wave drag (GWD) parameterization. The latitude-dependent nonorographic GWD source was increased in the tropics by nearly a factor of 8, producing a realistic QBO in model runs [see Figs. 3 and 4 in Molod et al. (2015)]. With the model-generated QBO now in MERRA-2, the analysis perturbations are expected to be smaller (see below), leading to the potential for more consistent mean meridional circulations and improved stratospheric transport. In MERRA and MERRA-2 the analysis modifications to the first-guess forecasts (analysis increments) are divided by the 6-h data analysis window and ingested over the window time as tendencies to the model wind and temperature fields (Bloom et al. 1996).

Analysis tendencies relevant to the QBO are examined in detail below.

Also important, especially for ozone, is that MERRA-2 assimilates ozone and temperature profiles from the NASA Aura Microwave Limb Sounder (MLS) instrument from August (for temperature, only above 5 hPa) and October (for ozone) 2004 to present (Froidevaux et al. 2006). The limb profile information allows for better-resolved vertical ozone gradients and hence improvements in identifying downward QBO ozone propagation after August 2004 (see below). Prior to October 2004, MERRA-2 assimilated ozone fields are based on measurements from the series of solar backscatter ultraviolet (SBUV) radiometers (Frith et al. 2014). On 1 October 2004, the SBUV data are replaced by retrieved total ozone column from the ozone monitoring instrument (OMI) and stratospheric profiles from the MLS [see Bosilovich et al. (2015a) for more details]. MERRA ozone was based solely on SBUV throughout its analysis time period. Ozone in both MERRA and MERRA-2 is a fully prognostic model variable with tendencies calculated from advection and chemistry, as well as from the data analysis. The ozone chemistry in both MERRA-2 and MERRA is specified as monthly two-dimensional (latitude and pressure) production and loss coefficients.

The MERRA-2 system starts in 1980 after nearly a year of spinup time and is ongoing. For this study the data record from January 1980 through May 2015 (35 years) is used. This gives 15 cycles of the QBO over the 425-month time period with an average QBO period of about 28.3 months. The data analysis was done using standard MERRA-2 and MERRA monthly average fields on a set of 42 constant pressure levels from the surface up to 0.1 hPa (Global Modeling and Assimilation Office 2015b,c,d). There are different horizontal grids that can be considered, even for the same data assimilation system, as the forecast model component and data analysis component can be on different horizontal grids and final assimilated output can be on a different grid as well. The gridded longitude by latitude resolution in the monthly mean output files used here is 0.635° by 0.5° (also the analysis grid resolution) for MERRA-2 and 1.25° by 1.25° for MERRA, though the analysis resolution for MERRA is 0.67° by 0.5°, similar to MERRA-2.

The annual cycle and its harmonics were removed by subtracting the 35-yr average of each month from the dataset. The resulting time series was Fourier analyzed in two ways: first, by keeping only a single harmonic (the 15th, with a 28.3-month period) for a typical QBO cycle with reduced amplitude (single harmonic) and no variability from cycle to cycle for the purpose of examining typical phase relations between variables and second, by keeping a range of periods (the 2nd–32nd harmonics with periods of 13.3–212.5 months) to include the next-higher QBO harmonic (the 30th) and QBO variability longer than a year. Using a single harmonic to characterize the QBO phase relations between variables assumes that, while QBO variability exists between cycles, the basic QBO structure (downward-propagating winds and temperatures and their associated circulations) repeats with each cycle. The higher harmonics include the vertical advection of the zonal wind by the mean circulation, as both terms change sign with QBO phase.

In addition to the Fourier analysis, after the removal of the annual cycle and its harmonics, the root-mean-squared values are multiplied by $\sqrt{2}$ as an estimate of the QBO zonal wind and temperature amplitude (Pawson and Fiorino 1998). A composite QBO cycle was constructed by averaging (after filtering, as above) all the months with zero wind near selected levels (10, 20, 30, and 40 hPa) as in Pawson and Fiorino (1998). The only exception to the use of monthly averaged pressure level fields is in Fig. 1, where the instantaneous assimilation fields on model levels (Global Modeling and Assimilation
Office 2015a) were daily averaged over 0000, 0600, 1200, and 1800 UTC.

The meridional residual mass streamfunction (kg s$^{-1}$) is calculated from the monthly averaged files as follows:

$$
\psi(f, z) = \int_z^{z_T} 2\pi a \cos f \nabla(\phi, \xi) \rho_o(\xi) d\xi
+ \int_0^f 2\pi a^2 \rho(z_T) \cos f \nabla(\phi, z_T) d\phi,
$$

(1)

where $V$ and $W$ are the meridional and vertical velocity components, $\rho_o$ is the basic state density, $a$ is the radius of Earth, $\phi$ is latitude, $z$ is the log-pressure vertical coordinate, $z_T$ corresponds to the top saved pressure level (0.1 hPa), the overbar denotes a zonal average, and prime denotes deviations from the zonal average. The first term in Eq. (1) gives the northward Eulerian mass flux above the level $z$ up to $z_T$ by integrating over the dummy vertical variable $\xi$. The second term, evaluated at $z_T$, gives the small northward Eulerian mass flux between the top saved pressure level and the top of the model (0.01 hPa), allowing for the possibility of a non-zero streamfunction at the top of the pressure level fields. While the Eulerian streamfunction could have been calculated over the entire domain based on the vertical velocity alone, it was more convenient to use the saved, monthly averaged, meridional wind and base only the upper boundary on the vertical velocity. Use of the continuity equation to switch between meridional and vertical winds and then reversing the order of the latitude and vertical integrations allows for consistent streamfunction calculation based on either the meridional or vertical winds. The third term gives the contribution from the wave motions, making $\psi$ in Eq. (1) the residual mass streamfunction, consistent with the definition in Andrews et al. (1987, p. 128). The meridional circulation $\psi$ is calculated from the full, unfiltered fields using Eq. (1) and then filtered for the QBO signal, as described above.

3. QBO structure

This section describes the structure of the QBO as found in the MERRA-2 system and makes comparisons with the MERRA system.

Figure 1 shows a time-versus-pressure cross section of the MERRA-2 and MERRA daily and zonally averaged zonal wind, averaged from 10°S to 10°N and covering the years 1990–2000. The time period and contouring were chosen so that Fig. 1 can be compared with the corresponding published MERRA and ERA-Interim cross sections (Rienecker et al. 2011, their Fig. 22). While the
overall patterns are the same, the MERRA-2 QBO winds are slightly stronger, especially the westerly winds as will be shown more directly in Fig. 2 comparisons. The semiannual oscillation (SAO) is noticeably stronger at 5 hPa and above. As pointed out in Rienecker et al. (2011), the nadir-viewing satellite observations have difficulty resolving the temperature perturbations associated with the strong vertical wind shears of the SAO creating large uncertainty in the SAO winds. One possible explanation for the stronger SAO winds in MERRA-2 is the stronger nonorographic GWD forcing in the tropics (Molod et al. 2015). Further validation is required to assess the accuracy of the stronger SAO wind amplitudes.

Direct comparisons between MERRA-2, MERRA, and the observed, monthly averaged Singapore winds at 1°N, 104°E are presented in Fig. 2. The Singapore winds are compiled by Free University of Berlin and available for the years 1987–2015, so that the formation of the monthly averages (which specific soundings and levels to include) has been done independently. While the Singapore wind soundings are assimilated in both MERRA-2 and MERRA, the relative weighting of the radiosondes, along with analysis mass wind relation settings, can change how closely the analysis fits the observations. At 10 hPa (Fig. 2a) MERRA-2 and MERRA both fit the data well after 1994. During the 1987–94 time period MERRA-2 appears to overemphasize the annual signal. This is especially apparent in 1988. The improved agreement with Singapore winds in MERRA-2 after 1994 can be seen by comparing the mean values and standard deviations calculated for the 1997–2014 time series with the 1995–2016 time series at 10 hPa. For the means, MERRA-2 decreases from 1.98 to 0.35 m s⁻¹, while MERRA decreases (relative to zero) from −1.01 to −0.44 m s⁻¹; for the standard deviations, MERRA-2 decreases from 8.26 to 3.77 m s⁻¹, while MERRA decreases from 4.15 to 3.29 m s⁻¹, so that the numbers are similar between

![Fig. 2. Monthly averaged zonal wind (m s⁻¹) at 1°N, 104°E as a function of time (1987–2014) for MERRA-2 (blue), MERRA (red), and Singapore (black with gray shading) for (a) 10, (b) 30, and (c) 50 hPa. Monthly averaged Singapore winds are products from Free University of Berlin.](image-url)
MERRA-2 and MERRA for the shorter, more recent time period. At 30 hPa (Fig. 2b) both MERRA-2 and MERRA fit the data well over the whole time period, with MERRA-2 having a slightly smaller standard deviation. At 50 hPa (Fig. 2b), the MERRA-2 winds fit the Singapore observations much more closely than MERRA, especially during the westerly phase where the winds are consistently underestimated in MERRA. The mean differences are greatly reduced in MERRA-2 compared to MERRA. The reason for the improved agreement at 50 hPa is not clear from this analysis.

The wind and temperature QBO-estimated amplitudes (√2 times the root-mean-squares) are very similar between MERRA-2 and MERRA (Fig. 3). The main differences are in the temperature amplitudes at 10 hPa, where MERRA-2 is stronger. Comparing with Pawson and Fiorino (1998, their Fig. 12) shows that the more modern MERRA-2 and MERRA system give stronger zonal mean winds than the older NCEP–NCAR reanalyses and ERA. The temperature amplitudes are also larger (~3.5 K at 30 hPa) in the MERRA-2 and MERRA systems than in the older reanalysis systems (~2–3.5 K at 30 hPa). The good agreement seen with the Singapore winds (Fig. 2) suggests that the newer reanalyses (MERRA and MERRA-2) are providing more realistic representation of the QBO wind and temperature amplitudes. The cause of the temperature differences at 10 hPa between MERRA and MERRA-2 is not understood at this time; however, the equatorial MERRA-2 QBO temperature amplitude nearly constant with altitude appears to be more consistent with the nearly constant equatorial QBO wind amplitudes found above ~30 hPa.

Figure 4 shows the time series of monthly mean ozone mixing ratio from MERRA-2, MERRA, and ozonesondes at 30 and 50 hPa at the Nairobi site (1°S, 37°E; for the reanalyses the nearest grid points were used). The ozonesonde data are from the Southern Hemisphere Additional Ozonesondes (SHADOZ; Thompson et al. 2003). Monthly values were computed by straightforward averaging of the available soundings. Only the months with three or more soundings were considered, and data gaps were filled by cubic spline interpolation. The sonde observations were averaged within two layers centered at 50 and 30 hPa. The layers are 8.7 and 5.4 hPa deep, respectively. Even though the monthly sampling is sparse, the clear QBO signal in the Nairobi ozone observations (black dots in Figs. 4a,b) suggests
that averaging three or more soundings each month is adequate to represent the ozone QBO and also implies that day-to-day fluctuations must be relatively small compared to the ozone QBO signal. In addition, a six-point boxcar smoother (results shown as the black curve in Figs. 4a,b) was applied to the sonde (black dots in Figs. 4a,b) and reanalysis time series in order to reduce short-term variability. Differences between the assimilation systems and the ozonesondes shown in Figs. 4c and 4d were then done with respect to the smoothed (black curve) ozonesondes.

A clear QBO signature with seven cycles between 1997 and 2013 is seen in all three datasets at both levels, although the signal is weak at 50 hPa between 2000 and 2004. The amplitude of the oscillation (after smoothing) is \( \sim 1 \) ppmv at 30 hPa and \( \sim 0.4 \) ppmv at 50 hPa and varies from cycle to cycle. The reanalysis-minus-sondes differences are comparable between MERRA and MERRA-2 before 2005, but in the later period MERRA-2 exhibits a much closer agreement with the ozonesonde data. In particular, the QBO-like residual pattern, indicative of a phase shift between the datasets, seen in the MERRA–ozonesonde differences is not evident in the MERRA-2 differences after 2004 (Figs. 4c,d). This is explained as follows. Prior to October 2004 the only ozone data assimilated by both reanalyses are retrieved partial ozone columns from the SBUV radiometers. While MERRA-2 assimilates MLS ozone profiles after that date, MERRA continues to use SBUV. Kramarova et al. (2013) demonstrated that the QBO signal in the SBUV ozone data lacks the expected downward phase propagation compared to MLS (the signal at all altitudes tends to be in phase in SBUV data) owing to large smoothing errors in the vertical inherent in nadir satellite observations. These errors propagate into the analysis because of the high frequency of data insertion (daily), which cannot be compensated by the dynamics, whose time scales for the QBO are on the order of months. The labels in
Figs. 4c and 4d give the mean and standard deviations of the differences between the smoothed curves over the entire time period shown. The standard deviations are reduced for MERRA-2 at both 30 and 50 hPa, while the means are reduced for MERRA-2 at 30 hPa and very small for both systems at 50 hPa.

To explore the phase relationships between the QBO zonal wind and the QBO signals in vertical motion and ozone, we now turn to the filtered data (13–212-month periods). As a baseline reference, Fig. 5a shows the unfiltered equatorial wind (from 10°S to 10°N) for the 35-yr (1980–2015) MERRA-2 record for the 100–1-hPa pressure range. While Fig. 5a repeats some of the time period shown in Fig. 1a, showing the full time series, Fig. 5a, plotted on the same scale as the following filtered figures, is useful in qualitatively evaluating the effects of the time filtering. Figure 5b shows the corresponding filtered zonal wind cross section. Removing the annual harmonics and the mean highlights the QBO and the QBO variability. The vertical extent of the QBO varies from cycle to cycle with some starting from as high as ~2 hPa (1983 and 1987, e.g., looking at the 12 m s⁻¹ contour). Also, the 4 m s⁻¹ contour reaches up to 1 hPa throughout the time period, giving evidence of a QBO signal near the stratopause, though the phase becomes more irregular at that altitude. At the lower end some QBO cycles reach down to ~90 hPa (1993–99, e.g., at the 4 m s⁻¹ contour). The altitude of the wind maximum in each half cycle varies between 10 and 30 hPa. These variations are typical of the variation seen in earlier studies (Baldwin et al. 2001).

The filtered ozone QBO cross section (averaged from 10°S to 10°N) is shown in Fig. 6. The ozone QBO reveals a tendency for two peaks, one near 10 hPa and one near 30 hPa. This agrees with past studies that found two peaks in the ozone signal, depending on the ozone lifetime being long (below ~28 km) or short (above ~28 km; see, e.g., Chipperfield et al. 1994). The ozone QBO signal is somewhat vertical (little descent) for much of the time period; however, after the introduction of the MLS ozone in August 2004 the pattern shows consistent descent. During this time the lower peak shows high ozone in regions of generally downward vertical motion (westerly wind shear) and low ozone in regions of upward vertical motion (easterly wind shear) consistent with vertical advection of the mean ozone vertical gradient by the QBO-generated mean meridional circulation in agreement with the results of Schoeberl et al. (2008). The higher ozone peak (near 10 hPa) is likely dominated by the vertical advection and time scales associated with trace gases, particularly NO₂, that then interact with ozone through photochemistry.

The QBO phase relation between the equatorial zonal winds, the vertical pressure velocity, and ozone is shown in Fig. 7, where only the peak QBO Fourier component amplitude and phase is plotted, creating an identically repeating pattern that is shown for 5 years. In this case the vertical pressure velocity (omega) is calculated from the residual mean streamfunction. Comparison to the Eulerian omega (not shown) reveals that the resolved
waves contribute somewhat to the equatorial vertical motion at levels below 30 hPa. The vertical motion peaks in the zonal wind shear regions, as expected, from about 30 to 3 hPa (Fig. 7a). At lower levels the phase shifts to being in phase with the zonal wind rather than the shear zones, though the magnitudes are relatively small by 100 hPa (less than 1 hPa month$^{-1}$). The resolved waves may be important in determining the phase at these lower altitudes, though understanding these phase relations requires further investigation. The ozone QBO signal (Fig. 7b) clearly shows the two-peaked structure and is phase shifted by about an eighth of a cycle relative to the vertical motion as it responds to the vertical motion.

The composite averages of the QBO bandpass-filtered zonal wind and residual mean circulation are shown in Fig. 8. Comparison of Figs. 8a–d (composited on easterly shear) and Figs. 8e–h (composited on westerly shear) show the symmetry between the two transitions as the wind fields (filled contours) appear oppositely signed but similar in overall structure. The “v” shape to the wind contours shows that the winds change first at the equator and then spread outward. This QBO phase lag with latitude is especially noticeable at levels above 20 hPa. Time series (not shown) at 10 hPa reveal an average delay of ~2 months between the equator and 15°N. The streamfunction (solid and dashed contours) shows maximum vertical motion generally in the shear regions, especially above 30 hPa, with more complex patterns in the lower stratosphere. The streamfunction is more confined to the equatorial region at 10 hPa and above and expands meridionally as it descends. Note that the 40-hPa easterly shear wind and streamfunction pattern (Fig. 8d) is similar to the 10-hPa westerly shear pattern (Fig. 8e) and that the 40-hPa westerly pattern (Fig. 8h) is similar to the 10-hPa easterly pattern (Fig. 8a), indicating that the QBO cycle is repeating in a consistent fashion in this composite analysis.

Figure 9 shows the same QBO meridional circulation as in Fig. 8, with the ozone QBO in place of the zonal winds. As with the zonal wind the easterly (Figs. 9a–d)
and westerly (Figs. 9e–h) ozone show similar structure with reversed signs. While difficult to see the downward propagation of the ozone signal, Fig. 9 highlights the latitudinal structure of the ozone QBO with strong reversed-sign perturbations at \( \pm 20^\circ \) latitude, especially noticeable in the 10-hPa composites (Figs. 9a,e).

4. Analysis forcings

This section examines the zonal wind forcing terms and the ozone forcing terms in both MERRA and MERRA-2. For the zonal momentum equation the main physical terms are the dynamics (mean advection

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**Fig. 8.** Latitude vs pressure composite plots showing MERRA-2 QBO (13–212-month periods) residual mean meridional circulation (black contours; \( \times 10^7 \) kg s\(^{-1}\), contour interval of 4 kg s\(^{-1}\), negative contours dashed) and zonal wind (filled contours; m s\(^{-1}\), contour interval of 4 m s\(^{-1}\)). Composites based on the filtered wind being near zero with easterlies above at (a) 10, (b) 20, (c) 30, and (d) 40 hPa and westerlies above at (e) 10, (f) 20, (g) 30, and (h) 40 hPa. The composite levels are denoted by a heavy black line. The number of months averaged for each composite is given by the upper right number in each panel.

**Fig. 9.** As in Fig. 8, but for ozone (filled contours; \( \times 10^{-6} \) ppmv, contour interval of 0.1 ppmv) in place of the zonal wind.
and resolved wave forcing) and the GWD parameterization tendencies. In addition, the analysis adds the observations as a tendency based on the GEOS-5 incremental analysis update (IAU) procedure (Bloom et al. 1996). In the IAU procedure, the observations (in a 6-h window) along with a short (3 h) forecasted background field are analyzed globally, and the difference between the analysis and the background forecast, when divided by the 6-h data window, becomes tendencies that are added as additional forcing terms to the prognostic wind, temperature, and ozone fields. These tendencies vary in space but are constant during the model integration over the 6-h observation window time period. These analysis tendencies are updated every 6 h with each new analysis. Note that this differs from a “nudging” approach where the prognostic forcing amplitudes change as the model state evolves (Bloom et al. 1996). The use of the GEOS-5 IAU procedure therefore enables direct comparisons of the analysis and model forcing terms since both are expressed as tendencies. The main ozone physical terms are the dynamics and the parameterized chemistry, along with the ozone analysis IAU tendencies. The output plotted is filtered to save only a single frequency (28.3 months) to highlight the basic phase relationships between the zonal mean wind and the tendencies.

Figures 10 and 11 show the zonal mean zonal wind tendencies and their sum, plotted over the zonal mean...
zonal QBO signal, for MERRA-2 and MERRA, respectively. As expected from the increased GWD in MERRA-2, the GWD tendencies are much greater in MERRA-2 (Fig. 10a) than in MERRA (Fig. 11a), with peak values nearly a factor of 3 higher. The analysis tendencies (Figs. 10b and 11b), however, are smaller in MERRA-2 than in MERRA (especially at \( \sim 20 \) hPa), indicating that the DAS short (3 h) analysis background forecast with the increased GWD agrees better with the observations. The dynamics tendencies (Figs. 10c and 11c) are similar in the lower stratosphere; however, MERRA-2 values are much larger than MERRA at \( \sim 10 \) hPa and above. The lower stratosphere (below \( \sim 30 \) hPa) dynamics tendency represents both resolved waves and mean advection and would need more detailed investigation than the monthly averaged fields to separate the two effects. Since mean vertical zonal wind shears are typically small in the lower stratosphere, the main contribution to the dynamics tendency may be from the resolved waves, and the MERRA-2–MERRA agreement then implies that the resolved waves are similar in both systems. The large dynamics tendency in the MERRA-2 upper levels tends to oppose the GWD, so it may be that the GWD is too strong in that region. The sums of the three terms (Figs. 10d and 11d) are similar, consistent with the amplitude of the QBO being similar in both systems; the same overall result is obtained, though the relative amplitude of the forcing tendency terms is different between the two systems.

Figures 12 and 13 show the zonal mean ozone tendencies and their sum, plotted over the zonal mean ozone

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Comparing the ozone QBO (filled contours) shows the two-peaked structure of the ozone QBO and the phase shift in time of one-quarter cycle between the two peaks. The separation between the two peaks is more distinct and the downward propagation of the QBO signal is more apparent in MERRA-2. The more distinct downward propagation results mainly from the later years (2005–15) in the time series when MLS ozone is assimilated. The chemistry ozone tendency (Figs. 12a and 13a) is somewhat greater in MERRA-2 than in MERRA, with little effect below ~20 hPa in both cases. Since the monthly ozone production and loss rates do not have a QBO signal (ozone-parameterized chemistry tends to a monthly balanced production and loss state), the ozone chemistry tendency opposes the QBO ozone perturbation. The analysis tendency (Figs. 12b and 13b) acts to cancel the chemistry ozone tendency at ~10 hPa and above, maintaining the ozone QBO. Unlike the chemistry tendency, the analysis tendency continues, with reduced amplitude, below ~10 hPa. The MERRA tendency was smaller than intended because of a processing error and therefore is smaller than the MERRA-2 values. The ozone tendency due to dynamics (Figs. 12c and 13c) shows a reversal near 10 hPa, where the mean ozone mixing-ratio vertical gradient changes sign.

**Fig. 12.** MERRA-2 QBO-filtered (28.3-month period) ozone tendencies ($10^{-6}$ ppmv month$^{-1}$; red contours positive, blue contours negative), as a function of time and pressure, due to (a) parameterized chemistry, (b) analysis increments, (c) dynamics, and (d) the sum of (a)–(c). The contour intervals ($10^{-6}$ ppmv) are (a) 0.4, (b) 0.4 above 20 hPa and 0.2 below 20 hPa, (c) 0.2, and (d) 0.01. Also plotted is the QBO-filtered ozone (filled contours; $10^{-6}$ ppmv, contour interval of $0.1 \times 10^{-6}$ ppmv).
The level is somewhat higher in MERRA-2 (~8 hPa). The phase of the ozone dynamics tendency peak corresponds to the vertical wind shear and hence the vertical motion regions of the QBO secondary circulation, yielding a tendency based on QBO perturbation vertical motion acting on the mean ozone vertical gradient. The sum of the three terms (Figs. 12d and 13d) is relatively small (note the large change in the contour interval from the earlier figures), indicating a close balance between the three terms, with the lower stratosphere mainly a two-way balance between the dynamics tendency and the chemistry tendency.

5. Summary and conclusions

The NASA MERRA-2 produces a realistic QBO in the zonal winds, mean meridional circulation, and ozone over the 1980–2015 time period. In particular, the MERRA-2 zonal winds show improved representation of the QBO 50-hPa westerly phase amplitude at Singapore when compared to MERRA. Since the MLS temperatures are only assimilated after August 2004 at 5 hPa and above, they cannot be responsible for the improvement at 50 hPa, and therefore the improvement is likely produced by the stronger GWD in MERRA-2. Changes in the analysis system may play a role as well; however, the analysis increments (Fig. 10b) are relatively small in MERRA-2.

The use of limb ozone observations creates improved vertical structure and downward propagation of the ozone QBO signal during times when the MLS ozone limb observations are available (from October 2004 to present). While the ozone forcing is mainly from the chemistry and dynamics terms in the lower stratosphere (Fig. 12), the analysis is playing an important role as seen
by the improvement in the downward-propagating ozone QBO signal when the MLS observations begin (Fig. 6). The QBO mean meridional circulation appears consistent with theoretical expectations.

The increased equatorial GWD in MERRA-2 has reduced the zonal wind analysis increments compared to MERRA so that the QBO mean meridional circulation can be expected to be more physically forced and therefore more physically consistent. This can be important for applications in which MERRA-2 winds are used to drive transport experiments.

Future investigations into the resolved equatorial wave structure are planned to determine the extent to which resolved waves contribute to the QBO in current assimilation systems. These studies will be based on the instantaneous MERRA-2 fields rather than the monthly averages. In addition, offline global transport studies may reveal weaknesses in the QBO mean residual circulation that can provide the basis of more detailed analysis. More can also be done on relating seasonal variations to the QBO. For example, Strahan et al. (2015) found that the Antarctic N2O is modulated by the phase of the QBO in the preceding year.

The QBO is a major component of the equatorial stratospheric variability that also influences the global stratospheric circulation. The realistic QBO found in the MERRA-2 DAS should provide an improved representation for further diagnostic and transport studies.

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