

1 **The anomalous change in the QBO in 2015-16**
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11 **Key Points:**

- 12 • The 2015-16 quasi-biennial oscillation had an unprecedented deviation from the 1953-
13 present observational record
- 14 • Easterlies unexpectedly appeared in the westerly phase of the quasi-biennial oscillation
- 15 • The remaining quasi-biennial oscillation westerlies showed an upward displacement, not
16 the normal downward propagation
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18

19 **Abstract**

20 The quasi-biennial oscillation (QBO) is a tropical lower stratospheric, downward
21 propagating zonal wind variation, with an average period of ~28 months. The QBO has been
22 constantly documented since 1953. Here we describe the evolution of the QBO during the
23 Northern Hemisphere winter of 2015-16 using radiosonde observations and meteorological
24 reanalyses. Normally, the QBO would show a steady downward propagation of the westerly
25 phase. In 2015-16, there was an anomalous upward displacement of this westerly phase from ~30
26 hPa to 15 hPa. These westerlies impinge on, or “cut-off” the normal downward propagation of
27 the easterly phase. In addition, easterly winds develop at 40 hPa. Comparisons to tropical wind
28 statistics for the 1953-present record demonstrate that this 2015-16 QBO disruption is
29 unprecedented.

30 **1 Introduction**

31 The quasi-biennial oscillation (QBO) is a tropical lower stratospheric, downward
32 propagating zonal wind variation, with an average period of ~28 months, but its period is
33 variable by more than a year between the shortest and longest QBO periods. Ebdon [1960] and
34 Reed et al. [1961] independently first detected the QBO. Tropical radiosonde wind observations
35 that document the QBO have been made continuously since 1953 [e.g., *Naujokat*, 1986]. The
36 importance of the QBO is that it dominates the variability of the tropical lower stratospheric
37 meteorology [*Wallace*, 1973]. The QBO also has an associated temperature and meridional
38 circulation structure. The structure and dynamics of the QBO have been extensively reviewed in
39 *Baldwin et al.* [2001]. Here we report on a significant, anomalous, adjustment of the QBO
40 structure during the Northern Hemisphere (NH) winter of 2015-16: it is the only such disruption
41 to the regular QBO propagation in the data record between 1953 and 2016.

42 **2 Data and Methodology**

43 Radiosondes provide a long-term QBO record. Because of the variation in the length of
44 QBO cycles, composite wind comparisons have been constructed from radiosondes based on the
45 transition from easterly to westerly equatorial winds at 40 hPa and westerly to easterly at 10 hPa
46 for each available QBO cycle. This enables a direct comparison of the length of the QBO
47 westerly and easterly phases for each year. These composites are based on the monthly-mean
48 radiosonde data updated from *Naujokat* [1986] and available at the Freie Universität Berlin
49 (FUB). These monthly means have been derived from three radiosonde stations: Canton Island
50 (Jan. 1953 – Aug. 1967, 3°S and 172°W), Gan/Maledive Islands (Sept. 1967 – Dec. 1975, 1°S
51 and 73°E) and Singapore (since Jan 1976, 1°N and 104°E).

52 The twice-daily wind data derived from the Singapore radiosonde data (WMO station
53 48698, 1°N, 104°E) have been used over the January 1979 to June 2016 period. These Singapore
54 radiosondes are of high quality, long-term (since 1976), and routinely reach levels above 10 hPa.
55 This radiosonde site provides one of the best datasets for monitoring the QBO from the ground.
56 Singapore currently uses the Vaisala VRS92G radiosonde, and Vaisala DigiCORA III sounding
57 system to receive and process the wind information.

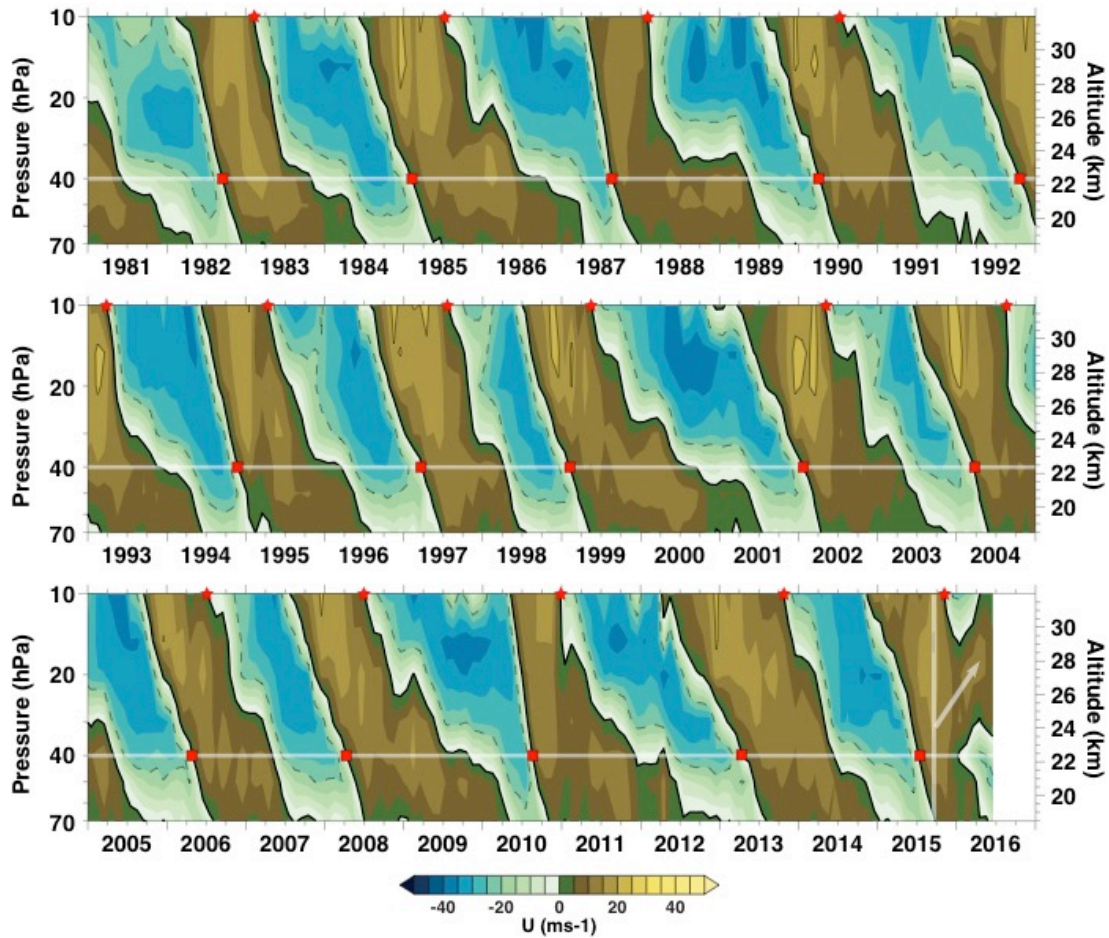
58 Assimilated meteorological fields complement the in-situ wind observations by providing
59 a complete three-dimensional picture of the QBO and its evolution on a regular global grid. Here
60 we use the Modern-Era Retrospective analysis for Research and Applications-Version 2,

61 MERRA-2 [Bosilovich *et al.*, 2015] that begins in 1980 and is ongoing. MERRA-2 shows
62 realistic QBO structures [Coy *et al.*, 2016], encompassing 14-15 QBO cycles. Time altitude cross
63 sections of the QBO winds from the initial time until 2012 are presented in Kawatani *et al.*
64 [2016]. In MERRA-2, the gravity-wave drag parameterization [Molod *et al.*, 2015] generates a
65 QBO, even in the free-running model, so that the resulting assimilation circulations are not based
66 solely on the assimilation of observations. The MERRA-2 instantaneous winds on standard
67 pressure levels [GMAO, 2015a] and monthly averaged temperatures on standard pressure levels
68 [GMAO, 2015b] were used in this study.

69 **3 Results**

70 The 2015-16 QBO has shown highly anomalous behavior. Figure 1 displays the QBO
71 over the last 36 years (January 1981-July 2016) as computed from monthly-mean zonal wind
72 averages derived from the twice-daily Singapore radiosonde data. The QBO downward
73 progression is clearly seen, with an extended westerly phase in the tropical lower stratosphere
74 [Reed, 1962]. The novel behavior of interest here began in the Sept.-Oct. 2015 period (denoted
75 by the semitransparent vertical line in the bottom right of Figure 1). There is an apparent upward
76 displacement of an anomalous westerly winds, which developed at 20 hPa in late 2015 (denoted
77 with the semi-transparent white arrow in Fig. 1). This late-2015 westerly is also accompanied by
78 the development of easterlies in the 30-70 hPa layer. The anomalous westerlies appear to curtail
79 the easterly phase downward propagation that is apparent at 10 hPa in late 2015 and early 2016.

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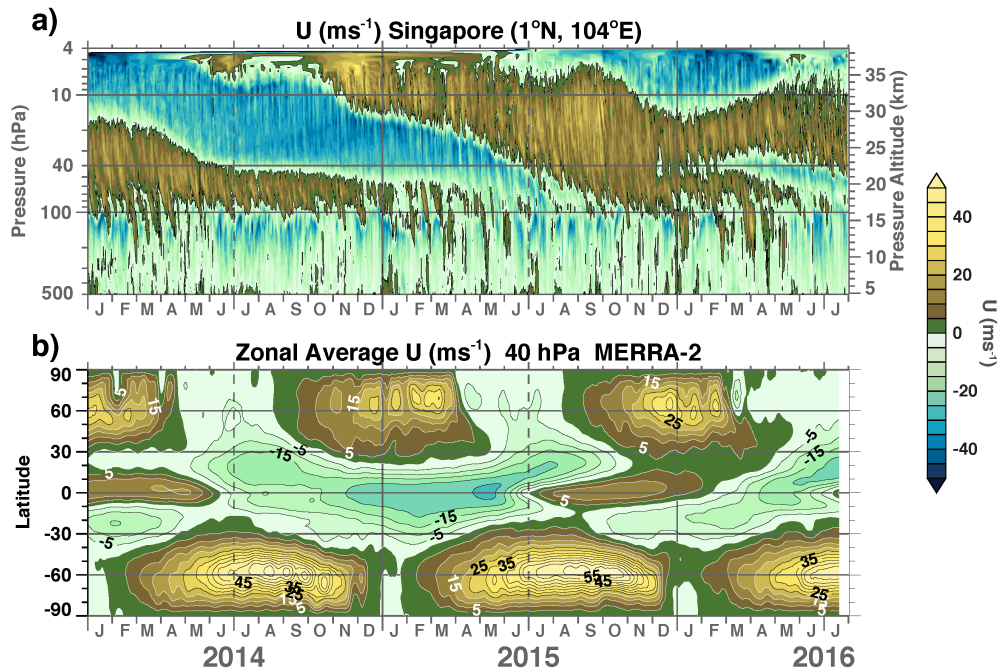
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83 **Figure 1.** Monthly-mean zonal wind (m s^{-1}) derived from Singapore radiosondes (1°N , 104°E)
 84 between 70 and 10 hPa for 1981 through July 2016. The color scale is on the bottom with 5 m s^{-1}
 85 color increments. Easterlies are shown in cyan-blue, while westerlies are in green-brown.
 86 Contours are every 20 m s^{-1} , with easterlies dashed and westerlies solid, and a thick black zero
 87 wind. The red squares show the dates of the 40 hPa easterly-to-westerly transition, while the red
 88 stars show the 10 hPa dates of the westerly-to-easterly transition.

89 The development of this QBO anomaly is also evident in the twice-daily radiosondes
 90 launched in the tropics from a variety of locations. Figure 2a displays the Singapore radiosonde
 91 time series, illustrating the upward westerly wind displacement along with the development of
 92 the easterlies that are centered at the 40-hPa level. This 40-hPa easterly reverted back to a
 93 westerly in July 2016. This anomalous QBO behavior is also observed at all of the radiosonde
 94 sites near the Equator. Examples include Nairobi (WMO 63741, 1.3°S , 37°E), Menado (WMO
 95 97014, 1.5°N , 123°E), Pontianak (WMO 96581, 0°N , 109°E), Fortaleza (WMO 82397, 3.8°S ,
 96 39°W), and Macada (WMO 82099, 0°N , 51°W). The consistency of the westerlies-to-easterlies
 97 development at all of the radiosonde locations means that the QBO anomaly cannot be attributed
 98 to data errors or radiosonde problems from one station.

99 The MERRA-2 assimilation includes these radiosonde observations, and yields a similar
 100 vertical structure in the zonal mean as shown in Figs. 1 and 2a (not shown). Figure 2b shows the
 101 meridional structure of the zonal wind evolution at 40-hPa from MERRA-2 (smoothed with a 10-
 102 day running mean). The westerlies develop at 40 hPa in July 2015, with the switch to easterlies
 103 in February 2016. While the westerlies appear at the Equator in July 2015, subtropical westerlies
 104 also appear at 20°N in early-November 2015 and persist through mid-April before reversing to
 105 easterlies. Westerly zonal mean winds at 40 hPa, 20°N in the mid-winter accompanied by a QBO
 106 westerly phase are not uncommon in the full MERRA-2 record (e. g., 1980-81, 1982-83, 1987-
 107 88, 1990-91, 1992-93, 1994-95, 1997-98, 2006-07, 2010-11).

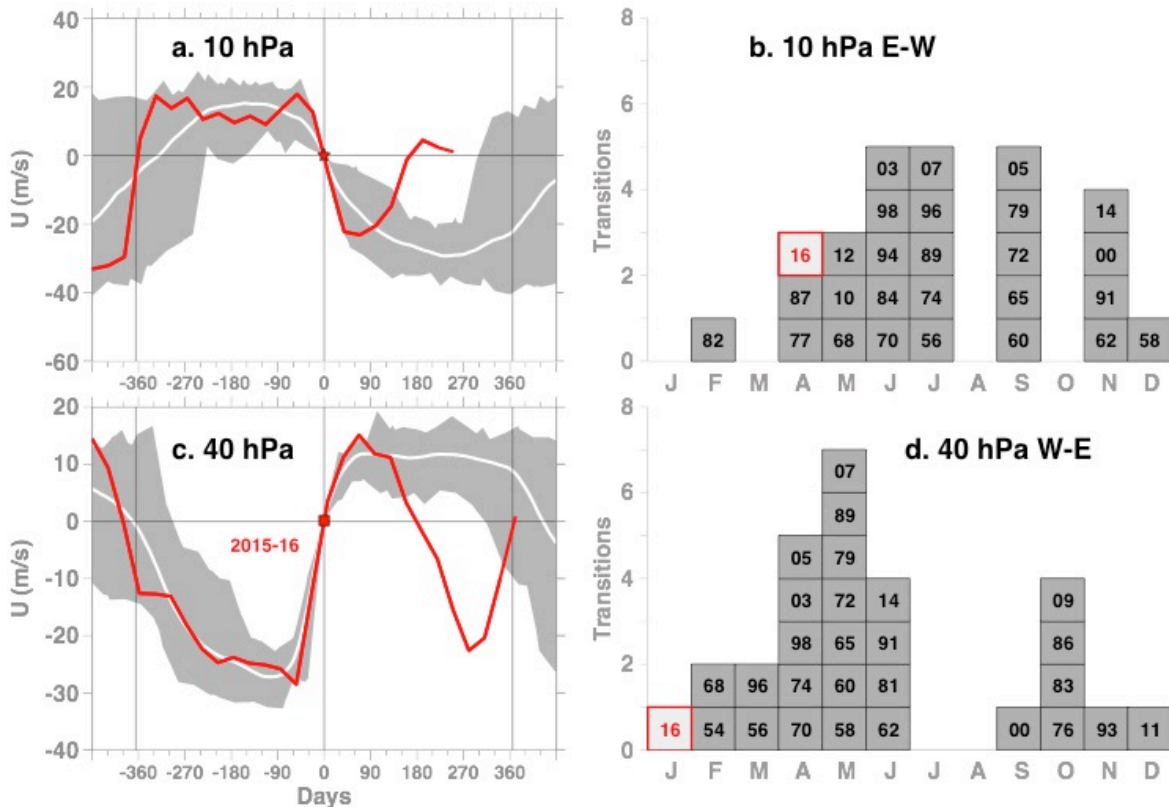
108 The temporal evolution of this QBO anomaly is relatively slow. However, in addition to
 109 the QBO, Kelvin waves are evident in the Singapore radiosonde observations. Fig. 2a shows
 110 short time-scale, near-vertical “striping” that is most probably upward propagating Kelvin waves
 111 with typical downward phase velocities of $\sim 1 \text{ km day}^{-1}$. The easterlies at 40 hPa first begin to
 112 appear in the Singapore data in early December 2015 and this easterly phase is fully developed
 113 by mid-April. The zonally averaged data also show a slow evolution at 40 hPa. Hence, this
 114 easterly anomaly develops in a steady but unusual manner by a mechanism (or a combination of
 115 mechanisms) that supplies a steady forcing. Another feature of the anomalous 2015-16 QBO is
 116 the 40-hPa location of the developing easterlies. Model and data studies of the QBO generally
 117 place the tropical stratospheric zonal mean wind accelerations in regions of strong vertical wind
 118 shear, conducive to the deposition of momentum by vertically propagating equatorial waves, and
 119 producing the signature descending shear zones [Baldwin *et al.*, 2001; Holt *et al.*, 2016]. In
 120 contrast, Figs. 1 and 2a show that the easterlies develop in the strongest region of the westerlies
 121 where the vertical wind shear is relatively small, suggesting that an anomalous forcing
 122 mechanism may be in play.



124 **Figure 2.** Daily zonal winds (Jan. 2014 through July 2016) for (a) altitude-time plot of Singapore
 125 radiosondes, and (b) latitude-time plot of MERRA-2 zonal-mean zonal winds at 40 hPa.
 126 Easterlies are shown in cyan-blue, while westerlies are in green-brown.

127 No similar QBO anomaly has ever been observed. The long-term QBO FUB dataset
 128 [Naujokat, 1986] has been used to construct a composite of the QBO over the 66 years between
 129 1953 and 2016. This period includes 27 easterly-to-westerly transitions at 40 hPa, effectively
 130 describing 26 complete oscillations, with an average QBO duration of 27.6 months as measured
 131 between the easterly-to-westerly transitions. Easterly-to-westerly transitions at 40 hPa are shown
 132 as red squares in Figure 1, while westerly-to-easterly transitions are shown as red stars in Figure
 133 1. Figure 3 shows zonal wind composites around these transition dates for 10 hPa (Fig. 3a) and
 134 40 hPa (Fig. 3c). The transition dates for each QBO are phase rectified to the same date to create
 135 the QBO composites. In Fig. 3c, the average line shows the 40-hPa easterly phase is typically
 136 ~12 months, while the average duration of the 40-hPa westerly phase is 15.3 months (excluding
 137 the 2015-16 QBO event, which lasted for only six months). The previous earliest reversal to
 138 easterlies was in the 1959-1960 QBO (a 10-month westerly phase). The behavior of 2015-16 was
 139 near normal during the easterly phase, but within a few months of switching to westerlies this
 140 phase began to switch back to easterlies. The 2015-16 QBO at 40 hPa was thus highly
 141 anomalous and well outside the previous observational range for the westerly phase.

142 The 10-hPa level also showed the highly anomalous rapid phase reversal. Fig. 3a shows a
 143 comparable pattern to the 40-hPa level, but for westerly to easterly transitions. The easterly
 144 phase appears in 2015, but reverses in about five months back to westerlies (see Fig. 1). As at the
 145 40-hPa level, this 10-hPa transition is well outside the range of the historic observations record.

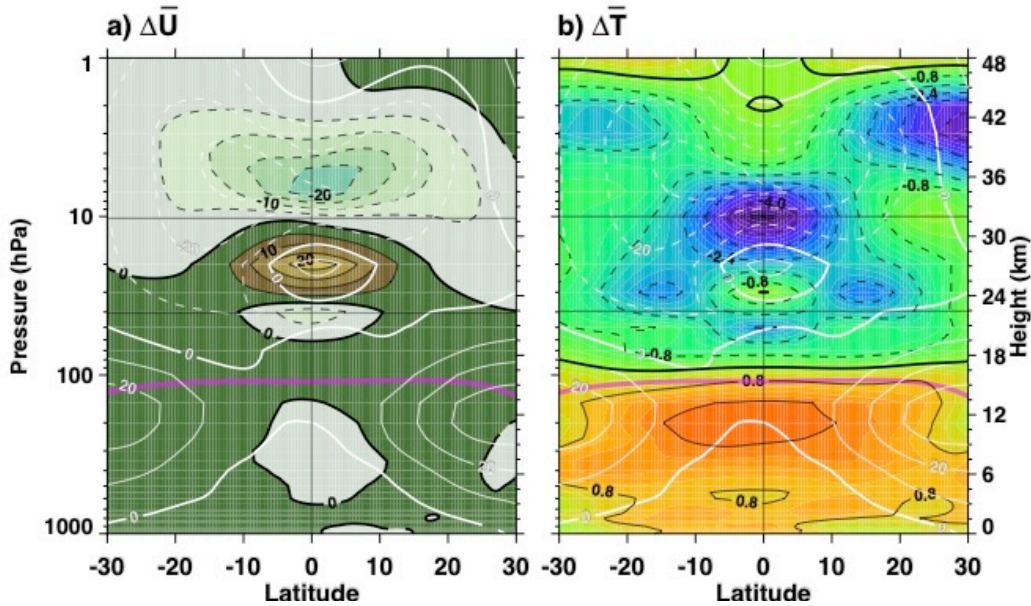


147 **Figure 3.** Composite of monthly zonal winds around the QBO transition time from the FUB
148 Singapore-Canton Island-Gan/Maledive Island time series at: (a) 10 hPa, and (c) 40 hPa. As
149 noted in the text, the time of the transition is calculated from the QBO time series (27 events),
150 and each event is then shifted to this “day 0” (i.e., phase rectified). Transition dates are noted in
151 Figure 1 as red squares for 40 hPa E-W and red stars for 10 hPa W-E. The white line shows the
152 average of the 27 events, while the grey shading shows the minimum to maximum range of all of
153 the QBOs (excluding the 2015-16 event). The 2015-16 event is plotted in red. The vertical black
154 lines show ± 1 year. Also shown in the right panels are the months when: (b) the easterly to
155 westerly transition occurs at 10 hPa, and (d) the westerly to easterly transition occurs at 40 hPa.
156 In b) and d) the boxes are labeled by year with 2016 highlighted in red.

157 The westerly to easterly phase change at 40 hPa occurred in January 2016. Figure 3d
158 displays the months of the phase changes for the westerlies-to-easterlies for all years using the
159 FUB radiosonde data set (following *Pawson et al.*, 1993). The 2015-16 QBO anomaly stands out
160 as having the only transition in January for the 28 phase transitions. Most of the 40-hPa
161 transitions occur in the NH spring or fall periods. The 10-hPa easterly-to-westerly transition
162 occurred in April 2016, but is not anomalous with respect to many other easterlies-to-westerlies
163 phase transitions during the NH spring to early summer.

164 The structure of the 2015-16 QBO anomaly appears to have a similar spatial structure to
165 a normal QBO phase, as can be seen in the zonal mean winds and temperatures. Figure 4
166 displays the (4a) zonal mean wind deviations and (4b) temperature deviations derived by
167 averaging the zonal means over Jan. through May 2016 and subtracting them from the 1980-
168 2015 time average over this same Jan-May period. The easterly anomaly centered at 40 hPa is
169 only a few kilometers in depth, as is clear in Figs. 1 and 2. The westerly anomaly is centered at
170 about 20 hPa, and is somewhat deeper. As with most QBOs, the easterly-westerly structure is
171 symmetric about the equator covering the zone from 15°S to 15°N. It is also notable that westerly
172 wind anomalies dominate the upper troposphere-lower stratosphere (UTLS, 100-70 hPa) in a
173 region that usually has rather weak winds. The Fig. 4 white lines show the zonal-mean zonal
174 wind from MERRA-2 for Jan.-May 2016. As is also seen in Figure 2, a westerly wind is apparent
175 in the sub-tropics (20°N) in the lower stratosphere (100-40 hPa) during this period (up to 40 hPa
176 at 25°N for example). The wind structure in the troposphere is also found to be somewhat
177 anomalous with stronger than average easterly winds in the 900–500 hPa layer associated with
178 the 2015-16 ENSO (El Niño–Southern Oscillation) event.

179 In addition to the wind deviations, the mean circulation induced by this anomalous QBO
180 zonal winds also modifies the temperatures. The 2016 temperature deviations from the 1980-
181 2015 average (Fig. 4b) show the vertical and latitudinal anomalies associated with the equatorial
182 zonal wind vertical shears with cooling below and warming above the 40 hPa easterlies along
183 with the oppositely signed temperature perturbations at 15°S and 15°N produced by the mean
184 circulation response to the equatorial winds. This temperature pattern is typical of the mean
185 circulation response to QBO-like equatorial wind changes with altitude [*Plumb and Bell*, 1982].
186 Note that the implied positive vertical motion perturbation (adiabatic cooling) in the upper part
187 of the 20-hPa westerlies may explain at least part of the anomalous upward displacement of the
188 westerlies seen in Fig. 1. The Jan.-May 2016 tropical tropospheric temperatures are much
189 warmer than the Jan.-May 1980-2015 average, while the stratosphere temperatures are generally
190 cooler than the Jan.-May 1980-2015 average.



192

193 **Figure 4.** The Jan.-May 2016 deviations from the Jan.-May 1980-2015 average of (a) zonal-
 194 mean zonal wind and (b) temperature, as computed from MERRA-2. Both panels have the Jan.-
 195 May 2016 averaged zonal mean zonal winds (white lines) and tropopause (thick magenta line).
 196 Units are m s^{-1} and K.

197 4 Summary and Conclusions

198 The QBO dominates the variability of the tropical stratospheric zonal winds and has
 199 impacts on the interannual variability throughout the stratosphere. The 2015-16 equatorial zonal
 200 winds revealed a rapid and highly anomalous QBO phase change in a manner that is
 201 unprecedented in the historic (66-year) data record.

202 This QBO anomaly appeared as an “upward displacement” of the westerly phase,
 203 accompanied by the development of easterlies at 40 hPa. This westerlies upward displacement
 204 appeared to “cut-off” the normal downward propagation of the easterlies, resulting in the shortest
 205 10 hPa easterly phase ever observed in the 1953-2016 record. In a corresponding manner, the
 206 easterlies at 40 hPa appeared below this upward displaced westerly, resulting in the shortest
 207 westerly phase ever observed in the 1953-2016 record. By the May-late July 2016 period, the
 208 QBO appeared to have resumed a normal downward propagation.

209 This QBO anomaly began developing in December 2015, and was fully complete by mid-
 210 April 2016. The anomaly’s evolution was relatively steady over the course of this period,
 211 suggesting a steady forcing mechanism (or a combination of mechanisms) that supplied a steady
 212 forcing. In addition, this QBO anomaly was distinguished by the development of easterlies in the
 213 strongest region of the westerlies, where the vertical wind shear was relatively small.

214 Clues to the causes of this QBO anomaly are found in the wind and temperature structure.
 215 First, the westerlies at 40 hPa extend from the subtropical jet axis ($\sim 30^\circ\text{N}$) to the Equator for an
 216 extended period. The absence of a critical line (zero wind line) would allow propagation of

217 planetary scale Rossby waves from the NH mid-latitudes into the tropical region, where they
218 could deposit additional easterly momentum. Second, the anomalous easterlies develop in a weak
219 wind-shear, this suggests an anomalous forcing mechanism since the QBO is normally driven by
220 momentum deposition from upward propagating waves in high wind-shear levels. Third, the
221 tropical troposphere was much warmer than the 1980-2015 average, while the stratosphere was
222 colder than the 1980-2015 average. This thermal structure was likely a combined result of both
223 the strong 2015-16 ENSO and climate effects.

224 The QBO is a regular feature of the climate system with predictable skill beyond three
225 years [Scaife, 2014]. However, the QBO's predictability is based on models adjusted to imitate
226 its relatively regular past record. The anomalous 2015-16 QBO evolution may prove to be a
227 challenge to future predictability studies.

228 Because of the unprecedented nature of this anomalous 2015-16 QBO and its importance
229 to the stratosphere, it is crucial to begin analysis of its causes and implications for the
230 stratospheric-tropospheric system. We plan to continue investigating several aspects of the QBO
231 anomaly, including the dynamical forcing, the evolution of stratospheric trace gases, and the
232 possible relationships to ENSO and climate change. In particular, the role of mid-latitude Rossby
233 wave dynamical forcing on the equatorial winds will be studied with the complete MERRA-2 set
234 of diagnostics. Past barotropic model results have highlighted the ability of Rossby waves to
235 sharpen tropical westerly shear zones without changing the magnitude or location of the
236 equatorial westerlies [O'Sullivan, 1997]. MERRA-2 based diagnostics can determine if such a
237 mechanism was modified during the boreal 2015-16 season.

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241 Atmospheric Composition Modeling and Analysis Program. The MERRA-2 reanalysis fields
242 were obtained from the NASA Earth Observing System Data and Information System
243 (<https://earthdata.nasa.gov>). The monthly-mean QBO data for the 1953-1978 period were
244 obtained from the Freie Universität Berlin ([http://www.geo.fu-](http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/)
245 [berlin.de/en/met/ag/strat/produkte/qbo/](http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/)). Daily global radiosondes have been collected at
246 NASA/GSFC and are provided from the Global Telecommunications System (available via the
247 NOAA/NCEP web site: <ftp://ftp.cpc.ncep.noaa.gov/wd53rl/rsonde/>).

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