The Quasi-Biennial Oscillation: A Second Disruption in Four Years

M. A. Saunders[1], A. S. R. Lea[1], and J. R. Smallwood[1]

[1] Mullard Space Science Laboratory, University College London, Surrey, UK.

Corresponding author: M. A. Saunders (m.saunders@ucl.ac.uk)

Key Points:

- In 2019/20 the quasi-biennial oscillation (QBO) exhibited its second split in four years; this after 63 years without such a disruption
- The QBO splitting in 2019/20 was initiated by southern hemisphere Rossby waves dissipating momentum in the equatorial lower stratosphere
- Large vertical differences in upwelling appear to sustain the QBO split and contribute to an anomalous upward-moving westerly QBO regime

Abstract

The quasi-biennial oscillation (QBO) is a pattern of descending easterly and westerly winds in the equatorial stratosphere that repeats every 28 months on average. The QBO matters because it influences environmental variables and phenomena in both the stratosphere and troposphere, and because its recurrent nature offers the potential for predictability. However, in 2015/16 after at least 62 years of regular behavior the QBO experienced an unprecedented disruption. Here we report and examine a second and similar QBO disruption that occurred just four years later in 2019/20. This second event shows that the original disruption was not unique and suggests an increased chance of further QBO disruptions. The QBO splitting in 2019/20 was initiated by unusually strong southern hemisphere Rossby waves that dissipated momentum in the equatorial stratosphere. Large vertical differences in upwelling speed sustained the QBO split and contributed to an anomalous upward-moving westerly QBO regime.

Plain Language Summary

A curious phenomenon called the quasi-biennial oscillation (QBO) occurs high in the tropical atmosphere. The QBO comprises a sequence of descending easterly and westerly strong winds that repeats about every 28 months. In 2015/16 the QBO was disturbed in a way not seen in over 60 years of observations: descending westerly winds split in two with one branch then ascending. Now a second and similar QBO disruption event has occurred in 2019/20. We describe the nature and unusualness of this second event and examine the dynamical factors that preconditioned the disruption and caused the anomalous upward-moving QBO regime. We find that the 2019/20 QBO disruption was initiated by atmospheric waves generated in the southern hemisphere extratropics that reached the equator and then transferred their large momentum to split the QBO. We also find that large vertical differences in upwelling sustained the QBO split and contributed to the anomalous upward-moving QBO regime. The two QBO disruptions matter because of the many stratosphere and troposphere phenomena that they potentially influence including ozone concentrations at all latitudes. The second QBO disruption also matters because it shows that the original event was not unique and suggests an increased chance of further such disruptions.

1. Introduction

The quasi-biennial oscillation (QBO) was discovered (Ebdon, 1960; Reed et al., 1961) and named (Angell & Korshover, 1964) in the early 1960s, and has been recorded in radiosonde data since 1953

(Naujokat, 1986). The QBO comprises alternating easterly and westerly winds in the equatorial stratosphere (in particular the lower stratosphere at ~18-31 km altitude), that descend slowly at a speed of ~ 1 km month^{-1} and recur with a mean period of 28 months (Baldwin et al., 2001). The QBO winds exhibit the highest interannual variability of any zonal wind in the atmosphere. The QBO matters because it modulates the air temperature and the concentrations of ozone and water vapor in the stratosphere (Gray & Pyle, 1989; Randel et al., 1998; Tweedy et al., 2017), affects the strength of the northern hemisphere (NH) winter polar vortex that links to extratropical surface variability (Holton, 1980; see also Anstey & Shepherd, 2014), influences tropical convection (Collimore et al., 2003) and the Madden-Julian oscillation (Yoo & Son, 2016; Klotzbach et al., 2019), and has been predictable out to three years ahead (Scaife et al., 2014).

After at least 62 years of regular behavior the QBO experienced an unexpected and unprecedented disruption during the NH winter of 2015/16 (Newman et al., 2016; Osprey et al., 2016; see also Coy et al., 2017; Lin et al., 2019; Tweedy et al., 2017). Downward propagating westerly QBO winds were split in two at 40 hPa (~22 km) by the development of anomalous easterly winds with the upper part of the westerly winds then undergoing anomalous upward displacement. This disruption and the easterly wind development is unforeseen by conventional QBO theory which considers that the QBO is driven by the momentum absorbed from upward propagating tropical waves (Lindzen & Holton, 1968). However, examination of the momentum budget terms for the zonal mean zonal wind at 40 hPa shows that the primary cause for the disruption was momentum absorbed from northern hemisphere Rossby waves propagating horizontally into the tropical stratosphere (Coy et al., 2017; Lin et al., 2019; Newman et al., 2016; Osprey et al., 2016) and, in particular, from a single strong wave episode in February 2016 (Lin et al., 2019). Here we report a second and similar QBO disruption event that happened just four years after the first disruption. We describe the nature of this second event and examine its unusualness and cause.

2. Data and Methods

Our study uses monthly-mean zonal wind data, daily zonal wind data, and monthly gridded reanalysis data. We obtain the monthly zonal wind data from the Freie Universität Berlin (FUB) (FUB, 2020; Naujokat, 1986). These widely-used QBO data are based on balloon radiosonde recordings above three equatorial stations (Canton Island/Kiribati, Gan/Maldives and Singapore). We use the FUB monthly records between January 1953 and June 2020 from 12 levels between 70 hPa and 10 hPa (~18-31 km altitude). Daily QBO zonal wind data are obtained from the 00 UT radiosonde ascents above

Singapore (station number 48698) archived in the Integrated Global Radiosonde Archive (IGRA) (IGRA, 2020; Durre et al., 2006). Singapore radiosonde data are used because this station provides one of the best data sets for monitoring the QBO from the ground (Newman et al., 2016). We use daily data recorded between January 1981 and June 2020 at levels between 200 hPa and 10 hPa and interpolate these data onto a 500 m vertical grid.

We use monthly gridded reanalysis data from the Modern-Era Retrospective analysis for Research and Applications-Version 2 (MERRA-2) (Bosilovich et al., 2015). MERRA-2 reanalysis data are used because this reanalysis is unique in providing data at the 40 hPa level (Martineau et al., 2018); a level crucial for the QBO disruption event in 2015/16 (hereafter called 'QBO 2015/16'). Furthermore the addition of 40 hPa data improves the reanalysis vertical resolution in the lower stratosphere thereby enhancing the ability to compute realistic zonal mean wind momentum budget terms that involve vertical gradients (Holt et al., 2020). The following MERRA-2 data are used in this study: monthly averaged zonal winds on standard pressure levels (Global Modeling and Assimilation Office (GMAO), 2015a), monthly mean momentum budget files (GMAO, 2015b), and 3-hour assimilated output on constant pressure levels (GMAO, 2015c).

We examine the role of large-scale propagating waves in contributing to the 2019/20 QBO disruption event (hereafter called 'QBO 2019/20') by computing Eliassen-Palm (EP) fluxes. EP fluxes quantify the origin and impact of wave disturbances on the mean zonal flow. We compute the monthly meridional and vertical components of the EP flux following Andrews et al. (1987) (their Eq. 3.5.3). Fields in the MERRA-2 monthly mean momentum budget files (GMAO, 2015b) and 3-hour assimilated output (GMAO, 2015c) are used for this calculation. To ensure the clear display of EP flux vectors we follow Coy et al. (2017) and display EP flux vectors only for the domain 30°S to 30°N and 70 hPa to 5 hPa.

The cause of QBO 2019/20 is explored further by computing monthly zonal-mean wind momentum budget terms and monthly zonal mean wind upwelling speeds for different levels and across 12 months that span the event. The momentum terms examined are the meridional and vertical EP flux divergences, and the meridional and vertical momentum advections (Osprey et al., 2016; Coy et al., 2017). Positive (negative) values of the EP flux divergence in the stratosphere indicate an acceleration (deceleration) of the zonal-mean zonal wind. The momentum budget terms are computed as described in Martineau et al. (2018) (their section 3.5 and Table 6) and with all derivatives calculated by using a three-point stencil (Martineau et al., 2018, section 3.1).

We examine the role of upwelling in contributing to the anomalous upward-moving westerly QBO signal that accompanies QBO 2019/20. Upwelling is thought to resist the descent of the QBO and contribute to stalls in the QBO downward motion and to changes in the QBO cycle duration (Saravanan, 1990; see also Rajendran et al., 2016; Match & Fueglistaler, 2020). We calculate the monthly zonal mean upwelling speed as the vertical component of the residual mean circulation (for example, Martineau et al., 2018, Eq. 5). These upwelling values and their standardized anomalies are computed at different pressure levels for each of 12 months using fields from the three MERRA-2 data sets described above.

3. Results

3.1 Characteristics of QBO 2019/20

The height-time plots in Figure 1 display anomalies in stratospheric monthly-mean zonal wind and daily zonal wind. Figure 1a shows how QBO 2015/16 and QBO 2019/20 differ in their nature to the downward propagating QBO zonal wind patterns that occurred consistently between 1953 and 2015. The two disruptions are characterized by (i) a split in the downward propagating westerly QBO winds at around 40 hPa (~22 km) and (ii) the occurrence of an anomalous upward-moving westerly QBO signal that later merges with the next cycle of downward propagating westerly QBO zonal wind. Further characteristics of QBO 2015/16 are described in Newman et al. (2016) and in Osprey et al. (2016); see also Coy et al. (2017), Tweedy et al. (2017) and Lin et al. (2019).

The development and attributes of QBO 2019/20 are clearer in Figure 1b. The main features of this event are: (i) a splitting of the westerly QBO zonal wind in December 2019 at 50-40 hPa; (ii) the development of anomalous easterly QBO winds coincident with the westward QBO split; (iii) a preconditioning of the weakened westerly QBO zonal wind between June and November 2019 at 50-40 hPa; (iv) the occurrence of an anomalous upward-moving westerly QBO signal between December 2019 and May 2020 at 30-20 hPa; (v) a merging of the anomalous upward-moving westerly QBO with a new cycle of downward propagating westerly QBO in June 2020. Although the altitude-span of the anomalous upward moving westerly QBO signal in 2019/20 is smaller than in 2015/16 (Figure 1a), the physical characteristics of QBO 2019/20 appear similar to those of QBO 2015/16.

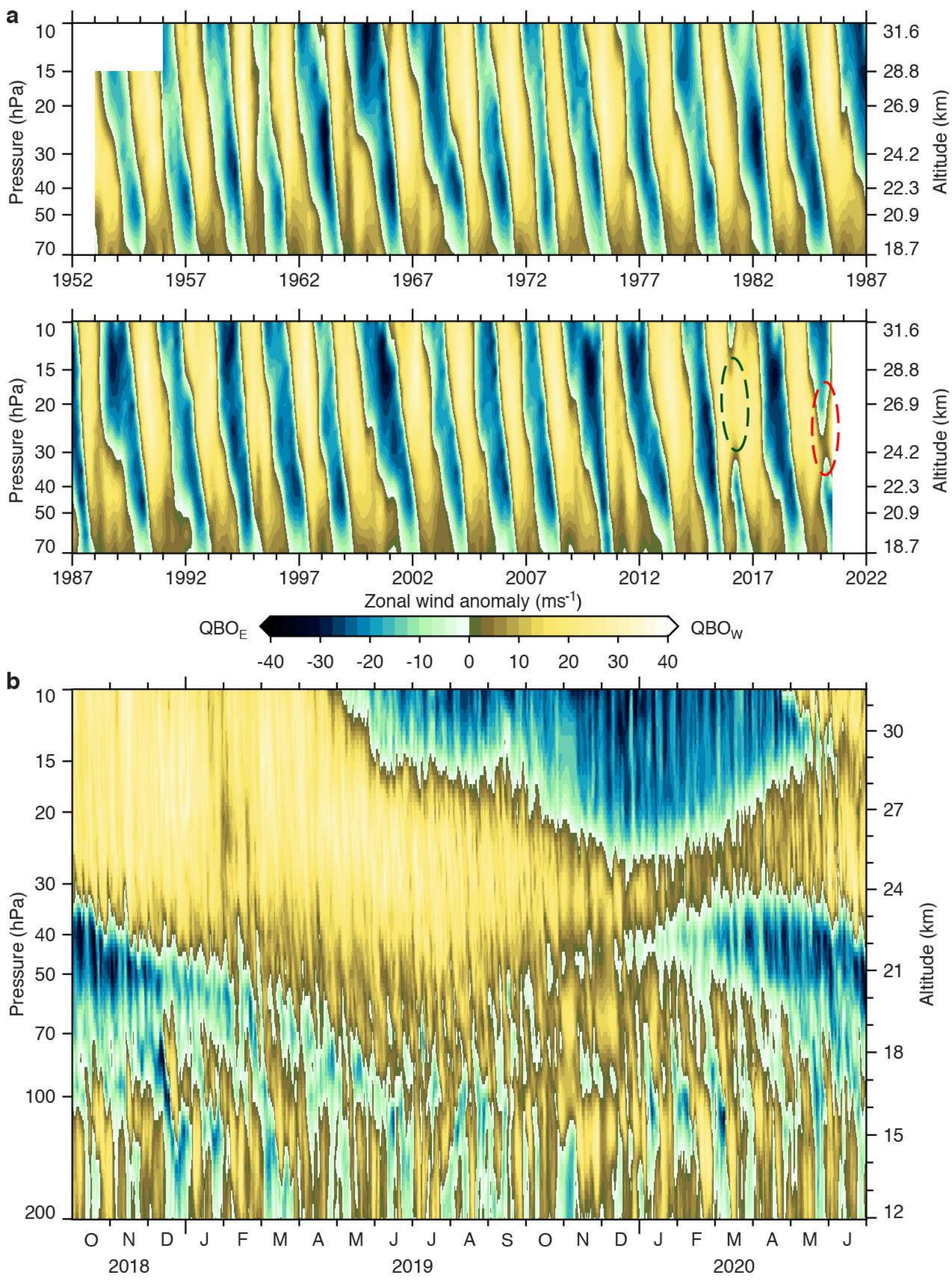

Figure 1. QBO historical data and the nature of the QBO cycle disruption in 2019/20. (**a)** Anomalies in monthly mean stratospheric zonal wind between January 1953 and June 2020 (FUB, 2020). **(b)** Anomalies in daily stratospheric zonal wind above Singapore between 1 October 2018 and 30 June 2020. The QBO disruptions in 2015/16 and 2019/20 are marked in **(a)** by green and red dashed ellipses. Westerly (QBO_W) and easterly (QBO_E) QBO zonal wind anomalies are distinguished by color. The anomalies in **(a)** are relative to a 1981-2010 monthly climatology and in **(b)** are relative to a 15-day centered 1981-2010 climatology. All data are interpolated onto a 500 m vertical grid.

3.2 Unusualness of QBO 2019/20

We quantify the historic unusualness of QBO 2019/20 by using FUB (2020) monthly zonal wind vertical profile data recorded at 12 levels between 70 hPa and 10 hPa, and by computing root mean square (RMS) differences compared to the 772 other months back to January 1956. A similar measure of QBO unusualness was used by Osprey et al. (2016). Figure 2 and its caption present our full method and findings. The two QBO disruption events stand out as extreme RMS outliers but with QBO 2019/20 ranking as more unusual than QBO 2015/16. The month with the most unusual QBO zonal wind vertical profile in the FUB data is April 2020 followed by March 2020. The most unusual month from QBO 2015/16 is March 2016. The April 2020 zonal velocity vertical profile is displayed in Fig 2b together with the 10 most similar monthly profiles after excluding months that are separated by less than nine months from April 2020 to ensure only months from different QBO cycles are considered. We conclude that the monthly zonal wind vertical profiles during QBO 2019/20 contain the most extreme outliers in the FUB (2020) high vertical resolution QBO data record exceeding 64 years.

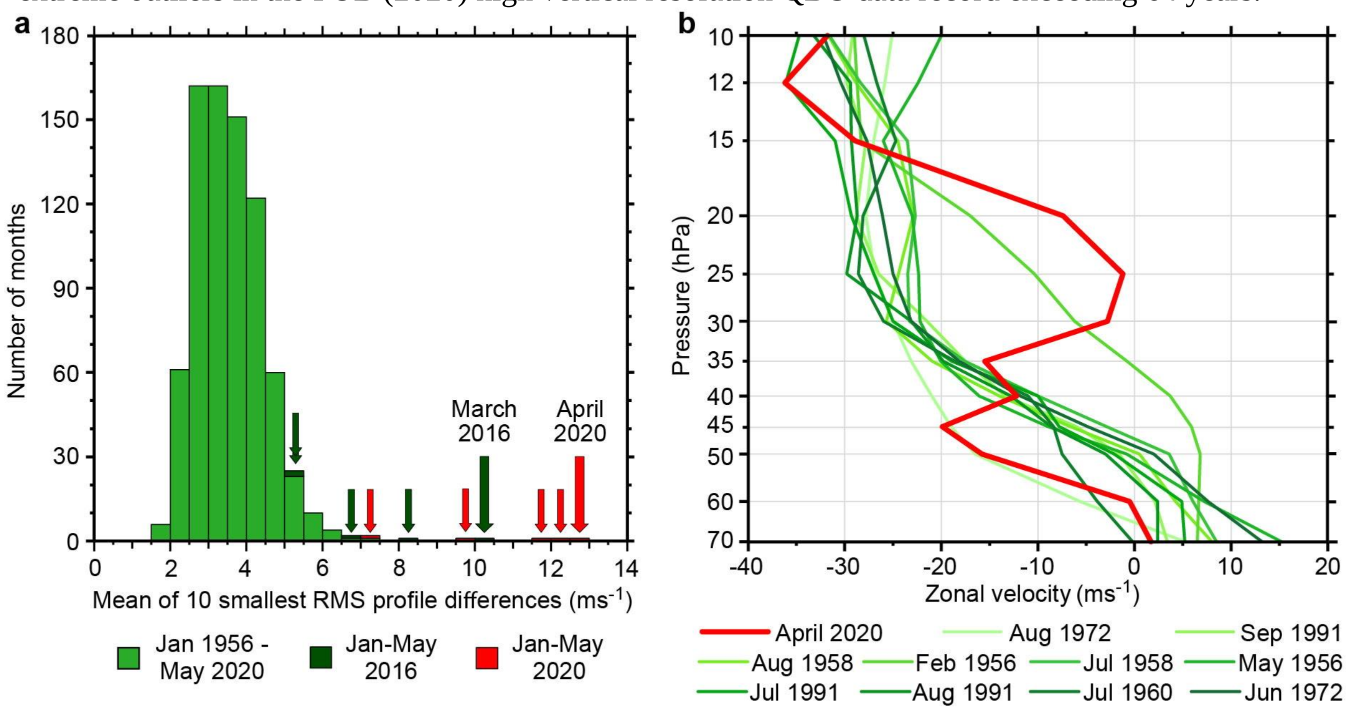

Figure 2. Unusualness of the 2019/20 QBO disruption event computed from FUB (2020) data. Unusualness is expressed as the root mean square (RMS) difference between a month's vertical zonal wind profile based on data from 12 levels between 70 hPa and 10 hPa and the mean of the 10 smallest RMS vertical profile differences for that month taking all other monthly profiles between January 1956 and May 2020 separated by at least nine months from the original month. **(a)** Histogram of the RMS differences / unusualness values for each month with values for the two QBO disruption events highlighted. **(b)** Vertical profile of zonal velocity for April 2020 and for the ten months with profiles that are most similar ordered in terms of increasing misfit.

3.3 Preconditioning and Cause of QBO 2019/20

We explore the process(es) behind the development of QBO 2019/20 by examining the role of large-scale propagating waves in dissipating momentum and potentially disrupting the QBO zonal flow. Monthly MERRA-2 reanalysis data are used. Figure 3 shows how wave disturbances impacted the tropical stratosphere zonal-mean zonal wind over the 12-month period that spans QBO 2019/20. Before describing these wave-flow interactions we note that the QBO signal is evident between latitudes 10°N and 10°S (for example, the QBO in May 2019 is westerly between 70-20 hPa and is easterly above 20-15 hPa), and that the tropical zonal-mean zonal wind in the stratosphere and upper troposphere exhibits a seasonal cycle. The direction and magnitude of the monthly EP fluxes are shown by blue arrows. These fluxes are computed for 5° latitude bins at the eight pressure-levels between 70 hPa and 5 hPa provided by MERRA-2.

EP fluxes in Figure 3 are observed mainly where the zonal wind is eastward in agreement with wave propagation theory (Charney & Drazin, 1961; Domiesen et al., 2018). Extrapolating the EP flux vectors backward suggests that the waves responsible originate in the extratropics and are Rossby waves. Rossby waves occur mainly in the winter hemisphere, propagate up into the stratosphere and refract towards the equator (Dickinson, 1968; Hamilton, 1982; Domiesen et al., 2018). The momentum carried by a propagating Rossby wave is absorbed by the mean flow when the wave breaks. Wave breaking occurs at critical layers where the wave phase velocity matches the background zonal wind velocity (Andrews et al., 1987). Because Rossby waves only transport westward momentum the zonal wind undergoes westward acceleration when these waves are absorbed (Andrews et al., 1987).

Large meridional EP fluxes in Figure 3 reach the equator where the QBO zonal winds are westerly. These EP fluxes originate from the southern hemisphere (SH) between June and October 2019 and from the NH between November 2019 and January 2020. Examination of the MERRA-2 40-yr data record shows that the three months with the largest northward zonal-mean eddy momentum flux at 50 hPa for the 5°S to 5°N domain are June, September and July 2019 (not shown). A rare SH minor sudden stratospheric warming event in September 2019 (Rao et al., 2020) may have contributed to the September high momentum flux.

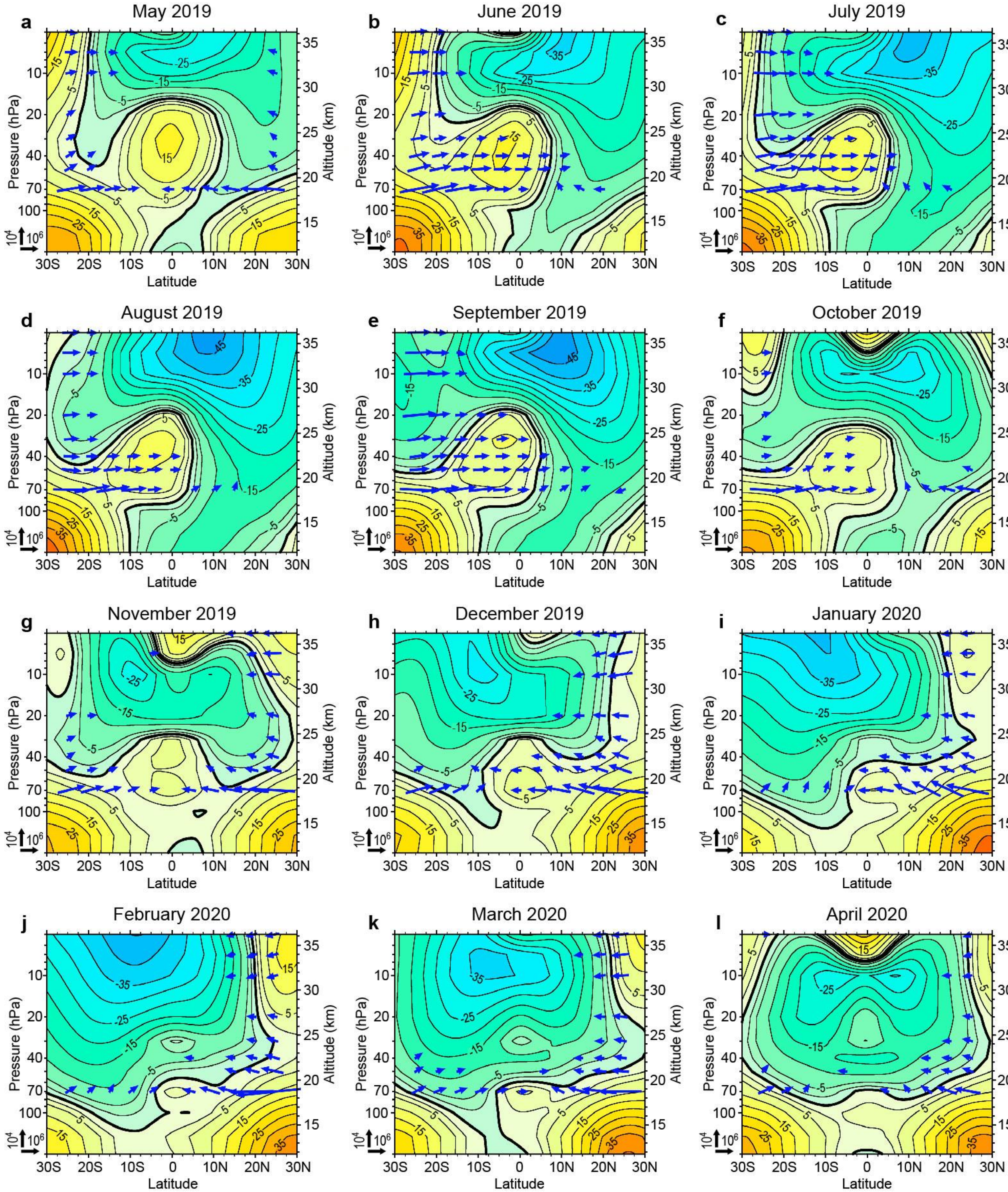

Figure 3. Latitude-height plots of monthly zonal-mean zonal wind and monthly zonal-mean Eliassen-Palm (EP) flux. The domain ranges from 30°S to 30°N and from 200 hPa to 5 hPa. Months range from May 2019 to April 2020 and are labelled (**a**) to (**l**). Blue arrows display the EP flux vectors at 70 hPa and above. The scale arrows in the lower left-left corner represent a meridional EP flux of 10^6 kg s^{-2} and a vertical EP flux of 10^4 kg s^{-2}. Black contours with color infills show the magnitude and direction of the zonal-mean zonal wind in m s^{-1}. Westerly (eastward) winds are colored yellow-orange, and easterly (westward) winds are green-blue. The contour spacing is 5 m s^{-1} except adjacent to the 0 m s^{-1} contour where it is 2.5 m s^{-1}.

Figure 3 suggests that EP flux dissipation near to the equator is associated with weakening of the QBO westerly (eastward) zonal wind. Since there is qualitative agreement between the QBO data in Figures 1b and 3 this association suggests that the splitting of the westerly QBO zonal wind in December 2019 at 50-40 hPa was preconditioned and initiated by SH Rossby waves dissipating unusually large amounts of momentum in the equatorial lower stratosphere between June and October 2019, and then further enhanced by NH Rossby waves dissipating momentum between November 2019 and January 2020. The development of anomalous easterly QBO winds at 50-40 hPa is attributed to the large cumulative Rossby wave absorption at these levels.

Support for the above analysis is provided by the monthly zonal-mean wind momentum budget (Figures 4a, 4b). At 40 hPa the term dominating the westward acceleration of the equatorial winds between June 2019 and February 2020 is the EP flux divergence due to the momentum absorbed from horizontally propagating waves. The same momentum term is dominant at 50 hPa between June and September 2019. The forcing contribution from this term declines in each case when the zonal-mean wind becomes westward.

3.4 Upwelling and the upward-moving westerly QBO signal

A defining feature of QBO 2019/20 is the anomalous upward-moving westerly QBO signal. The same phenomenon occurred in QBO 2015/16 and appears central to sustaining the split QBO. However, this upward motion has received limited study. To further understand this feature we examine the role of upwelling during QBO 2019/20 and, in particular, when the upward QBO signal occurs; this as upwelling is thought to oppose the normal downward QBO motion.

We observe large changes in upwelling speed before and during the QBO 2019/20 (Figure 4). Comparing the data in Figures 4 and 1b for the period June to November 2019 suggests that upwelling has a sizeable influence on QBO descent speed. When upwelling is enhanced between June and September the QBO easterly and westerly shear zones show virtually no downward motion. In September 2019 when the upwelling speed is greatest (coinciding with the SH sudden stratospheric warming event) the QBO easterly shear zone even moves upward by 1 km. In contrast, when upwelling decreases to slightly below-norm in October and November the QBO exhibits normal downward motion.

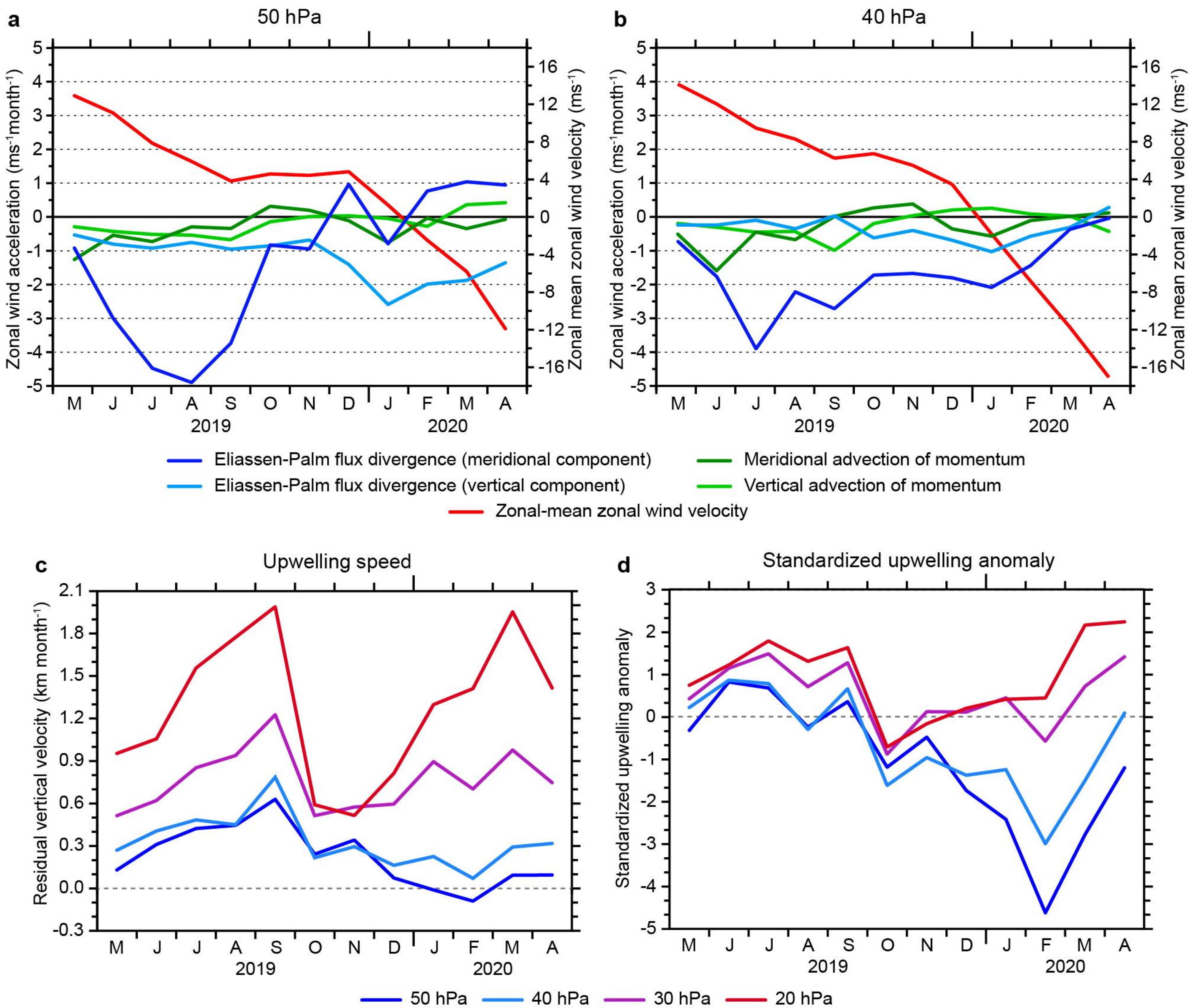

Figure 4. Dynamics of the 2019/20 QBO disruption event determined from MERRA-2 reanalysis data. All panels show zonal-mean data averaged for the 5°S-5°N domain for each month between May 2019 and April 2020. The upper panels display zonal-mean zonal wind accelerations at the 50 hPa (**a**) and 40 hPa (**b**) pressure levels arising from four momentum-forcing terms. These terms are the meridional and vertical EP flux divergences, and the meridional and vertical momentum advections. Also presented is the zonal-mean zonal wind velocity (right ordinate axis). The lower panels display zonal-mean upwelling data at the 50 hPa, 40 hPa, 30 hPa and 20 hPa pressure levels. Panel (**c**) displays the monthly zonal-mean residual vertical velocity. Panel (**d**) presents the standardized anomaly of the data in (**c**) relative to the 1981-2010 monthly climatology at each level.

With the above in mind we note the presence of large vertical differences in upwelling when the anomalous upward-moving westerly QBO signal occurs between December 2019 and April 2020 (Figure 4). The 30-20 hPa levels show an increase in upwelling but the lower 50-40 hPa levels show a marked decrease in upwelling such that the residual flow at 50 hPa in February 2020 is computed to be weakly sinking rather than rising. At 30-20 hPa, where the anomalous upward-moving westerly QBO signal occurs, the upwelling speed is about 1 km month^{-1} and the QBO upward speed is about 0.7 km month^{-1} (Figure 1b). This similarity in values suggests that the large vertical differences in upwelling contributed to the anomalous upward QBO regime and to sustaining the QBO split from December 2019 until June 2020 when a new cycle of downward propagating westerly QBO began. Establishing the cause for the large upwelling differences warrants careful study using data with better vertical resolution than afforded by MERRA-2. Possible causes are changes with altitude in the equatorial Brewer-Dobson circulation (Gómez-Escolar et al., 2014) and/or vertical motion perturbations arising from the QBO temperature pattern (Plumb and Bell, 1982).

4. Concluding Remarks

The unexpected QBO disruption in 2015/16 was considered to be a rare event. Climate models that simulate the QBO suggested that similar disruptions may occur up to three times every 100 years in the more extreme climate change scenarios (Osprey et al., 2016). The occurrence of a second and similar QBO disruption just four years later in 2019/20 shows that the original disruption was not unique and suggests an increased chance of further QBO disruptions.

The primary cause of both QBO disruptions appears to be momentum absorption from extratropical Rossby waves propagating horizontally into the equatorial lower stratosphere. These Rossby waves originate from the NH for QBO 2015/16 and from the SH for QBO 2019/20. Each event is associated with record (since 1980) horizontal momentum fluxes reaching the equator at either the 40 hPa or 50 hPa level. Further investigation needs to clarify the origins of these wave fluxes, why horizontal wave fluxes reaching the equator have increased in recent years and whether this increase is linked to global warming. The anticipated future strengthening of the Brewer-Dobson circulation due to increasing stratospheric wave activity (Butchart, 2014) may be relevant to these investigations.

The two QBO disruptions matter because of the many stratosphere and troposphere phenomena that are potentially affected (section 1). For example, the anomalous changes in upwelling associated with QBO 2015/16 are thought to have contributed to near-record low levels of column ozone in the subtropics in 2016 (Tweedy et al., 2017), to a global decrease in stratospheric water vapour (Tweedy et al., 2017) and to a positive arctic oscillation during the NH winter of 2016/17 (Osprey et al., 2016).

Acknowledgments

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References

Andrews, D. G., Holton, J. R., & Leovy, C. B. (1987). *Middle Atmosphere Dynamics*. International Geophysics Series, Vol. 40, 489 pp. Academic Press, San Diego.

Angell, J. K., & Korshover, J. (1964). Quasi-biennial variations in temperature, total ozone, and tropopause height. *J. Atmos. Sci*., *21*, 479–492. https://doi.org/10.1175/1520-0469(1964)021<0479:QBVITT>2.0.CO;2

Anstey, J.A., & Shepherd, T.G. (2014). High-latitude influence of the quasi-biennial oscillation. *Q. J. R. Meteorol. Soc.*, 140, 1–21. https://doi.org/10.1002/qj.2132

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., et al. (2001). The quasi-biennial oscillation. *Rev. Geophys*., *39*, 179–229. https://doi.org/10.1029/1999RG000073

Bosilovich, M. G., Akella, S., Coy, L., Cullather, R., Draper, C., Gelaro, R., et al. (2015). MERRA-2: Initial evaluation of the climate. NASA Tech. Rep. series on global modeling and data assimilation, NASA/TM-2015-104606, vol. 43, 145 pp., NASA. [Available at https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich803.pdf].

Butchart, N., (2014). The Brewer-Dobson circulation. *Rev. Geophys.*, *52*, 157–184. https://doi.org/10.1002/2013RG000448

Charney, J. G., & Drazin, P. G. (1961). Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, *66*, 83–109. https://doi.org/10.1029/JZ066i001p00083

Collimore, C. C., Martin, D. W., Hitchman, M. H., Huesmann, A., & Waliser, D.E. (2003). On the relationship between the QBO and tropical deep convection. *J. Climate*, *16*, 2552–2568. https://doi.org/10.1175/1520-0442(2003)016<2552:OTRBTQ>2.0.CO;2

Coy, L., Newman, P. A., Pawson, S., & Lait, L. R. (2017). Dynamics of the disrupted 2015/16 quasi-biennial oscillation. *J. Climate*, *30*, 5661–5674. https://doi.org/10.1175/JCLI-D-16-0663.1

Dickinson, R., E. (1968). Planetary Rossby waves propagating vertically through weak westerly wind wave guides. *J. Atmos. Sci*., *25*, 984–1002. https://doi.org/10.1175/1520-0469(1968)025<0984:PRWPVT>2.0.CO;2

Domeisen, D. I. V., Martius, O., & Jiménez-Esteve, B. (2018). Rossby wave propagation into the Northern Hemisphere stratosphere: The role of zonal phase speed. *Geophys. Res. Lett.*, *45*, 2064–2071. https://doi.org/10.1002/2017GL076886

Durre, I., Vose, R. S., & Wuertz, D. B. (2006). Overview of the Integrated Global Radiosonde Archive. *J. Climate*, *19*, 53–68. https://doi.org/10.1175/JCLI3594.1

Ebdon, R. A. (1960). Notes on the wind flow at 50 mb in tropical and subtropical regions in January 1957 and January 1958. *Q. J. R. Meteorol. Soc*., *86*, 540–542. https://doi.org/10.1002/qj.49708637011

FUB (2020). The quasi-biennial-oscillation (QBO) Data Serie. [Available at: https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo, last accessed 7 July 2020].

Gómez-Escolar, M., Calvo, N., Barriopedro, D., & Fueglistaler, S. (2014). Tropical response to stratospheric sudden warmings and its modulation by the QBO. *J. Geophys. Res. Atmos.*, *119*, 7382–7395. https://doi.org/10.1002/2013JD020560

GMAO (2015a). MERRA-2 instM_3d_asm_Np: 3D, monthly mean, instantaneous, pressure-level, assimilation, assimilated meteorological fields, version 5.12.4. GSFC Distributed Active Archive Center. Last accessed 20 June 2020, doi:10.5067/ 2E096JV59PK7.

GMAO (2015b). MERRA-2 tavgM_3d_trb_Np: 3D, monthly mean, time-averaged, pressure-level, assimilation, turbulence diagnostics, version 5.12.4. GSFC Distributed Active Archive Center. Last accessed 20 June 2020, doi:10.5067/2YOIQB5C3ACN.

GMAO (2015c). MERRA-2 inst3_3d_asm_Np: 3D, 3-hourly, instantaneous, pressure-level, assimilation, assimilated meteorological fields, version 5.12.4. GSFC Distributed Active Archive Center. Last accessed 20 June 2020, doi:10.5067/QBZ6MG944HW0.

Gray, L. J., & Pyle, J. A. (1989). A two-dimensional model of the quasi-biennial oscillation of ozone. *J. Atmos. Sci*., *46*, 203–220. https://doi.org/10.1175/1520-0469(1989)046,0203:ATDMOT.2.0.CO;2.

Hamilton, K. (1982). Some features of the climatology of the Northern Hemisphere stratosphere revealed by NMC upper atmosphere analyses. *J. Atmos. Sci*., *39*, 2737–2749. https://doi.org/10.1175/1520-0469(1982)039<2737:SFOTCO>2.0.CO;2

Holt, L. A., Lott, F., Garcia, R. R., Kiladis, G. N., Cheng, Y-M., Anstey, J. A., et al. (2020). An evaluation of tropical waves and wave forcing of the QBO in QBOi models. *Q. J. R. Meteorol. Soc*., 1-27. https://doi.org/10.1002/qj.3827

Holton, J. R. (1980). Wave propagation and transport in the middle atmosphere. *Philos. Trans. R. Soc. Lond., Series A*, *296*, 73–85. https://doi.org/10.1098/rsta.1980.0157

IGRA (2020). Integrated Global Radiosonde Archive. [Available at https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive, last accessed 30 June 2020].

Klotzbach, P., Abhik, S., Hendon, H. H., Bell, M., Lucas, C., Marshall, A. G. et al. (2019). On the emerging relationship between the stratospheric quasi-biennial oscillation and the Madden-Julian oscillation. *Sci. Rep*., *9*, 2981. https://doi.org/10.1038/s41598-019-40034-6

Lin, P., Held, I., & Ming, Y. (2019). The early development of the 2015/16 quasi-biennial oscillation disruption. *J. Atmos. Sci*., *76*, 821-836. https://doi.org/10.1175/JAS-D-18-0292.1

Lindzen, R. S., & Holton, J. R. (1968). A theory for the quasi-biennial oscillation. *J. Atmos. Sci.*, 25, 1095–1107. https://doi.org/10.1175/1520-0469(1968)025<1095:ATOTQB>2.0.CO;2

Martineau, P., Wright, J. S., Zhu, N., & Fujiwara, M. (2018). Zonal-mean data set of global atmospheric reanalyses on pressure levels. *Earth Syst. Sci. Data*, *10*, 1925-1941. https://doi.org/10.5194/essd-10-1925-2018

Match, A., & Fueglistaler, S. (2020). Mean-flow damping forms the buffer zone of the quasi-biennial oscillation: 1D theory. *J. Atmos. Sci*., *77*, 1955-1967. https://doi.org/10.1175/JAS-D-19-0293.1

Naujokat, B. (1986). An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci*., *43*, 1873–1877. https://doi.org/10.1175/1520-0469(1986)043<1873:AUOTOQ>2.0.CO;2

Newman, P. A., Coy, L., Pawson, S., & Lait, L. R. (2016). The anomalous change in the QBO in 2015–2016. *Geophys. Res. Lett.*, *43*, 8791–8797. https://doi.org/10.1002/2016GL070373

Osprey, S. M., Butchart, N., Knight, J. R., Scaife, A. A., Hamilton, K., Anstey, J. A., et al. (2016). An unexpected disruption of the atmospheric quasi-biennial oscillation. *Science*, *353*, 1424–1427. https://doi.org/10.1126/science.aah4156

Plumb, R. A., & Bell, R. C. (1982). A model of the quasi-biennial oscillation on an equatorial beta-plane, *Q. J. R. Meteorol. Soc*., *108*, 335–352. https://doi.org/10.1002/qj.49710845604

Rajendran, K., Moroz, I. M., Read, P. L., & Osprey, S. M. (2016). Synchronisation of the equatorial QBO by the annual cycle in tropical upwelling in a warming climate. *Q. J. R. Meteorol. Soc*., *142*, 1111–1120. https://doi.org/10.1002/qj.2714

Randel, W. J., Wu, F., Russell, J. M., Roche, A., & Waters, J. W. (1998). Seasonal cycles and QBO variations in stratospheric CH_4 and H_2O observed in UARS HALOE data. *J. Atmos. Sci*., 55, 163–185. https://doi.org/10.1175/1520-0469(1998)055<0163:SCAQVI>2.0.CO;2

Rao, J., Garfinkel, C. I., White, I. P., & Schwartz, C. (2020). The Southern Hemisphere minor sudden stratospheric warming in September 2019 and its predictions in S2S models. *J. Geophys. Res. Atmos*., *125*, e2020JD032723. https://doi.org/10.1029/2020JD032723

Reed, R. J., Campbell, W. J., Rasmussen, L. A., & Rogers, R. G. (1961). Evidence of a downward propagating annual wind reversal in the equatorial stratosphere. *J. Geophys. Res*., *66*, 813–818. https://doi.org/10.1029/JZ066i003p00813

Saravanan, R., 1990: A multiwave model of the quasi-biennial oscillation. *J. Atmos. Sci*., *47*, 2465–2474. https://doi.org/10.1175/1520-0469(1990)047,2465:AMMOTQ.2.0.CO;2.

Scaife, A. A., Athanassiadou, M., Andrews, M., Arribas, A., Baldwin, M., Dunstone, N., et al. (2014). Predictability of the quasi-biennial oscillation and its northern winter teleconnection on seasonal to decadal timescales. *Geophys. Res. Lett*., *41*, 1752–1758.https://doi.org/10.1002/2013GL059160

Tweedy, O. V., Kramarova, N. A., Strahan, S. E., Newman, P. A., Coy, L., Randel, W. J., et al (2017). Response of trace gases to the disrupted 2015-2016 quasi-biennial oscillation. *Atmos. Chem. Phys*., *17*, 6813–6823. https://doi.org/10.5194/acp-17-6813-2017

Yoo, C., & Son, S.W. (2016). Modulation of the boreal wintertime Madden–Julian oscillation by the stratospheric quasi-biennial oscillation. *Geophys. Res. Lett.*, *43*, 1392–1398. https://doi.org/10.1002/2016GL067762