Response of stratospheric tracers to the 2015/16 QBO disruption

Mohamadou Diallo[1]; **Chen Schwartz**[2] **and Abebe Kebede**[3].

[1]Institute of Energy and Climate Research, Stratosphere (IEK-7), Forschungszentrum Jülich, 52425 Jülich, Germany.

[2]Hebrew University of Jerusalem, Israel,

[3]Bahir Dar University, Ethiopia.

Abstract

Mostly driven by equatorially trapped gravity waves that propagate from the troposphere to the stratosphere, the quasi-biennial oscillation (QBO) is a downward propagation of alternating westerly and easterly zonal wind shears in the tropical stratosphere with a period of ∼28 months. The QBO strongly modulates the upwelling associated with the Brewer-Dobson circulation, therefore impacting the composition of trace gases entering the stratosphere. During the winter of 2015/16, an unexpected shift from a westerly wind shear to an easterly wind occurred at 40 hPa. Here, we analyse the impact of the 2015/16 disrupted QBO on the observed water vapor and ozone tracer gases from Aura Microwave Limb Sounder (MLS) in the tropical lower stratosphere by using a multiple linear regression method. We find a decrease in water vapor and ozone between 380–450 K following the unexpected QBO disruption during the 2015/16 boreal winter and an increased rates of the same tracers between 450–600 K from boreal spring to fall.

1 Overview

1.1 Introduction

The quasi-biennial oscillation (QBO) is a downward propagation of alternating westerly and easterly zonal wind shears in the tropical stratosphere with a period of ∼28 months. It is driven mostly by equatorially trapped gravity waves that propagate from the troposphere to the stratosphere (see Fig. 1A) [1]. The QBO was first discovered during the late 1950s by the independent work of R. A. Ebdon [2] in the United Kingdom and R. J. Reed [3] in the United States. The QBO has a direct influence on the stratospheric polar vortex through the Holton-Tan effect [4] and thus can affect the extra-tropical surface weather during boreal wintertime through downward coupling [5].

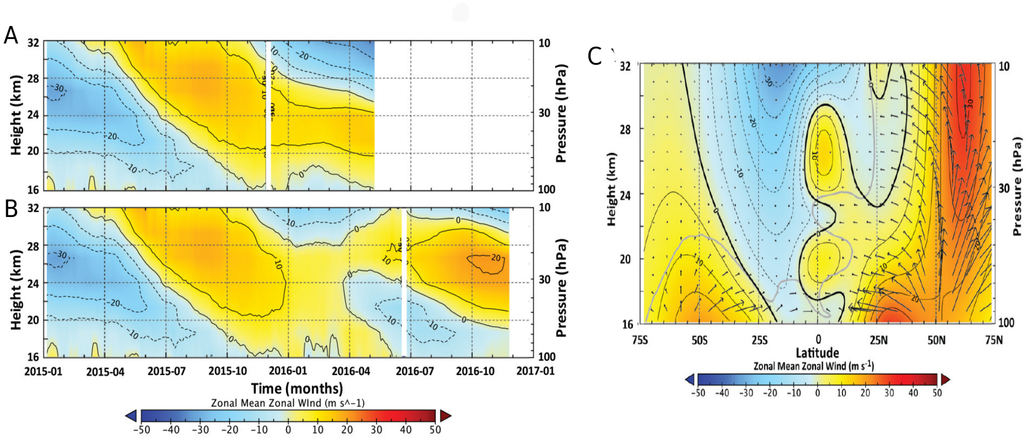

Figure 1: **Long range forecasts of the QBO from before and during the 2016 disruption, and wave driven circulation changes associated with the formation of 40 hPa westward zonal wind.** Forecasts from 1st December (A) show the usual phase progression of descending eastward wind in the lower stratosphere. Forecasts from June (B) show growth, descent and decay of the anomalies westward wind near 50 hPa and a second period of eastward QBO winds in late 2016. (C) Latitude-pressure plot showing February 2016 mean zonal mean wind (filled and black contours), Eliassen-Palm (EP) flux (25) (black arrows) and their extent (grey contour) (from Osprey et al.,2016 [7]).

1.2 Mechanism of the 2015/16 disrupted QBO

During the winter of 2015/16, an unexpected shift from westerly (w_{QBO}) to easterly (e_{QBO}) winds occurred. In January 2016, e_{QBO} phase develops in the center of the w_{QBO} phase early before the w_{QBO} phase completed the 28 months cycle (see Fig. 1B) [6, 7]. As suggested by Osprey et al. 2016 [7], planetary Rossby waves propagating from the northern hemisphere (NH) to the southern hemisphere (SH) in the winter stratosphere most likely accounted for the QBO disruption. During winter, planetary waves normally propagate upward from the mid-latitudes to the upper stratosphere, break and deposit their westward momentum there. In February 2016, a strong easterly subtropical jet developed in the upper stratosphere between 35–10 hPa, which prevented the waves from propagating upward causing them to be reflected horizontally equatorward (see Fig. 1C). The austral summertime westward winds prevented the Rossby waves from propagating into the SH, resulted in wave breaking and westward acceleration [7, 8]).

2 Impact of the disruption on tracer gases in the tropical lower stratosphere

The Brewer-Dobson circulation (BD-circulation) [9] is the stratospheric mean meridional circulation defined as a slow circulation, in which air rising from equator is transported polarward into the stratosphere. BD-circulation undergoes an annual cycle and changes on interannual timescales. A major mode of variability is the QBO, which triggers a modulation of vertical transport in the stratosphere by affecting temperature and thus heating rates [10, 11]. According to Plumb and Bell, 1982 [12], the e_{QBO} phase enhances upward transport while w_{QBO} reduces the upward motion and transports rapidly stratospheric trace gases and aerosols towards the poles. This modulation of the BD-circulations is illustrated on Fig. 2 modified from Trepte et al., 1992 [13]. Thus, this disruption of the QBO during the winter of 2015/16 is expected to modify the BD-circulation, therefore impacting the transport and distribution of stratospheric trace gases [8]. Using Aura Microwave Limb Sounder (MLS) ozone (O_3) and water vapor (H_2O), Tweedy et al., 2017 [14] analysed the response of these trace gases to the disrupted 2015/16 QBO. This study concluded that while changes in the global stratospheric O_3 and H_2O from late spring–fall 2016 are attributed mostly to the disrupted QBO event, strong El Niño in the 2015/16 winter could strongly bias their analyses in the lower stratosphere. Randel et al., 2009 [15] showed that El Niño cools the tropical lower stratosphere and strengthens the tropical upwelling, therefore decreasing O_3 and increasing H_2O in the lower stratosphere.

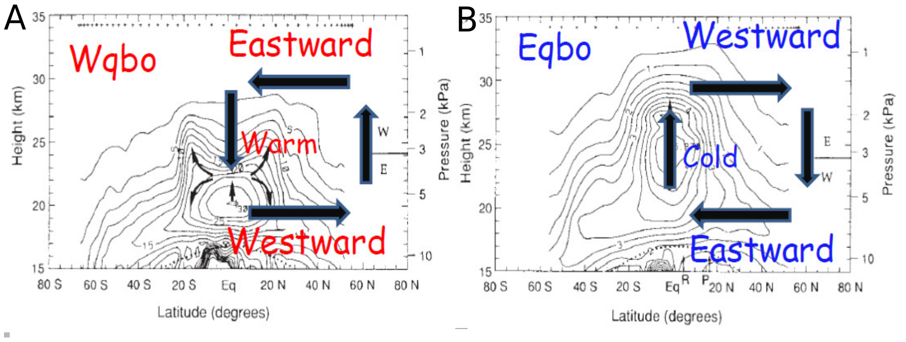

Figure 2: **QBO modulation of the BD-circulation.** Latitude-altitude cross-sections of aerosol extinction ratio at 1 μm during two 40-day periods representative of two different phases of the QBO. (A) Dominant w_{QBO}, centred about 11 November 1984, contour interval 2.5. (B) dominant e_{QBO}, centred about 4 October 1988, with contour interval 0.5. Arrows indicate the infered QBO circulation based on the aerosol distribution. The climatological tropopause is indicated by a dashed line. R and P indicate the latitudes of Mounts Ruiz and Pinatubo (from Trepte et al.,1992 [13]).

2.1 Multiple linear regression model

To properly disentangle the QBO impact on the tracer gases in the tropical lower stratosphere from the other natural variabilities, the 2005–2016 monthly zonal mean ozone (O_3) and water vapor (H_2O) from MLS satellite product [16], as a function of latitude (ϕ) and altitude (z), is analysed by using a multiple linear regression model from Diallo et al., 2012 [17]. We go beyond this previous work by including the Aerosol Optical Depth (AOD)[18] term into the multiple linear regression method in order to take into account the effect of aerosol on the mean age and its trends. This model yields for a give trace gas, χ

$$\chi(t,\phi,z) = a(\phi,z)\cdot t + C(t,\phi,z) + b_1(\phi,z)\cdot \mathrm{qbo}(t-\tau_{\mathrm{qbo}}) + b_2(\phi,z)\cdot \mathrm{enso}(t-\tau_{\mathrm{enso}}) + \\ b_3(\phi,z)\cdot \mathrm{aod}(t-\tau_{\mathrm{aod}}) + \varepsilon(t,\phi,z) \qquad (1)$$

where qbo is a normalised QBO index from CDAS/Reanalysis zonally averaged winds at 30 hPa, enso is the normalised Multivariate ENSO Index (MEI) [19] and aod is the AOD from satellite data [18]. AOD from the other data sets yields the similar result.The coefficients are a linear trend a, the annual cycle $C(t,\phi,z)$, the amplitude b_1 and the delay τ_{qbo} associated to the QBO, the amplitude b_2 and the delay τ_{enso} associated to ENSO and the amplitude b_3 and the delay τ_{aod} associated to AOD. The constraint applied to determine the parameters a, b_1, b_2, b_3, τ_{qbo}, τ_{enso}, τ_{aod} and C is to minimise the residual $\varepsilon(t,\phi,z)$ in the least square sense. As the combination of amplitude and delay introduces a non linear dependency, there are multiple minima as a function of the parameters. In order to determine the optimal values of τ_{qbo}, τ_{enso} and τ_{aod}, the residual is first minimised at fixed lag and then over a range of lags. Here we neglect solar forcing, because our data set covers only two solar periods.

2.2 Tropical lower stratospheric O_3 and H_2O response to the QBO disruption

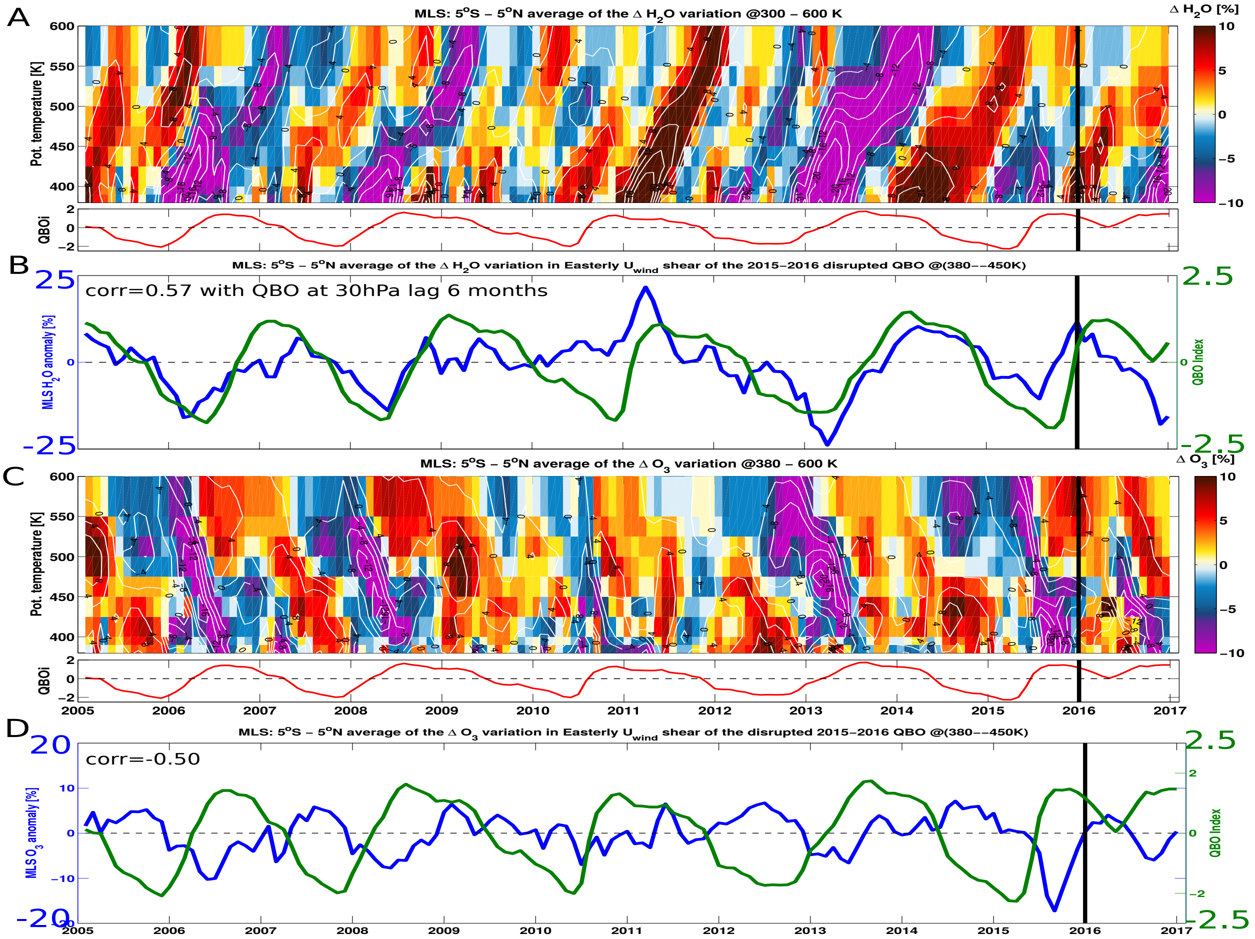

Figure 3: **Disrupted 2015/16 QBO impact on tropical lower stratospheric ozone and water vapor from MLS data set.** (A) Time-altitude cross-sections of the 10°S–10°N monthly-mean H_2O response to the QBO variability derived from the multiple linear regression fit over the 2005-2016 time period. The small panel below indicates the QBO index (red line). (B) Tropical H_2O changes related to the QBO variability derived from (A) and averaged over 380-450 K. (Blue line): H_2O anomalies, (Green line): QBO index at 30 hPa. (C) Time-altitude cross-sections of the monthly-mean tropical O_3 response to the QBO variability derived from the multiple linear regression fit over the 2005-2016 time period. The small panel below indicates the QBO index (red line). (D) Tropical O_3 changes related to the QBO variability derived from (C) and averaged over 380-450 K. Vertical black line indicates the January 2016. Black contours indicate the anomalies. The Lag-correlation of the QBO is estimated from the fit and is equal to 6 months.

Figures 3(A-D) show the amplitudes of the QBO impact on the variability of the water vapor and ozone in the tropical lower stratosphere. Clearly, QBO strongly modulates the tropical water vapor and ozone entering the stratosphere. Remarkably, these trace gases reveal a footprint of the disruption (black vertical line in the figures). The e_{QBO} phase decreases O_3 and increases H_2O with a delay by enhancing upward transport of young air poor in ozone and rich in water vapor. The water vapor changes related to disruption at 40 hPa are delayed in the lower stratosphere due to fact that water vapor is a tropospheric trace gases. The w_{QBO} phase decreases the upward motion of the circulation inducing the opposite effect on trace gases in the lower stratosphere. Figure 3A shows a regular QBO impact on the H_2O anomaly from 2005-2015 followed by its drastic decrease in the tropical lower stratosphere (up to about 20%), which reaches its maximum in fall 2016. Our results show an increase of water vapor in the tropical lower stratospheres. Figure 3B shows that the decreasing H_2O in the lower stratosphere is correlated at 0.57% to the QBO variability. The e_{QBO} and w_{QBO} phases induce a regular variability in the stratospheric O_3 as shown on Figure 3(C,D). With a simultaneous presence of e_{QBO} and w_{QBO} wind shear in the tropics, the stratospheric circulation responded to the disruption by decreasing the tropical stratospheric O_3 between 380–450 K by up to 10% and increasing O_3 by up to 15% above (Fig. 3C). This O_3 anomaly correlates with the disrupted 2015/16 QBO at -0.55 in the lower stratosphere (Fig. 3D). The O_3 response to the disruption is consistent with Tweedy et al., 2017 [14].

3 Conclusion

The unexpected disruption of the QBO, induced by the planetary Rossby waves propagating from the NH into the tropics during the 2015/16 winter, and its impact on the stratospheric circulation was presented in this report. By using a multiple linear regression model and stratospheric observed trace gases from MLS data set, we found that the 2015/16 disrupted QBO during the NH winter substantially changed the composition of the stratosphere. These changes are due to the close relationship between the BD-circulation and QBO variability. The unexpected shift from w_{QBO} to an e_{QBO} during the NH winter of 2015/16 induced a decreasing water vapor and ozone between 380–450 K and an increase between 460-600 K after April 2016. Overall, our findings are consistent with Tweedy et al., 2017 [14].
[1]

---

[1] **Acknowledgments:** We thank the SPARC Organising committee of the training school in Cape Town, particularly to Fiona Tummon, who made everything easy for us and for the chocolates. The authors want also to thanks all the professors (Elisa Manzini, Bernd Funke, Nili Harnik, Joan Alexander, Thando Ndarana, Michaela Hegglin, Katja Matthes and Mark Baldwin) for sharing their interesting research and findings and, particularly for their helps and time. Finally, we thanks all the beautiful people that we met during the training school, hopefully collaborating in near future.

References

[1] Baldwin, M. P. and Gray, L. J. and Dunkerton, T. J. and Hamilton, K. and Haynes, P. H. and Randel, W. J. and Holton, J. R. and Alexander, M. J. and Hirota, I. and Horinouchi, T. and Jones, D. B. A. and Kinnersley, J. S. and Marquardt, C. and Sato, K. and Takahashi, M., The quasibiennial oscillation, *Reviews of Geophysics*, *39*(2), pp. 179-229, 2001, doidoi:10.1029/1999RG00007.

[2] Ebdon, R. A. 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*, 86, pp. 540-542, 1960.

[3] Reed, R. J., W. J. Campbell, L. A. Rasmussen, and R. G. Rogers, Evidence of a downwardpropagating, annual wind reversal in the equatorial stratosphere, *J. Geophys. Res.*, *66*, 813-818, doidoi: 10.1029/JZ066i003p00813, 1960.

[4] Holton, James R., and Hsiu-Chi Tan. The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb, *J. Atmos. Sci.*, *37*, 2200-2208, doidoi:10.1175/1520-0469(1980)037¡2200:TIOTEQ¿2.0.CO;2, 1980.

[5] Peter Hitchcock and Isla R. Simpson, Quantifying Eddy Feedbacks and Forcings in the Tropospheric Response to Stratospheric Sudden Warmings, *Journal of the Atmospheric Sciences*, *73*(9), pp. 3641-3657, 2016, doidoi:10.1175/JAS-D-16-0056.1.

[6] Newman, P. A., L. Coy, S. Pawson, and L. R. Lait (2016), The anomalous change in the QBO in 2015-2016, *Geophys. Res.Lett.*, *43*, 8791-8797, doidoi:10.1002/2016GL070373.

[7] Osprey, S. M., Butchart, N., Knight, J. R., Scaife, A. A., Hamilton, K., Anstey, J. A., Schenzinger, V. and Zhang, Ch., An unexpected disruption of the atmospheric quasi-biennial oscillation, *Science*, *353*, 1424-1427, 2016, doidoi:10.1126/science.aah4156

[8] Coy, L., Newman, P. A., Pawson, S. and Lait, L. R., Dynamics of the Disrupted 2015/16 Quasi-Biennial Oscillation, *Journal of Climate*, *30*(15), 5661-5674, 2017, doidoi:10.1175/JCLI-D-16-0663.1.

[9] Butchart, N. (2014), The brewer-dobson circulation, *Reviews of Geophysics*, *52*(2), 157–184, doidoi: 10.1002/2013RG000448.

[10] Niwano, M. and Yamazaki, K. and Shiotani, M.,Seasonal and QBO variations of ascent rate in the tropical lower stratosphere as inferred from UARS HALOE trace gas data, *J. Geophys. Res.*, *108*, pp. 4794, 2003, doidoi:10.1029/2003JD003871.

[11] Punge, H. J. and Konopka, P. and Giorgetta, M. A. and Müller, R., Effect of the quasi-biennial oscillation on low-latitude transport in the stratosphere derived from trajectory calculations, *J. Geophys. Res.*, *114*, D03102, doidoi:10.1029/2008JD010518.

[12] Plumb, R. Alan and Bell, Robert C., A model of the quasi-biennial oscillation on an equatorial beta-plane, *Q. J. R. Meteorol. Soc.*, *108*(456), 335–352, doidoi:10.1002/qj.49710845604, 1982.

[13] Trepte, C. R., and M. H. Hitchman (1992), Tropical stratospheric circulation deduced from satellite aerosol data, *Nature*, *355*(0028-0836), 626–628, doidoi:10.1038/355626a0.

[14] Tweedy, O. V., Kramarova, N. A., Strahan, S. E., Newman, P. A., Coy, L., Randel, W. J., Park, M., Waugh, D. W., and Frith, S. M.: Response of trace gases to the disrupted 20152016 quasi-biennial oscillation, *Atmos. Chem. Phys.*, *17*, 6813-6823, doidoi:https://doi.org/10.5194/acp-17-6813-2017, 2017.

[15] Randel, W. J., R. R. Garcia, N. Calvo, and D. Marsh (2009), Enso influence on zonal mean temperature and ozone in the tropical lower stratosphere, *Geophys. Res. Lett.*, *39*(L15822), doidoi: 10.1029/2009GL039343.

[16] Livesey, N. J., M. J. Filipiak, L. Froidevaux, W. G. Read, A. Lambert, M. L. Santee, J. H. Jiang, H. C. Pumphrey, J. W. Waters, R. E. Cofield, D. T. Cuddy, W. H. Daffer, B. J. Drouin, R. A. Fuller, R. F. Jarnot, Y. B. Jiang, B. W. Knosp, Q. B. Li, V. S. Perun, M. J. Schwartz, W. V. Snyder, P. C. Stek, R. P. Thurstans, P. A. Wagner, M. Avery, E. V. Browell, J.-P. Cammas, L. E. Christensen, G. S. Diskin, R.-S. Gao, H.-J. Jost, M. Loewenstein, J. D. Lopez, P. Nedelec, G. B. Osterman, G. W. Sachse, and C. R. Webster (2008), Validation of aura microwave limb sounder o3 and co observations in the upper troposphere and lower stratosphere, *J. Geophys. Res.*, *113*(D15S02), 10,195–10,213, doidoi:10.1029/2007JD008805.

[17] Diallo, M., B. Legras, and A. Chédin (2012), Age of stratospheric air in the era-interim, *Atmos. Chem. Phys.*, *12*, 12,133–12,154, doi:10.5194/acp-12-12133-2012.

[18] Vernier, J. P and Thomason, L. W. and Pommereau, J. P. and Bourassa, A. and Pelon, J. and Garnier, A. and Hauchecorne, A. and Trepte,C. and Degenstein, D. and Vargas, F. (2011), Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade, *Geophys. Res. Lett.*, *38*, L12,807, doidoi:10.1029/2011GL047563.

[19] Wolter, K., and M. S. Timlin (2011), El nino/southern oscillation behaviour since 1871 as diagnosed in an extended multivariate enso index (mei.ext), *Int. J. Climatol.*, *31*, 1074–1087, doidoi:10.1002/joc.2336.