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Atmospheric Chemistry and Physics Discussions

Interactive comment on "On the forcings of the unusual QBO structure in February 2016" *by* Haiyan Li et al.

Anonymous Referee #3

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This is an interesting study that sheds more light on the dynamics that led to the anomalous QBO structure in early 2016. By spectral filtering horizontal momentum flux of Rossby waves and vertical momentum flux of Kelvin waves is deduced for the years 1958-2017 using the ERA-40 and ERA-Interim reanalyses. In agreement with previous work, it is found that the anomalous QBO westerlies are forced by Rossby waves from the extratropics. The three known cases of strong extratropical Rossby wave forcing during QBO easterly phases (1959/1960, 2010/2011, and 2015/2016) are compared. What is new and exciting in Lin et al. is the attribution of the anomalous QBO forcing to different regimes of Rossby waves. It is shown that Rossby waves of 5-20days period play an important role, and different from the 1959/1960 and 2010/2011 events, a wavenumber 3 Rossby wave is generated at 15N by wave wave interaction of

quasi-stationary waves 1 and 2. This wave also seems to play an important role in the anomalous forcing. The extended period of QBO westerlies is attributed to enhanced Kelvin wave activity caused by El Nino.

Overall, the paper is well written and of relevance for the readership of ACP. Publication is therefore recommended after addressing my major comments. Addressing these comments should however be straightforward.

Major comments:

(1) Usually, to capture the propagation and interaction of global scale waves Eliassen Palm (EP) fluxes are calculated. You are calculating only <u'w'> (vertical momentum flux) and <u'v'> (horizontal momentum flux) which are only part of the EP flux and do not mention the limitations of this approach.

(2) The whole study is based on the kf-filter method. However, almost no information is given how this method was applied.

Specific comments:

(1) General comment: When discussing momentum fluxes, you often do not state clearly what you are discussing - the momentum fluxes, or their anomaly. This happens in the text, as well as in the figure captions and in the figure legends! In my comments, I mentioned only a few occurrences because they are too many. Please revise carefully throughout!

(2) General comment: 20hPa (about 27.5 km altitude) is in the middle stratosphere, not the upper stratosphere. The stratosphere extends from about 10-20km to about 50km. Please revise carefully throughout the paper!

(3) p.2, l.44-46 here you write: The eastward propagating Kelvin waves provide the

main eastward acceleration for the initiation of the QBO westerly phase. In contrast, the westward propagating Rossby waves provide the main westward acceleration for the initiation of the QBO easterly phase.

This is not entirely correct because also small scale gravity waves contribute. Mainly both Kelvin waves and small scale gravity waves contribute to the forcing of the QBO westerly phase, while global scale westward traveling tropical waves and small scale gravity waves contribute to the forcing of the QBO easterly phase (see for example Ern and Preusse, GRL, 2009 and Ern et al., JGR, 2014, Garcia and Richter, JAS, 2019).

References:

Ern, M., and P. Preusse, Quantification of the contribution of equatorial Kelvin waves to the QBO wind reversal in the stratosphere, Geophys. Res. Lett., 36, L21801, doi:10.1029/2009GL040493, 2009.

Ern, M., F. Ploeger, P. Preusse, J. C. Gille, L. J. Gray, S. Kalisch, M. G. Mlynczak, J. M. Russell III, and M. Riese, Interaction of gravity waves with the QBO: A satellite perspective, J. Geophys. Res. Atmos., 119, 2329-2355, doi:10.1002/2013JD020731, 2014.

Garcia, R. R., and J. H. Richter, On the Momentum Budget of the Quasi-Biennial Oscillation in the Whole Atmosphere Community Climate Model, J. Atmos. Sci., 76, 69-87, 2019.

(4) p.3, l.68: These references address only global scale waves. A reference for small-scale gravity waves should be added. Using model simulations, differences in the QBO forcing by gravity waves for different ENSO conditions were investigated, for example, by Kang et al., JAS, 2018.

Reference:

Kang, M.-J., H.-Y. Chun, Y.-H. Kim, P. Preusse, and M. Ern, Momentum Flux of Convective Gravity Waves Derived from an Offline Gravity Wave Parameterization. Part II:

Impacts on the Quasi-Biennial Oscillation, J. Atmos. Sci., 75, 3753-3775, 2018.

(5) p.3, l.91: Please state more clearly that a merged ERA-40/ERA-Interim dataset is used to have a longer time series because ERA-Interim starts with the year 1979 and does not cover the earlier period.

(6) p.4, l.114/115: You should elaborate much more on the kf-filter! As far as I understand, for a fixed latitude and altitude, you enter the whole time series of 60 years with a longitude resolution of 2.5 deg into the kf-filter. The time series is tapered to zero at both ends. Which function is used? Split-cosine-bell as stated in https://www.ncl.ucar.edu/Document/Functions/Built-in/taper.shtml ? Did you use the standard settings of the taper of p=0.1? In this case, you would have to discard 3 years at each end of the time series and valid data are obtained only for 1961-2014. This would contradict your statement on p.5, l.139 that only the years 1958 and 2017 would be affected. Please explain!

(7) p.5, about section 2.3: Please explain why you calculate momentum fluxes in this way! Possibly, you are missing something or biasing your analysis by not calculating the full EP flux vector! Therefore at least the limitations of your approach should be clearly stated.

Usually, for global scale waves EP fluxes are calculated to capture their propagation and effect on the background flow, however you are neglecting heat fluxes.

By calculating <u'v'> you are using the quasi-geostrophic approximation of the EP flux in meridional direction (see for example Matthias and Ern, ACP, 2018). This approximation can be used for extratropical Rossby waves and should be sufficient for diagnosing the meridional propagation direction of Rossby waves from the extratropics. In the tropics, however, wave motions can become ageostrophic, and this approximation may no longer hold. This is the case for tropical waves like Kelvin waves or tropical Rossby waves.

The term <u’w’> is part of the vertical component of the EP flux and should be a a good approximation for Kelvin waves because v’ is zero for these waves.

Reference: Matthias, V., and M. Ern, On the origin of the mesospheric quasi-stationary planetary waves in the unusual Arctic winter 2015/2016, Atmos. Chem. Phys., 18, 4803-4815, 2018.

(8) p.5, l.149/150: here you state that Rossby waves would not contribute much to <u’w’> as could be seen from Figs. S1 and S2 in the supplement. In the supplement, however, only "anomalies" of <u’v’> and <u’w’> from their monthly means are shown.

(9) captions of Figs. 3, S1 and S2: First you write that horizontal momentum fluxes would be shown, and later in the caption you write that color shadings would be anomalies with respect to the monthly climatology. This is very confusing, please write more clearly!

(10) Follow-up question: Were the monthly climatologies temporally interpolated to single days to avoid jumps in the anomalies from one month to the other? Please clarify!

(11) p.5, l.152/153 and l.155: This is not entirely correct: Shuckburgh et al. (2001) investigated only barotropic instabilities, not baroclinic instabilities! Only Coy et al. (2017) included also baroclinic instabilities.

(12) p.7, l.210: Why did you select w2040 for the quasi-stationary Rossby waves, and not w2070? Choosing w2070 would be much more intuitive!

(13) p.7, l.214-219: Would also the contributions of w2070 be similar in all three cases? Please note that w0520 and w2040 do NOT sum up to the "total Rossby" fluxes! Possibly w4070 might show also considerable case to case variability.

(14) p.10, l.305: here you state: "the quasi-stationary W1 and the faster W2 which came from the extratropics, generated W3 locally..."

This contradicts your statements from above that W3 was generated by W1 and W2 of 0.033 dayˆ-1 which are both in your quasi-stationary range of frequencies. Please clarify!

(15) p.10, l.313/314: here you state that: "W3 cannot be an equatorial wave mode in principle, otherwise its amplitude would be by definition maximizing at the equator."

I think that this statement does not generally hold. Equatorial Rossby modes can be symmetric or anti-symmetric with respect to the equator. Therefore either u’ or v’ could be zero at the equator, leading to zero <u’v’>. For a survey of equatorial modes see, for example, Yang et al., JAS, 2003, their Fig.3.

Reference: Yang, G.-Y., B. Hoskins, and J. Slingo, Convectively Coupled Equatorial Waves: A New Methodology for Identifying Wave Structures in Observational Data, J. Atmos. Sci., 60, 1637-1654, 2003.

(16) p.10, l.325: Enhanced momentum flux does not necessarily mean that the zonal wind is accelerated or decelerated. There is only an effect on the background flow when this momentum is deposited (if there is a non-zero divergence of the EP-flux). Of course, enhanced momentum fluxes can lead to stronger EP-flux divergences.

(17) About Figs.13 and 14: As Kelvin waves in the stratosphere are modulated rather by the QBO than by a seasonal cycle, does it really make sense to show deviations of Kelvin wave amplitudes or momentum flux from a monthly mean climatology?

(18) p.12, l.360/361: Another possibility could be that these Kelvin waves have phase speeds that exceed the westerly wind. As can be seen, for example, in Ern et al., ACP, 2008, Kelvin waves with high phase speeds are not much modulated by the QBO, while slower phase speed Kelvin waves are strongly modulated by the QBO with minimum amplitudes during westerly winds.

Reference: Ern, M., P. Preusse, M. Krebsbach, M. G. Mlynczak, and J. M. Russell III, Equatorial wave analysis from SABER and ECMWF temperatures, Atmos. Chem.

Phys., 8, 845-869, 2008.

(19) p.13, l.417/418: This is not correct: Both W1 and W2 have the same frequency and fall in the frequency range that you call quasi-stationary.

Other comments:

(1) p.2, l.35: The westerly mean flow in the tropical stratosphere generally favors -> If the mean flow in the tropical stratosphere is westerly, it generally favors

(2) p.5, l.150: Fig.12a does not exist! Should this read Fig. S1? Please check!

(3) Caption of Fig.1, l.2: ??? horizontal Rossby wave momentum flux -> Rossby wave horizontal momentum flux anomaly

(4) Caption of Fig.1: Different from what is stated in the caption, there are no red triangles in Fig.1a

(5) p.6, l.180 / Fig.2: It is unclear what is shown! Probably your notation is misleading! In the figure legend of Fig.2 it reads: <du'ˆ2>, suggesting that you calculate a climatological u' distribution, and you are showing deviations from that average u' for a particular period. In this case, however, there could be no negative values because values are squared for display! So my guess is that it should read d<u'ˆ2> in the figure legend. Similar, in Fig.3 it should probably read d<u'v'> instead of <du'v'>.

(6) p.6, l.190: horizontal Rossby waves momentum flux -> Rossby wave horizontal momentum flux anomalies

(7) Fig.5: Please mention in the figure caption that "total Rossby wave" corresponds to w0570.

(8) p.8, l.251: momentum flux -> momentum flux anomaly

(9) p.8, l.251, suggested rewording, as this cannot be seen from Fig.9: The contribution

of Rossby waves w0520 is largest in February -> In the tropics, the largest anomaly of Rossby waves w0520 is found in February

(10) p.8, l.252: momentum flux was stronger -> momentum flux anomaly was stronger

(11) caption of Fig.10, l.1: horizontal momentum fluxes -> horizontal momentum flux anomalies

(12) Caption of Figs. S5 and S6: Please mention the altitude/pressure of these sections.

(13) p.9, l.283: and below -> and at higher altitudes

(14) p.9, l.284: period below 40 hPa. -> period at pressures below 40 hPa.

(15) p.9, l.284: The meridional gradient starts -> At 40 hPa the meridional gradient starts

(16) p.9, l.285: barotropic and baroclinic -> barotropic and/or baroclinic

(17) p.10, l.298: W3 has the most complex peaks, the stronger peaks are corresponding to the frequencies are at -> W3 has a broad peak with the strongest contributions at

(18) In Fig.14b: why are the lines interrupted? Are no-shows insignificant values? If yes, please state in the figure caption!

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