Response to reviews of "On the forcings of the unusual QBO structure in February 2016" by Haiyan Li et al.

Dear Editor,

We would like to thank the three anonymous reviewers for their comments and suggestions, which led to a substantial improvement of the manuscript's quality. In our 'General comments from the authors' (below), the most significant changes made in the manuscript are grouped and explained in more detail.

In the following paragraphs, we include our *point-by-point responses (in dark gray)* to each **reviewer comment (bold black)**.

In the revised manuscript with tracked changes, minor and technical revisions are marked in blue, whereas more substantial changes are highlighted in yellow.

Yours sincerely,
Haiyan Li
Robin Pilch Kedzierski
Katja Matthes

General comments from the authors:

In going through all reviewer's comments, we identified three main issues in our manuscript:

1) Clarity of 'Wave filtering' section (2.2), justification and limitations of the 'Momentum flux calculation' section (2.3):

Significant parts of sections 2.2 and 2.3 have been rewritten. In section 2.2 we prioritized clarity about the options the kf-filter has, as well as the use the use given to them. In section 2.3 we specify that ours is a simplified approach, stating its limitations while reassuring the reader that the method is sufficient for the purposes of the study. Here we particularly appreciate the reasoning and reference suggestion by reviewer #3.

2) The wave resonance mechanism: reviewers #1 and #3 pointed out inconsistencies in our interpretation of Fig. 11 and attributing specific peaks in the frequency spectra to the resonating W1 and W2 of extratropical origin.

We didn't realize these inconsistencies before, and as the reviewers pointed out the interpretation of the resonance mechanism wasn't in line with the results from Figs. 10 and 11.

We've performed a more detailed analysis of the frequencies of W1-3, and it turned out that all had varying speeds/frequencies during the Feb. 2016 event (see the updated Fig.11 and related discussion in section 3.1.3 in the new manuscript version). Therefore individual peaks in the frequency spectra of the previous manuscript version didn't really correspond to the W1-3 properties during the resonance event. The more detailed results presented now support the main conclusions in a more robust way.

3) Lack of literature and discussion about ENSO and Kelvin waves:

We apologize for this, we should have looked more into this topic before completing the submitted manuscript. We appreciate the reviewer's suggestions and literature, which we inserted into the introduction and the discussion of the results in section 3.2.

Point-by-point responses to Reviewer #1:

Specific Comments:

1. **Line 268- All components of a Rossby wave packet do not necessarily travel together since the Rossby wave is dispersive.**

We meant that the relative contributions of the different wavenumbers of a travelling Rossby wave packet remain more or less similar during its lifetime, since the troughs-ridges do not expand-contract in longitude (e.g. in Hovmoller diagrams of upper-tropospheric extratropical RWPs). We rephrased this sentence into: *'Strictly speaking, the wavenumber composition of a travelling Rossby wave packet should remain similar during its lifetime: the dominant wavenumber does not change. Our analysis shows that this is not the case with W3 which becomes dominant.'*

2. **Line 300 - It seems somewhat contrived to choose the 0.066/day peak to discuss the W3 being locally generated when that is not the frequency with the strongest power. Where does the power at 0.055/day come from?**

   +

3. **Line 303 - I am also somewhat unclear on the following: you claim that a combination of the fast W2 (momentum flux Fig. 10c) and slow W1 (amplitude Fig. 10e) create the slow W3. When you say fast W2 are you talking about the w0520 Rossby wave? The 0.033/day frequency implies a period of 30 days, which is inconsistent with your "fast W2" resonance theory. Can you elaborate?**

Thank you for pointing this out. We agree with your and reviewer #3 comments that the results in Fig. 11 and the corresponding discussion in section 3.1.3 contained some inconsistencies, which we didn't realize previously. We've performed a much more detailed analysis, shown in the new Fig. 11 and we've rewritten the corresponding part in section 3.1.3. It turned out that all wavenumbers have changing speeds/frequencies during their lifetime in early 2016, therefore a single peak in their Fourier spectrum (Fig. 11 in the previous manuscript) was not necessarily representative of what was happening in February 2016.

In the new Fig. 11 it is shown that, despite the changing wave frequencies, resonance conditions (dark blue in Fig. 11d) were present for a fair amount of time in the subtropics and near the equator during late January and the first half of February, coincidentally with the amplification and the strongest momentum fluxes of W3 (Fig. 10d). In other latitudes and times, resonance conditions (dark blue) do not last more than a couple of days in a row. We hope that the current analysis of the resonance theory is more convincing now.

4. **Line 350- Enhanced with respect to what? The previous winter? Of course the Kelvin wave activity depends on the wind structure. There are no Kelvin waves here until February because the winds are too strong westerly. The general tropospheric Kelvin wave activity looks to be lower than the previous winter too.**

   +

5. **Line 356 - Again, is the Kelvin wave momentum flux "enhanced" just because Kelvin waves can propagate into this region of weak westerlies? If yes, this is not surprising.**

We rephrased these two paragraphs using 'above-average' instead of 'enhanced' for clarity.

6. **Line 360 - This is not necessarily true. Kelvin waves can propagate through westerly flow as long as their phase speed is greater than the flow speed. So the fact that the westerlies are weak in this case allows them to do so.**

Many thanks for this comment, this makes more sense. We substituted the reasoning for vertical Kelvin wave propagation within weak westerlies accordingly.

7. **Line 374 - In the standard QBO paradigm, increased Kelvin wave activity causes descent of the westerlies, because the waves accelerate the flow below their critical level, which in turn lowers the critical level, and so on. Why in this case does the increased Kelvin wave activity not promote descent?**

We added the following discussion at the end of the paragraph: *'Typically, Kelvin wave momentum deposition promotes downward propagation of the QBO westerly phase, since the waves encounter westerly shear and a rather narrow region below the critical level near the bottom of the QBO* *westerlies where the Kelvin wave momentum is deposited. This is not the case in early 2016, with weak westerlies (weak easterlies later on), low shear between 100 hPa and 20 hPa, and easterly shear above. These sub-critical conditions make the height range for Kelvin wave momentum deposition quite broader than usual, thereby enabling a prolongation and even upward propagation of the westerly QBO phase. This interpretation would be in agreement with Das and Pan (2015), who found faster-descending QBO westerly phase only when the lower stratospheric winds favored Kelvin wave upward propagation (not the case in early 2016).'*

8. **Line 394 – There are a few studies to have linked Kelvin wave activity to El Nino. Cf. Yang and Hoskins (https://doi.org/10.1175/JAS-D-13-081.1), Das and Pan (https://doi.org/10.1016/j.scitotenv.2015.12.009), Rakhman et al (doi:10.1088/1755-1315/54/1/012035)**

Thank you for this suggestion and for the valuable references. We removed the sentence '*To our knowledge, the enhanced Kelvin wave activity and its relation to ENSO has not been noted previously.'* which was wrong, and we added the references into the previous paragraph discussing Fig. 15.

Technical Corrections:

9. **Figure 1 caption - Please delete the first instance of "The vertical blue lines denote the time periods..." in the first sentence (it is repeated later). In panel (a) there are no red triangles, so either add them or do not mention them in the penultimate sentence.**

Corrected.

10. **Figure 5 - The label should read "Total Rossby wave" (typo)**

Corrected.

11. **Figure 8 - Can you add a legend to this figure? Also, are the time axes correct? You mention on Line 241 different months for the peaks in each year, but these all peak in February.**

Corrected. Note that in the sentence referring to Fig. 8, the peaks where meridional propagation is most clear are mentioned, not necessarily the strongest ones. We rephrased this sentence for better clarity.

12. **Figure 10 caption - Please move the sentence about Panel (e) to the end, the descriptions that follow it all refer to the other panels so it is a little confusing.**

Corrected.

13. **Figure 11 caption - "February" (typo)**

Corrected.

Point-by-point responses to Reviewer #2:

General comments: First of all, this manuscript can benefit from some revisions and editing to improve for clarity and conciseness. Some recommendations are provided in the comments below. As everyone's writing style is different, those comments are by no means requirement but rather indications where writing could benefit from some editing to make your massage clearer. Second, some clarifications should be done in Data and Methods section. Line by line comments are provided below. For example, I strongly recommend to rewrite "Wave filtering" subsection in a more clear way as it can be very confusing to some. In several places, your statements like "It is difficult to (do something) " can be confusing as it is not very clear if you've applied your technique to the dataset. How did you do your filtering or any other analysis step by step? State these steps first without any unnecessary information and then provide any relevant comments regarding these techniques at the end. See more detailed comments below. Furthermore, Introduction or/and Discussions are lacking a discussion of literature on relationship between ENSO and Kelvin waves. While a role of enhanced Kelvin Wave activity due to strong 2015/2016 El Nino event in producing the extended westerly zonal wind near 20 hPa is definitely new (and very interesting) result, the enhanced Kelvin wave activity and its relation to ENSO definitely was previously looked at and documented. For instance paper by Yang and Hoskins (2013) along with others should be mentioned and cited. [Yang, G. and B. Hoskins, 2013: ENSO Impact on Kelvin Waves and Associated Tropical Convection. J. Atmos. Sci., 70, 3513–3532, https://doi.org/10.1175/JAS-D-13-081.1]

Many thanks for your suggestions and new literature. We've addressed all the detailed line-by-line comments below.

Specific comments:

1. **Line 95: Why is combined ERA-40 and ERA-Interim reanalyses are used instead of just using ERA-40 or ERA-Interim reanalyses by itself. It would be useful for readers to see a short statement explaining benefits and limitations of individual datasets vs combined one.**
   The sentence now reads: *'For this study, we use the combined European Center for Medium-Range Weather Forecasts (ECMWF) ERA-40 and ERA-Interim reanalysis data sets (Uppala et al. 2005, Dee et al. 2011), which extends from 1958 to 2017. This was done to use the longest timeseries up to the 2016 QBO reversal to cover as many QBO cycles and ENSO events as possible, instead of starting from 1979 with ERA-Interim alone.'*

2. **Line 96: Using layer averaging (30-50 hPa) to represent 40hPa level is fine if 40 hPa level is not available as an output. However, this (or other reasons for layer averaging) should be mentioned.**
   We mention this now in the sentence.

3. **Line 106: "similar to U40". Is U20 also defined as a layer averaged U between two pressure levels? Please clarify.**
   We added '*Both ERA-40 and ERA-Interim provide the 20 hPa level so no averaging is needed*' for clarity.

4. **Line 115-117: "Previous studies... " How this sentence connects to the filtering techniques you are discussing? This seems an odd place for comparison with previous studies unless you are comparing techniques that you are using in this study with one's in previous studies.**
   We agree with the reviewer and this sentence has been deleted.

5. **Line 118: "following dispersion curve" Is it a part of the "kf-filter" function technique or something you performed after applying this filter. If it is unrelated to the "kf-filter" than Line 112 shouldn't be a fist sentence of this paragraph.**
   +

6. **Line 118, also line 124 A use of statements like "it is difficult … " or "we can .." are very confusing and distracting since I am not sure if you applied the technique to your data or just speculating about it. Make sure you are clearly explaining your methods.**

We've rewritten parts of section 2.2 to improve clarity, especially in the first half. We hope the filtering method is easier to follow now.

7. **Line 173: “was weaker”. What do you mean by this (its amplitude or persistence in time)? To my eye these three events don’t stand out very well when compared to other years in this record but I could be missing something. Being specific may help.**

   We rephrased this sentence as follows:

   'Figure 1b shows that the amplitude of westerly zonal wind was weaker in a number years (e.g., 1959/1960, 2010/2011) but the westerly zonal wind only reversed its direction in the 2015/2016 at 40 hPa.'

   There are many other events where westerlies are weaker than usual, as the reviewer is pointing out, but the ones we picked also show strong deviations of Rossby wave momentum fluxes (Fig. 1d). This is shortly mentioned in the next paragraph but now we highlight this feature earlier on.

8. **Line 184: “However, we cannot ...” very wordy sentence. How about something like this : “Since enhanced Rossby wave behavior doesn’t extend to the lower and higher levels, the observed signal less likely originated from vertical propagation.” Side note: Please comment a strong signal in enhanced Rossby wave activity during October 2015.**

   Corrected.

   Section 3.1 focuses on motivating the subsections 3.1.1, 3.1.2 and 3.1.3 and the analyses made on the 2016 QBO reversal, we feel that commenting on the Rossby U^2 anomaly increase of October 2015 will only distract the reader.

   Later in Figures 3 or 6, one can track the momentum flux anomalies of October 2015 to wave activity originating in the SH extratropics (blue colors). However, the Oct. 2015 momentum flux anomalies are not as strong in magnitude as the ones from February 2016: note they are not necessarily proportional to U^2 anomalies from Fig. 2. In addition, the anomalous fluxes in Oct. 2015 do not seem to disrupt the westerly QBO core in the tropics, and thus they are not of high relevance for our study.

9. **Line 224: What do you mean under “it’s different components”. What components exactly do you mean? Be more specific.**

   We meant the Rossby waves with different wavenumbers (1, 2 and 3). We rephrased the sentence as follows:

   '... and our analysis will describe the evolution of the Rossby waves with wavenumber 1, 2 and 3, independently.'

10. **Line 236: What do you mean by “weaker but similar”? These are two contradictive words. Weaker in strength (or amplitude) but similar in shape?**

    We meant wavenumbers 1 and 2 had a similar contribution, but anyways weaker than the other cases, but we see that this was confusing. We removed 'but similar' from the sentence.

11. **Line 245: “slower than 0.15 cpd, or 6-7 day frequency”. Should it be day-1 ? Also, can you change these to a more familiar timescales which you are using (in days)? This will make comparison with your study easier and you’ll support your augment for their study to include both, the faster and quasi-stationary Rossby waves”. Otherwise it is not very obvious.**

    We apologize for the mix-up, we were referring to 6-7 day periods of course. Now the sentence says: *'(with periods above 6 days)'*, and we also corrected freq.--> perdiods at the end of the paragraph.

12. **Line 325: Very confusing. Please rewrite. First sentence of the paragraph should reflect its main idea or statement.**

    The sentence *“The reversal event not only depends on the enhanced Rossby wave activity in the tropics but also on the different background zonal winds.”* is moved to the start of the paragraph.

13. **Line 351: “50 to 20 hPa” Do you mean “50 -200 hPa” because I see a strong signal in the upper troposphere as well?**

    We've rewritten the entire sentence for better clarity:

    'Figure 13 shows a predominance of above-average Kelvin wave squared perturbations in zonal wind (mostly red and yellow shading and absence of blue) in the upper troposphere around 200 hPa and 100 hPa throughout 2015 and early 2016. The upper tropospheric Kelvin waves can be seen propagating upward within easterly winds most of the time. Also, from December 2015 to April 2016, vertical propagation of Kelvin waves can be observed within weak westerly winds

between 50 hPa and 20 hPa, which will be discussed in more detail below.'

13. **Line 384 and also 393-394: As mentioned in General Comments, this is definitely not a new result. Previous studies, discussing enhanced KW activity during El Niño events, have to be cited and also discussed. One of these studies is by Yang and Hoskins (2013). Yang, G. and B. Hoskins, 2013: ENSO Impact on Kelvin Waves and Associated Tropical Convection. J. Atmos. Sci., 70, 3513–3532, https://doi.org/10.1175/JAS-D-13-081.1**

Many thanks for this reference, it's been added among others into this section. Particularly the last paragraph of section 3.2 has been rewritten discussing this topic.

##

Technical comments:

1. **Line 136: "In order to explore" -> "To explore" (remove "In order")**

   Corrected.

2. **Line 152: "We explore a possible ...... in section 3.1.3". -> remove this sentence**

   Sentence removed.

3. **Line 180: "Figure 2 illustrates .... ." Remove entire sentence since the same information is included in Figure 2 caption.**

   Sentence removed.

4. **Line 183: "Enhanced Rossby wave ... in the NH" -> remove the entire sentence (it doesn't have a logical connection with sentences before and after)**

   Corrected.

5. **Line 202: "Figure 4 shows that the horizontal .." -> "As expected, the horizontal Rossby wave momentum fluxes peak in the ..."**

   Corrected.

6. **Line 211: "We calculated the mean ...". -> "The mean horizontal ... in the tropics are shown in Figure 5. The maximum ..."**

   Corrected.

7. **Line 223-224 “Their study was ...” -> “Although their study ... (35.8 hPa and 40 hPa respectively), we describe the evolution ...”**
   We kept this part of the sentence as is, as we want to emphasize the similarity of our study with Lin et al. 2019.

8. **Line 229-230: Remove “As shown in Figure 5” and connect it with next sentence -> “The Rossby waves ... (red triangles in Figure 5) with horizontal momentum flux having maximum values of about ... .”**
   Corrected.

9. **Line 233: “We calculated ... ” -> “To explore the sources of quasi-stationary Rossby waves, Figures 6 and 7 show the horizontal ....”**
   Corrected.

10. **Line 234: remove entire sentence “Then we analyzed ...”**
    Corrected.

11. **Line 235-237: Remove “Figures 6 and 7 show” and combine this sentence with a next one -> “The contribution of Rossby waves .... in November 2010, while ... ”**
    Corrected.

12. **Line 239: Put a dot after “in Figure 8”, remove “which reveals that”**
    Corrected.

13. **Line 240-242: change to : “The peaks of Rossby waves w2040 in Jan 1960, Nov 2010 and Feb 2016 at 40 hPa occurred earlier at higher latitudes, which is indicative of their extratropical origins. This is in agreement with Figures 5, 6, and 7 revealing an important contribution of quasi-stationary Rossby waves to the enhanced Rossby activity in the tropics mainly by wavenumber 1 and to a lesser degree by wavenumber 2 of extratropical origin.”**
    We rephrased this sentence slightly differently making clearer that we refer to the peaks whose equatorward propagation is best visible, not all the strongest ones (to also account for comment 11 by reviewer #1).

14. **Line 252-260: Need some revisions for conciseness. For example, there are few sentences that can be combined together into one and extra words have to be removed (e.g., "as shown in" (line 256), "the results reveal that in particular" and so on).**
We rephrased the sentences as bellow in the manuscript:
Figure 9 shows that the amplitude of the horizontal Rossby waves w0520 momentum flux was stronger in extratropics in January 1960 and November 2010, while there were two peaks in February 2016 which is in extratropics (around 40°N) and in the tropics (around 15°N). We therefore focus now on the contributions of W1, W2 and W3 separately during the 2016 reversal event by analyzing the time-latitude cross section of their horizontal momentum flux from November 2015to April 2016 at 40 hPa (Figure 10). The result reveals that the activity of W2 and W3 was enhanced while W1 was very weak in early February 2016. The maximum horizontal momentum flux of W2 occurred around 40°N in early February 2016 (Figure 10), and propagated equatorward with some days lag between 40N and 15°N (see Figure S4), indicating its extratropical origin and equatorward propagation.

15. **Line 284: How about : "The meridional gradients are negative in late March 2016, which indicates barotropic – baroclinic instability (see section 2.4). In this study, W3 maximizes one month prior to March 2016. This is consistent with Coy et al. (2017)**
Corrected slightly differently to also account for reviewer #3 technical comments.

16. **Line 341: Start this sentence with "The average period ..." and remove all words before it ("By performing ... we found that").**
Corrected.

17. **Line 342: Add -> "(Figure 12). However, in 2015/2016 the ..."**
Corrected.

18. **Line 351: Remove "Figure 13 shows that ...pertubations had" -> "from 50 to 200 hPa with maximum amplitudes ..."**
This paragraph has been rephrased for better clarity.

19. **Line 380: remove parenthesis around 20 hPa**
Corrected.

20. **Figures: It would be great if you can increase thickness of the zonal mean zonal wind contours.**

Corrected.

Point-by-point responses to Reviewer #3:

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.**

   We've rewritten a big part of section 2.3 to address this: now we state our method's limitations but at the same time we also reassure the reader that for the purposes of our study it is sufficient. Related to this, we also appreciate the reviewer's suggestions in specific comment #7, which we've introduced into section 2.3.

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

   Parts of section 2.2 have been rewritten to increase clarity about the options used with the kf-filter, we hope it is easier to follow now.

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!**

   We apologize for the unclear presentation of the momentum flux anomalies, we've corrected the terminology throughout the manuscript.

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!**
   Corrected throughout the manuscript.

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.

   Many thanks for the references and additional detail for this paragraph. The sentences were rephrased in the introduction as follows:
   'The eastward propagating Kelvin waves and small-scale gravity waves provide the main eastward acceleration for the initiation of the QBO westerly phase, while the westward propagating Rossby waves and small-scale gravity waves provide the main westward acceleration for the initiation of the QBO easterly phase (Ern et al., 2009, 2014; Garcia et al., 2019).'

4. **p.3, l.68: These references address only global scale waves. A reference for smallscale 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.
   Thank you for the reference, it has been added.

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.**
   The sentence now reads: *'For this study, we use the combined European Center for Medium-Range Weather Forecasts (ECMWF) ERA-40 and ERA-Interim reanalysis data sets (Uppala et al. 2005, Dee et al. 2011), which extends from 1958 to 2017. This was done to use the longest timeseries up to the 2016 QBO reversal to cover as many QBO cycles and ENSO events as possible, instead of starting from 1979 with ERA-Interim alone.'*

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!**
   The taper's p parameter cannot be chosen when using the kf-filter function (see *https://www.ncl.ucar.edu/Document/Functions/User_contributed/kf_filter.shtml*), there's no input argument for the taper.
   We did check the different filter outputs and cutting 1 year of data seemed perfectly fine: see the two graphics below for Kelvin u2 at 200hPa (10S-10N) and Rossby w0570 at 40hPa (35-45N)

Also, parts of section 2.2 have been rephrased to improve clarity, but we feel that details such as the taper settings belong in the kf-filter / taper documentation to which the readers are referred to.

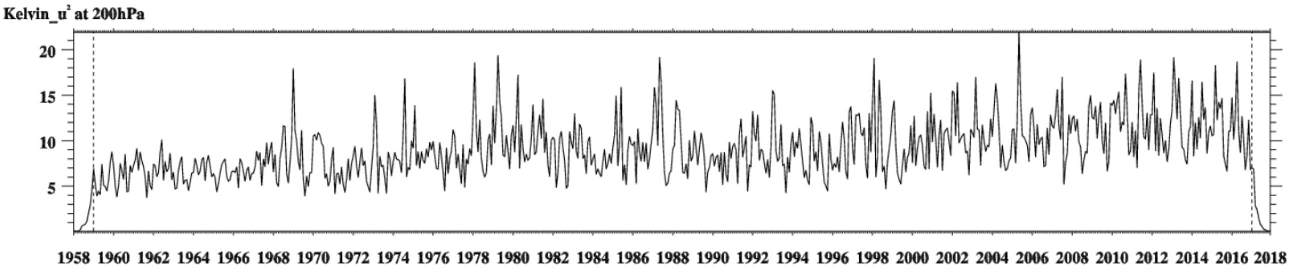
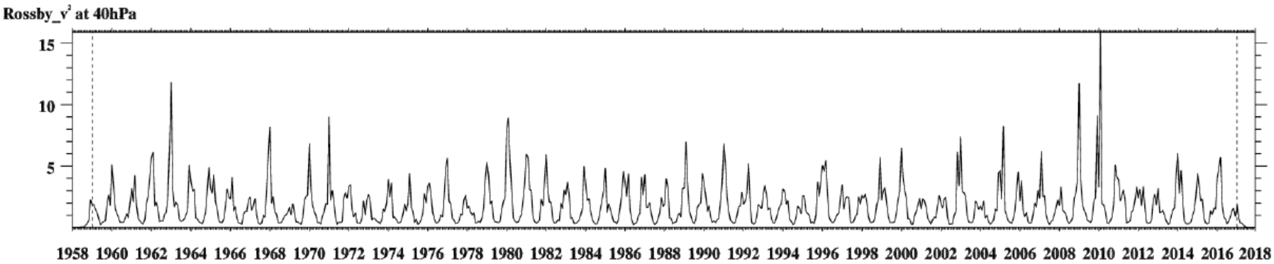


Figure. The temporal variation of squared Kelvin wave zonal wind perturbations at 200 hPa. The vertical dashed lines denote the January of 1959 and 2017.



The timeseries of Rossby wave (with 5-70 day periods) squared meridional wind perturbations at 40hPa averaged for 35-45°N

RPK: I went through the code of the kf-filter ncl function (*https://k3.cicsnc.org/carl/carl-ncl-library/blob/24eb0d1bf7913c8d63fb7d43ad5e2b298269b931/kf/kf_filter.ncl*) and in line 49 the tapering is set:

tempData = taper(tempData, 0.05, 0) → Option '0' is for tapering to the series mean instead of to zero. This is inside the kf_filter.ncl function, and not for the user to choose.

With p=0.05 only 1.5 years of the data would be affected, and taking into account the cosine-bell shape, the data 1-1.5 years away from the timeseries ends is affected relatively much less. In any case, the first half of 2016 is not affected by the taper.

As mentioned above, and since this issue does not affect our results, we believe the inclusion of such intricate details about the kf-filter is unnecessary.

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 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.
   Many thanks for the suggested reference, now added into section 2.3, and for pointing out these issues with the momentum flux calculations. We completely agree with the reviewer about the limitations of our method, and we've rewritten section 2.3 to state that this is a simplified approach, nevertheless sufficient for the goals of our study. We also mention that, despite ageostrophy holding near the equator, we see no discontinuities in the time-latitude sections of Rossby wave activity crossing into the SH (e.g. Figs. 3 and 10).

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!**
   We apologize for the inconsistencies. We've changed Figs. S1 and S2 into momentum fluxes (not anomalies) and we've updated figure captions and sentences throughout the manuscript stating that what's shown are anomalies from climatology. We hope it's not confusing any more in the new manuscript version.

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!**

We kept the monthly climatology without interpolation, as we didn't see any jumps of importance in any figure.

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.**

We rephrased this paragraph as follows:

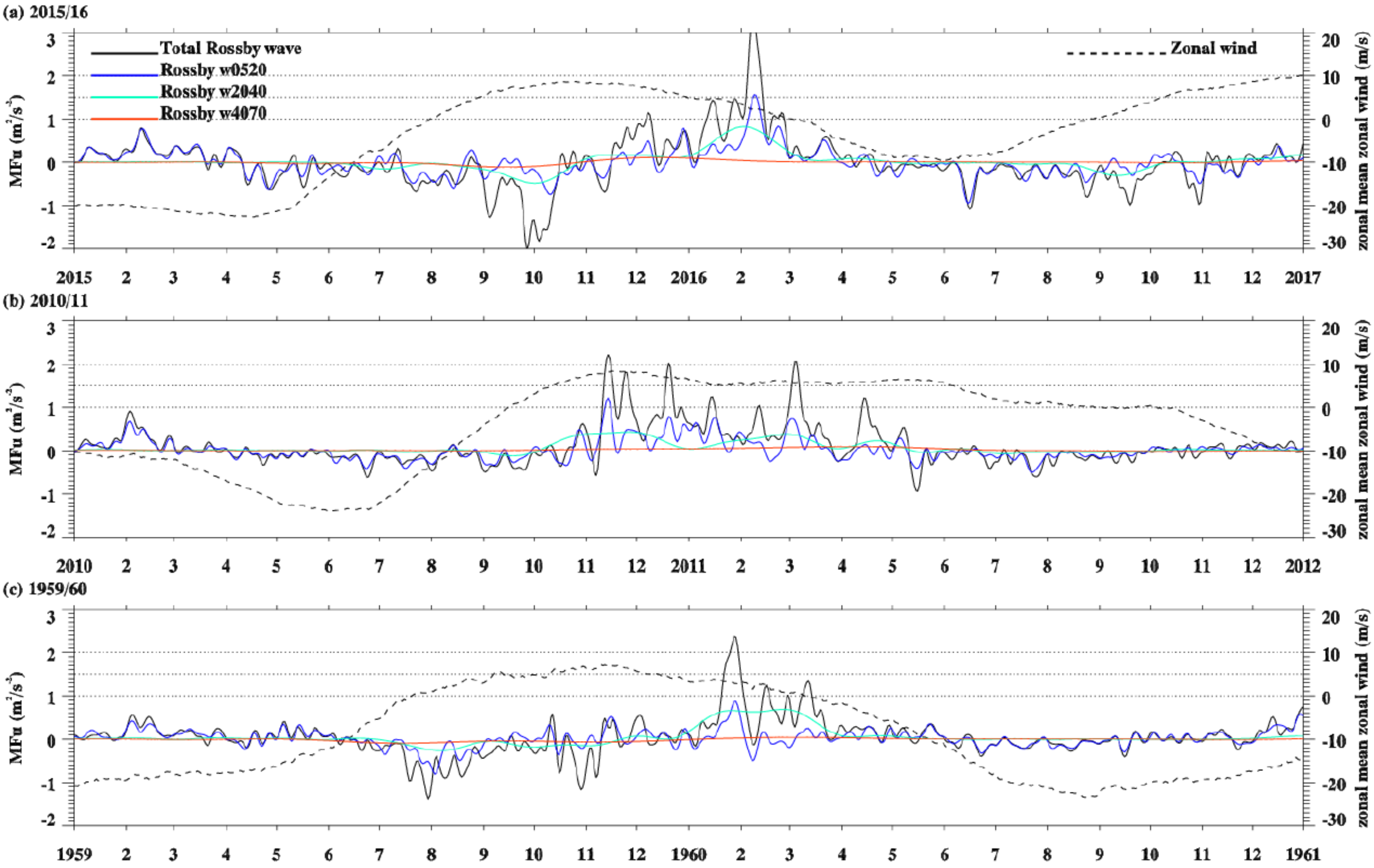
'Shuckburgh et al. (2001) revealed that barotropic instability in tropical regions could be associated with QBO westerlies. Coy et al. (2017) later studied both barotropic and baroclinic instability following Andrews et al. (1987). We use a similar approach calculating the meridional gradient of potential vorticity in 2015/2016 from 70 hPa to 10 hPa following Andrews et al. (1987) and Coy et al. (2017).'

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.**

We originally divided the total Rossby wave into three kinds: w0520, w2040 and w4070. We found that Rossby w4070 had near-zero values in all cases, therefore we didn't include it in the figures. We now mention this more clearly in sections 2.2 and 3.1 in the manuscript. We repeated Fig. 5 from the manuscript including w4070 (see below), but we'd advocate to keep the less busy one (without w4070) for the main manuscript.



Please also note that ($U_aV_a + U_bV_b$) is not necessarily equal to ($U_a + U_b$)*($V_a + V_b$), this is why the Total Rossby wave momentum flux is not the linear sum of the momentum fluxes from w0520+w2040.

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 day^-1 which are both in your quasi-stationary range of frequencies. Please clarify!**

We performed a more detailed analysis in the new Fig. 11 and rewritten the interpretation of the wave resonance mechanism in section 3.1.3. It turned out all W1-3 are changing speeds/frequencies throughout January-March 2016 and that a single Fourier spectrum did not entirely represent what was happening during February 2016. However, the main conclusion remains similar.

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.
    We agree with the reviewer and we deleted the sentence in the manuscript.

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.**
    Also related to specific comment #7: we state this now within section 2.3 as another limitation of our methods.

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?**
    In this case it is useful for commenting on upper-tropospheric anomalies, which do show a seasonal cycle, and to discuss their relation to El-Nino as done later in Fig. 15.

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.
    Many thanks for pointing this out and the reference, of course this makes more sense. We added the following explanation in section 3.2:
    'Also, if the Kelvin wave's phase speed exceeds that of the westerly flow, it is possible that the

Kelvin wave propagates upward within weak westerlies as reported by Ern et al. (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.**
    We refined the analysis in our new Fig. 11 and rewritten the corresponding discussion in section 3.1.3, which now do support this conclusion.

##

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**
   Corrected.

2. **p.5, l.150: Fig.12a does not exist! Should this read Fig. S1? Please check!**
   Thank you for your remark, it should have been Figure 14a. We have corrected this in the manuscript.

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

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

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’>.**
   Yes, as you said Figure 2 shows the deviations of the squared zonal wind perturbation respect to the climatology. We rephrased the sentence as follows:
   'Figure 2 illustrates the time-height cross section of the deviations of the squared Rossby wave

anomalies in zonal wind respect to the monthly climatology (1959-2014) averaged over tropics (10°N-10°S).'

We've also applied the correct terminology **d<u’v’>** in all corresponding figures, we apologize for the unclear presentation in the previous manuscript version.

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

   Corrected.

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

   Corrected.

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

   Corrected.

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**

   Corrected.

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

    Corrected.

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

    Corrected.

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

    Corrected.

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

    Corrected for 'at lower altitudes' since we refer to levels below 40 hPa throughout this paragraph (at levels 20 hPa and above, there are little structures to comment on and q meridional gradient is mostly positive).

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

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

16. **p.9, l.285: barotropic and baroclinic -> barotropic and/or baroclinic**
    Corrected.

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**
    This paragraph has been completely rewritten due to the inclusion of the new figure 11.

18. **In Fig.14b: why are the lines interrupted? Are no-shows insignificant values? If yes, please state in the figure caption!**
    We only show the westerly zonal wind condition. The easterly wind and its corresponding Kelvin wave momentum fluxes are not shown. We rephrased the figure caption to make this clearer.

On the forcings of the unusual QBO structure in February 2016

Haiyan Li[1,2,3], Robin Pilch Kedzierski[2], and Katja Matthes[2,4]

[1]School of Atmospheric Sciences, Sun Yat-Sen University, Zhuhai, China
[2]Marine Meteorology Department, GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
[3]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China
[4]Faculty of Mathematics and Natural Sciences, Christian-Albrechts-Universität zu Kiel, Germany

Correspondence: Haiyan Li (lihaiyan@whu.edu.cn)

Abstract. The westerly phase of the stratospheric Quasi-Biennial Oscillation (QBO) was reversed during Northern Hemisphere winter 2015/2016 for the first time since records began in 1953. Recent studies proposed that Rossby waves propagating from the extratropics played an important role during the reversal event in 2015/2016. Building upon these studies, we separated the extratropical Rossby waves into different wavenumbers and time-scales by analyzing the combined ERA-40 and ERA-Interim reanalysis zonal wind, meridional wind, vertical velocity and potential vorticity daily mean data from 1958 to 2017. We find that both synoptic and quasi-stationary Rossby waves are dominant contributors to the reversal event in 2015/2016 in the tropical lower stratosphere. By comparing the results for 2015/2016 with two additional events (1959/1960 and 2010/2011), we find that the largest differences in Rossby wave momentum fluxes are related to synoptic-scale Rossby waves of periods from 5-20 days. We demonstrate for the first time, that these enhanced synoptic Rossby waves at 40 hPa in the tropics in February 2016 originate from the extratropics as well as from local wave generation. The strong Rossby wave activity in 2016 in the tropics happened at a time with weak westerly zonal winds. This coincidence of anomalous factors did not happen in any of the previous events.

In addition to the anomalous behavior in the tropical lower stratosphere in 2015/16, we explored the forcing of the unusually long-lasting westerly zonal wind phase in the ~~upper~~middle stratosphere (at 20 hPa). Our results reveal that mainly enhanced Kelvin wave activity contributed to this feature. This was in close relation with the strong El Niño event in 2015/2016, which forced more Kelvin waves in the equatorial troposphere. The easterly or very weak westerly zonal winds present around 30-70 hPa allowed these Kelvin waves to propagate vertically and deposit their momentum around 20 hPa, maintaining the westerlies there.

1 Introduction

The variability of zonal winds in the tropical lower stratosphere (100 to 10 hPa) is dominated by the Quasi-Biennial Oscillation (QBO) with descending easterly and westerly zonal wind regimes and a varying period from 22 to 36 months (Baldwin et al., 2001). The QBO was discovered by Reed et al. (1961) and Ebdon (1960) independently and its characteristics have been observed for many decades (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Kawatani and Hamilton, 2013). The tropical QBO not only influences the tropical stratosphere, but also impacts the tropical troposphere, for example the

Hadley circulation (Gray et al., 1992) and the Madden-Julian oscillation (Yoo and Son, 2016). Furthermore, the QBO impacts the extratropical stratosphere by modulating the strength of the stratospheric polar vortex (Baldwin et al., 2001; Holton and Austin, 1991; Holton and Tan, 1980; Gray et al., 2004). ~~The westerly mean flow in the tropical stratosphere generally favors~~If the mean flow in the tropical stratosphere is westerly, it generally favors the penetration of planetary waves into the tropical regions even across the equator without encountering a critical limit. The wave-mean flow interaction theory proposed that vertically propagating equatorial waves are the main forcing mechanism for the QBO through the selective filtering by the background wind (Lindzen and Holton, 1968; Holton and Lindzen, 1972). The vertically propagating equatorial waves deposit their momentum into the regions where the background zonal wind is equal to the wave phase speed. This mechanism explains the descent of the wind regimes alternating the QBO phase. The responsible equatorial waves include Kelvin waves, equatorial Rossby waves and smaller scale gravity waves (Lindzen and Holton, 1968; Holton and Lindzen, 1972).

Kelvin waves are excited by tropospheric convection and propagate upward and eastward (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Baldwin et al., 2001). The eastward propagating Kelvin waves and small-scale gravity waves provide the main eastward acceleration for the initiation of the QBO westerly phase~~. In contrast,~~ , while the westward propagating Rossby waves and small-scale gravity waves provide the main westward acceleration for the initiation of the QBO easterly phase (Ern and Preusse, 2009; Ern et al., 2014; Garcia and Richter, 2019). The period of the stratospheric QBO depends on the amount of vertically propagating equatorial waves (Baldwin et al., 2001).

In February 2016, the regular descent of the QBO westerly phase was interrupted and reversed near 40 hPa. The reversed westerly zonal mean zonal wind at 40 hPa (shown in Figure 1b) is named "reversal event" in the following. This reversal event occurred for the first time in 2016 since the QBO is recorded (Naujokat, 1986). Several studies tried to explore the possible reasons for the anomalous QBO behavior (Osprey et al., 2016; Dunkerton, 2016; Coy et al., 2017; Tweedy et al., 2017; Barton and McCormack, 2017; Lin et al., 2019). Their results showed that Rossby waves propagating from the extratropical Northern Hemisphere might have been the most likely cause of the reversed westerly zonal wind at 40 hPa. Coy et al. (2017) also found high amounts of momentum flux divergence present in the tropical lower stratosphere in 1987/1988 and 2010/2011, but the westerly zonal wind at the equator did not reverse as a consequence of this extratropical Rossby wave activity. Another possibility for the enhanced Rossby wave activity in the equatorial stratosphere is local wave generation from instability within the QBO westerlies. Coy et al. (2017) calculated the meridional gradient of the potential vorticity field ($\bar{q_\phi}$, (Andrews et al., 1987)) during the anomalous QBO reversal event. Regions with negative $\bar{q_\phi}$ indicate the presence of barotropic shear instability associated with the QBO winds. Coy et al. (2017) found that $\bar{q_\phi}$ was positive during the reversal event in 2015/2016, implying an unlikely instability of the large-scale flow. However, in the model study by Peter et al. (2018) it is suggested that the $\bar{q_\phi}$ distribution present in February 2016 favored wave flux convergence over a narrow region, providing a dynamical feedback, not the source of the wave forcing. One goal of our study is to investigate the responsible waves for the reversal event in the lower stratosphere in February 2016 by separating the contributions of individual wavenumbers and different timescales.

As highlighted in previous studies, the stratospheric QBO can interact with other large scale oscillations. ENSO events influence tropical convection. The ENSO warm phase (El Niño) enhances the tropical tropospheric convection and the ENSO cold phase (La Niña) decreases the tropical tropospheric convection (Maury et al., 2013; Yang and Hoskins, 2013). Through modulating the tropospheric convection, ENSO could affect the equatorial wave behavior and hence the forcing of the QBO (Maury et al., 2013; Yang and Hoskins, 2013; Schirber, 2015; Hansen et al., 2016; Christiansen et al., 2016; Kang et al., 2018). Based on this mechanism, many studies investigated the interaction between ENSO and the QBO. Taguchi (2010) and Yuan et al. (2014) revealed that the QBO has a weaker amplitude and faster phase speed during El Niño conditions by investigating radiosonde data from 1953 through 2008. Recently, some studies (Barton and McCormack, 2017; Hirota et al., 2018) highlighted the potential role of the exceptionally strong El Niño conditions on the reversed QBO westerlies in 2015/2016. Their results agree with a modeling study by Calvo et al. (2010), which found that the subtropical zonal wind has a westerly tendency in the Northern Hemisphere in conjunction with a strong El Niño in winter (NDJ). Newman et al. (2016) reported that the QBO westerlies propagated upward instead of the regular downward propagation above 30 hPa in 2015/2016. The upward migration of QBO westerlies above 30 hPa caused the westerly zonal winds to last unusually long at 20 hPa in 2015/2016. Another goal of our study is to explore the responsible waves and the role of the strong El Niño event for the upward migration and unusually long westerly zonal mean zonal wind regime at 20 hPa.

The remaining parts of this paper are organized as follows. In section 2, the data and methods used in our study are described. The possible reasons for the reversed westerly zonal wind at 40 hPa are explored in section 3.1. The Rossby waves are divided into quasi-stationary Rossby waves and faster Rossby waves. Their contributions and sources (propagating from the extratropics or generated locally in the tropics) during the QBO westerly phase reversal event are investigated in subsections 3.1.1 and 3.1.2, respectively. We explore possible mechanisms for local Rossby wave generation during the reversal event in subsection 3.1.3. Section 3.2 will analyze the unusual behavior of Kelvin waves and the influence of the strong El Niño event during the long-lasting westerly zonal mean zonal wind phase at 20 hPa. The summary and conclusions are given in section 4.

2 Data and Methods

For this study, we use the combined European Center for Medium-Range Weather Forecasts (ECMWF) ERA-40 and ERA-Interim reanalysis data sets (Uppala et al., 2005; Dee et al., 2011), which extends from 1958 to 2017. This was done to use the longest timeseries up to the 2016 QBO reversal to cover as many QBO cycles and ENSO events as possible, instead of starting from 1979 with ERA-Interim alone. We use daily averaged pressure level data ~~from 1958 to 2017~~ including zonal wind, meridional wind, vertical velocity and potential vorticity with a horizontal resolution of 2.5° longitude $\times$ 2.5° latitude. The ERA-40 and ERA-Interim reanalysis data sets have 23 and 37 pressure levels in the vertical direction, respectively, from 1000 hPa to 1 hPa. We use a merged dataset of ERA-40 and ERA-Interim on the 23 pressure levels they have in common (Blume et al., 2012). The NOAA Extended Reconstructed Sea Surface Temperature (SST) V4 was used to calculate the ENSO index. Furthermore, we also used the monthly Outgoing Long-wave Radiation (OLR) data to represent the amount of convective activity from https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html.

2.1 Index Definitions

We define the QBO phase using the monthly zonal mean zonal wind at 40 hPa (averaged from 50 hPa to 30 hPa since the 40 hPa level is not available in ERA-40 or ERA-Interim) and averaged over 2.5°S-2.5°N (U40) (following Hansen et al. (2016). The westerly QBO phase (QBOW) is defined when U40 is greater than $2m/s$ and the easterly QBO phase (QBOE) is defined when the U40 is less than -2 m/s (shown in Figure 1b) following Hansen et al. (2016). To examine the reliability of the QBO index, we compared the ERA-40 and ERA-Interim reanalysis data with the monthly zonal mean zonal wind at 40 hPa from the Free University of Berlin (FUB) data set (FU40) (Naujokat, 1986). The amplitude of the QBO index is only slightly larger in FU40 compared with U40 (not shown). The index of FU40 is an average of three stations (Canton Island station (1953-1967), Gan/Maledive Islands station (1968-1975) and Singapore station (1976-present)), all of them at a similar latitude around the equator (Naujokat, 1986). Note that, the result of U40 comes from the zonal mean and averaged from 2.5°S to 2.5°N. The U40 and FU40 agree well in the duration and phase of zonal wind regimes, suggesting that the result of U40 is robust and the difference between U40 and FU40 are negligible. We therefore use the ERA-reanalysis dataset for the rest of this study. Similar to U40, we also defined the direction of zonal wind at 20 hPa (U20). Both ERA-40 and ERA-Interim provide the 20 hPa level so no averaging is needed. The westerly zonal wind was defined when U20 is greater than 2 m/s and when U20 is less than -2 m/s it is defined as easterly zonal wind (as shown in Figure 1a).

The ENSO index is obtained as deviations from the monthly climatology, with 5 months running average in the Niño 3.4 region (70°W-120°W, 5°S-5°N)(Hansen et al., 2016). An El Niño event is defined when the ENSO index is greater than 0.5 K and a La Niña event is defined when the ENSO index is less than -0.5 K (shown in Figure 1c).

2.2 Wave filtering

In order to explore the roles of tropical and extratropical waves during the unexpected QBO reversal event in 2015/2016, we extracted Rossby and Kelvin wave perturbations in the wavenumber-frequency domain by applying the "kf-filter" function (a two-dimensional Fast Fourier Transform in longitude and time Schreck (2009)) on horizontal winds and vertical velocity. ~~Previous studies revealed that the reversal event near 40 hPa in 2015/2016 has been caused by Rossby waves propagating from the Northern extratropical regions (Osprey et al., 2016; Osprey et al., 2016; Osprey et al., 2017). We extracted the equatorial Rossby waves following their dispersion curve (Wheeler and Kiladis, 1999). It is difficult to define a single filter in the wavenumber-frequency domain to extract extratropical and tropical Rossby waves that will work for the whole time period, all latitudes and different stratospheric levels.~~

The "kf-filter" function enables defining the filtered wavenumber-frequency domain with its boundaries following the dispersion curves of the different equatorial wave modes, as introduced by Wheeler and Kiladis (1999). In our study we use this feature to extract Kelvin wave anomalies in the tropics.

The "kf-filter" also has the option of defining a simple box in the wavenumber-frequency domain, bounded by a wavenumber and period range, without following any dispersion curve. This has proven to be useful for wave filtering in the extratropics (Pilch Kedzierski et al., 2017), where the propagation of waves is highly affected by the background winds through Doppler shifting, and thus a single Rossby wave mode can occupy any region in the wavenumber-frequency domain depending on the background wind condition. This option of the "kf-filter" will be used to filter Rossby waves from 60°N to 60°S, as our study wants to diagnose extratropical waves that propagated into the equatorial region during the 2016 QBO reversal, as reported by Osprey et al. (2016); Newman et al. (2016); Coy et al. (2017). This filtering technique does not distinguish equatorial from extratropical Rossby wave modes, but their origin and propagation will be tracked by separating different wavenumbers and time-scales and using time-height and time-latitude sections. The detailed information about the different filter boundaries used in our study is shown in Table 1. The filter boundaries for Rossby waves are -0.5 and -3.5: negative wavenumbers indicate westward-propagating waves.

~~The propagation of waves is affected by the background winds through Doppler shifting. Both tropical and extratropical waves can travel in the same wavenumber-frequency domain depending on the background zonal winds. In order to extract the Rossby waves from 60°N to 60°S we used wide boxes in the wavenumber-frequency domain (see Table 1) instead of defining certain dispersion curves following Pilch Kedzierski et al. (2017).It is difficult to separate the tropical and extratropical Rossby waves with this filtering technique.~~

~~We can track their origins by dividing them into different wavenumbers and time-scales, with the use of time-height and time-latitude sections of each Rossby wave type. The detailed information about the Rossby waves filter boundaries is shown in Table 1. The filter boundaries for Rossby waves are -0.5 and -3.5: negative wavenumbers indicate westward-propagating waves. In our study we focus on planetary-scale westward propagating Rossby waves with wavenumbers 1 to 3 and periods from 5 to 70 days.~~

Extratropical Rossby waves can also propagate eastward relative to the ground with strong westerly mean zonal winds, but their activity and fluxes are limited to the winter stratospheric polar vortex, therefore not affecting tropical regions. We confirm that momentum flux anomalies of relevance for tropical regions only originate from westward propagating waves (see and compare Figures 3 and S1 from the supplement), and thus the eastward propagating Rossby waves are not included in our study. The westward propagating Rossby waves produce a westward acceleration of the background zonal wind and hence weaken the westerly zonal wind in the extratropics during Northern Hemisphere (NH) winter. First, the total amount of Rossby wave activity (periods of 5-70 days) is presented in section 3.1. ~~Then~~Since we found that very slow waves (40-70 day periods) show very little activity, we focus on the two dominant time-scales: quasi-stationary (20-40 days) and faster (5-20 days) Rossby waves in subsections 3.1.1 and 3.1.2, respectively. ~~In order to~~To explore their sources and contributions during the 2015/2016 reversal event, for each time-scale we further separate the filtered Rossby waves into individual wavenumbers 1, 2, and 3. We also study the Kelvin wave activity (wavenumbers 1 to 14, periods of 4-30 days, see table 1) in section 3.2.

Please note that the output of the filter near the temporal ends (years 1958 and 2017) of the data set in our analysis is neglected because the amplitude of the filtered waves is underestimated there. The monthly climatology is calculated from January 1959 through December 2014, to avoid any influence of the unique structure of the stratospheric QBO in 2015/2016.

2.3 Momentum Flux Calculation

The contribution of each wave type defined in section 2.2 during the 2015/2016 QBO reversal event is estimated by calculating the horizontal (Mf_h) and vertical (Mf_v) momentum fluxes:

$$Mf_h = \overline{u'v'} \quad (1)$$

$$Mf_v = \overline{u'w'} \quad (2)$$

u', v' and w' denote the perturbations (waves) in the zonal wind, meridional wind and vertical velocity. The overbar denotes the zonal mean.

~~In the following, only results for~~ Vertical momentum flux calculations will be used only for Kelvin waves in our study, since no relevant contribution from Rossby waves was detected in the tropics (see and compare Figures ~~12a~~14a and S2 from the supplement.) Kelvin waves do not propagate meridionally, therefore Mf_v, as part of the vertical component of the Eliassen-Palm (EP) flux, represents their propagation well.

Regarding Rossby waves, EP flux analyses of the 2016 QBO reversal showed that, around 40 hPa, wave propagation in the tropics and subtropics was mainly meridional, with little vertical component (Osprey et al., 2016; Lin et al., 2019). Vertical EP flux components were of importance in the extratropics.

Rather than showing the full latitude-height path of the extratropical Rossby waves that propagated into the tropics, our study aims at confirming extratropical or local origin of the different wavenumbers of quasi-stationary and faster Rossby waves present in the tropics during the 2016 QBO reversal, and to compare their amounts (see section 3.1). For the purposes of our study, the simplified use of Mf_h is sufficient. Our approach is equivalent to the quasi-geostrophic approximation of the EP flux by Matthias and Ern (2018), and even though ageostrophy holds near the equator, we found no discontinuities in time-latitude sections of Rossby wave activity crossing into the SH (see e.g. Figs. 3 and 10).

Another limitation of our method is that with Mf_h and Mf_v alone, the interaction of the waves with the mean flow cannot be diagnosed as done with the full EP flux divergence in e.g. (Lin et al., 2019), but this is not the goal of our study, and in any case increased momentum fluxes tend to cause stronger EP flux divergences.

2.4 Barotropic and Baroclinic Instability Calculation

~~We explore a possible generation mechanism for enhanced Rossby wave activity in section 3.1.3.~~ Shuckburgh et al. (2001) revealed that barotropic ~~and baroclinic~~ instability in tropical regions could be associated with QBO westerlies. Coy et al. (2017) later studied both barotropic and baroclinic instability following Andrews et al. (1987). We use a similar approach calculating the meridional gradient of potential vorticity in 2015/2016 ~~was calculated~~ from 70 hPa to 10 hPa following Andrews et al. (1987) ~~as used in Shuckburgh et al. (2001)~~ and Coy et al. (2017).

$$q_\phi = 2\Omega\cos\phi - [\frac{(\bar{u}\cos\phi)_\phi}{a\cos\phi}]_\phi - \frac{a}{\rho_0}(\frac{\rho_0 f^2}{N^2}\bar{u_z})_z \quad (3)$$

Where Ω is the Earth's rotation frequency, a is the Earth's radius, $\bar{u}$ denote the zonal and time averaged zonal wind, ρ_0 is the basic state density, z is the log pressure vertical coordinate, ϕ is the latitude and N^2 denotes the Brunt-Väisälä frequency squared. A negative meridional potential vorticity gradient is indicative of barotropic-baroclinic instability and hence is used as condition for local Rossby wave generation in section 3.1.3.

3 Details and Mechanisms of the Unusual QBO Behavior in 2015/2016

The result chapter is divided into two parts. First, the interruption of the westerly zonal wind in the lower stratosphere (40 hPa) in February 2016 and possible reasons are investigated (section 3.1). Then, the reasons for the unusually long lasting westerly zonal winds in the ~~upper~~middle stratosphere (20 hPa) are investigated in more detail. Figure 1b shows the reversal of the westerly zonal wind regime and the onset of easterlies around 40 hPa in February 2016. A weakening of westerly zonal winds occurred in several earlier winters, for example, in 1959/1960 and 2010/2011 winter (Coy et al., 2017), but so far no other winter resulted in a reversal of the wind. This is exceptional to the winter 2015/2016 and resulted in a number of publications. We will add significant new aspects to the existing literature. As shown in Figure 1a, the westerly zonal wind around 20 hPa lasted unusually long in 2015/2016. Newman et al. (2016) and Kumar et al. (2018) noticed the unusual behavior of westerly zonal wind above 30 hPa but none of them explored it in detail. The goal of this study is to investigate both, the unusual behavior of the QBO in winter 2015/2016 in the lower and ~~upper~~middle stratosphere in more detail than earlier studies.

3.1 Interruption of the westerly zonal wind at 40 hPa

Figure 1a-b shows that the amplitude of westerly zonal wind was weaker in a number years (e.g., 1959/1960, 2010/2011) but the westerly zonal wind only reversed its direction in the 2015/2016 winter at 40 hPa. Prior to 2016, many events show weakened westerlies either at 40 hPa or 20 hPa (Figure 1a-b), but only 1959/1960 and 2010/2011 had large Rossby wave momentum flux anomalies comparable to 2016 (Figure 1d). Previous studies (Osprey et al., 2016; Newman et al., 2016; Coy et al., 2017) reported that the reversal event in 2015/2016 winter at 40 hPa was caused by enhanced Rossby wave activity in the tropical stratosphere, mainly of extratropical origin. Based on these studies, we investigate the Rossby wave activity in the tropical stratosphere during the reversal event in more detail by looking not only at wavenumbers 1-3 but also by separating quasi-stationary Rossby waves (20-40 days) and faster Rossby waves (5-20 days).

First, to show the total amount of Rossby wave activity, we extracted all Rossby waves with periods of 5-70 days and with wavenumbers from 1 to 3. Figure 2 illustrates the time-height cross section of the squared Rossby wave anomalies in zonal wind averaged over the tropics (10°S-10°N) with respect to the monthly climatology (1959-2014). As shown in Figure 2, the Rossby wave activity was enhanced in the tropics before the westerly zonal wind reversed near 40 hPa in February 2016. ~~Enhanced Rossby wave activity in the tropics usually occurs in November and December but seldom in January and February~~

in the NH (O'Sullivan, 1997). However, we cannot find enhanced Rossby wave behavior at lower or higher levels in the tropics, which suggests that it did not originate from vertical propagation.Since enhanced Rossby wave behavior does not extend to lower and higher levels in February 2016, the observed signal less likely originated from vertical propagation. Besides vertical propagation, Rossby waves can propagate in the meridional direction (O'Sullivan, 1997; Osprey et al., 2016). We choose two additional cases to compare the results with the 2015/2016 case: 1959/1960 and 2010/2011. Both have increased horizontal Rossby wave momentum fluxes (shown inFig. 1d). We investigated the role of meridionally propagating Rossby waves during the reversal event as previous studies (Osprey et al., 2016; Newman et al., 2016; Coy et al., 2017; Tweedy et al., 2017).

Figure 3 shows the time-latitude cross section of the horizontal Rossby wavesRossby wave horizontal momentum flux anomalies during three related cases (marked as blue and red vertical lines in Figure 1b). The result is in agreement with the findings of Barton and McCormack (2017) which found that westerly subtropical zonal winds favor extratropical Rossby waves to propagate into the tropics. Rossby wave horizontal momentum flux anomalies maximize in the extratropics and the magnitude generally decreases with decreasing latitude. Equatorward propagation of Rossby waves is observed in all three example winters (Figure 3) in agreement with Osprey et al. (2016) and Coy et al. (2017). However, the specific time-scales and wavenumbers of the responsible Rossby waves have not been explored before. While previous studies discussed the extratropical Rossby wave origin, a tropical origin of the enhanced Rossby waves in February 2016 is still unclear and will be explored in more detail in section 3.1.3.

Our filtered Rossby waves in the tropics include Rossby waves generated in the tropics and in the extratropics. In order to detect where the Rossby waves were generated, we analyzed the time-series of the mean Rossby wave horizontal momentum flux anomaly separately in the tropics (10°S-10°N) and extratropics (35°N-45°N), for the three selected winters 1959/1960, 2010/2011 and 2015/2016 (Figure 4).

Figure 4 shows thatAs expected, the horizontal Rossby wave momentum flux anomalies peak as expected in the extratropics but some also peak in the tropics. For example, the extratropical momentum flux anomalies in February 2015 and 2010 do not coincide with any wave activity in the tropics. The horizontal Rossby wave momentum flux anomaly were not able to propagate into the tropics due to the prevailing easterly background zonal wind in the subtropics around 20°N (see Figure 3). Figure 4 suggests that the peaks of the horizontal Rossby wave momentum flux anomaly in the tropics in January 1960, November 2010 and February 2016 are related to extratropical Rossby waves (highlighted with red triangles in Figure 4), since there is a few days lag between the peaks in the tropics and extratropics. This implies that they need some days to propagate from the extratropics into the tropics, which can be easily seen in Figure 3.

We now focus on faster Rossby waves (5-20 days, w0520) and quasi-stationary Rossby waves (20-40 days, w2040) as described in section 2.2. We calculated theThe mean horizontal momentum flux anomaly for the total as well as the contribution from fast and quasi-stationary Rossby waves in the tropics (are shown in Figure 5). Figure 5 shows that theThe maximum amplitude of the horizontal Rossby wave momentum flux anomalies occurred in February 2016 (3.43 m^2/s^2). In addition, the Rossby w0520 horizontal momentum flux anomaly was stronger during January 1960, November 2010 and February 2016 than Rossby w2040, which had similar values in all three cases. This suggests a dominant contribution from faster Rossby waves (w0520) during the QBO reversal event, which was not noted in previous studies (Osprey et al., 2016; Newman et al., 2016; Coy et al., 2017).

From Figure 5 we conclude that quasi-stationary Rossby waves contribute significantly to the observed momentum flux anomalies in the tropics, in a fairly similar way in all three cases. Faster Rossby waves (w0520) are responsible for most of the case to case variability, being especially dominant in February 2016. It is worth analyzing the contributions from individual wavenumbers for Rossby waves of both time-scales, which also enables tracing their origins more precisely. Such a detailed analysis of the wave forcings of the QBO reversal event in February 2016 has not been performed yet and may lead to results of high interest. Lin et al. (2019) reported an important contribution to the 2016 QBO disruption made by a single wave packet, with dominating wavenumbers 1-3 in its wave spectrum. Their study was performed at a similar vertical level as ours (35.8 hPa and 40 hPa respectively), ~~and our analysis will describe the evolution of its different components in further detail.~~and our analysis will describe the evolution of the Rossby waves with wavenumber 1, 2 and 3, independently. The following subsections 3.1.1 and 3.1.2. will focus on behavior of quasi-stationary and faster Rossby waves, respectively, whereas subsection 3.1.3 will explore possible mechanisms for an observed locally generated wave whose contribution was important and only present in February 2016.

3.1.1 The Role of Quasi-Stationary Rossby waves

Firstly, we discuss the contribution of quasi-stationary Rossby waves (Rossby w2040, light blue lines in Figure 5). ~~As shown in Figure 5, the~~The Rossby waves w2040 were enhanced in January 1960, November 2010 and February 2016 (red triangles in Figure 5)~~. The Rossby waves w2040~~ with horizontal momentum flux ~~had~~anomaly having maximum values ~~(~~of about 0.78 m^2/s^2~~)~~ in February 2016 in the tropics at 40 hPa. In November 2010 and January 1960, the Rossby waves w2040 horizontal momentum flux anomaly were 0.41 m^2/s^2 and 0.66 m^2/s^2, respectively, close to the values in February 2016. ~~We calculated the horizontal momentum flux anomaly from Rossby waves w2040 with wavenumber 1 and 2, respectively. Then we analyzed their variation in time-latitude sections (shown in Figures 6 and 7).~~To explore the sources of quasi-stationary Rossby waves, Figures 6 and 7 show the horizontal momentum flux anomaly from Rossby waves w2040 with wavenumber 1 and 2, respectively. ~~Figures 6 and 7 show that the~~The contribution of Rossby waves w2040 with wavenumber 1 and 2 was weaker ~~but similar~~ in November 2010~~. While in~~, while January 1960 and February 2016 were characterized by a strong Rossby wave w2040 with wavenumber 1. However, the total contribution of quasi-stationary Rossby waves was similar in all cases as shown in Figure 5. In order to highlight the latitudinal variation of the Rossby waves w2040 with wavenumber 1, we analyzed its horizontal momentum flux anomaly at the equator, 10°N, 20°N and 30°N during each case, as shown in Figure 8. ~~which reveals that~~ The peaks of Rossby waves w2040 (with wavenumber 1) in the extratropics occurred earlier at higher latitudes, propagating and peaking later near the equator, which is especially clear in January 1960, November-December 2010 and January-February 2016. Figures 5, 6 and 7 reveal that quasi-stationary Rossby waves have an important contribution to the enhanced Rossby wave activity in the tropics, mainly by wavenumber 1 (and 2 to a lesser degree) of extratropical origin.

3.1.2 The Role of Faster Rossby Waves

Lin et al. (2019) reported that the low frequency waves ~~(slower than 0.15 cpd, or 6-7 day frequency)~~(with periods above 6 days) with wavenumbers 1-3 were important contributors to the reversal event in February 2016. This category would include the faster and quasi-stationary Rossby waves from our analysis. In the previous sections we demonstrated that the case to case differences are mostly due to the faster wave type (5-20 day ~~frequencies~~periods), which will be explored in this section.

We explored the activity of faster Rossby waves (Rossby w0520, dark blue lines in Figure 5), separating wavenumbers 1, 2, and 3 which will be referred to as W1, W2 and W3 in the following. The time-latitude structure of the horizontal Rossby waves w0520 momentum flux anomaly for each case is shown in Figure 9. ~~The contribution of Rossby waves w0520 is largest in February 2016.~~In the tropics, the largest anomaly of Rossby waves w0520 is found in February. ~~Figures 9b and 9c show~~Figure 9 shows that the amplitude of the horizontal Rossby wave w0520 momentum flux anomaly was stronger in the extratropics in January 1960 and November 2010, while there were two peaks in February 2016 around 40°N and 15°N).. ~~In February 2016, there were two peaks of Rossby waves w0520 horizontal momentum flux~~ anomaly~~, in the extratropics (around 40°N) and in the tropics (around 15°N) as shown in Figure 9a.~~ We therefore focus now on the contributions of W1, W2 and W3 separately during the 2016 reversal event~~. We analyzed~~ by analyzing the time-latitude cross section of their horizontal momentum flux anomaly from November 2015 to April 2016 at 40 hPa (~~as shown in~~ Figure 10). ~~The result reveals that in particular~~The activity of W2 and W3 ~~activity~~was enhanced in 2015/2016 but the activity due to W1 was very weak. The maximum horizontal momentum flux anomaly of W2 occurred around 40°N in early February 2016 (Figure 10c), and propagated equatorward ~~since early February 2016. Although it is difficult to distinguish in Figure 10, W2 activity shows~~ with some days lag between 40°N and 15°N (see Figure S4), indicating its extratropical origin and equatorward propagation.

The peak of W3 occurs in early February 2016, around 15°N (as shown in Figure 10d). Furthermore, as shown in Figure 2, the enhanced Rossby wave activity was concentrated on the lower stratosphere (from 50 hPa to 30 hPa). Figures 2 and 10d suggest that the W3 peak does not originate from the extratropics or the vertical propagation, therefore the remaining possibility is local wave generation. The record high horizontal momentum flux anomaly from Rossby waves in February 2016 at 40 hPa seems to be the combination of a quasi-stationary W1 (Rossby waves w2040), a faster W2 generated in the extratropics, as well as a possibly local generated W3. Figure 10e reveals that the peaks of W1 (Rossby waves w2040) and W2 occurred earlier compared to the peak of the W3 in early February 2016. This result implies that not all components of the wave packet described by Lin et al. (2019) were of extratropical origin. Strictly speaking, the wavenumber composition of a travelling Rossby wave packet should remain similar during its lifetime: the dominant wavenumber does not change. Our analysis shows that this is not the case with W3 which becomes dominant. The amplitudes of W1 (Rossby waves w2040), W2 and W3 are 0.74 m^2/s^2, 0.931 m^2/s^2 and 1.312 m^2/s^2, and hence W3 was stronger than W2 and W1 (Rossby waves w2040). The locally generated W3 only occurred in February 2016 and we do not find such behavior in other cases, whose Rossby wave contributions are exclusively of extratropical origin (see Figures S5 and S6 for comparison with Figure 10).

3.1.3 The Possible Source of Local Rossby Wave Generation

Figure 10e demonstrates that the quasi-stationary W1 (Rossby waves w2040) and the faster W2 and W3 have stronger horizontal momentum flux anomalies in February 2016 at 40 hPa around 15°N. This suggests that the possibly locally generated W3 was as important as the Rossby waves which propagated from the extratropics during the reversal event in 2015/2016. Therefore it is important to investigate the possible source of the locally generated Rossby waves. As demonstrated in the previous section, the W3 generated in early February 2016 is not related to vertical or meridional propagation. In this section we will discuss two possible generation mechanisms: barotropic and baroclinic instability and nonlinear interactions.

We analyzed the barotropic and baroclinic instability in the lower stratosphere with the meridional gradient of potential vorticity at 40 hPa in February 2016 similar to Coy et al. (2017). The meridional gradient of potential vorticity was calculated at 70 hPa, 50 hPa, 40 hPa, 30 hPa, 20 hPa and 10 hPa from January 2015 to December 2016 (as shown in Figure S7). Figure S7 reveals that the meridional gradient of potential vorticity was greater than zero in February 2016 at 40 hPa and belowat lower altitudes, meaning that the atmosphere was stable during our analysis period below 40 hPaperiod at pressures below 40 hPa. The meridional gradient starts to be negative which indicates barotropic and baroclinic instability (see also section 2.4) in late March 2016. At 40 hPa the meridional gradient starts to be negative in late March 2016, which indicates barotropic and/or baroclinic instability (see section 2.4.) In this study, W3 maximizes one month prior to March 2016. This is consistent with Coy et al. (2017). This indicates that W3 maximizing in February 2016, so one month before, was not generated by instability. Our result is consistent with Coy et al. (2017) which showed that $\bar{q_\phi}$ was positive during the reversal event in 2015/2016, implying that instability of the large-scale flow was unlikely. Peter et al. (2018) also suggested that the distribution of the $\bar{q_\phi}$ could have directed and concentrated wave fluxes to this narrow region.

Another possible mechanism for the local generation of W3 is the nonlinear interaction between several different Rossby waves. Previous studies (Reznik et al., 1993; Huang et al., 2009; Tamarin et al., 2015) pointed out that nonlinear coupling processes could occur between different waves. Based on the wave interaction theory (Reznik et al., 1993; Huang et al., 2009), two waves could force a third wave if the first two waves satisfy the resonant interaction condition:

$$\omega(k_1) \pm \omega(k_2) = \omega(k_3), k_1 \pm k_2 = k_3 \quad (4)$$

Where ω and k are the frequency and wavenumber of the Rossby waves.

We analyzed the Fourier spectrum of the Rossby wave perturbations in zonal wind with wavenumbers 1, 2 and 3 at 40 hPa averaged over 10°N-20°N from January 2016 to February 2016 (Figure 11). Figure 11 shows that W1 had the strongest power at a frequency of 0.033 day^{-1}. W2 has two strong peaks, at frequencies 0.033 day^{-1} and 0.066 day^{-1}. W3 has the most complex peaks, the stronger peaks are corresponding to the frequencies are atW3 has a broad peak with the strongest cor 0.054 day^{-1} and 0.066 day^{-1}. Equation 4 reveals that the W1 with frequency of 0.033 day^{-1}, W2 with frequency of 0.033 day^{-1} and W3 with frequency 0.066 day^{-1} almost perfectly satisfy the nonlinear resonance interaction condition (see equation 4). The W3 power peak at 0.066 day^{-1} frequency belongs to the filtered Rossby waves w0520 whose horizontal momentum flux anomalies are displayed in Figures 9 and 10.

Moreover, the quasi-stationary Rossby wave W1 and the faster Rossby wave W2 occur first and the faster Rossby wave W3 appears to peak afterwards (as shown in Figure 10e). These results imply that nonlinear interactions and resonance between the quasi-stationary W1 and the faster W2 which came from the extratropics, generated W3 locally at 15°N, 40 hPa.

We analyze the frequency behavior of W1, W2 and W3 by using the phase position of the filtered Rossby w0540 of each wavenumber to calculate their phase speeds and transform them into frequencies at a daily resolution. This analysis is very sensitive to the wave's phase position, therefore it is applied directly on the standard 30 hPa level without any interpolation, and using only zonal winds. W1, W2 and W3 frequencies for January-March 2016 at 30 hPa are presented in Figure 11a-c. We repeated the same analysis also at the 50 hPa level, obtaining similar results (see Figure S8 in the supplement).

It can be observed in Figure 11a-c that during periods of increased wave activity, all wavenumbers' frequencies do not remain constant: they accelerate and slow down many times during January-March 2016. During the end of January and February 2016, W1 frequency (Fig. 11a) in the subtropics and equator varies around 0.02 and 0.04 cpd (i.e. periods above 20 days), in agreement with the previously diagnosed quasi-stationary W1 from extratropical origin. W2 (Fig. 11b) in the end of January 2016 at 15-30°N has frequencies around 0.03 cpd (30 day period, also in the quasi-stationary range) while having relatively low amplitude and showing signs of equatorward propagation. At the beginning of February, W2 can be seen accelerating while it amplifies, reaching frequencies of 0.07 cpd coinciding with its maximum amplitude near 10°N, then quickly losing amplitude and frequency by mid-February. W3 (Fig. 11c) in late January shows no activity or very low amplitudes throughout the extratropics, starting to gain amplitude within the NH tropics with frequencies around 0.06-0.09 cpd. Between the beginning and mid-February, W3 maximizes its amplitude and seems to propagate outward from the tropics, with a similar frequency range. In the second half of February 2016, W3 starts to slowly decay in amplitude while occupying a large area from 20°S to about 40°N, with markedly higher frequencies of around 0.09-0.14 cpd. W3 is nearly dissipated by March.

According to equation 4, to satisfy the resonance mechanism the frequency of W3 minus the sum of W1 and W2 needs to be close to zero. Figure 11d highlights where this happens by only showing where the absolute value of W3 - (W1+W2) in terms of frequency is below 0.04 cpd (blue colors, the rest is masked out). In Fig. 11d dark blue colors, or values close to resonance, rarely last more than a couple of days or they tend to have significant amounts of lighter blue colors. Only by the end of January and the first half of February, the values are close to resonance (less than 0.02, dark blue in Fig. 11d) for about two weeks in a row, a fair amount of time for a resonant wave to build up. This coincides with the amplification of w3 and its expansion outward from the tropics in Fig. 11c, as well as the large W3 momentum flux anomalies in Fig. 10d.

In mid-February there's a break in the resonance condition, depicted by the absence of blue color in Fig. 11d. It can be noted that W2 is nearly dissipated near 15°N by this time (Fig. 11b), and interestingly this is immediately followed by a sudden acceleration of W3, with higher frequencies as yellow and red colors in Fig. 11c. Perhaps this is an indicator that the W3, in the absence of forcing (no resonance of W1 and W2 as the latter dissipated), starts a transition into a faster and decaying free mode in the second half of February 2016.

It was noted by Reznik et al. (1993) that this wave resonance mechanism generally works in the short-wave domain, with resonant interaction at planetary-scales happening only in exceptional cases. The reasons for this special behavior and the exact timing and location of the waves would need further work and is beyond the scope of this paper.

Both W2 and W3 had important contributions to the enhanced Rossby wave horizontal momentum flux anomaly in the tropics (Figure 10). Our results from Figures 10 and 11 indicate that the mechanism for the local generation of W3 at 15°N, 40 hPa was nonlinear interaction and resonance between a quasi-stationary Rossby wave W1 and a faster Rossby wave W2 of extratropical origin. ~~The reasons for the special behavior and the exact timing and location of the waves would need further work and are beyond the scope of this paper.~~ Coy et al. (2017) noted that the horizontal momentum flux anomalies were very concentrated at a specific height range and latitude during the QBO reversal of the 2015/2016 winter, which is in agreement with our result. The very rare origin of W3 at 15°N and its important contribution to these momentum fluxes could explain why it was so localized, since the conditions for nonlinear interaction and resonance must have been very localized too. ~~In addition, W3 cannot be an equatorial wave mode in principle, otherwise its amplitude would be by definition maximizing at the equator.~~

In summary, we explored the Rossby wave horizontal momentum flux anomaly in the extratropics as well as in the tropics for three different cases (1959/1960, 2010/2011 and 2015/2016). The results show that the Rossby wave horizontal momentum flux anomaly in the tropics is dominated by a quasi-stationary Rossby wave W1 originating from the extratropics, as well as enhanced activity of faster Rossby waves which amount for the largest case-to-case differences (e.g., an equatorward propagating extratropical Rossby wave W2 and the locally generated Rossby wave W3 in the 2015/2016 case). During the 2015/2016 reversal event at 40 hPa, the locally generated Rossby wave W3 had the largest and most localized contribution (among faster Rossby waves) to the record horizontal momentum flux anomalies in the tropics.

Whereas the total structure from W1, W2 and W3 around 15°N resembles that of a wave packet as described by Lin et al. (2019), our results suggest that only the W1 and W2 components are of extratropical origin~~, both with similar frequency~~. The W3 component seems to originate later from the resonant interaction between W1 and W2.

The reversal event not only depends on the enhanced Rossby wave activity in the tropics but also on the different background zonal winds. The peaks of the Rossby wave horizontal momentum flux anomaly almost correspond to the strongest westerly zonal wind (greater than 10 m/s) in November 2010 (see Figure 5). Meanwhile, in January 1960 and February 2016 the peaks of the Rossby wave horizontal momentum flux anomalies correspond to a weaker zonal wind (less than 5 m/s). Through a comparison of the results in January 1960 and February 2016 when the background zonal winds were similar (see Figures 9a and 9c), we found that the enhanced Rossby wave activity is an important factor for the reversal event in 2015/2016.~~The reversal event not only depends on the enhanced Rossby wave activity in the tropics but also on the different background zonal winds.~~ The stronger Rossby wave horizontal momentum flux anomaly together with the weaker westerly zonal mean zonal wind both played significant roles for the reversed westerly zonal wind at 40 hPa in February 2016. Lin et al. (2019) pointed out that the westerly flow was decelerated by mixed Rossby-gravity wave momentum fluxes (MRG, ~~0.15-0.5 cpd frequency,~~ with ∼6-2 day periods: mostly faster waves than those analyzed in our study) prior to the appearance of the low-frequency waves, i.e. the W1-3 wave packet.

3.2 Reasons for the Unusually Long Westerly Zonal Wind at 20 hPa

This subsection will focus on the behavior of Kelvin waves during the unusually long westerly zonal wind at 20 hPa in 2015/2016. The possible role of the strong El Niño event during the long lasting westerly zonal wind will be also explored.

As shown in Figure 1a the westerly zonal mean zonal wind lasted unusually long in 2015/2016 at 20 hPa. Previous research mainly focused on the interruption of the westerly zonal wind near 40 hPa in 2015/2016, and only a few other studies (Newman et al., 2016; Coy et al., 2017; Kumar et al., 2018) noticed the unusual behavior of the zonal mean zonal winds above 30 hPa. By performing a statistical analysis of the the average period of the westerly zonal mean zonal wind at 20 hPa, We found that the average period of westerly zonal mean zonal wind at 20 hPa is 10.6 months between 1958 to 2014 (Figure 12). InHowever, in 2015/2016 the westerly zonal wind lasted 23 months (from May 2015 to March 2017) which is much longer than the maximum period (16 months) from 1958 to 2014. No similar westerly zonal wind period has ever been observed.

Newman et al. (2016) noticed that the westerly zonal wind started to migrate upward instead of downward from November 2015 to April 2016 above 30 hPa. The extended westerly zonal wind and the upward propagating westerly zonal wind above 30 hPa could result from wave-mean flow interaction. Since Kelvin waves are generated in the troposphere and propagate upward to the lower stratosphere where they initiate an eastward acceleration of the zonal mean zonal wind (Baldwin et al., 2001), they might play a role in the extended westerly zonal winds.

Figure 13 shows a predominance of above-average Kelvin wave squared perturbations in zonal wind (mostly red and yellow shading and absence of blue) in the upper troposphere around 200 hPa and 100 hPa throughout 2015 and early 2016. The upper tropospheric Kelvin waves can be seen propagating upward within easterly winds most of the time. Also, from December 2015 to April 2016, vertical propagation of Kelvin waves can be observed within weak westerly winds between 50 hPa and 20 hPa, which will be discussed in more detail below. Figure 13 shows that the squared zonal wind perturbations had maximum amplitudes around the tropopause. Since the vertical momentum flux from westward-propagating Rossby waves (Figure S2) is very weak during this time, we will focus only on vertical momentum flux anomalies from Kelvin waves in the following (Figure 14).

Figure 14a demonstrates that the vertical momentum flux anomaly from Kelvin waves was strong during most of the easterly zonal wind condition from the troposphere to the stratosphere in 2015. Furthermore, the vertical momentum flux anomaly from Kelvin waves was also above-average from December 2015 to April 2016 from 50 hPa to 20 hPa which agrees with the increased squared zonal wind perturbations of Kelvin waves (Figure 13). It should be noted that from December 2015 to around April 2016 near 20 hPa the background zonal mean zonal wind is westerly. Also in the levels down to 300 hPa, from December 2015 until February 2016, the mean zonal winds are weak westerlies or around zero. Kelvin waves were propagating upward at the time, while in theory they only do within easterlies. Also, if the Kelvin wave's phase speed exceeds that of the westerly flow, it is possible that the Kelvin wave propagates upward within weak westerlies as reported by Ern et al. (2008). One explanation for these seemingly contradicting facts is the possibility that a zonally constrained - but large enough area of easterlies existed at the time, allowing synoptic-scale Kelvin waves to propagate upward.

We analyzed the vertical momentum flux anomaly from Kelvin waves during the westerly zonal wind conditions at 20 hPa from 1958 to 2016 (Figure 14b). The result shows that the maximum vertical momentum flux anomaly from Kelvin waves corresponds to the beginning of the westerly zonal wind phase in general (Figure 14b). The vertical Kelvin wave momentum flux anomaly becomes weaker when the westerly zonal wind gets stronger. The westerly zonal wind starts in May 2015 (around 3 m/s). Meanwhile the vertical Kelvin wave momentum flux anomaly was around $0.4 \times 10^{-3} m^2 s^{-2}$. From late 2015 to early

2016 the amplitude of the background zonal wind was similar to the background zonal wind in May 2015, but the vertical momentum flux anomaly from Kelvin waves was much stronger. The amplitudes of the vertical Kelvin wave momentum flux anomaly in December 2015, January, February, March and April 2016 are 0.88, 1.54, 1.31, 0.872 and $1.025 \times 10^{-3} m^2 s^{-2}$, respectively. They are much larger than the average values ($0.45 \times 10^{-3} m^2 s^{-2}$) in westerly zonal wind conditions from 1958 to 2014. The vertical momentum flux anomaly from Kelvin waves started to increase from December 2015 and ended in April 2016 which corresponds to the upward propagating westerly zonal winds (Figure 2) reported in Newman et al. (2016). The unusually large vertical momentum flux anomaly from Kelvin waves from December 2015 to April 2016 was deposited to the westerly zonal wind and resulted in additional eastward momentum and hence a prolongation of the westerly winds at 20 hPa. Typically, Kelvin wave momentum deposition promotes downward propagation of the QBO westerly phase, since the waves encounter westerly shear and a rather narrow region below the critical level near the bottom of the QBO westerlies where the Kelvin wave momentum is deposited. This is not the case in early 2016, with weak westerlies (weak easterlies later on), low shear between 100 hPa and 20 hPa, and easterly shear above. These sub-critical conditions make the height range for Kelvin wave momentum deposition quite broader than usual, thereby enabling a prolongation and even upward propagation of the westerly QBO phase. This interpretation would be in agreement with (Das and Pan, 2015), who found faster-descending QBO westerly phase only when the lower stratospheric winds favored Kelvin wave upward propagation (not the case in early 2016).

We also analyzed the temporal variation of the ENSO index and the convective activity in the tropics (Figure S9). The ENSO index was larger than 2 K (strong El Niño event) from October 2015 to January 2016. Tropospheric convective activity is represented by the Outgoing Long-wave Radiation (OLR). The deviations of zonal mean OLR from the monthly climatology had minimum values in February 2016 which corresponds to enhanced convective activity and at the same time to the enhanced Kelvin wave activity at 20 hPa (Figure S9). Moreover, the convective activity and the vertical momentum flux anomaly from Kelvin waves (at 20 hPa have much stronger values in January, February, March and April 2016 which corresponds to the reversal event at 40 hPa (Figure 14). ~~Our results suggest that there is a close relationship between the strong El Niño event and enhanced Kelvin wave activity in 2015/2016.~~ We also calculated the squared perturbations in zonal wind for Kelvin waves as deviation from the monthly climatology at 200 hPa during La Niña, Neutral and El Niño conditions (Figure 15). This indicates that Kelvin wave activity is suppressed during La Niña and enhanced during El Niño conditions, in agreement with previous studies that linked increased Kelvin wave activity to El Niño (Yang and Hoskins, 2013; Das and Pan, 2015; Saeful et al., 2017). The enhanced vertical Kelvin wave momentum flux anomaly is ~~could be~~ excited by enhanced convective activity in the troposphere~~ which might be~~ caused by the strong El Niño event. The wind structure below 20 hPa that combined weak westerly and easterly zonal winds ~~favored~~allowed Kelvin waves to propagate vertically. Moreover, as shown in Figure 14a, the westerly zonal wind was very weak in January and February 2016. In March and April 2016 the zonal wind was in its easterly phase below 30 hPa and weak westerly around 20 hPa. This condition allowed the Kelvin waves to reach 20 hPa and deposit their vertical momentum to the background wind.

From our investigation, the extended westerly zonal wind near 20 hPa was possibly caused by enhanced Kelvin wave activity in 2015/2016. The ~~strong~~above-average Kelvin wave activity (Fig 13) and related vertical momentum flux anomalies (Fig 14a) correspond to a~~has a close relationship with the~~ strong El Niño event in 2015/2016. Although it is known that climatologically

El Niño events enhance Kelvin wave activity (Yang and Hoskins (2013); Das and Pan (2015); Saeful et al. (2017), Fig. 15), the 2015/2016 El Niño is one of the strongest on record (Fig. 1c). The strong Kelvin waves in the troposphere together with ~~the weaker zonal winds below~~ the unusual wind structure around 20 hPa finally lead to the extended westerly zonal winds at 20 hPa. ~~To our knowledge, the enhanced Kelvin wave activity and its relation to ENSO has not been noted previously.~~

4 Conclusions

The QBO westerly phase was reversed by an unexpected easterly jet near 40 hPa and the westerly zonal wind lasted unusually long at 20 hPa during NH winter 2015/2016. By analyzing the horizontal momentum flux anomaly from Rossby waves in the extratropics and tropics we find that Rossby waves propagating from the northern extratropics were important contributors to the easterly jet around 40 hPa, in agreement with previous studies (Osprey et al., 2016; Newman et al., 2016; Coy et al., 2017). We additionally explored different time-scales and wavenumbers of the Rossby waves and concluded that quasi-stationary Rossby W1 and faster Rossby W2 waves which propagated from the extratropics had important contributions to the reversed westerly zonal wind at 40 hPa in 2015/2016 (Figures 6 and 10). Furthermore, we find that during the reversal event a locally generated Rossby wave W3 around 15°N with a period of 5-20 days also played an important role (Figure 10). We explored two possible generation mechanisms for this locally generated Rossby wave: barotropic-baroclinic instability and nonlinear wave-wave interaction. The locally generated Rossby wave w0520 with W3 in the tropics was unlikely caused by large scale instability (Figures 2 and 3). Our results imply that nonlinear interactions between the quasi-stationary Rossby wave W1 and faster Rossby wave W2 of extratropical origin, generated the local Rossby wave W3 around 15°N (Figure 11). The reasons for the special behavior and the exact timing and location of the waves is beyond the scope of this paper. In addition to the extratropical horizontal Rossby wave momentum flux anomalies and the locally generated Rossby waves in the tropics, the weaker background winds as compared to two similar winters in 1959/1960 and 2010/2011 helped to favor this unusual reversal event in February 2016. Three important and novel take-home messages result from section 3.1 of our study:

1) The largest differences in horizontal Rossby wave momentum flux anomalies among all three investigated cases are related to faster Rossby waves (periods of 5-20 days) of extratropical origin.

2) The February 2016 case is unique, in the sense that it shows a local generation (in latitude and height) of a Rossby wave W3, which is not observed in any other case and has the largest and most localized contribution to the observed horizontal momentum flux anomalies.

3) We relate local generation of the aforementioned W3 to a resonant interaction between quasi-stationary Rossby wave W1 and a faster Rossby wave W2 of extratropical origin that were present at 15°N.

Lin et al. (2019) reported that the reversal event of the QBOW in February 2016 had a dominant contribution from a wave packet at 35.8 hPa. They also proposed that MRG played an important role for preconditioning this event. Peter et al. (2018) revealed that the influence of nonlinear feedbacks of the $\bar{q_\phi}$ structure is important for the disruption of the QBOW in February 2016. Our results, studying the components of the above mentioned wave packets in more detail, are consistent with previous studies while highlighting the responsible mechanisms (local W3 generation from resonant interaction).

Besides the upward propagation of westerly zonal wind regime at 20 hPa in the 2015/2016 winter (Newman et al., 2016), we find that the westerly zonal wind lasted unusually long (Figures 12 and 13). Our results suggest that the upward propagating and prolonged westerly zonal winds at 20 hPa could be caused by enhanced Kelvin wave activity (Figures 13 and 14). The enhanced Kelvin wave activity could be related to strong convective activity. Indeed, the strong El Niño event in 2015/2016 favored strong convective activity, which in turn excited stronger Kelvin wave activity. Under La Niña conditions Kelvin wave activity is suppressed (Figure 15). The weaker zonal winds in the troposphere and lower stratosphere (related to the combination of anomalous factors around 40 hPa as summarized above) favored the upward propagation of Kelvin waves. The increased Kelvin wave activity then produced more eastward and upward acceleration of the zonal mean zonal winds and lead to the unusual westerly zonal wind structure at 20 hPa in 2015/2016.

Author contributions. HL performed the analysis, produced most figures and wrote the manuscript. RPK assisted in the methodology development, performed the analysis for - and produced Fig. 11, and rewrote parts of the manuscript. KM motivated the study, supervised its development and rewrote parts of the manuscript.

Acknowledgements. We thank the European Center for Medium-Range Weather Forecasts (ECMWF) for the freely available ERA-40 and ERA-Interim data, and the Free University of Berlin for the provision of the QBO data. We thank NOAA for the freely available Sea Surface Temperature data. This work was carried out during a stay of Haiyan Li as a joint training Ph.D student with funding provided from the Chinese Scholarship Council at GEOMAR in Kiel (Germany). We thank Dr. Sebastian Wahl for his help with processing the ECMWF, OLR and SST data, and Dr. Wenjuan Huo for help with the figures. The article processing charges for this publication are covered by China Postdoctoral Science Foundation Grant (Grant Number: 2019M663204). The authors would like to thank three anonymous reviewers whose comments and suggestions substantially improved the quality of the manuscript.

References

Andrews, D. G., R., H. J., and B., L. C.: Middle Atmosphere Dnamics, International Geophsics Series, 1987.

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Marquardt, C., Sato, K., and Takahashi, M.: The quasi-biennial oscillation, Rev. Geophys., https://doi.org/10.1029/1999RG000073, 2001.

Barton, C. A. and McCormack, J. P.: Origin of the 2016 QBO Disruption and Its Relationship to Extreme El Niño Events, Geophys. Res. Lett., 44, 11,150–11,157, https://doi.org/10.1002/2017GL075576, 2017.

Blume, C., Matthes, K., and Horenko, I.: Supervised Learning Approaches to Classify Sudden Stratospheric Warming Events, Journal of the Atmospheric Sciences, 2012.

Calvo, N., Garcia, R. R., Randel, W. J., and Marsh, D. R.: Dynamical Mechanism for the Increase in Tropical Upwelling in the Lowermost Tropical Stratosphere during Warm ENSO Events, J. Atmos. Sci., 67, 2331–2340, https://doi.org/10.1175/2010JAS3433.1, http://journals.ametsoc.org/doi/abs/10.1175/2010JAS3433.1, 2010.

Christiansen, B., Yang, S., and Madsen, M. S.: Do strong warm ENSO events control the phase of the stratospheric QBO?, Geophys. Res. Lett., 43, 10,489–10,495, https://doi.org/10.1002/2016GL070751, 2016.

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

Das, U. and Pan, C.: Equatorial atmospheric Kelvin waves during El Nino episodes and their effect on stratospheric QBO, Science of the Total Environment, 2015.

Dee, D. P., Uppala, S. M., Simmons, A. J., and Coauthers: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quart. J. Roy. Meteor. Soc., https://doi.org/10.1002.qj.828, 2011.

Dunkerton, T. J.: The quasi-biennial oscillation of 2015–2016: Hiccup or death spiral?, Geophysical Research Letters, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016GL070921, 2016.

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, 540–542, https://doi.org/10.1002/qj.49708637011, 1960.

Ern, M. and Preusse, P.: Quantification of the contribution of equatorial Kelvin waves to the QBO wind reversal in the stratosphere, Geophysical Research Letters, 2009.

Ern, M., Preusse, P., Krebsbach, M., Mlynczak, M. G., and Russell III, J. M.: Equatorial wave analysis from SABER and ECMWF temperatures, Atmos. Chem. Phys., 2008.

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

Garcia, R. R. and Richter, J. H.: On the Momentum Budget of the Quasi-Biennial Oscillation in the Whole Atmosphere Community Climate Model, Journal of the Atmospheric Sciences, 2019.

Gray, L. J., Crooks, S., Pascoe, C., Sparrow, S., and Palmer, M.: Solar and QBO Influences on the Timing of Stratospheric Sudden Warmings, J. Atmos. Sci., 61, 2777–2796, https://doi.org/10.1175/JAS-3297.1, 2004.

Gray, W. M., Sheaffer, J. D., and Knaff, J. A.: Hypothesized mechanism for stratospheric QBO influence on ENSO variability, J. Geophys. Res., 19, 107–110, https://doi.org/10.1029/91GL02950, 1992.

Hansen, F., Matthes, K., and Wahl, S.: Tropospheric QBO-ENSO interactions and differences between the atlantic and pacific, J. Clim., 29, 1353–1368, https://doi.org/10.1175/JCLI-D-15-0164.1, 2016.

Hirota, N., Shiogama, H., Akiyoshi, H., Ogura, T., Takahashi, M., Kawatani, Y., Kimoto, M., and Mori, M.: The influences of El Nino and Arctic sea-ice on the QBO disruption in February 2016, npj Clim. Atmos. Sci., 1, 10, https://doi.org/10.1038/s41612-018-0020-1, http://www.nature.com/articles/s41612-018-0020-1, 2018.

Holton, J. R. and Austin, J.: The Influence of the Equatorial QBO on Sudden Stratospheric Warmings, J. Atmos. Sci., 48, 607–618, https://doi.org/10.1175/1520-0469(1991)048<0607:TIOTEQ>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0469{%}281991{%}29048{%}3C0607{%}3ATIOTEQ{%}3E2.0.CO{%}3B2, 1991.

Holton, J. R. and Lindzen, R. S.: An Updated Theory for the Quasi-Biennial Cycle of the Tropical Stratosphere, J. Atmos. Sci., 29, 1076–1080, https://doi.org/10.1175/1520-0469(1972)029<1076:AUTFTQ>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0469{%}281972{%}29029{%}3C1076{%}3AAUTFTQ{%}3E2.0.CO{%}3B2, 1972.

Holton, J. R. and Tan, H.-C.: The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb, J. Atmos. Sci., 37, 2200–2208, https://doi.org/10.1175/1520-0469(1980)037<2200:TIOTEQ>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0469{%}281980{%}29037{%}3C2200{%}3ATIOTEQ{%}3E2.0.CO{%}3B2, 1980.

Huang, K. M., Zhang, S. D., and Yi, F.: Gravity wave excitation through resonant interaction in a compressible atmosphere, Geophys. Res. Lett., 36, 1–5, https://doi.org/10.1029/2008GL035575, 2009.

Kang, M.-J., Chun, H.-Y., Kim, Y.-H., Preusse, P., and Ern, M.: Momentum Flux of Convective Gravity Waves Derived from an Offline Gravity Wave Parameterization. Part II: Impacts on the Quasi-Biennial Oscillation, Journal of the Atmospheric Sciences, 2018.

Kawatani, Y. and Hamilton, K.: Weakened stratospheric quasibiennial oscillation driven by increased tropical mean upwelling, Nature, 497, 478–481, https://doi.org/10.1038/nature12140, 2013.

Kumar, K. K., Mathew, S. S., and Subrahmanyam, K. V.: Anomalous tropical planetary wave activity during 2015/2016 quasi biennial oscillation disruption, J. Atmos. Solar-Terrestrial Phys., 167, 184–189, https://doi.org/10.1016/j.jastp.2017.12.004, https://doi.org/10.1016/j.jastp.2017.12.004, 2018.

Lin, P., Held, I., and Ming, Y.: The Early Development of the 2015/16 Quasi-Biennial Oscillation Disruption , Journal of Atmospheric Sciences, https://journals.ametsoc.org/doi/pdf/10.1175/JAS-D-18-0292.1, 2019.

Lindzen, R. S. and Holton, J. R.: A Theory of 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, 1968.

Matthias, V. and Ern, M.: On the origin of the mesospheric quasi-stationary planetary waves in the unusual Arctic winter 2015/2016, Atmos. Chem. Phys., 18, 4803–4815, https://doi.org/10.5194/acp-18-4803-2018, 2018.

Maury, P., Lott, F., Guez, L., and Duvel, J. P.: Tropical variability and stratospheric equatorial waves in the IPSLCM5 model, Clim. Dyn., 40, 2331–2344, https://doi.org/10.1007/s00382-011-1273-0, 2013.

Naujokat, B.: 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, http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1986)043{%}3C1873:AUOTOQ{%}3E2.0.CO;2, 1986.

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

Osprey, S. M., Butchart, N., Knight, J. R., Scaife, A. A., Hamilton, K., Anstey, J. A., and Zhang, C.: An unexpected disruption of the atmospheric quasi- biennial oscillation, Science, 4156, 441–444, 2016.

O'Sullivan, D.: Interaction of extratropical Rossby waves with westerly quasi-biennial oscillation winds, J. Geophys. Res., 102, 19 461–19 469, https://doi.org/10.1029/97JD01524, 1997.

Peter, H., H., H. P., J., R. W., and Thomas, B.: The Emergence of Shallow Easterly Jets within QBO Westerlies, Journal of the Atmospheric Sciences, 2018.

Pilch Kedzierski, R., Matthes, K., and Bumke, K.: Wave modulation of the extratropical tropopause inversion layer, Atmos. Chem. Phys., 17, 4093–4114, https://doi.org/10.5194/acp-17-4093-2017, 2017.

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

Reznik, G. M., Piterbarg, L. I., and Kartashova, E. A.: Nonlinear interactions of spherical Rossby modes, Dyn. Atmos. Ocean., 18, 235–252, https://doi.org/10.1016/0377-0265(93)90011-U, 1993.

Saeful, R., Lubis, S. W., and Sonni, S.: Impact of ENSO on seasonal variations of Kelvin Waves and mixed Rossby-Gravity Waves, IOP Conf. Series: Earth and Environmental Science, 2017.

Schirber, S.: Influence of ENSO on the QBO: Results from an ensemble of idealized simulations, J. Geophys. Res., 120, 1109–1122, https://doi.org/10.1002/2014JD022460, 2015.

Schreck, C.: Extract equatorial waves by filtering in the Wheeler-Kiladis wavenumber-frequency domain, https://www.ncl.ucar.edu/Document/Functions/User_contributed/kf_filter.shtml, 2009.

Shuckburgh, E., Norton, W., Iwi, A., and Haynes, P.: Influence of the quasi-biennial oscillation on isentropic transport and mixing in the tropics ans stutropics, Journal of Geophysical Research, 106, 327–337, 2001.

Taguchi, M.: Observed connection of the stratospheric quasi-biennial oscillation with El Niño-Southern Oscillation in radiosonde data, J. Geophys. Res. Atmos., 115, 1–12, https://doi.org/10.1029/2010JD014325, 2010.

Tamarin, T., Heifetz, E., Umurhan, O. M., and Yellin, R.: On the nonnormal–nonlinear interaction mechanism between counter-propagating Rossby waves, Theor. Comput. Fluid Dyn., 29, 205–224, https://doi.org/10.1007/s00162-015-0346-9, 2015.

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 2015-2016 quasi-biennial oscillation, Atmos. Chem. Phys., 17, 6813–6823, https://doi.org/10.5194/acp-17-6813-2017, 2017.

Uppala, S. M., KÅllberg, P. W., Simmons, A. J., Andrae, U., Costa Bechtold, V. D., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van, L., Berg, D., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J., Morcrette, J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Quarterly Journal of the Royal Meteorological Society, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1256/qj.04.176, 2005.

Wheeler, M. and Kiladis, G. N.: Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber–Frequency Domain, J. Atmos. Sci., 56, 374–399, https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2, http://journals.ametsoc.org/doi/abs/10.1175/1520-0469{%}281999{%}29056{%}3C0374{%}3ACCEWAO{%}3E2.0.CO{%}3B2, 1999.

Yang, G.-Y. and Hoskins, B.: ENSO Impact on Kelvin Waves and Associated Tropical Convection, J. Atmos. Sci., 70, 3513–3532, https://doi.org/10.1175/JAS-D-13-081.1, http://journals.ametsoc.org/doi/abs/10.1175/JAS-D-13-081.1, 2013.

Yoo, C. and Son, S. W.: 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, 2016.

Yuan, W., Geller, M. A., and Love, P. T.: ENSO influence on QBO modulations of the tropical tropopause, Q. J. R. Meteorol. Soc., 140, 1670–1676, https://doi.org/10.1002/qj.2247, 2014.

Table 1. Exact boundaries of the Rossby wave and Kelvin wave filters.

	Period (days)	Wavenumber	Equivalent depth (m)
Rossby wave	5∼70	-3.5∼-0.5	/
Rossby w0520	5∼20	-3.5∼-0.5	/
Rossby w2040	20∼40	-3.5∼-0.5	/
Kelvin wave	4∼30	1∼14	6∼600

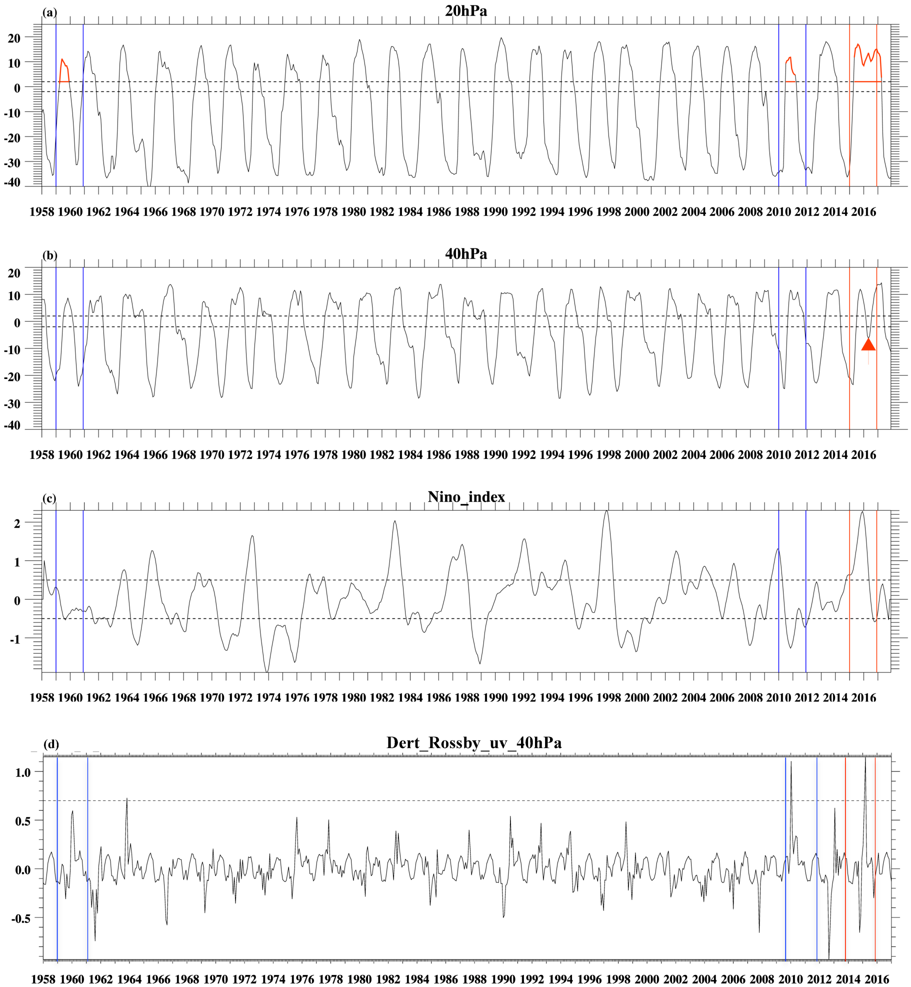


Figure 1. Zonal mean zonal wind at (a) 20 hPa, (b) 40 hPa, (c) ENSO index in the Niño 3.4 region. ~~The vertical blue lines denote the time periods of 1959/1960 and 2010/2011 and~~ Panel (d) denotes the~~(d)~~ time series of the horizontal Rossby wave momentum flux anomaly with respect to the monthly climatology averaged over the tropics (from 10°S to 10°N) at 40 hPa from 1958 to 2017 (unit is m^2/s^2). The horizontal dashed lines denote the speed of 2 m/s and -2 m/s in panels (a) and (b). In panel (c) the horizontal dashed lines denote 0.5 K and -0.5 K, respectively. The horizontal dashed line denotes the value of 0.7 m^2/s^2 in panel (d). The vertical red lines denote the time period of 2015/2016 and the vertical blue lines denote the periods of 1959/1960 and 2010/2011. In panel (a) the horizontal red lines denote the westerly phase periods during 1959/1960, 2010/2011 and 2015/2016 at 20 hPa. In panel (b) the red triangle denotes the reversed westerly zonal wind in 2015/2016 at 40 hPa.

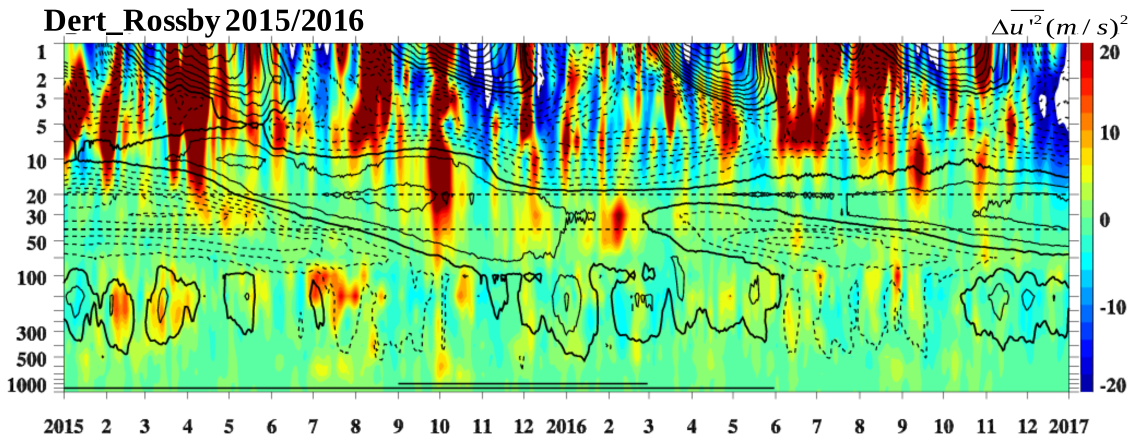


Figure 2. Temporal evolution of Rossby wave activity as squared zonal wind anomalies averaged over 10°S-10°N in the vertical direction. Color shading denotes the anomalies with respect to the monthly climatology (the unit is m^2/s^2). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line. The horizontal dashed lines denote the altitudes of 20 and 40 hPa. The horizontal solid lines denote the El Niño (single line) and strong El Niño periods (double line) in the bottom.

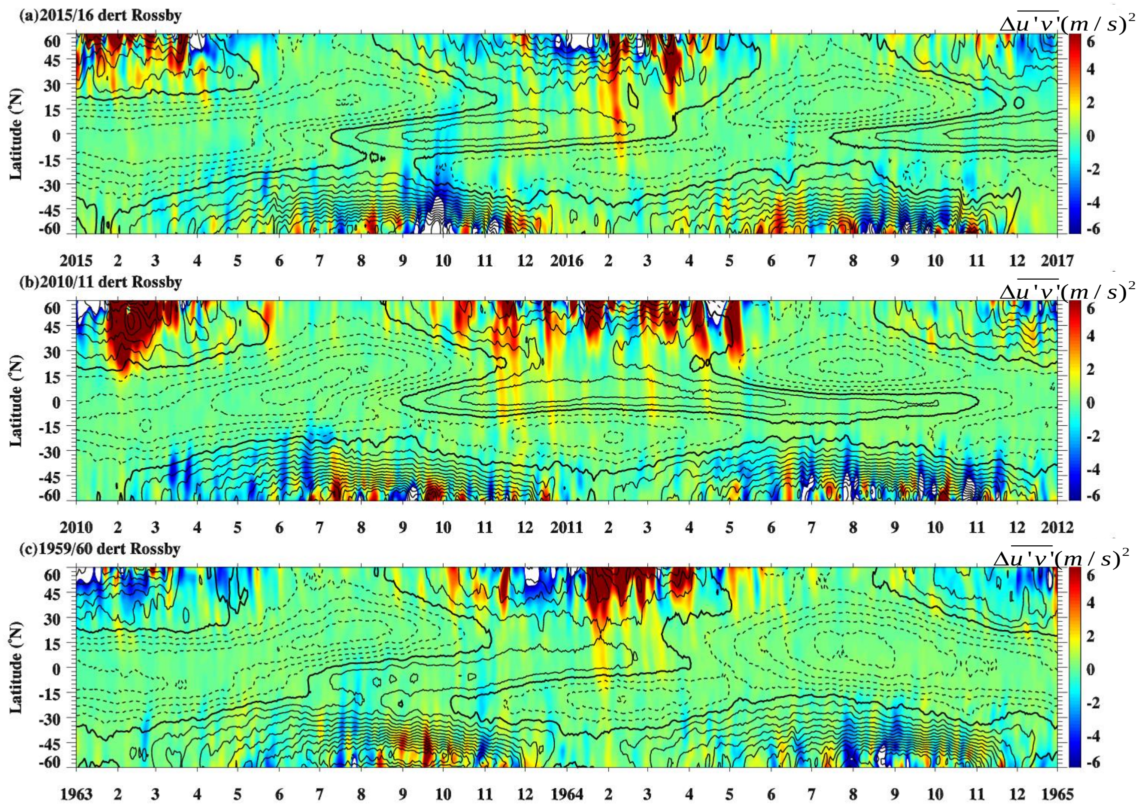


Figure 3. Temporal evolution of meridional propagation of westward propagating Rossby waves (with period of 5-70 days) horizontal momentum flux anomaly in (a) 2015/2016, (b) 2010/2011 and (c) 1959/1960 at 40 hPa. Color shadings denote the anomalies with respect to the monthly climatology (unit is m^2/s^2). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line.

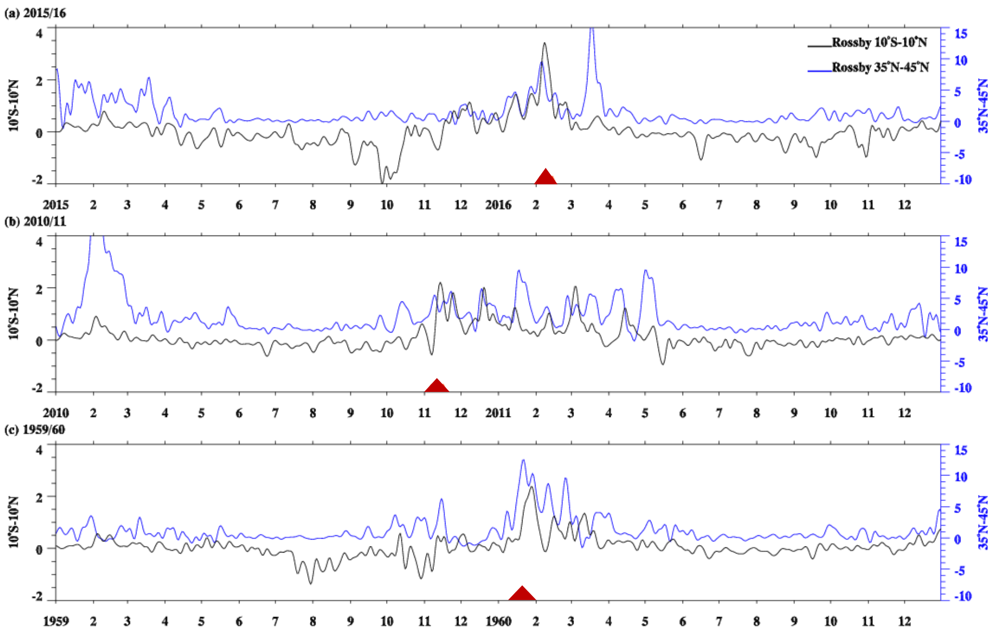


Figure 4. Temporal evolution of horizontal Rossby wave (with period of 5-70 days) momentum flux anomaly averaged over 10°S-10°N (black lines) and 35°N-45°N (blue lines) during (a) 2015/2016, (b) 2010/2011 and (c) 1959/1960 at 40 hPa. Red triangles in panels (a), (b) and (c) denote February 2016, November 2010 and January 1960, respectively.

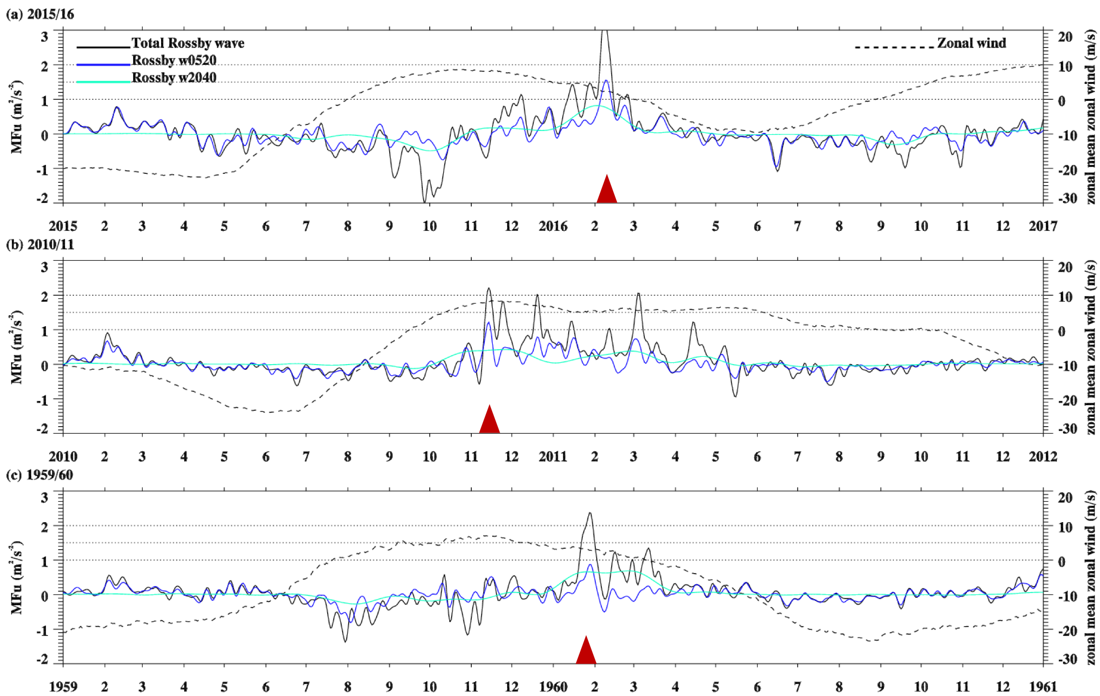


Figure 5. Temporal evolution of horizontal Rossby wave momentum flux anomalies over the tropics (10°S-10°N) during (a) 2015/2016, (b) 2010/2011 and (c) 1959/1960 at 40 hPa. The horizontal dotted lines denote the values of horizontal momentum flux anomaly of Rossby waves of 1 m^2/s^2, 1.5 m^2/s^2 and 2 m^2/s^2. The black, dark blue and light blue solid lines denote the horizontal momentum flux anomaly of total Rossby wave (corresponding to Rossby w0570), Rossby w0520 and Rossby w2040, respectively. The dashed lines denote the background zonal wind during each case. Red triangles in panels (a), (b) and (c) denote February 2016, November 2010 and January 1960, respectively.

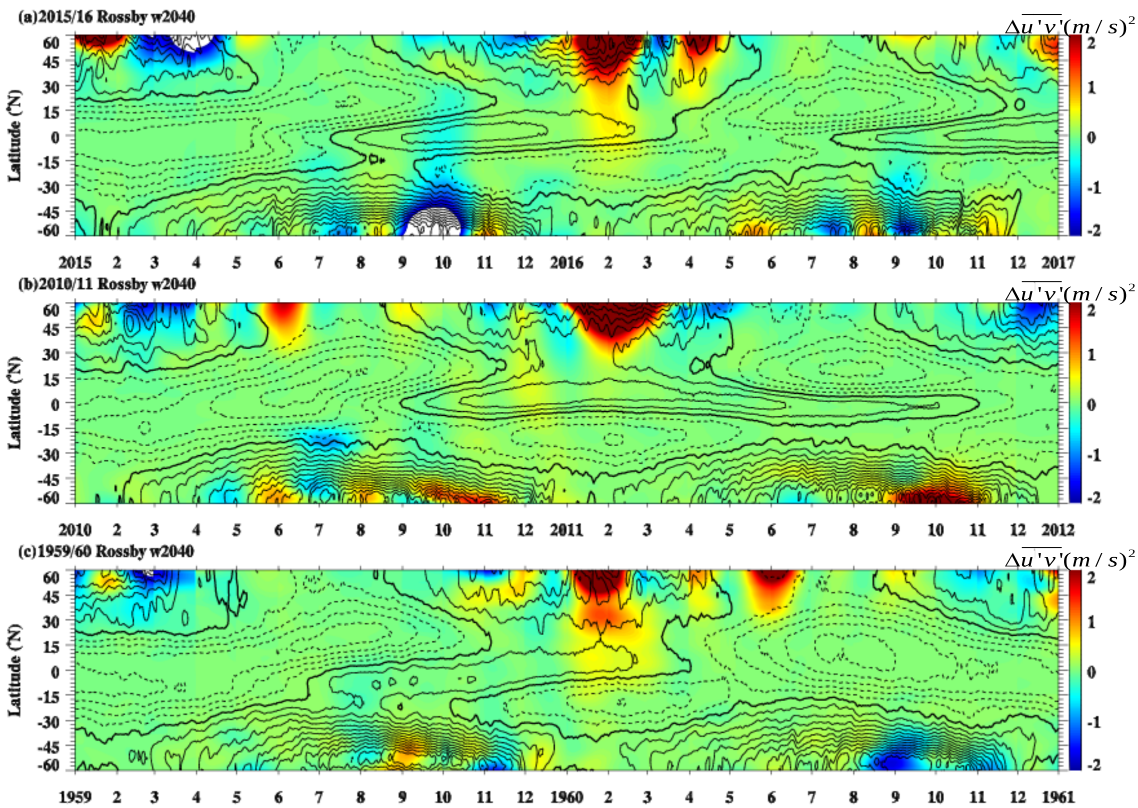


Figure 6. The time-latitude cross section of Rossby waves (with periods of 20-40 days and with wavenumber 1) horizontal momentum flux anomaly in (a) 2015/2016, (b) 2010/2011 and (c)1959/1960 at 40 hPa. Color shadings denote the anomalies with respect to the monthly climatology (0 m^2s^{-2}). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line.

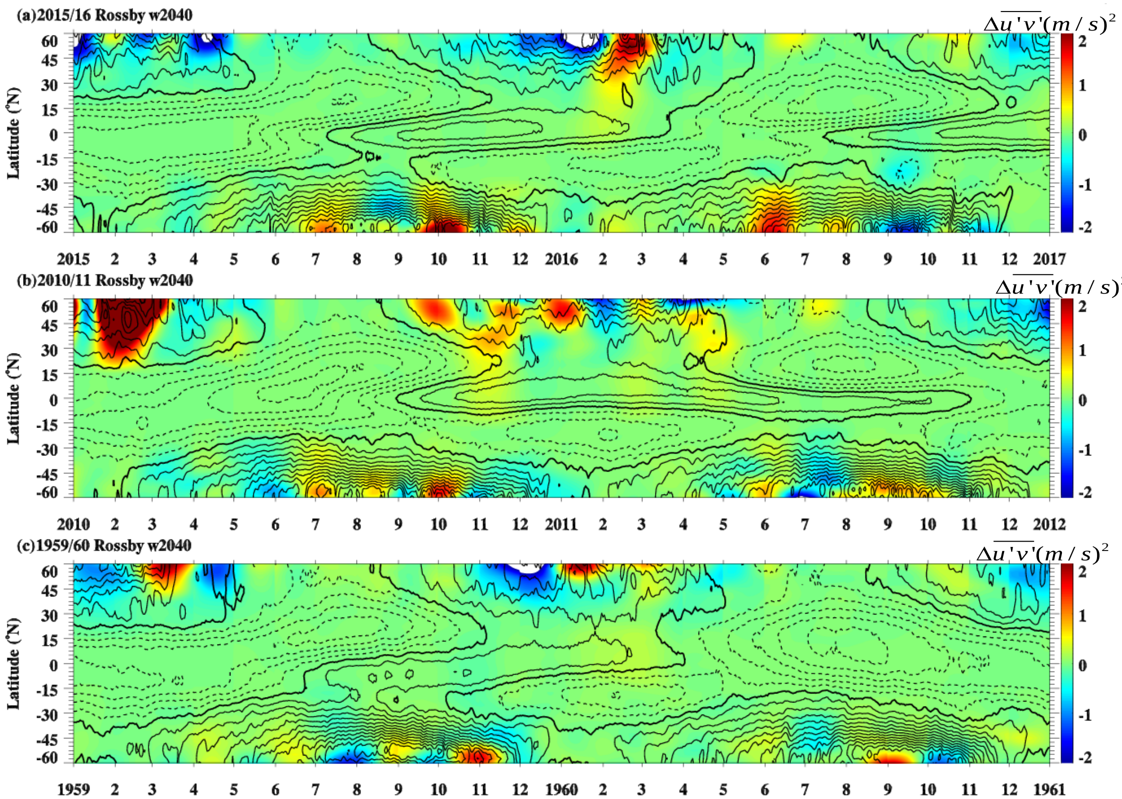


Figure 7. The latitude-time cross section of Rossby wave w2040 (with wavenumber 2) horizontal momentum flux anomalies in (a) 2015/2016, (b) 2010/2011 and (c) 1959/1960 at 40 hPa. Color shadings denote the anomalies with respect to the monthly climatology. The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line.

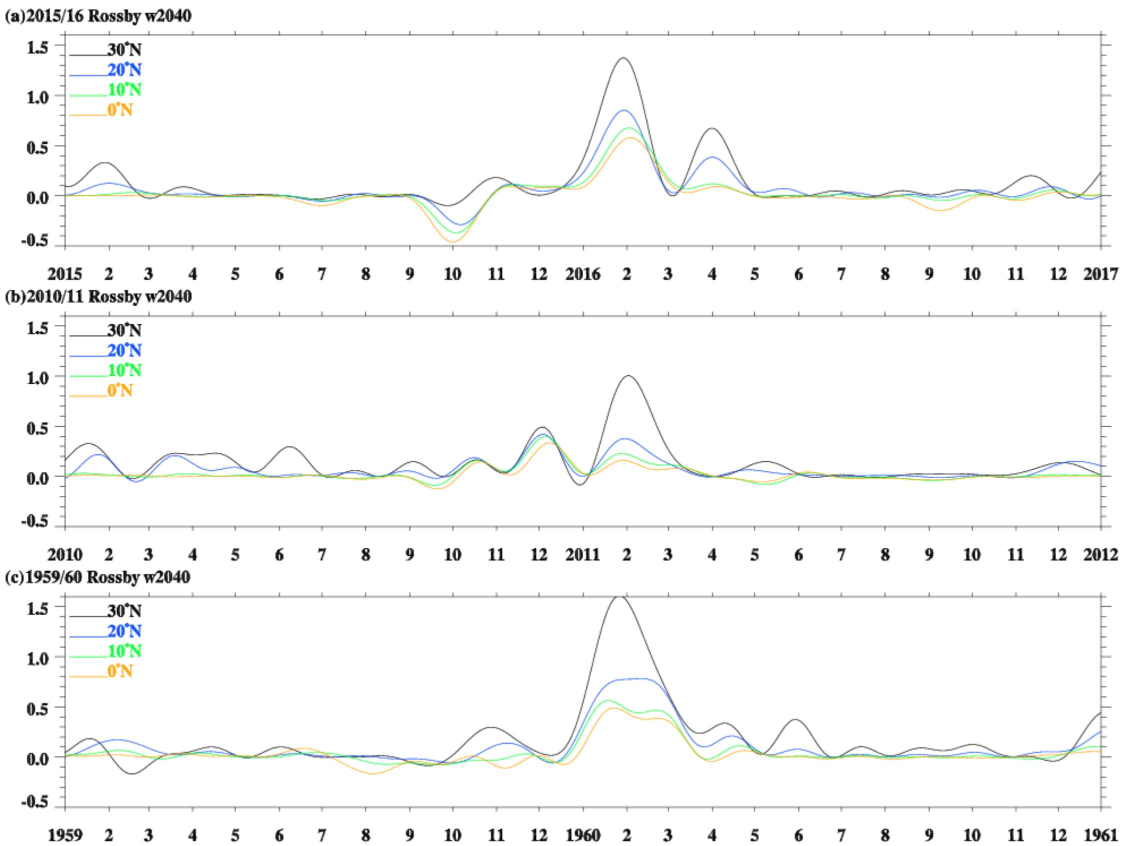


Figure 8. The temporal variation of Rossby w2040 (with wavenumber 1) horizontal momentum flux anomaly at 0°N (orange lines), 10°N (green lines), 20°N (blue lines) and 30°N (black lines) in 2015/2016, 2010/2011 and 1959/1960 at 40 hPa.

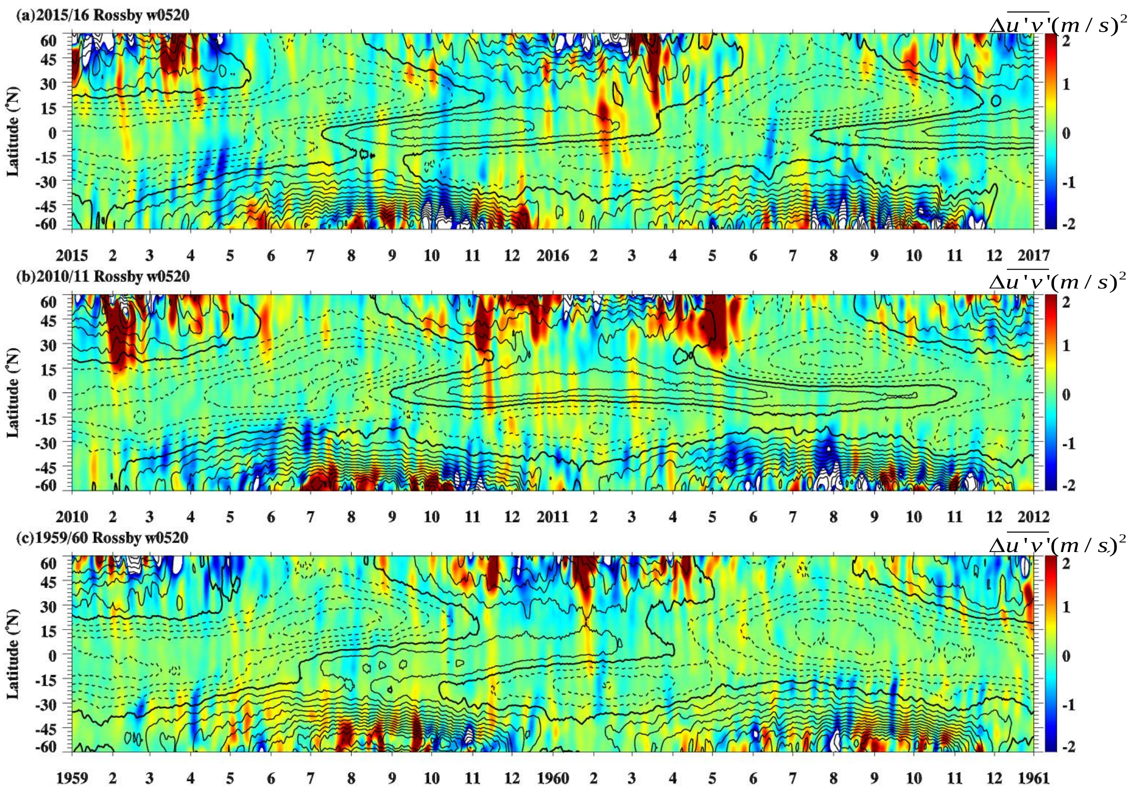


Figure 9. The time-latitude cross section of the Rossby waves (with periods of 5-20 days) in (a) 2015/2016, (b) 2010/2011 and (c) 1959/1960 at 40 hPa. Color shadings denote the anomalies with respect to the monthly climatology (0 m^2s^{-2}). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line.

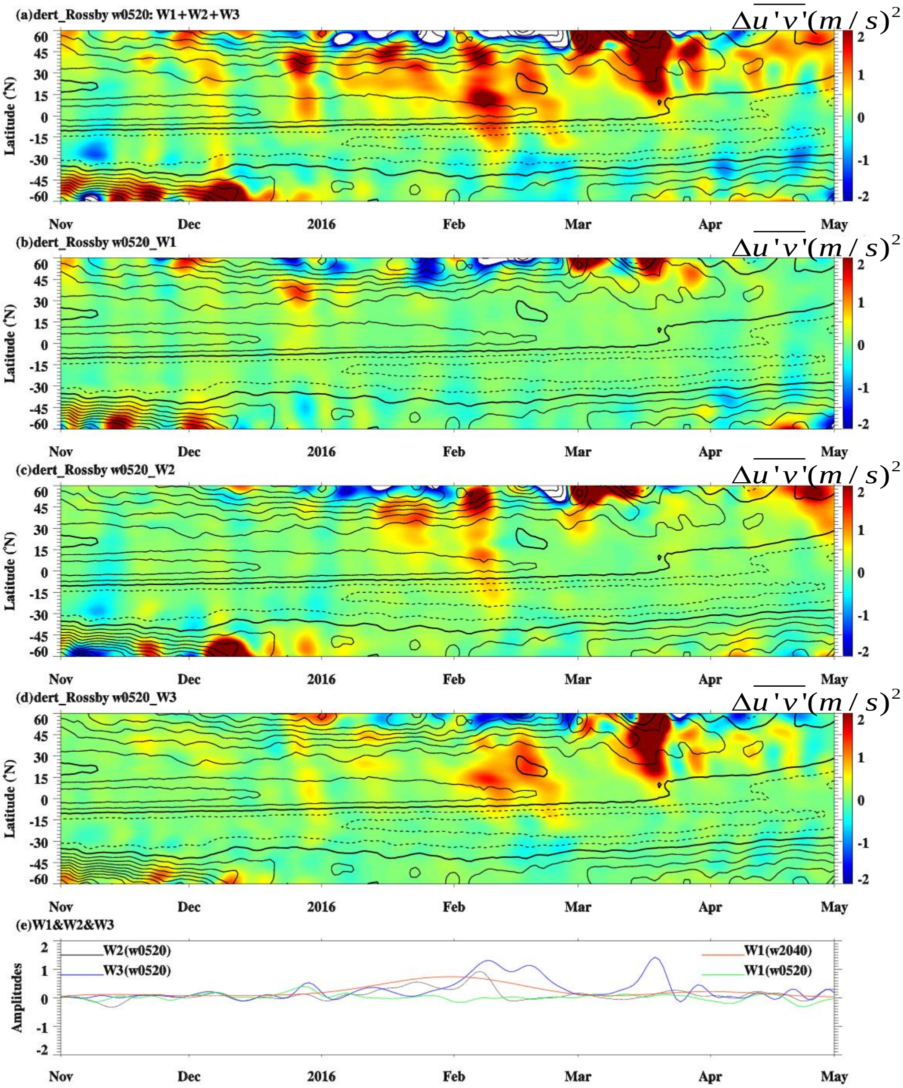


Figure 10. The time-latitude cross section of Rossby w0520 horizontal momentum flux anomalies (a) W1+W2+W3, (b) W1, (c) W2 and (d) W3 from November 2015 to April 2016. ~~Panel (e) shows the horizontal momentum flux anomaly of W1, W2, W3 and Rossby w2040 (with wavenumber 1) at 40 hPa averaged from 10°N to 20°N.~~ Color shadings denote the anomalies with respect to the monthly climatology (0 m^2s^{-2}). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line. W1, W2 and W3 denote the Rossby w0520 with wavenumber 1, 2 and 3, respectively. Panel (e) shows the horizontal momentum flux anomaly of W1, W2, W3 and Rossby w2040 (with wavenumber 1) at 40 hPa averaged from 10°N to 20°N.

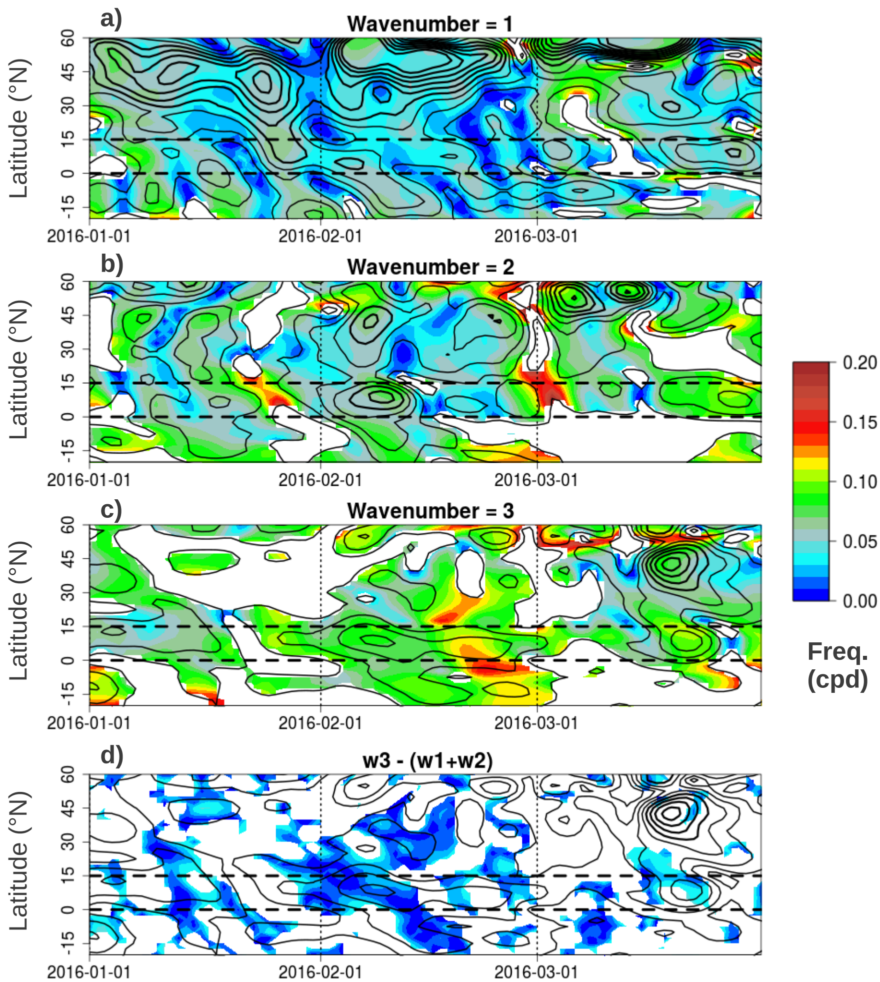


Figure 11. Time-latitude cross sections of 30 hPa Rossby w0540 wave frequencies as color shadings for January-March 2016: (a) W1, (b) W2 and (c) W3. In (d) the absolute difference in frequency of W3 - (W1+W2) is shown, indicating the deviation from resonant conditions. Black contours indicate amplitudes of the corresponding wavenumbers in (a-c), starting at 1 m/s with that same interval. In (d) the black contours repeat W3 amplitudes. In (a), (b) and (c), frequencies of waves with very low amplitude (below 1 m/s) are masked out. In (d), frequency differences above 0.04 cpd (i.e. far from resonant condition) are masked out for better visibility. Wave properties were obtained using zonal winds.

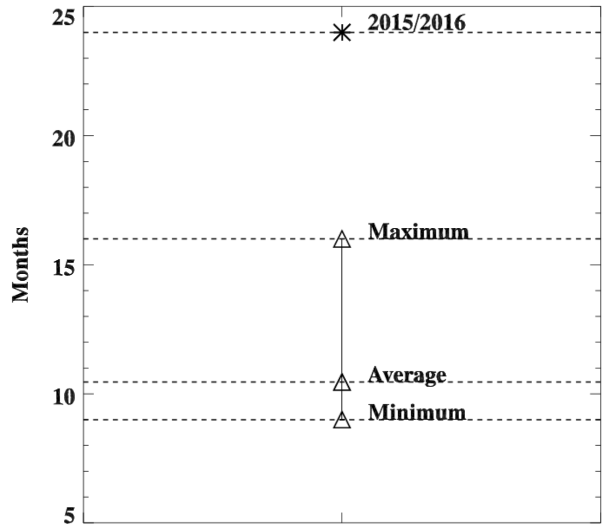


Figure 12. The minimum, average and maximum periods (triangles) of the westerly zonal wind at 20 hPa from 1958 to 2014. The star signal denotes the period of westerly zonal wind at 20 hPa in 2015/2016.

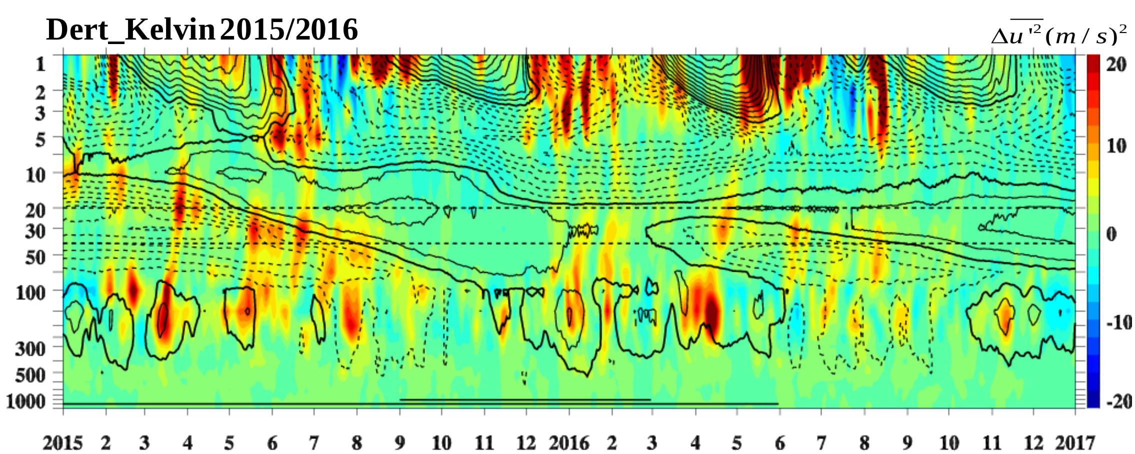


Figure 13. Temporal evolution of Kelvin wave activity as squared zonal wind anomalies averaged over 10°S-10°N in the vertical direction. Color shading denotes the anomalies with respect to the monthly climatology (0 m^2s^{-2}). The horizontal dashed lines denote the altitudes of 20 and 40 hPa. The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line. The horizontal solid lines denote the El Niño (single line) and strong El Niño periods (double line) in the bottom.

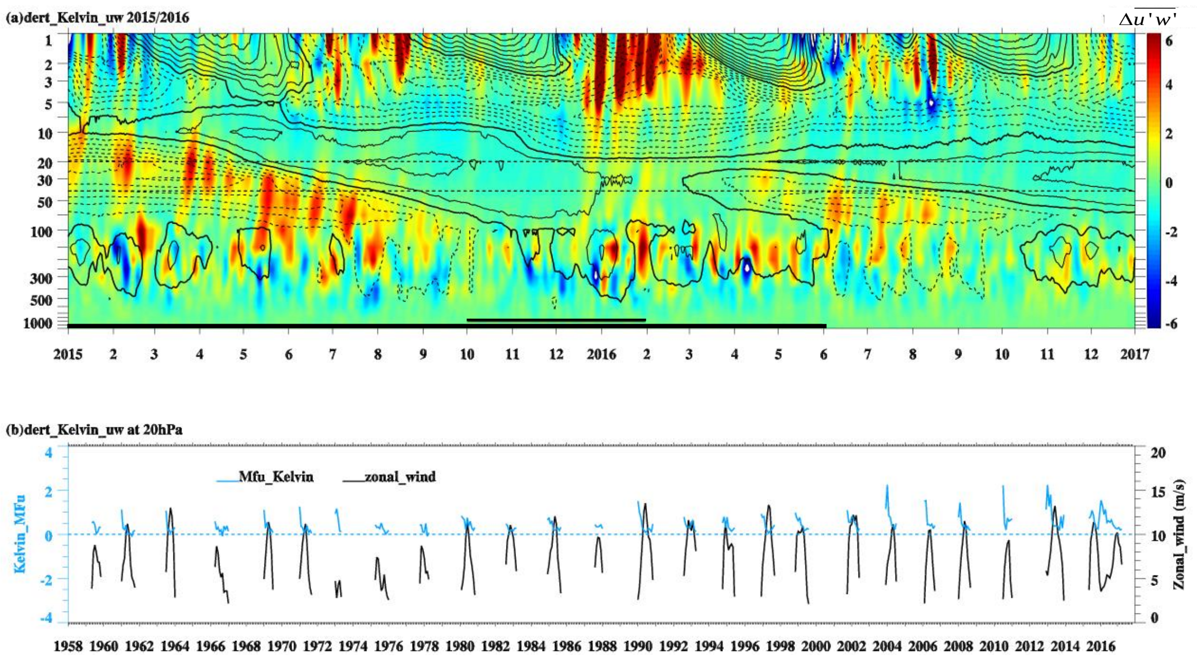


Figure 14. Temporal evolution of Kelvin wave vertical momentum flux anomalies averaged over 10°S-10°N. Panel **(a)** shows the daily time-altitude cross section from 2015 to 2016. Color shading denotes the anomalies with respect to the monthly climatology (unit is 10^{-3} m^2s^{-2}). The zonal mean zonal wind is overlayed in black contours with contour interval of 5 m/s. The solid and dotted black contours denote westerly and easterly winds, respectively. The thick contours represent the zero wind line. In panel **(a)**, the horizontal dashed lines denote the altitudes of 20 hPa and 40 hPa, respectively. The horizontal solid lines denote the El Niño period (single line) and strong El Niño period (double line) in the bottom. Panel **(b)** shows the monthly mean Kelvin wave vertical momentum flux anomalies (blue line) and the westerly background zonal wind (black line) at 20 hPa from 1958 to 2017, exclusively during the westerly QBO phase. In panel **(b)**, the dashed line denotes the vertical Kelvin wave momentum flux anomaly value of 0 m^2s^{-2}

.

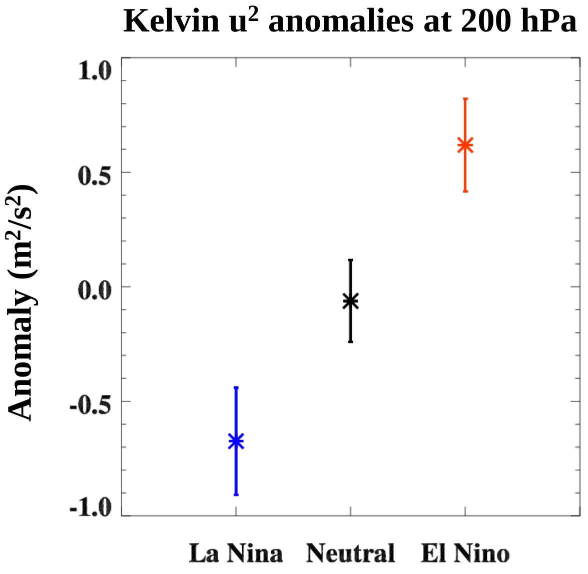


Figure 15. The squared perturbations in zonal mean zonal wind for Kelvin waves averaged over 10°S-10°N at 200 hPa for La Niña (blue star), Neutral (black star) and El Niño (red star) conditions. The error bars denote +- 1 standard deviation of the mean values.