

Answer to Reviewer #2 Comments on “Stratospheric water vapour and ozone response to different QBO disruption events in 2016 and 2020” by Mohamadou Diallo et al.

Dear Editor-in-Chief, S. Fadnavis,

We are submitting our revised article titled “Stratospheric water vapour and ozone response to different QBO disruption events in 2016 and 2020”. We thank the three Reviewers for their detailed and well thought-out comments, which helped to significantly improve the paper. We made substantial changes to the manuscript in order to thoroughly address the Reviewers’ suggestions and comments. The main changes concern:

- Merging of the former Fig S3 with the Figure 1 and Figure 2 in the manuscript
- Moving the Fig S4 into the manuscript as suggested by Reviewer #1 & Reviewer #2 and the related discussion.
- Redone all figures to change wind contours, increase font size and to improve their quality.
- Rephrasing of certain paragraphs in order to clarify the manuscript.

With these changes, we are convinced that the paper is highly relevant for a wide-ranging journal like *Atmospheric Chemistry and Physics*. Please see below our answers point by point to all reviewers’ comments and suggestions.

Reviewers comments are in bold, followed by our respective replies. Changes in the manuscript are in blue, allowing them to be tracked easily.

Kind regards,

Mohamadou Diallo (on behalf of the co-authors)

Reviewer #2 (Comment on acp-2022-382):

Diallo et. al use ERA5 data and Aura Microwave Limb Sounder (MLS) satellite observations to quantify the impact of anomalous QBO events that occurred in 2016/2017 and 2019/2020 on the Brewer-Dobson circulation, water vapour and ozone. They highlight the importance of understanding the reasons for disruptions in the QBO because of its impact on climate research within a changing climate by making use of multiple regression analyses to separate the impact of the QBO on the circulation, ozone and water vapour.

General Comments:

The paper is well written and well structured, but needs some more precision in some points to make concepts clearer (indicated below). The text is often very descriptive and it easily becomes tedious to read, but this is necessary in order to build the storyline and possible omissions have been applied where concepts for the first QBO disruption are similar to the second. The supplement only contains figures which are used extensively in the text. An effort should be made to include the really necessary images in the text and only put figures and add explanatory text in the supplement that is not necessary to understand the idea behind the paper. It does not help the reader to have to refer to the supplement to understand the main text.

Thanks for these good suggestions. We have now moved figures and added corresponding explanatory text into the main text.

Specific and technical comments:

1. ***Most comments I have are questions about understanding and precision. I noticed that you mix American (A) and British (B) spelling (center (A) vs centre (B), vapour (B) vs vapor (A)). Could you check for consistency?***

We have chosen the British spelling and rephrased the text.

2. **Line 1: What do you mean with “major mode of climate variability”? Do you want to speak about the disruption as a change to the QBO as a mode of climate variability? Climate change impacting this mode?**
We are speaking about the QBO, which is a mode of natural climate variability, which modulates the year-to-year variability of the climate system.
3. **Line 3: It sounds as if there was a fixed 28-month period for previous QBO periods when in fact it varied before. Maybe giving a range indicating in what the disruption consisted is better here.**
The QBO has a predominant cycle of 28.3 months even though its mean period can vary between 28-months and 29 months. We have rephrased the sentence (Page 1, line 3 and Page 2, line 37).
4. **Line 5: Better write “Both, water vapour and ozone in the lower stratosphere” instead of “Both lower stratospheric trace gases”**
Thanks for this good suggestion. We have rephrased the sentence (Page 1, line 5-6).
5. **Line 7: Do you mean “anomalous circulation response“ instead of “circulation anomalous response”?**
Thanks. We have rephrased the sentence (Page 1, line 8).
6. **Line 11: Do you mean “hiding/obscuring/concealing” instead of “hidding”?**
Thank you. Yes that’s what we mean. We have rephrased the sentence (Page 1, line 12).
7. **Lines 21/22: The two following sentences essentially say the same thing: “Ozone is mainly produced in the middle stratosphere and is a good proxy of the tropical upwelling. In addition, ozone variability in the tropical lower stratosphere is affected by variability in tropical upwelling of the BDC.” Please revise.**
We have rephrased the sentences (Page 2, line 23-26).
8. **Lines 24/27: Do you mean “natural climate variability, including the QBO” or “modes of climate variability, such as the QBO”? The term “natural mode of climate variability” is confusing.**
We have rephrased the wording (Page 2, line 28-29).
9. **Lines 33/37: “oscillation between tropical westerly and easterly zonal wind shears” Do you mean “oscillation of the zonal wind”? The easterly and westerly shear zones descend differently.**
We have rephrased the sentence (Page 2, line 37, 43).
10. **Line 34: “QBO phases” You have not defined what you mean with phase, here. Looking at a vertical profile the QBO has easterly and westerly phases at different altitudes, so for the Brewer-Dobson circulation one might argue that there is on average no influence.**
Yes indeed the QBO has easterly and westerly phases at different altitudes, which alternate every 28-29 months. In addition, the easterly and westerly shear zones descend differently therefore it affects BDC as the phases do not have the same length at different altitude as well. The QBO easterly are oftentimes shorter than the QBO westerly. We have rephrased the sentence (Page 2, line 39).
11. **Line 38: It was not the “anomalous QBO westerlies” but the “QBO westerlies” that got disrupted (by an anomaly).**
We have rephrased the sentence (Page 2, line 43).
12. **Line 44: I would write “climate change“ instead of “climate changes”**
We have rephrased the sentence (Page 2, line 49).
13. **Line 46: Osprey et al 2016 do not mention CMIP6?!**
We have rephrased the sentence.
14. **Lines 54/55: This sentence appears not to be grammatically correct because verb and substantive have similar forms. It is better to reformulate the sentence, e.g: “Here we use satellite observations to quantify the similarities and differences in the strength and depth of perturbed/disrupted QBO effects in 2015-2016 and 2019-2020 on water vapor and ozone in the lower stratosphere. “**
Thanks for this very good suggestion. We have rephrased the sentence (Page 3, line 60-62).

15. **Lines 60 to 63:** Please reform the sentence to make your statement more lucid. The same issue of verb and substantive confusion might occur especially for the non English native reader. You probably mean something like: “Finally, we discuss the main reasons for the anomalous differences in BDC and UTLS composition between the 2015-2016 and 2019-2020 perturbed QBO effects associated with planetary and gravity wave dissipation, which are likely caused by the anomalous surface conditions associated with the strong El Niño Southern Oscillation (ENSO) in 2015-2016 and the strong Indian Ocean Dipole (IOD) in 2019-2020. “
- We have rephrased the sentences (Page 3, line 67-70).
16. **Lines 63/64:** Maybe better: “We also discuss the differences between 2016 and 2020 in terms of the particularly warm stratosphere in the context of Australian wildfire smoke in 2020.”
- We have rephrased the sentence (Page 3, line 71).
17. **Line 69:** “lower systematic uncertainty” lower with respect to what?
- We have rephrased the sentence (Page 3, line 81).
18. **Line 70:** It is better to explain “multi-instrument mean”? From the text it is not obviously clear what you mean without reading Hegglin et al., 2013, 2021
- We have clarified the sentence (Page 3, line 81-84).
19. **Line 71:** I presume that the ERA5 data used is also 2005-2020?
- We have added the time period for ERA5 (Page 3, line 86-87).
20. **Line 79:** “... impact on these monthly..” should be “... impact on the monthly..” or “... impact on the MLS monthly..”
- Yes, that is correct. We have rephrased the sentence (Page 3, line 81-84).
21. **Line 81:** “To highlight the two QBO disruptions, figures only show the 2013–2020 period.” Do you mean “To highlight the impact of the two QBO disruptions, figures only show the shorter 2013–2020 period.”?
- Thank you for this very good suggestion. We have rephrased the sentence (Page 3, line 60-62).
22. **Is the water vapour and the ozone from ERA5 much different from the MLS data? Because it would actually be really good to see the impact of the QBO on water vapour and ozone from 2005 to 2013 to visually see what “normally” happens, maybe as supplement.**
- Thank you for this very good suggestion. Our Konopka et al, 2022 GRL have compared the trends between MLS and ERA5 and found very good agreement. Assessing the differences of the QBO impact on water vapour and the ozone from ERA5 and the MLS data is out of scope of the paper. Therefore, we leave that for a future study.
23. **Line 89:** In this context (mathematical, technical) I prefer “indices” over “indexes”. See for example <https://books.google.com/ngrams/graph?content=climate+indexese=true>
- Thank you for this very good suggestion. We have rephrased the sentence (Page 3, line 60-62).
24. **Line 90:** Please define “tropical” here. (for example averages over 5S to 5N)
- We have rephrased the sentence (Page 4, line 105-106).
25. **Line 93:** Please define “AOD”
- We have rephrased the sentence (Page 4, line 109-110).
26. **Line 95:** “The solar forcing is neglected because our data set is relatively short.” You have a data set comprising 16 years. That means that you have more than one solar cycle. I don’t think that this is short, especially not because a linear trend does not take into account the end of solar cycle 23 and solar cycle 24. Have you checked whether it matters? Is it too much work to include the solar forcing?
- Thank you for the suggestion. One and half solar cycle is too short to include in the regression analysis because of the long time-lag needed for decadal variability indices.
27. **Line 99:** There is an “In” too many at the beginning of the sentence.
- We have rephrased the sentence (Page 4, line 115).

28. **Line 99: “unexpected tropical QBO easterlies (negative QBOi) developed in the center”** Here “in the center” is not clear, what is the center of the QBO? Is there a center? Over which altitude does the QBO exist? There are many questions that you raise by using “center” here. Maybe it is better to say at 22 km). Furthermore, it seems that the disruption already starts earlier than where you indicate at an altitude of 32 km. As the wind shear seems to shift downwards the disruption of the QBO may have been started earlier. By emphasizing your study on the disruption in the altitude range 15 to 24 km you might oversee something? Or are there two independent disruptions, one aloft and one starting at 22 km? The interesting thing is why at 26 km the westerlies persist.

We agreed about the terminology. Regarding the disruption, it did not start early at least according to the literature. The appearing of the QBO easterly in the lower stratosphere is defined as the disruption actually, which upward shifted the descending QBO westerly above 26 km. We have rephrased the sentence (Page 4, line 116).

29. **Line 112: The references should not be in brackets.**

We have rephrased the sentence (Page 4, line 138-140).

30. **Line 114: Here you use “center” again. Better indicate the altitude range or ‘center of the image’.**
We have rephrased the sentence (Page 5, line 138-144).

31. **Line 119: You say that the disruption is visible in the water vapour ozone plots. This is difficult to judge if you only show 2013 to 2021. In the water vapour plot it even looks as if water vapour shows a strange behaviour before the onset of the disruption in 2016 that you indicate. Which would point towards a previous event maybe the onset of easterlies at 32 km at the beginning of the year. Tropical ozone anomalies are closely related to temperature anomalies show the QBO disruption, as you say, and are therefore to be expected.**

The 2013-2015 period is associated with the normal QBO, where we can see the imprint of the descending QBO easterly and westerly on the trace gas anomalies. It is well admitted in the community that the onset of easterlies is at about 26 km. At 32 km, it is onset of next QBO easterly, which was supposed to propagate downward after the QBO westerly. In addition, we have previously published a paper regarding the 2015-2016 QBO disruption and the strong El Niño, where actually the entire time series were shown from 2005 to 2017 (Diallo et al 2018).

32. **Line 125: “is the most effective” should be “is most effective”.** This sentence is not clear. Do you mean that the disruption impacts tropical upwelling via its impact on tropical upwelling? Do you mean the water vapour anomaly minimum at 17 km and the ozone anomaly minimum at 16 km the end of the disruption that you indicated? What do you mean by “when the signal reaches”? Why do you think that this is due to the disruption impact on tropical upwelling (if this is what you meant to say)?

Thanks for this comment. We mean that the impact of the QBO disruption on H₂O and O₃ is stronger when the anomalous QBO easterlies (signal) reach the cold point temperatures because of its impact on tropical upwelling. We have rephrased the sentence (Page 7, line 154-156).

33. **Line 127: You refer to the wind at 30 hPa but this is not shown in the figure. Please add the pressure altitudes to the figure or indicate altitudes in km (with pressure in brackets) whenever you mention pressure altitude in the text. Also indicate where this event happens. Do you mean at 26 km between the two vertical lines indicated, i.e. the uninterrupted westerlies during the disruption?**

Thank you for the good suggestion. We have rephrased the sentence and indicated the altitudes in km (25km) (Page 7, line 157-158).

34. **Line 129: I would not speak about an upward shift of the westerlies. Westerlies are rather maintained longer and reestablish at the top moving downwards.**

We have rephrased the sentence (Page 7, line 160).

35. **Line 133: “substantially increased H₂O mixing ratios and decreased O₃ mixing ratios” do you mean “coincided with an increase of H₂O mixing ratio anomalies and a decrease of O₃ mixing ratios anomalies”? This is true for water vapour anomalies but for the ozone anomalies there is an earlier onset with a slight increase and it does not reach as high up as the water vapour (25 km).**

This a conclusion of our previous findings (Diallo et al 2018) that we report here. As we are talking about the anomalies of both trace gases, therefore, we defined an altitude range in which their changes are happening "between the tropopause and the altitude of 25 km". Of course the maximum H₂O and O₃ anomalies are below 25km but they are still in the defined range (16–25km). This small increase in ozone mixing ratio remains below 15 km, therefore, located below the tropopause level, which is of about 16 km in the tropics. We have rephrased the sentence (Page 7, line 164-165).

36. **Line 134/135: "sudden occurrence of the QBO disruption". An interesting question here is if the disruption was not caused by this, and the ozone and water vapour response is just due to the thermodynamic balance.**

Yes indeed it is an interesting question. Note that the disruption is caused by wave propagation toward tropics, therefore, prior to the water vapor and ozone response even though these trace gas responses may feedback to the anomalous circulation (Page 7, line 166-167).

37. **Line 138: the spelling of structural is wrong here (strutural).**

We have rephrased the spelling (Page 7, line 168).

38. **Line 145: "compare" should be "compared" (or compares but then there should be an "and" before "suggests").**

We have rephrased the sentence (Page 7, line 177).

39. **Line 147: Figure S3 is mentioned before S2 please switch the order of the figures.**

We have adjusted the text after including the Fig. S3 in the main text (Page 7, line 178).

40. **Line 158: Spelling: "33 anomalies" should be "O3 anomalies"**

We have rephrased the sentences (Page 8, line 192).

41. **Line 160: "The difference... gives the QBO-induced impact." Is it not only "the linear part of the QBO-induced impact"?**

The regression model contains a time-lag, allowing to capture the impact of QBO on these trace gases.

42. **Line. 170: I don't really see this. I presume that you refer to the region between the two vertical lines. There ist seems the other way round? Or for water vapour it is negative when the QBOi increases (from negative to positive).**

When the QBO increases from negative to positive e.g. from westerly to easterly, the H₂O and O₃ vary from positive anomalies to negative anomalies because of the impact of the QBO on tropical upwelling. The QBO easterly is associated with negative cold point anomalies (Plumb and Bell, 1982) and enhances upwelling, leading to negative ozone and water vapor anomalies. In addition, the water vapor response is always time-lagged by about a few months because of its tropospheric origin. The QBO westerly does the opposite. This is clearly visible for all years. It is also the case for 2020, even though this is a special year because of the Australian wildfire in 2020.

43. **Line 171: Here I would only mention that the ozone anomaly changes follow closely the disruption in the zonal wind. I would not speak about suddenness.**

We have rephrased the sentence (Page 8, line 205).

44. **Line 173: Here it would help to have the months as minor tick marks. I can see the alignment with ozone but for water vapour this is only speculation and is not true further up, i.e it might only be true for one altitude level.**

The water vapor response also is delayed by about a few months. Adding the months tick marks will overload the xlabel of the figures this is the reason we decided to not add them. We have rephrased the sentence (Page 8, line 205-208).

45. **Line 179: 40 hPa please also give the altitude.**

We have rephrased the sentence (Page 8, line 215).

46. **Line 179/180: The response is different for the ozone and water vapour anomalies. For ozone the altitude range and the temporal extend true but for water vapour it is rather from mid 2016.**

We have rephrased the sentence (Page 8, line 215-217).

47. **Line 182: “anomalously cold point temperatures” should be “anomalously low cold point temperatures”**
We have rephrased the sentence (Page 8, line 219)
48. **Line 183: Why is there enhanced tropical upwelling?**
There is enhanced tropical upwelling because of the presence of QBO easterly in the lower stratosphere, which is associated with the secondary circulation modulating the BDC (Plumb and Bell, 1982), which modulates the upwelling.
49. **Line 184: “indueced” should be “induced”**
We have rephrased the sentence (Page 8, line 221).
50. **Line 186/187: I don’t understand: 1st statement: disruption induced O3 anomalies are small between 2016 and 2020; 2nd statement: disruption induced O3 differences are large between 2016 and 2020. I am not sure what you want to say here. Could you reformulate this sentence please to make it clearer?**
We have rephrased the sentence in order to enhance clarity.
51. **Line 192: What do you mean with “early” in “. . . we note that the early QBO westerly. . .”**
We mean the QBO westerly pre-disruption. We have rephrased the sentence.
52. **Line 197: “zonal mean impact“ what do you mean with “impact”?**
By “impact” we mean the QBO–induced impact/effect on H₂O and O₃ shown in zonal mean plot.
53. **Line 201: Are those responses due to the disruption or due to the QBO in general? I.e. Do the responses just follow the stratospheric wind regime no matter if there is a disruption or not?**
Figure 3 shows the H₂O and O₃ responses due to the QBO disruptions. Yes, their responses also follow the stratospheric wind regimes such that negative anomalies are associated with QBO easterlies and positive anomalies with QBO westerlies.
54. **Line 204: “below the altitude of 20 km”: at about 20 km there is the maximum hydration?! It is rather 18 km? You could add minor tick marks to the plot to see clearly where the sign changes.**
We have rephrased the sentence (Page 8, line 244).
55. **Line 204ff: How can you be sure?**
The H₂O and O₃ response in the tropics is mainly due to dynamical mechanism. We have discussed that in Sect. 4.2, page 12.
56. **Line 209f: “but stronger in winter hemisphere” Do you mean “but more in the winter hemisphere” or “but is stronger in the winter hemisphere”?**
We have rephrased the sentence (Page 10, line 247-250).
57. **Line 212: “consistent” Do you mean “correspond”?**
We mean “agrees/matches/consistent with” We have rephrased the sentence (Page 10, line 252).
58. **Line 226: “particularly large“ please indicate what figures you are referring to.**
This is true for all figures. We have added that we are referring to (Fig 2, 3, S2 and S3).
59. **Line 234: “induced secondary circulation are weaker” should I not see this in figure S4a,b?**
The weaker secondary circulation is visible in Fig. 3 and 5c, d, g, h. We have added the reference (Page 12, line 276).
60. **Line 260: It is very difficult to follow your argument here, especially because the tropospheric w* differences look very strange. In your argument you don’t mention altitude ranges so which makes it difficult to follow.**
Here were are refering to Fig 4a, b and Fig. 4S. The tropospheric w* does not matter here, but the tropical upwelling of the BDC changed between the tropopause (16km) and the altitude of 23 km is what matters for stratosphere (Page 10, line 247-250).

61. **Line 264: “(Fig. 4c in the supplement)” does not show cold point temperatures. What do you mean with substantially in “substantially negative”? Maybe better “strongly negative”?**
We have rephrased the sentence (Page 15, line 305-306).
62. **Line 266 Figure 4 which you refer to does not show water or ozone? Neither does Figure S4?! Please correct.**
We were referring to temperature and w^* . We have rephrased the sentence (Page 10, line 305-308).
63. **Line 279 “hidding” should be “hiding”**
We have rephrased the sentence (Page 15, line 320).
64. **Line 297 “net wave forcing is stronger and broader” do you mean the red region between 20 and 25 km altitude?**
No we mean the blue region, as it is negative EP-flux divergence which is associated with wave breaking. The red regions mean less waves breaking. It is not straightforward to put an altitude as the region change with time as well (see the supplement). Indicating always the altitude range maybe misleading as the area of wave breaking varies as a function of latitude as well (Fig. 4). We have rephrased the sentence (Page 17, line 337-339).
65. **Line 298 “wave breaking near the equatorward” do you mean the blue region between 18 and 22 km between latitudes of about -20S and +17N?**
The position of the subtropical jet is well known in the literature to be centred at 30N/S. The equatorward upper flank of the subtropical jet is the region between 10-30S/N above the tropopause level. We have rephrased the sentence (Page 17, line 334).
66. **Line 303ff: “The wave forcing evolution. . .” what do you mean? Adding the components gives you the total? I guess I misunderstand this sentence?**
We mean “the variation in time of wave forcings”. We have rephrased the sentence.
67. **Line 322: What do you mean with “for the tropical upwelling of the BDC differences”?**
We mean “the differences in the tropical upwelling”. We have rephrased the sentence.
68. **Line 341: “few months after the sudden shift from the QBO westerly to QBO easterly wind shear reached the tropical tropopause. “ For ozone it seems to have happened already earlier!**
we have rephrased the sentence.
69. **Line 349ff: How can you be sure of this statement? (“strengthening of the tropical upwelling of the BDC”)**
That is what we have shown with the analysis of the tropical upwelling of the BDC (w^*).
70. **Line 362 “warmed the cold point temperature” should be “raised the cold point temperature”**
We have rephrased the sentence.
71. **In the Figure captions you repeat the definitions for a, b, c etc very often. It would be good to remove the repetitions.**
We think it is better to keep these few repetition in order to have a clearer description in the captions.
72. **In the Figure captions you repeat the definitions for a, b, c etc very often. It would be good to remove the repetitions. Figure 1: I would prefer omitting the first (a) and putting the ERA in the description under the second (a).**
We have removed the first (a).
73. **“50hPa” it would be good to have an approximate altitude at 50 hPa to see where we are in the panels (a) to (c).**
We have added the approximated altitude and rephrased the text.
74. **The QBOi line looks weird because of the disruptions. Also here it would be good to see how regular it looked before. Please add months as minor tick marks.**
The 2013-2014 is a regular QBO years, showing the QBO effect. We have decided to not use month tick marks because of esthetical reasons.

75. **Figure 4: The labeling seems wrong in the first sentence. What you call b should be c and vice versa. What you call "impact" I presume comes from the multiple regression analysis?**

We have rephrased the sentence. By "impact" we mean the quantified effect of QBO using the regression model.

76. **Figure S1: The altitudes in the text refer to pressure altitudes whereas here are only altitudes in km. Please make consistent. The whole year average for Figures a) and b) depends a lot on the phase of the QBO for that year.**

We have given the corresponding altitude–pressure levels in the main text.

77. **It appears that Figure S3 is mentioned before Figure S2 in the text, please reverse order.**

We have rephrased the sentence.

78. **Figure S2: There is a mistake: instead of 2016 (a, c) and 2020 (b, *c*) it should be 2016 (a, c) and 2020 (b, *d*).**

We have rephrased it.