

## Point-by-point response to the reviewers

### Anonymous Referee #1

Received and published: 10 March 2017

We thank the reviewer for their very helpful comments. We have taken all the points raised into consideration. Our specific responses / changes are below (in red).

The QBO showed a behavior in 2015-2016 which has never been seen before. The development of the meteorological fields has been described elsewhere but the present paper contributes by describing how ozone and HCL changes during the event. I find that the paper contributes with new information and that it is well written. However, I have a few relatively minor points that the authors should consider before the paper is accepted.

#### Major comments:

In the introduction, the QBO in ozone is described. However, I find this description somewhat confusing. First of all, I miss a statement about if the ozone QBO is in phase with the QBO in the zonal mean wind. I am also confused about the statements about the seasonal synchronization (line 33 and 57). There is only a weak seasonal signal in the QBO in the zonal wind.

*We have rewritten this part of the Introduction to make it clearer. Deseasonalized ozone anomalies are out-of-phase between the tropics and extratropics; the QBO in equatorial winds are in-phase with tropical ozone anomalies but out-of-phase with extratropical ozone anomalies. "Seasonal synchronization" means the QBO influence on deseasonalized ozone anomalies in the extratropics are observed mainly in winter-spring of each respective hemisphere.*

There is only very little mention of statistical significance (line 214). The statistical significant regions should be indicated in Figs. 1 and 3 and the method to calculate the significance should be described in more details.

*The statistical significant regions are highlighted in **Figure 1c** and **3c,f** and method to calculate the significance is described in Methods section. Since we have very limited number of QBO cases in the observational record (5 QBO cycles in MLS and 14 cycles in the SBUV total ozone, see Table 1), we don't perform any sophisticated statistical tests (degree of freedom is very small) and simply indicate regions where absolute difference between last QBO cycle and the composite larger than 2 standard deviations.*

#### Minor comments:

l49: downward -> downward propagating? – *changed*

l88: How can temperature and ozone have different vertical resolutions (3 and 4 km) when they both are reported on 12 pressures per decade?

*There is a difference between the vertical grid that data are reported and the actual vertical resolution. The vertical grid is usually finer than the actual instrumental vertical resolution. The vertical resolution is defined by the number of independent measurements (degrees of freedom for signal or DFS) that the instrument makes, and this varies between MLS temperature and*

*ozone measurements [see MLS Version 4.2x Level 2 data quality and description document for more details]. Clarifications were made in the first paragraph of the Methods section.*

1186: The authors could be more specific here. Will the interfering make it more difficult to determine the trends? In fact, one could argue that the disruption will make it easier to establish the connection between QBO and ozone and therefore easier to determine the residual trend.

*This sentence was edited to make it more specific. Certainly, a series of similar disruptions would make it more difficult to determine the residual trends because we won't be able to rely on two EOFs to remove QBO variability in ozone timeseries. EOF 1 and 2 typically explain 96 percent of the variance while during the disruption it falls to only 71 percent. Thus, the first two EOF patterns don't match the disruption very well, with the lowest percent variance explained by the two EOFs in the entire data record occurring during the disruption.*

Figure 2. I am not sure this figure helps and I cannot see that this analysis is used elsewhere in the paper. I would suggest that it is removed or, if the authors find it important, that also the EOFs are shown and the amount of variance they explain is mentioned.

*We believe this figure is relevant and we have decided to keep it. It demonstrates how unusual and unprecedented this current QBO disruption event is. Based on Wallace et al. (1993), the first two EOFs explain 95.5 percent of the normalized variance of the deseasonalized smoothed time series of zonal winds at seven pressure levels between 70 to 10 hPa combined. We don't think additional EOF plots are necessary for this paper but discussion about the recent QBO variances is added (in Methods section)*

Actually, a similar figure was shown in Dunkerton 2016 (GRL 10.1002/2016GL070921) which should be cited.

*Our calculations follow the standard Wallace et al. (1993) EOF structures. The results look quite different from the figure in Dunkerton 2016, which came from a blog/twitter site. We are unsure exactly how the calculations were done in his case (and calculations are not clearly explained in Dunkerton 2016, on twitter, or the blog site). Our plot really doesn't suggest a 'death spiral' and plot in Dunkerton 2016 plot shows \*NO\* anomaly for the 2015-16 period! Since we don't understand this figure, how it was produced, and it was not published in peer reviewed source (except for the twitter post in Dunkerton 2016 article), we think it is best not to cite it.*

## Anonymous Referee #2

Received and published: 17 March 2017

We thank the reviewer for their very helpful comments. We have taken all the points raised into consideration. Our specific responses /changes are below (in red).

Response of Trace Gases to the Disrupted 2015-2016 Quasi-Biennial Oscillation

O.V. Tweedy, N.A Kramarova, S.E. Strahan, P.A. Newman, L. Coy, W.J Randel, M. Park, D.W. Waugh, and S. Frith

This paper examines the impact of the 2016 QBO disruption on stratospheric temperature, residual (vertical) circulation and distribution of trace gases (esp. ozone) from the equator to mid-latitudes. The paper highlights circulation and transport characteristics being dynamically consistent with the QBO anomaly. These impacts include an anomalous reduction in total ozone out to mid-latitudes (during April and August anyway) which are at near record lows. This has implications for trends in downwelling UV, if similar events were to recur more frequently in the future. The authors also highlight the possible signature of the QBO disruption in tropical cold-point tropopause temperature and UTLS water vapor. This is a very well written paper and does a great job of highlighting those points it considers important, without the distraction of unnecessary details. I would hope the points below can be addressed quickly as I recommend prompt publication.

### Main Points:

- I. Effect of strong polar vortex: What effect will the unusually strong polar vortex, occurring from early-mid winter 2015/2016, have on the Brewer-Dobson circulation and the redistribution of ozone? Presumably, it would create a weaker BDC and reduced downwelling outside the tropics, and so (vertical) transport of ozone at mid-latitudes. I think the conclusions of the paper also need to reflect these other environmental influences, especially as statements of attribution are being made. Here is a suitable reference for the strong vortex (and AO in general) and perhaps other conditions relevant to the 2016 QBO disruption (and redistribution of ozone):

Cheung HHN, Zhou W, Leung MYT, Shun CM, Lee SM, Tong HW. A strong phase reversal of the Arctic Oscillation in midwinter 2015/2016: Role of the stratospheric polar vortex and tropospheric blocking. J Geophys Res Atmos. 2016; 10.1002/2016JD025288

Scaife AA, Comer R, Dunstone N, Fereday D, Folland C, Good E, et al. Predictability of European winter 2015/2016. Atmos Sci Lett. 2017 Feb;18(2):38–44. doi:10.1002/asl.721

*The reviewer makes a good point and we agree that a strong polar vortex occurring from early-mid winter 2015/2016 is likely to contribute (to some extent) to the observed midlatitude anomalies in late spring and through the summer. Recent study by Strahan et al. [JGR, 2016] showed that the impact of Arctic ozone depletion on the midlatitudes in spring after winters with moderate depletion (such as 2016) was about 5 DU (south of 45N). But they also found that the dynamical impact on O<sub>3</sub> due to a strong vortex winter roughly opposed the depletion changes,*

*resulting in very little net impact. Our analysis shows that midlatitude anomalies during boreal summer and fall of 2016 are symmetric around equator, which strongly suggests QBO induced nature of observed anomalies. We have added possible mention of the vortex playing a role in ozone anomalies in the third paragraph of section 4 (“Concluding remarks”); however, a full estimation of exact contribution is a separate study of its own.*

- II. Effect of ENSO and subsequent interpretation of CPT and [H<sub>2</sub>O] (figure 7). The authors should acknowledge the possible influence of the 2015/2016 El Nino and the perhaps recent trends in CP temperature and pressure. One possible reference might include:

Hu D, Tian W, Guan Z, Guo Y, Dhomse S. Longitudinal Asymmetric Trends of Tropical Cold-Point Tropopause Temperature and Their Link to Strengthened Walker Circulation. J Clim. 2016 Nov; 29(21):7755–71. doi:10.1175/JCLI-D-15-0851.1

*We agree that it is possible that strong El-Nino event during 2015-2016 winter could impact CP temperature and pressure. However, the role of this ENSO event and its impact of the distribution of chemical constituents in the lower stratosphere remains an open question. As suggested by the reviewer, we have included in the text the acknowledgment of the possible influence of the 2015/2016 El Nino.*

- III. How much of the 2016 QBO wind (during disruption) is accounted for by the first 2 EOFs (in U)? In this this regard, how meaningful is it to show PC1 and PC2 during these times?

*Figure 2 shows the smaller amplitude (closer to the center) of PC1 and PC2 during the disruption. This means the winds are either weaker than the typical QBO or not fitting the EOFs well. Looking at the variance explained by two EOFs, the answer is that it's not fitting the QBO well. Prior to the 2015, the first two EOFs explain 95.5 % of the normalized variance of the deseasonalized smoothed time series of zonal winds at seven pressure levels between 70 to 10 hPa combined while during the disruption it falls to only 71 percent. Thus, the first two EOF patterns don't match the disruption very well, with the lowest percent variance explained by the two EOFs in the entire data record occurring during the disruption. Therefore, there shouldn't be any objection to plotting just PC1 and PC2 during the disruption as it illustrates how odd the disrupted QBO is.*

#### Minor Points:

(line 104) One for the editorial team: superscript asterisk for TEM residual vertical velocity. Also, a reference for the TEM residual vertical velocity should be added (e.g. AHL, 1987) - *changed asterisk and a reference is added*

(figure 2 caption) “spacial”->“spatial” deriv. spatium (latin). - *changed*

(figure 7) The HALOE H<sub>2</sub>O measurements show a jump around 2001. Where does this come from? Does it affect the (statistical) significance of your results.

*The drop in HALOE H<sub>2</sub>O around 2001 is a well reported phenomenon (e.g. Randel et al., JGR 2006). The cause of this drop is unclear, but previous studies have related it to changes in SSTs*

*(e.g. Garfinkel et al., JGR, 2013) and ENSO (Brinkop et al. ACP 2016). This does not affect any of our conclusions.*

**A list of all relevant changes made in the manuscript:**

- Figure 1c and Figure 3c,f were updated to fill the gaps in missing data that was not yet available during first submission (Nov'16-Feb'17 )
- We have rewritten a part of the Introduction to make it clearer (Referee #1 – major comment 1)
- The statistical significant regions are highlighted in **Figure 1c** and **3c,f** and method to calculate the significance is described in Methods section.
- Clarifications were made in the first paragraph of the Methods section to specify why vertical grid and resolution are not the same and reader is referred to MLS manual for more details.
- A short discussion about the recent QBO variances is added to Methods section.
- Possible mention of the vortex playing a role in ozone anomalies in the third paragraph of section 4 (“Concluding remarks”) and references have been added.
- The acknowledgment of possible influence of the 2015/2016 El Nino and references have been included in the text.

## Response of Trace Gases to the Disrupted 2015-2016 Quasi-Biennial Oscillation

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**Abstract.** The quasi-biennial oscillation (QBO) is a quasi-periodic alternation between easterly and westerly zonal winds in the tropical stratosphere, propagating downward from the middle stratosphere to the tropopause with a period that varies from 24 to 32 months ( $\sim 28$  months on average). The QBO wind oscillations affect the distribution of chemical constituents, such as ozone ( $O_3$ ), water vapor ( $H_2O$ ), nitrous oxide ( $N_2O$ ) and hydrochloric acid (HCl), through the QBO induced meridional circulation. In the 2015-2016 winter, radiosonde observations revealed an anomaly in the downward propagation of the westerly phase, which was disrupted by the upward displacement of the westerly phase from  $\sim 30$  hPa up to 15 hPa, and the sudden appearance of easterlies at 40 hPa. Such a disruption is unprecedented in the observational record from 1953-present. In this study we show the response of trace gases to this QBO disruption using  $O_3$ , HCl,  $H_2O$  and temperature from the Aura Microwave Limb Sounder (MLS) and total ozone measurements from the Solar Backscatter Ultraviolet (SBUV) Merged Ozone Data Set (MOD). Results reveal development of positive anomalies in stratospheric equatorial  $O_3$  and HCl over  $\sim 50$ -30 hPa in May-September of 2016 and a substantial decrease in  $O_3$  in the subtropics of both hemispheres. The SBUV observations show near record low levels of column ozone in the subtropics in 2016, resulting in an increase of surface UV index during northern summer. Furthermore, cold temperature anomalies near the tropical tropopause result in a global decrease in stratospheric water vapor.

## 1 Introduction

The quasi-biennial oscillation (QBO) is a quasi-periodic alternation between easterly and westerly zonal winds in the tropical stratosphere that is driven by a broad spectrum of vertically propagating Kelvin and mixed Rossby-gravity waves along with smaller-scale gravity waves (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Dunkerton, 1997). The alternating wind regimes (i.e., the easterly and westerly phases) propagate downward from the middle stratosphere to the tropopause with a period that varies from 24 to 32 months ( $\sim 28$  months on average).

There is also a QBO in ozone ( $O_3$ ), which was first observed by Funk and Garnham (1962) in Australian mid-latitude total column  $O_3$  observations. Ramanathan (1963) showed the connection between [the QBO in total  \$O\_3\$](#)  and the QBO in [equatorial zonal winds using](#) a series of ground stations spanning both hemispheres, but most importantly noted the ~~total-ozone~~ out-of-phase relationship between [ozone in](#) mid-latitudes and the equator. Angell and Korshover (1964) found a QBO signal in Shanghai ( $31.2^\circ N$ ) total  $O_3$  observations in the 1932-1942 period. Zawodny and McCormick (1991) used satellite  $O_3$  profile observations to show the ozone QBO vertical structure from 20-50 km and  $50^\circ S$ - $50^\circ N$ . Randel and Wu (1996) used numerical techniques to filter the QBO ozone structure showing the equatorial and mid-latitude “out-of-phase” relationship ~~;~~ [but also and](#) revealing the seasonal synchronization between the equatorial QBO and the large amplitude winter-to-spring ~~QBO anomalies in both~~ [extratropical  \$O\_3\$  anomalies that appear in both winter](#) hemispheres.

Because most  $O_3$  is found in the lower stratosphere where its lifetime is more than 1 year, the tropical  $O_3$  distribution is strongly controlled by the tropical lower stratosphere transport (Ling and London, 1986). Gray and Pyle (1989) used a two-dimensional (latitude vs. altitude) model to simulate the relationship between winds, temperatures, and the  $O_3$  distributions. Those modeled relationships were confirmed by the observations of Zawodny and McCormick (1991). The Gray and Pyle (1989) simulation revealed that the wave-induced QBO drove a secondary meridional circulation which modulated the  $O_3$  distribution. Assimilated meteorological data and modern transport models confirm these early results, and satellite instruments such as the Microwave Limb Sounder (MLS) have shown additional QBO impacts on water ( $H_2O$ ), hydrochloric acid (HCl), nitrous oxide ( $N_2O$ ), and carbon monoxide (CO) (Schoeberl et al., 2008).

The QBO meridional circulation develops between the tropics and subtropics (from the equator to  $\sim 30^\circ N$  and  $30^\circ S$ ) to maintain the thermal wind balance between the descending QBO wind shear and its temperature anomaly. At the equator, westerly shear (westerlies aloft and easterlies below) is in balance with a downward [propagating](#), adiabatically warmed perturbation, while easterly shear (easterlies aloft and westerlies below) produces an upward, adiabatically cooled perturbation. The enhanced upwelling during easterly shear and reduced upwelling during westerly shear in the tropics are mass balanced by the changes in the subtropical descent. The circulation is ‘completed’ by the equatorial divergence/convergence of air at the levels of maximum easterly/westerly winds (Choi et al., 2002). The QBO-induced meridional circulation acts on local trace gas gradients to modify



55 their distributions (Gray and Chipperfield, 1990). O<sub>3</sub> responds with increased/decreased values in  
the tropics and decreased/increased values in the extratropics during descending westerly/easterly  
shear.

QBO effects on composition are found throughout the extratropics. QBO-driven column O<sub>3</sub> anom-  
alies originating in the southern subtropics in early winter reach 60°S by the early spring (Gray and  
60 Ruth, 1993; Randel and Wu, 1996; Kinnersley and Tung, 1998). Strahan et al. (2015) also showed a  
transport pathway by which the midlatitude middle stratosphere QBO signal affects polar O<sub>3</sub> deple-  
tion by modulating Antarctic inorganic chlorine.

The QBO has been widely analyzed because it is a major source of stratospheric O<sub>3</sub> inter-annual  
variability (Baldwin et al., 2001), and the QBO in total column O<sub>3</sub> is a dominant factor controlling  
65 inter-annual variations of surface ultraviolet levels (Udelhofen et al., 1999). Further, the detection  
and attribution of long-term O<sub>3</sub> changes caused by ozone depleting substances (ODSs) requires  
accurate statistical models that include QBO regression terms in order to remove the QBO driven  
natural O<sub>3</sub> variability and thereby reveal the residual ODS forced ozone depletion (e.g. Stolarski  
et al., 1991). Hence, investigating the QBO driven variability is fundamental to understanding O<sub>3</sub>  
70 levels and trends, and the resulting changes to surface ultraviolet (UV) radiation.

During the Northern Hemisphere (NH) winter of 2015-2016, radiosonde observations revealed  
that the normal downward propagation of the QBO westerly phase was disrupted by upward prop-  
agation of westerlies from ~30 hPa up to 15 hPa, and the sudden appearance of easterlies at 40  
hPa (Newman et al., 2016; Osprey et al., 2016). This disruption began in November 2015, and the  
75 easterlies were fully developed by March 2016. Such a disruption is unprecedented in the equatorial  
wind observational record from 1953-present. Osprey et al. (2016) showed that this anomalous event  
was linked to the transport of easterly momentum from the northern extratropics into the equatorial  
region, and Coy et al. (2017), using meteorological analysis fields beginning in 1980, showed that  
the 2015-2016 tropical easterly momentum flux had the largest values over the December-February.  
80 None of these studies examined the changes in O<sub>3</sub> or other trace gases during 2015-2016.

In this study we investigate the response of stratospheric trace gases to the 2015-2016 event. We  
quantify the impact of the disruption on O<sub>3</sub> and other trace gases and further compare their observed  
changes to the expected behavior due to the QBO in the absence of the disruption. Furthermore, we  
examine the interannual variations in total ozone and water vapor.

## 85 **2 Methods and Data**

We use Aura MLS version 4.2 Level 2 measurements of temperature (T), O<sub>3</sub>, and HCl from January  
2005 to ~~September 2016~~ February 2017 between 10-100 hPa. O<sub>3</sub> and T are reported on a ~~vertical~~  
~~resolution-fixed vertical~~ grid with 12 ~~pressures per decade~~ surfaces per decade change in pressure  
between 1000 hPa and 1 hPa; HCl is reported on 6 pressures per decade. O<sub>3</sub> and HCl have vertical

90 resolution of  $\sim 3\text{--}3$  km in the pressure range used in this analysis ~~while the vertical resolution~~  
of T is  $\sim 4$  km. ~~Although  $\text{O}_3$  and T are reported on the same pressure grids, their vertical resolution~~  
~~is not the same because the number of independent measurements that the instrument makes varies~~  
~~between MLS T and  $\text{O}_3$  (Livesey et al., 2015).  $\text{O}_3$  accuracy varies from 50 to 300 ppb in this range~~  
~~between 100 and 10 hPa while HCl accuracy is estimated at  $\sim 10\%$ . The vertical resolution of T is~~  
95  ~~$\sim 4$  km;~~ MLS temperatures have a -1 K bias in the stratosphere with respect to correlative measure-  
ments. Details on MLS measurements, data quality and improvements over previous versions can be  
found in MLS v4.2 data quality document (Livesey et al., 2015).

We examine total column  $\text{O}_3$  during the anomalous QBO event using total  $\text{O}_3$  observations from  
the Solar Backscatter Ultraviolet (SBUV) Merged Ozone Data Set (MOD). The MOD is constructed  
100 from monthly zonal mean ozone profiles by individual SBUV instruments, providing the longest  
available satellite-based time series of profile and total  $\text{O}_3$  from a single instrument type (Frith et al.,  
2014). The MOD used here includes observations from January 1980 to the present to evaluate the  
temporal and spatial distribution of total  $\text{O}_3$ .

We use monthly averaged analyses of meteorological data on constant pressure levels from the  
105 Modern-Era Retrospective analysis for Research and Applications- Version 2, (MERRA-2) (Bosilovich  
et al., 2015) to determine the vertical wind shear and QBO phase. The MERRA-2 analysis begins in  
January 1980. Coy et al. (2016) showed that MERRA-2 produces a realistic QBO from 1980-2016,  
a period encompassing 15 QBO cycles. We show changes in the meridional circulation due to the  
disrupted QBO using the vertical component of the MERRA-2 residual mean meridional circula-  
110 tion ( $\overline{w^*}$ ,  $\overline{w^*}$  (Andrews et al., 1987), which is calculated using 3-hourly output.

To determine the impact of the 2015-2016 disruption on the distribution of trace gases, we create  
a QBO composite ('QBO climatology') for each analyzed dynamical variable (T, zonal winds ( $\overline{u}$ ),  
and upwelling by the residual circulation ( $\overline{w^*}$ )) and trace species ( $\text{O}_3$ , HCl, and total  $\text{O}_3$ ). These  
QBO composites include all available data except for 2015-2016. We composite based on the month  
115 of change from zonal mean easterly (negative) to westerly (positive) vertical wind shear at 40 hPa.  
This is identified by month '0' in the figures. Compositing based on this criterion emphasizes that  
chemical trace gases are most closely related to the changes in the wind shear ( $\frac{\partial \overline{u}}{\partial z}$  or  $\overline{u}_z$ ), not the  
zonal wind ( $\overline{u}$ ) (Baldwin et al., 2001). Compositing dates (month 0) for each QBO cycle are listed in  
Table 1. Prior to compositing, we use monthly  $\overline{u}$  data to compute  $\overline{u}_z$  as a first vertical derivative of an  
120 unevenly-spaced array of  $\overline{u}$  using three-point (quadratic) Lagrangian interpolation. The annual cycle  
was removed from T,  $\overline{w^*}$ ,  $\overline{w^*}$  and trace gases to better isolate QBO variations, and values are shown  
in percent difference relative to the monthly climatology, except for the total column  $\text{O}_3$ , which is  
shown as absolute difference in Dobson Units (DU). ~~The Anomalies due to the 2015-2016 event are~~  
~~calculated as the difference between '2015-2016' and the composite~~ ~~highlights anomalies due to the~~  
125 ~~2015-2016 event, with values larger than two standard deviations considered as "significant".~~

Empirical orthogonal function (EOF) analysis has been applied to specify the instantaneous state of the QBO (Wallace et al., 1993). The two leading EOFs (EOF1 and EOF2) were derived from the deseasonalized monthly mean zonal mean wind data from Singapore radiosondes.

Interannual changes in global stratospheric water vapor and cold point tropical tropopause temperatures were analyzed by forming timeseries from multiple observational data sets. Data were deseasonalized to isolate anomalies due to the QBO. Time series of stratospheric water vapor anomalies were derived from combined HALOE (1991-2005) and Aura MLS (2004- 2016) satellite measurements. These data represent near-global ( $\sim 60^\circ\text{N-S}$ ) averages in the lower stratosphere (83 hPa). HALOE and MLS data were combined using the overlap period during 2004-2005. Cold point temperatures are derived from radiosonde data (1991-2016) and GPS radio occultation data (2001–2016). More details of the data and analysis are provided by Randel and Jensen (2013).

### 3 Results

#### 3.1 The response of the equatorial stratosphere to the anomalous QBO event

Prior to 2015, wind observations show the robust features of the QBO’s zonal wind pattern of descent in the middle and lower equatorial stratosphere (Newman et al., 2016; Coy et al., 2017). The  $\bar{u}$  composite in Fig. 1 (top, column a) shows typical descending easterlies (blue) and westerlies (red) with the zero wind shear (thick solid black contours). The alternating regime of downward propagating wind shear leads to a modification of lower stratospheric tracers. Composites of tropical  $\text{O}_3$  and HCl (Fig. 1, column a) show decreases/increases in mixing ratios, relative to the climatological seasonal values, during negative (easterly)/positive (westerly) wind shear. This  $\text{O}_3$  and HCl behavior results from the QBO-induced (“secondary”) meridional circulation, acting on local gradients of these chemical tracers (Gray and Chipperfield, 1990). A downward (adiabatically warmed) perturbation (decreased  $\overline{w^*w^*}$  and increased T) is associated with descending westerly wind shear (positive  $\bar{u}_z$ ) while an upward (adiabatically cooled) perturbation is associated with easterly shear (negative  $\bar{u}_z$ ). Since the tracer’s tendency ( $\bar{\chi}_t$ ) is proportional to  $-\overline{w^*}\bar{\chi}_z - \overline{w^*}\bar{\chi}_z$  and mixing ratios of both chemical species increase with height in the lower stratosphere (positive vertical gradient,  $\bar{\chi}_z$ ),  $\text{O}_3$  and HCl decrease with time when  $\overline{w^*w^*}$  increases. The opposite is true for a downward perturbation (decreased  $\overline{w^*w^*}$ ). This is supported by the good agreement between the analyzed  $\overline{w^*w^*}$  and observed T,  $\text{O}_3$  and HCl composites with vertical wind shear. As discussed in the introduction, horizontal transport completes the circulation and also contributes to some changes in tropical stratospheric composition (not shown).

In late 2015 westerlies were displaced upward between 30 and 15 hPa and anomalous easterlies developed at  $\sim 40$  hPa in early 2016 (Newman et al., 2016; Coy et al., 2017), see Fig. 1b (top). During the northern spring the anomalous ascending westerlies reverted back to a more typical descent, reaching 50 hPa in September [2016–2016](#) and [70 hPa in February 2017](#). The vertical residual

velocity,  $\overline{w^*w^*}$  (Fig. 1b bottom), responded to the changes in equatorial zonal winds during 2015-2016 with decreased upwelling in association with the westerly shear and increased upwelling below the easterly maximum. A strong positive temperature perturbation developed in the 50-30 hPa layer (westerly shear zone) due to this reduced upwelling, while a strong negative perturbation developed in the easterly shear zone – due to the enhanced upward motion. Although analyzed  $\overline{w^*w^*}$  is noisy and involves greater uncertainty because of its highly derived nature, the excellent agreement between the wind shear and temperature changes (Fig. 1b bottom panels) provide evidence of secondary circulation changes resulting from the anomaly.

The circulation anomalies created by the 2015-2016 event altered stratospheric composition patterns (Fig. 1b, O<sub>3</sub> and HCl) relative to the composites seen in the left column. Changes in O<sub>3</sub> and HCl are in good agreement with changes in the wind shear and temperature (and thus  $\overline{w^*w^*}$ ). Prior to November 2015, both trace gases were following similar tendencies to their composites. Beginning February 2016 (black vertical line in Fig. 1b), O<sub>3</sub> and HCl increased between 50-30 hPa (due to the reduced upward motion) and decreased below 50 hPa (due to the enhanced upward motion). When the composites are subtracted from the last QBO cycle (Fig. 1c), QBO-induced anomalies in T, O<sub>3</sub> and HCl are seen to be co-located with the changes in wind shear during the last QBO cycle; and anomalies in U, T and O<sub>3</sub> are larger than 2 standard deviations (hatched gray lines), indicating that their changes were driven by the 2015-2016 QBO disruption.

The unprecedented nature of the 2015-2016 event is demonstrated in Fig. 2 showing "the orbits of the QBO" in two dimensional phase space, based on the projections on two leading empirical orthogonal functions (EOF1 and EOF2), following Wallace et al. (1993). QBO orbits are used to quantify the amplitude and phase propagation among the QBO cycles. Each point in this figure describes the instantaneous state of the QBO, described by the amplitude and phase angle of the vector in polar coordinates and specified in terms of variables (EOF1 and EOF2) that define the vertical structure of the zonal wind. EOF1 reflects the negative correlation between zonal wind fluctuations at 10 and 70 hPa while EOF2 indicates the variability at intermediate levels. Time progression corresponds to counterclockwise transits and each orbit corresponds to an individual QBO cycle.

Prior to 2016, the QBO orbits (blue dots in Fig. 2) are roughly circular and data points are distributed uniformly along the orbits, indicating the remarkably uniform structure and nearly constant amplitude of the QBO in this record (~~1987-2016~~)-1987-2015). During this time, EOF1 and EOF2 combined explain ~95.5% of the variance of the deseasonalized smoothed time series of zonal winds between 70 to 10 hPa. Based on this stability, EOF1 and EOF2 are commonly used to isolate the variability related to the QBO when deriving ODS-induced changes in long-term ozone records.

The repetitive QBO pattern was disrupted in 2016, as shown by the red points that deviate from the regular circular pattern. The smaller amplitude (closer to the center) of EOF1 and EOF2 in Figure 2 during the disruption means the zonal winds either are weaker than the typical QBO or not fitting the EOFs well. Analysis of the variance explained by two leading EOFs shows that the first two EOF

patterns don't match the disruption very well, with the lowest percent variance (~71%) explained by the two EOFs in the entire data record occurring during the disruption (not shown). Such disruptions add unpredictable variability to the time series, ~~directly interfering with the ability to determine regression-based trends in stratospheric ozone~~ reducing the accuracy of stratospheric ozone trends determined by multivariate regressions.

### 3.2 Latitudinal changes in ozone

The stratospheric impact of the 2015-2016 event extends into the extratropics. Figure 3 shows the evolution of O<sub>3</sub> for the composite (left), 2015-2016 (middle) and their difference (right). The top panels of Fig. 3 (a, b, and c) show MLS O<sub>3</sub> at 38 hPa, the pressure level of maximum O<sub>3</sub> anomaly during the NH summer of 2016. As shown in the composite (Fig. 3a), the positive O<sub>3</sub> perturbation during the westerly shear in the tropics and the negative perturbations in the extratropics are replaced by anomalies of opposite signs as the wind shear reverses to easterly 12-14 months later. However, in 2016 (Fig. 3b) the 40 hPa westerly shear changes to a weak easterly shear for only a short time interval (Jan-Apr) before switching back to westerly shear (note that the wind shear at 30 hPa remains westerly). O<sub>3</sub> responds by decreasing/increasing in mixing ratios during the easterly/westerly shear changes. The O<sub>3</sub> anomalies due to the 2015-2016 event are highlighted in Fig. 3c, which show large differences after February 2016 (black line). A strong negative tropical O<sub>3</sub> perturbation developed by early spring 2016, propagating to the extratropics in both hemispheres by the end of the NH summer. In the equatorial region, a positive perturbation replaced the negative O<sub>3</sub> perturbation as the wind shear switched back to westerly. QBO-induced anomalies after February 2016 are larger than two standard deviations.

The 2016 NH summer positive tropical O<sub>3</sub> anomaly at 30-50 hPa - the level of maximum O<sub>3</sub> number density - contributed to substantial changes in the total column O<sub>3</sub>. As in the 38 hPa O<sub>3</sub> from MLS (Fig. 3, top), the typical QBO behavior of SBUV total O<sub>3</sub> (Fig. 3d) contrasts to the anomalous 2015-2016 behavior (Fig. 3e), with their difference (Fig. 3f) highlighting the 2016 anomalies. The SBUV total O<sub>3</sub> QBO composite is based on 14 transitions of wind shear at 40 hPa (excluding 2015-2016). Total O<sub>3</sub> was deseasonalized and values are shown as absolute difference from the monthly climatology (in Dobson Units). This SBUV composite captures the major features of the typical QBO and the O<sub>3</sub> perturbations.

Prior to February 2016, Fig. 3f shows small total O<sub>3</sub> differences except for the large midlatitude anomalies from 0 to +6 months in the southern (negative anomaly) and northern (positive anomaly) hemispheres. However, only the negative anomaly in the southern midlatitudes is ~~significant at the 2-sigma level(not shown)~~ larger than 2 standard deviations. The cause of these anomalies prior to the 2015-2016 disruption remains unclear and is a subject of ongoing investigation. After February 2016 (black line in Fig. 3e), there is a large decrease in total ozone in the extratropics and midlatitudes of both hemispheres and the total O<sub>3</sub> differences between composite and last QBO cycle (Fig. 3f)

are very similar to the differences in 38 hPa O<sub>3</sub> from MLS (Fig. 3c). This strongly suggests that the  
235 2015-2016 event had a significant impact on both tropical and extratropical total O<sub>3</sub>.

### 3.3 Temporal and spatial morphology of ozone in April and August 2016

Large negative O<sub>3</sub> anomalies in the lower stratosphere start in April 2016 in the tropics and propagate  
to the extratropics by August 2016. Note, these two months occur at 11 and 15 months after month  
0 on the "composited" time axes and are indicated by arrows in Fig. 3. Therefore, we compare the  
240 latitudinal and vertical extent of the QBO-induced anomalies in T and O<sub>3</sub> during these two months  
(Fig. 4b and Fig. 4d) to the expected behavior based on the composite eleven (+11 mon) and fifteen  
(+15 mon) months after the wind shear reversal (Fig. 4a and Fig. 4c). In agreement with Fig. 1b,  
in April 2016 the anomalous easterly shear below 40 hPa (dashed horizontal line in Fig. 1b) leads  
to strong negative T and O<sub>3</sub> perturbations in the tropics while the appearance of ascending westerly  
245 shear leads to weak tropical T and O<sub>3</sub> increases between 20-40 hPa. By August 2016, the westerly  
shear strengthens and descends to 30-50 hPa resulting in strong positive T and O<sub>3</sub> perturbations  
in this layer, while the easterly shear below 50 hPa leads to negative perturbations in the equatorial  
(10°N-10°S) stratosphere. This is consistent with our understanding of trace gas response to changes  
in tropical upwelling. The consistency of O<sub>3</sub> and T anomalies during 2015-2016 is evidence of  
250 circulation changes.

In the subtropics, the deseasonalized O<sub>3</sub> QBO signature is out-of-phase with that at the equator,  
in agreement with Fig. 3b. In August 2016, strong negative O<sub>3</sub> perturbations develop during the NH  
summer on both sides of the equator (although much stronger in the winter southern hemisphere)  
as a response to the QBO-induced meridional circulation. In the composites at +11 and +15 months  
255 (Fig. 4a and Fig. 4c) anomalies in MLS O<sub>3</sub> and T are opposite to those observed in April and August  
2016 (Fig. 4b and Fig. 4d) due to the descending easterly shear. Thus, O<sub>3</sub> is responding as expected  
to a QBO-induced meridional circulation but this period is anomalous with respect to a normal QBO  
progression.

The observed 2015-2016 anomalies are unique in the total O<sub>3</sub> record. Figure 5 compares the  
260 latitudinal distribution of deseasonalized total O<sub>3</sub> from April and August 2016 (in red) to the total  
O<sub>3</sub> composite (the average from the 14 composited QBO cycles) shown in Fig. 3d at +11 and +15  
months respectively (in black). Total O<sub>3</sub> from each individual QBO cycle included in the composite  
is shown in blue, with light blue shading indicating the range of total O<sub>3</sub> from all QBO cycles  
(excluding 2015–2016). In the absence of the disruption, we expect total O<sub>3</sub> at +11 (Fig. 5a) and  
265 +15 (Fig. 5b) months to lie within the blue shaded range of past observations. Instead, in April 2016  
total O<sub>3</sub> is lower than during other QBO cycles in the NH tropics (10°N - 20°N). Furthermore,  
during August 2016 total ozone is higher at the equator and lower/near the edge in the extratropics  
between 10°S-40°S / 30°N-50°N compared to other QBO cycles.

Calculations suggest that anomalously low total column  $O_3$  at  $22.5^\circ S$  in August 2016 increased the monthly zonal mean surface clear-sky UV index by  $\sim 8.5\%$  compared to the 36-yr mean (Newman and McKenzie, 2011). Increased surface UV radiation has a harmful effect on health by damaging cells, DNA, and increasing the risk of developing skin cancer. Increased exposure to UV in plants leads to enhanced plant fragility, growth limitation, and yield reduction affecting our ability to secure food production (Caldwell et al., 1995; Tevini, 1993).

### 3.4 QBO-driven changes in total ozone and water vapor in the context of long-term time series

Examination of the interannual variations in SBUV monthly and zonal mean total  $O_3$  shows very low total  $O_3$  values in the extratropics during spring and summer of 2016 compared to other years within this observational record. Figure 6 displays the time series for April (top panels) and August (bottom panels) total  $O_3$  values in the northern and southern extratropics. The regions shown are locations with large anomalies in Fig. 3f. The individual 1-sigma error estimates are shown as the vertical gray bars in Fig. 6, while the horizontal line is the 2016 value. Each of these plots show that the 2016 value was the record or near record low in the more than 40 years of the SBUV data.

Near record low total  $O_3$  in the extratropics during the spring-summer 2016 is due to the 2015-2016 QBO disruption event. As shown in Fig. 3e, beginning about February 2016 the disruption in the descent of easterly zonal winds led to lower  $O_3$  values in both the northern and southern extratropics and persisted into the fall of 2016. The ozone anomalies, shown in Fig. 3e, are up to -12 DU at  $12.5^\circ N$  in April 2016, and -15 DU at  $17.5^\circ S$  in August 2016. This strongly contrasts with the expected behavior (Fig. 3d) that would have been either near zero or small positive anomalies.

The 2015-2016 QBO event also significantly impacted the global amount of stratospheric water vapor in 2016.  $H_2O$  enters the stratosphere from the troposphere primarily in the tropics. The amount of  $H_2O$  in the stratosphere is controlled by the tropical tropopause temperature ("cold point tropopause temperatures", or  $T_{cp}$ ) with colder  $T_{cp}$  resulting in less  $H_2O$  entering the tropical stratosphere from the troposphere. Figure 7 demonstrates very strong correlation of stratospheric water vapor anomalies with  $T_{cp}$  (also see Randel and Jensen, 2013). In 2016, cold tropical tropopause temperatures (in balance with anomalous easterlies) led to a global decrease in the stratospheric  $H_2O$  in October-December 2016. Global  $H_2O$  in November is amongst the lowest in the record (1992-2016) due to very low  $T_{cp}$ .

In addition to the QBO disruption, there was a strong El-Niño in 2015-2016 winter [Hu et al., 2016]. While changes in the global water content and stratospheric ozone from late spring to the end of fall 2016 are attributed mostly to the unprecedented QBO event, El-Niño could strongly influence the lower stratosphere during the winter of 2016. Previous studies showed cooling of the tropical lower stratosphere and strengthening of the Brewer-Dobson circulation during El-Niño (Randel et al., 2009; Calvo et al., 2010) followed by an associated decrease in ozone and increase in  $H_2O$  in this

305 region. The impact of ENSO on stratospheric water vapor, however, is non-linear and often depends  
on the phase of the QBO (Liess and Geller, 2012), time of the year (early or late in the winter)  
and location (Central or Eastern Pacific) where ENSO maximum occurs (Garfinkel et al, 2013).  
The interplay between El-Niño and the QBO disruption during 2015-2016 boreal winter is not well  
understood and their relative importance on trace gas distribution requires a detailed investigation.

#### 310 **4 Concluding remarks**

This study demonstrates that the 2015-2016 QBO disruption had a substantial impact on the com-  
position of the stratosphere. It led to a modified circulation that reduced the equatorial upward cir-  
culation in association with the positive (westerly) shear, while the negative shear below the easterly  
maximum led to enhanced upward motion. Following the appearance of the disruption in February  
315 2016, there were two layers of zonal wind shear in the tropics. Westerly shear in the 30-50 hPa layer  
was linked to increased temperature and decreased upwelling, resulting in positive perturbations  
in O<sub>3</sub> and HCl. The easterly shear from the disruption in the 50-100 hPa layer produced negative  
temperature perturbations in association with increased tropical upwelling, inducing negative per-  
turbations in O<sub>3</sub> and HCl. Cold temperature anomalies extended to the tropopause level in late 2016,  
320 resulting in decreases in global stratospheric water vapor. Because the ozone number density maxi-  
mum is in the 50-30 hPa layer, the QBO disruption increased total O<sub>3</sub> at the equator.

The decrease in tropical ascent during the disruption was balanced by reduced downwelling in the  
extratropics. This reduced extratropical downward motion decreased O<sub>3</sub> in those regions (although  
the horizontal component to this circulation contributes as well). In this study we focused mostly on  
325 O<sub>3</sub> changes, however, the response of other long-lived tracers such as HCl and N<sub>2</sub>O is consistent with  
the QBO meridional circulation induced by the disrupted QBO. While HCl anomalies are consistent  
with the O<sub>3</sub> anomalies, the N<sub>2</sub>O anomalies have an opposite sign due to the negative vertical gradient  
of this tracer. The similarities in the responses of temperature and observed changes in chemical trace  
gases to the QBO disruption shows that these composition changes are primarily dynamically driven.  
330 Trace gases show perturbed behavior compared to the past, but their response is consistent with our  
understanding of the QBO-induced meridional circulation.

At nearly the same time as the QBO disruption, there was one of the strongest in record El-Niño  
event and very strong stratospheric polar vortex in early to mid- winter [Cheung et al.,2016; Hu et  
al.,2016; Scaife et al., 2017]. The interplay of these three events and their potential impact on trace  
gas distributions remains to be investigated. For instance, we acknowledge the possible influence  
of 2015-2016 El-Niño event on tropical tropopause temperature and therefore global redistribution  
of stratospheric water vapor. Furthermore, previous studies by Fioletov and Shepherd [2003, 2005]  
showed very strong correlations between polar and midlatitude total ozone. Ozone depleted air inside  
cold polar vortex could mix into the northern hemisphere midlatitudes contributing to the negative



340 [anomalies in total ozone during 2016 boreal summer. Strahan et al. \[2016\] showed that the impact of Arctic ozone depletion on the midlatitudes in spring after winters with moderate depletion \(such as 2016\) was about 5 DU \(south of 45°N\). But they also found that the dynamical impact on O<sub>3</sub> due to a strong polar vortex winter roughly opposed the depletion changes, resulting in very little net impact. Furthermore, very symmetric nature of negative anomalies around equator during the boreal](#)  
345 [summer and fall strongly suggests a dominant role of circulation changes due to the 2015-2016 QBO disruption.](#)

It is unclear if this QBO disruption is an event of great rarity or if similar events will reoccur. Similar disruptions with the same timing could potentially alter ozone and trace gas distributions, affecting the stratospheric climate and making it more difficult to accurately estimate climate trends.  
350 For example, a series of disruptions could drive a downward ozone trend and lead to a long-term increase in the surface UV index during the peak of northern summer.

At present, numerical models are unable to predict such events (Osprey et al., 2016), pointing to incomplete understanding of QBO forcing mechanisms. The model failures could result from missing processes, poor representation of necessary wave forcings, or resolution. Osprey et al. (2016)  
355 pointed out that only one event similar to the observed during 2016 was identified among the available models that produce an internally-generated QBO. Our inability to simulate and/or predict a disrupted QBO will add uncertainty to future predictions of ozone and other chemical constituents from coupled chemistry climate models, as well as limit our ability to resolve statistically-significant ODS-related changes in the observed O<sub>3</sub> record. This event, whether unique or the first of many QBO  
360 disruptions, emphasizes the crucial need to continue collecting and evaluating high quality satellite measurements to trace the impact of stratospheric dynamical changes.

## 5 [Data availability](#)

[The observational data sets used in this study are publicly available. MLS data are available from the NASA Goddard Space Flight Center Earth Sciences \(GES\) Data and Information Services Center \(DISC\). SBUV total ozone data have been obtained from the NASA Goddard Space Flight Center Website \(\[https://acd-ext.gsfc.nasa.gov/Data\\\_services/merged/\]\(https://acd-ext.gsfc.nasa.gov/Data\_services/merged/\)\). The MERRA-2 reanalysis fields were obtained from the NASA Earth Observing System Data and Information System \(<https://earthdata.nasa.gov>\). Daily global radiosondes have been collected at NASA/GSFC and are provided from the Global Telecommunications System \(available via the NOAA/NCEP web site: <ftp://ftp.cpc.ncep.noaa.gov/wd53rl/rsonde/>\).](#)  
370 [HALOE data set is available at <http://haloe.gats-inc.com> and GPS radio occultation data is obtained from the COSMIC data center at <http://www.cosmic.ucar.edu/>](#)

*Acknowledgements.* Authors acknowledge, and thank, Luke Oman for providing us with vertical component of the residual circulation,  $\overline{w^*w^*}$ , calculated from MERRA-2 reanalysis product and all those who are members of

the MLS and SBUV data science and support teams. Olga Tweedy is supported by the National Science Foundation Graduate Research Fellowship Program under Grant No.DGE-1232825. Support for this study was also provided under the NASA Atmospheric Composition Modeling and Analysis Program. NCAR is operated by the University Corporation for Atmospheric Research, under sponsorship of the National Science Foundation.

## References

- Andrews, D. G., Holton, J. R., and Leovy, C. B.: Middle atmosphere dynamics, 40, Academic press, 1987.
- 380 Angell, J. K. and Korshover, J.: Quasi-biennial variations in temperature, total ozone, and tropopause height, *Journal of the Atmospheric Sciences*, 21, 479–492, 1964.
- Baldwin, M., Gray, L., Dunkerton, T., Hamilton, K., Haynes, P., Randel, W., Holton, J., Alexander, M., Hirota, I., and Horinouchi, T.: The quasi-biennial oscillation, *Reviews of Geophysics*, 39, 179–229, 2001.
- Bosilovich, M. G. and yih Sun, W.: Monthly simulation of surface layer fluxes and soil properties during FIFE, 385 *Journal of the Atmospheric Sciences*, 72, 2015.
- Caldwell, M., Teramura, A. H., Tevini, M., Bornman, J., Björn, L. O., and Kulandaivelu, G.: Effects of increased solar ultraviolet-radiation on terrestrial plants, *Ambio*, 24, 166–173, 1995.
- Calvo, N., Garcia, R., Randel, W., and Marsh, D.: Dynamical mechanism for the increase in tropical upwelling in the lowermost tropical stratosphere during warm ENSO events, *Journal of the Atmospheric Sciences*, 67, 390 2331–2340, 2010.
- Cheung, H. H., Zhou, W., Leung, M. Y., Shun, C., Lee, S., and Tong, H.: A strong phase reversal of the Arctic Oscillation in midwinter 2015/2016: Role of the stratospheric polar vortex and tropospheric blocking, *Journal of Geophysical Research: Atmospheres*, 121, 2016.
- Choi, W., Lee, H., Grant, W. B., Park, J. H., Holton, J. R., LEE, K., and Naujokat, B.: On the secondary 395 meridional circulation associated with the quasi-biennial oscillation, *Tellus B*, 54, 395–406, 2002.
- Coy, L., Wargan, K., Molod, A. M., McCarty, W. R., and Pawson, S.: Structure and dynamics of the quasi-biennial oscillation in MERRA-2, *Journal of Climate*, 29, 5339–5354, 2016.
- Coy, L., Newman, P., Pawson, S., and Lait, L. R.: Dynamics of the Disrupted 2015-16 Quasi-Biennial Oscillation, *Journal of Climate*, 2017, submitted.
- 400 Dunkerton, T. J.: The role of gravity waves in the quasi-biennial oscillation, *Journal of Geophysical Research: Atmospheres*, 102, 26 053–26 076, 1997.
- Frith, S. M., Kramarova, N. A., Stolarski, R. S., McPeters, R. D., Bhartia, P. K., and Labow, G. J.: Recent changes in total column ozone based on the SBUV Version 8.6 Merged Ozone Data Set, *Journal of Geophysical Research: Atmospheres*, 119, 9735–9751, doi:10.1002/2014JD021889, 2014.
- 405 Funk, J. and Garnham, G.: Australian ozone observations and a suggested 24 month cycle, *Tellus*, 14, 378–382, 1962.
- Garfinkel, C. I., Hurwitz, M. M., Oman, L. D., and Waugh, D. W.: Contrasting effects of Central Pacific and Eastern Pacific El Niño on stratospheric water vapor, *Geophysical Research Letters*, 40, 4115–4120, 2013.
- Gray, L. and Chipperfield, M.: On the interannual variability of trace gases in the middle atmosphere, *Geophysical Research Letters*, 17, 933–936, 1990.
- 410 Gray, L. and Pyle, J.: A two-dimensional model of the quasi-biennial oscillation of ozone, *Journal of the Atmospheric Sciences*, 46, 203–220, 1989.
- Gray, L. J. and Ruth, S.: The modeled latitudinal distribution of the ozone quasi-biennial oscillation using observed equatorial winds, *Journal of the Atmospheric Sciences*, 50, 1033–1046, 1993.
- 415 Holton, J. R. and Lindzen, R. S.: An updated theory for the quasi-biennial cycle of the tropical stratosphere, *Journal of the Atmospheric Sciences*, 29, 1076–1080, 1972.

- Kinnersley, J. S. and Tung, K.-K.: Modeling the global interannual variability of ozone due to the equatorial QBO and to extratropical planetary wave variability, *Journal of the Atmospheric Sciences*, 55, 1417–1428, 1998.
- 420 Lindzen, R. S. and Holton, J. R.: A theory of the quasi-biennial oscillation, *Journal of the Atmospheric Sciences*, 25, 1095–1107, 1968.
- Ling, X.-D. and London, J.: The quasi-biennial oscillation of ozone in the tropical middle stratosphere: A one-dimensional model, *Journal of the Atmospheric Sciences*, 43, 3122–3137, 1986.
- Livesey, N. J., Read, W. G., Wagner, P. A., Froidevaux, L., Lambert, A., Manney, G. L., Millán-Valle, L. F.,  
425 Pumphrey, H. C., Santee, M. L., Schwartz, M. J., Wang, S., Fuller, R. A., Jarnot, R. F., Knosp, B. W., and  
Martinez, E.: Version 4.2x Level 2 data quality and description document, Tech. Rep. JPL D-33509 Rev. B,  
Jet Propulsion Laboratory, available at <http://mhs.jpl.nasa.gov>, 2015.
- Newman, P., Coy, L., Pawson, S., and Lait, L.: The anomalous change in the QBO in 2015–2016, *Geophysical Research Letters*, 43, 8791–8797, 2016.
- 430 Newman, P. A. and McKenzie, R.: UV impacts avoided by the Montreal Protocol, *Photochemical and Photobiological Sciences*, 10, 1152–1160, 2011.
- Osprey, S. M., Butchart, N., Knight, J. R., Scaife, A. A., Hamilton, K., Anstey, J. A., Schenzinger, V., and Zhang, C.: An unexpected disruption of the atmospheric quasi-biennial oscillation, *Science (New York, N.Y.)*, 353, 1424–1427, doi:science.aah4156 [pii], IR: 20161006; CI: Copyright (c) 2016; JID: 0404511; ppublish, 2016.
- 435 Ramanathan, K.: Bi-annual variation of atmospheric ozone over the tropics, *Quarterly Journal of the Royal Meteorological Society*, 89, 540–542, 1963.
- Randel, W. J. and Jensen, E. J.: Physical processes in the tropical tropopause layer and their roles in a changing climate, *Nature Geoscience*, 6, 169–176, 2013.
- Randel, W. J. and Wu, F.: Isolation of the ozone QBO in SAGE II data by singular-value decomposition, *Journal of the Atmospheric Sciences*, 53, 2546–2559, 1996.
- 440 Randel, W. J., Garcia, R. R., Calvo, N., and Marsh, D.: ENSO influence on zonal mean temperature and ozone in the tropical lower stratosphere, *Geophysical Research Letters*, 36, 2009.
- Scaife, A. A., Comer, R., Dunstone, N., Fereday, D., Folland, C., Good, E., Gordon, M., Hermanson, L., Ineson, S., and Karpechko, A.: Predictability of European winter 2015/2016, *Atmospheric Science Letters*, 18, 38–44, 2017.
- 445 Schoeberl, M., Douglass, A., Newman, P., Lait, L., Lary, D., Waters, J., Livesey, N., Froidevaux, L., Lambert, A., and Read, W.: QBO and annual cycle variations in tropical lower stratosphere trace gases from HALOE and Aura MLS observations, *Journal of Geophysical Research: Atmospheres*, 113, 2008.
- Stolarski, R. S., Bloomfield, P., McPeters, R. D., and Herman, J. R.: Total ozone trends deduced from Nimbus  
450 7 TOMS data, *Geophysical Research Letters*, 18, 1015–1018, 1991.
- Strahan, S., Oman, L., Douglass, A., and Coy, L.: Modulation of Antarctic vortex composition by the quasi-biennial oscillation, *Geophysical Research Letters*, 42, 4216–4223, 2015.
- Strahan, S., Douglass, A., and Steenrod, S.: Chemical and dynamical impacts of stratospheric sudden warmings on Arctic ozone variability, *Journal of Geophysical Research: Atmospheres*, 121, 2016.
- 455 Tevini, M.: UV-B radiation and ozone depletion: effects on humans, animals, plants, microorganisms, and materials, Lewis Publishers Boca Raton, FL., 1993.

- Udelhofen, P. M., Gies, P., Roy, C., and Randel, W. J.: Surface UV radiation over Australia, 1979–1992: effects of ozone and cloud cover changes on variations of UV radiation, *Journal of Geophysical Research: Atmospheres*, 104, 19 135–19 159, 1999.
- 460 Wallace, J. M., Panetta, R. L., and Estberg, J.: Representation of the equatorial stratospheric quasi-biennial oscillation in EOF phase space, *Journal of the Atmospheric Sciences*, 50, 1751–1762, 1993.
- Zawodny, J. M. and McCormick, M. P.: Stratospheric Aerosol and Gas Experiment II measurements of the quasi-biennial oscillations in ozone and nitrogen dioxide, *Journal of Geophysical Research: Atmospheres*, 96, 9371–9377, 1991.

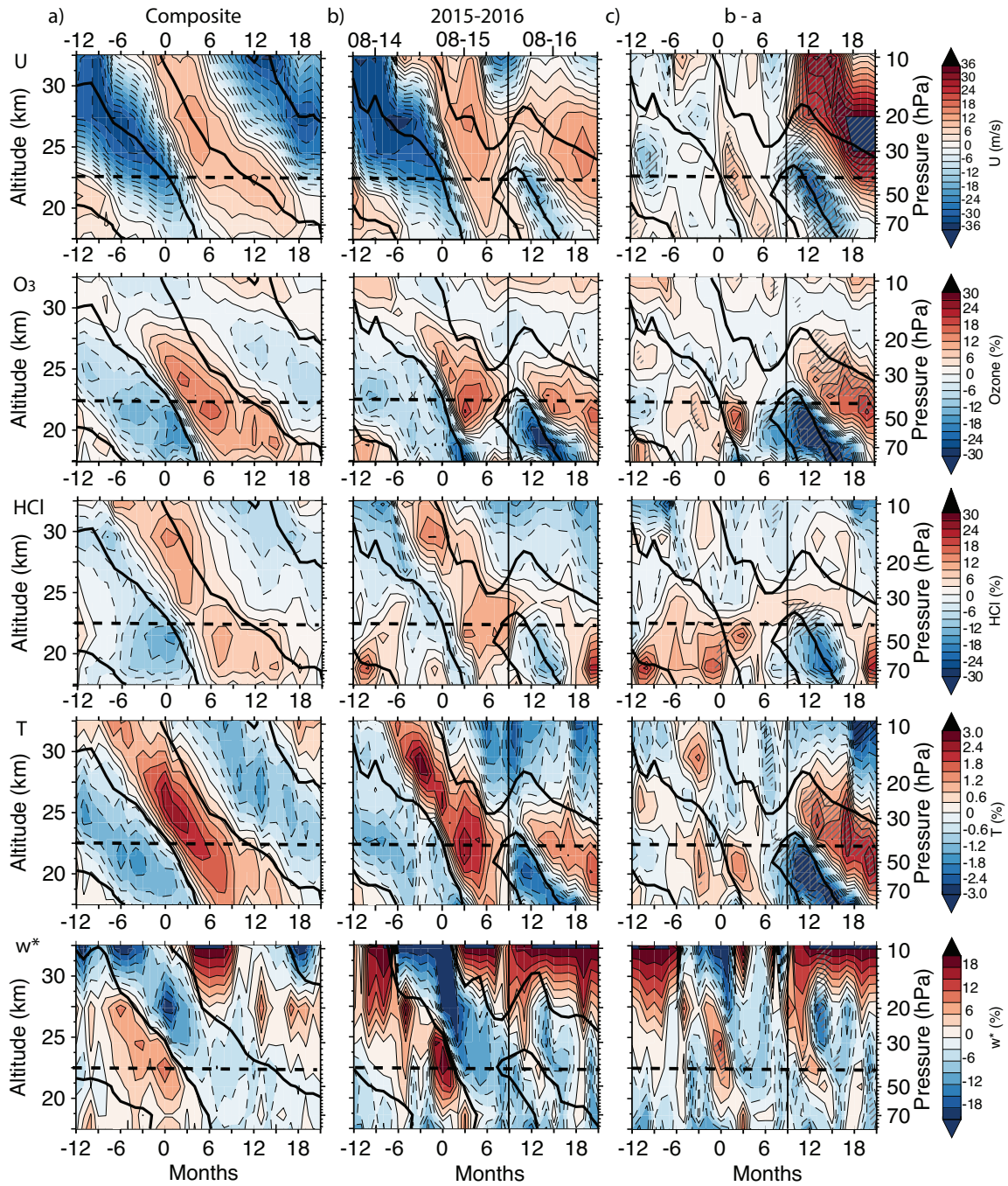


Fig. 1. The rows show the MERRA-2 zonal mean zonal wind component,  $\bar{u}$  ( $\text{m s}^{-1}$ ), deseasonalized MLS  $\text{O}_3$ , HCl, temperature (T) and vertical component of the MERRA-2 residual circulation ( $\overline{w^*w^*}$ ), as a function of time and pressure (in percent change from long term monthly averages), averaged over  $5^\circ\text{S}$ – $5^\circ\text{N}$ . The left column (a) shows the composite of the easterly-to-westerly shear transitions based on 4 shear transitions at 40 hPa. The middle column (b) shows the 2015-2016 QBO cycle, which includes the data from April 2014 to September 2016, with month 0 in May 2016. The right column (c) shows the difference between the 2015-2016 event and the climatology (b-a) with hatching indicating regions with absolute difference (b-a) larger than two standard deviations. The thick black contours denote the zero wind shear. The horizontal dashed line indicates the 40 hPa level while vertical line indicates February 2016.

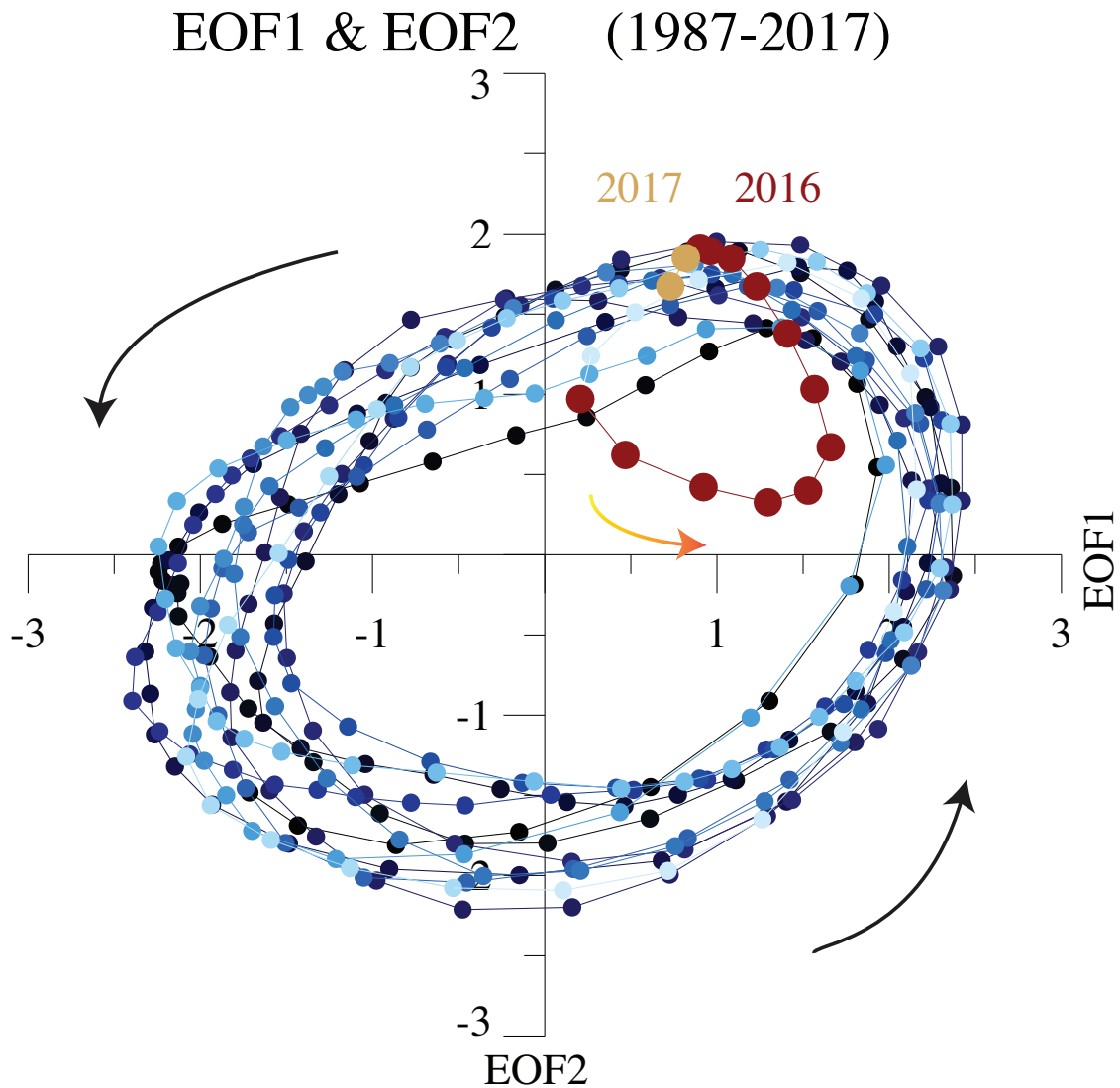


Fig. 2. Phase space diagram of the projection of the monthly equatorial zonal wind anomalies onto spacial-spatial structures EOF1 and EOF2. Time progression coincides with counterclockwise orbit transits. Dots represent each month from 1987-2016-January 1987 to February 2017. Different shades of blue indicate different years from 1987-2015 (from darker to lighter), while red and yellow dots correspond to 2016-2016 and 2017 respectively

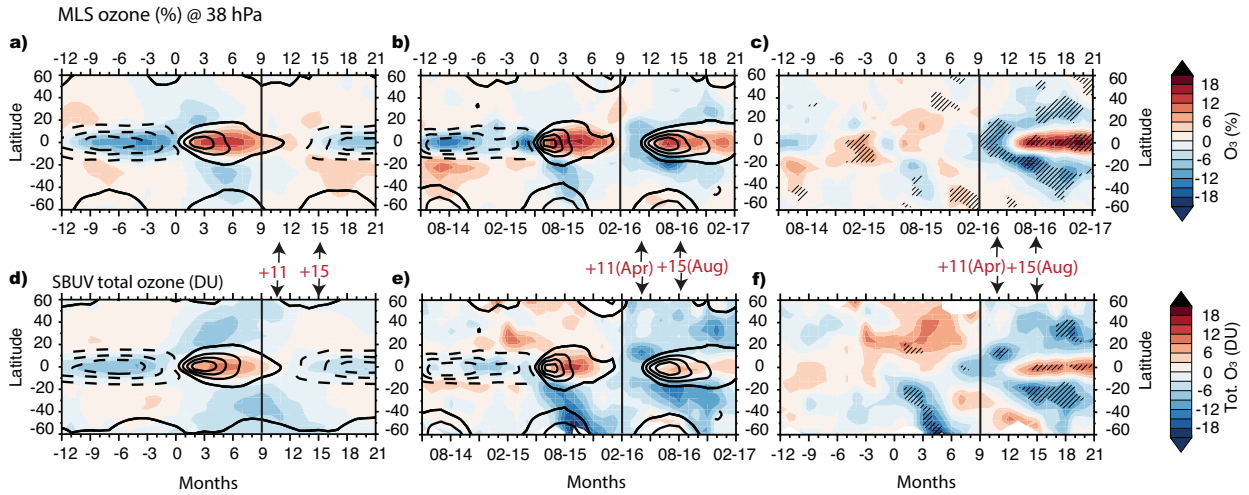


Fig. 3. Latitude and time evolution of MLS ozone at 38 hPa (top row) for (a) the composite, (b) 2015-2016, and (c) their difference (b-a), highlighting the anomalies due to the disruption. MLS ozone values are shown in percent change from long term monthly averages with contour intervals every 3 % (zero contour is omitted). The bottom row shows the deseasonalized SBUV total ozone (in Dobson Units, contour intervals every 3 DU) for d) the composite, e) 2015-2016, and f) their difference (e-d). Black thick solid and dashed contours show westerly and easterly vertical wind shear respectively for (a and d) the composites and (b and e) 2015-2016. MLS (SBUV) composites are based on 4(14) transitions from easterly to westerly vertical wind shear at 40 hPa. Vertical black line highlights +9 months after windshear reversal from negative to positive (month 0), corresponding to February 2016 in (b) and (e) while arrows indicate ozone at +11 and +15 months after month 0, corresponding to April 2016 and August 2016 in (b) and (e). Gray hatching in (c) and (f) indicates regions with absolute difference between 2015-2016 and the composites being larger than two standard deviations

Table 1: the QBO composite dates (month 0)

QBO cycle	1	2	3	4	5	6	7	8
Month 0	1982-06	1984-10	1987-06	1989-12	1992-06	1994-09	1996-11	1998-09
QBO cycle	9	10	11	12	13	14	15	
Month 0	2001-10	2003-12	2006-02	2008-01	2010-06	2012-12	2015-05	



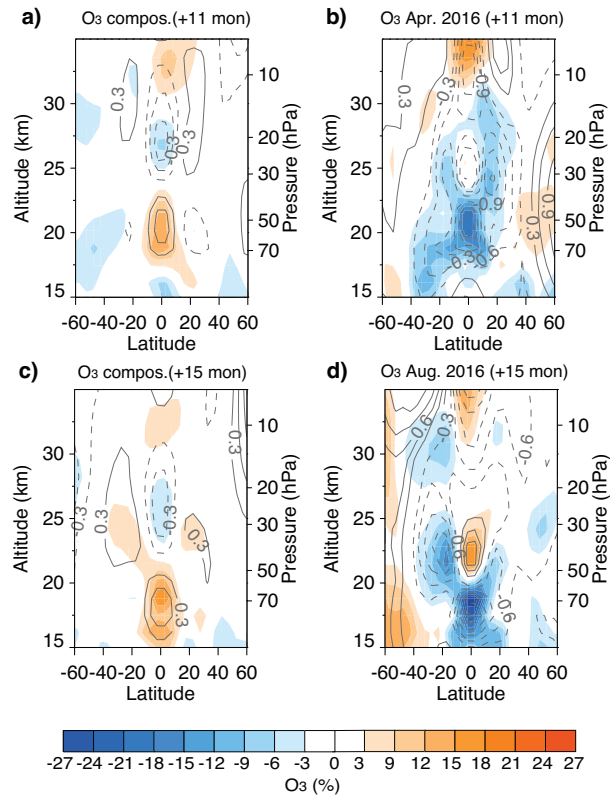


Fig. 4. Latitude-height cross sections of deseasonalized MLS ozone (filled) and temperature (gray contours) in the composite (a) 11 and (c) 15 months after the wind shear reversal based on 4 QBO cycles and during (b) April (+11 mon.) and (d) August 2016 (+15 mon.). Ozone and temperature values are shown in percent change from long term monthly averages with contour intervals every 3% and 0.3% respectively (zero contour is omitted).

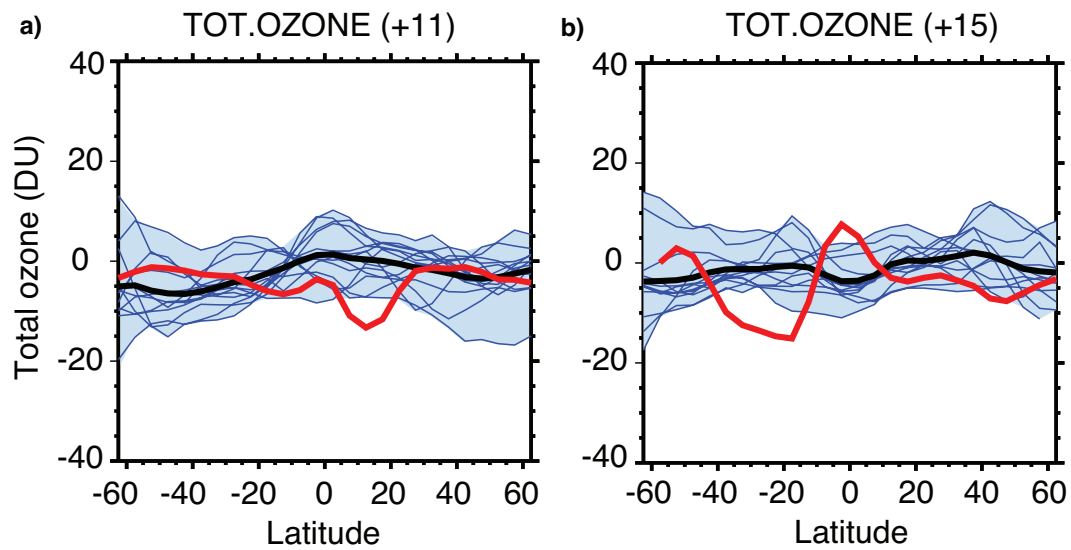


Fig. 5. (a) Deseasonalized SBUV total ozone (in Dobson Units) as a function of latitude 11 months after wind shear reversal from easterly to westerly from fourteen QBO cycles prior to 2015-2016 (blue lines), the composite (black line) based on 14 QBO cycles and 2015-2016 (April 2016, red line). (b) The same as in (a) only for total ozone at +15 months, corresponding to August 2016. The blue shading shows the observed  $O_3$  range at +11 and +15 months respectively for all 14 QBO cycles (excluding the 2015–2016 event).

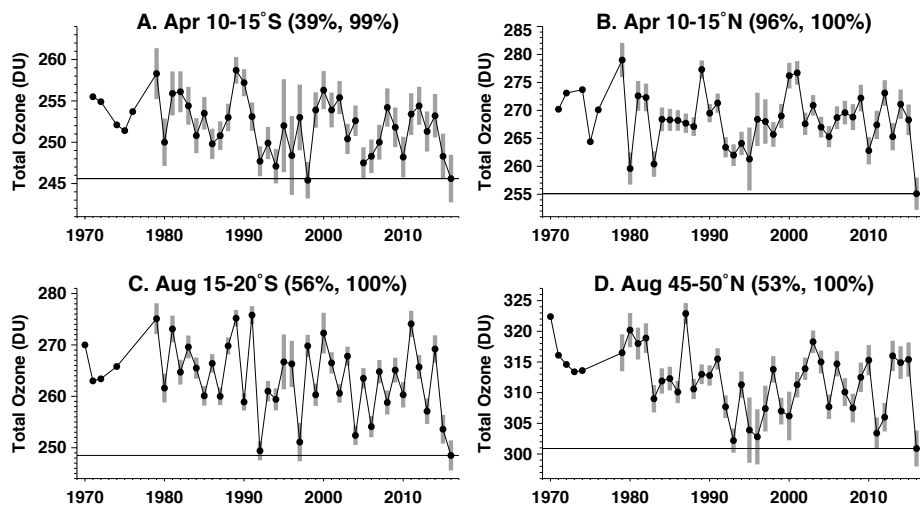


Fig. 6. SBUV total ozone (in Dobson Units) timeseries from 1970-2016 for April, averaged over (a) 10°S -15°S and (b) 10°N -15°N, and for August, averaged over (c) 15°S -20°S and (d) 45°N -50°N . Vertical bars show 1-sigma uncertainties in the measurements. The horizontal line shows the total ozone value in April or August 2016 and the panel titles show the percentage estimates of the 2016 value being the lowest and amongst the lowest 20% of all values. The probability that the 2016 values were record lows was estimated using a 10,000 Monte Carlo simulations of the monthly means in the time series (Frith et al, 2014).

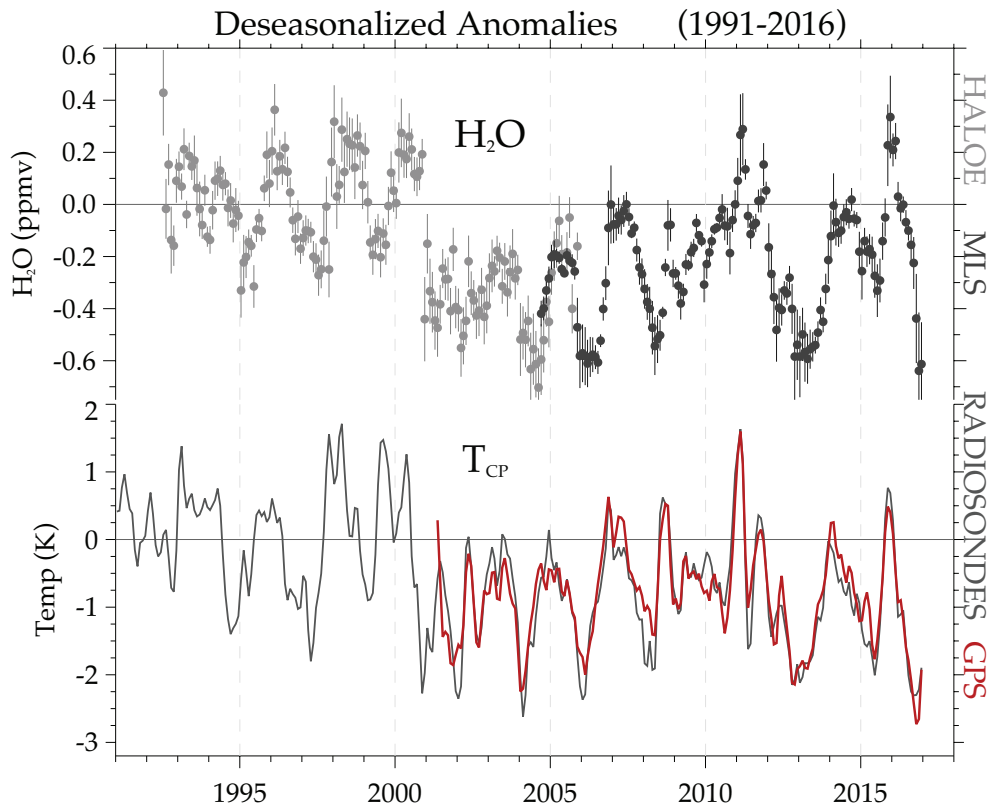


Fig. 7. Observed variations in lower stratospheric water vapor and tropical cold-point tropopause temperatures from satellite measurements over the period 1992–2016. Water vapor data are deseasonalized near-global averages at 83 hPa from combined HALOE and MLS satellite measurements. Each dot represents a monthly average. Temperatures are deseasonalized anomalies derived from radiosonde data (black line) and GPS radio occultation data (red line, for 2001–2016). Vertical bars are one sigma standard deviations of the monthly averages.