



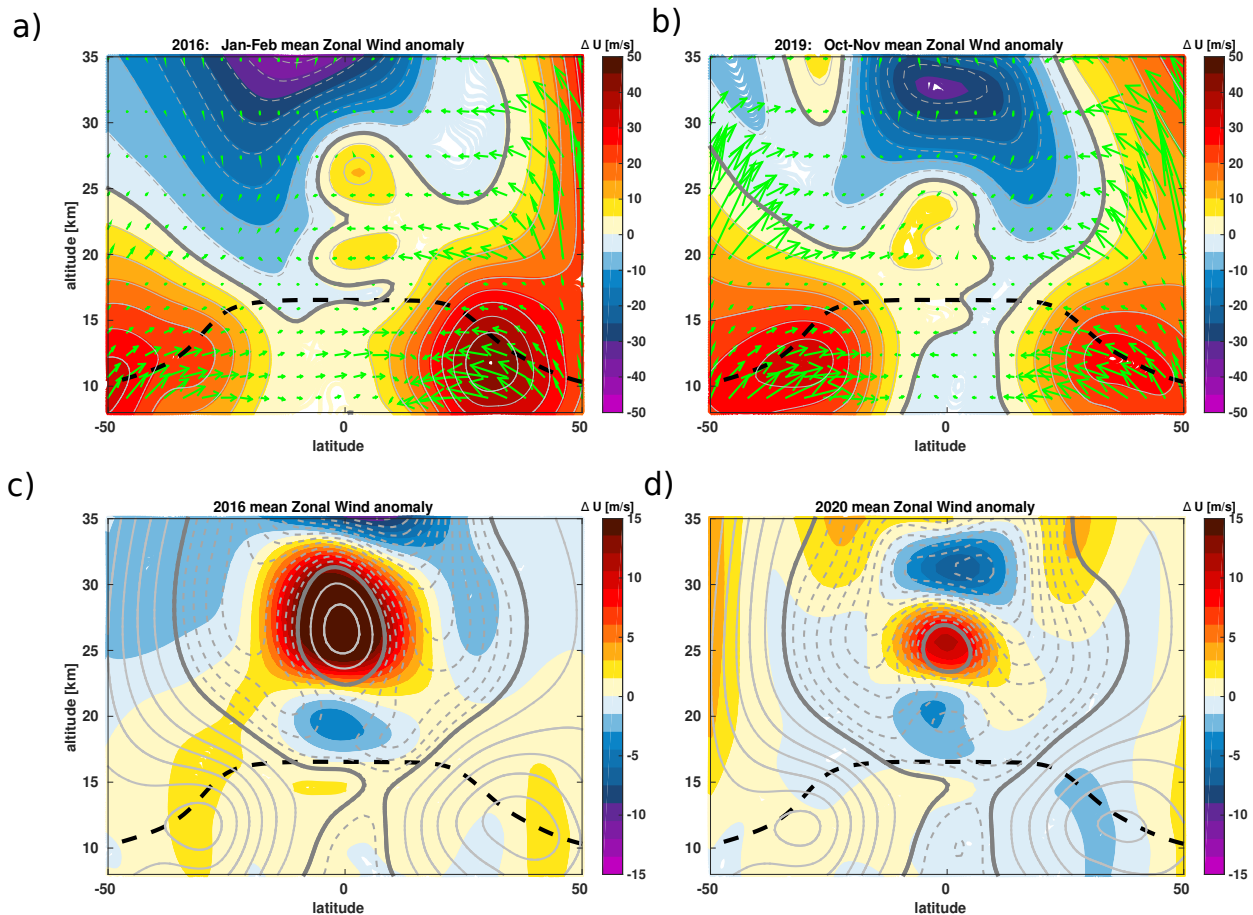
*Supplement of*

## **Stratospheric water vapour and ozone response to the quasi-biennial oscillation disruptions in 2016 and 2020**

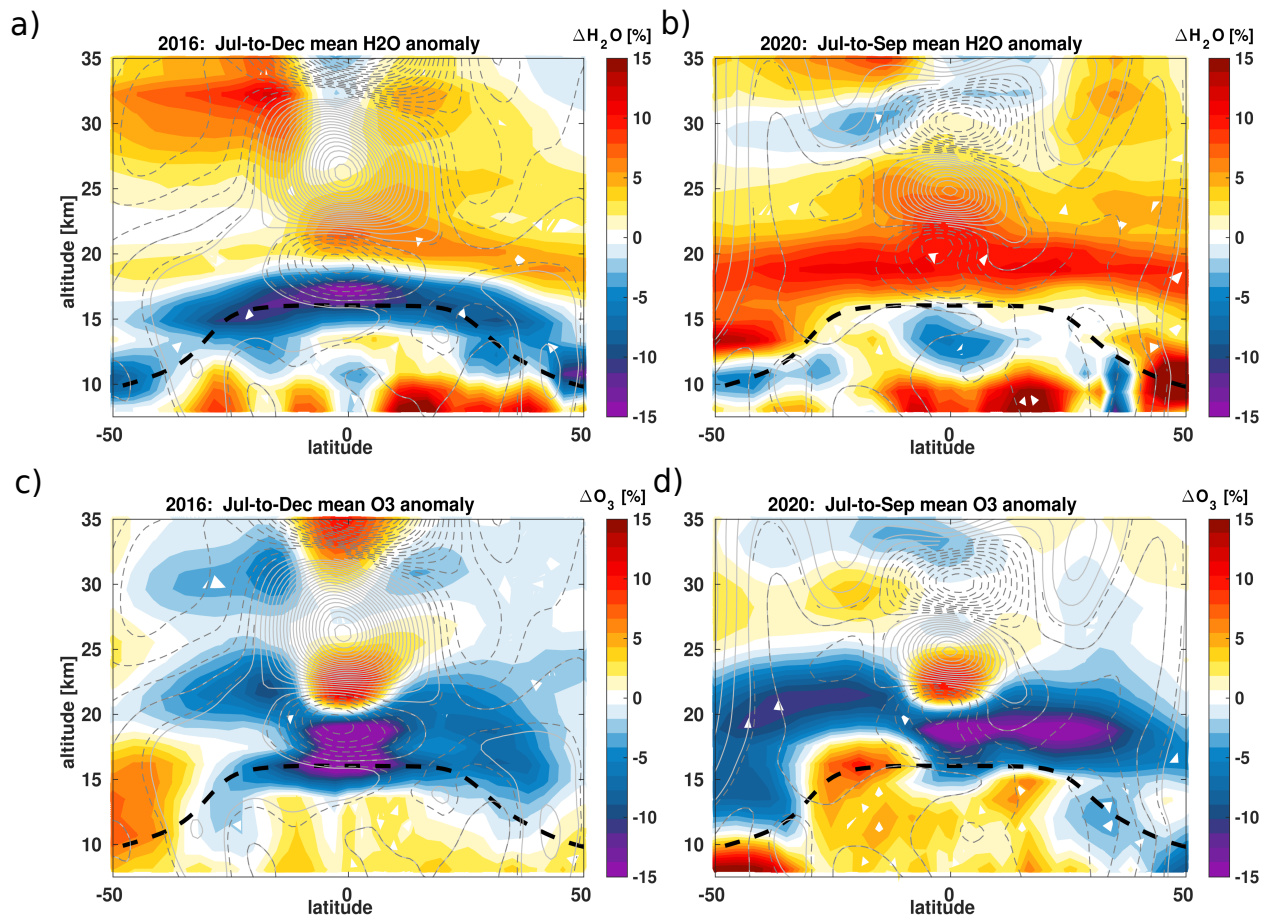
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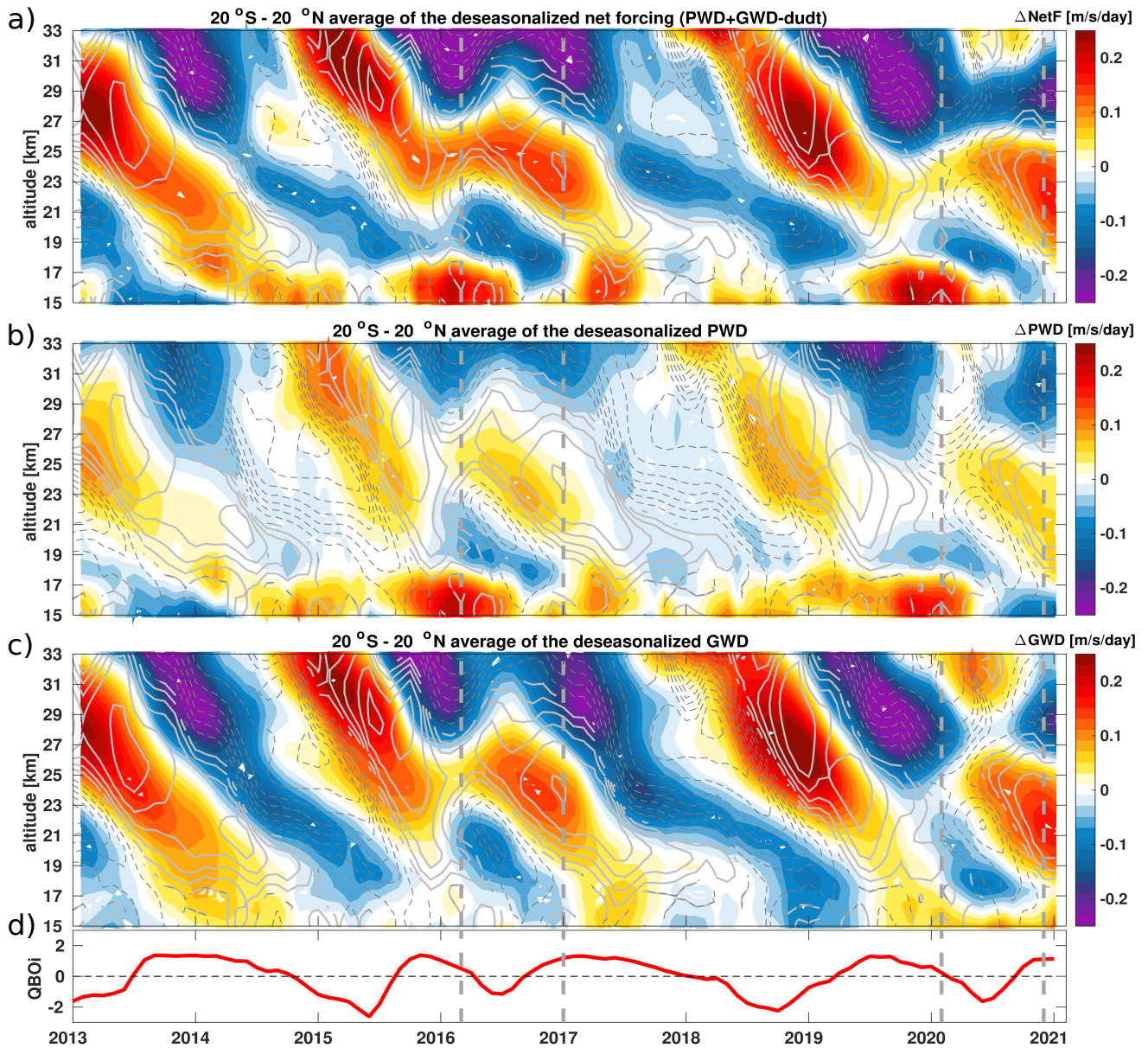
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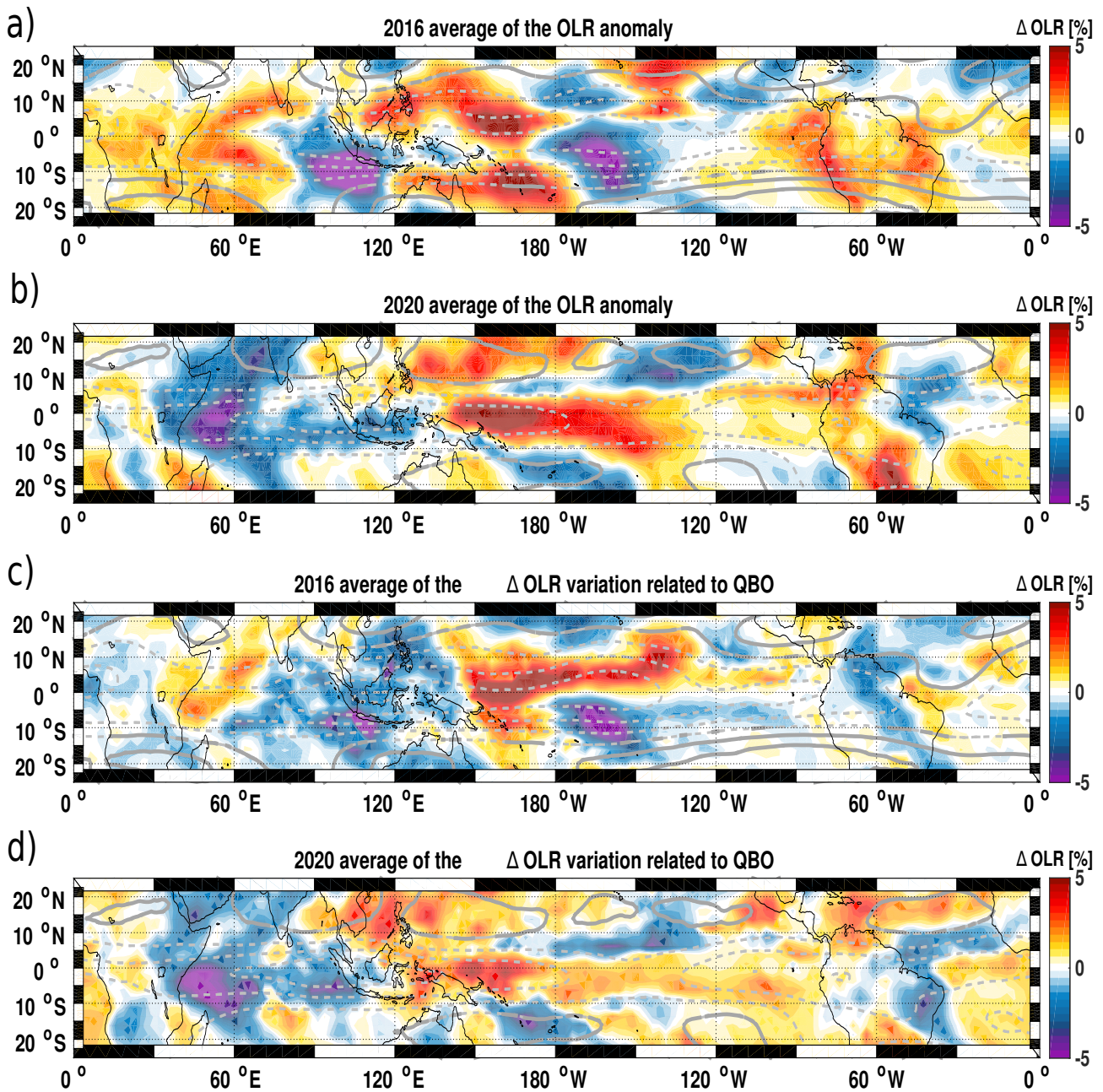
**Figure 1.** The onsets of the QBO disruption events (filled and black contours): January-to-February 2016 (a) and October-to-November 2019 (b) deviations from the January-to-February and October-to-November 1979–2014 average of zonal mean zonal wind from the ERA5 reanalysis (filled contours) together with the January-to-February and October-to-November 1979–2014 zonal mean zonal wind (grey contours). The 2016 (c) and 2020 (d) deviations from the 1979–2014 average of zonal mean zonal wind (filled contours) together with 2016 and 2020 zonal mean zonal wind (grey contours) from the ERA5 reanalysis as a function of latitude and altitude (filled and black contours). Eliassen–Palm flux (green arrows) is indicative of wave propagation direction and shows wave activity leaving the troposphere near 50° N and entering the tropics near 23 km (40 hPa). The black dashed horizontal line indicates the tropopause from the ERA5 reanalysis. Monthly mean zonal mean wind component,  $U$  ( $\text{m s}^{-1}$ ), from the ERA5 reanalysis is overlaid as solid grey contours (westerly) and dashed grey contours (easterly) lines. The solid thick grey line indicates the zero zonal wind.



**Figure 2.** Zonal mean deseasonalized stratospheric H<sub>2</sub>O (a, b) and O<sub>3</sub> (c, d) anomalies from MLS satellite observations for the respective period in the years 2016 (a, c) and 2020 (b, d) period in percent change from long-term monthly means as a function of time and altitude and calculated as a deviation from the 2005–2014 zonal mean stratospheric H<sub>2</sub>O and O<sub>3</sub> mixing ratios. The black dashed horizontal line indicates the tropopause from ERA5. Monthly mean zonal mean wind component,  $U$  ( $\text{m s}^{-1}$ ), from ERA5 is overlaid as solid grey (westerly wind) and dashed grey (easterly wind) contour lines.



**Figure 3.** Time series of the anomalous monthly mean tropical net wave forcings (NetF) (a), planetary wave drag (PWD) (b) and gravity wave drag (GWD) (c) drag time series from ERA5 for the 2013–2020 period as a function of time and altitude. The anomalies are calculated as a deviation from the 2005–2014 zonal mean NetF, PWD and GWD. The vertical grey dashed lines indicate February 2016 and January 2020 for the QBO disruption onset and December 2016 and November 2020 for the QBO disruption offset. The lowermost panel shows the QBO index at 50 hPa (21 km) in red. Monthly averaged zonal mean zonal wind component,  $U$  ( $\text{m s}^{-1}$ ), from ERA5, is overlaid as solid grey contours (westerly) and dashed grey contours (easterly) lines.



**Figure 4.** 20° S–20° S Latitude-Longitudinal variations of the monthly mean Outgoing Longwave Radiation (OLR) anomalies (a, b) for the years 2016 (a, c) and 2020 (b, d) period together with the impact of the QBO disruption events in 2016 and 2020 (c, d) associated with the convective activity derived from the multiple regression fit. Monthly averaged zonal mean zonal wind component,  $U$  ( $\text{m s}^{-1}$ ), from ERA5, is overlaid as solid gray contours (westerly) and dashed grey contours (easterly) lines.