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Quasi-Biennial Oscillation Influence on Tropical Convection and El Niño Variability

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Key Points:

- The Quasi-Biennial Oscillation (QBO) modulates climatological upper-tropospheric divergence over the Maritime Continent
- The westerly QBO phase accentuates the weakening of the Walker circulation during developing El Niño events
- The QBO state could improve El Niño prediction and projection

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The Quasi-Biennial Oscillation (QBO) of descending zonal winds is the leading mode of tropical stratospheric variability. Numerous studies have explored its connection with the troposphere, including its sensitivity to El Niño-Southern Oscillation (ENSO). While it is accepted that an upward ENSO impact on the QBO exists, little investigation has been devoted to the potential downward influence of the QBO. Observational and model evidence show that the QBO modulates upper-tropospheric divergence, with reduced outflow over the Maritime Continent during the westerly phase. It can also impact the warm phase of ENSO, El Niño, characterized by a weakened Walker circulation. Results show that the westerly phase of the QBO further suppresses tropical convection in the western Pacific and thus accentuates the weakening of the Walker circulation during El Niño. These results suggest that considering the QBO state could improve El Niño prediction and projection, particularly for extreme events.

Plain Language Summary

The El Niño-Southern Oscillation (ENSO) is a mode of large-scale ocean-atmosphere variability in the tropical Pacific with global impacts. El Niño, the positive phase of ENSO, occurs when the trade winds and the zonal Walker circulation over the Pacific Ocean weaken. On the other hand, the Quasi-Biennial Oscillation (QBO) consists of alternating westerly and easterly winds that descend from the upper stratosphere and dissipate upon reaching the tropopause. In our analysis, we first found that the westerly QBO phase reduces the climatological outflow of tropical convection over the Maritime Continent. We then observed that when an El Niño event coincides with the westerly QBO phase in the lower stratosphere, the reduced outflow over the Maritime Continent leads to a further weakening of the Walker circulation. Accounting for this modulation of the zonal tropospheric circulation by the QBO could enhance the accuracy of El Niño prediction and projection.

1. Introduction

The El Niño-Southern Oscillation (ENSO) is a coupled climate phenomenon that constitutes the major source of interannual variability in the troposphere. Its oceanic component is an irregular oscillation in sea surface temperature (SST) across the central-eastern equatorial Pacific (Chang & Battisti, 1998), whose anomalies generally develop in boreal summer (JJA) and peak in boreal winter (DJF). The warm (cold) phase, defined by positive (negative) SST anomalies, is known as El Niño (La Niña). The atmospheric component, termed the Southern Oscillation, is characterized by a seesaw in sea level pressure between the tropical eastern and western Pacific that controls the intensity of the trade winds over the basin (C. Wang and Picaut, 2004). The Southern Oscillation also modulates deep convection over the Indo-Pacific region and is strongly tight to the strength of the Walker circulation, the zonal atmospheric circulation in the equatorial Pacific. Bjerknes was the first to identify a connection between the two ENSO components (Bjerknes, 1966, 1969). He postulated a positive ocean-atmosphere feedback involving low-level trade winds in the Walker circulation, SSTs and equatorial upwelling that amplifies the initial SST and wind anomalies. This positive feedback can eventually lead the equatorial Pacific to a full-blown El Niño (La Niña).

The most powerful El Niños, called super El Niños (Chen et al., 2015), feature intensified eastern Pacific warming and an eastward expansion of the warm-pool (Takahashi & Dewitte, 2016). These rare events, with only three in the past 70 years (L'Heureux et al., 2017; Santoso et al., 2017), are constraint by "self-limiting" ENSO dynamics and by the seasonal SST cooling during summer and autumn (SON), that is, the development of the cold tongue (Hameed et al., 2018; Wallace et al., 1989). Their existence, therefore, requires external factors that must be effective during the seasonal cooling and should act to reinforce the positive Bjerknes feedback over the cold tongue (Hameed et al., 2018). Based on observations and model simulations, it has been suggested that a super El

Niño can emerge if an early onset El Niño coincides with an Atlantic La Niña in summer and a positive Indian Ocean Dipole in autumn. The combined remote influence of these ocean-atmosphere interactions is termed the "Indo-Atlantic booster" (J. Z. Wang and Wang, 2021). A Southern Hemisphere booster in the Indo-Pacific region has also been suggested as a potential factor (Hong et al., 2014).

The leading mode of tropical stratospheric variability on interannual timescales is the Quasi-Biennial Oscillation (QBO). Previous studies have shown that the QBO can modulate tropical deep convection (García-Franco et al., 2022; Liess & Geller, 2012; Nie & Sobel, 2015; Serva et al., 2022), particularly that associated with the Madden-Julian oscillation (Klotzbach et al., 2019; Martin et al., 2021). However, there is no clear understanding of the mechanism controlling this downward QBO impact. Different hypotheses have been proposed involving static stability in the upper troposphere-lower stratosphere (UTLS; Collimore et al., 2003; Liess & Geller, 2012; Nie & Sobel, 2015), vertical wind shear (Collimore et al., 2003; Gray et al., 1992b), Walker modulation (García-Franco et al., 2022, 2023) and cloud-radiative effects (García-Franco et al., 2023; Nie & Sobel, 2015). Other studies have evidenced that the QBO signal becomes zonally asymmetric in the UTLS, with the largest temperature anomalies being found over regions of active convection, such as the warm pool in the western tropical Pacific and the African continent (Tegtmeier et al., 2020). Likewise, QBO-related zonal wind anomalies in the UTLS exist only in the eastern hemisphere, with maximum prominence in summer (Yang et al., 2012), coincident with the onset/growing phase of ENSO.

While it is well-known that ENSO affects the strength and fluctuations of the stratospheric circulation in both the tropics (Geller et al., 2016; Randel et al., 2009), including the QBO (Christiansen et al., 2016; Maruyama & Tsuneoka, 1988; Taguchi, 2010; Yuan et al., 2014), and extratropics (Anstey et al., 2022; Domeisen et al., 2019), little investigation has been devoted to the downward influence of the QBO on El Niño (Yasunari, 1989). Only one mechanism has been proposed involving a meridional redistribution of convection in the warm pool in response to QBO-induced changes in vertical wind shear, such that during the easterly phase, the surface pressure and circulation anomalies are conducive to El Niño (Gray et al., 1992a).

In this study, we separately evaluate the downward QBO influence on the mean state and El Niño-related variability of tropospheric circulation, using several observational data sets and simulations from a state-of-the-art global climate model (GCM). Targeted experiments are conducted to isolate the impact of mean-flow conditions in the lower stratosphere. We focus on JJA, a key season for El Niño development and preconditioning of super El Niño events, which we also examine. Additionally, summer is when the QBO signal in the UTLS is strongest.

2. Data and Methods

2.1. Reanalyses and Observations

This study employs monthly wind and temperature data at different vertical levels from the three longest reanalysis products: the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 Reanalysis (Hersbach et al., 2020); the NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996); and the Japanese 55-year Reanalysis (Kobayashi et al., 2015). Here, we only report results from ERA5, referred to as "reanalysis", due to its consistency with results from JRA-55 and NCEP/NCAR (available in the Figures S1 and S2 of Supporting Information S1). SST data from the Hadley Center Sea Ice and Sea Surface Temperature (HadISST) v1.1 data set (Rayner et al., 2003) are used to characterize El Niño variability. The Extended Reconstructed Sea Surface Temperature (ERSST) v5 data set provides almost identical results (not shown). The period considered is from 1950 (1958 for JRA-55) to 2021 and all anomalies have been linearly detrended before analysis.

2.2. Model and Simulations

The GCM used in this study is the European Consortium Earth-system (EC-EARTH) model version 3.1 (Christiansen et al., 2016). Three 100-year-long experiments, after 30 years of spin up, with different vertical configurations in the atmosphere are compared. The radiative forcing in all experiments is fixed at a forcing representative of present climate, that is, year 2000. The standard configuration is a high-top experiment (HIGH-TOP or HT) with the top at 0.01 hPa and 91 vertical levels. It is the only experiment that generates a realistic QBO in terms of period and amplitude as discussed in Davini et al., 2017 and Palmeiro et al., 2020 (cf. Figures S3 and S4 in Supporting Information S1). In the second configuration, the stratosphere is degraded to only 62 vertical levels and top at 5 hPa (LOW-TOP or LT). This low-top version does not simulate QBO variability. The third one is a high-top configuration with the tropical stratospheric circulation [30°N–30°S] nudged to the climatology of HIGH-TOP from 50 hPa upwards (hereafter NUDGED). Note that only vorticity and divergence are nudged, leaving temperature and humidity free to adjust. In NUDGED, the tropical stratospheric variability is artificially suppressed, including the QBO (Figure S5 in Supporting Information S1). Whereas LOW-TOP simulates permanent zonal-mean easterlies in the lower stratosphere (Figure S6 in Supporting Information S1 and Palmeiro et al., 2020), NUDGED yields permanent zonal-mean weak westerlies at 50 hPa. These two experiments are used as proxies for the QBO phases in terms of their zonal wind anomalies in the lower stratosphere, that is the climatological difference between them (NUDGED minus LOW-TOP) is interpreted as a proxy QBO westerly-minus-easterly (W–E) phase composite.

2.3. ENSO and QBO Definition

ENSO is characterized by using the DJF ONI index (Trenberth & Stepaniak, 2001), a 3-month running mean of SST anomalies in the Niño-3.4 region (5°N–5°S, 120°W–170°W). An ONI index threshold of +1 K anomaly is used for El Niño composite analysis. With this threshold, there are 13 El Niños in observations, 15 in HIGH-TOP, 14 in LOW-TOP and 19 in NUDGED. When the El Niño composite is stratified into QBO phases in observations and HIGH-TOP, more sampling is needed, and the threshold is reduced to +0.5 K anomaly. With this new threshold, there are 25 El Niños in both observations and HIGH-TOP.

The QBO is characterized using zonal-mean zonal wind at 50 hPa (Schenzinger et al., 2017), which is the lowest stratospheric level with a distinc QBO signal (Figures S3 and S4 in Supporting Information S1) but no statistically significant ENSO signal in both reanalysis (Figure S7a in Supporting Information S1) and EC-EARTH (Figure S7b in Supporting Information S1). A threshold of ±0.75 standard deviations is used to define the westerly and easterly QBO phases in ERA5 and HIGH-TOP for the QBO composite analysis, focusing on the JJA season as explained below. With this threshold, there are 24 westerly and 19 easterly phases in ERA5 (Figure S8a in Supporting Information S1) and 33 and 32 in HIGH-TOP (Figure S8b in Supporting Information S1). However, the results are qualitatively independent of the selected threshold (Figure S9 in Supporting Information S1).

The QBO definition has to be adjusted when subsampling El Niño years into QBO phases, because the sampling is reduced and the QBO phases are not always constant during the development seasons of an El Niño event (JJA and SON; cf. Figures S8a–S8d in Supporting Information S1). Thus, a westerly (easterly) QBO phase is defined when there is either a constant westerly (easterly) phase or a transition toward a westerly (easterly) phase during El Niño development seasons. All El Niño events are classified according to this adjusted definition. In ERA5, the 25 El Niño events are divided into 12 westerly and 13 easterly phases (Figure S8c in Supporting Information S1), while in HIGH-TOP, they are divided into 10 westerly and 15 easterly phases (Figure S8d in Supporting Information S1).

2.4. Statistical Significance

When comparing composites, a two-tailed *t*-test is used to evaluate the null hypothesis that two independent samples have equal means, assuming identical population variances. Additionally, and to assess robustness, a two-tailed bootstrap test of equal means is also conducted, which does not assume any specific distribution. The main results using both tests are very similar (Figure S10 in Supporting Information S1). The probability that the null hypothesis can be rejected is assessed at 95% confidence level for all statistical tests.

3. Results

3.1. Simulation of El Niño Variability

The model representation of El Niño is first evaluated during its peak season, DJF. In observations, the defining feature of El Niño is a broad region of positive SST anomalies in the central-eastern tropical Pacific (contours in Figure S11a of Supporting Information S1; C. Wang and Picaut, 2004). These anomalies spread along the coast into the subtropical latitudes of both hemispheres and are surrounded by horseshoe-shaped negative anomalies that extend from the warm pool to the extratropics. EC-EARTH (in its standard configuration) simulates this SST pattern (Figure S11a in Supporting Information S1; Haarsma et al., 2020), although the warming extends too far into the western tropical Pacific, a common bias in GCMs (Guilyardi et al., 2009; Planton et al., 2021).

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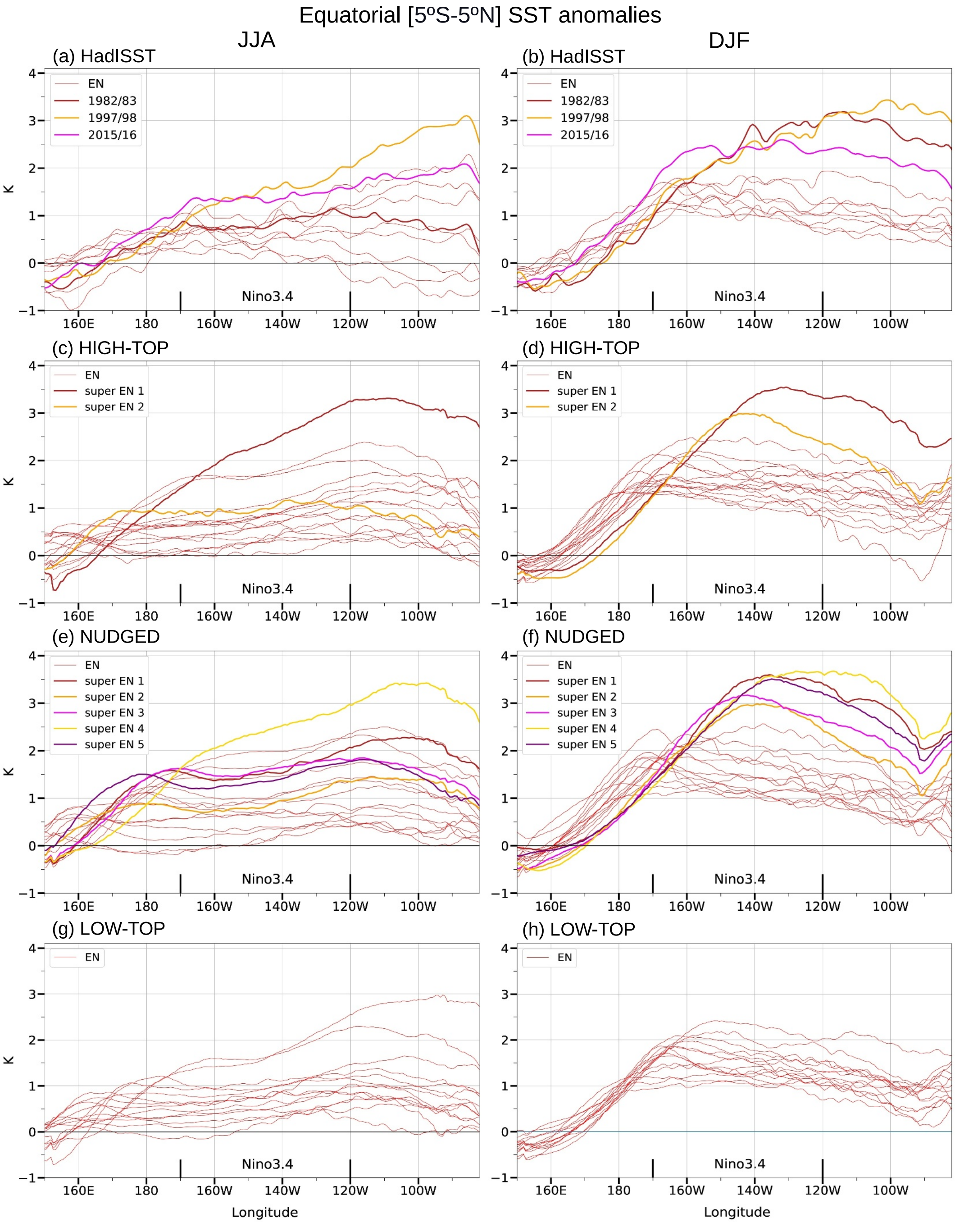

Figure 1. Observed and simulated equatorial SST (K) anomalies during El Niño events in JJA and DJF. HadISST (a, b), HIGH-TOP (c, d), NUDGED (e, f) and LOW-TOP (g, h). El Niño events are defined by a 1 K anomaly in the ONI DJF index, with super El Niño events highlighted.

Individual observed El Niños are examined via spaghetti plots of equatorial Pacific SST anomalies in Figure 1b. Positive anomalies above 1 K are seen over the Niño-3.4 region (by construction) that weaken and become zero west of the dateline. Three exceptional events with anomalies exceeding 2 K can be identified—the well-known super El Niños of 1982/83, 1997/98 and 2015/16 (Hong et al., 2014). The corresponding plot for the standard configuration (HIGH-TOP) is shown in Figure 1d: the model bias can be seen again around the dateline, where several simulated events exceed the 1 K anomaly. Nonetheless, EC-EARTH does simulate super El Niños, with two events standing above the rest in HIGH-TOP. Five super El Niños can also be seen in NUDGED (permanent lower stratospheric westerlies; Figure 1f). However, no super El Niño events are observed in LOW-TOP (permanent easterlies; Figure 1h). A similar identification can be done using precipitation anomalies (Figure S12 in Supporting Information S1).

The model representation of El Niño is also assessed in JJA, a key season for El Niño development (Hong et al., 2014; Takahashi & Dewitte, 2016). The observed composite shows warm anomalies over the central-eastern tropical Pacific (contours in Figure S11b of Supporting Information S1) but weaker than in DJF. EC-EARTH correctly captures this pattern, although with the same warm bias west of the dateline as in winter (Figure S11b in Supporting Information S1). In the SST spaghetti plots for summer (Figures 1a, 1c, 1e and 1g), only one super El Niño is identifiable ahead of the mature phase in winter, while the other events are unremarkable in both observations and the model at this time. In LOW-TOP, events as strong as those in other experiments are present in JJA but fail to grow toward DJF, suggesting that some factor may modulate super El Niño events between summer and winter.

Overall, the El Niño spatial pattern and temporal evolution are well simulated in EC-EARTH during both summer and winter, which allows investigating the potential influence of the stratosphere.

3.2. The QBO Impact on the Upper Troposphere-Lower Stratosphere (UTLS)

Before addressing the impact of the QBO on El Niño, its impact on the summertime UTLS and troposphere is examined, analyzing the downward influence of the QBO in reanalysis and the three EC-EARTH simulations. Longitude-height W-E QBO composites of equatorial zonal wind and temperature are shown in Figure 2.

Consistent with our chosen phase definition of the QBO, there are zonally symmetric westerly anomalies at around 50 hPa, with easterlies above (Figure 2a). These zonal wind anomalies and the associated temperature anomalies are in thermal-wind balance, with anomalous warm (cold) conditions below the maximum westerlies (easterlies) (Andrews et al., 1987; Garfinkel & Hartmann, 2011; Plumb & Bell, 1982). Hence, the QBO temperature signal reaches the UTLS before the QBO zonal wind signal.

In agreement with previous studies (Tegtmeier et al., 2020; Yang et al., 2012), the observed QBO signal at the UTLS, between 70 and 150 hPa, is not zonally symmetric. In particular, westerly winds and warm anomalies extend further downward between 60°E–120°E, over the Maritime Continent region (Figure 2a). In the troposphere, the QBO related anomalies vanish.

The W-E QBO composite in HIGH-TOP (Figure 2b) resembles the observed pattern, exhibiting zonal wind anomalies that are also not zonally symmetric in the UTLS. The comparison of climatology between NUDGED and LOW-TOP (Figure 2c) displays differences primarily in the UTLS, where NUDGED shows a warmer and more westerly mean state than LOW-TOP; in particular, it also reproduces the zonal asymmetry over the Maritime Continent. The similarity of these differences with the W-E differences observed in reanalysis and HIGH-TOP strongly supports the interpretation of NUDGED minus LOW-TOP as a proxy W–E composite.

The analysis in Figures 2a–2c suggests that the QBO signal in the UTLS is not zonally symmetric in terms of temperature and the total zonal wind field. To further explore this zonal asymmetry, we focus on the anomalous divergent circulation. First, Figure 3d presents the JJA climatological upper-level (100 hPa) velocity potential at the Equator (see also Figure S13a in Supporting Information S1). The reanalysis reveals a global-scale dipole pattern, with upper-level divergence over the central-western tropical Pacific and upper-level convergence over the rest of the tropical belt. This divergence is related to deep convection in the Maritime Continent and south-eastern Asia during the monsoon season (Figure S13b in Supporting Information S1; Meenu et al., 2010). The model climatology displays a similar pattern (see also Figure S14 in Supporting Information S1, which includes HIGH-TOP), but with a biased, larger amplitude, as the maximum amplitude in reanalysis occurs at a lower level (~150 hPa; see Figures S15a and S15b in Supporting Information S1).

The W–E composite in both reanalysis (Figure 3a) and HIGH-TOP (Figure 3b) displays a weakening of the climatological dipolar pattern (Figure 3d), with reduced upper-level divergence over the Maritime Continent (positive anomalies) and compensating reduced convergence over the Indian Ocean and Tropical Atlantic (negative anomalies). Interestingly, the climatological difference between NUDGED and LOW-TOP, the proxy for a permanent W–E state, yields a similar pattern (Figure 3c). This result provides additional evidence that the sign of the zonal-mean zonal wind in the lower stratosphere modulates the strength of the upper-tropospheric

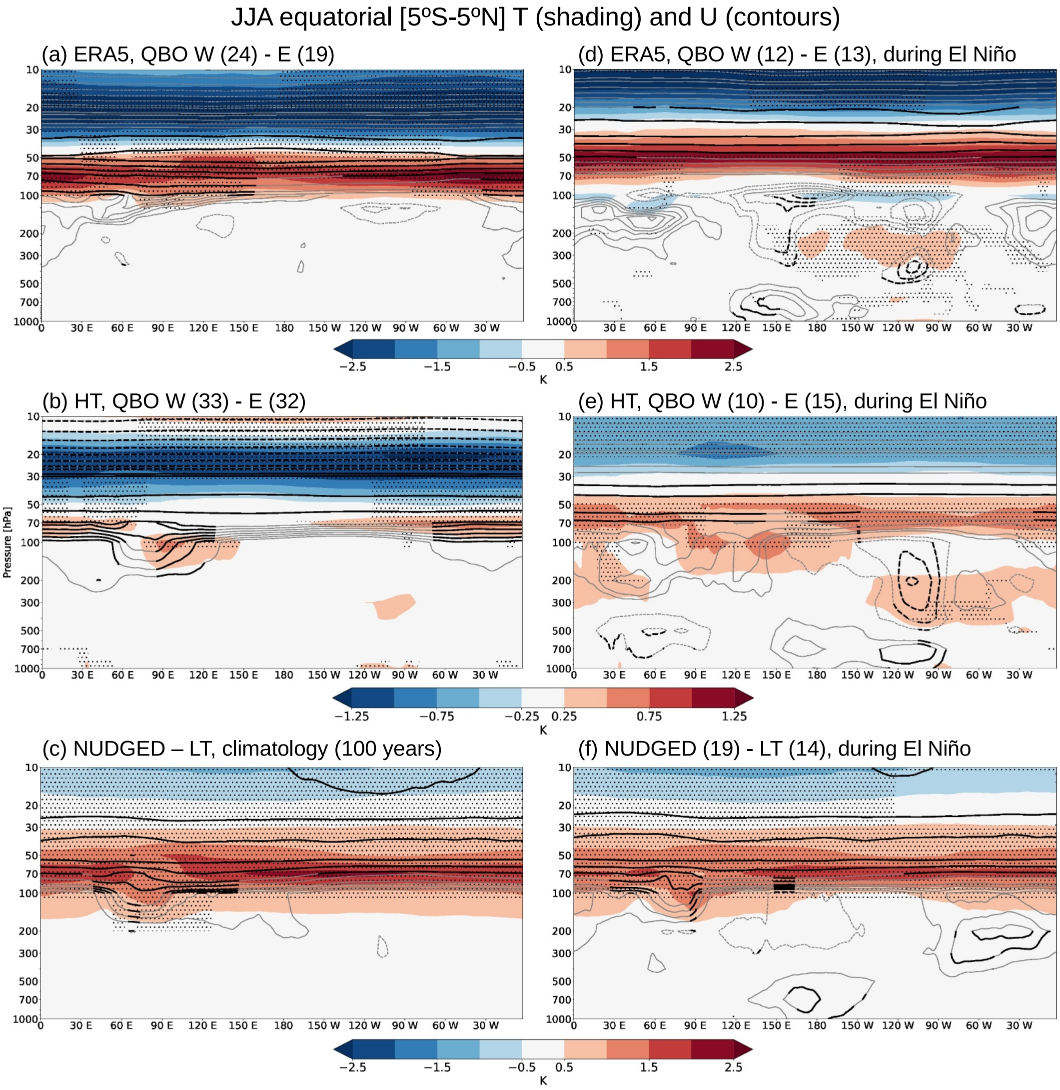

Figure 2. JJA QBO signal in equatorial temperature (shading, K) and zonal wind (contours, m s^{-1}). (a, b) Composite differences between westerly (W) and easterly (E) QBO phases in ERA5 (a) and HIGH-TOP (HT) (b). (c) NUDGED minus LOW-TOP (LT) climatology. (d, e) Composite differences between W and E QBO phases during El Niño events in ERA5 (d) and HT (e). (f) NUDGED minus LT composite of El Niño events. Contours are drawn every 0.5 m s^{-1} below 70 hPa and every 4 m s^{-1} above. Numbers in parentheses indicate the number of QBO events included in the composites. Statistically significant differences in temperature and zonal wind are indicated with dots and bold contours, respectively.

divergence over the Maritime Continent. A similar, albeit less pronounced, signal is found in other seasons (Figure S16 in Supporting Information S1), consistent with convection in the Maritime Continent being strongest and deepest in summer. However, even for JJA, the QBO signal is limited to the UTLS, with no statistically significant differences observed in the troposphere or SST (Figures 2a–2c and Figure S17 in Supporting Information S1).

3.3. The QBO Modulation of the Tropospheric Circulation During El Niño

Results suggest no direct QBO impact on the mean middle-lower tropospheric circulation, which aligns with the weak statistical significance of the QBO signal in precipitation reported previously (Collimore et al., 2003; Liess & Geller, 2012; Nie & Sobel, 2015). However, it does not exclude the possibility of the QBO having an impact on the variability (e.g., El Niño), an issue that has not been investigated in depth.

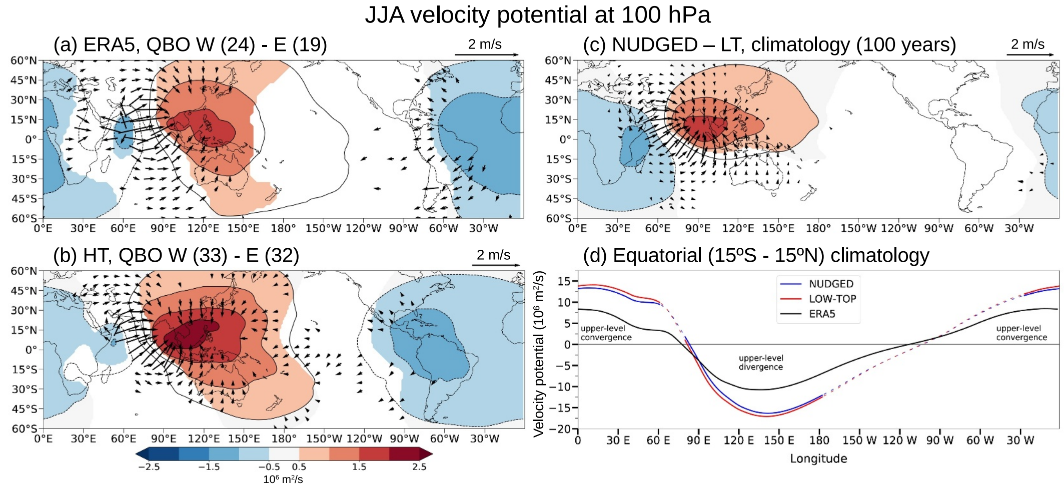

Figure 3. JJA QBO signal in velocity potential (shading and contours, 10^6 m^2 s^{-1}) at 100 hPa. (a, b) Composite differences between westerly (W) and easterly (E) QBO phases in ERA5 (a) and HIGH-TOP (HT) (b). (c) NUDGED minus LOW-TOP (LT) climatology. Statistically significant differences in velocity potential and divergent wind (vectors, m s^{-1}) are shaded and plotted, respectively. (d) Velocity potential climatology averaged over equatorial latitudes. HT is not included as it closely matches NUDGED (see Figure S14 in Supporting Information S1). Solid (dashed) lines represent longitudes where NUDGED minus LT is (not) significantly different.

The observed and simulated El Niño events are subsampled into westerly and easterly QBO composites (see Section 2.3). In both reanalysis and HIGH-TOP, during El Niño events coinciding with a westerly phase, compared to an easterly phase, there is anomalous upper-level convergence over the Maritime Continent-Indian Ocean (Figures 4a and 4c) together with anomalous lower-level divergence (Figures 4b and 4d). Since El Niño is already associated with reduced upper-level outflow and lower-level inflow in this region (Chang & Battisti, 1998; C. Wang and Picaut, 2004; Figure S18 in Supporting Information S1), these findings suggest that the effect of the westerly QBO phase is to further weaken the Walker circulation. This result is supported by the comparison of El Niño composite between NUDGED and LOW-TOP simulations in Figures 4e and 4f: under mean westerly flow conditions in the lower stratosphere, tropical convection over the Maritime Continent-Indian Ocean is further suppressed during an El Niño (less divergence aloft and less convergence below), implying an additional weakening of the Walker circulation.

This summertime QBO signal in the divergent component of tropospheric variability is equally found in the rotational component, via analysis of streamfunction and rotational wind (not shown). The total wind field reflects this QBO-El Niño impact on upper-level convergence (lower-level divergence) in the tropical Pacific with anomalous easterlies (westerlies) at upper levels (lower levels) (Figures 2d–2f). Surface winds also exhibit this QBO impact, showing enhanced anomalous westerlies (Figure S19 in Supporting Information S1); indicating that the QBO state could affect the strength of El Niño. These results indeed suggest that the westerly QBO phase during summer could add to the Indo-Atlantic Booster (J. Z. Wang and Wang, 2021) as another potential predictor for super El Niño events.

In autumn and winter, the Walker circulation remains further weakened during a westerly QBO phase, but the differences are smaller and shifted eastward compared to summer (see Figure S20 in Supporting Information S1 for SON); the latter consistent with El Niño seasonal evolution. However, unlike in summer, the differences between QBO phases in these seasons, particularly in winter, are highly influenced by the super El Niños themselves (e.g., Figure S21 in Supporting Information S1 shows SSTs in DJF with and without super El Niños).

4. Discussion and Conclusions

Our approach separately evaluates the downward QBO influence on the mean state and El Niño-related variability of tropospheric circulation. Observational and model results show that the QBO impact on the mean state is restricted to the UTLS. The lowest level with a significant signal is found at around 100 hPa over the Maritime Continent, where the strength of upper-tropospheric divergence is reduced during the westerly QBO phase.

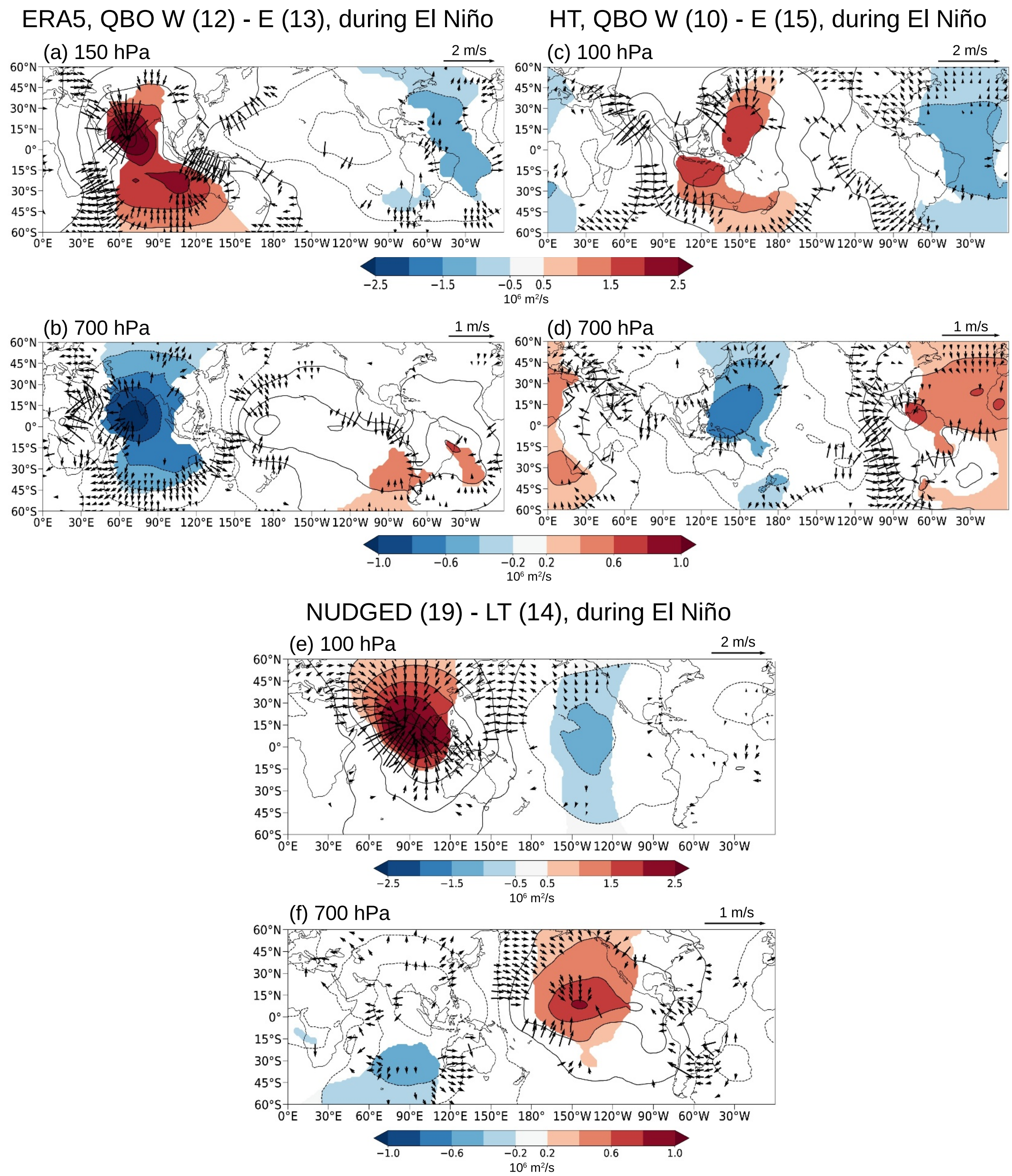

Figure 4. QBO modulation of the tropospheric divergent circulation in JJA during El Niño events. (a, b) Composite differences between westerly (W) and easterly (E) QBO phases of velocity potential (shading and contours, 10^6 m^2 s^{-1}) and divergent wind (vectors, m s^{-1}) in ERA5 for the upper (a) and lower (b) troposphere. (c, d) Same as (a, b), but for HIGH-TOP. (e, f) Same as (a, b), but for NUDGED minus LOW-TOP composite of El Niño events. Note that for reanalysis, a different level in the upper troposphere is considered with respect to EC-EARTH (150 hPa instead of 100 hPa) due to maximum amplitude occurring at different levels (see Section 3.2; Figure S15 in Supporting Information S1). Statistically significant differences in velocity potential and divergent wind are shaded and plotted, respectively.

However, during El Niño, we observe a much deeper impact, characterized by either a dampening or a reinforcement of the anomalous zonal circulation, depending on the QBO phase. Under westerly flow conditions in the lower stratosphere, there is more suppressed tropical convection over the Maritime Continent-Indian Ocean and a further weakening of the Walker circulation, primarily in summer. At surface, this westerly QBO signal shows enhanced anomalous westerlies over the central-eastern Pacific basin (Figures 2d–2f and Figure S19 in Supporting Information S1). This further weakening of the trade winds could help overcome the “self-limiting” ENSO dynamics and the seasonal SST cooling in the tropical Pacific, thereby increasing the likelihood of super El

Niños, complementing previous studies pointing at other precursors (Hameed et al., 2018; Hong et al., 2014; J. Z. Wang and Wang, 2021).

In support of this hypothesis, it is worth noting that the three observed DJF super El Niños (Figure 1a) coincide with a JJASON westerly QBO phase (Figures S22a and S22b in Supporting Information S1; see Section 2.3 for the definition of the QBO phases during El Niño events). Similarly, the two simulated super El Niños in HIGH-TOP (Figure 1b) also occur during a JJASON westerly QBO phase (Figures S22c and S22d in Supporting Information S1). Additionally, and maybe most revealing, there are no super El Niño events in LOW-TOP (permanent easterlies), while five occur in NUDGED (permanent westerlies) (Figures 1c and 1d), a result extremely unlikely according to a binomial distribution.

While the precise mechanism of the QBO influence on El Niño is not clear, our results suggest that westerly winds in the lower stratosphere accentuate the weakening of the Walker circulation during summer and autumn preceding El Niños in winter (Figures 2d–2f). These findings underscore the importance of considering the QBO state to improve El Niño prediction and projection, particularly for extreme events.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

We have used publicly available data. Three-dimensional wind and temperature data from ERA5 are available at Hersbach et al. (2023) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). For the same variables, we have also used NCEP-NCAR Reanalysis 1 data provided by the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory (PSL), Boulder, Colorado, USA, from their website at https://psl.noaa.gov (Kalnay et al., 1996) and the Japanese 55-year Reanalysis available at Kobayashi et al. (2015; https://jra.kishou.go.jp/JRA-55/index_en.html). SST data from HadISST v1.1 is available at Rayner et al. (2003; https://www.metoffice.gov.uk/hadobs/hadisst/); SST data from ERSST v5 is provided by the NOAA-PSL from their website at https://psl.noaa.gov (Kalnay et al., 1996). Precipitation data from ERA5 is also available at Hersbach et al. (2023) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). The computations of the velocity potential (associated with the divergent component of the wind) and the streamfunction (associated with the rotational component of the wind) used are provided through the **WindSPharm** package (Dawson, 2016) and are available at Dawson et al., 2018.

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Erratum

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