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Influence of the Quasi-Biennial Oscillation on Summer Precipitation in Eastern and Southern Africa

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Abstract

The Quasi-Biennial Oscillation (QBO) is a vital mode of stratospheric variability with significant influence on tropical and subtropical climate systems. However, its influence on precipitation variability across Eastern and Southern Africa remains insufficiently understood. This study examines the impact of the QBO on summer precipitation and associated circulation anomalies over Eastern and Southern Africa from 1979 to 2021. Using ERA5 and NOAA reanalysis datasets, we applied composite and correlation analyses to assess precipitation responses to westerly (WQBO) and easterly (EQBO) phases. Results show a dipole-like pattern, with WQBO linked to enhanced precipitation in both Eastern and Southern Africa, while EQBO is associated with reduced precipitation. Circulation analysis reveals that WQBO phases promote upper-level divergence, low-level moisture inflow, and vertical ascent, whereas EQBO phases enhance subsidence and upper-level convergence. These findings highlight the QBO role in modulating precipitation through stratosphere-troposphere coupling and its interaction with regional circulation patterns. The quasi-periodic nature of QBO offers substantial potential for enhancing seasonal precipitation predictions when integrated with other regional circulations, such as the Botswana High and the Angola Low.

Keywords

The QBO, Precipitation Variability, Eastern and Southern Africa, Circulation Analysis

1. Introduction

The Quasi-Biennial Oscillation (QBO) is a famous mode of atmospheric variability that is characterized by alternating easterly and westerly wind regimes in the equatorial stratosphere, with a mean period of 28 months (Ern et al., 2023; Anstey et al., 2022; Baldwin et al., 2001; Gray et al., 1992; Zhou et al., 2024). The QBO is formed through a complex interaction between atmospheric waves and the mean flow in the equatorial stratosphere. The mechanism begins when vertically propagating atmospheric waves, primarily Kelvin waves and mixed Rossby-gravity waves, generated in the tropical troposphere by deep convection, propagate upward into the stratosphere and encounter the existing zonal wind flow. When the waves reach regions where their phase speeds match the background wind speeds, they become absorbed or break, depositing their momentum into the mean flow through wave-mean flow interaction. This momentum deposition creates acceleration or deceleration of the zonal winds, gradually reversing the wind direction (Baldwin et al., 2001). The process is self-limiting because, as the wind regime changes, it affects which waves can propagate upward and where they deposit their momentum, creating the characteristic downward propagating pattern of alternating wind regimes that defines the QBO.

This phenomenon is confined to the stratosphere, but it interacts with the troposphere and influences convective circulation and hence precipitation and temperature anomalies through different dynamical stratosphere-troposphere coupling mechanisms (Li et al., 2022; Hu et al., 2022; Gao et al., 2023; Hu et al., 2024; Anstey et al., 2022; Garcia-Franco et al., 2022; Gray et al., 1992; Jiang et al., 2024; Hirahara et al., 2025; Ern et al., 2023).

In Africa, the QBO has received limited research attention, particularly Eastern and Southern Africa (ESA), which is also highly vulnerable to precipitation variability (Kekana et al., 2025; Fiwa et al., 2014; de Kock et al., 2021; Berhane & Zaitchik, 2014). Some studies have examined precipitation variability in these two parts of Africa and they showed that it is mainly modulated by large-scale drivers such as El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Intertropical Convergence Zone (ITCZ) and small-scale (local circulation) such as Angola low intensity and Botswana high (Roy & Troccoli, 2024; Zheng et al., 2025; Kekana et al., 2025; Kilavi et al., 2018)

This research addresses a fundamental gap in our understanding of the role of the QBO in ESA precipitation variability. By clarifying this relationship, the study will provide a foundation to understand the link between the QBO, regional circulation and regional precipitation.

Previous studies have reported that the QBO phase can influence different regional precipitation patterns globally, with distinct impacts observed across different regions (Hu et al., 2022; Gray et al., 1992; Jaramillo et al., 2021; Jiang et al., 2024; Liang et al., 2023; Randall et al., 2023; Seo et al., 2013; Takasuka et al., 2024). On a global scale, the QBO influences precipitation patterns by modulating tropical convection, the strength of the Walker circulation, and monsoon systems.

Stratospheric wind anomalies affect the vertical structure of the atmosphere, resulting in fluctuations in large-scale circulation patterns.

In Asia, studies on the QBO impacts on precipitation show that the alternating wind phases affect the intensity and timing of seasonal rainfall, influence the Asian summer monsoon circulation and modulate precipitation variability across the Indian subcontinent, Asia, and Australia (Jiang et al., 2024; Hu et al., 2022; Seo et al., 2013; Takasuka et al., 2024; Liang et al., 2023).

In Europe, the QBO influences manifest through changes in winter circulation patterns, which affect storm tracks across the North Atlantic and modulate temperatures and precipitation through stratosphere-troposphere coupling mechanisms. This, in turn, influences the North Atlantic Oscillation, which impacts weather patterns across Europe (Jaramillo et al., 2021; Gray et al., 1992; Randall et al., 2023).

In Africa, research on the influence of the Quasi-Biennial Oscillation (QBO) remains limited. For instance, a simple correlation analysis by (Ng'ongolo & Smyshlyaev, 2010) demonstrated that East Africa tends to experience wetter conditions during the westerly QBO (WQBO) phase. Expanding the scope to West Africa a study by (Ballo et al., 2022) suggested the existence of a major teleconnection pattern across the continent. This finding underscores the importance of moving beyond simple correlations to study the underlying atmospheric circulation associated with both QBO phases.

Studying how QBO phases induced circulations relate with regional systems like the Congo air mass (CA), the Angola Low (AL) intensity and Botswana High (BH) (Kekana et al., 2025). The primary objective now is to investigate how QBO phases significantly modulate precipitation over ESA, identify the atmospheric circulation anomalies associated with these QBO phases, and determine how precipitation in ESA responds significantly to QBO phases.

2. Data and Methods

The data used are ERA5 reanalysis monthly datasets spanning 42 years, from 1979 to 2021, with pressure levels ranging from 1000 hPa to 10 hPa. The data includes zonal wind, geopotential height, precipitation in mm per day, vertical velocity (omega), the vertical integral water vapor data and meridional wind the resolution of $1^{\circ} \times 1^{\circ}$. The data can be obtained from https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels-monthly-means?tab=download. Outgoing longwave radiation (OLR) from NOAA with a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$ can be obtained through https://www.psl.noaa.gov/data/gridded/data.olrcdr.interp (Chang et al., 2022; Li et al., 2022).

We constructed a seasonal QBO index based on the monthly zonal-mean zonal wind at 50 hPa. First, the monthly wind data from 1979 to 2021 were standardized using the climatological mean and standard deviation. This was done separately for three overlapping seasonal windows: December-February (DJF), January-

March (JFM), and February-April (FMA). For each year, a single seasonal QBO anomaly was calculated by averaging the standardized anomalies from these three windows.

Years where this average seasonal anomaly was greater than positive 1.0 were classified as westerly QBO (WQBO) years, while years where it was less than negative 1.0 were classified as easterly QBO (EQBO) years. Using this criterion, we identified 12 years for each phase during the 1979-2021 period: WQBO years (1979, 1981, 1987, 1989, 1994, 1996, 1998, 2000, 2010, 2014, 2016, 2020) and EQBO years (1980, 1985, 1990, 1993, 1995, 1997, 1999, 2002, 2004, 2006, 2008, 2019).

To analyze the relationship, we defined a new precipitation index by grouping months into seven seasons: ASO (August-October), SON (September-November), OND (October-December), NDJ (November-January), DJF (December-February), JFM (January-March), and FMA (February-April). A lead-lag correlation analysis between each QBO index and the precipitation index revealed that the DJF QBO index had the strongest correlation with the DJF precipitation index. Therefore, the DJF months were chosen as the representative.

To study the influence of the QBO on precipitation, we began by quantifying the link between the two variables. This was achieved by computing grid-point Pearson correlations between the DJF QBO index, representing standardized 50 hPa zonal wind, and concurrent precipitation anomalies.

Secondly, we conducted composite analysis for precipitation, winds, moisture flux, and OLR for WQBO and EQBO years. The WQBO–EQBO difference field isolates the QBO-forced signal and is spotted where the student's t exceeds the 95% threshold. Before each step above, the linear influence of the Indian Ocean Dipole (IOD) is removed by regressing each field onto the Dipole Mode Index (DMI) and retaining the residual.

$$A_{DMI} = A^{*}\left(DMI\right)\times\frac{cov\left(A, DMI\right)}{var\left(DMI\right)}$$

Where A_{DMI} is the remaining field after the removal of the IOD in a meteorological field. A^* is the original meteorological element field (precipitation, wind velocity and geopotential height), cov is the temporal covariance of the IOD and original meteorological fields A, and var is the variance of the IOD.

The resulting correlations and composites reflect pure QBO effects without simultaneous IOD forcing. These two processes, correlation and QBO-phase compositing after prior removal of another mode, have been adopted in several recent QBO studies (Hu et al., 2022; Jiang et al., 2024). This guide confirms that the combination of linear correlation, phase compositing, and prior removal of overlapping SST modes (IOD in our case) is a well-established and robust method for extracting the QBO signal from noisy precipitation records.

3. Precipitation Cycle

Precipitation cycle in ESA is significantly related; a large part of Eastern Africa

(EA) experiences a bimodal precipitation cycle, with the principal peaking in March-May and a secondary short rain peak in October-December (Makula & Zhou, 2022; Nicholson, 2017; Babaousmail et al., 2023; Nicholson, 2017). However, much of Southern Africa (SA) experiences a single, unimodal summer wet season that peaks between December and February and is followed by a long May to September dry season (Awala et al., 2019; Dieppois et al., 2019; Engelbrecht et al., 2023). Building on this seasonal description, we extracted QBO indices and investigated their relationship to ESA summer precipitation.

Figure 1(a) illustrates the annual precipitation cycle for ESA, characterized by a unimodal wet season that peaks during DJF (Awala et al., 2019). To capture the stratospheric QBO signal during this peak rainy period, we constructed a unified DJF QBO index. Notably, although this index is based on ESA's seasonality, it also reveals robust teleconnection patterns with precipitation variability in both EA and SA. This suggests a persistent stratospheric influence, involving atmospheric coupling mechanisms that allow the QBO to modulate climate beyond the DJF season itself.

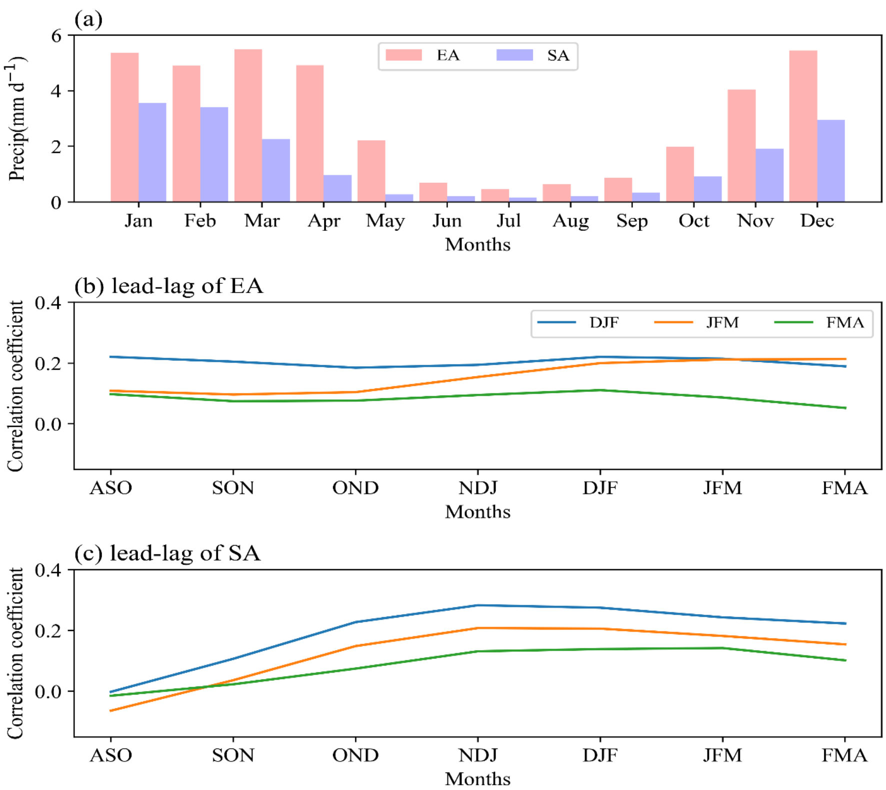

Figure 1. (a) Annual cycle of mean monthly precipitation (mm day^{-1}) averaged over (EA) and (SA) for 1979 - 2021. (b) Lead-lag correlations between the QBO index and EA precipitation for DJF, JFM and FMA. (c) As in (b) but for SA precipitation. Positive lags indicate that the QBO leads precipitation at a 95% confidence level.

The influence of the QBO on precipitation is seasonally phased, as quantified by the lead-lag correlations in Figure 1(b) and Figure 1(c). These figures reveal that the DJF QBO index is significantly linked not only to concurrent rainfall but also to subsequent precipitation. For SA, the correlation with subsequent precipitation is notable (positive 0.35). For EA, the DJF QBO exhibits strong cross-seasonal coherence, showing a significant correlation with precipitation in the following months (positive 0.3). This highlights that ESA precipitation anomalies are most sensitive to the QBO during the DJF season, a critical period when stratospheric-tropospheric interactions reach optimal coherence.

4. Results

4.1. The QBO Influence on DJF Precipitation in ESA

The correlation analysis in Figure 2(a) exhibits a dipole-like response to QBO phases over the study area. Positive correlation between DJF QBO indices and DJF precipitation indices over parts of EA and SA (areas within blue boxes), indicating that WQBO years tend to have above-normal precipitation, while EQBO years are drier (below normal precipitation).

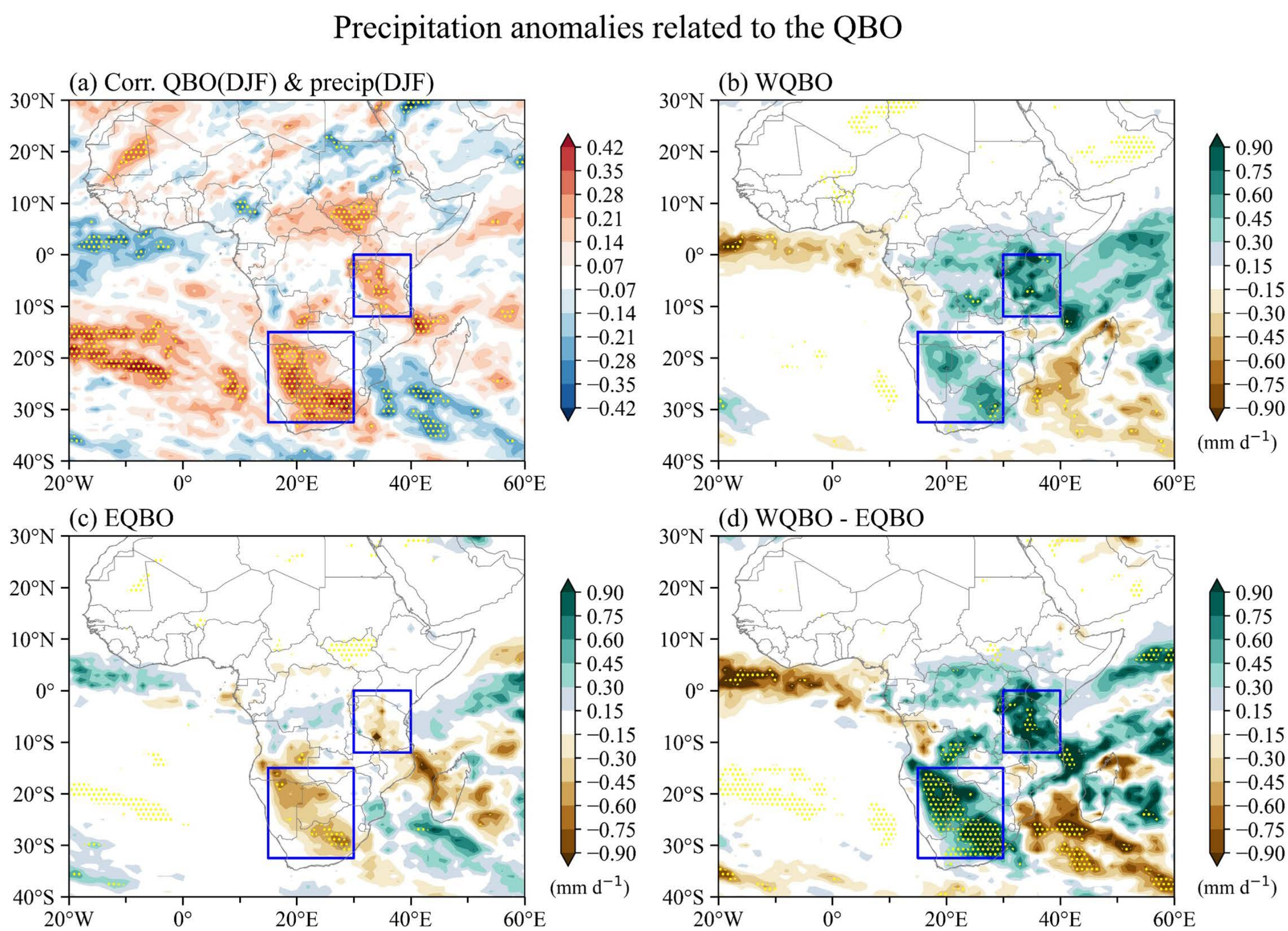

Figure 2. (a) Correlation between DJF precipitation and the QBO index at 50 hPa. (b) Composite precipitation anomalies (mm day^{-1}) during westerly WQBO. (c) Same as (b) but for EQBO (d). Difference between WQBO and EQBO composites. Stippling indicates regions significant at the 95% confidence level (two-tailed Student's t-test). Blue boxes highlight EA (top) and SA (bottom) study domains.

Composite analysis supports this finding. Figure 2(c) shows an increase in DJF precipitation across the study domain. While individual phase composites, such as WQBO or EQBO, alone are more variable, the difference field aligns well with the correlation pattern, confirming that the QBO influence is best captured by comparing the two phases.

To understand well the underlying physical mechanism too, we analyzed 200 hPa, 500 hPa 700 hPa and 850 hPa winds pattern and vertical motion, and the WQBO-EQBO composite shows enhanced low level easterly flow across the Indian Ocean, increased convergence over the Congo Basin and reduced subsidence over the Kalahari These changes weaken the AL which shifts westward enhancing onshore flux of Indian Ocean moisture toward the ESA.

Alongside, the BH, mid-tropospheric anticyclone that caps convection over the Kalahari weakens and moves southeastward, allowing the uplifted air mass to spill southward (Kekana et al., 2025). The result is a coherent precipitation surplus in the area south of 20˚S, which corresponds precisely to where the correlation map shows the strongest positive signal.

The spatial organization is consistent with the QBO modulation of deep convection in the tropics and the restructuring of moisture convergence on a regional scale, as shown by several studies (Hu et al., 2024; Baldwin et al., 2001; Jiang et al., 2024; Garcia-Franco et al., 2022).

4.2. Circulation Anomalies

We studied upper and lower circulations to understand how QBO influences rainfall patterns in both ESA. Composite analysis in **Figures 3-5** represents circulation responses at level 70 hPa, 200 hPa, 500 hPa and 850 hPa. Results demonstrated that during the WQBO phase, there is a geopotential anomaly between the latitude of 10˚S-10˚N, and strong upper-level westerly and anticyclonic anomalies in our study areas (**Figure 3(d)**).

During the WQBO phase, the 70 hPa winds exhibit robust westerlies around the Equator (**Figure 3(a)**). However, at 200 hPa, the fields in **Figure 3(b)** display wide anticyclonic height anomalies, accompanied by strong divergence over the western Indian Ocean. Both mid-level 500 hPa and surface-level 850 hPa anomalies exhibit a low-level cyclonic tendency and onshore flow into EA (**Figure 3(c)**, **Figure 3(d)**). In contrast, the EQBO composite features upper-level Easterlies at 70 hPa (**Figure 4**), weak outflow over EA at 200 hPa and the reverse system at the low level.

The WQBO-EQBO differences in **Figure 5** exhibit the downward propagating sign of the QBO where tropical westerly shear aloft coincides with the upper tropospheric warming off the equator and enhanced divergence near the convective core, whereas easterly shear shifts the divergence pattern away from EA (Baldwin et al., 2001; Anstey et al., 2022). This modulation of circulation is further reflected in precipitation, as the QBO influences EA precipitation by modulating the regional ITCZ and Indian-Ocean moisture transport (Garcia-Franco et al., 2022).

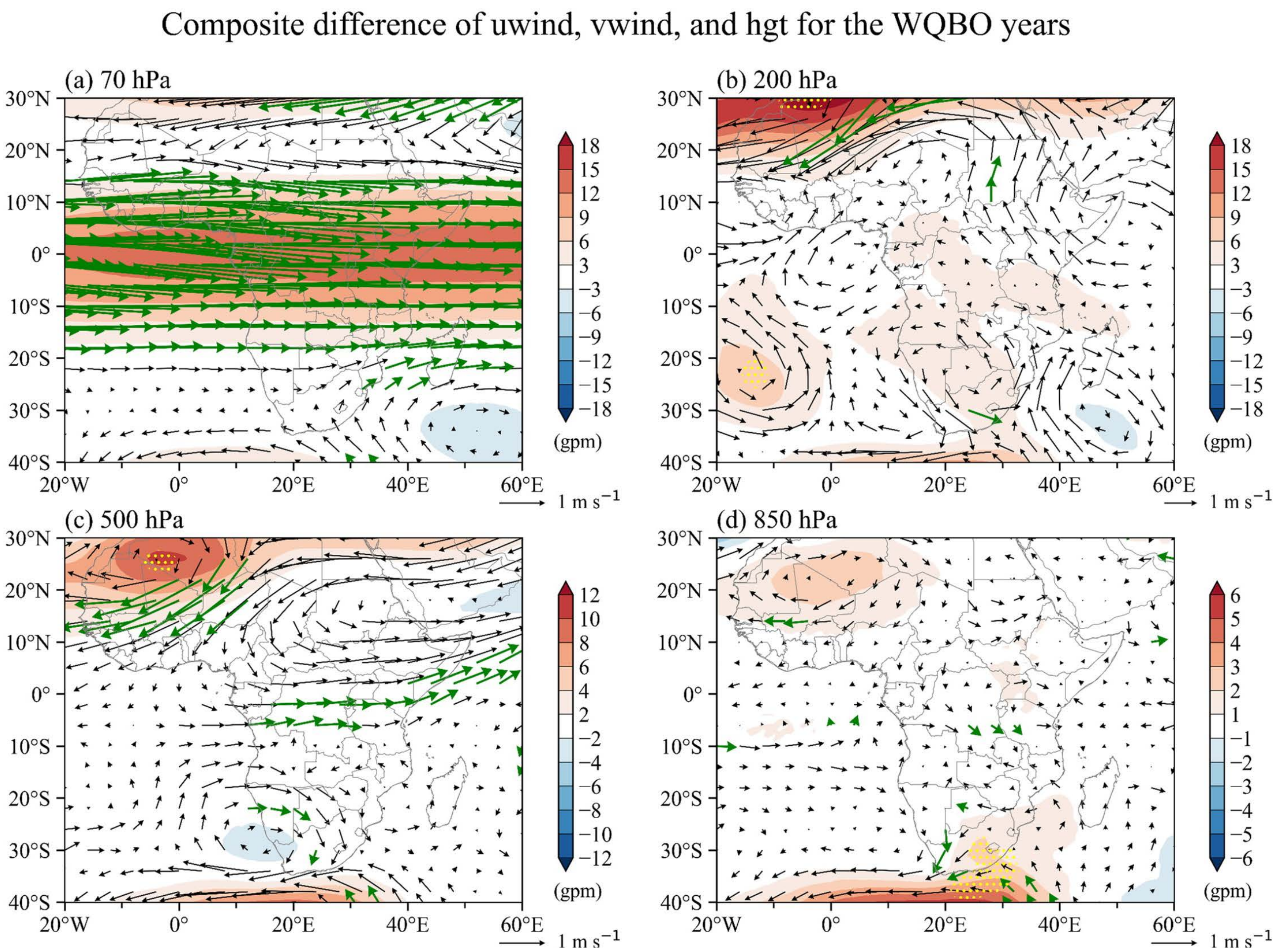

Figure 3. Composite differences of zonal wind (m s^{-1}), meridional wind (m s^{-1}), and geopotential height (gpm) between WQBO and EQBO years at four pressure levels:(a) 70 hPa, (b) 200 hPa, (c) 500 hPa, and (d) 850 hPa. Shading represents geopotential height anomalies, and arrows depict horizontal wind anomalies; green arrows indicate wind anomalies significant at the 95% confidence level based on a two-tailed Student's t-test.

During the WQBO phase at 70 hPa, robust equatorial westerlies (Figure 3(a)) enhance upper-level divergence over the equator, intensifying the ascending branch of the Hadley cell. Rather than shifting the ITCZ, this amplification deepens convection within its climatological DJF position, increasing moisture convergence and rainfall over EA. Conversely, EQBO easterlies weaken the upper-level divergence, reducing ITCZ intensity without displacing its location. Aloft, the 200-hPa pattern (Figure 3(b)) mirrors this modulation, broad anticyclonic height anomalies and strong divergence prevail over the western Indian Ocean, consistent with the anomalous ascent described above.

This pattern enhances the typical East African atmospheric circulation by strengthening the upper-level outflow associated with the ITCZ convective systems. A primary explanation for the two rainy seasons in EA is the movement of the ITCZ, and our results indicate that WQBO phases amplify this natural migration pattern through stratospheric-tropospheric coupling. The enhanced moisture transport during WQBO is consistent with the regional understanding that

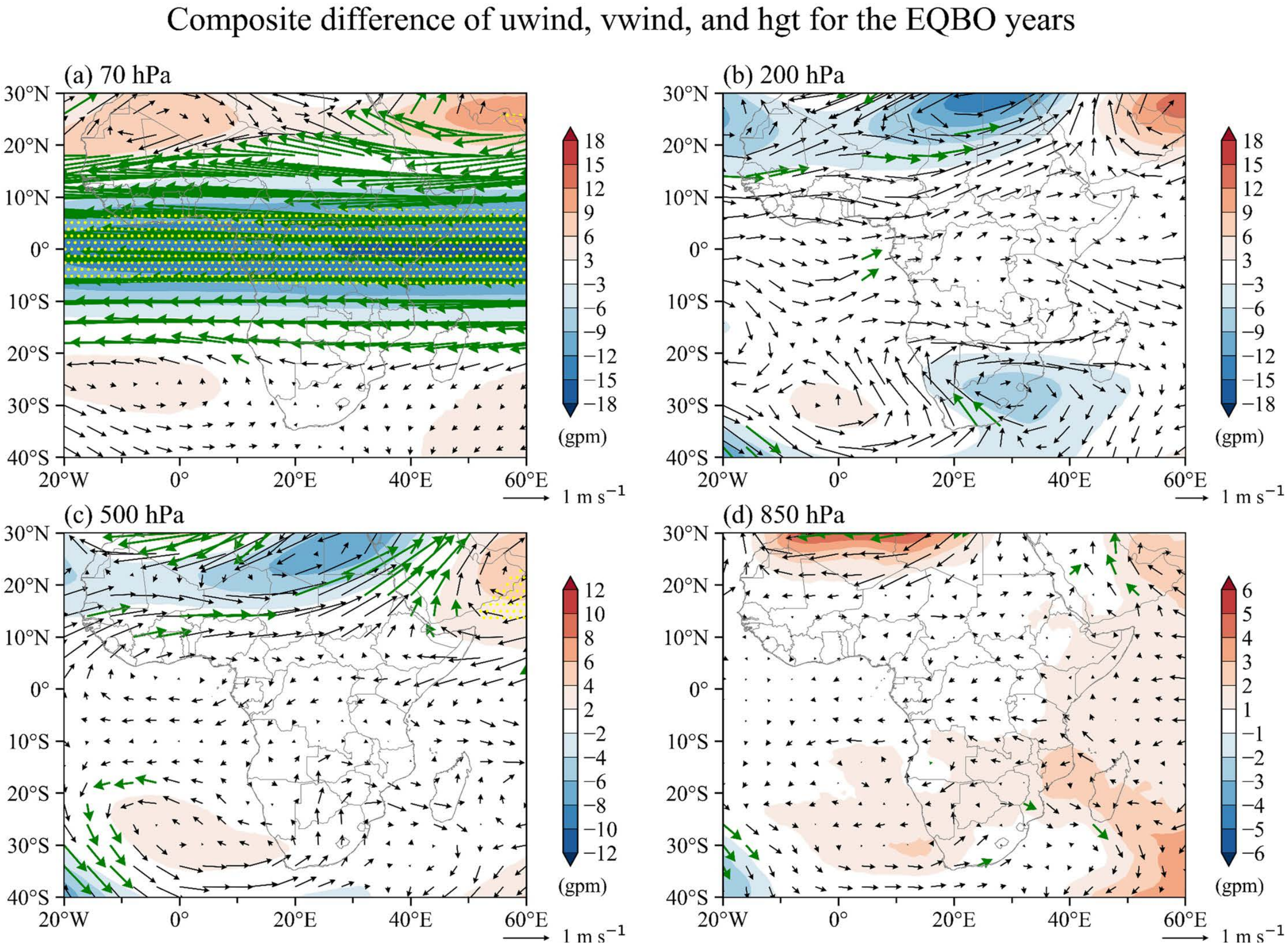

Figure 4. Composite differences of zonal wind (m s⁻¹), meridional wind (m s⁻¹) and geopotential height (gpm) between EQBO and WQBO years at four pressure levels. Shading represents geopotential height anomalies and arrows depict horizontal wind anomalies. Green arrows indicate wind anomalies significant at the 95% confidence level based on a two-tailed Student's t-test.

EA rainfall depends heavily on moisture influx from the Indian Ocean and the Congo basin.

Both mid-level 500 hPa and surface-level 850 hPa (**Figure 3(c)**, **Figure 3(d)**) anomalies exhibit a low-level cyclonic tendency and onshore flow into EA, which amplifies the normal monsoon circulation patterns that bring moisture from the western Indian Ocean during peak rainfall seasons (Nicholson, 2017; Palmer et al., 2023).

Our results demonstrate that during WQBO phases, enhanced convection contributes to the development of negative height anomalies over SA. Furthermore, we find that the QBO systematically alters regional moisture transport patterns. Specifically, the WQBO phase leads to distinct patterns of moisture advection and convergence, thereby directly enhancing precipitation. The WQBO–EQBO differences in **Figure 5** exhibit the downward propagating signature of the QBO, where tropical westerly shear aloft coincides with upper tropospheric warming off the equator and enhanced divergence near the convective core. This pattern effectively weakens the typical BH subsidence while simultaneously strengthening the

AL moisture transport capacity from the Atlantic Ocean.

In contrast, the EQBO composite features upper-level easterlies at 70 hPa (**Figure 4**), weak outflow over EA at 200 hPa, and the reverse system at the lower level. This configuration strengthens the typical dry season circulation patterns in both regions, enhancing the BH in Southern Africa and weakening the AL circulation, which is consistent with the observed reduction in SA precipitation during these phases and the weakening of ITCZ convection in EA. The patterns at 200 hPa and 500 hPa are consistent with the rephasing of the upper-level outflow channel (**Figures 3-5**).

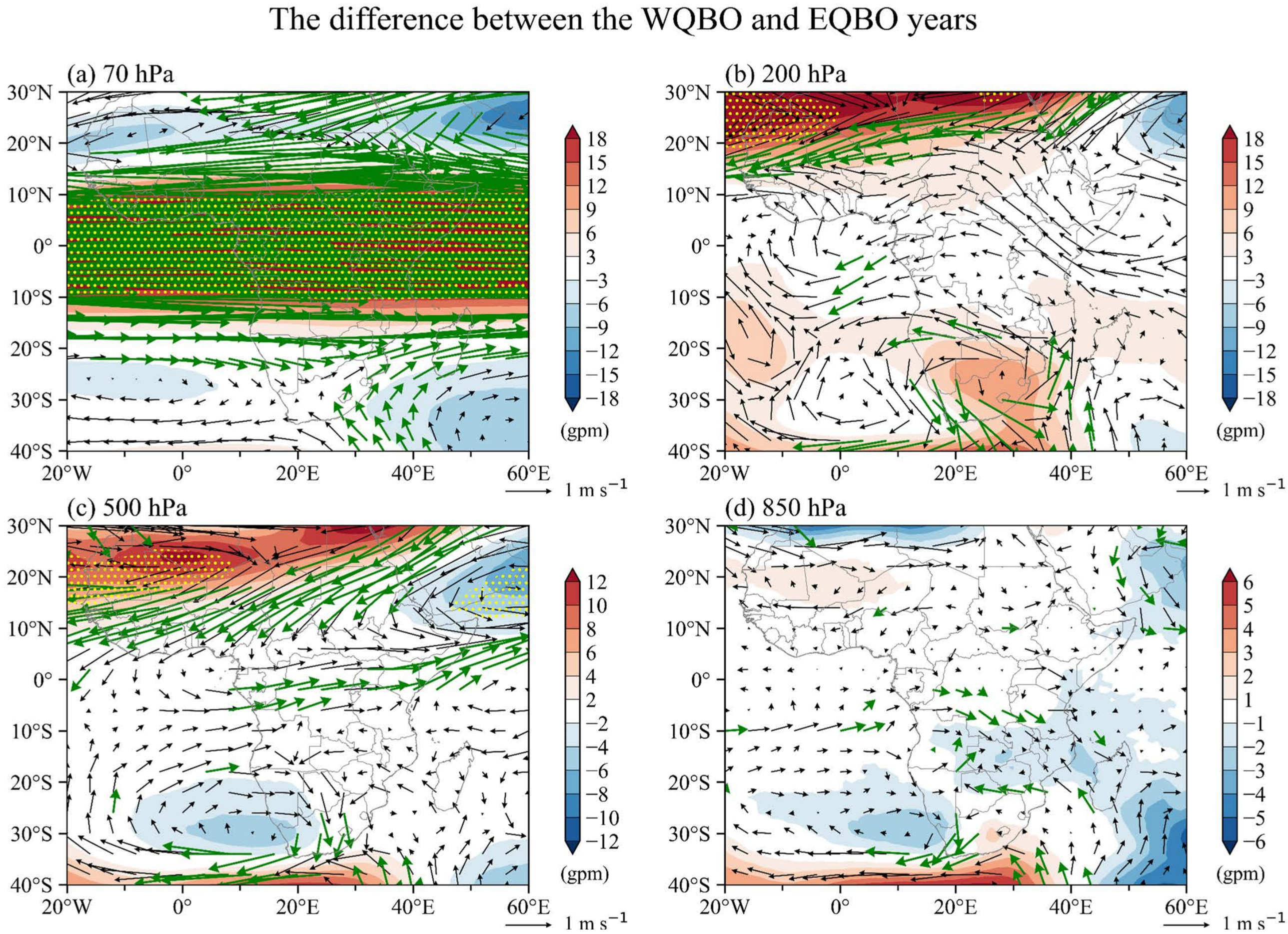

Figure 5. Composite differences of zonal wind (m s^{-1}), meridional wind (m s^{-1}), and geopotential height (gpm) between WQBO and EQBO years at four pressure levels:(a) 70 hPa, (b) 200 hPa, (c) 500 hPa, and (d) 850 hPa. Shading indicates geopotential height anomalies and arrows show horizontal wind anomalies. Green arrows denote wind anomalies statistically significantly at the 95% confidence level according to a two-tailed Student's t-test.

4.3. Moisture Flux and Wind Convergence, Regional Transport Mechanisms

To prove the relationship of the above circulations with QBO, we also studied the composite difference between wind convergence and the water vapor flux in WQBO and EQBO. **Figure 6(a)** shows wind divergence at the upper level, while strong convergence on the lower level, which agrees with water vapor transport. **Figure 7** shows the difference in water vapor transport and its divergence during WQBO

(Figure 7(a)). We observed moisture flux vectors from the Indian Ocean towards the EA and from Central Africa (Congo Air mass), while we can see moisture convergence over Southern Africa. This pattern directly enhances the two primary moisture transport pathways that sustain rainfall in each region: the Indian Ocean moisture corridor and the Congo Basin and Atlantic moisture transport for SA.

The enhanced moisture transport during WQBO phases operates through systematic modifications of the typical regional circulation patterns. In EA, the normal moisture transport from the western Indian Ocean during the passage of the ITCZ is amplified by QBO-induced circulation changes. In SA, the AL typically enhances moisture transport from the Atlantic, while the BH blocking effect is reduced, allowing for greater moisture penetration into the SA region.

Figure 7(b) shows enhanced divergence over the ESA region, while Figure 7(c) isolates a net onshore integrated water vapor transport anomaly into region with convergence centers over EA and SA. This moisture distribution explains why the wind anomaly, as seen in Figures 3-5, causes a large precipitation response during an insufficient moisture regime, which is also proved by (Nicholson, 2017; Kilavi et al., 2018).

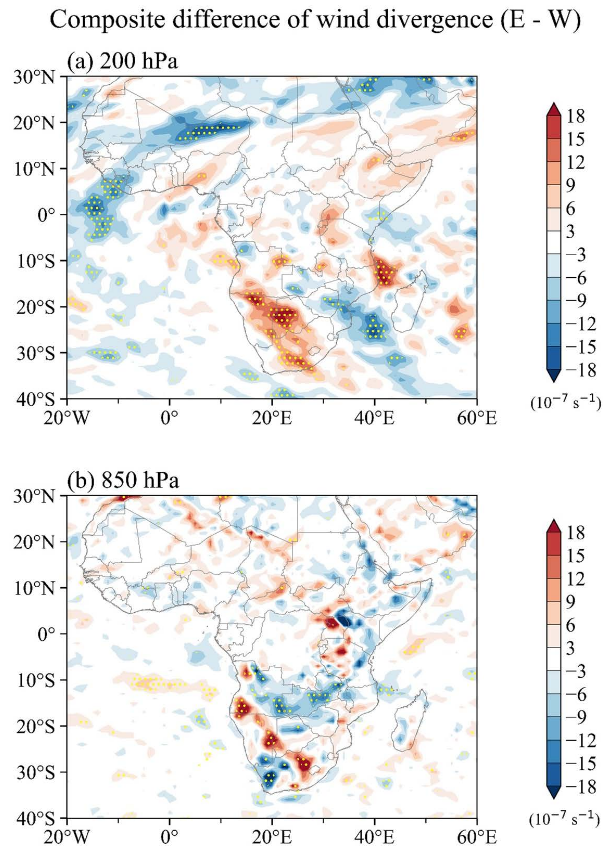

Figure 6. Composite differences in horizontal wind divergence (E–W) between EQBO and WQBO years at (a) 200 hPa and (b) 850 hPa. Shading represents divergence anomalies ($\times10^{-7}$ s^{-1}) with positive values (red) indicating divergence and negative values (blue) indicating convergence. Stippling denotes regions statistically significant at the 95% confidence level based on a two-tailed Student's t-test.

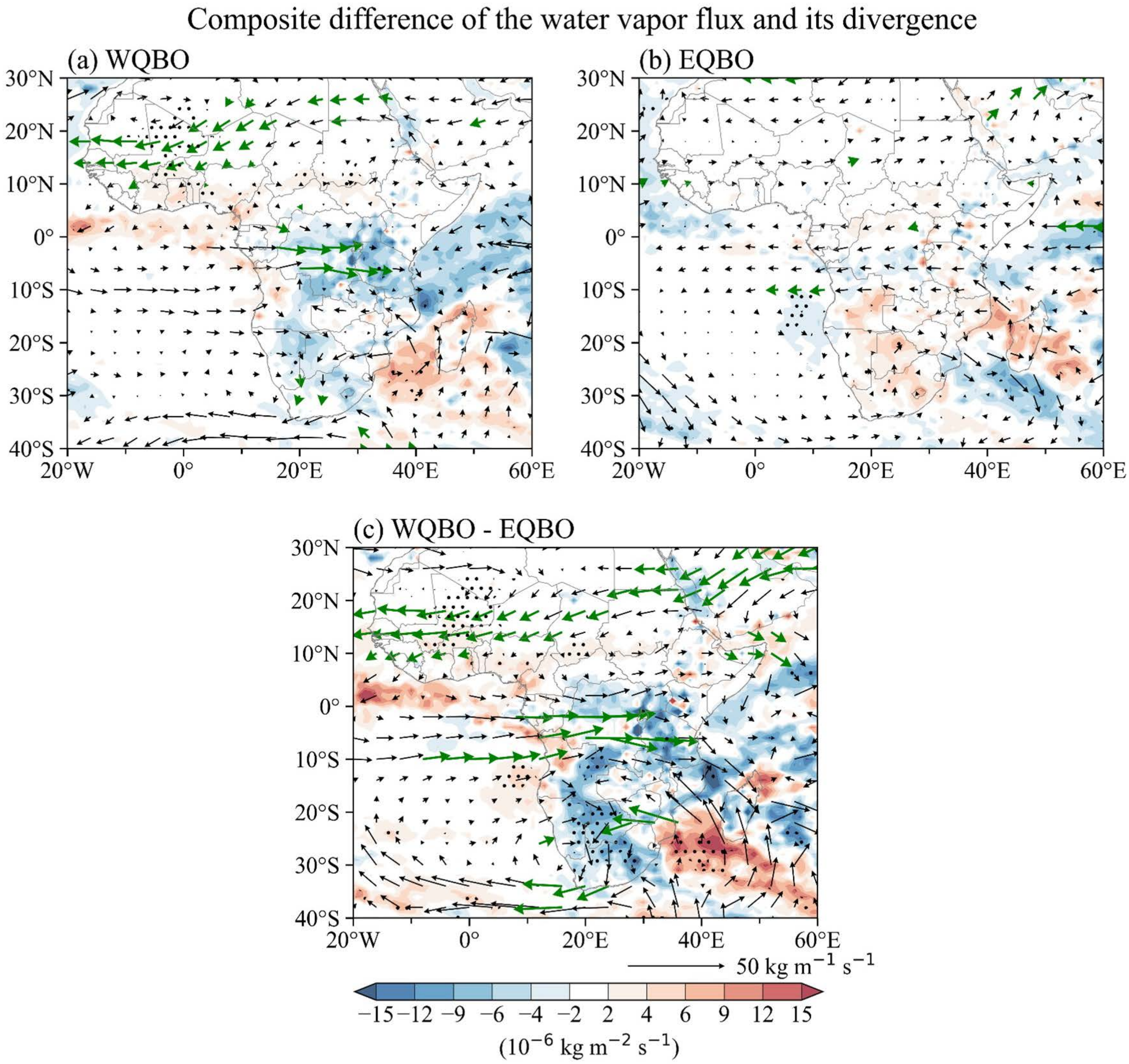

Figure 7. Composite differences in vertically integrated water vapor flux and its divergence for (a) WQBO, (b) EQBO, and (c) WQBO-EQBO. Shading represents water vapor flux divergence (×10^{-6} kg m^{-2} s^{-1}), with positive (brown) indicating divergence and negative (blue) indicating convergence. Vectors indicate water vapor flux (kg m^{-1} s^{-1}).

4.4. Convective Mechanism

Vertical ascent and moisture convergence (divergence) also dominate during WQBO (EQBO) over much of ESA, as shown in **Figure 8**, which favors convective rainfall (dry anomalies). The QBO influence on regional convection operates by either enhancing or suppressing the natural convective systems associated with the ITCZ in EA and the AL convection in SA.

The analysis of OLR strengthens the above dynamical explanations. **Figure 9** shows that the WQBO is characterized by enhanced deep convection over Southern Central Africa, extending into EA (**Figure 9(a)**). In contrast, the EQBO exhibits positive OLR anomalies (indicating suppressed convection) over the SA (**Figure 9(b)**). The difference between the two phases reveals a significant enhancement of convection between 15˚S - 35˚S and 10˚E - 35˚E during the WQBO relative to the EQBO (**Figure 9(c)**), with a dominant suppression of convection over SA region during the EQBO.

This convective response pattern aligns perfectly with the known convective centers associated with regional atmospheric systems. In SA, convective enhancement occurs over the typical AL convection centers and the escarpment regions, where orographic lifting normally enhances precipitation.

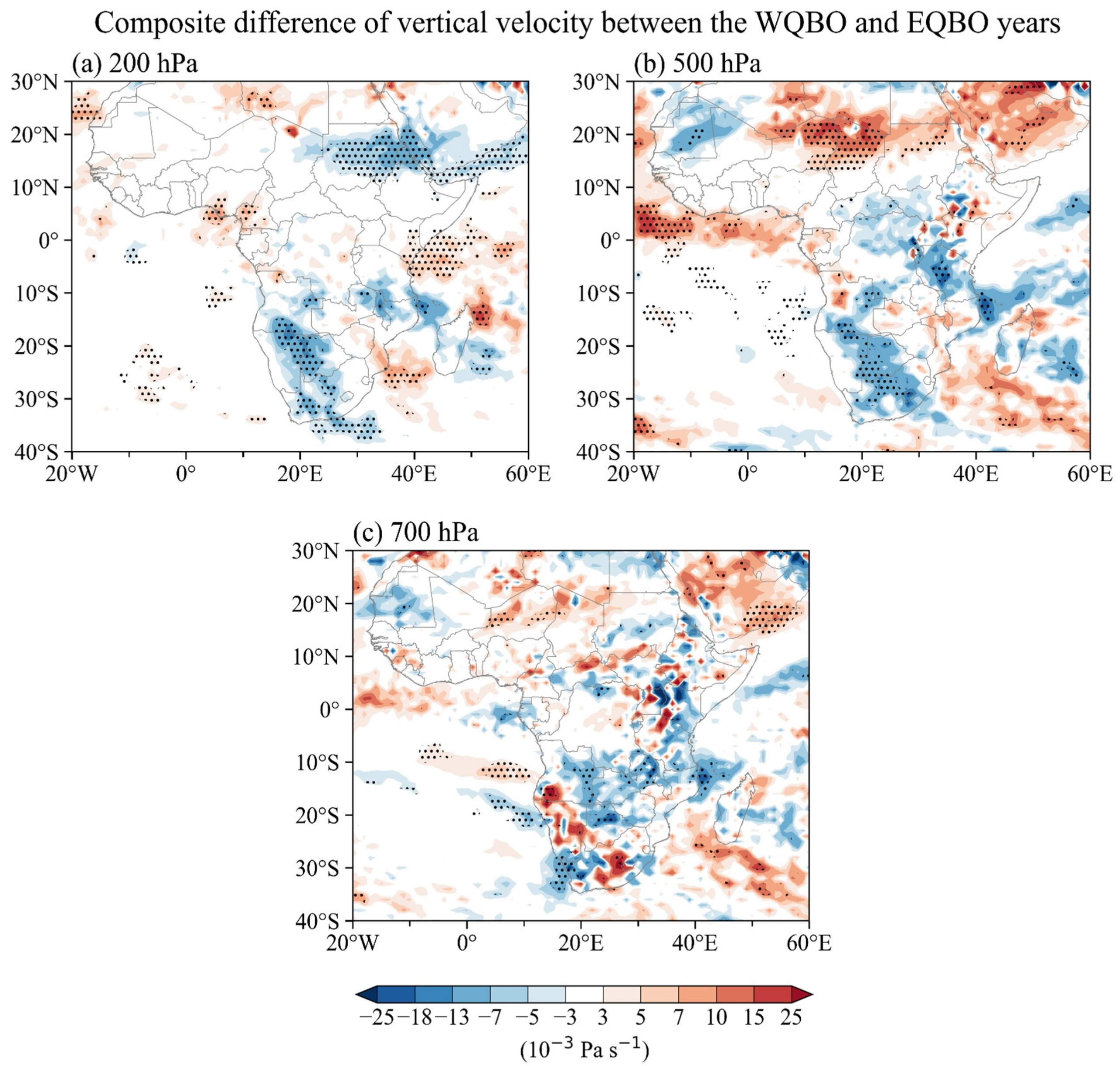

Figure 8. Composite differences in vertical velocity ($\omega \times 10^{-3}$ Pa s^{-1}) between WQBO and EQBO years at (a) 200 hPa, (b) 500 hPa, and (c) 700 hPa. Blue shading denotes anomalous upward motion, while red shading indicates anomalous downward motion. Stippling represents statistically significant differences at the 95% confidence level.

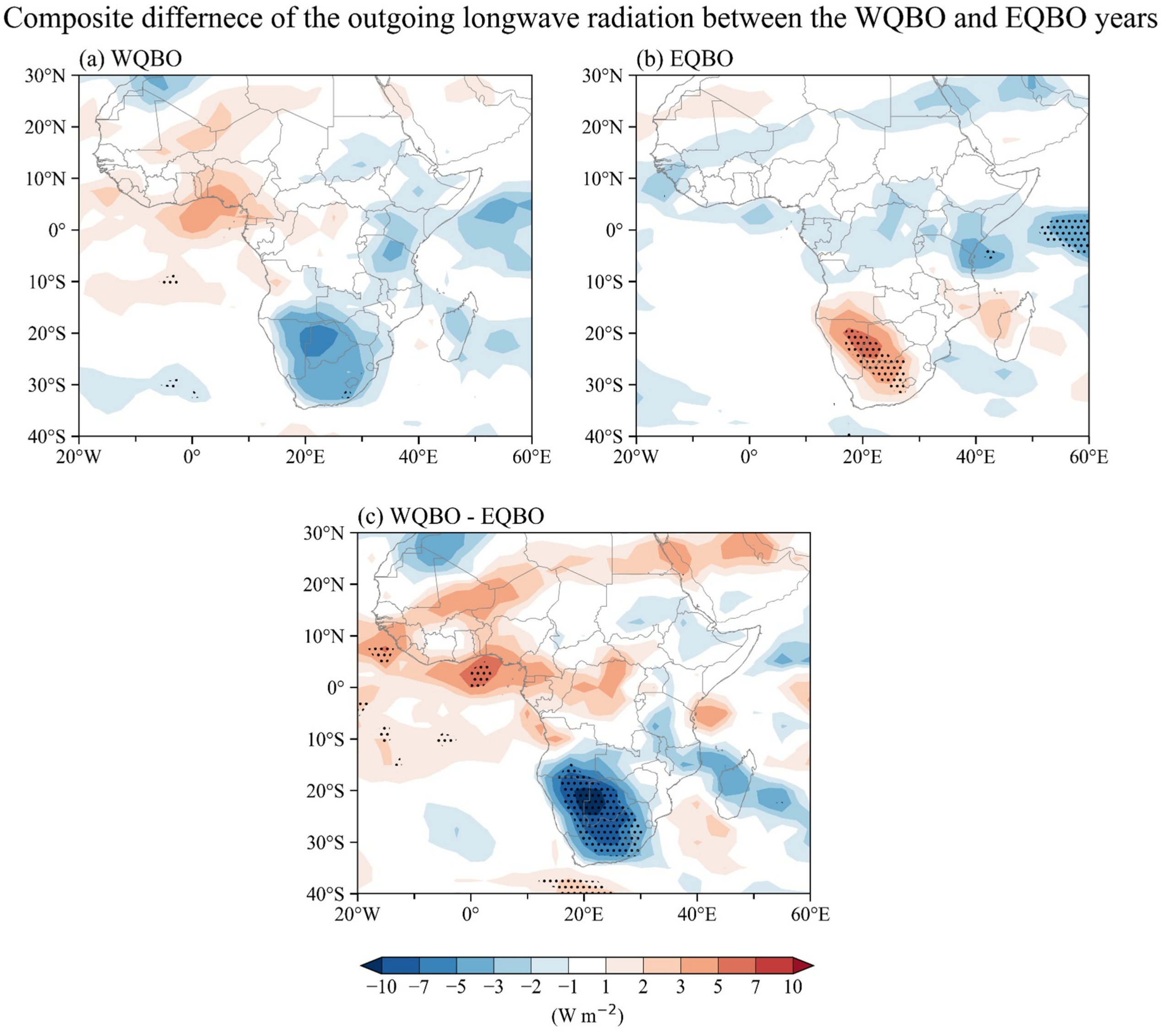

Figure 9. Composite differences in OLR (W m^{-2}) between WQBO and EQBO years: (a) WQBO, (b) EQBO, and (c) WQBO−EQBO. Blue shading indicates reduced OLR (enhanced convection), while red shading denotes increased OLR (suppressed convection). Dotting highlights statistically significant differences at the 95% confidence level.

The agreement between OLR, Omega, divergence and moisture flux proves the physical consistency of the implication that QBO phases organize deep convection over EA and SA by modifying the regional atmospheric circulation systems.

This echo prior studies linking QBO to tropical convective susceptibility and intraseasonal activity, for example, the Madden-Julian Oscillation amplitude and occurrence, which then projects onto seasonal mean rainfall (Garcia-Franco et al., 2022; Kang et al., 2024).

5. Discussion and Conclusion

This study investigated the influence of the QBO at 50 hPa. The results support the following during WQBO: lower stratospheric westerlies induce anomalous circulations between the troposphere and stratosphere, followed by adjustments in wave propagation, which foster upper-level divergence over the EA convective corridor and modify SA circulation patterns.

The low-level flow aligns to enhance moisture inflow from the Western Indian Ocean, Atlantic Ocean, and the Congo Basin, resulting in convergence and strong ascent over EA and SA. EQBO represents a reverse phenomenon, weakening EA convective activity and allowing subsidence to dominate, while simultaneously strengthening the BH circulation that suppresses SA precipitation.

Since QBO is a quasi-periodic and predictable phenomenon, with strong WQBO and EQBO rainfall symmetry over the ESA region identified here, it provides us with actionable seasonal guidance. Combining both QBO phases with concurrent ENSO and IOD indicators, along with monitoring of regional circulation systems such as the AL and BH positions, will contribute substantially to seasonal forecasts.

Building on a defined physical mechanism, this analysis confirms that the QBO influences ESA precipitation through predictable shifts in key regional circulations. During the WQBO phase, a stronger ITCZ over ESA and a strengthened AL, coupled with a weaker BH, create ideal conditions for increased precipitation. The strengthened AL draws moist winds further inland from the Western Indian Ocean, fueling convection in Eastern, Central, and SA. Simultaneously, a weaker BH attenuates its normal production of mid-level divergent winds, which typically disrupts the low-level convergence necessary for deep convection; this weakening allows for more profound convective activity and precipitation, with SA being particularly affected. Conversely, the EQBO phase weakens this convection and strengthens the BH, leading to widespread drought. This impact is also seasonal, with SA most responsive during its core wet season (DJF) when the AL-BH dipole is dominant, and EA most affected during its transitional rainy periods.

Our analysis focuses on linear relationships, potentially missing nonlinear interactions or threshold effects. Although we removed the influence of the Indian Ocean Dipole, other major climate modes, such as the Southern Annular Mode, may still exert residual confounding effects. Furthermore, the study period (1979 - 2021) is relatively short for capturing the full range of QBO variability, and the coarse resolution of the reanalysis data may not fully resolve local-scale precipitation processes, especially over complex topography. Finally, as our analysis is observational, it does not include model simulations to test causality. Future studies using high-resolution climate models that explicitly incorporate QBO phases will be crucial for validating these findings and for exploring the underlying mechanisms in greater detail.

The study concludes that the QBO quasi-periodic and predictable nature provides a robust scientific basis for significantly improving seasonal forecasts. By incorporating the QBO phase alongside other climate indicators, such as ENSO and the IOD, forecasters can achieve greater accuracy in their predictions. The consistency of these findings across different atmospheric levels reinforces the

QBO as critical, which was previously less discussed. In addition, future studies could further investigate nonlinear interactions with other climate patterns, such as the Southern Annular Mode (SAM).

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Conflicts of Interest

The authors declare no conflicts of interest concerning the publication of this paper.

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