

Relationship between the Quasi-Biennial Oscillations and Surface Air Temperature over Southern Africa during Early Austral Spring

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Abstract

The Quasi-Biennial Oscillation (QBO) is a dominant mode of interannual variability in the tropical stratosphere, known to influence global weather and climate patterns through stratosphere-troposphere coupling. While its impacts on the Northern Hemisphere are well-documented, its role in the Southern Hemisphere subtropical climate remains less explored. This study investigates the relationship between the QBO and September surface air temperature (SAT) over Southern Africa during the early austral spring from 1979 to 2021. We find that the QBO's easterly phase (EQBO) at 50 hPa is associated with a significant dipole pattern in SAT, characterized by warming over southeastern Africa and cooling along the southwestern coastal area. Analysis reveals that this temperature pattern is driven by a coherent teleconnection pathway: the EQBO forces a quasi-barotropic geopotential height anomaly, which modulates vertical velocity, leading to enhanced convection and increased cloud cover over the cooling region and suppressed convection over the warming area. Outgoing Longwave Radiation data confirm this dipole in convective activity. A latitudinal-vertical cross-section demonstrates the descent of QBO-related wind anomalies into the subtropical troposphere, outlining the direct stratospheric pathway for this distant influence. Our results identify the QBO as a key stratospheric precursor for early spring temperature variability in Southern Africa, with important implications for improving regional seasonal forecasting.

Keywords

Quasi-Biennial Oscillation, Southern Africa, Surface Air Temperature, Stratosphere-Troposphere Interaction

1. Introduction

Quasi-Biennial Oscillation (QBO) is the regular periodic phenomenon observed in the lower stratosphere (approximately 16 - 50 km), with a typical period of about 28 months, characterized by alternating phases of zonal winds over the equator, shifting between westerlies (WQBO) and easterlies (EQBO) (Angell & Korshover, 1964; Anstey et al., 2022; Anstey & Shepherd, 2014; Baldwin et al., 2001; Gray et al., 2018). Initially discovered in the early 1960s, it is primarily driven by vertical momentum fluxes generated by a wide range of tropical waves that propagate upward from the troposphere (Baldwin et al., 2001; Hu et al., 2022, 2024; Gao et al., 2023; Lindzen & Holton, 1968). It is now recognized as a key mechanism coupling the stratosphere and troposphere, hence influencing weather and climate patterns through several distinct ways (Gettelman et al., 2011).

QBO links zonal wind anomalies with temperature fields through thermal wind balance, modulating vertical wind shear, temperature, and static stability, thereby influencing convective activity and cloud formation in the tropics (Collimore et al., 2003; Haynes et al., 2021; Liess & Geller, 2012; Luo et al., 2024; Zhang et al., 2024). The alternating WQBO and EQBO can subsequently influence tropospheric circulation systems, such as the subtropical high, thereby affecting regional precipitation and temperature patterns (Hu et al., 2022, 2024; Luo et al., 2024). For example, when easterly winds prevail at 50 hPa, the tropical tropopause becomes colder and higher, static stability decreases, convective activity intensifies, and cirrus cloud formation is enhanced as well (Liess & Geller, 2012; Luo et al., 2024; Zhang et al., 2024).

Depending on where the QBO is located, its impact occurs through three main routes. First is the polar route that modulates the strength of the stratospheric polar vortex, which then affects the tropospheric circulation, surface temperatures and pressure distributions (Baldwin & Dunkerton, 2001; Lu et al., 2017; Mitchell et al., 2013; Perlwitz & Harnik, 2003; Shaw & Perlwitz, 2013; Thompson et al., 2002). Second is the tropical route that alters the tropical tropopause temperatures and convection through induced meridional circulation and thermal wind balance changes (Collimore et al., 2003; Garfinkel & Hartmann, 2011; Ho et al., 2009; Liess & Geller, 2012; Son et al., 2017). Last is the subtropical route that affects the subtropical jet and mid-latitude wave activity, linking the QBO signal to surface variations (Garfinkel & Hartmann, 2011; Ruti et al., 2006; Simpson et al., 2009). These routes usually act together, making their individual impacts difficult to differentiate (Hoskins & Karoly, 1981; Scaife et al., 2017). Thus, there are multiple teleconnections between the QBO and the surface.

Previous studies have investigated the impact of the QBO index across different pressure levels according to specific study objectives; however, no consensus has been established on the level that best represents the QBO (Gray et al., 2018; Jiang et al., 2024; Li et al., 2022; Zhang et al., 2019). Over South Asia, QBO signals at 20, 30, and 50 hPa induce June temperature anomalies opposite in sign to those associated with the 70 hPa level, with the weakest and statistically insignificant re-

sponse observed at 50 hPa (Luo et al., 2024). During EQBO (WQBO) phases at 20 and 30 hPa, northern and central South Asia exhibit anomalously high (low) June temperatures, with inter-phase differences exceeding 1.2°C (Luo et al., 2024). However, compared to the Northern Hemisphere, the role of the QBO in Southern Hemisphere subtropical climate, particularly over Southern Africa (SA), remains less explored, despite evidence of its far-reaching influence (Gray et al., 2018). This raises an important question: does the QBO similarly modulate surface air temperature (SAT) over SA? To address this, the present study investigates the relationship between the 50 hPa QBO and September 2-meter temperature (T2m) across SA and associated physical mechanisms that transmit this stratospheric signal to the surface. We concentrate on September simply because the intra-seasonal climate variability during this period, particularly thermal regimes, serves as the principal determinant for agricultural decision-making at the onset of the cropping season. The cumulative heat units and the incidence of extreme temperatures in this period directly regulate the planting date, a non-compensable factor that establishes the ceiling for potential yield by governing phenological development and ultimately dictating seasonal productivity and farm-level food security

2. Data and Methods

Our study area spans over SA comprising southeastern Africa (SEA) (10°S-25°S, 20°E-35°E) and southwestern coastal (SWC) area (20°S-35°S, 15°E-20°E). In this study, we used data from multiple sources including European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5) and Hadley Centre of U.K. Met. Office (HadISST). ERA5 is monthly reanalysis data at 17 standard pressure levels, ranging from 1000 to 10 hPa. Parameters obtained from ERA5 include zonal wind, meridional wind, 2-meter SAT, geopotential height, vertical velocity, and cloud cover (Dee et al., 2011; Uppala et al., 2005). Outgoing longwave radiation (OLR) data were obtained from the National Oceanic and Atmospheric Administration (NOAA) at a resolution of 2.5° × 2.5° (Gruber & Krueger, 1984). Monthly sea surface temperature (SST) was obtained from HadISST (Rayner et al., 2003). Except for OLR, all other datasets are provided on 1° × 1° grids. In general, the study analyzes monthly mean data for the period 1979-2021 (43 years). All datasets were regridded to a common 2.5° × 2.5° grid, and anomalies were computed relative to the 1979-2021 climatology for each grid point.

We defined the climatological baseline as the mean over the entire study period. All subsequent anomaly values represent deviations from this 1979-2021 mean. Following Huangfu et al. (2021), the monthly QBO index is defined as the zonal-mean zonal wind area averaged between 5°S and 5°N at 50 hPa. The 50 hPa level was selected because it is widely used in QBO-troposphere teleconnection studies (e.g., Gray et al., 2018; Hu et al., 2022) and represents a level where the QBO signal is strong and directly relevant to subtropical circulations modulations. In line with

previous studies, we further employed a univariate linear regression to remove the influence of Indian Ocean Dipole (IOD) from the original datasets (Gray et al., 2018). IOD is a more direct and dominant driver of September climate variability over SA than El Niño-Southern Oscillation (ENSO) during the early spring (e.g., Behera et al., 2005). Therefore, we prioritized removing the IOD signal to isolate the QBO's influence more cleanly. The IOD index was obtained from SST anomalies across the Indian Ocean, calculated as the difference between SST anomalies in the western (50°E - 70°E, 10°S - 10°N) and the eastern (90°E - 110°E, 0° - 10°S) tropical regions (Saji et al., 1999). To isolate the effects of climate variability from long-term warming trends, the SST anomalies were detrended to remove the influence of basin-wide warming. A year was classified as a positive (negative) IOD event when the detrended SST anomaly was greater (smaller) than +0.5°C (-0.5°C); otherwise, it was considered a neutral year (Behera et al., 2005; Saji et al., 1999; Yamagata et al., 2013).

A year was categorized as a WQBO (EQBO) year when the standardized QBO index in September was greater than 0.8 (less than -0.8) standard deviations during 1979-2021. This classification yields 12 years for each category: WQBO (1983, 1985, 1988, 1990, 1993, 1995, 1997, 1999, 2006, 2009, 2011, 2013) and EQBO (1979, 1984, 1992, 1994, 1996, 1998, 2001, 2003, 2005, 2007, 2012, 2018). Note that if the zonal wind at 70 hPa is chosen to define the QBO index, the conclusion remains unchanged. Based on this sorting, composite analyses were further conducted to determine how the two QBO phases influence the SAT over the region. In addition, we also calculated the correlation between the QBO index and the SAT. All statistical significance tests were computed using Student's t-test.

3. Results and Discussion

3.1. Relationship between QBO and SAT

Our analysis reveals that the QBO is a significant driver of early spring SAT over SA. The correlation map between the 50 hPa QBO index and September 2-meter temperatures establishes a clear statistical link (Figure 1(a)). A coherent region of positive correlation is evident over the SWC area, while a negative correlation dominates SEA. This dipole pattern suggests that during the EQBO, SEA experiences warmer conditions, whereas the SWC area experiences cooler conditions. This dipole pattern is a robust feature evident in the composite analysis of all 12 EQBO years. While interannual variability is naturally present, the coherence of the pattern across the composite mean and its alignment with the significant correlation map in Figure 1(a) confirm that it represents a systematic response to the EQBO phase, rather than an artifact of a few outlier years.

This statistical relationship is further substantiated by composite analyses, which illustrate the QBO's distinct influence during its different phases. The EQBO composite (Figure 1(b)) confirms the presence of significant positive temperature anomalies over SEA and negative anomalies along the SWC. Conversely, during the WQBO (Figure 1(c)), the temperature anomalies are generally weaker

and statistically insignificant over much of the region, which nevertheless confirms the same broad relationship observed in **Figure 1(a)**. The difference between the EQBO and WQBO composites effectively isolates the QBO's specific influence, highlighting that the warming over SEA and the cooling over the SWC area are substantial and robust signals associated with the EQBO phase (**Figure 1(d)**).

The observed surface temperature pattern can be understood as part of a dynamical chain reaction with downstream effects. One plausible mechanism which involves the QBO's influence is the Southern Annular Mode (SAM), whereby during the EQBO phase, the unique wind structure in the tropical stratosphere refracts planetary waves, ultimately contributing to a weakening of the Antarctic stratospheric polar vortex (**Baldwin & Dunkerton, 2001**). A weaker polar vortex often promotes a more negative phase of the SAM, which can alter pressure patterns and favor enhanced warm air advection over parts of SA, resulting in the

T2m anomalies related to the QBO

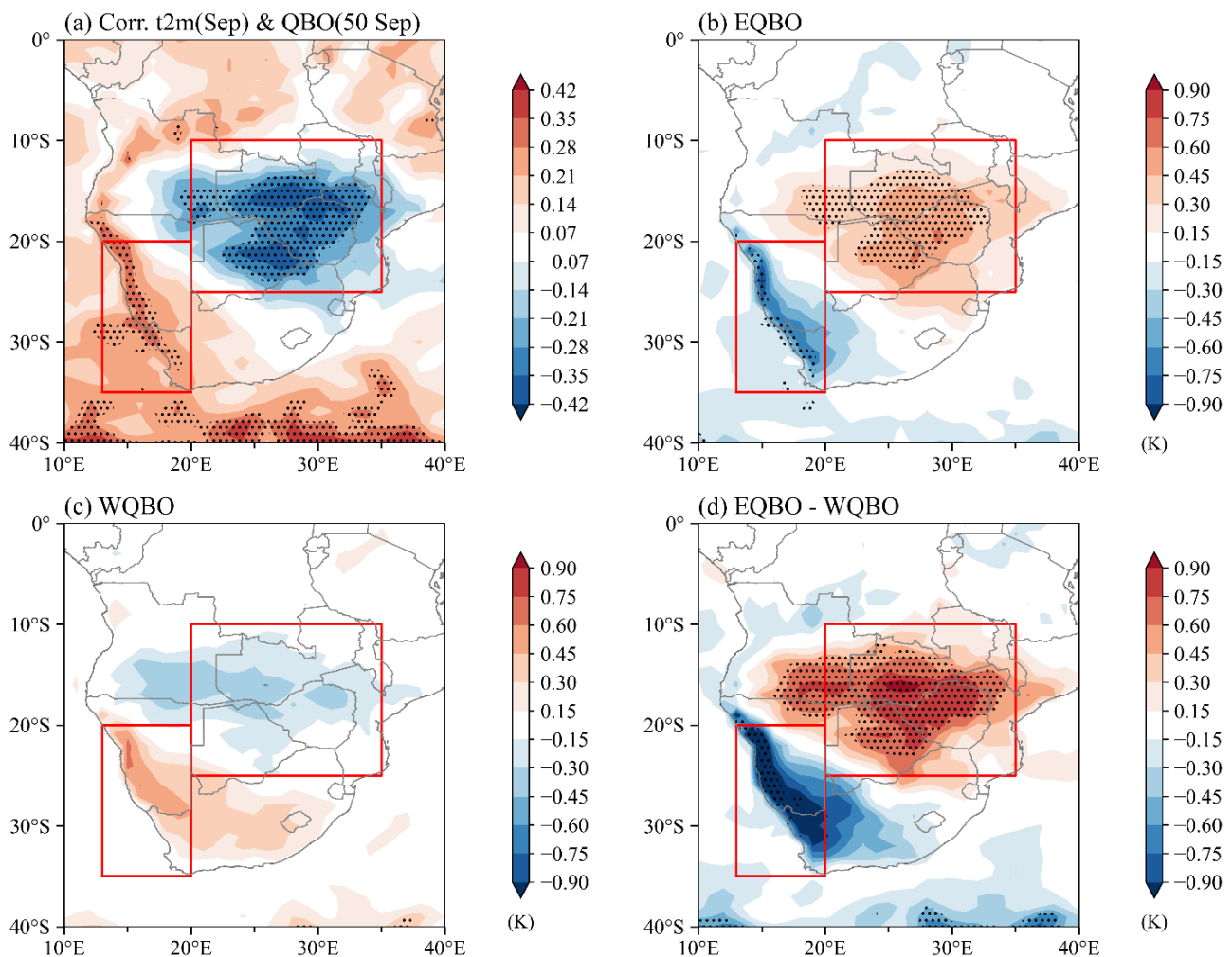


Figure 1. (a) The correlation coefficient between 2-meter temperature (T2m) in Kelvin (K) and quasi-biennial oscillation (QBO) at 50 hPa in September. (b), (c), and (d) are T2m composite anomalies in September during EQBO, WQBO, EQBO-WQBO respectively. The dotted areas are those which are significant at the 95% confidence level.

surface warming documented here (Thompson et al., 2002). While this pathway is supported by established literature on stratosphere-troposphere coupling, a detailed analysis of the QBO-SAM relationship is beyond the scope of this study. Nonetheless, this pathway underscores that the QBO is not merely a tropical phenomenon but a key remote influencer of regional climate variability, highlighting the deep interconnections within the global atmospheric system (Gray et al., 2018).

The sensitivity of regional surface climate to the QBO phase, as demonstrated in Figure 1, aligns with growing evidence that the QBO's influence extends beyond the tropics into the subtropics and mid-latitudes, and can be sensitive to its vertical structure (Gray et al., 2018; Luo et al., 2024). Our findings thus identify the QBO as a previously overlooked stratospheric precursor for seasonal temperature variability over SA during the critical early spring season.

3.2. Physical Mechanism Influencing the Relationship

To explore the physical mechanism by which QBO influences September SAT in SA, we assessed: the horizontal wind circulation and geopotential height, vertical wind velocity, OLR, and cloud cover as presented below. Figure 2 presents the composite differences in horizontal wind and geopotential height anomalies between EQBO and WQBO years at 50, 200, 500, and 850 hPa. The signal originates in the lower stratosphere, at the 50 hPa level, a pronounced dipole of geopotential height anomalies (Figure 2(a)). Negative geopotential height anomalies are centered over the equatorial (mid-latitude) region, characteristic of the thermal wind balance associated with the EQBO's easterly (westerly) shear zone (Baldwin & Dunkerton, 2001). Near these equatorial anomalies are nonsignificant positive geopotential height anomalies in the subtropics of the Southern Hemisphere. This anomalous wave-like pattern shows a quasi-barotropic vertical structure, propagating clearly downward through the tropospheric levels (Figures 2(b)-(d)). By the 850 hPa level (Figure 2(d)), the region of SEA (red box) is dominated by significant negative geopotential height anomalies, with a center of positive values situated over the southwestern Indian Ocean (SWIO).

Correspondingly, anomalous easterly wind prevails in the deep tropics across the lower stratosphere, while anomalous westerlies border the subtropical ridges. This configuration suggests an alteration of the subtropical jet stream and a modulation of large-scale circulation patterns (Hu et al., 2024; Luo et al., 2024). The persistent positive geopotential height anomalies over and to the SEA during EQBO years link to the observed surface warming, as they are typically associated with sinking motion and adiabatic warming (Gray et al., 2018). This mechanism confirms the stratosphere-troposphere pathway for the QBO's distant influence on the region.

The thermodynamic link between the large-scale circulation and surface temperatures is further described by examining mid-tropospheric vertical motion. Figure 3 presents the composite vertical velocity at 500 hPa for the (a) EQBO and

The difference between the EQBO and WQBO years

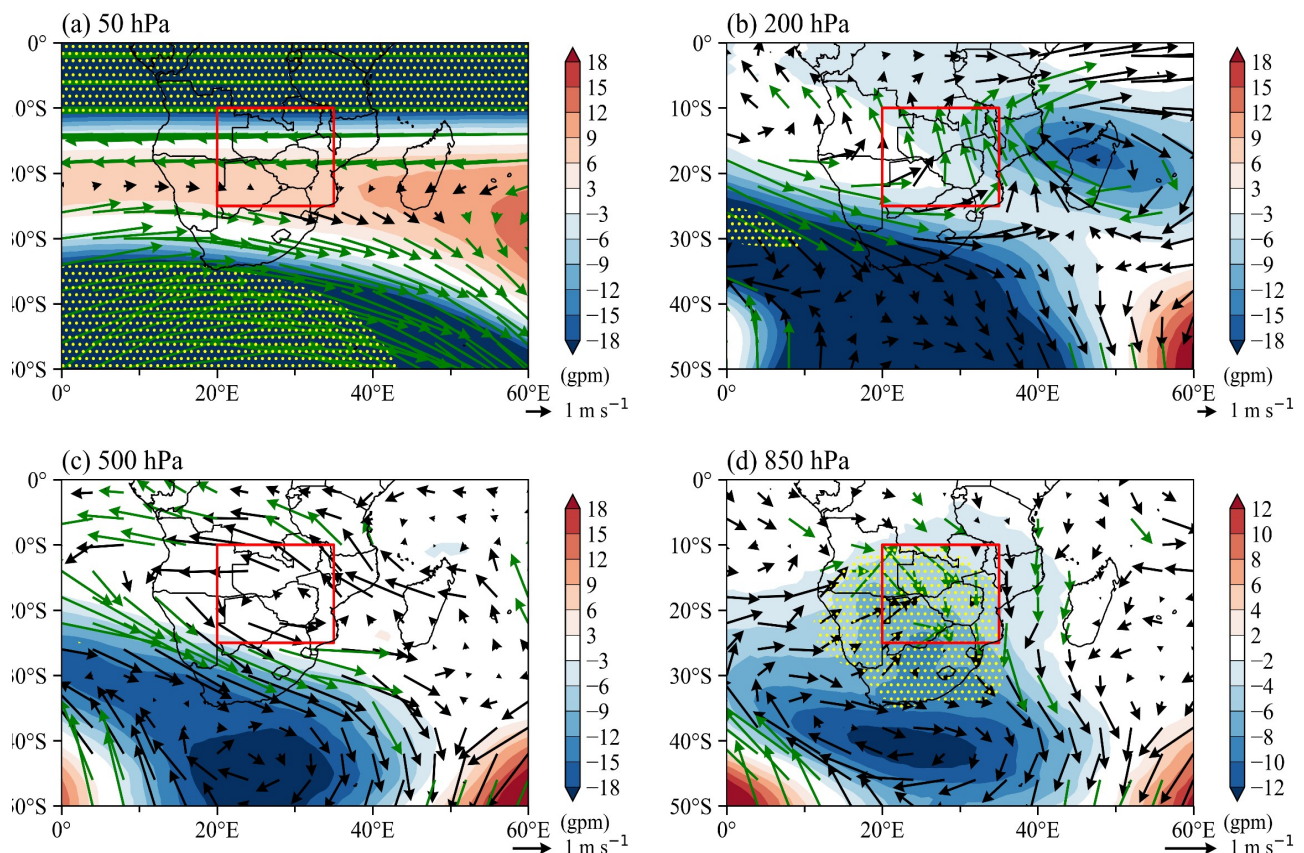


Figure 2. Composite differences; wind in meter per second (vectors, ms^{-1}) and geopotential height in geopotential-meter (shadings, gpm) anomalies between easterly phase (EQBO) and westerly phase (WQBO) at (a) 50 hPa, (b) 200 hPa, (c) 500 hPa, and (d) 850 hPa, respectively. Dotted areas and green vectors indicate anomalies that are significant at the 95% confidence level. The red box is the key area of study.

(b) WQBO phases, along with (c) their difference (EQBO minus WQBO). In the mid-troposphere, EQBO (WQBO) corresponds to an anomalous negative (positive) vertical velocity over the SWC area which favors ascending motion (**Figure 3(a)-(b)**). The composite difference (**Figure 3(c)**) reveals a statistically significant dipole pattern in vertical velocity anomalies across SEA and the SWC area, which is characterized by pronounced negative anomalies which cause upward motion. This pattern is dynamically consistent with the geopotential height anomalies observed in **Figure 2**. The existence of negative geopotential height over the SWC area at 50 hPa creates a region of low (high) pressure during EQBO (WQBO) years. This anomalous low (high) pressure in the low stratosphere causes upper-level convergence, which then favors sinking motion leading to surface warming. This suppresses convection at the surface over SWA (**Baldwin et al., 2001**).

This dipole in vertical motion provides a direct physical explanation for the surface temperature patterns described in **Figure 1**. The enhanced upward motion over the SWA area during EQBO favors increased cloud formation, which will block incoming solar radiation, which typically results in net cooling at the surface

(Thompson & Solomon, 2002). Conversely, the descending motion over SEA suppresses cloud formation, allowing for greater incoming solar radiation, leading to warmer surface temperatures. The consistency between the geopotential height, vertical velocity, and temperature fields underscores a robust tropospheric pathway for the QBO's influence.

Composite difference of 500hPa vertical velocity between the EQBO and WQBO years

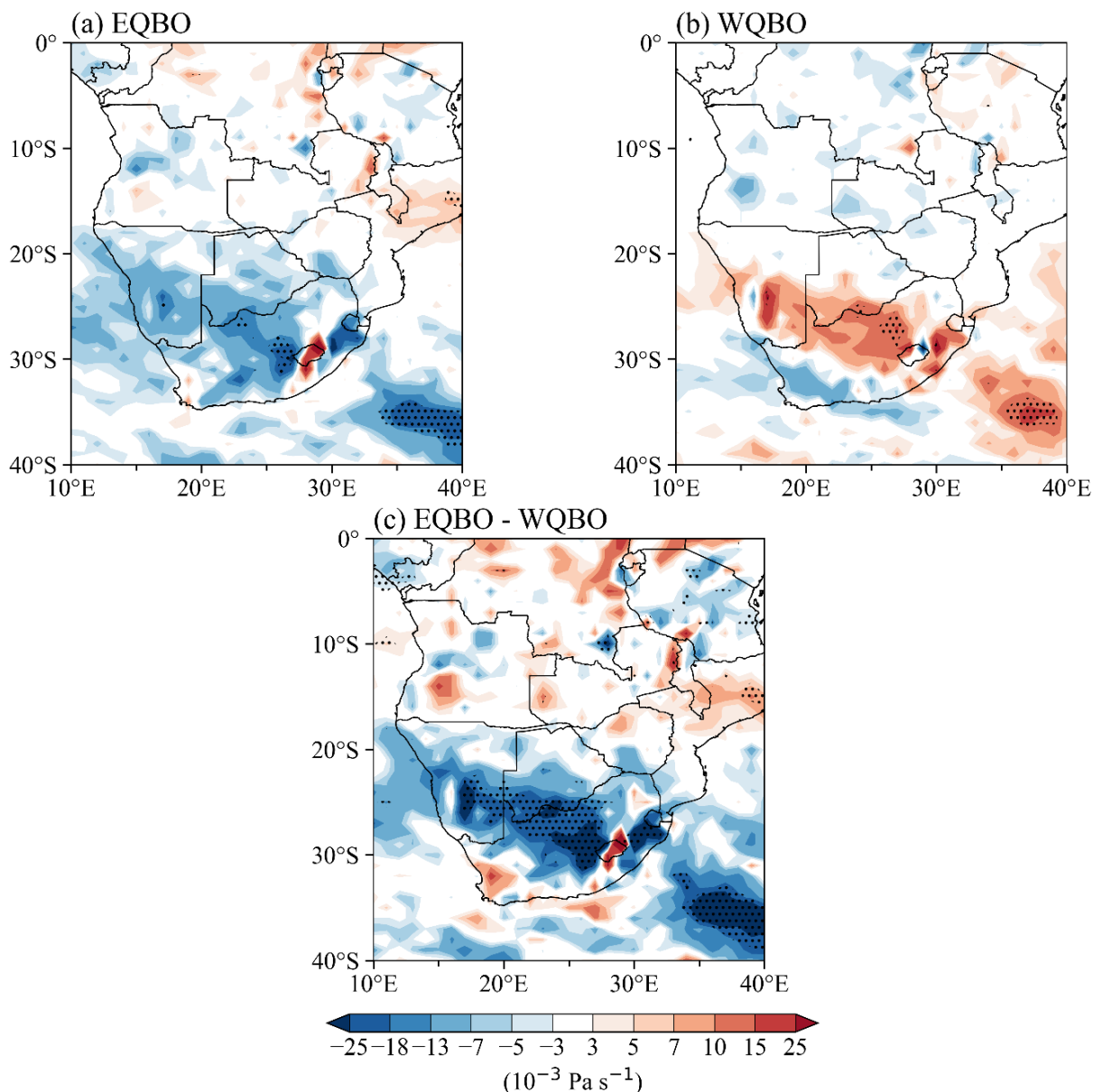


Figure 3. Composite 500 hPa vertical velocity in Pascal per second (Pa s^{-1}) for the (a) easterly phase (EQBO), (b) westerly phase (WQBO), and (c) the difference between EQBO and WQBO, respectively. Dotted areas are significant at 95% confidence level.

The modulation of atmospheric convection and cloudiness by the QBO is quantitatively assessed through OLR, a reliable representation of deep convective activity and high-level cloud cover. At the surface, EQBO (WQBO) corresponds to

an anomalous positive (negative) OLR over SEA, which favors lower-level divergence (convergence) (**Figure 4(a)-(b)**). Increased OLR is a well-established indicator of suppressed deep convection and decreased upper-level cloud cover (Luo et al., 2024). The increase (decrease) of OLR during EQBO in the SEA (SWC area) is a direct consequence of the dynamic forcing of sinking (rising), which stimulates divergence (convergence). This enhances (suppresses) latent heat release within these systems and contributes directly to the tropospheric warming (cooling) and the positive (negative) temperature anomalies observed at the surface (Thompson et al., 2002). This OLR pattern provides critical evidence linking the QBO-driven circulation anomalies to changes in cloud and convection that ultimately drive the surface temperature response.

Composite difference of the outgoing longwave radiation between the EQBO and WQBO years

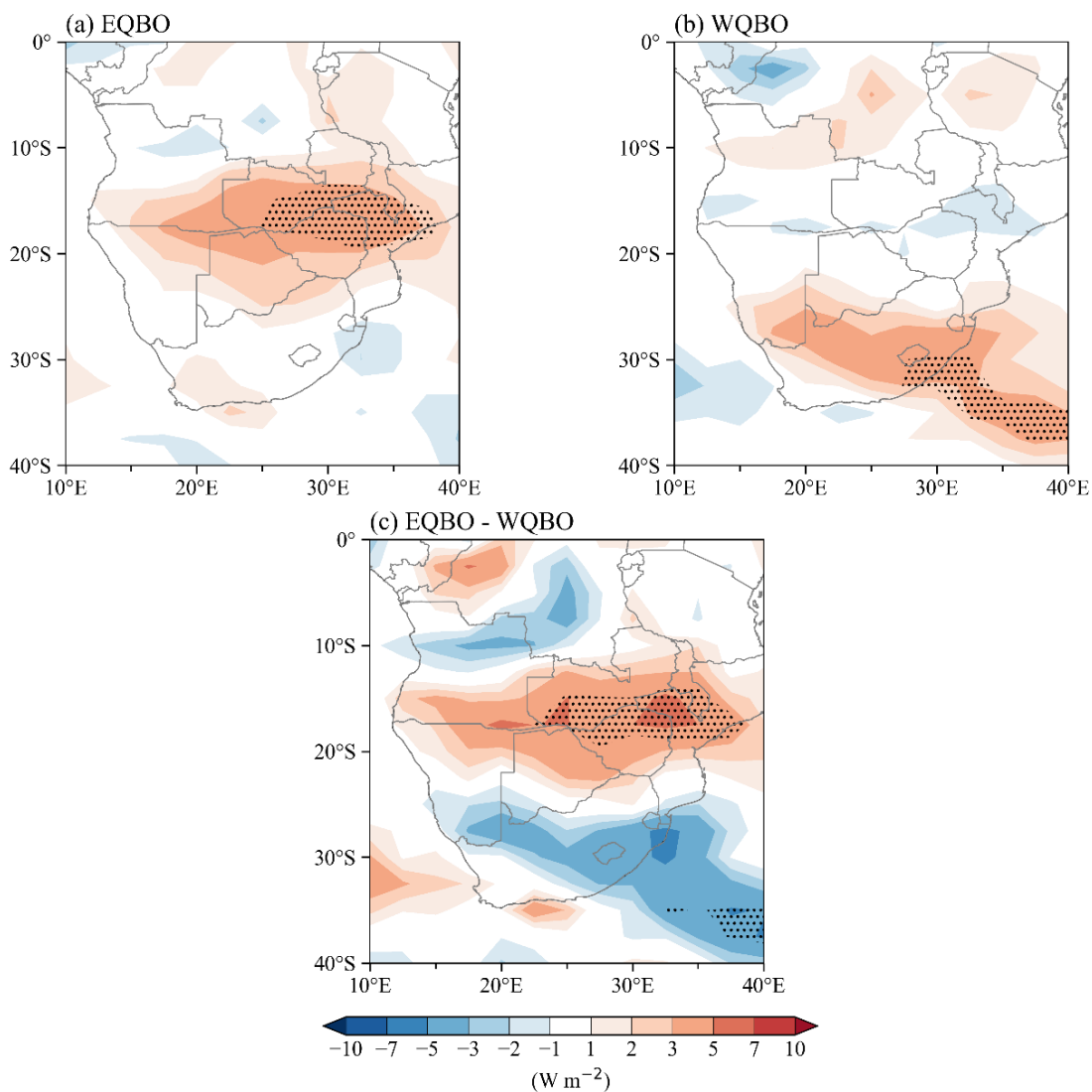


Figure 4. Composite outgoing longwave radiation in Watt per squared meter (Wm^{-2}) for the (a) easterly phase (EQBO), (b) westerly phase (WBQO), and (c) the difference between EQBO and WQBO, respectively. Dotted areas are significant at 95% confidence level.

A significant decrease in total cloud cover is observed over SEA during the EQBO (**Figure 5(a)**). This decrease in cloudiness directly explains the increased OLR values documented in **Figure 4**. Decreased cloud cover alters the local radiative budget by increasing the shortwave radiation (warming effect) (**Hartmann & Lo, 1998**). The co-location of decreased cloud cover (**Figure 5(c)**) and positive OLR anomalies (**Figure 4(c)**) forms a physically consistent and robust explanation that conclusively explains the mechanism behind the surface warming over the continental interior.

Composite difference of the total cloud cover between the EQBO and WQBO years

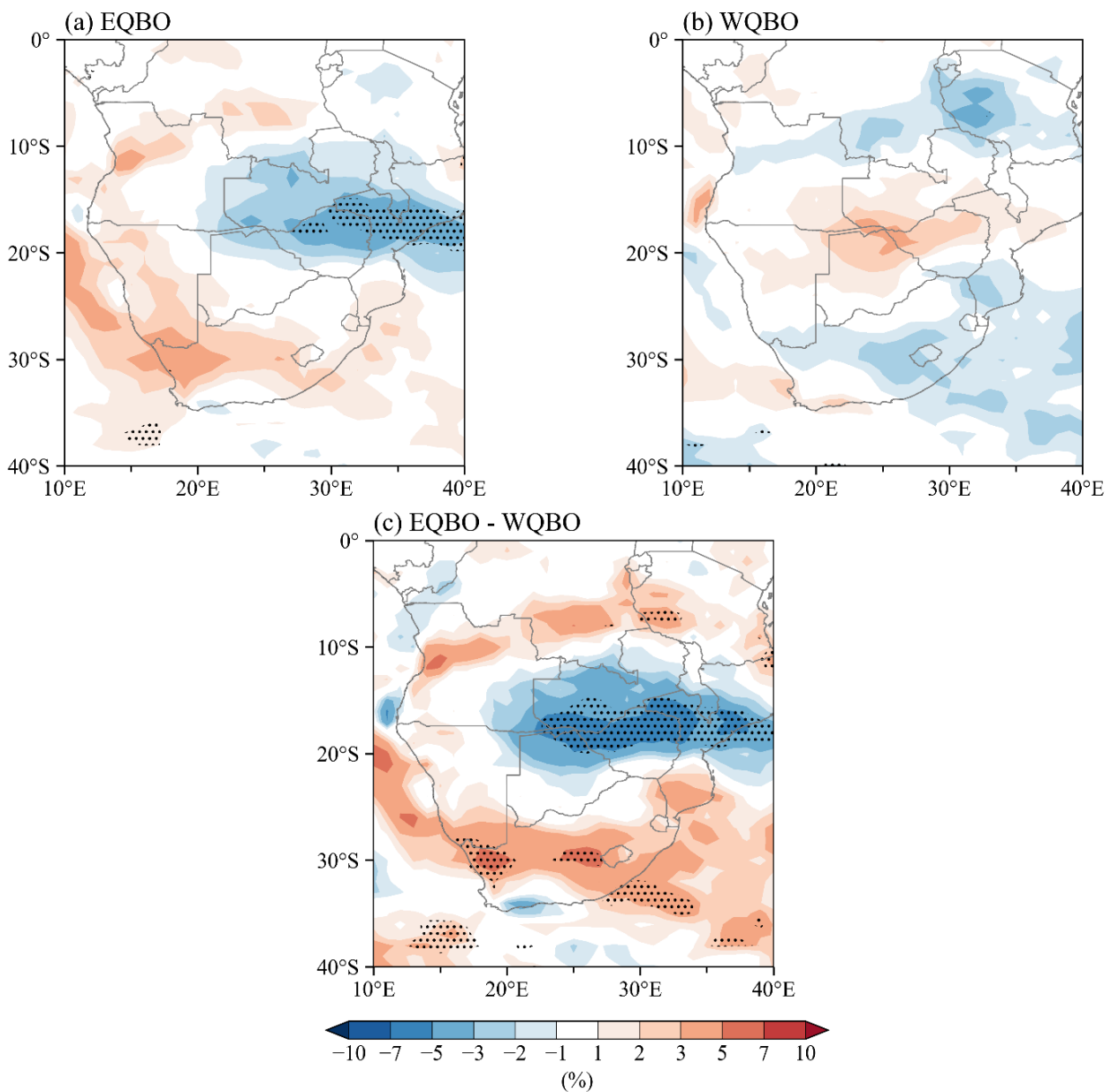


Figure 5. Composite cloud cover in percentage (%) for the (a) easterly phase (EQBO), (b) westerly phase (WBQO), and (c) the difference between EQBO and WQBO, respectively. Dotted areas are significant at 95% confidence level.

3.3. Latitudinal and Vertical Distribution of QBO over SA

To consolidate the stratospheric initiation of the teleconnection and illustrate the vertical coupling into the troposphere, **Figure 6** shows the latitude-pressure cross-section of the zonal wind composite difference (EQBO minus WQBO), averaged over the longitudinal domain of SA ($0^{\circ}\text{E} - 40^{\circ}\text{E}$). The cross-section reveals the canonical QBO wind signal in the tropical lower stratosphere, with a core of significant easterly anomalies centered at the equator, consistent with the definition of the EQBO phase at 50 hPa (Baldwin & Dunkerton, 2001). **Figure 6** demonstrates that this stratospheric anomaly is not confined to the tropics

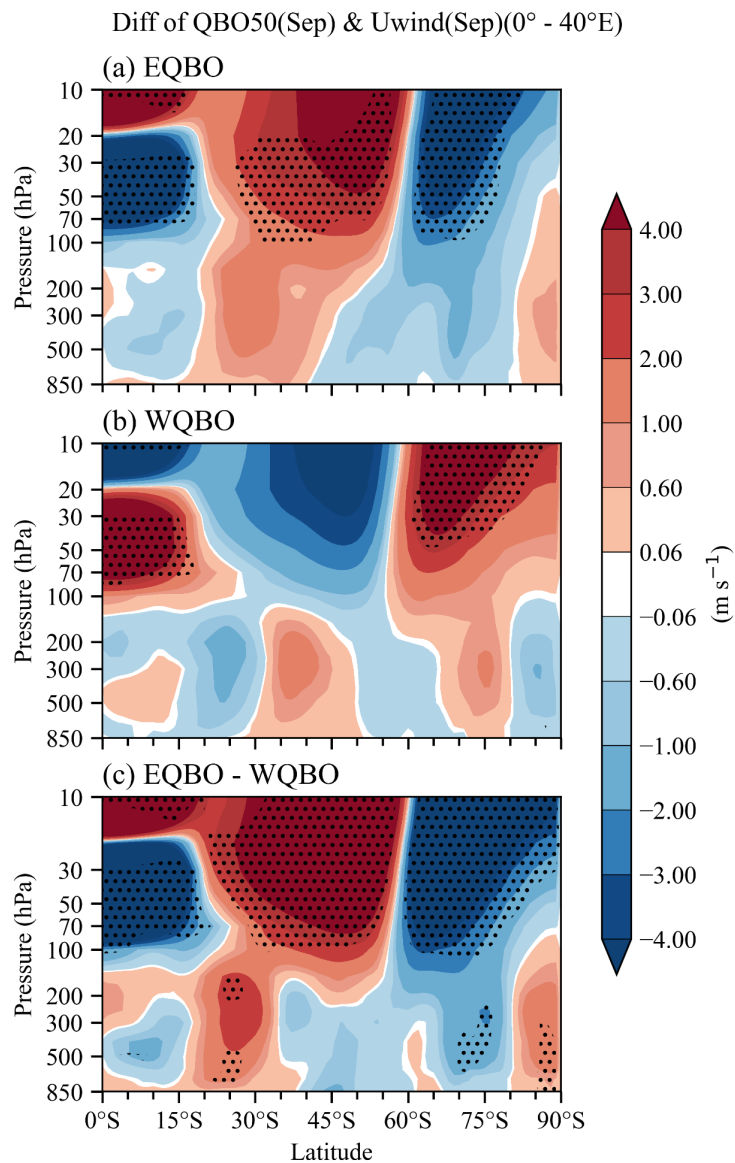


Figure 6. Composite difference of 50 hPa QBO and uwind (ms^{-1}) during September for the (a) easterly phase (EQBO), (b) westerly phase (WBQO), and (c) the difference between EQBO and WQBO, respectively. Dotted areas are significant at 95% confidence level. Latitudinal values were averaged between 0°E and 40°E longitudes.

but extends its influence both poleward and downward. A pronounced dipole pattern emerges, with the equatorial easterly anomalies bordered by significant westerly anomalies in the mid-latitudes. This meridional dipole structure descends from the stratosphere deep into the troposphere, creating a distinctive vertical wind shear pattern that reaches the mid-troposphere around 20°S - 30°S.

This deep vertical structure is consistent with a mechanism whereby the QBO, by altering the background wind and thermal structure in the stratosphere, diverts planetary waves and modulates the subtropical tropospheric jet stream (Garfinkel & Hartmann, 2011; Gray et al., 2018). The resulting anomalous circulation, characterized by the descending westerly margin over the subtropics, directly projects onto the tropospheric circulation over the African sector. Therefore, this cross-section confirms the existence of a coherent vertical pathway, establishing how the tropical QBO can distantly force the circulation, cloud, and temperature anomalies over SA during the early austral spring.

4. Conclusion

This study provides conclusive evidence that the QBO is a significant driver of early austral spring SAT variability over SA. By analyzing the relationship between the 50 hPa QBO index and September climate fields, we have identified a clear teleconnection pathway that originates in the tropical stratosphere and projects onto regional tropospheric circulation.

The key finding is a distinct dipole pattern in surface temperature response: EQBO is associated with significant warming over SEA and associated with cooling along the SWC. This pattern is not just a statistical artifact but is supported by a physical mechanism. The teleconnection is initiated by the QBO's influence on the stratospheric circulation, which propagates downward and poleward, establishing as a quasi-barotropic wave-like pattern in geopotential height. This results in an anomalous anticyclonic circulation over the SWIO, which in turn drives a dipole in vertical velocity, enhancing sinking and divergence over SEA and promoting ascent over the SWC area. The thermodynamic implications of this circulation anomaly are clear. The region of enhanced upward motion exhibits reduced OLR and a significant increase in total cloud cover, confirming strengthened convective activity. This provides the direct physical link to the cooling observed over SWC area. Conversely, the suppressed convection and clearer skies under the subsidence branch explain the warming signal along the SEA.

Our results are consistent with the broader understanding of QBO teleconnections that its influence extends effectively into the Southern Hemisphere subtropics (Gray et al., 2018). The vertical cross-section of zonal wind anomalies confirms the deep coupling from the equatorial stratosphere into the subtropical troposphere over Africa, illustrating the viability of this pathway.

In summary, this work identifies the QBO as a previously overlooked stratospheric precursor for seasonal temperature variability in SA during September. The intra-seasonal climate variability during September, particularly thermal re-

gimes, serves as the principal determinant for agricultural decision-making at the onset of the cropping season. The cumulative heat units and the incidence of extreme temperatures in this period directly regulate the planting date, a non-compensable factor that establishes the ceiling for potential yield by governing phenological development and ultimately dictating seasonal productivity and farm-level food security. Incorporating the state of the QBO into seasonal prediction models could potentially enhance the skill of early spring temperature outlooks, with valuable applications for sectors such as agriculture and water resource management. For instance, more reliable temperature forecasts could directly inform the timing of planting dates for key crops (e.g., maize), helping to avoid heat stress during critical germination stages and supporting yield potential. Furthermore, anticipating warm and dry conditions associated with the identified SAT patterns can improve seasonal water demand forecasts, guiding reservoir management and irrigation planning to enhance water-use efficiency and food security at the farm level. Our study relies on reanalysis data and uses linear methods to remove the influence of other climate modes, which may not capture non-linear interactions. Future work will incorporate model experiments and non-linear methods to confirm its potential interactions with other major modes of climate variability, such as the ENSO and the 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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