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Assessing the Impact of the South Indian Ocean High-Pressure System Using a Novel Index

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ABSTRACT

The South Indian Ocean High-Pressure (SIOHP) system plays a crucial role in modulating atmospheric circulation, precipitation, and temperature patterns across the Indian Ocean basin and adjacent regions. Despite its significance, a comprehensive index for quantifying SIOHP variability, intensity, and impacts has been lacking. To address this gap, this study utilises a novel SIOHP index to systematically assess its climatic influence. Our findings reveal that the SIOHP's seasonal variability significantly impacts regional precipitation, temperature, and humidity. During austral winter (JJA), a stronger SIOHP is associated with drier and cooler conditions in southeastern Africa and Madagascar, while its weakening in summer (DJF) corresponds to increased precipitation in these regions. Additionally, a westward shift of the SIOHP enhances rainfall in southwestern Australia, mitigating drought conditions. Furthermore, the SIOHP-driven moisture transport plays a vital role in shaping regional hydroclimate variability, influencing moisture advection and precipitation. These findings highlight the SIOHP's critical role in regional climate variability, underscoring the need for further research on its drivers and interactions with larger climate modes. This study provides a quantitative framework for improving seasonal forecasting, climate adaptation planning, and early warning systems in a changing climate.

1 | Introduction

The South Indian Ocean High-Pressure (SIOHP) system is a dominant subtropical anticyclone associated with the descending branch of the Hadley circulation. It plays a crucial role in modulating atmospheric and oceanic circulation across the Indian Ocean basin, influencing climate variability in Southern Africa, East Africa, the Indian subcontinent, Australia, Madagascar, and surrounding islands (Lennard 2019; Dhame et al. 2020). This high-pressure system regulates key weather patterns, including monsoons, tropical cyclones, and rainfall variability, while also impacting sea surface temperatures (SSTs), ocean salinity, and regional wind patterns (Reason and Rouault 2005; Morioka et al. 2015; Lazenby et al. 2016; Reason 2016; Phillips et al. 2021; Lazenby and Todd 2023). The intensity and position of the SIOHP can significantly affect hydrological extremes,

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such as prolonged droughts and intense flooding events, with profound implications for water resources, agriculture, and ecosystems in the affected regions.

Although the SIOHP's geographic positioning and seasonal shifts suggest a strong influence on local and regional climate, studies directly assessing its impact remain relatively limited. Most existing research has primarily focused on larger-scale climate oscillations, such as the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO), without explicitly isolating the role of the SIOHP as an independent driver of climate variability (Terray et al. 2005; Manhique et al. 2011; Dieppois et al. 2015). However, interactions between the SIOHP and these large-scale climate modes contribute to significant fluctuations in temperature, precipitation patterns, and atmospheric circulation across the region (Hameed et al. 2011; Lenka et al. 2022). A more refined understanding of the SIOHP's variability and influence is therefore critical for improving seasonal forecasting, enhancing climate model simulations, and strengthening disaster risk management strategies.

Despite the recognised importance of the South Indian Ocean High-Pressure (SIOHP) system in shaping regional climate, relatively few studies have developed comprehensive indices to quantify its variability and intensity (e.g., Rizvi and Iqbal 2017; Rehman et al. 2019; Rehman et al. 2024, Goddard and Graham 1999). Quagraine et al. (2025) introduced a novel SIOHP index, expanding on the methodology previously applied to the South Atlantic High-Pressure system by Quagraine et al. (2024). This index, based on mean sea level pressure (MSLP), a widely available and reliable variable, offers a systematic and practical framework for improving our understanding of the behaviour and variability of the SIOHP.

Building on previous work, this study applies the SIOHP index to evaluate the climatic influence of the SIOHP system across the Indian Ocean basin and adjacent continental regions. The use of this index enables a systematic and quantitative assessment of the spatiotemporal variability of the SIOHP, its interactions with other large-scale climate drivers, and its role in modulating regional hydroclimatic extremes. In addition to advancing mechanistic understanding of subtropical high-pressure systems, the findings offer practical insights for improving early warning capabilities and informing climate adaptation and resilience planning. The analysis specifically focuses on identifying SIOHP-associated anomalies in temperature and precipitation, with implications for forecasting and long-term climate risk assessments.

2 | Data and Methods

2.1 | Data

The primary dataset used for categorising the Southern Indian Ocean High Pressure (SIOHP) system is the mean sea level pressure (MSLP) from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5). The ERA5 dataset offers high-resolution data (0.25° ×0.25°) with hourly temporal coverage. Spanning from 1950 to the present, it provides quality-assured monthly updates and preliminary daily updates available within 5 days in real-time (Hersbach et al. 2020; Antonini et al. 2024).

For atmospheric composites and precipitation analyses, we utilise both ERA5 and the Integrated Multi-satellite Retrievals for GPM (IMERG) precipitation dataset (Huffman et al. 2015). The IMERG dataset is preferred for precipitation studies due to its finer spatial and temporal resolution, its accurate near-real-time and post-real-time precipitation estimates, and its ability to effectively capture the spatiotemporal variability and patterns of extreme precipitation events. GPM-IMERG is an observational dataset derived from satellite-based measurements, specifically designed to capture precipitation using instruments such as the Dual-Frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), which are particularly effective at detecting light and solid precipitation (Hou et al. 2014). The GPM IMERG algorithm combines, calibrates, and integrates infrared (IR), microwave (MW), and gauge-based observations to produce high-resolution precipitation estimates (0.1° ×0.1° at 30-min intervals) (Huffman et al. 2015). Furthermore, IMERG has proven to provide reliable precipitation estimates for the region under consideration (Ramahaimandimby et al. 2022; Pradhan et al. 2022).

2.2 | Methods

The SIOHP index over the 20°S–40°S and 35°E–100°E domain was developed following the methodology outlined in Quagraine et al. (2024). In that study, the subtropical high-pressure index was defined using a robust approach that dynamically adjusts the isobar threshold for each identified high-pressure system to estimate the contiguous area surrounding the maximum pressure. Using mean sea level pressure (MSLP) as the primary variable, the SIOHP monthly index was calculated as the weighted centroid of the area identified within 3 hPa of the maximum pressure. The choice of MSLP as a proxy for high-pressure systems was based on its role as a direct and reliable measure of atmospheric pressure at the surface, making it a practical and effective indicator for identifying such systems (See Supporting Information for more details on calculation).

To evaluate the concurrent impacts of the SIOHP system, we first analysed its surrounding regions. Seasonal anomalies were computed relative to the climatological mean (1979–2021), and their significance was assessed using the Student's *t*-test (Lydersen 2015). Additionally, we examined the regional correlation of key atmospheric variables (specific humidity, Q; 2 m-temperature, T; potential vorticity, PV, and geopotential height, Z) with the SIOHP.

We note here that while correlation does not imply causation, identifying statistical relationships between physically co-located dynamic systems and weather patterns enhances our understanding of regional climate variability (Barry and Carleton 2013). To achieve this, we computed Pearson's correlation coefficients for all assessed variables across different regions, including Madagascar, Australia, the South Asian islands, and southeastern Africa (see Table 1). The choice of Pearson's correlation was to help quantify how strongly and in what direction the SIOHP relates to the key atmospheric

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variables. For instance, a negative Pearson correlation coefficient between SIOHP and any of the atmospheric variables would infer an inverse relationship and vice versa.

3 | Results

The results presented in this study highlight the significant influence of the South Indian Ocean High-Pressure (SIOHP) system on regional atmospheric and climate dynamics across the Indian Ocean basin and adjacent areas. Employing a novel SIOHP index, we analysed its seasonal variability and impacts on key meteorological variables, including temperature, specific humidity, geopotential height, and potential vorticity. The findings reveal distinct spatial and temporal patterns, underscoring the SIOHP's pivotal role in modulating atmospheric circulation, stability, and moisture distribution. These results provide critical insights into the SIOHP's contribution to regional weather systems and its potential sensitivity to climate change, offering a robust foundation for further investigation of its interactions with global climatic oscillations.

The results reveal distinct seasonal patterns in surface pressure variations. During summer (DJF), there is a general reduction in surface pressure and decreased SIOHP intensity (Figure 1a). Conversely, the winter season (JJA) shows an intensification of the SIOHP with increased surface pressure (Figure 1c). This seasonal pattern aligns with the findings of Quagraine et al. (2025) as shown in the Supporting Information S1.

The transition seasons, autumn (MAM) and spring (SON), exhibit the progressive changes in the SIOHP system. Autumn is characterised by gradual SIOHP intensification with building high-pressure anomalies (Figure 1b), while spring shows a decline in SIOHP intensity accompanied by decreasing surface pressure (Figure 1d). Climatologically significant surface pressure intensification ($\geq$10 hPa) is observed primarily over Australia, parts of Madagascar, and mainland southeastern Africa. This observation underscores the SIOHP's influence on

TABLE 1 | Regions under the impact of SIOHP.

Region	Madagascar	Australia	Southeast Africa	South Asia Islands
Boundaries	[40°–50°] E [15°–30°] S	[115°–135°] E [15°–50°] S	[20°–40°] E [15°–40°] S	[110°–130°] E [0°–10°] S

Note: The table shows the regional boundaries under the impact of SIOHP.

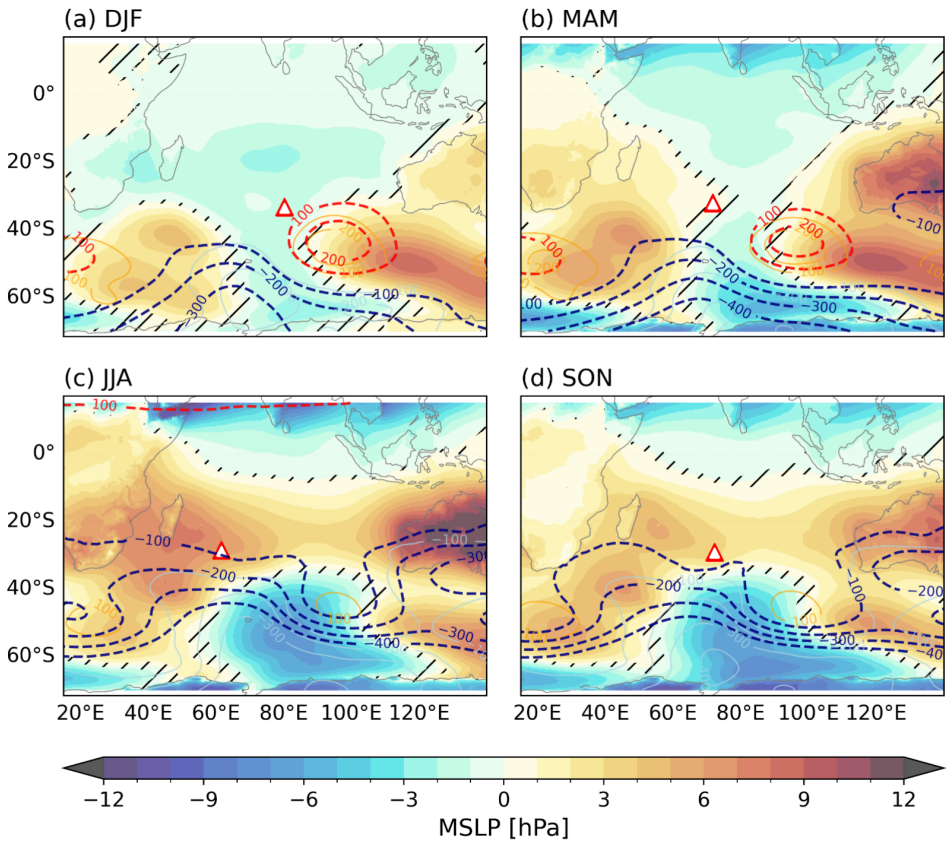

FIGURE 1 | Seasonal sea level pressure anomalies. The figure shows the seasonal sea level pressure anomalies (shading) overlaid with geopotential height anomalies at 150 hPa (contours; red is positive and blue is negative). South Indian high-pressure centroid (triangle). Hatched areas are non-significant surface pressure anomalies. [Colour figure can be viewed at wileyonlinelibrary.com]

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these regions, which is consistent with previous studies highlighting its impact on regional climate variability (Lennard 2019; Dhame et al. 2020). Also, an interesting vertical structure with a low-pressure geopotential height anomaly above the surface high-pressure anomaly is observed. This configuration suggests surface divergence and upper-level (150 hPa) divergence, although the pattern inverts during winter. This vertical structure plays a crucial role in shaping regional weather patterns and atmospheric circulation. A notable feature is the persistent high-pressure system southwest of Australia, present across all seasons. This consistent presence suggests its importance in regional weather patterns regardless of seasonal variations (Lenka et al. 2022). It may be associated with clear-sky conditions when other atmospheric parameters are favourable, potentially influencing the local climate in southwestern Australia and the adjacent ocean areas.

Figure 2 illustrates the seasonal variations in specific humidity anomalies across the Indian Ocean basin, providing insights into the atmospheric moisture patterns in relation to the South Indian Ocean High-Pressure (SIOHP) system. During summer (DJF) and autumn (MAM), the atmosphere is generally more humid (> 2 g/kg) in central Australia and southern Madagascar (Figure 2a,b). This increased humidity during these seasons could be attributed to warmer temperatures and enhanced evaporation rates. Interestingly, the immediate vicinity (within a 5° radius) of the SIOHP maintains higher moisture levels compared with other study regions across all seasons. This observation suggests that the SIOHP may play a role in moisture accumulation or retention in its immediate surroundings, potentially influencing local weather patterns. In contrast to summer and autumn, the winter (JJA) and spring (SON) seasons experience significant atmospheric dryness (> −3 g/kg) across all regions surrounding the SIOHP (Figure 2c,d). This pattern indicates a strong association between the SIOHP and dry conditions during these seasons, which aligns with the typical characteristics of high-pressure systems promoting subsidence and clear skies. During summer and autumn, localised dry patches are observed near the SIOHP. These dry areas might be a result of localised subsidence associated with the high-pressure system, creating pockets of reduced humidity amidst generally more humid conditions.

The seasonal shifts in humidity patterns may have implications for the development and intensity of regional weather systems. For instance, the increased moisture during summer and autumn could potentially fuel tropical cyclones or monsoon systems, while the drier conditions in winter and spring might suppress convective activity. This is consistent with previous research highlighting the SIOHP's impact on weather phenomena such as monsoons and tropical cyclones (Reason and Rouault 2005; Rizvi and Iqbal 2017; Morioka et al. 2015).

The observed humidity patterns closely correspond with seasonal precipitation patterns, as noted in the analysis of Figure 3, which provides a comprehensive visualisation of how the South Indian Ocean High-Pressure (SIOHP) system modulates

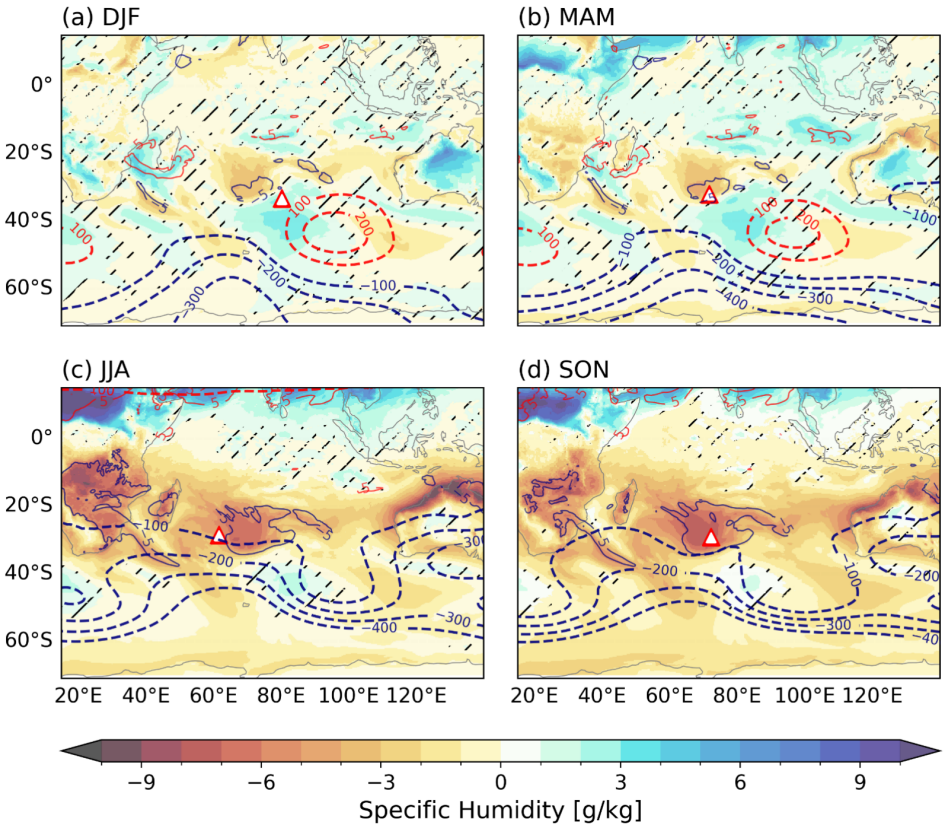

FIGURE 2 | Seasonal specific humidity anomalies. The figure shows the seasonal specific humidity anomalies (shading) overlaid with geopotential height anomalies at 150 hPa (contours; red is positive and blue is negative). South Indian high-pressure centroid (triangle). Hatched areas are non-significant specific humidity anomalies. [Colour figure can be viewed at wileyonlinelibrary.com]

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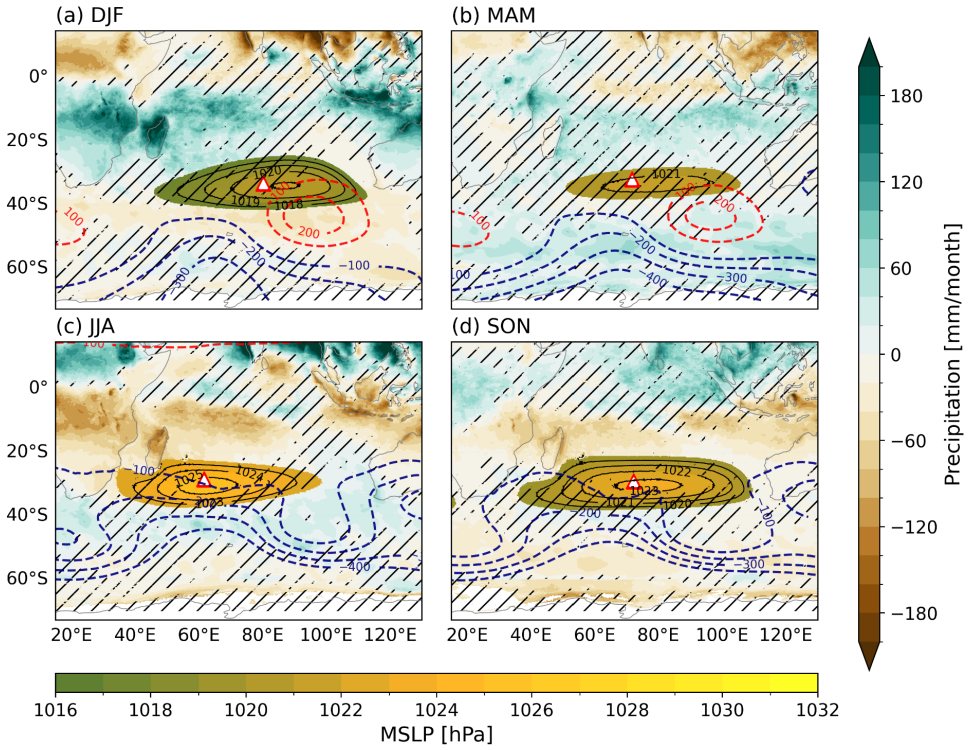

FIGURE 3 | Seasonal precipitation anomalies. Figure shows the seasonal precipitation anomalies (brown-green shading), and sea level pressure (green-yellow shading) overlaid with geopotential height anomalies at 150 hPa (contours; red is positive and blue is negative). South Indian high-pressure centroid (triangle). Hatched areas are non-significant precipitation anomalies. [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation patterns across the region. The interplay between sea level pressure (SLP), geopotential height anomalies, and precipitation anomalies reveals a complex but clear relationship. For instance, the SIOHP's seasonal movement significantly influences regional rainfall patterns (Han et al. 2017; Rehman et al. 2019, 2024). During summer (DJF), we observe a weakened SIOHP with substantial precipitation increases between 0° and 30°S, with rainfall exceeding 80 mm/month—the highest among all seasons. This coincides with the SIOHP's southeastward shift from Madagascar, resulting in increased rainfall in the region (Figures 2 and 3a,b).

The transition seasons, autumn (MAM) and spring (SON) demonstrate progressive changes in the SIOHP system and its impact on precipitation. During autumn, we observe gradual SIOHP intensification with building high-pressure anomalies across the Indian Ocean. This likely leads to a gradual shift in precipitation patterns, transitioning from wet summer conditions towards drier winter patterns. Spring (SON) exhibits the opposite pattern, characterised by SIOHP intensity decline accompanied by decreasing surface pressure and low-pressure development (Figure 3d). This season likely sees a gradual increase in precipitation as the system transitions from the drier winter patterns to the wetter summer conditions. The SIOHP intensifies in winter (JJA) showing an increased surface pressure (Figure 3c) associated with a distinctive latitudinal band of positive rainfall anomalies during this season (e.g., Rehman et al. 2024). This suggests that the intensified high-pressure system in winter plays a role in organising regional rainfall, albeit with generally drier conditions compared with summer (DJF).

The relationship between SIOHP intensity and precipitation is further highlighted by examining the vertical structure of the atmosphere. It is observed that low-pressure geopotential height anomalies (shown by blue contours) often occur above high-pressure areas on the surface. This configuration indicates surface divergence and upper-level (150 hPa) divergence, though this pattern is inverted during winter. Such vertical structures can significantly influence atmospheric stability and moisture transport, thereby modulating precipitation (Usmani et al. 2019).

A clear north–south precipitation gradient emerges during summer, with dry conditions south of the SIOHP and wet conditions to the north. This pattern undergoes a reversal by winter, characterised by minimal precipitation anomalies in the south and predominant dryness north of the SIOHP. This seasonal reversal in the precipitation gradient highlights the SIOHP's role as a key modulator of rainfall distribution in the region. The consistent presence of a high-pressure system southwest of Australia across all seasons, typically associated with clear-sky conditions when other atmospheric parameters are favourable, further demonstrates the SIOHP's persistent influence on regional weather patterns.

Figure 4 depicts the seasonal changes in 2 m-temperature anomalies in relation to upper-level (150 hPa) geopotential height anomalies in the Southern Indian Ocean region. The analysis identifies clear seasonal distribution patterns for temperature, using the SIOHP centroid location as a key reference. In summer (DJF), positive temperature anomalies (3–6 K) are prevalent in the midlatitudes (30°S–50°S), especially near the

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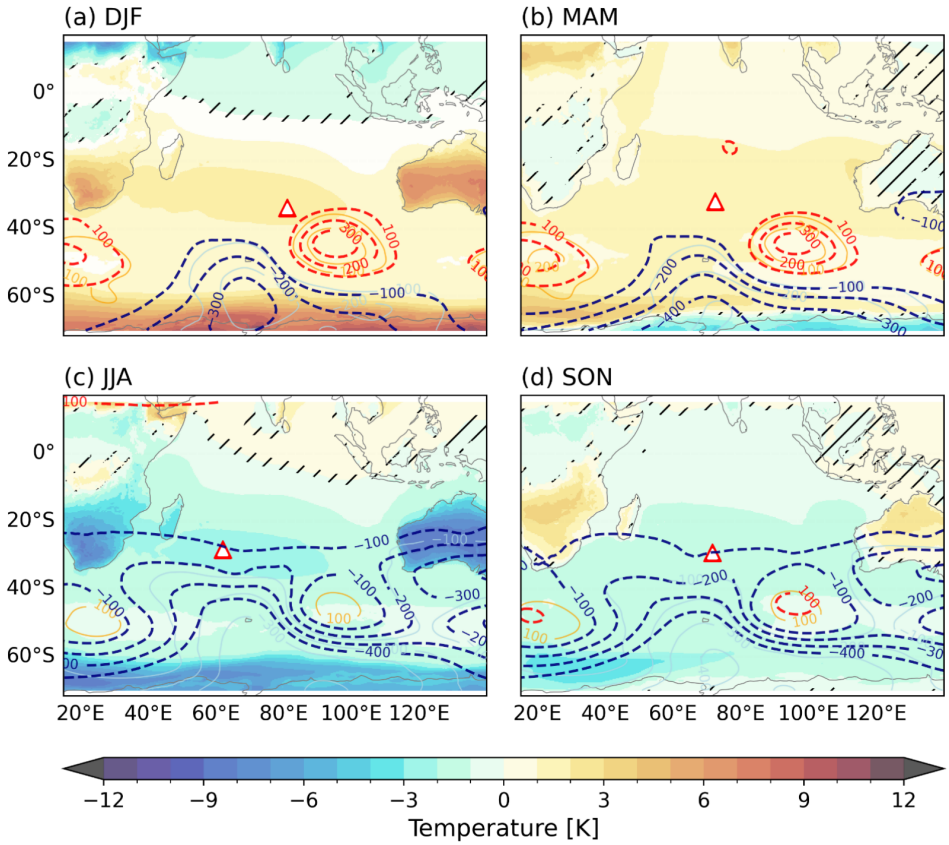

FIGURE 4 | Seasonal 2 m—Temperature anomalies. Figure shows temperature anomalies (shading) overlaid with 150 hPa geopotential height anomalies. The red triangle is the SIOHP centroid location. Hatches represent locations with non-significant temperature anomalies. [Colour figure can be viewed at wileyonlinelibrary.com]

SIOHP centroid. These warm anomalies correlate with positive geopotential height anomalies, indicating a continuing high-pressure influence. In autumn (MAM), this pattern continues, although with a slight decrease in the intensity of both temperature and geopotential height anomalies. A significant change is noted in winter (JJA), marked by substantial negative temperature anomalies (6–10 K) across the subtropical and mid-latitude regions, with particularly severe cooling in the western Indian Ocean, where values exceed 9 K. This phenomenon corresponds with negative geopotential height anomalies, demonstrating a strong link between upper-level atmospheric circulation and surface temperature conditions. The spring season (SON) brings a gradual return to warmer temperatures, although some cooler anomalies linger in the subtropical regions. This transitional behaviour illustrates the dynamic nature of the region's climate as it shifts from winter to summer conditions.

The temperature anomalies consistently relate to upper-level (150 hPa) geopotential height patterns throughout the seasons. Summer and autumn's warm anomalies align with positive height anomalies, suggesting a sustained high-pressure effect, while winter cooling correlates with negative height anomalies. This relationship illustrates the strong impact of atmospheric dynamics on regional temperature variability.

The considerable anomalies across much of the region indicate strong temperature signals, particularly in the mid-latitudes during winter. The statistical significance of these observations reinforces the reliability of the seasonal temperature patterns and their connection to upper-level atmospheric dynamics. The temperature patterns observed have substantial implications for regional climate, where the strong seasonal variations in temperature, influenced by the SIOHP's behaviour, play an essential role in shaping ecosystems, agriculture, and human activities in these areas. This is consistent with prior studies highlighting the SIOHP's effect on regional climate variability (Lennard 2019; Dhame et al. 2020).

The South Indian Ocean High-Pressure (SIOHP) system exhibits distinct seasonal patterns in its relationship with atmospheric variables (Q, T, PV, and Z) across different regions, as shown in Figure 5. During summer (DJF), temperature shows predominantly negative correlations across all regions, while humidity displays regional variation, with Madagascar showing a notably positive correlation. These patterns align with Reason and Rouault's (2005) findings of SIOHP-induced cooling during austral summer. The moisture patterns likely reflect SIOHP's interaction with regional monsoon systems, aligning with an earlier study by Terray et al. (2005).

A significant shift occurs during autumn (MAM) when temperature correlations become strongly positive for Southeast Africa and Australia while remaining weakly positive for Madagascar and the South Asian Islands. Geopotential height shows weak correlations across all regions during this period.

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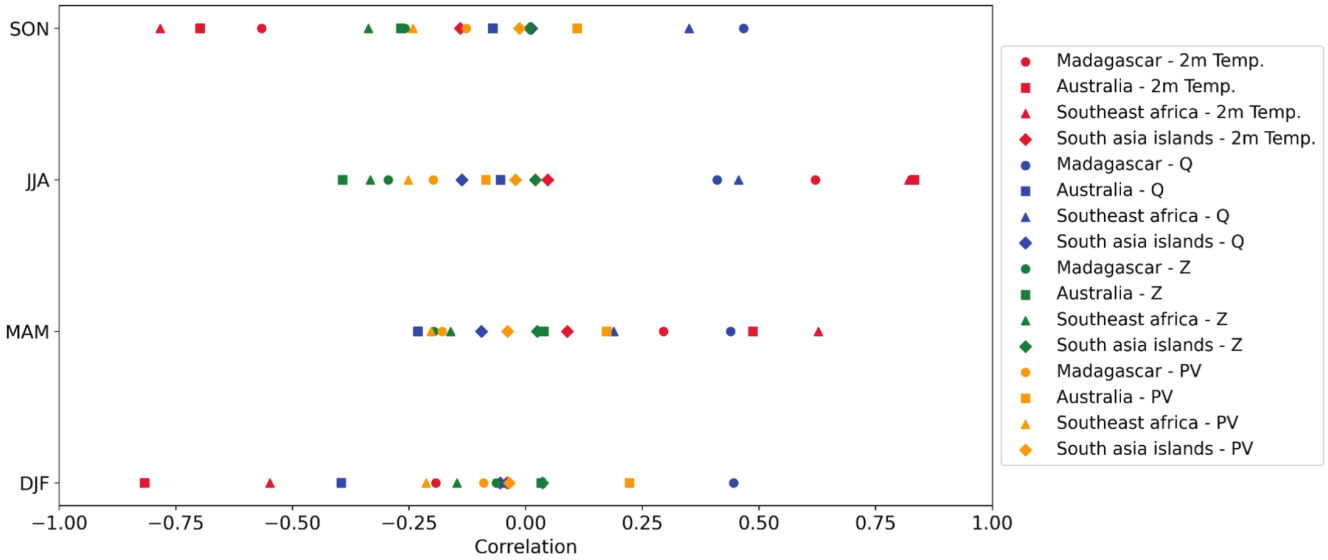

FIGURE 5 | Correlation between SIOHP and atmospheric variables 2 m temperature (2 m Temp.), specific humidity (Q), geopotential height anomalies (Z), and potential vorticity (PV). The figure shows the correlation between SIOHP and anomalies of atmospheric variables (Q, T, PV, and Z). Different shapes represent different regions, and different colours represent different variables. Red for T, blue for Q, Green for Z, and yellow for PV. [Colour figure can be viewed at wileyonlinelibrary.com]

This transitional period in atmospheric patterns aligns with Reason's (2016) observations of shifting large-scale circulation patterns.

In winter (JJA), we see robust positive temperature correlations in Australia and Southeast Africa, while Madagascar shows a moderate positive correlation. During this season, humidity correlations also become moderately positive for Madagascar and Southeast Africa. These observations indicate that the intensification of SIOHP may play a role in winter warming and elevated regional moisture, thereby supporting the conclusions of Lazenby et al. (2016) regarding regional rainfall patterns.

Temperature correlations return to negative values across all regions, with Australia and Southeast Africa showing the strongest negative correlations in spring (SON). Results show varying humidity patterns across the different regions: Madagascar and Southeast Africa experience moderately positive correlations, whereas Australia and South Asia Islands experience weak negative correlations. These patterns align with the work by Morioka et al. (2015) on SIOHP's influence on rain-bearing systems.

Some patterns remain consistent throughout the year. For instance, geopotential height maintains weak to very weak negative correlations year-round, while potential vorticity correlations vary by season and region, suggesting complex interactions with atmospheric stability. This seasonal analysis reveals the SIOHP's dynamic influence on regional climate patterns, with particularly notable transitions between summer and winter regimes. The complex interplay between these variables demonstrates the significant role of the SIOHP in shaping regional climate dynamics across the Southern Hemisphere.

4 | Conclusion

Understanding the role of large-scale atmospheric systems in modulating weather and climate is crucial in the context of a changing climate. This study has assessed the impact of the South Indian Ocean High-Pressure (SIOHP) system on key atmospheric variables: temperature, specific humidity, and geopotential height (Q, T, PV, Z). Our findings underscore the SIOHP's critical role in shaping regional climate dynamics, particularly in modulating seasonal precipitation, temperature variability, and moisture transport across the Indian Ocean basin and adjacent landmasses.

The results reveal that the SIOHP's influence varies significantly across seasons and regions, reinforcing the need for season-specific and region-specific approaches in climate analysis and forecasting (eg. Murtugudde and Annamalai 2004). During the austral winter (JJA), when the SIOHP is strongest and positioned closer to southeastern Africa, it is associated with drier and cooler conditions in this region. Conversely, a weakened SIOHP during summer (DJF) corresponds to increased precipitation over Madagascar, southeastern Africa, and parts of the Indian Ocean. These findings align with previous studies, such as Randriamarolaza et al. (2022), which suggest that temperature trends in Madagascar may be linked to synoptic-scale weather systems like the SIOHP. Additionally, our analysis corroborates earlier work indicating that the westward displacement of the SIOHP enhances precipitation over southwestern Australia, mitigating drought-like conditions in the region (Hameed et al. 2011).

Furthermore, the SIOHP-driven moisture transport plays a fundamental role in regulating regional humidity and precipitation patterns. During summer (DJF), increased atmospheric moisture and precipitation are observed in central southeastern

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Africa, consistent with previous Lagrangian and Eulerian studies (Rapolaki et al. 2020; Reason et al. 2006; Cook et al. 2004). These results emphasise the SIOHP's integral role in modulating moisture advection and influencing regional hydroclimatic variability.

Despite these insights, several key knowledge gaps remain. The drivers of SIOHP variability, its seasonal shifts, and its interaction with other climate modes require further investigation to improve predictive capabilities. Future research should explore sub-seasonal SIOHP dynamics, its connections with broader climate oscillations, and its implications for weather extremes, agricultural productivity, and water resource management. A deeper understanding of SIOHP variability and its cascading effects will be essential for enhancing climate resilience and improving regional climate projections in the face of ongoing climatic changes.

Author Contributions

Kwesi Twentwewa Quagraine: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, data curation, resources. **Kwesi Akumenyi Quagraine:** investigation, writing – original draft, methodology, validation, visualization, formal analysis, writing – review and editing. **Francis Nkrumah:** writing – original draft, writing – review and editing, methodology, data curation. **Temitope Egbebiyi:** writing – original draft, writing – review and editing. **Nana Ama Browne Klutse:** writing – original draft, writing – review and editing, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The Data analysed in this study are re-analysis datasets, which are openly available at locations cited in-text and in the reference section. The data for the South Indian Ocean High-Pressure index is available at https://github.com/Akumenyi/SIOHP_index.

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Supporting Information

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