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# The 2019–21 drought in southern Madagascar

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ABSTRACT

Two consecutive failed rainy seasons in the southern part of Madagascar in 2019–21 had devastating impacts on the population, including an amplification of the ongoing food insecurity in the area. The drought events were second in severity only to the 1990–92 drought and were estimated in a previous study to have a return period of 135 years. In this study, the physical mechanisms that led to these consecutive drought events are investigated.

We found that the anomalously cold sea surface temperatures (SSTs) that persisted to the south of Madagascar between December 2019 and December 2020 led to a decrease in the transport of moist air over land. These cold SST anomalies were the most negative anomalies in the past four decades and intensified the rainfall deficit resulting from a negative Subtropical Indian Ocean Dipole (SIOD) mode during the rainy season of December 2019 to March 2020 and during December 2020. We also found that the rainfall response to the SST anomaly south of Madagascar was three times greater than that of a canonical SIOD.

A weak Mozambique Channel Trough and a strong Angola low system, on the other hand, modulated the expected above-normal rainfall from a La Niña event in January–February 2021. Our study demonstrates how local factors can modulate the impacts of large-scale drivers, and that both local and global drivers, and their interactions, should be considered when producing seasonal forecasts and advisories, as well as climate change adaptation and mitigation plans for southern Madagascar.

## 1. Introduction

The November–April rainy season is a critical period for the semi-arid area of southern Madagascar, where the population relies heavily on rain-fed subsistence agriculture and pastoralism (Healy, 2018). On average, the area receives around 800 mm of rain annually, with more than 80% of the rainfall arriving between December and March (DJFM hereafter). In 2019–21, the southern part of the region (hereafter Grand Sud) suffered from two consecutive failed rainy seasons, leading to crop losses, as well as reduced pasture and drinking water. [Please note that the so defined Grand Sud here is the same as that in Harrington et al. (2022), where the impacts of the drought were most severe (box 1 in Fig. 1a)].

During the past four decades, the Grand Sud area has experienced only two instances of intense consecutive droughts: in 1990–92 and 2019–21. The former was more severe than the latter (see Fig. 1k). The cause of the dry 1990–91 season has not been fully investigated while the 1991–92 drought could be due to the very strong El Niño event that affected many countries globally. The drought in 2019–21 was more unexpected, given the anticipated normal to above normal rain from the 2020–21 La Niña event (DGM, 2020).

The Integrated Food Security Phase Classification indicated that in April 2021, 43% of the region's population were facing acute food insecurity challenges (IPC, 2021). An attribution study of the two-year drought event estimated it as a 1-in-135-years dry event (Harrington et al., 2022), in recent times only surpassed by the 1990–92 drought. The study also demonstrated that the extremely low rainfall anomalies were likely dominated by natural variability rather than human-induced climate change, which may yield an increase in the frequency of drought in the Grand Sud region later this century (Rabezanahary et al., 2024). In contrast, a recent study attributed the drought conditions between 2017 and 2022 (which were dominated by the 2019–21 drought) to anthropogenic forcing by investigating the trends in soil moisture proxy data (Rigden et al., 2024). They showed that the human-induced decrease in rainfall was manifested through a delay in the rainfall onset, caused by a poleward migration of the mid-latitude jets that steer the storm tracks in southern Madagascar. However, the daily accumulated rainfall in the Grand Sud area during

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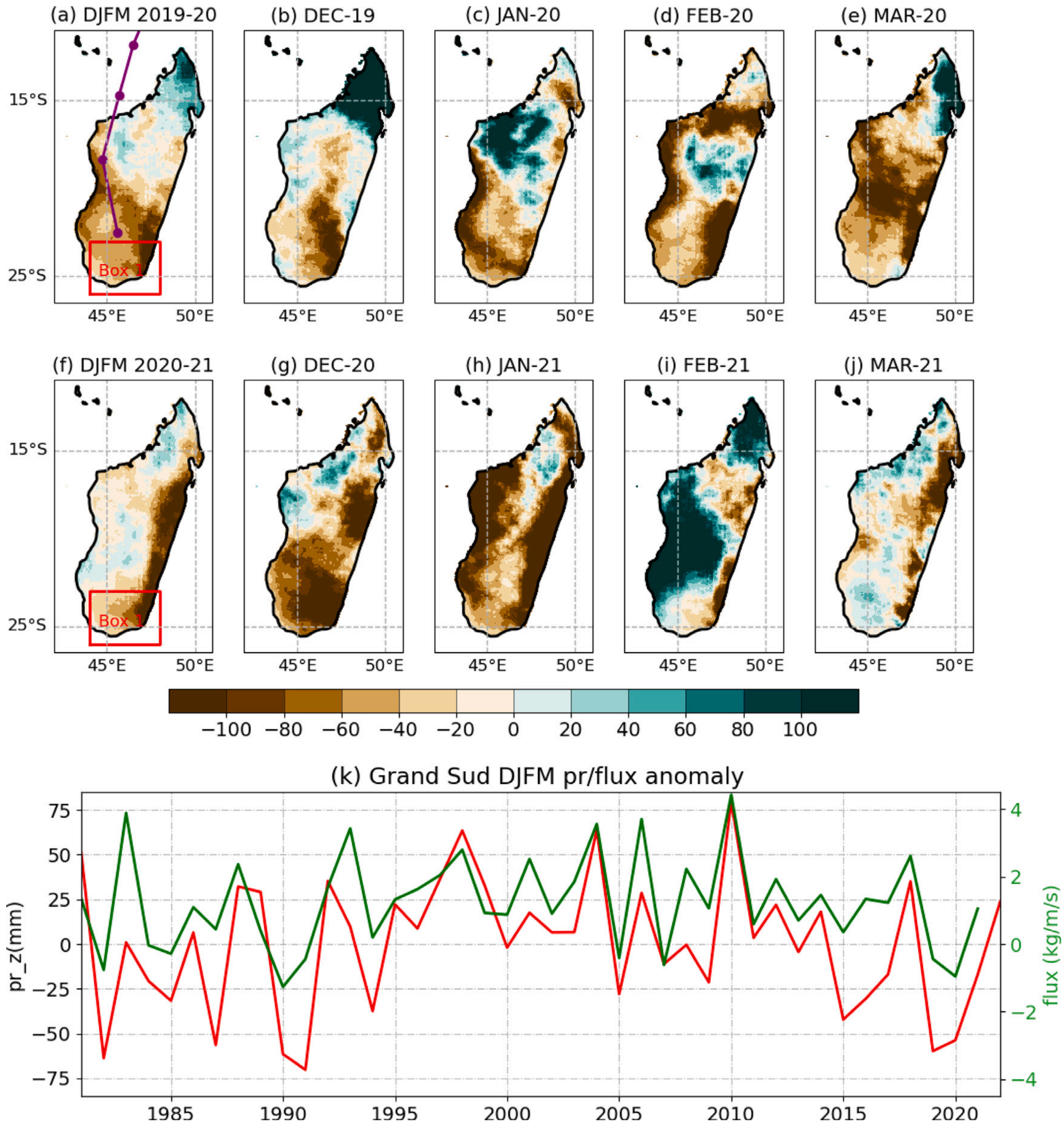


**Fig. 1.** DJFM and monthly rainfall anomaly in Madagascar during 2019–20 (a–e), and 2020–21 (f–j). (k) Red line: time series of the DJFM rainfall anomaly over the 'Grand Sud box' (Box 1 in (a) and (f)), Green line: net moisture flux through Box1 (negative values indicate influx < outflux, and vice versa for positive values). The year indicated along the *x*-axis representing the year of December within each season. The purple line in (a) shows the track of Tropical Cyclone Belna over Madagascar in December 2019. Cyclone track data are from IBTrACS. In all the panels the rainfall unit is mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2019–20 and 2020–21 indicates an overall deficit of rain throughout the seasons rather than just a delay in the onset (Fig. 2). This suggests the existence of additional mechanisms, whether through natural variability or externally forced, leading to the two-year consecutive droughts.

The El Niño–Southern Oscillation (ENSO) and the Subtropical Indian Ocean Dipole (SIOD, a dipole event that evolve in the subtropical southern Indian Ocean during austral summer Behera et al. (2001)) are the two main climate modes that drive seasonal rainfall variability in southern Africa. In general, the subcontinent receives below-average rainfall during El Niño and excess rain during La Niña events, with some discrepancies in the spatial responses depending on the flavor of ENSO (Reason, 2001; Ratnam et al., 2014; Hoell et al., 2015; Blamey et al., 2023). Harrington et al. (2022) argue that while there is a significant relationship between mainland southern Africa rainfall and ENSO, the link between southern Madagascar rainfall and ENSO is relatively weak. Negative SIOD events, on the other hand, lead to rainfall deficits over southern Africa, including Madagascar, and above-normal rain is associated with a positive SIOD (e.g. Behera et al. (2001), Reason (2001, 2002), Suzuki et al. (2004), Randriatsara et al. (2022)). The interaction between these two main modes of variability also affects the regional rain non-linearly. When ENSO and SIOD are in opposite phases, their effects are complementary and produce strong rainfall anomalies. In contrast, when they are in the same phase, their responses disrupt one another, leading to a weak rainfall anomaly (Hoell et al., 2017). When examining specific cases, such as the 1990–91 drought that coincided with neutral ENSO and SIOD conditions, the 1997–98 normal rainy season which took place during a strong El Niño event, and the 2020–21 drought in a La Niña year, it becomes apparent that ENSO and SIOD may not be the sole factors driving abnormal dry conditions in the Grand Sud.

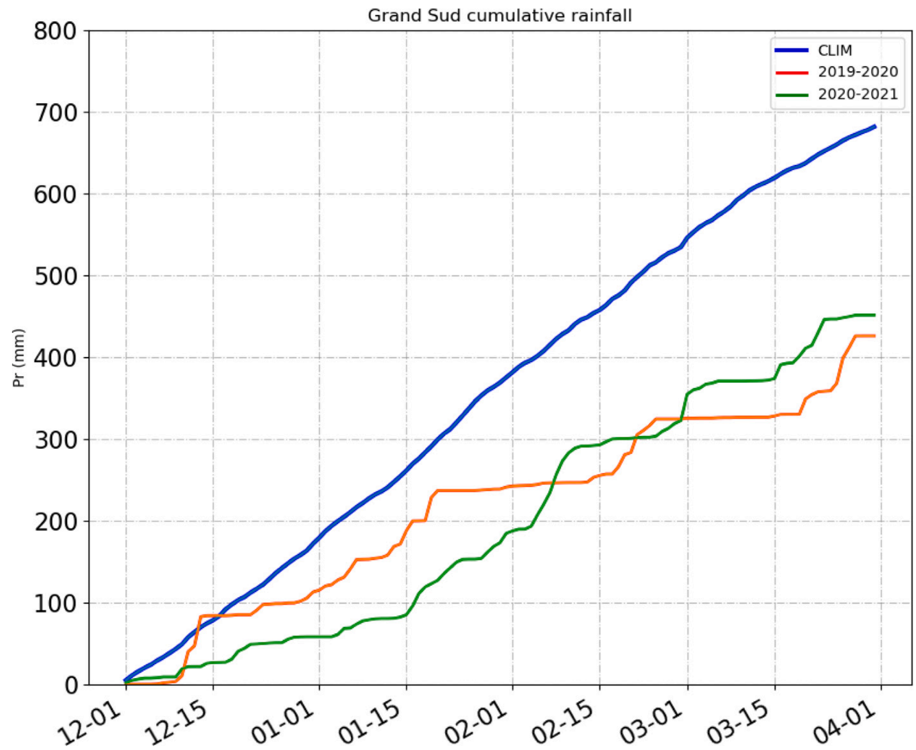


**Fig. 2.** Grand Sud cumulative rainfall during December–March in 2019–20 (orange); 2020–21 (green); averaged between 1981 and 2023 (blue), (unit: mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Apart from the influence of large-scale modes of variability, regional factors like tropical temperate troughs and cut-off lows have a significant impact on Grand Sud rainfall at an intraseasonal time scale (Favre et al., 2012; Hart et al., 2013, 2018). Additionally, local circulation patterns, including the Mozambique Channel Trough (MCT) and the Mascarene high-pressure system, play a role in modulating seasonal rainfall (Barimalala et al., 2018, 2020). A recent study revealed that prolonged dry periods in Madagascar are primarily influenced by fluctuations in the MCT (Hoell et al., 2023). However, it is important to note that their findings were based on averages computed from events occurring across Madagascar as a whole. Consequently, these conclusions may not provide a complete representation of the specific mechanisms at play in the southern region, which differ from those observed in the northern and eastern parts of the country.

In this study, we focus on the potential large- to local-scale variability patterns that could have led to the Grand Sud 2019–21 consecutive droughts. Identifying and understanding such mechanisms are crucial in the pursuit of understanding rainfall predictability in the region. Ultimately, this knowledge is essential for developing strategies to alleviate the severe consequences of future failed rainy seasons. To the best of our knowledge, no studies have thoroughly examined the possible mechanisms that drive impactful droughts, such as the 2019–21 event, in southern Madagascar.

## 2. Data and methods

The Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) daily rainfall dataset was used for 1981–2023. CHIRPS uses 0.05° resolution satellite imagery and in-situ station data to create gridded rainfall time series; CHIRPS also includes monthly precipitation climatology, and atmospheric model rainfall fields from the NOAA Climate Forecast System, version 2 (CFSv2) (Funk et al., 2015). In an evaluation of multiple gridded rainfall datasets over Madagascar, Randriatsara et al. (2022), found that CHIRPS most accurately represents the rainfall amount from existing stations within the country in comparison to other products.

Monthly wind, evaporation, mean sea level pressure, geopotential height and specific humidity data were from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5). ERA5 combines the Integrated Forecast System Cy41r2 with data assimilation (Hersbach et al., 2020).

Monthly SST data from HadISST (Hadley Centre Sea Ice and Sea Surface Temperature, Rayner et al. (2003)) produced by the UK Met Office from 1981–2023, and tropical cyclones tracks from the International Best Track Archive for Climate Stewardship (IBTrACS) data (Knapp et al., 2010) were used.

The SIOD index is defined as the difference between the SST anomaly over the western (55°E–65°E, 27°S–37°S) and eastern (90°E-100°E, 18°S-28°S) subtropical Indian Ocean (Behera et al., 2001). The South Indian Ocean (SIO) index is given by the area average in SST anomaly within 30°E–70°E, 28°S–45°S, while the Grand Sud Index is defined as the rainfall anomaly within 44°E–48°E, 23°S–26°S.

Correlation coefficients in this study were computed using the Pearson Correlation Coefficient after linearly detrending the analyzed data.

The moisture flux is given by $\boldsymbol{Q} = q\boldsymbol{U}$ Where $q$ is the specific humidity and $\boldsymbol{U}$ the wind vector.

## 3. Results

Figs. 1a–j show the DJFM and monthly rainfall anomalies over Madagascar during the 2019–20 and 2020–21 drier-than-average rainy seasons. In 2019–20, consistent dry anomalies occurred in the southern part of the island during the whole season, whereas only December and January were extremely dry in 2020–21. February and March 2021 received normal to above-normal rainfall. In the Grand Sud region (see boundaries in Fig. 1a) where the rainfall deficit was most impactful (Harrington et al., 2022), the 2019–20 and 2020–21 seasons were the driest since the 1980s, only surpassed by the 1990–91 and 1991–92 events (Fig. 1k, red line). This finding is further confirmed by the negative vertically integrated net moisture flux through the region, indicating a deficit in moisture transported into the Grand Sud area

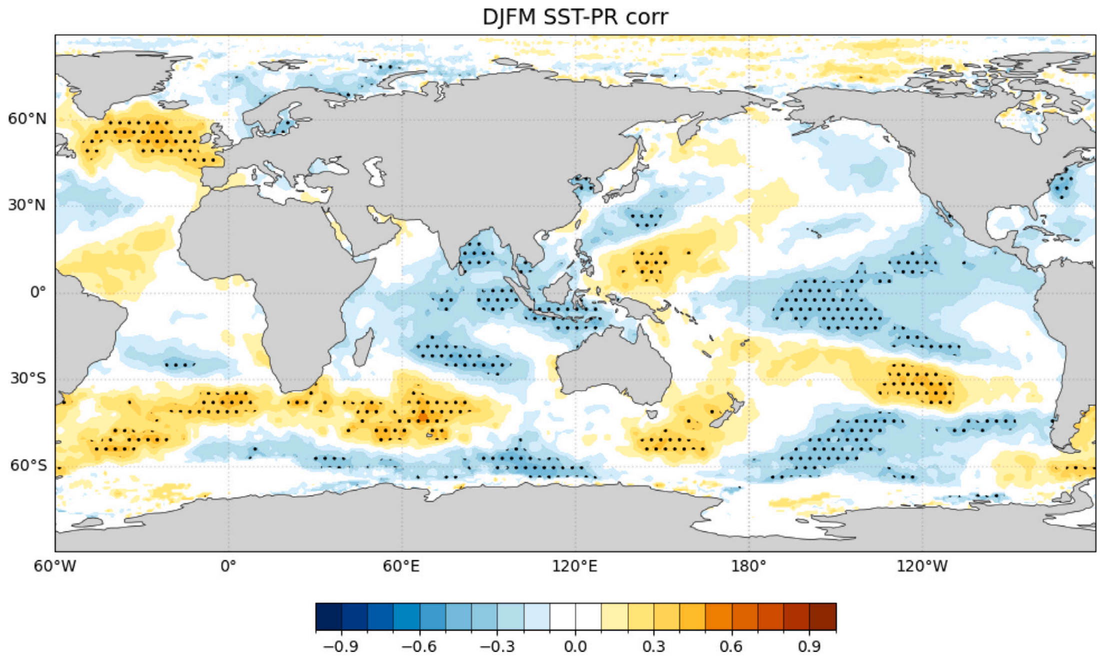


**Fig. 3.** Correlation between DJFM Grand Sud rainfall anomaly and global SST. Statistically significant correlations at the 5% level are stippled.

(Fig. 1k, green line). The already semi-arid area only received about 70% and 60% of the climatological rain during DJFM in 2019–20 and 2020–21, respectively (Fig. 2; see also Harrington et al. (2022)). Examination of the daily rainfall within the Grand Sud region suggests that around 20% of the DJFM 2019–20 total rainfall can be attributed to tropical cyclone Belna. This cyclone originated north of Madagascar, moved southward, impacting the southern part of the island, and ultimately dissipated on 11 December 2019 (France, 2019). After that, the area experienced both wet periods and prolonged dry spells (Fig. 2).

During DJFM 2020–21, the month of December and the first two weeks of January were relatively dry compared to the climatology, while February and March received normal to slightly above-normal rainfall amounts (Fig. 1). About 30% of the February rain appears to have derived from tropical cyclone Guambe, a system that formed in the Mozambique Channel, made landfall in Mozambique, and brought rain to southwestern Madagascar. The cumulative daily rainfall also suggests that there was a delay in the rainfall onset and a shorter than average rainy season during 2020–21 (Fig. 2).

When analyzing the connection between the mean DJFM rainfall averaged across the Grand Sud region and DJFM global SSTs, we find a significant negative correlation over the tropical Pacific Ocean, as shown in Fig. 3. Although this correlation pattern does not project exactly onto the standard ENSO pattern, it aligns with previous research associating La Niña conditions with increased rainfall in this region. Additionally, a northeast–southwest dipole correlation pattern manifests in the southwestern Indian Ocean. Part of the pattern seen in the southwestern Indian Ocean pattern coincides with that of the subtropical Indian Ocean dipole (SIOD), with the western pole extending further towards South Africa's coastal area. Since the DJFM 2019–20 season had neutral ENSO conditions, the potential large-scale forcing likely came from the Indian Ocean. On the other hand, a La Niña period like the 2020–21 DJFM season is typically associated with above-average rainfall, which contrasts with the observed drought conditions during that time.

In light of the observed dry conditions that do not seem to be linked to tropical Pacific teleconnections, we will now examine regional and basin-wide SST anomalies as well as atmospheric circulation patterns to explore potential mechanisms responsible for the drought during these two seasons.

### *3.1. Circulation and SST features during DJFM 2019–20*

Fig. 4a shows the DJFM 2019–20 SST anomaly. A cold SST anomaly is found to the south of Madagascar, while a warm anomaly is observed across the broader expanse of the Indian Ocean basin. Notably, the warm anomaly reaches its maximum magnitude between 10°S and 20°S, forming a dipole pattern akin to a negative SIOD phase. It is worth highlighting a key distinction between these observed patterns and the classical SIOD as defined by Behera et al. (2001). Compared to Behera et al. (2001), the 2019–20 cold SST anomaly extends over a relatively expansive area, stretching from the eastern coast of South Africa to approximately 90°E.

The monthly SST anomalies (Fig. 5) show that the cold SSTs persisted for about a year in this region until November 2020, when it moved slightly to the east to cover all longitudes of the southern Indian Ocean basin, forming a north–south dipole in December 2020. There is a striking similarity between Fig. 3 and the 2019–20 anomaly over the southern Indian Ocean (Fig. 4a). Given that 2019–20 was a neutral ENSO year, the SST patterns suggest a potential response to the southern Indian Ocean SST anomaly, independent of ENSO. The large southwest–northeast SST gradient over the southern Indian Ocean basin in 2019–20 gave rise to the strongest negative SIOD event in the past four decades (Figure S1). Such events are normally associated with rainfall deficits in southern Africa.

During DJFM 2019–20, the cold SST anomaly south of Madagascar was associated with a decrease in both evaporation and humidity in the area, as shown in Figs. 4b and 4d. Anomalously high MSLP formed over the cold SSTs, and a negative MSLP anomaly occurred further to the northeast. A similar pattern was in place for the 800-hPa geopotential height (Fig. 4c). These patterns reflect the linear quasi-geostrophic theory (Fandry et al., 1984), which dictates that a warm (cold) SST anomaly generates a low (high) pressure anomaly that decays with height.

The cold SST patterns associated with the resulting high-pressure anomaly generated an anomalously dry southeasterly wind from over a cold oceanic area towards the relatively warm south of Madagascar (Fig. 4d). There was also enhanced upper-level convergence at 200 hPa

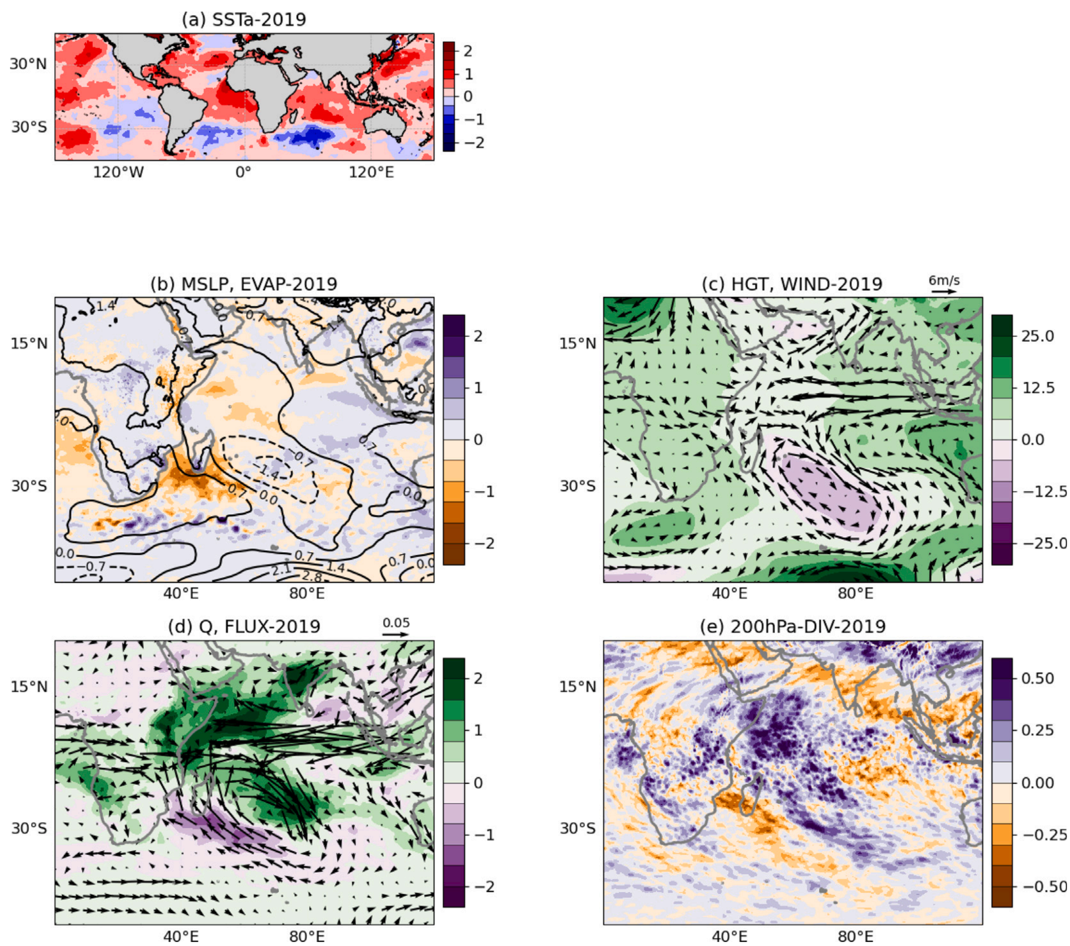


**Fig. 4.** 2019 DJFM anomaly in: (a) SST (unit: °C); (b) evaporation (shaded area, unit: m of water equivalent) and MSLP (contour, unit: hPa); (c) 800 hPa geopotential height (shaded area, unit: hPa) and winds (vectors, unit: m $s^{-1}$); (d) Vertically integrated moisture from surface to 700 hPa (shaded area, unit:m) and moisture flux (vectors, unit: kg $m^{-1}$ $s^{-1}$); (e) Divergence at 200-hPa level (unit: $s^{-1}$).

in the area, which signifies suppressed convection (Fig. 4e). The confluence of these anomalous patterns appears to have contributed to reduced rainfall in the southern part of Madagascar.

Furthermore, the warm SST and low pressure anomalies between 10°S and 20°S were associated with a cyclonic circulation, which reduced the amount of moisture transported from the eastern Indian Ocean to Madagascar, thus reinforcing the reduced rainfall over the southern part of the island (Figs. 4b-d). We also conducted an analysis of the four summer months individually, and the anomalous patterns observed during these months align consistently with the findings for the DJFM mean (not shown).

During the DJFM 2019–20 season, the cold anomaly in the southwestern Indian Ocean was located close to the coastal regions and extended across a substantial geographical expanse. Consequently, we define an index, referred to hereafter as the Southern Indian Ocean (SIO) index. This index is calculated as the area-averaged SST anomaly to the south of Madagascar (from 30°E to 70°E and from 28°S to 45°S; see green box in Fig. 5a). A time series of this SIO index (Fig. 6) shows that 2019–20 was the coldest season in the area in the past 40 years, which could help explain the dry conditions during that season.

A regression of the Grand Sud rainfall index onto SIO and SIOD shows that the rainfall response in the Grand Sud region to SIO index anomalies is up to three times stronger than the response to the more commonly known SIOD index (Fig. 7). Based on these findings, it is advisable to place emphasis on monitoring the expansion of the cold pole within the southwestern Indian Ocean basin, rather than solely relying on the conventional SIOD index, when attempting to predict rainfall patterns in the southern regions of Madagascar.

### 3.2. Circulation and SST features during DJFM 2020–21

Unlike in 2019–20, the DJFM season in 2020–21 coincided with La Niña conditions. Figure S2a shows that, locally, the SSTs were anomalously warm in the Mozambique Channel and to the south of Madagascar in this period. This warm anomaly extended eastwards towards southern Australia. According to Hoell et al. (2017), the presence of such positive SIOD-like patterns in conjunction with La Niña conditions typically leads to increased precipitation in southern Africa. However, it is noteworthy that this does not hold true for the southern region of Madagascar during 2020–21 DJFM. Indeed, as previously discussed, the rainfall during that season was below average.

Additionally, the anomalies in MSLP and geopotential height are also positive in the southern Indian Ocean (Figure S2), with a relatively weaker pattern extending towards Madagascar. On both sides of this high-pressure anomaly, cyclonic circulations emerge, potentially resulting in the diversion of moisture away from the island. However, it is important to note that these variables do not exhibit a discernible and coherent connection that would provide a straightforward explanation for the dry conditions observed during the DJFM period. Conversely, the spatial variations observed in the monthly rainfall anomalies (Fig. 1) and the monthly SST anomalies (Fig. 5) suggest that the distinct months within the 2020–21 season may have been influenced by diverse mechanisms. We, therefore, undertake a month-by-month analysis of the 2020–21 drought, with particular attention to the period between December and February, given the prevalence of dry conditions during this period.

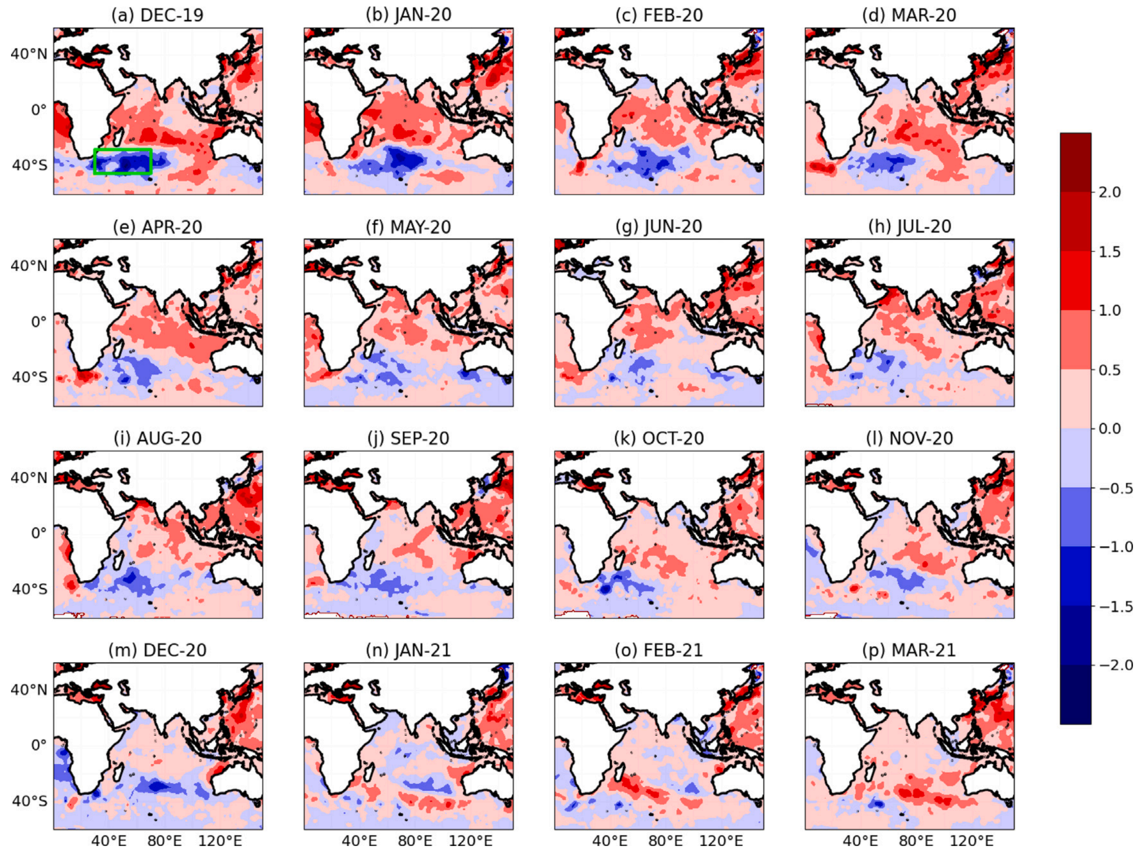


**Fig. 5.** Monthly SST anomalies over the Indian Ocean from December 2019 to March 2021 (unit: °C). The green box in (a) indicates the area used to calculate the South Indian Ocean (SIO) index. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

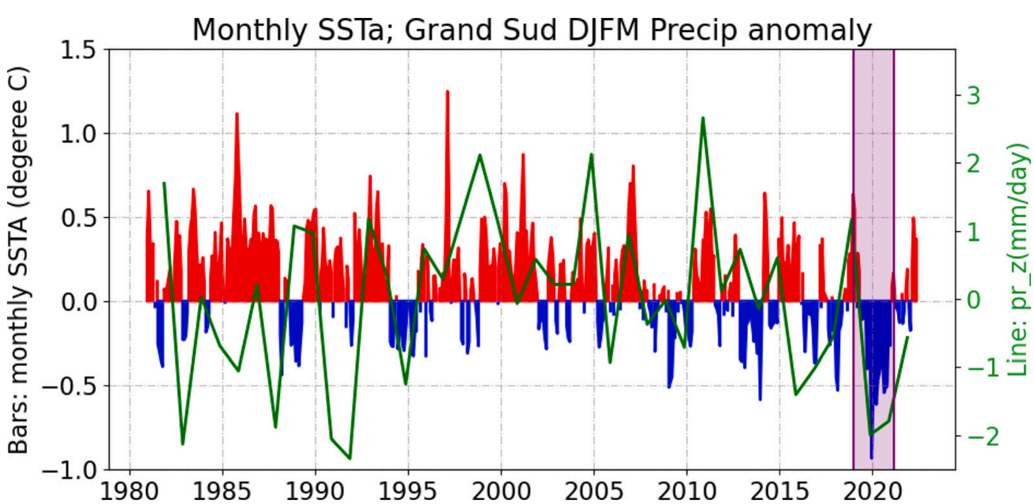


**Fig. 6.** Area averaged monthly SST anomaly (SSTa) over the cold SST pole (SIO) south of Madagascar (bars, unit: °C) with the Grand Sud precipitation index (solid green line, unit: mm $day^{-1}$). The purple area delimits the period of January 2019–March 2022. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As shown in Fig. 5, the SST dipole anomaly near Madagascar persisted until the end of 2020, with the December 2020 pattern transforming into a north–south dipole configuration, deviating from the prior southwest–northeast dipole pattern. Yet, based on the canonical SIOD definition, December 2020 was still a negative SIOD month. Areas with both cold and warm SST anomalies stretched zonally across the southern Indian Ocean, leading to MSLP and geopotential height anomalies similar to the 2019–2020 case (Figs. 8a, 9a). An anticyclonic (cyclonic) circulation associated with the cold (warm) SST anomaly then formed off the southeast (northeast) coast of Madagascar, bringing dry air into the southern part of the island (Fig. 10a). These patterns emphasize that the presence of the cold SST anomaly over the southwestern Indian Ocean basin modulated the effect of La Niña in southern Madagascar. This observation aligns with Hoell et al. (2017), who suggested that the SIOD can disrupt the atmospheric response to ENSO over southern Africa when both ENSO and SIOD exhibit the same phase. In our case, the concurrent presence of La Niña and a negative SIOD-like signal in December exemplifies this disruption.

In January 2021, the SST dipole switched sign, turning into a positive SIOD-like pattern (Fig. 5), during which mainland southern

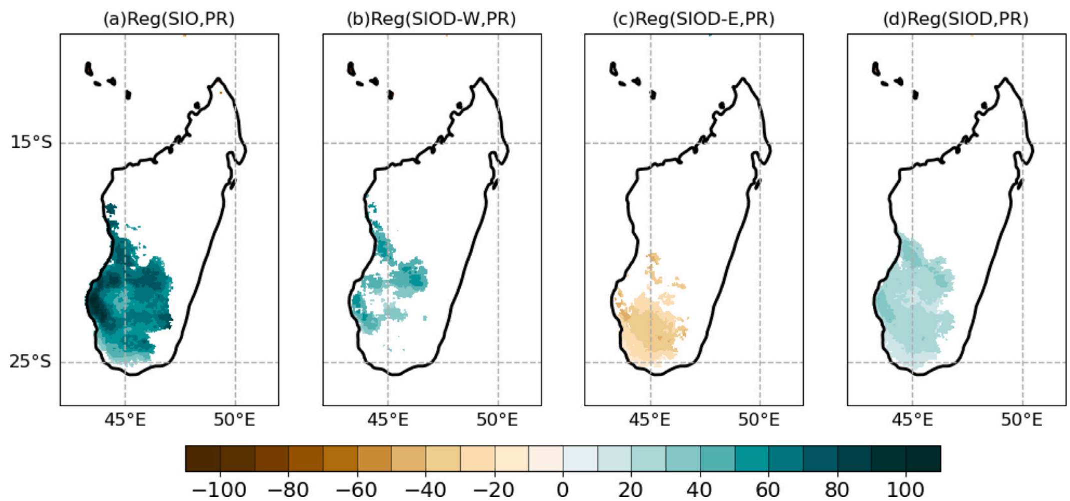


**Fig. 7.** Regression of DJFM precipitation onto (a) South Indian Ocean Index; (b) Western pole of SIOD; (c) Eastern pole of SIOD; (d) SIOD index. Shaded areas are where the regression is statistically significant (*pvalue* < 0.05).

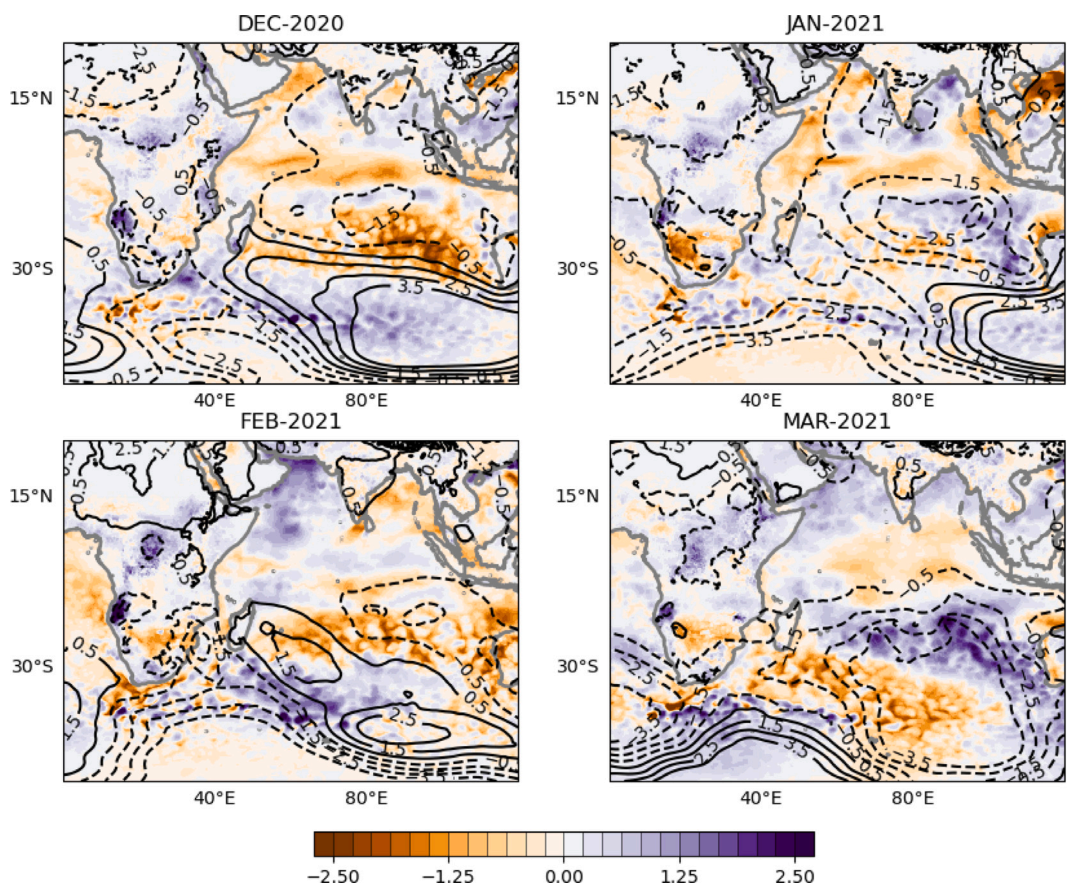


**Fig. 8.** Monthly evaporation (shaded area, unit: m of water equivalent) and MSLP (contours, unit: hPa) anomalies from December 2020 to March 2021.

Africa received excess rain while southern Madagascar stayed dry. An analysis of the 850-hPa geopotential height reveals an anomalous ridge over the southern Mozambique Channel, weakening the Mozambique Channel Trough (MCT), Figs. 8b, 9b. A weak MCT is known to reduce rainfall in southern Madagascar and enhance rainfall over the southern African mainland (Barimalala et al., 2018, 2020). Further to the west, the Angola low-pressure system was relatively strong and shifted towards the south. Such a pattern is often associated with La Niña events (Howard et al., 2018, 2019; Pascale et al., 2019) and excess rainfall over mainland southern Africa. The Angola low-pressure system tends to attract moisture towards the mainland, and the intensity of this low-pressure system directly correlates with the level of precipitation in the region. In other words, a stronger Angola low results in wetter conditions in mainland southern Africa. Munday et al. (2017) showed that CMIP5 models with a weak representation of the MCT tend to have strong Angola low and excessive rainfall over southern Africa through enhanced moisture inflow into the mainland. The geopotential height anomalies over Angola and the Mozambique Channel therefore suggest a potential role of local circulation patterns in triggering the dry January of 2021. In addition, the month was also characterized by

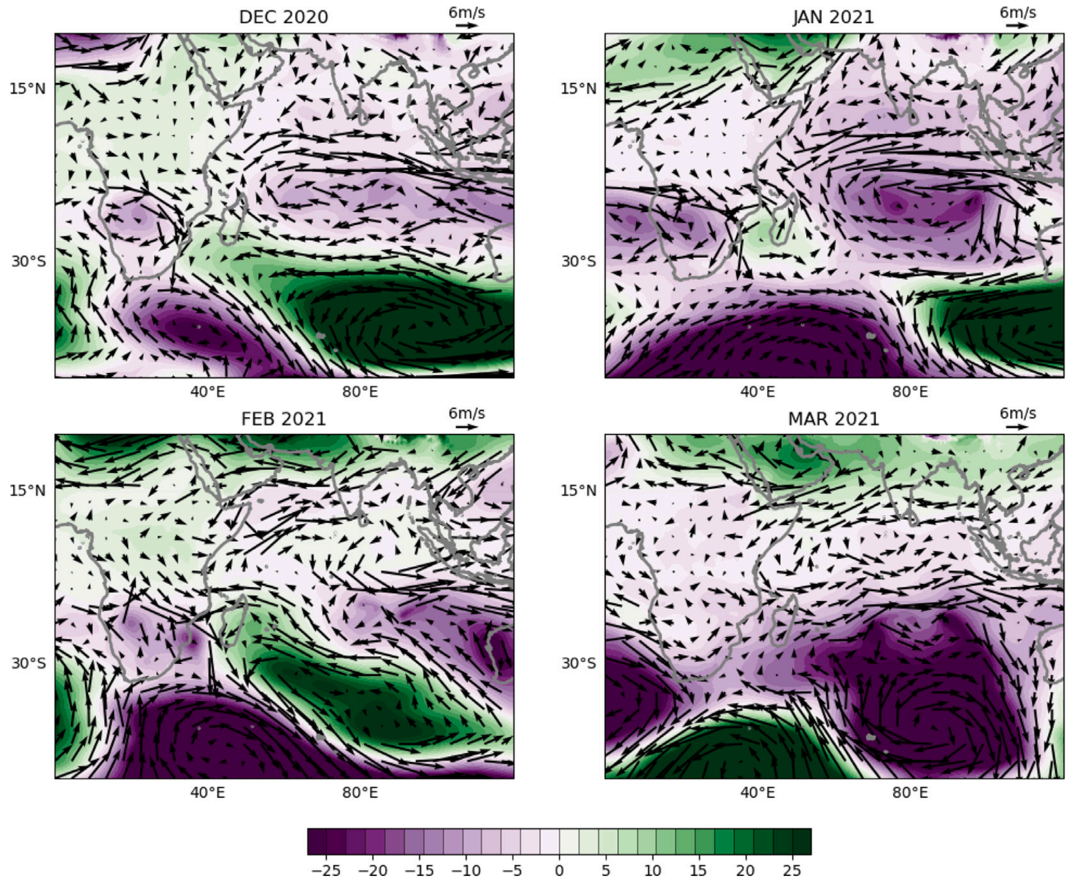


**Fig. 9.** Same as Fig. 8 but for 800-hPa geopotential height (shaded areas, unit: m) and wind (vectors, unit: m s$^{-1}$).

a weakened penetration of the northeasterly monsoon towards Madagascar due to the warm and cyclonic circulation anomalies northeast of the island. These further fueled the high-pressure anomaly over the Mozambique Channel, leading to a weakened MCT and subsequently reduced rainfall over Madagascar (Barimalala et al., 2020).

Fig. 9c shows that during February 2021, a diagonally stretched high-pressure anomaly again persisted over the southern Indian Ocean basin, similar to what happened in December 2020. The result of this situation was a deficit in rainfall along the eastern part of Madagascar (Fig. 1i). This contrasted starkly with the situation in the west, where tropical cyclone Guambe over the Mozambique Channel brought very large rainfall amounts to western Madagascar (Fig. 1i, the track of tropical cyclone Guambe is outside the focus area and is not shown). During March 2021, the levels of rainfall observed were nearly in line with the typical or normal patterns (Fig. 1j).

### *3.3. Comparison with the 1990–1991 drought*

As shown in Fig. 1k, 1990–92 was the only period in which the Grand Sud region experienced two consecutive droughts more intense than the one in 2019–2021. The dry 1991–92 season was expected as a response to the strong 1991 El Niño, while the potential causes of the 1990–1991 drought have not been fully analyzed and are therefore the focus of this subsection. Fig. 11 shows a widespread rainfall deficit across Madagascar in December 1990 and January 1991. In contrast, the drought in the Grand Sud region was mostly intense in the east and lasted throughout the rainy season. There is no consistent signal in the SST anomalies over the Indian Ocean, except for the positive anomalies that developed off the southern coast of Madagascar in February and March (Figure S3). On the other hand, the low-level circulation and geopotential height anomalies show particularly pronounced patterns, consistent with the decrease in rainfall during each month of the season (Fig. 12). In December, a cyclonic circulation anomaly was active south of Madagascar. This weakened the moisture-carrying easterly winds towards the island and led to reduced rainfall (Fig. 12a). In January, a strong high-pressure anomaly associated with subsidence was observed over the southwestern Indian Ocean (Fig. 12b). Such a pattern resulted in a widespread rainfall deficit across the island until the development of Tropical Cyclone Cynthia in the southern Mozambique Channel, which brought excess rain to the western part of Madagascar. However, the anomalously high pressure system still lingered over the east, where it remained dry throughout February and March (Figs. 12c–d). Overall, the dry months appear to have been mainly caused by local circulation anomalies and the associated changes in the low-level pressure. In contrast to the 2020–21 case, where the anomalies were confined over the Mozambique Channel and significantly weakened the MCT, the 1990–91 anomalies extended over Madagascar. These results highlight the importance of local circulation in driving rainfall in the region. The factors leading to these anomalous circulation, however, require further investigation.

## 4. Summary and discussion

This study has investigated the underlying mechanisms responsible for two consecutive years of drought in southern Madagascar spanning from 2019 to 2021. The droughts amplified the ongoing food insecurity situation in the area, and partly led to the acute food insecurity challenges in April 2021. Our investigation revealed that the drought event during the period of December 2019 to March 2020 was primarily driven by a negative SST anomaly south of Madagascar, stretching from the eastern coast of South Africa to the central southern Indian Ocean. Such an anomaly intensifies the rainfall reduction from a negative SIOD

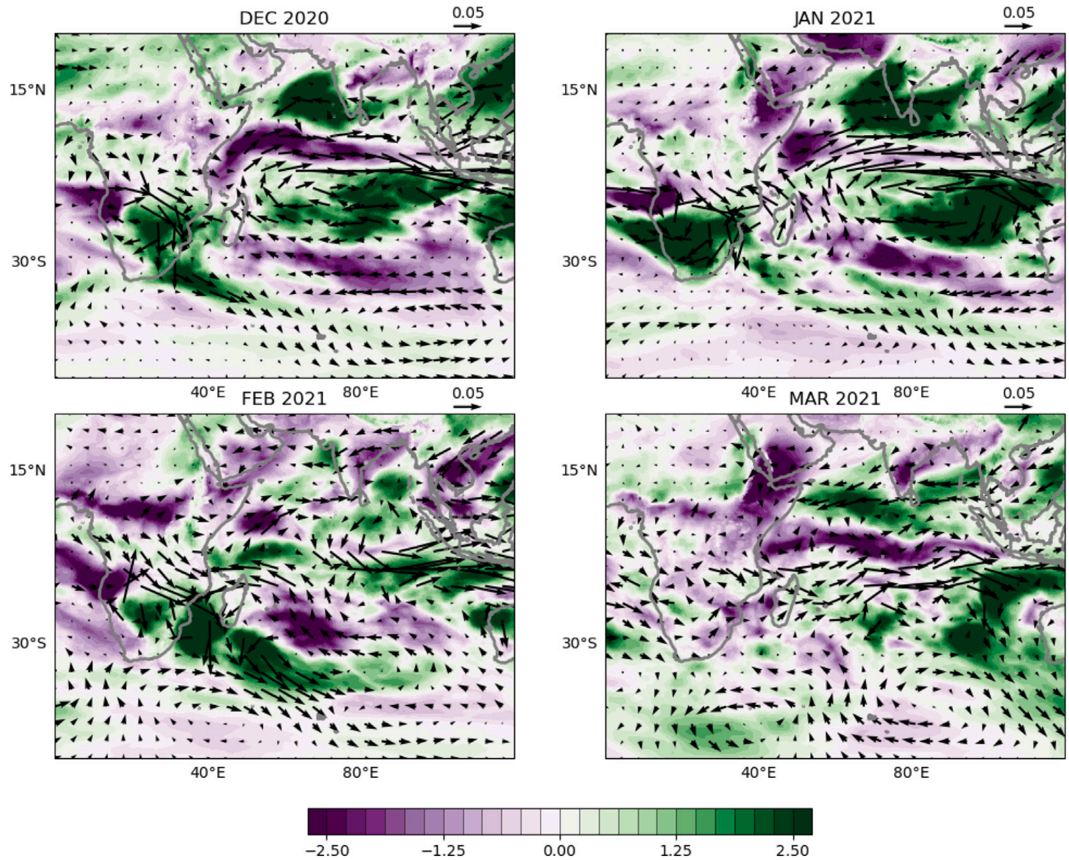


**Fig. 10.** Same as Fig. 8 but for vertically integrated moisture from surface to 700 hPa (shaded areas, unit: kg kg$^{-1}$) and moisture flux (vectors, unit: kg m$^{-1}$ s$^{-1}$).

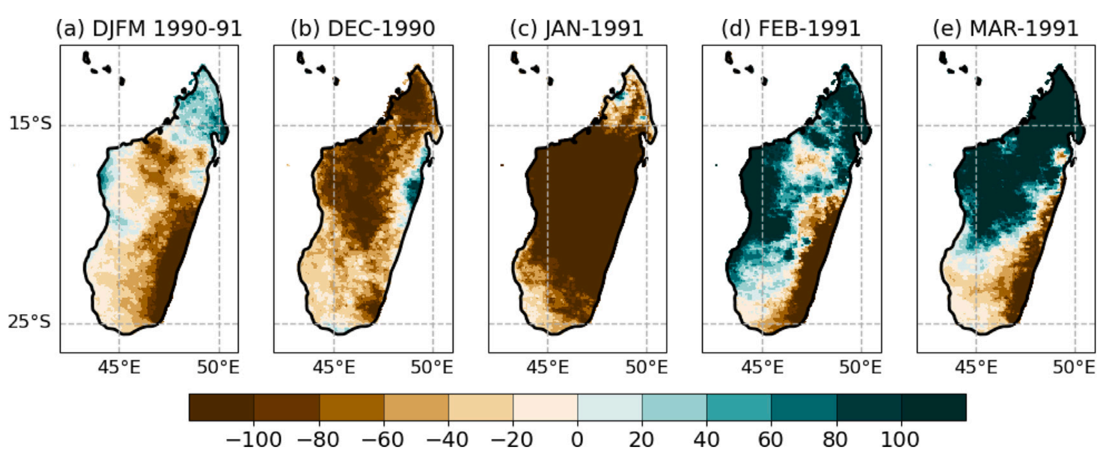


**Fig. 11.** DJFM and monthly rainfall anomaly during 1990–91 (unit: mm).

condition, aligning with the linear quasi-geostrophic theory (Fandry et al., 1984). Simultaneously, the presence of a warm lobe off the coast of Australia limited the transport of moisture from the eastern and central sectors of the Indian Ocean towards the west, further contributing to the drought conditions observed in southern Madagascar.

These results are in agreement with previous studies (Behera et al., 2001; Reason, 2001, 2002; Suzuki et al., 2004; Hoell et al., 2017), which found that negative SIOD events are associated with a decrease in rainfall over the southern part of Madagascar. The mechanism by which a cold SST anomaly situated to the south of the island influences rainfall amounts is in line with the outcomes of a series of sensitivity experiments conducted as detailed in Reason (2002). Furthermore, the same study suggested that variations in the position of the poles of the SIOD play a significant role in modulating the southern African rainfall. Specifically, it indicates that the proximity of the warm or cold pole to the African continent correlates with the magnitude of the response in terms of rainfall. This phenomenon can be attributed to the impact of the elevated topography of Madagascar and the presence of the Drakensberg mountains in South Africa, which tend to maintain the easterly wave in a semi-stationary position within the region. Additionally, the prevailing winds in the southwestern part of the basin are weaker than those in the eastern region. Consequently, the localized responses in this area are primarily governed by thermodynamic effects (Reason, 2001).

The cold SST anomaly observed south of Madagascar during 2019–20, the most negative anomaly in the past four decades, persisted throughout 2020 (Fig. 6). This persistent anomaly played a key role in

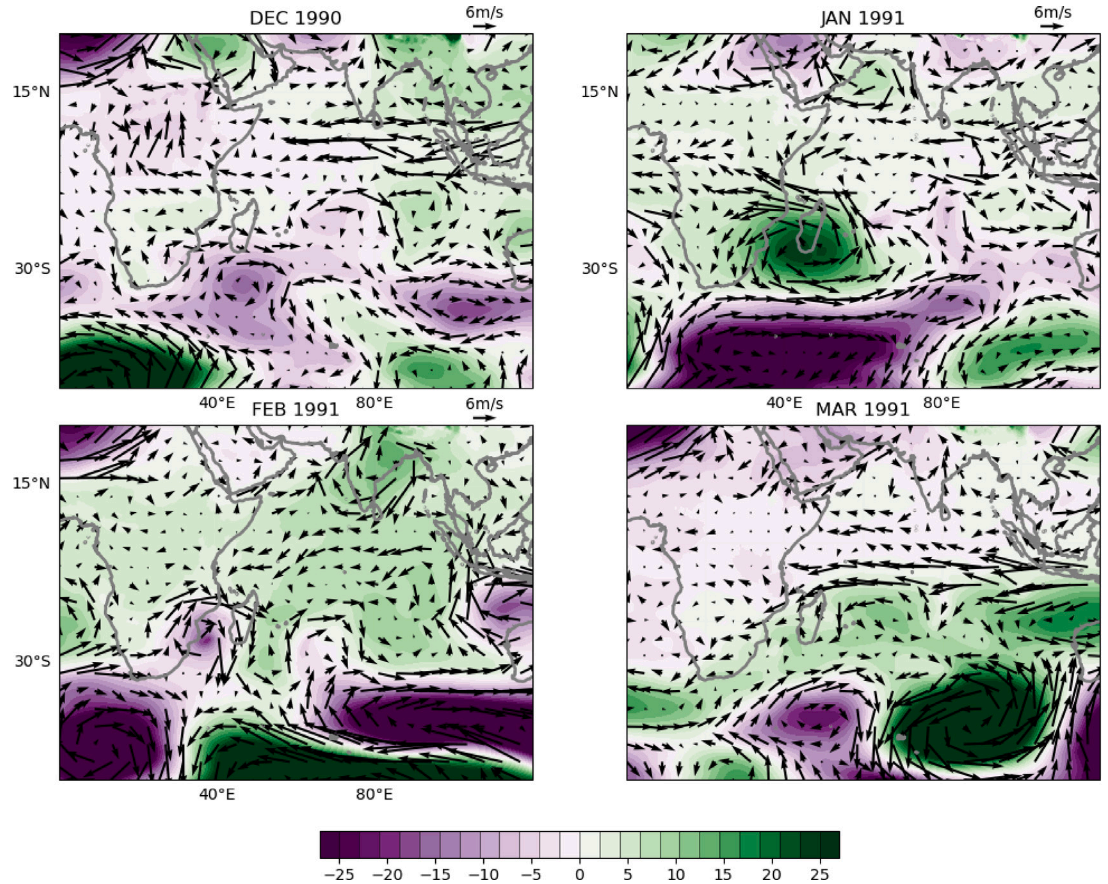


**Fig. 12.** Monthly 800-hPa geopotential height (shaded areas, unit: m) and wind (vectors, unit: m s$^{-1}$) anomalies from December 1990 to March 1991.

contributing to the dry conditions experienced in December 2020. Notably, the response in terms of rainfall to this cold SST anomaly, which extended from the eastern coast of South Africa to the central Indian Ocean basin, was three times greater than that typically associated with a canonical negative SIOD.

Given these findings, it is strongly advisable to monitor such SST anomalies in conjunction with other well-known large-scale atmospheric forcings, as they could prove to be a valuable source of rainfall predictability in the region. Additionally, it is important to conduct further research to discern the factors behind the westward expansion of cold SST anomalies, such as whether it stemmed from a strongly negative SIOD, a different variant of the dipole mode, or potentially originated from an entirely distinct mechanism.

In a recent study, the 2019–20 SIOD conditions were linked to the 2019 Indian Ocean Dipole (IOD) event, which was one of the strongest in the past decades (Anila et al., 2023). The development of an IOD due to SIOD is a known mechanism (e.g., Crétat et al. (2018), Huang et al. (2021)), whereas the opposite (IOD generating SIOD) is relatively new. Anila et al. (2023) indicated that, through a wind-evaporation-SST cyclic feedback between the tropical and subtropical Indian Ocean, a positive SIOD in January–March (year = 0) leads to a positive IOD in June–August (year = 0), which in turn triggers a negative SIOD in January–March (year = 1). Such a finding induces a question on whether the increase in the frequency of negative SIO and SIOD events (Figs. 6 and S1), as well as the decrease in rainfall over Grand Sud since 2010, are somewhat linked to the observed increase in the occurrence of extreme IOD (Cai et al., 2014). In addition, with the more frequent positive IOD events projected in the future (Cai et al., 2018), a deeper understanding of the link between the IOD, SIOD, SIO and the regional rainfall would be beneficial for improved predictions of Grand Sud rainfall. Further, such studies would enhance the current level of understanding of the impacts of potential changes in the strength and frequency of IOD events under future climate change (MacLeod et al., 2024). A preliminary analysis of the surface heat flux from the Ocean Reanalysis System 5 (ORAS5, C3S (2021)) data during DJFM 2019–20 and 2020–21 indicates positive anomalies over the SIO area (not shown), suggesting that the ocean received more heat from the atmosphere while the SST stayed cooler than the long-term average. These findings suggest a potential role of the ocean in cooling the SIO area. Nevertheless, understanding the ocean–atmosphere processes leading to the cooling of the SIO is beyond the scope of this work and should be addressed in a separate study.

In contrast to the large-scale atmospheric factors influencing the 2019–20 drought and the dry conditions in December 2020, the period of January and February 2021 was primarily influenced by local circulation anomalies. During this time, these anomalies were characterized by a relatively weak Mozambique Channel Trough (MCT) anomaly and a westward shift of the Mascarene High. Normally, the presence of these two pressure system anomalies results in reduced rainfall in Madagascar and increased rainfall in mainland southern Africa. Given that 2020–21 was a La Niña year, it was expected that the southern part of the island would experience a positive rainfall anomaly during DJFM 2020–21. However, the development occurred as the strong response of the Angola low-pressure system to the La Niña forcing had the effect of weakening the MCT and redirecting moisture away from the southern region of Madagascar. This departure from the anticipated La Niña impact contributed to the meteorological conditions observed during this period.

Interestingly, the geopotential height and associated circulation anomaly patterns observed during January–March 1991 also show pronounced linkages with the very dry conditions in Grand Sud area during a neutral ENSO and neutral SIOD year (Figs. 11,12).

In summary, our study shows that regardless of the different phases of ENSO and SIOD, which are both widely known to drive the rainfall variability in southern Africa, SST anomalies in the southwestern Indian Ocean basin as well as anomalies in the local circulation heavily modulate the impacts of the large scale forcings in southern Madagascar. As these supplementary drivers play a substantial role in shaping the region's climate dynamics, they should be carefully considered when producing forecasts over the region. Further work should explore the interactions between these drivers in greater detail; while Harrington et al. (2022) concluded that the 2019–21 Madagascar drought was not intensified by anthropogenic climate change, a greater understanding of how the drivers may interact and change is crucial for climate change adaptation and preparedness, in a region vulnerable to multiple climate hazards.

## Code availability

Codes to get all figures can be obtained from RB (ronb@norceresearch.no) upon request.

## CRediT authorship contribution statement

**Rondrotiana Barimalala:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caroline Wainwright:** Writing – review & editing, Investigation, Conceptualization. **Erik W. Kolstad:** Writing – review & editing, Formal analysis, Data curation. **Teferi D. Demissie:** Writing – review & editing, Validation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The CHIRPS data set, produced by the Climate Hazards Group, is available at https://chc.ucsb.edu/data/chirps. Monthly HadISST observed SST data are available from https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The ERA5 and ORAS5 data can be downloaded from the Copernicus Climate Change Service - Climate Data Store website https://cds.climate.copernicus.eu, and IBTrACS data are available at https://www.ncei.noaa.gov/products/international-best-track-archive.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.wace.2024.100723.

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