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Linking Southern Annular Mode variability to Western Ghats tree growth via monsoon teleconnections

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Abstract:

The present study established the influence of Southern Hemisphere high-latitude climate variability on tropical monsoon hydroclimate using a 293-year (1725–2017 CE) tree-ring chronology of teak from the Western Ghats (WG), India. The chronology captures a robust signal of the Southern Annular Mode (SAM), a dominant mode of Southern Hemisphere climate variability. The tree-ring series shows a strong positive correlation ($r = 0.72$) with May–August sea surface temperatures (SSTs) over the Southern Indian Ocean (SIO; 48°–56°S, 36°–50°E). Composite analyses reveal enhanced growth years coincide with a pronounced meridional gradient in SST and mean sea level pressure (like the negative phase of SAM)

across the SIO, strengthened low-level winds (850 hPa), increased moisture transport over the SIO and Arabian Sea, leading to positive rainfall anomalies over the monsoon region, including WG. Opposite anomalies characterize suppressed growth years. These results indicate a persistent cross-hemispheric teleconnection linking Southern Ocean variability to tropical monsoon dynamics. Leveraging the SST–tree-ring relationship, we reconstruct May–August SST variability for 1842–2017 CE (176 years), explaining 51.7% of the observed variance. This reconstruction provides a rare proxy-based constraint on Southern Ocean variability and its role in modulating tropical hydroclimate.

Keywords: Southern Annular Mode, Summer monsoon rainfall, Tree ring width, Western Ghats, Southern Ocean SST.

1. Introduction

The ring-width patterns of teak (*Tectona grandis*) have long been used as reliable proxies for understanding decadal- to centennial-scale rainfall variability in the tropics (Bhattacharyya et al., 1992). In India, where nearly 70% of the agro-economy depends on rainfall from the Indian Summer Monsoon (ISM; June–September), understanding monsoon variability during both instrumental and pre-instrumental periods remains a scientific priority (Borgaonkar et al., 2007). Teak chronologies from peninsular India have therefore been widely used to reconstruct past ISM rainfall variability (Borgaonkar et al., 2010; Shah et al., 2007; Sengupta et al., 2018 and 2023). Beyond providing insights into regional climate variability (D'Arrigo et al., 1999, 2011, 2013; Buckley et al., 2000, 2018, 2019; Pumijumnong, 2012; Shah and Mehrotra, 2017; Zaw et al., 2020), teak ring-width indices (RWI) have also been shown to respond to large-scale climate modes such as the El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Indian Ocean Dipole (IOD) (Yuan et al., 2008; Leupold et al., 2021; Sinha et al., 2010).

For instance, narrow teak rings in a 523-year RWI series from Kerala, South India, correspond to known drought years associated with El Niño events. That study reported a strong positive correlation between RWI and ISM rainfall and a negative correlation between equatorial Pacific sea-surface temperature (SST) and RWI (Borgaonkar et al., 2010), indicating that global climate variability modulates ISM rainfall, which in turn influences teak growth (Goswami et al., 2016). Such relationships provide a basis for reconstructing large-scale climate variability beyond the instrumental period. However, proxy-based reconstructions have inherent spatial and temporal limitations (Wilson et al., 2010). For example, recent studies suggest that the ENSO–ISM teleconnection has strengthened over northern India, weakened over central India, and remained relatively stable over southern India (Nimmakanti et al., 2021; Athira et al., 2023). These regional differences may influence the growth–climate relationship of tree rings and affect the stability of climate reconstructions (Kang et al., 2012).

In addition to ENSO-related influences, several studies have suggested that the Southern Annular Mode (SAM), the dominant mode of climate variability in the Southern Hemisphere, can induce decadal-scale changes in ISM rainfall (Prabhu et al., 2016; Pal et al., 2017; Huang et al., 2021; Dwivedi et al., 2022). The SAM–ISM relationship appears particularly significant over central India and the Western Ghats (WG), regions characterized by high summer rainfall variability (Gnanaseelan and Anila, 2021). The Western Ghats, often described as the gateway to the ISM, host extensive teak forests and serve as an important archive of dendroclimatic records (Ramachandra et al., 2023). Despite this potential, no study has yet examined whether variability in WG teak ring widths reflects SAM influence.

The SAM is characterized by a large-scale oscillation in mean sea-level pressure (MSLP) between mid- and high-latitude regions of the Southern Hemisphere (Thompson and Wallace, 2000). Positive SAM phases are associated with negative MSLP anomalies over Antarctica and positive anomalies at mid latitudes, whereas the opposite pattern occurs during negative SAM

phases (Reboita et al., 2009). The SAM index (SAMI) is typically defined as the difference between average zonal MSLP at 40°S and 65°S (Gong and Wang, 1999). Positive SAM phases correspond to a poleward shift of the westerly wind belt, characterized by strengthened westerlies near ~60°S and weakened westerlies near ~40°S; the reverse occurs during negative SAM phases (Hartmann and Lo, 1998; Gillett et al., 2006; Prabhu et al., 2016; Pai et al., 2023).

However, the relationship between SAM and proxy records remains complex and region-dependent. Paleoclimate reconstructions of SAM have sometimes produced inconsistent results, likely due to non-stationary teleconnections and proxy-specific responses. For example, a recent multi-proxy investigation reported no discernible SAM signal in several proxy records prior to the twentieth century, whereas other studies have identified strong SAM imprints in diverse environmental archives. These include links between SAM variability and wildfire activity across southern-hemisphere biomes, as well as temperature variations captured in Antarctic climate proxies (Holz et al., 2017). These contrasting findings highlight the need to identify additional proxies that reliably record SAM variability. To date, however, the potential of tropical tree rings to preserve SAM signals remains largely unexplored.

Another key knowledge gap concerns the Southern Indian Ocean, a region strongly influenced by SAM but lacking long, high-resolution SST reconstructions (Gersonde et al., 2003 and 2005). The scarcity of such records limits our understanding of SAM-related ocean–atmosphere interactions in this basin. Establishing a connection between Western Ghats teak growth and SAM-related climate variability could therefore reveal a previously unrecognized teleconnection and provide a novel proxy for reconstructing SST variability in the southern Indian Ocean.

In this study, we address these gaps by developing a 293-year teak ring-width chronology from the Western Ghats and examining its climatic signals. Specifically, we investigate whether SAM influences teak growth in this region and evaluate the potential of the chronology

to reconstruct May–August SST variability in the southern Indian Ocean since the mid-nineteenth century.

2. Study area, samples, data, and methods:

2.1 Study Area

Teak tree samples were collected in 2017 from two forests, Thithimati and Nagarhole, in the Kodagu district of Karnataka, India. These sites lie on the leeward (eastern) side of the Central Western Ghats (WG) and span approximately 12°00′–12°30′ N and 75°45′–76°15′ E, covering ~848 km² (Fig. 1; Table 1). The growth of tropical teak is primarily influenced by temperature, rainfall, and soil moisture; therefore, the regional climatology of these parameters is briefly reviewed. Kodagu experiences high annual rainfall (~2067 mm), strongly concentrated during the Indian Summer Monsoon (ISM). The monsoon season contributes ~1544 mm (≈74.7%) of the annual total, while pre-monsoon (March–May) and post-monsoon (October–November) rainfall account for ~12.3% and ~11.9%, respectively; winter rainfall is minimal (~1.2%) (Karthik et al., 2024). The region averages 127 rainy days annually (range: 106–148), indicating a strongly monsoon-dominated climate with most rainfall during ISM (Maraddi et al., 2023).

Kodagu experiences a warm but seasonally modulated maximum-temperature regime. The annual mean maximum temperature is 27.19 °C (SD ≈ 0.99 °C), indicating relatively low variability. The hottest month occurs during the pre-monsoon season, with a mean maximum of 31.73 °C in March, while the coolest month occurs during the peak monsoon, with a mean maximum of 23.51 °C in July. The monthly mean maximum temperature ranges from ~20.10 to 34.20 °C across the record (Fig. 2) (Mote et al., 2017;

119 https://kodagu.nic.in/en/about-district/). The dataset indicates a clear increasing trend in
120 maximum temperature, whereas minimum temperature shows a slight decline. The study area
121 comprises moist deciduous forests with heterogeneous soils, including red, black, and alluvial
122 lateritic types derived from weathered crystalline rocks. Volumetric soil moisture varies from
123 0.20-0.50 cm^3cm^{-3} annually, typically peaking in October 2–3 months after peak ISM rainfall,
124 reflecting a delayed increase of soil moisture in response to monsoon rainfall (Venkatesh et al.,
125 2011).

126 **2.2 Sample collection, processing, and chronology development**

127 A total of 68 tree cores were collected from 34 teak trees using a 5 mm increment borer
128 (two cores per tree) across the two study locations, Thithimati and Nagarhole (Table 1). This
129 sampling strategy eliminates individual tree variability, yields a stand-level signal, and
130 increases sample depth (Speer, 2010). During sampling, attempts were made to collect tree
131 samples of similar girth size from 1.25 to 2.19 m above the ground level. This ensures
132 population homogeneity and avoids the impact of age on radial growth trend.

133 Due to insect activity, forest fire, or other anthropogenic activities, five samples were
134 disqualified during the quality check; 63 samples were used in this study (39 samples of 22
135 trees from Thithimati forest, and 24 samples of 12 trees from Nagarhole forest). The collected
136 core samples were air-dried and mounted on grooved wooden strips and polished papers. Rings
137 were counted, and the thickness was measured using a binocular microscope and LinTab 2006
138 tree ring measurements system, with a precision of 0.001 mm, respectively. The samples are
139 then crossdated by the curve method using the software C-dendro software version 9.0
140 (https://cybis.se/forfun/dendro/index.htm) and reevaluated by COFECHA (Holmes, 1983;
141 Grissino-Mayer, 2001; Maxwell 2021).

These crossdated series were standardized to remove age-related growth trends by fitting a growth curve using an age-dependent spline (Carrer & Urbinati, 2004; Melvin et al., 2007). A signal-free approach was applied during standardization to preserve low-frequency signals and minimize biases from varying segment lengths in tree ring chronology (Cook et al., 1995). The two parameters, the average correlation between series (RBAR) and the Expressed Population Signal (EPS), were calculated in a running window of 50 years (Wigley et al., 1987). These parameters measure the common signal strength of the chronologies, and an EPS value above 0.85 is generally considered for climate reconstruction. A statistical summary of chronology metrics is presented in Table 2 and Fig. 3 and further discussed in Section 3 (results).

2.3 Meteorological dataset and ring growth-climate relationship

Understanding the relationship between ring growth and climate parameters is important for assessing the sensitivity of trees to climate variations and for further climate reconstruction. Monthly rainfall and temperature data for 1901–2017 were obtained from the India Meteorological Department (IMD) for the Madikeri and Kodagu observatories in Karnataka. These stations are located approximately 50 km from the two sampling sites and are assumed to represent the local climatic conditions of the study area. To complement station observations and incorporate spatial climate information, gridded datasets were also used. High-resolution IMD gridded rainfall data (0.25° × 0.25°; Pai et al., 2014) were used to analyze rainfall patterns across the Western Ghats and assess spatial coherence between rainfall variability and tree growth.

Soil moisture data from the Global Land Data Assimilation System (GLDAS; 0.5° × 0.5° resolution) were used, as soil moisture strongly influences water availability and tree physiological processes, particularly during droughts, delayed monsoon onset, or extreme rainfall events (Seneviratne et al., 2010; Wang et al., 2019). Sea surface temperature (SST)

data were obtained from three datasets: NOAA/NCEP Reynolds Optimally Interpolated SST (OISST; 1° × 1°), the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; 1° × 1°), and ERA5 reanalysis (0.25° × 0.25°; Rayner et al., 2003; Reynolds et al., 2002, 2007; Hersbach et al., 2020). The multiple datasets of SST are used to confirm ring growth-SST relationship as SST variation which is a primary component and indicator of ENSO and other major modes of climate variability (Shekhar et al., 2022; Athira et al., 2023). Monthly ERA5 reanalysis fields (0.25° × 0.25°), including wind, specific humidity, and mean sea level pressure, were also analyzed to characterize atmospheric circulation, moisture transport, and their relationship with hydroclimatic variability affecting tree-ring growth (Gimeno et al., 2012). We further computed Pearson correlation coefficients between the ring width index (RWI) and monthly climate variables spanning a 12-month window (January–December) to identify the seasons of influence.

2.4 Reconstruction of SST

Based on the observed relationship between Southern Ocean SST and RWI, we performed an SST reconstruction. The methodology is outlined below, and results are discussed in Section 4.2. In brief, the May-August average SST over the identified Southern Ocean region was treated as the predictand, while teak RWI served as the predictor. The DUPLEX data-splitting algorithm (Kennard and Stone, 1969; Snee, 1977) was applied to split the calibration and verification periods and to validate the regression model (Joseph et al., 2022).

Data from 1982–2017 were split into two subsets (1982–1999 and 2000–2017) and alternately used for calibration and verification. Model performance was evaluated using the coefficient of determination (R^2), reduction of error (RE), and coefficient of efficiency (CE). Positive RE indicates skill beyond the climatological mean, while positive CE suggests the model captures observed variability. The Prediction Sum of Squares (PRESS) statistics were

also calculated during calibration to assess robustness (Huang et al., 2020). This approach uses teak RWI as a climate proxy to infer historical SST variability and ocean–atmosphere interactions (Helama et al., 2004).

3. Results

The statistical attributes of the teak chronology demonstrate its robustness and suitability for dendroclimatic analysis (Table 2; Fig. 3). Evaluation of these parameters is essential for interpreting the chronology and its climate–growth relationships. The 63 cross-dated samples show a mean series inter-correlation of 0.41, indicating a strong common growth signal among the trees. The mean sensitivity value of 0.165 reflects the responsiveness of tree rings to climatic variability, an important characteristic for capturing extreme climatic events (Büntgen et al., 2010).

The final signal-free regional chronology (KOD) integrates data from the Thithimati and Nagarhole forests. Age-related growth trends and other non-climatic influences were removed through detrending. The overall Expressed Population Signal (EPS) is 0.93, which confirms that the sample size is adequate and that the chronology is dominated by a coherent climatic signal. The high Signal-to-Noise Ratio (SNR) of 14.17 further indicates a strong climatic signal relative to biological or environmental noise, enhancing the reliability of climate reconstructions derived from tree rings (Franke et al., 2020).

Key statistics for the KOD chronology are presented for both the full period (1725–2017) and the common period (1940–2010). Mean inter-correlations within trees (0.24), between trees (0.21), and among all radii (0.21) during the common period demonstrate a consistent climatic response across the dataset. The relatively low first-order autocorrelation (0.15) suggests that annual growth is largely independent of the previous year’s growth, an important

213 requirement for reliable climate reconstruction (Fritts, 1971). These statistical characteristics
214 confirm the robustness of the KOD chronology for dendroclimatological studies.

215 The chronology spans 293 years (1725–2017) and shows clear peaks and troughs
216 representing periods of high and low growth. A mean value of 0.99 and a standard deviation
217 of 0.13 were used to identify extreme growth events. The record reveals more frequent low-
218 growth events than high-growth events, suggesting recurring adverse climatic conditions
219 affecting tree growth.

220 The chronology begins with a dry year in 1727, followed by relatively stable high growth
221 until 1787, indicating favourable climatic conditions. The lowest growth occurred in 1803
222 (0.20), likely reflecting severe drought or environmental stress, followed by a sharp recovery
223 with extremely high growth in 1806 (1.52). Similar fluctuations throughout the 19th and 20th
224 centuries highlight the strong sensitivity of teak growth to inter-annual climatic variability.
225 Low-growth years such as 1873, 1902, 1912, 1949, 1968, 1973, 1989, and 2004 likely
226 correspond to major climatic anomalies, including droughts, excessive rainfall, or temperature
227 extremes.

228 **4. Discussion**

229 In this section, we examine tree growth and climate relationships at local and regional
230 scales, explore the physical processes behind any observed teleconnections, and develop a
231 climate reconstruction based on the identified relationships.

232 **4.1 Tree Growth and Local Climate Response**

233 Three climate parameters mainly control teak growth in the tropics: temperature, rainfall
234 and soil moisture. Their relations with teak growth are displayed in Fig. 4. It shows significant
235 positive correlation with local temperature in late springs and summer months of March-July,

as well as with the pre-monsoon to monsoon season average (May-August, Fig. 4a). In contrast, rainfall shows positive but mostly insignificant correlations with RWI during the monsoon months (June–September, Fig. 4b). Interestingly, soil moisture exhibits positive correlations with RWI in all winter months till February, suggesting that higher soil moisture in the post-monsoon/winter period is beneficial for teak growth (Fig. 4c). This finding aligns with the soil moisture climatology of the region: soil moisture in the WG builds up over the monsoon, peaking in late summer or early autumn and remaining elevated into the dry winter months (Venkatesh et al., 2011). Thus, residual soil moisture after the monsoon likely extends the growing period of teak into the cooler dry season, contributing to ring formation in winter.

4.2 Relationship of SST, MSLP, and SAMI with ring width

As noted in the Introduction (Section 1), a primary objective of this study is to assess the influence of large-scale climate variability on teak growth in the study region. Given strong teleconnections affecting the South Asian climate, we explored the relationship between the Kodagu tree-ring width index (RWI) and global sea surface temperature (SST) variability. Previous studies indicate that teak growth in India and other tropical regions often exhibits negative correlations with equatorial Pacific SST, particularly during El Niño events that induce drought conditions and reduced radial growth (Borgaonkar et al., 2010). Building on this framework, we computed spatial correlations between RWI and monthly global SST anomalies.

The correlation map for SST of the May-August season, showing the strongest association (Fig. 5a). The analysis uses gridded SST data from the NOAA NCEP OI SST dataset for 1982–2017, considering only correlations significant at the 95% confidence level. Three regions exhibit significant positive correlations with teak growth: (A) the high-latitude North Pacific near the Gulf of Alaska, (B) the central equatorial Pacific, and (C) the Southern Ocean south

of the Indian Ocean sector. Among these, the Southern Ocean shows the most consistent and strongest relationship with the Kodagu RWI.

The highest correlations occur within a sector of the Southern Ocean approximately bounded by 46°–51°S and 18°–24°E (Fig. 5b–d). In this region, May–August SST correlates with the RWI at $r \approx 0.72$, explaining roughly 50% of the variance. This area lies within the highly dynamic Southern Ocean, where monthly SST anomalies can reach magnitudes of ±2.5°C (Dorman & Winant, 1995; Gower, 2002). Except during September–October, correlations between the RWI and SST within this region remain positive and statistically significant throughout most months, with a pronounced peak during May–August (Fig. 5b). The strong seasonal concentration suggests that climatic conditions in the Southern Ocean during austral autumn and winter coinciding with the South Asian summer monsoon season may exert a measurable influence on teak growth in the Western Ghats.

To ensure that this relationship is not dependent on a particular SST dataset, the analysis was repeated using the HadISST dataset. May–August SST averages for the same Southern Ocean region (46°–51°S, 18°–24°E) were extracted for 1982–2017 from both datasets. The resulting time series shows nearly identical variability (Fig. 6), with a correlation of $R^2 = 0.99$. This strong agreement confirms that the identified SST–RWI relationship is robust and not an artefact of dataset selection.

The pronounced SST signal over the Southern Ocean suggests that extratropical Southern Hemisphere climate variability may influence teak growth in the Western Ghats. To investigate a possible atmospheric mechanism, we analyzed correlations between RWI and mean sea level pressure (MSLP) anomalies during May–August using ERA5 reanalysis data for 1982–2017. The correlation pattern (Fig. 7a) reveals a dipole structure over the Southern Ocean sector identified in the SST analysis. At high latitudes (~50°–60°S, 0–40°E), RWI correlates

positively with MSLP, whereas around ~40°S the correlation becomes negative. Thus, years of wider rings correspond to higher pressure at high latitudes and lower pressure at mid-latitudes.

This spatial pattern closely resembles the structure of the Southern Annular Mode (SAM), which is typically defined by the normalized MSLP difference between mid-latitudes (~40°S) and high latitudes (~65°S). The results therefore suggest that teak growth variability is linked to the phase of the SAM, with enhanced growth associated with a negative SAM-like pressure pattern and reduced growth with a positive phase.

To further evaluate this link, we calculated a regional SAM index following Gong and Wang (1999), based on the zonal MSLP difference between 40°S and 65°S. The index was computed for the 0°–40°E sector and averaged over May–August for 1980–2017, consistent with the approach of Pai et al. (2023). Comparison with the Kodagu RWI (Fig. 7b) reveals a clear inverse relationship, with a significant correlation ($\rho \geq 0.05$). Years of strong teak growth correspond to lower SAM index values (negative SAM phase), whereas weaker growth coincides with positive SAM conditions.

Overall, these results indicate that teak growth in the Western Ghats is linked to large-scale Southern Hemisphere climate variability. Specifically, enhanced growth tends to occur during negative SAM phases characterized by higher pressure over the Antarctic region and a weakened subtropical jet, whereas reduced growth is associated with positive SAM phases marked by lower high-latitude pressure and a strengthened, poleward-shifted jet. These findings highlight a previously underexplored pathway through which Southern Ocean climate variability may influence hydroclimatic conditions affecting tree growth in the Western Ghats.

4.3 Physical processes explaining SAM-RWI teleconnection:

The key question arising from these results is how a climate phenomenon centered in the extratropical Southern Hemisphere can influence tree growth in the tropical Northern Hemisphere. To investigate this mechanism, we applied a composite analysis approach. The study period (1980–2017), for which reliable climate data are available, was divided into high-growth and low-growth years based on the standardized ring-width index (RWI). High-growth years were defined as those when RWI exceeded the mean by more than 0.5 standard deviation ($> \mu + 0.5\sigma$), while low-growth years were defined as RWI $< \mu - 0.5\sigma$. Using these criteria for the KOD chronology, 12 high-growth and 12 low-growth years were identified. Composites of sea surface temperature (SST), mean sea-level pressure (MSLP), winds, vertically integrated moisture transport, rainfall, and soil moisture were then calculated for these two groups to identify consistent climatic patterns associated with favorable and unfavourable conditions for teak growth.

The composite anomalies for high-growth minus low-growth years are summarized in Fig. 8–11. SST composites for May–August (Fig. 8a, c) reveal a pronounced gradient between the Southern Ocean and the northern Indian Ocean. High-growth years are characterized by warm SST anomalies south of ~40°S, including the Southern Ocean region identified earlier, as well as warming north of Madagascar and around the Maritime Continent. In contrast, low-growth years show weak or absent warming in the Southern Ocean, except for localized anomalies south of Madagascar. The strongest differences between the two composites occur east and south of South Africa and over parts of the South China Sea.

The MSLP composites (Fig. 8b, d) display a corresponding atmospheric circulation pattern. During high-growth years, positive pressure anomalies dominate the Southern Ocean and Antarctic fringe, while weak negative anomalies appear over Australia and parts of the subtropical Indian Ocean. This configuration resembles a negative phase of the Southern

Annular Mode (SAM). Conversely, low-growth years exhibit negative pressure anomalies at high southern latitudes and positive anomalies over Australia, consistent with a positive SAM phase. Thus, favourable tree-growth years correspond to a negative SAM state characterized by warmer Southern Ocean SSTs and higher pressure, whereas unfavourable growth years coincide with a positive SAM configuration.

To trace the influence of these large-scale anomalies on the Indian monsoon system, composites of wind and moisture fields were examined (Fig. 9). The 850-hPa wind anomalies indicate that high-growth years are associated with strengthened westerly flow over the Arabian Sea and southern India, implying an intensified southwest monsoon circulation. Westerly anomalies also extend along the equatorial Indian Ocean, while easterly anomalies appear over the western Pacific and parts of the Bay of Bengal. Together, these features suggest an enhancement of the cross-equatorial monsoon flow. In contrast, low-growth years show northeasterly wind anomalies over the Arabian Sea and the Western Ghats, indicating a weakened monsoon circulation. Overall, thick-ring years coincide with stronger low-level monsoon winds, whereas thin-ring years reflect weaker or disrupted monsoon flow.

The vertically integrated moisture transport composites (Fig. 9b, d) further highlight these differences. During high-growth years, strong southwesterly moisture transport toward the Indian subcontinent produces marked moisture convergence over the Western Ghats and central India. In low-growth years, moisture divergence dominates over much of India, indicating reduced atmospheric moisture supply. This contrast directly corresponds to the rainfall anomalies shown in Fig. 10, confirming that favorable growth years coincide with enhanced monsoon moisture influx and convergence over the study region.

Rainfall composites (Fig. 10) show that high-growth years are generally wetter than average across most of the Indian subcontinent. The largest positive anomalies occur along the

Western Ghats and central India, although parts of eastern India display slightly below-normal rainfall. In contrast, low-growth years exhibit widespread negative rainfall anomalies across western and central India, with only limited regions in eastern or northeastern India showing above-normal precipitation. These results demonstrate that wider tree rings correspond to years with stronger monsoon rainfall over the Western Ghats, whereas narrow rings are associated with deficient monsoon conditions.

The hydrological consequences of these rainfall variations are reflected in soil-moisture composites (Fig. 11). During high-growth years, soil moisture in the upper ~0–2 m layer is above normal across the Western Ghats and much of India. This reflects both enhanced rainfall and efficient recharge of soil water. In low-growth years, soil-moisture anomalies are predominantly negative. For teak growth, this difference is critical because soil moisture sustains cambial activity during the post-monsoon months. Elevated soil moisture in high-growth years likely prolongs the growing season and supports continued growth even into the typically dry winter period, consistent with the winter correlations observed in the chronology.

Runoff composites show a similar hydrological response. High-growth years are associated with above-normal runoff across the study region, indicating stronger surface and subsurface water flows, while low-growth years display deficient runoff. These patterns imply a more active regional hydrological cycle during favourable growth years: increased rainfall leads to greater infiltration, higher soil moisture, and enhanced runoff, all of which improve water availability for vegetation. In contrast, reduced rainfall and soil moisture during low-growth years likely impose water stress on trees during critical growth periods, resulting in narrower rings.

Overall, the composite analysis indicates that the teleconnection between SAM and Western Ghats teak growth operates through large-scale atmospheric circulation changes that

379 modulate the Indian summer monsoon. Negative SAM–like conditions favor enhanced
380 monsoon circulation, greater moisture transport toward India, increased rainfall, and sustained
381 soil-moisture availability, ultimately promoting wider tree rings. Positive SAM–like conditions
382 have the opposite effect, weakening monsoon circulation and producing drier regional
383 conditions that limit tree growth. This mechanistic link explains the observed relationship
384 between Southern Ocean SST variability and teak ring-width variability and supports the
385 interpretation that the teak chronology captures a robust signal of large-scale climate
386 variability.

387 The physical processes governing the relationship between ring width and Southern Ocean
388 SST are explained by a schematic diagram (Fig. 12). In this diagram, we consider only the
389 composites for the negative phases of SAM (Fig. 8a-b, 9a-b, 10a, 11a). The left panel (Fig.
390 12a) demonstrates large-scale processes occurring across the equator, while the right panel
391 (Fig. 12b) displays the local processes conducive to teak growth. During negative phase of
392 SAM, a positive MSLP anomaly is observed south of 40°S and north of it a negative MSLP
393 anomaly, which enhances the meridional gradient of pressure associated with the summer
394 monsoon. Supports stronger south-westerly monsoon winds, leads excess moisture transport
395 across equator towards northern hemisphere and subsequently converges over central and
396 southern India, including WG, which resulted in excess monsoonal precipitation over the WG.
397 This enhanced rainfall leads to increased runoff and soil moisture over the WG. On the other
398 hand, the local processes controlling soil moisture concentration and tree growth are sluggish
399 (Fig. 12b). Studies have shown that soil moisture concentration reaches its acme almost two
400 months later than the peak rainfall (Sengupta et al., 2023). This delayed response is further
401 modulated by the tree physiological processes. An optimum amount of moisture is required for
402 tree growth. Therefore, availability of excess soil moisture associated with above normal
403 monsoon supports tree growth mainly during the stress period, i.e., non-rainfall seasons (fall to

spring, October-May). Previous studies (e.g., Shaikh et al., 2024), evapotranspiration over the study period is higher during the non-monsoon months. Hence tree ring growth more rely on the soil moisture condition during post ISM (October-May), excess monsoon years lead to thick tree rings and vice versa in teak (e.g., Ram et al., 2010; Palakit et al., 2015; Preechamart et al., 2018). For the same reason, tree growth responds to regional processes during ISM but is sensitive to local soil moisture during winter (Fig. 4c)

4.4 Southern Ocean SST Reconstruction

Given the strong relationship between our tree-ring index and Southern Ocean SST (Section 4.2), proceeded to reconstruct the past SST of that region. We focused on the Box-B region SST (Southern Indian Ocean, ~46°–51°S, 18°–24°E as specified in Fig. 5a caption) averaged over May–August, since this metric showed the highest correlation with tree growth.

The calibration and verification statistics are summarized in Table 3. For the full calibration period (1982–2017) R^2 is 0.52, suggests about ~52% of the variance is explained by the regression model and captures the actual variability of SST (Fig. 13a). The RE (Reduction of Error) and CE (Coefficient of Efficiency) values are positive in all cases (Table 3), with RE around 0.30–0.59 and CE around 0.27–0.58 depending on the period (higher when verifying the later period, lower for the earlier) indicates the model has predictive skill better than the mean. The PRESS statistic for the full model is 0.47 (in standardized units), which is reasonably low. In simpler terms, the model is stable: it performs similarly in either split configuration, which gives us confidence that the relationship did not change drastically between these sub-periods. The drop in R^2 from calibration to verification (0.52 to ~0.31) is not unexpected given the short length of the series and possible noise in both tree rings and SST. It suggests there are other influences or some non-stationarity, but the presence of a

significant signal is undeniable. The fact that verification skill is positive and similar in both swaps indicates the reconstruction is robust (i.e., not an artifact of a single period).

Therefore, the model was utilised for reconstruction back in time. Fig. 13b shows the reconstructed May–Aug SST in the Southern Ocean from 1725 to 2017 (Fig. 13b). The mean reconstructed SST over the 1725–2017 period is around 3.8°C, with a standard deviation of ~0.24°C for the interannual variability.

4.5 Several features of long-term SST reconstruction

From the early to late 18th century (~1725–1800), SST appears relatively stable with modest fluctuations. Starting in the 19th century, variability seems to increase. The mid-19th century shows some notable swings, which might correspond to known climate events (perhaps volcanic eruptions or ENSO variability; though attribution is speculative). The 20th century shows an overall warming trend. In particular, early 20th century (1920s–1940s) SSTs rose to values higher than any in the previous 200 years of the reconstruction. The 1940s in our record stand out as a warm period. This timing interestingly coincides with early anthropogenic warming and perhaps a combination of natural variability (e.g., a positive phase of the Interdecadal Pacific Oscillation could also manifest as Southern Ocean warmth (Zhu et al., 2021; Yao et al., 2024).

The late 20th and early 21st century show a pronounced warming. Notably, 1998 is the highest value in the entire series, which aligns with the record-breaking 1997–98 El Niño event that caused widespread warmth (Ray and Giese, 2012). Our model captures 1998 as a significant positive excursion (even above what one might consider the “normal” range). Other recent warm peaks include 2005 and 2016, which were also El Niño years or near-record global

warmth years (Thirumalai et al., 2017). The reconstruction indicates that the post-1980 period contains some of the warmest summers in the last 293 years for this region.

There is a suggestion of a warming trend accelerating in the late 20th century, which is consistent with instrumental observations of Southern Ocean warming due to global climate change.

5. Conclusion

We present a 293-year teak tree-ring chronology from the Western Ghats that captures a clear imprint of Southern Ocean variability and the Southern Annular Mode (SAM).. The strong and consistent relationship between tree growth and Southern Indian Ocean SSTs, supported by coherent circulation and moisture transport anomalies, provides evidence for a persistent cross-hemispheric teleconnection linking Southern Ocean dynamics to Indian monsoon hydroclimate. Tree-ring chronology correlates positively with local temperature and soil moisture, particularly during and after the monsoon. Importantly, chronology exhibit a robust relationship with May–August SST and mean sea level pressure in the southern Indian Ocean (~48°–56°S, 36°–50°E), reflecting a Southern Annular Mode (SAM) signal. Composite climate analyses reveal that a negative SAM phase enhances monsoon strength, moisture convergence, and tree growth, while a positive SAM phase leads to drought and narrow rings. The reconstructed SST record (1842–2017) provides a valuable proxy-based constraint on variability in the Southern Indian Ocean, a region where long-term observational data remain scarce. These findings highlight the sensitivity of tropical hydroclimate to high-latitude Southern Hemisphere processes and demonstrate the potential of tropical tree rings to extend records of large-scale ocean–atmosphere variability. This framework provides new opportunities to investigate past and future interactions between Southern Ocean change and monsoon dynamics. .

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Declaration of Competing Interests:

The authors confirm that they have no known financial conflicts or personal relationships that could have influenced the work presented in this paper.

Data availability

All data necessary for supporting the scientific findings of this paper will be provided on reasonable request by the corresponding authors.

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692

693

694 **Figure captions**

695

696 **Fig. 1.** (a) Location of the study area in India, (b)Enlarged view of the study area with the teak-
697 core sampling sites denoted by red star symbols. The nearest IMD climate grid point is marked
698 by a cross symbol. 'T' represents Thithimati and 'N' represents Nagarhole. (c) An elevation
699 profile along A-B, showing across the WG. Point A(red) represents the windward side and
700 point B (blue) the leeward side on the Ghats.

701

702 **Fig. 2**. The Walter leith climate diagram (1901 to 2017) of the study region blue bar shows
703 mean monthly precipitation (mm), and the red line shows mean monthly Air temperature (°C).
704 The climate data (precipitation and temperature) are from the nearest IMD stations
705 (Kodagu/Madikeri).

706

707 **Fig. 3**. The regional signal free tree-ring chronology of Tectona grandis from Thithimati and
708 Nagarhole forest area, Karnataka India. (a) The tree ring chronology represents from years
709 1725-2017. Horizontal lines denote the mean (0.99) and ±1 standard deviation (0.13) of the
710 index; these thresholds are used to identify extreme growth years. (b) Sample depth and
711 chronology signal statistics: The changing inter-series correlation (RBAR) and corresponding
712 expressed population signal (EPS) over time. The EPS exceeds the 0.85 threshold back to ~1842
713 C.E., indicating that the chronology is robust for climate analysis up to that year.

714

Fig. 4. Monthly correlations between the KOD of RWI and local climate variables: (a) mean temperature, (b) total rainfall, and (c) soil moisture. The horizontal dashed lines mark the 95% significance level for correlation coefficients. Climate data are from the Kodagu/Madikeri stations (temperature and rainfall) and GLDAS (soil moisture). Notably, significant positive correlations are seen with temperature in March, April, June, July and the May–August seasonal mean, and with soil moisture in winter (February).

Fig. 5. (a) Spatial correlation map between average SST anomalies (May–August, 1982–2017) and the Kodagu teak RWI. Only correlations significant at the 95% level are shown. Three regions with notable positive correlations between RWI and SST averaged over regions b, c, and d, respectively, are marked: (b) Southern Ocean (Indian sector) (c) equatorial Pacific, and (d) high-latitude around the Gulf of Alaska, indicating the strongest and most consistent relationship for region b (Southern Ocean) during May–Aug. (Data source: NOAA NCEP OI SST)

Fig. 6. Comparison of Southern Ocean SST indices from two datasets: NOAA NCEP OI SST vs. HadISST, averaged over the Box-A region (46°–51°S, 18°–24°E) for May–August, 1982–2017. The scatter plot shows an almost perfect correspondence ($R^2 \approx 0.99$), indicating no bias between datasets and affirming the robustness of the SST–RWI correlation.

Fig. 7. (a) Spatial correlation between May–August MSLP anomalies (ERA5, 1982–2017) and the Kodagu RWI. A dipole in the Southern Hemisphere is evident: RWI correlates positively with MSLP in the high-latitude Southern Ocean (around 50°–60°S) and negatively around

739 ~40°S. Box-A marks the Southern Ocean region of interest (as in Fig. 5). (b) Time series of
740 RWI vs. SAMI (5-month running means) highlighting their out-of-phase relationship.

741

742 **Fig. 8.** Composite anomalies of (a) SST (°C) and (b) MSLP (hPa) for high-growth years, and
743 (c) SST and (d) MSLP for low-growth years (May–Aug, 1980–2017). Anomalies are relative
744 to the 1980–2017 mean.

745

746 **Fig. 9**. Composite anomalies of (a) 850 hPa winds (vectors, m/s) for high-growth years and (c)
747 for low-growth years, and (b) vertically integrated moisture transport (vectors) and moisture
748 divergence (colors) for high-growth years and (d) for low-growth years.

749

750 **Fig. 10.** Composite anomalies of Indian Summer Monsoon (ISM) rainfall (mm/day) for (a)
751 high-growth years and (b) low-growth years (May–Sept average).

752

753 **Fig. 11.** Composite anomalies of terrestrial hydrologic variables during high-growth years (left
754 panels) and low-growth years (right panels): (a, e) root-zone soil moisture anomalies (kg/m^2),
755 (b, f) total runoff anomalies (m), (c, g) surface runoff anomalies (m), and (d, h) sub-surface
756 runoff anomalies (m). All panels represent May–Sept composites for 1980–2017.

757

758 **Fig. 12**. Schematic showing regional (a) and local (b) processes governing growth-climate
759 relationships in our study during high ring growth period (negative phase of SAM). The
760 schematic is based on the results shown in **Fig. 8a-b, 9a-b, 10a and 11a**.

761

762 **Fig. 13.** (a) Reconstructed SST and observed SST for the Southern Ocean, May–Aug seasonal
763 averages, during the calibration period 1982–2017. The model captures much of the observed
764 variability (calibration $R^2 \approx 0.52$) (b) Reconstructed May–Aug SST in the Southern Indian
765 Ocean from 1725 to 2017 based on the Kodagu RWI chronology. The black curve is a 5-year
766 low-pass filter, and gray shading indicates the ±1 standard deviation range of interannual
767 variability. A warming trend in the late 20th–early 21st century is evident.

768