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Late Holocene Vegetation Dynamics and Sea Level Fluctuations: A High-Resolution Record from Southeast India

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Abstract: A detailed high-resolution study of climate and vegetation changes in two sedimentary profiles from the Godavari delta in India was conducted to understand extreme climate variability over the last 3000 years. These historical climate records are vital for predicting future climate changes influenced by increased human activity. Pollen records reveal several climatic periods: (1) an initial warm/humid phase (2260–1560 cal yr BP) with mangrove and tropical tree pollen and maximum pollen accumulation rate (PAR_{max}), (2) a gradual shift to drier conditions with reduced mangrove and arboreal pollen, coinciding with the Dark Ages Cold Period (1580–1070 cal yr BP), (3) a Medieval Warm Period (1090–580 cal yr BP) marked by a stronger summer monsoon, rejuvenation of mangroves and tree pollen, (4) a relatively cool and dry phase with abundant dry deciduous and non-arboreal pollen possibly linked to the Little Ice Age (580–80 cal yr BP), showing a weakened monsoon, and (5) recent warming since 80 cal yr BP. A semi-quantitative aridity, temperature, and moisture index based on pollen concentration variations have also been used to identify centennial-scale climatic cycles in the pollen record.

Keywords: palynology; mangroves; climatic events; late Holocene; Godavari delta



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1. Introduction

Earth's climate varies from interannual to geological timescale and this unpredictability results from both external and internal forces, the former being linked to the natural and human induced disturbances [1]. The use of fossil fuels has further enhanced the greenhouse-gas (GHG) emissions, which is the main cause of late Holocene climate change. Several natural processes, both internal (atmosphere and ocean) and external (solar, Earth-orbital changes and volcanic) are supposed to be crucial for the past two millennia [2]. The boundary condition of Earth's climate i.e., the continental arrangement, Earth's orbital parameters, spatial extent of continental ice sheets, and orography have not varied considerably in the last two millennia. Therefore, this period offers an analog for assessing the natural climate variations that in turn interprets the modern climate variability. As the instrumental records provide information only for the hemispheric (large-scale) climate changes for the past few centuries, it is essential that we turn to other lines of evidence to evaluate the longer-term changes over the past one or two millennia. Proxy data are one such signal from natural archives that describe the climatic variations in the past centuries. Relatively high-resolution proxy records such as pollen, corals, tree rings, ice cores, speleothems, marine and lacustrine sediments [3] may be used to reconstruct vegetation and climate changes over the past millennium. We are still facing a major challenge for accurate simulations of the intricacy of Earth's climate system with even the most innovative Earth system models. The key challenge in assessing the climate model performance in past projections is the scarcity of millennial to centennial-scale consistent climate proxy records from various regions of the world. Proxy-based palaeoclimate reconstruction offers

an outstanding database that helps in testing the models and validating their ability to precisely simulate long-term climate change signals [4]. The palaeoclimate record extends the ability to simplify the regional climate variability that characterizes the Holocene on decadal to millennial finer timescales.

Historical documents and oral traditions give an insight of the impacts that the global climate shifts had on the cultures, economies, and societies in the past two millennia. This spans the time of considerable warmth at the height of the Roman Empire called the Roman Warm Period (RWP) [5,6], and the expansion of Viking in the Medieval Climate Anomaly (MCA), opposing the socioeconomic disorder caused by the cold and dry Little Ice Age (LIA) [7–9]. Slow shifts to these climatic scenarios are dissimilar to the abrupt changes associated with major volcanic eruptions such as Samalas, Krakatoa, and Tambora [10] which lasted for several years, cyclic climate trends of North Atlantic Oscillation, El Niño–Southern Oscillation and Indian Ocean Dipole [11–13], and the solar forced Maunder Minimum [14,15]. Holocene is characterized by millennial-scale climate variability of weaker amplitude, assessed at c. 2 °C sea surface temperatures [16]. A good number of proxy records have been generated to lower the ambiguities in estimating pre-industrial climate inconsistency [17]. Numerous late Quaternary studies have documented cold and arid climates centered in the middle of the first millennium AD and described it under “Dark Ages Cold Period” (DACP) spanning between AD 400 and 765 [18]. However, little is known regarding the impact of this millennial-scale climate variation on the Indian subcontinent and, specifically the Indian Peninsula.

Palynological records are a suitable tool for vegetation and climate reconstruction that in turn estimates the plant–climate interactions. In this study, we present the centennial-scale palynological data derived from the sedimentary sequences in the Godavari delta, southeast coast of India. Our objective is to reconstruct local and regional vegetation dynamics from high-resolution palynological data and assess the probable impact of the major climatic events such as the Iron Age Cold Epoch (IACE), the Roman warm Period (RWP), Dark Ages Cold Period (DACP), Medieval Warm Period (MWP), Little Ice Age (LIA), and the Current Warm Period (CWP) during the late Holocene on the vegetation along the Godavari River delta.

2. Study Area

2.1. Godavari Delta: Regional Framework

The Godavari River flows across a major part of the Deccan Plateau in Central India. It covers a transitional climate zone ranging from wet to semi-arid. Cultivation of pulses, millets, barley, and wheat in the Deccan Plateau has been reported since ~5000 years BP [19]. Vegetation specifically in the upper ranges of the Deccan Plateau along the Godavari River is receptive to monsoonal precipitation along with extensive agricultural practices on the Deccan Plateau. Hence, it is anticipated that the vegetation changes, such as land use/landcover, deforestation, and agricultural expansion in response to population expansion, had induced changes in the sediment input from the Deccan Plateau, which is, however, less known. High-resolution continuous record of sediment source, erosion, vegetation, monsoonal changes, and anthropogenic activity for the time period between 6.1 and 1.3 cal. kyr BP revealed increased sedimentation rate with high sensitivity of proxies to climate in a sedimentary profile from the Godavari River delta, India [20]. Previous research works from the Godavari River delta were mainly based on the mapping of inland beach ridges that characterize the paleoshorelines and palaeo-distributary paths in the deltaic plains of the Godavari River. These studies are mainly based on the analysis of satellite imagery and aerial photographs [21,22].

The existing literature on the Godavari delta is thus essentially based on mapping of landforms as well as AMS 14C dating of fossil shells recovered from highly disturbed discrete samples collected through auger drilling into shallow subsurface sediments [23]. However, lack of detailed studies based on the analysis of continuous core sediments in the Godavari delta left a gap in understanding the impact of climatic events during the time

span when the delta was actively prograding, i.e., since ~3 kyr and the vegetation development during that time. The present study therefore is an attempt to record the vertical and horizontal changes in the vegetation cover due to major climatic events and anthropogenic pressure during the last two millennia based on high-resolution palynological records from undisturbed core sediments from the mangrove wetlands of the Godavari River delta.

2.2. Godavari Delta: Hydrological Setting and Human Settlement

The Godavari River, originating in the Western Ghats, flows southeast across the Indian Peninsula before reaching the Bay of Bengal [24]. The river's drainage basin is subject to the Indian monsoon climate, with an average precipitation of 923 mm during the wet season, which constitutes 82% of the annual rainfall [22]. Rainfall in the upper basin (Deccan Plateau) is less than 750 mm, while it exceeds 1000 mm in the lower basin. This variation in precipitation supports two primary vegetation types: thorny vegetation (mainly C4 plants) in the upper basin, and tropical dry/moist deciduous forests (primarily C3 plants) in the mid-lower basin [25].

Historical human cultures, including Neolithic and Iron Age communities, have been documented in the upper Godavari drainage basin of the Deccan Plateau [26]. The Neolithic era featured scattered scrubby savanna woodlands and thorny shrubs [27]. During the early Holocene, hunter–gatherer societies transitioned to millet and pulse cultivation and pastoralism, promoting food production through domesticated plants and animals [28,29]. Millet cultivation began around 5000 years ago, with wheat and barley introduced approximately 4000 years ago [26]. Settlements appeared around 4000 years ago, with further development around 3000 years ago [30]. Pit dwellings in the Godavari Basin, dating to about 2000–1800 BC, reflect the Savalda culture. Urbanization in the first millennium BC, exemplified by Pratisthana in the upper Godavari Basin, led to advanced irrigation systems for rice cultivation in Central India. Pratisthana, now called Paithan, was the capital of the Satavahana dynasty (2nd century BC to 2nd century AD) and is renowned for its ancient shrines and silk trade, situated near a major dam across the Godavari River.

The Godavari delta is a major wave-dominated delta, characterized by significant sediment delivery. It comprises two main units: the upper fluvial plain and the lower strand plain. The upper fluvial plain is a gently rolling area that slopes toward the sea from approximately 12 to 6 m above mean sea level (msl), featuring fluvial landforms like ancient river channels and natural levees. The lower strand plain, below 6 m above msl, includes beach ridge/swale complexes, tidal flats, mangrove swamps, lagoons, and creeks. A large mangrove swamp occupies the southern part of Kakinada Bay, with smaller patches along the Gautami Godavari distributary.

The delta formed around 6000 years ago through six stages of sediment deposition migration [20]. Sediment accumulation rates in the delta increased from about 12 m/yr between 6000 and 4000 cal yr BP to 27 m/yr between 4000 and 3000 cal yr BP and 52–62 m/yr between 3000 and 1000 cal yr BP, before decreasing to 44 m/yr in the last 1000 years [20]. The region experiences a humid tropical climate, with monsoon rains from June to December, resulting in low salinity during this period. The dry season begins in January and extends to the hot summer months of April and May. The area receives an average rainfall of about 1160 mm, with maximum and minimum temperatures in Kakinada averaging 32.36 °C and 24.4 °C, respectively. The wetland is notable for its intricate network of interconnected creeks, densely vegetated with mangroves. However, a 10 km stretch from Yanam to the Nilarevu tributary's mouth shows signs of erosion and substrate loss affecting the mangroves [31].

The geomorphology of the Godavari estuary includes features such as rivers, channels, floodplains, natural levees, mangrove forests, tidal channels, tidal flats, lagoons, Kakinada Bay, sand spits, mainland beaches, dunes, and palaeo sand ridges. The delta's natural levees are well-developed, measuring about 500 m in width and 2 m in height near Doweleswaram. In mangrove areas, these levees range from 3 to 5 m in width and about 1 m in height. These levees can obstruct tidal water flow in some mangrove regions. Fine silty-clay sediments

suspended during flood tides are deposited on tidal flats during high tide slack, providing suitable conditions for new mangrove colonization.

3. Materials and Method

Two sediment cores of 2.5 and 3.0 m depth were retrieved from Gogulanka (GL)- $16^{\circ}41'47.92''$ N, $82^{\circ}16'45.29''$ E and Boddovenkatapalem (B)- $16^{\circ}48'49.05''$ N, $82^{\circ}15'21.46''$ E village, respectively, located on the landward edges of the mangrove swamps along the Godavari River delta (Figure 1). The cores were obtained using a hand-operated augur cum piston corer (Eijelkamp, The Netherlands) and were immediately subsampled at 2 cm intervals and stored in a refrigerator at 4 °C. In the laboratory, sediment color was determined using Munsell color chart [32] and sediment grain size was estimated in alternate samples, from every 4 cm depth interval in the cores (77 samples from GL, 75 samples from B). The sand and mud contents from each sample were measured by using a 63- μ m sieve.

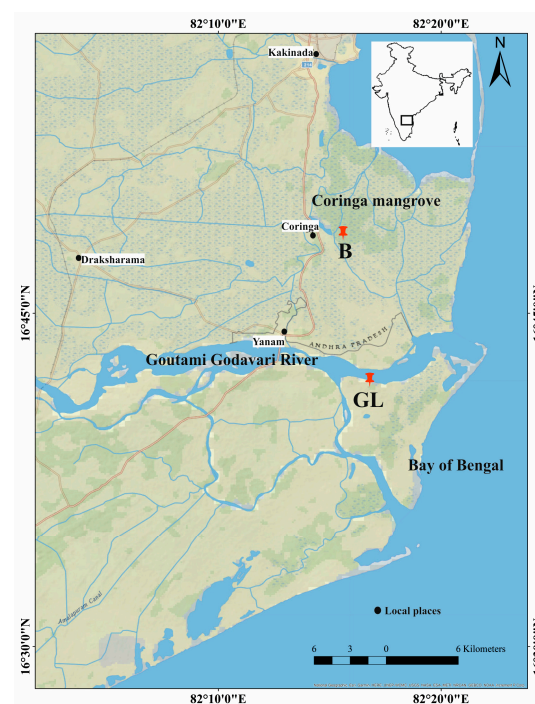


Figure 1. Location of coring sites in Coringa mangroves, Godavari delta, southeast coast of India.

3.1. Radiocarbon Dating

Organic-rich samples were selected for AMS ^{14}C dating at various depths for both GL and B core. The radiocarbon dates were calibrated using INTCAL 20 [33]. These calibrated dates were then applied to develop the age–depth model. The rbacon package v.3.2.0 [34] was utilized to construct this model, and Bayesian statistical methods were employed sediment accumulation rates through time.

3.2. Grain-Size Analysis

For grain-size analysis, the samples were treated with hydrochloric acid (10%) and hydrogen peroxide (3%) to remove carbonate and organic carbon, respectively [35–37]. Sodium hexametaphosphate (1%) used to avoid grain flocculation during pre-treatments [38,39]. Detailed grain-size analyses well performed using Laser Particle Size Analyzer (Beckman Coulter LSTM 13 320 California, USA) at Birbal Sahni Institute of Palaeosciences (BSIP), India. After that, the percentages of sand, silt (<63 μm – >4 μm) and clay (<4 μm) were calculated in each sample.

3.3. Pollen Analysis

For palynological preparations, sediment samples of 1 cm³ were taken and one tablet of exotic *Lycopodium* spores was added to each sample to calculate pollen concentrations and pollen fluxes. All samples were treated with standard preparation techniques including pre-treatment with KOH (10%), HF (1%) followed by Erdtman's (1960) [40] acetolysis technique. The palynomorphs were analyzed under Olympus BX-53 microscope and identified by referring to pollen atlases [41–43] and reference pollen slides from the Herbarium of Birbal Sahni Institute of Palaeosciences. For each sample, a minimum of 300 palynomorphs was counted when possible, including trees, shrubs, herbs, vines, and climbers (i.e., pollen sum). Fern spores, fungal spores, algae, thecamoebians, foraminifera and other palynomorphs were counted, but not included in the pollen sum. According to the modern vegetation distribution [44], pollen taxa were classified into six ecological groups: (1) Mangroves, (2) Terrestrial trees, (3) Terrestrial shrubs and (4) Herbs and open vegetation. Additionally, pteridophyte spores and aquatic microfossils were also grouped, and their relative abundances were calculated in relation to the pollen sum. The identified taxa are listed in Table 1. For calculation of pollen sum, pollen concentration, pollen accumulation rate (PAR), cluster analysis, and diagram plotting Tilia, CONISS and Tiliagraph software v.1.7.16 [45] were used.

Table 1. List of taxa identified in the palynological study with their habitat preferences.

Taxa	Growth Form	Habitat
Mangrove taxa		
<i>Acrostichum aureum</i>	Mangrove fern	Common in mangrove swamps and tidal backwaters
<i>Aegialitis rotundifolia</i>	Mangrove small tree or shrub	Occurs in exposed sites and creeks
<i>Aegiceras corniculatum</i>	Mangrove small tree or shrub	Abundant
<i>Conocarpus erectus</i>	Evergreen mangrove tree	Common
<i>Sonneratia apetala</i>	Broadleaved evergreen mangrove tree	Common
<i>Sonneratia caseolaris</i>	Broadleaved evergreen mangrove tree	Common
<i>Bruguiera cylindrica</i>	Broadleaved evergreen mangrove tree	Common along the river mouth
<i>Ceriops decandra</i>	Broadleaved evergreen mangrove tree	Common
<i>Rhizophora apiculata</i>	Broadleaved evergreen mangrove tree	Abundant
<i>Excoecaria agallocha</i>	Evergreen or deciduous mangrove tree	Common in landward side
<i>Xylocarpus mekongensis</i>	Broadleaved evergreen mangrove tree	Common in Central zone of mangrove forests
<i>Avicennia marina</i>	Evergreen mangrove tree	Common
<i>Avicennia officinalis</i>	Evergreen mangrove tree	Common
<i>Avicennia alba</i>	Evergreen mangrove tree	Common near the seaward side
<i>Acanthus ilicifolius</i>	Mangrove shrub	Common in less saline areas
Arboreal taxa		
<i>Pinus</i>	Evergreen coniferous tree	Common in mountain habitats
<i>Cocos</i>	Palm tree	Common in coastal lowlands
<i>Barringtonia</i>	Evergreen tree	Occurs on banks of streams, edges of swamps, and moist places
Meliaceae	Terrestrial evergreen tree	Abundant in shade or open habitats
<i>Azadirachta indica</i>	Terrestrial evergreen tree	Invades disturbed natural vegetation in open woodlands, grasslands, floodplains, and coastal regions

Table 1. Cont.

Taxa	Growth Form	Habitat
<i>Careya arborea</i>	Terrestrial deciduous tree	Common in semi-open forests and disturbed areas
<i>Palmae</i> (Arecaceae)	Palm tree	Range from the lowlands to mountain habitats
Sapotaceae	Evergreen tree	Pantropical distribution
<i>Syzygium</i>	Evergreen tree	Banks of streams in evergreen forests, scrub jungles and higher areas in swamps
Bombacaceae	Evergreen tree	Humid lowland forests
<i>Elaeocarpus</i>	Evergreen tree	Found in lowland rain forest, but also frequent in lower montane forest,
<i>Casuarina equisetifolia</i>	Evergreen tree	Common in open, coastal habitats including sand beaches, rocky coasts and sand dunes
Combretaceae	Evergreen tree	Grow in mangrove habitats
<i>Lumnitzera racemosa</i>	Evergreen tree	Common in landward side
<i>Thespesia populneoides</i>	Evergreen tree	Common in landward areas
<i>Strombosia ceylanica</i>	Evergreen tree	Occurs in lowland forests, mixed Dipterocarp and secondary forest, often close to the sea, on well drained flat land or lower slopes of ridges
Non-arboreal taxa		
<i>Dalbergia spinosa</i>	Terrestrial shrub, Thorny Lianas	Common in less saline areas
<i>Hibiscus tiliaceus</i>	Evergreen shrub	Common in landward areas
Malvaceae	Terrestrial shrub	Humid, semi-arid and arid habitats
<i>Clerodendrum inerme</i>	Evergreen shrub	Common
<i>Acacia</i>	Terrestrial shrub	Terrestrial habitats found in warm, tropical, and desert-like regions
Verbenaceae	Terrestrial shrub	Thrive in moist, shaded environments such as rainforests
Euphorbiaceae	Evergreen or semi- deciduous Terrestrial shrub or small tree	Seasonally dry forest, often in open and disturbed habitats
Solanaceae	Terrestrial herb	Common in moist to wet lowland forests
Alternanthera	Terrestrial herb	Found along the edges of ponds and watersides
<i>Caesalpinia crista</i>	Vine	Common in less saline areas
<i>Derris trifoliata</i>	Vine	Common in less saline areas
<i>Justicia</i>	Terrestrial herb	Grows on the plains and in moist deciduous forests and grasslands
Liliaceae	Terrestrial herb	Shade plants in closed shaded habitats
Rosaceae	Deciduous terrestrial herb	On mountain slopes, along streams and on disturbed sites
Asteraceae	Terrestrial herb	Mostly occur in hot desert, grasslands and cold or hot semi-desert climates
<i>Artemisia</i>	Terrestrial herb	Common in dry or semi-arid habitats
Chenopodiaceae/ Amaranthaceae	Terrestrial herb	Grow in dry, sandy areas, mostly found in weedy situations in cultivated or disturbed areas
Poaceae	Terrestrial herb	Almost everywhere from forest, open grassland, to the desert and the coast,
Cyperaceae	Terrestrial herb	Found especially in cooler, wetter habitats
<i>Typha</i>	Terrestrial herb	Common in wetlands, sedge meadows, along slow moving streams, river banks, and lake shores

3.4. Quantitative Estimates

The semi-quantitative aridity index of [46] was calculated by dividing the sum of Chenopodiaceae plus Artemisia pollen by the percentage of Poaceae pollen. Temperature and moisture were also estimated semi-quantitatively based on the ratios between groups of pollen taxa, which represented different temperature and moisture conditions [47–49].

$$\text{Temperature index (T)} = \frac{\text{Total woody/arboreal taxa}}{\text{Total grassland/herbaceous taxa}}$$

$$\text{Moisture index (M)} = \frac{\text{Total Evergreen + fern taxa}}{\text{Total deciduous + grassland taxa}}$$

$$\text{Aridity index (A)} = \frac{\text{Chenopodiaceae/Amaranthaceae + Artemisia}}{\text{Poaceae}}$$

$$\text{Palynomar ineindex (PMI)} = \frac{\text{Marine palynomorphs}}{\text{Terrestrial palynomorphs}}$$

4. Results

4.1. Chronology and Age–Depth Model

In total, 12 radiocarbon dates using ^{14}C are available from GL and B (see Table 2). All dates were obtained from Direct AMS ^{14}C laboratory in the USA. Calibrated radiocarbon dates are presented throughout the text in cal yr BP. The GL and B cores provide a record of vegetation over the past ~2009 and ~3014 years, respectively. The model chronology and sedimentation rate were estimated using the age–depth model, developed with the “Bacon” package in R software (<https://www.R-project.org/> (accessed on 5 August 2024)) [50]. The age–depth models indicate a mean sedimentation rate of 0.1 cm/yr for both the cores (Figure 2).

Table 2. List of AMS radiocarbon dates for GL and B cores from the Godavari River delta, Southeast coast of India.

S.No.	Lab Code	Sample No.	Depth	Radiocarbon Date (Uncalibrated)	Calibrated Date (yr BP) (1σ)
1.	D-AMS 024797	GL-17	34	Modern	Modern
2.	D-AMS 024794	GL-27	54	60 ± 24	71
3.	D-AMS 024803	GL-39	78	207 ± 31	180
3.	D-AMS 024801	GL-47	95	1077 ± 25	978
4.	D-AMS 024805	GL-58	116	1623 ± 29	1525
5.	D-AMS 024804	GL-88	176	1723 ± 27	1631
6.	D-AMS 024795	GL-96	192	1746 ± 36	1656
7.	D-AMS 024806	GL-117	234	1937 ± 31	1886
8.	D-AMS 024813	B-50	100	873 ± 30	779
9.	D-AMS 024812	B-95	190	1768 ± 29	1671
10.	D-AMS 024811	B-122	244	2104 ± 28	2076
11.	D-AMS 024810	B-145	290	2864 ± 39	2984

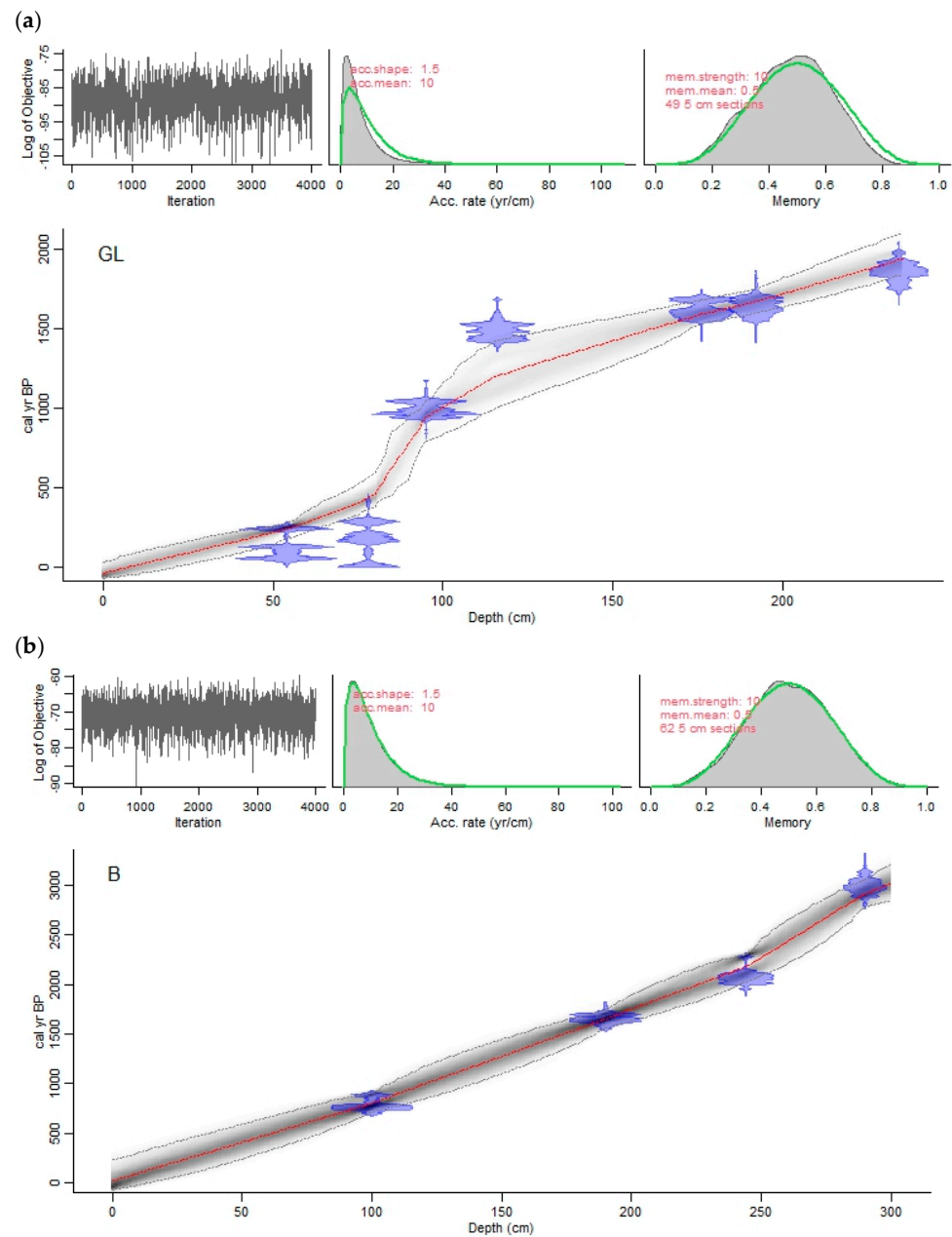


Figure 2. Age–depth model and rate of sedimentation of core GL (a) and B (b). The blue violet plots represent the probability distributions of the calibrated ages at different depths based on the age–depth model. The wider sections of the violin plots indicate greater uncertainty at those depths. The red line shows the best-fit model (mean age–depth relationship), and the shaded region around it represents the uncertainty envelope (likely the 95% confidence interval).

4.2. Grain-Size Distribution

Sediment zones are delimited based on the information content of core descriptions recorded on direct observations of archived core sections. These zones are prefixed with the site code and the letter “s” (e.g., GLs-) to distinguish them from independent biozones defined on the basis of pollen data. Zones are numbered from the base upwards.

4.3. Gogulanka Core (GL)

GL core, located on the floodplain of the Nilarevu River about 10 km inland of the river mouth, reached a depth of c. 250 cm. Based on variation in different proxies, the following lithological zones are distinguished from base to the top:

4.3.1. GLs-1: 250–238 cm

At the base of the GL sequence is a unit of sand and silt (5Y5/4). This is the coarsest unit at the base (250–238 cm) with sand (53%), silt (43%) and a low percentage of clay (4%).

4.3.2. GLs-2: 238–202 cm

This zone contains predominantly fine-grained sediments (silt) with clay (5Y4/2). Silt percentage is predominantly high (85%) with a less percentage of fine-grained clay (10.2%) and fine sand (5%), enriched in parts with organic material.

4.3.3. GLs-3: 202–100 cm

A thick zone of sandy-silt (5Y6/4) sediment overlies the fine clayey silt zone. Throughout the zone, the sediments show a fluctuating condition in sand (0.44–40%) and clay percentage (4.5–15%) with a higher percentage of silt (75.6%).

4.3.4. GLs-4: 100–64 cm

This zone contains compact silts with sand sediment (5Y3/2). A clay-rich (9–9.5%) soil with the highest percentage of silt (86%) is recorded at 78 cm and 86 cm depth. Sand percentage in the entire zone varies from 5.3% to 17.2% with an average of 11%.

4.3.5. GLs-5: 64–0 cm

The uppermost zone contains sandy-silt (5Y5/4) sediment with less organic material in the topmost layer. Average silt percentage is the lowest (66%) in comparison to the rest of the zones along with clay (5%). Sand percentage (29%) fluctuates between 6.3 and 53.6% with the highest at 34 cm depth.

4.4. Boddu Venkatapalem Core (B)

B core is located in an exposed mangrove marsh toward the landward end of Coringa mangrove wetland in the north of Godavari River delta. The core reached a depth of c. 300 cm. Based on variation in different proxies, the following lithological zones are distinguished from base to the top:

4.4.1. Bs-1: 300–280 cm

The basal deposits of the B sedimentary fill are composed of sandy-silt sediment (5Y6/4) with a low percentage of clay (6%). Sand in the unit varies from 14 to 35.7% with an average of 25.5% whereas silt percentage is between 58 and 78.6% with an average of 68.5%.

4.4.2. Bs-2: 280–202 cm

This zone contains predominantly fine-grained silt sediments with nearly equal proportions of sand and clay (5Y6/4). The zone shows a homogenous sediment composition with high silt percentage (82.2%) along with sand (9.7%) and clay (8%). The clay percentage is maximum (11.3%) with a minimum sand (3.2%) at a depth of 272 cm.

4.4.3. Bs-3: 202–130 cm

A thick zone of sandy-silt (5Y3/2) sediment follows the homogenous silt zone. Sand proportion in the zone varies from 12.3 to 37% while clay is nearly constant with an average of 4.3% with a higher percentage of silt (74.2%).

4.4.4. Bs-4: 130–82 cm

This zone contains compact silt with varying proportions of sand and clay sediment (5Y2/2). A clay-rich (9–10.6%) soil with the highest percentage of silt (89.8%) is recorded at 94–106 cm and at 122 cm depth. Sand percentage in the entire zone varies from 1.0% to 20.5% with an average of 8.5%.

4.4.5. Bs-5: 82–0 cm

The uppermost zone contains sandy-silt (5Y6/4) sediment with the least proportion of clay in the entire core. The average silt percentage is the lowest (50.8%) in comparison to the rest of the zones along with clay (3.7%). High fluctuations are observed in the sand percentage between 6.9 and 63.9%. At 62 cm depth, the highest proportion of clay (10.4%) with lowest value for sand (6.9%) in the sediment is observed.

Sedimentological parameters are also considered as an important index for understanding the hydrodynamics and depositional environment. Both the sediment cores are mainly composed of sand and silt contributing 89–97% for B and 85–97% for GL core.

4.5. Palynological Assemblage

The following section presents a zone-by-zone description of the pollen results to accompany the pollen percentage diagrams. Percentage values mentioned in the description of pollen analysis refer to percentages of the sums of mangrove/arboreal/non-arboreal taxa.

4.6. GL Gogulanka

In general, the condition of pollen and spore preservation in the basal part of the core (corresponding to sediment zones GLs-1/2/3) and at the top of the core (corresponding to sediment zones GLs-5) is good. However, in the middle part (corresponding to GLs-4), the preservation status of pollen grains is poorer. This contrast is reflected in less diverse pollen spectra for the middle section. Also, in some layers, the combination of low percentage and poor preservation meant that counts reaching the desired sum of 300 pollen were not possible. The summary pollen diagram (Figure 3) shows the results of analysis of 126 samples. Complete pollen data are presented in the Supplementary Figure S1.

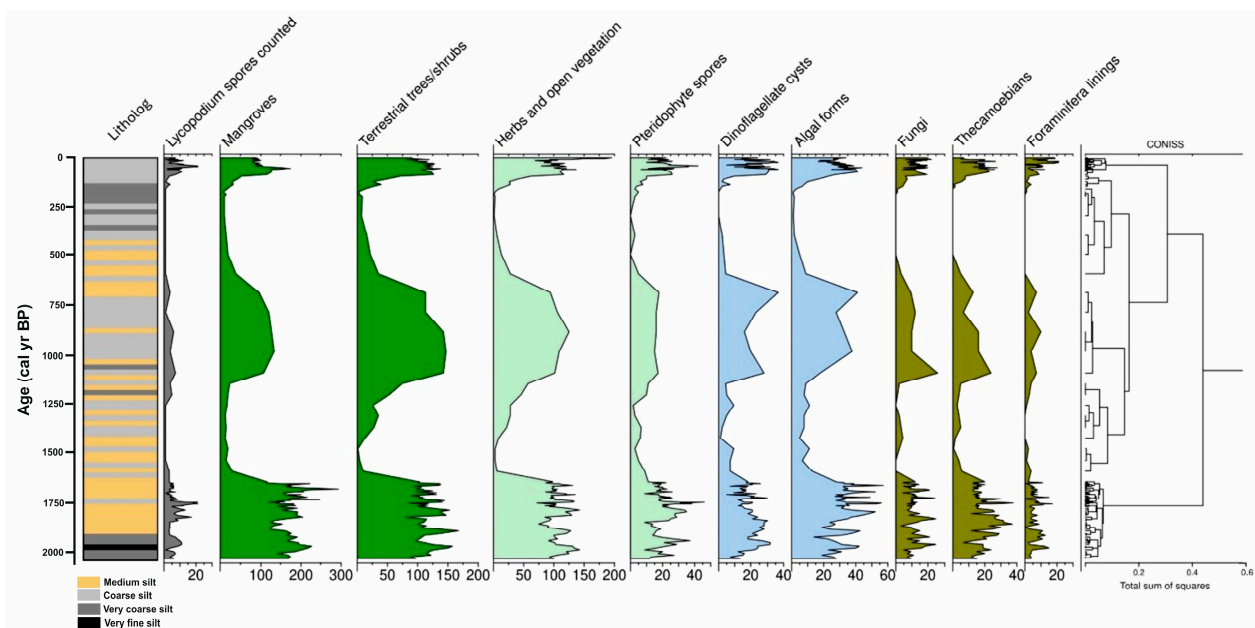


Figure 3. Summary Palynological diagram of GL core against age (cal yr BP). The timescale, supported with eight AMS 14 C dates is added to the left.

Five biozones are distinguished in the GL pollen record:

4.6.1. GL-I: 250–116 cm (2000 cal yr BP–1620 cal yr BP)

GL-I is characterized by good pollen preservation and a high abundance of mangroves, upland trees, and open vegetation taxa. Overall, the total pollen and spore assemblage are dominated by a good number of terrestrial taxa (*Dalbergia spinosa*, *Lumnitzera racemosa*, *Hibiscus tiliaceus*, *Barringtonia*, *Azardirachta indica*, *Careya arborea*, *Strombosia ceylanica*, *Palmae*,

Syzygium, *Elaeocarpus*, *Casuarina equisetifolia*, *Thespesia populneoides*, *Meliaceae*, *Sapotaceae*, *Bombacaceae*, *Combretaceae*, *Malvaceae* members) and are characterized by high values of herbaceous taxa (*Caesalpinia crista*, *Derris trifoliata*, *Clerodendrum inerme*, *Acacia*, *Alternanthera*, *Justicia*, *Artemisia*, *Typha* sp., *Euphorbiaceae*, *Solanaceae*, *Verbenaceae*, *Liliaceae*, *Rosaceae*, *Asteraceae*, *Chenopodiaceae*/*Amaranthaceae*, *Poaceae* and *Cyperaceae* members). The mangroves and terrestrial pollen types represent a major proportion of the pollen assemblage.

The mangrove group in GL-I is characterized by high values of *Sonneratia apetala* and *S. caseolaris* (3.6% each), *Excoecaria agallocha* (4.1%), *Conocarpus erectus* (3.6%), *Avicennia marina* (3.9%), *Xylocarpus mekongensis* (3.7%), *Rhizophora apiculata* (3.3%), *Acanthus ilicifolius* (2.8%), *Aegialitis rotundifolia* (2.8%) and *Aegiceras corniculatum* (2.6%). The biozone is characterized by high values of terrestrial taxa reflecting chiefly *Barringtonia* (2.2%), *Azardirachta indica* (1.7%), *Elaeocarpus* (1.7%), *Combretaceae* (1.7%), *Pinus* (0.3%), *Coccos* (1.3%), *Dalbergia spinosa* (1.3%), *Lumnitzera racemosa* (1.4%), *Hibiscus tiliaceus* (1.5%), *Meliaceae* (1.4%), *Careya arborea* (1.7%), *Strombosia ceylanica* (1.3%), *Palmae* (1.2%), *Sapotaceae* (1.2%), *Syzygium* (1.4%), *Bombacaceae* (1.2%), *Casuarina equisetifolia* (1.6%), *Malvaceae* (1.4%) and *Thespesia populneoides* (1.2%). Herbaceous and open forest taxa such as *Caesalpinia crista* (1.5%), *Derris trifoliata* (1.7%), *Clerodendrum inerme* (1.7%), *Acacia* (1.9%), *Alternanthera* (1.4%), *Euphorbiaceae* (2.5%), *Solanaceae* (1.4%), *Verbenaceae* (1.4%), *Justicia* (1.4%), *Liliaceae* (1.7%), *Rosaceae* (2.1%), *Asteraceae* (1.7%), *Artemisia* (1.6%), *Chenopodiaceae*/*Amaranthaceae* (1.4%), *Poaceae* (1.2%), *Cyperaceae* (1.4%), and *Typha* (1.6%) are found at various levels in the entire zone.

The non-pollen palynomorphs include spores of *Acrostichum aureum* or mangrove palm (2.1%) and *Selaginella* (5.4%) along with fungal spores (6.4%), *Tetraploa* (4.9%), freshwater algae like *Pediastrum boryanum* (5.9%), *Pediastrum simplex* (5.4%), *Botryococcus* (9.3%), Zooplankton (6.3%), *Pseudoschizaea* (6.7%), Testate amoebae like *Arcella* (5.7%), *Cyclopyxis* (5.8%), *Nebela* (7.4%) and marine forms such as dinoflagellate cysts like *Spiniferites* (7.2%), *Bitectodinium* (5.4%), *Dinocyst* (5.6%) and foraminifera linings (5.9%) in the basal biozone.

4.6.2. GL-II: 115–98 cm (1620–1130 cal yr BP)

GL-II displays low abundance of mangroves with the occurrence of *Sonneratia apetala* (3.2%), *Excoecaria agallocha* (4.0%), *Conocarpus erectus* (8.5%), *Aegiceras corniculatum* (5.2%), *Avicennia alba* (3.1%), *Bruguiera cylindrica* (3.0%), *Xylocarpus mekongensis* (2.8%), *Rhizophora apiculata* (2.4%) and *Avicennia marina* (1.7%). *Aegialitis rotundifolia* and *Avicennia officinalis* were also present in the zone in a low percentage (<1%).

The biozone is characterized by a decline in the percentage of terrestrial trees, shrubs, and herbs with significant values showing abundance of *Casuarina equisetifolia* (4.6%), *Hibiscus tiliaceus* (4.6%), *Coccos* (3.0%), *Palmae* (3.0%), *Lumnitzera racemosa* (2.8%), *Strombosia ceylanica* (2.8%), *Dalbergia spinosa* (1.8%), *Sapotaceae* (1.8%), *Combretaceae* (1.1%), *Barringtonia* (1.1%), *Meliaceae* (2.3%), *Malvaceae* (2.3%), *Azardirachta indica* (0.5%), *Thespesia populneoides* (0.5%), *Careya arborea* (0.8%), and *Elaeocarpus* (0.1%). Herbaceous taxa include *Liliaceae* (4.6%), *Euphorbiaceae* (3.0%), *Alternanthera* (2.2%), *Acacia* (1.9%), *Solanaceae* (1.8%), *Poaceae* (1.9%), *Cyperaceae* (2.2%), *Chenopodiaceae*/*Amaranthaceae* (0.8%), *Artemisia* (0.5%), *Asteraceae* (2.3%), *Rosaceae* (1.1%), *Justicia* (0.1%).

The biozone marks a rise in dinoflagellate cysts such as *Spiniferites* (16.0%), zooplanktons (16.0%) with presence of *Acrostichum aureum* (5.9%), *Selaginella* (9.5%), *Pediastrum boryanum* (7.4%), *Botryococcus* (6.3%), *Tetraploa* (7.4%), Testate amoebae *Nebela* (8.5%), and *Cyclopyxis* (6.3%).

4.6.3. GL-III: 97–88 cm (1070–670 cal yr BP)

GL-III is characterized by a generally high percentage of mangrove pollen types with the reappearance of *Sonneratia caseolaris* (3.0%) and *Acanthus ilicifolius* (2.1%). Mangrove pollen show dominance of *Avicennia marina* (4.7%), *Rhizophora apiculata* (3.1%), *Excoecaria agallocha* (2.4%), *Avicennia officinalis* (2.5%) with the presence of *Conocarpus erectus* (2.2%),

Sonneratia apetala (2.2%), *Xylocarpus mekongensis* (2.2%), *Bruguiera cylindrica* (2.0%), *Avicennia alba* (1.7%). Moderate to high values for upland tree taxa with Arecaceae (3.3%), Bombacaceae (2.4%), *Barringtonia* (2.3%), *Dalbergia spinosa* (2.3%), *Lumnitzera racemosa* (2.0%), *Hibiscus tiliaceus* (2.0%), Meliaceae (2.0%), *Careya arborea* (1.9%), Sapotaceae (1.9%), *Thespesia populneoides* (1.8%) were observed. *Syzygium*, *Azadirachta indica*, *Strombosia ceylanica*, *Elaeocarpus*, *Casuarina equisetifolia*, Malvaceae and Combretaceae members were also observed in the pollen assemblage (1.3–1.5%). Herbaceous taxa and open ground taxa show dominance of Liliaceae members (3.2%), Solanaceae (2.9%), *Caesalpinia crista* (2.7%), *Acacia* (2.2%), Verbanaceae (2.0%), Asteraceae (2.3%), *Justicia* (2.1%), *Alternanthera* (1.8%) and *Clerodendrum inerme* (1.6%). Other open ground taxa included Euphorbiaceae members (1.3%), Rosaceae (1.5%), *Artemisia* (1.5%), Chen/Ams (1.5%), Cyperaceae (1.6%), Poaceae (1.2%). Aquatic taxa pollen *Typha* (1.3%) reappeared in this zone.

High abundance of *Dinocyst* sp. (12.3%), *Bitectodinium* (7.8%), along with *Pediastrum simplex* (8.7%), *Pseudoschizaea* (8.5%) and *Botryococcus* (7.6%), fungal spores (6.5%), *Tetraploa* (10%) is also recorded. The biozone also marks the significant occurrence of thecamoebians *Cyclopyxis* (15–20%) and *Arcella* (10%) along with a continuous curve for foraminiferal linings (30%).

4.6.4. GL-IV: 87–62 cm (670–90 cal yr BP)

The transition to biozone GL-IV is marked by a decline in the diversity of mangrove taxa pollen with the dominance of *Aegiceras corniculatum* (11.6%), *Sonneratia apetala* (6.4%), *Aegialitis rotundifolia* (5.4%), and *Rhizophora apiculata* (3.9%). However, *Conocarpus erectus* (2.0%), *Excoecaria agallocha* (1.3%), *Xylocarpus mekongensis* (1.3%), *Avicennia marina* (1.2%), *Avicennia alba* (1.4%), and *Acanthus ilicifolius* (1.5%) show moderate abundance in the pollen assemblage. Terrestrial pollen data also show lower diversity of tree with minor peaks of *Dalbergia spinosa* (6.4%), *Hibiscus tiliaceus* (3.9%), Palmae (3.9%), and *Thespesia populneoides* (3.9%).

Shrubs and herbs also showed a loss in diversity and abundance reflecting *Artemisia* (3.9%), *Justicia* (2.0%), Liliaceae (1.8%), and Solanaceae (1.4%).

The non-pollen microfossils also display a continuous curve with high to low peaks for *Pediastrum colonies* (32.4%), *Spiniferites* (6.7%), *Bitectodinium* (7.1%), *Testate amoebae* (6.6%), Zooplanktons (6.4%), *Tetraploa* (5.8%), *Botryococcus* (4.7%), *Acrostichum aureum* (5.8%), *Pseudoschizaea* (2.1%), fungal spores (4.5%), and foraminifera linings (5.8%).

4.6.5. GL-V: 61–0 cm (90 cal yr BP–Present)

GL-V shows increased percentage values but a lower diversity of mangroves, terrestrial trees/shrubs, and herbaceous taxa. The biozone is characterized by moderate values of mangrove pollen types reflecting the dominance of *Avicennia marina* (4.0%), *Avicennia officinalis* (3.2%), *Acanthus ilicifolius* (2.8%), *Excoecaria agallocha* (2.4%), *Avicennia alba* (2.2%), *Xylocarpus mekongensis* (2.2%), *Rhizophora apiculata* (2.1%), and *Sonneratia caseolaris* (2.0%). The zone also displays a reoccurrence of the terrestrial tree/shrub taxa, reflecting moderate values of the representative taxa across the biozone. Increased abundance is noted for Meliaceae (3.3%), *Barringtonia* (1.9%), *Careya arborea* (1.3%), *Strombosia ceylanica* (2.0%), Sapotaceae (1.8), Bombacaceae (1.5%), *Elaeocarpus* (1.5%), Combretaceae (1.7%), and Malvaceae (2.7%). Herbaceous and open vegetation taxa also show an increase in abundance relative to the previous biozone with *Caesalpinia crista* (1.5%), *Derris trifoliata* (1.5%), *Clerodendrum inerme* (1.8%), *Acacia* (1.7%), *Alternanthera* (2.8%), Euphorbiaceae (1.7%), Solanaceae (1.9%), Verbanaceae (1.6%), Liliaceae (2.2%), Rosaceae (1.6%), Asteraceae (1.8%), Chenopodiaceae/Amaranthaceae (1.7%), Poaceae (3.2%), Cyperaceae (2.3%), *Typha* (2.3%).

Among non-pollen microfossils, increased values of *Spiniferites* (9.7%) and other *Dinocyst* sp. (6.1%) along with *Pediastrum boryanum* (6.3%), *P. simplex* (4.3%), *Botryococcus* (5.7%), *Pseudoschizaea* (5.4%), Fungal spores (6.6%), *Tetraploa* (5.8%), *Arcella* (4.9%), *Cyclopyxis* (6.6%) and foraminifera linings (9.3%) have been recorded.

4.7. B Boddu Venkatapalem

The B core is characterized by variable pollen preservation, with several major and minor peaks in the pollen record corresponding to the variation in climatic conditions.

The summary pollen diagram (Figure 4) shows the results of analysis of 151 samples. Complete pollen data are presented in the Supplementary Figure S2.

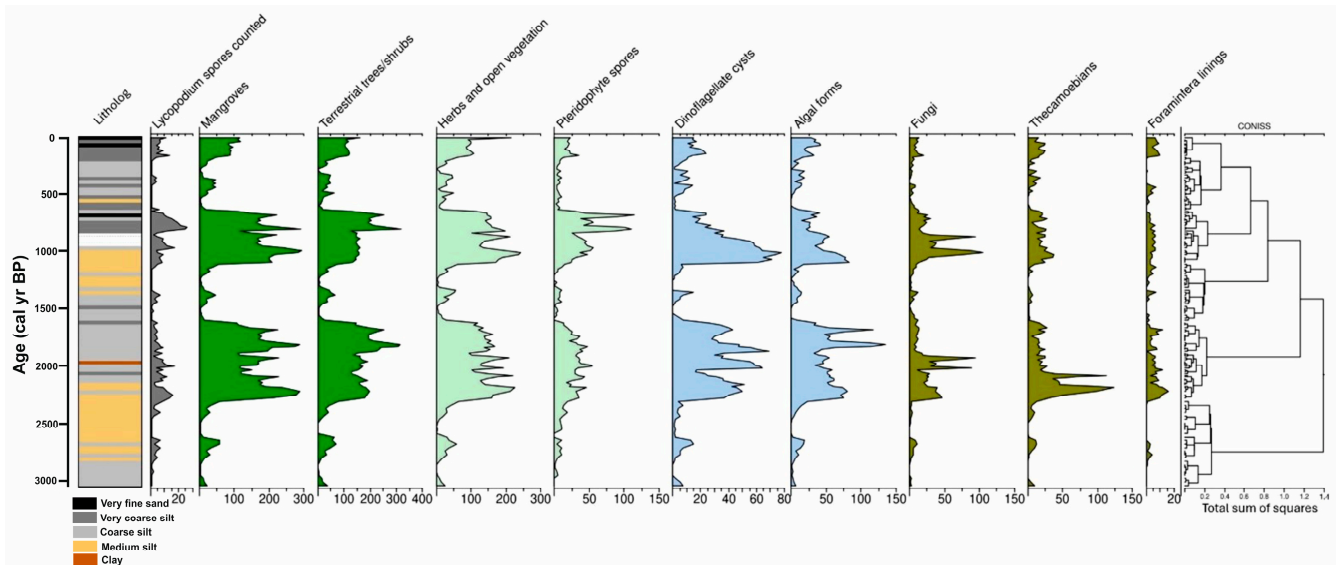


Figure 4. Summary Palynological diagram of B core against age (cal yr BP). The timescale, supported with eight AMS 14 C dates is added to the left.

4.7.1. B-I: 300–252 cm (3010–2290 cal yr BP)

Altogether B-I is characterized by the low abundance of mangroves and terrestrial tree pollen types. Mangroves show dominance of *Avicennia alba* (8.4%) and *Sonneratia caseolaris* (8.4%) followed by low percentage of other mangrove genera such as *Aegiceras corniculatum*, (2.3%), *Acanthus ilicifolius* (1.4%), *Ceriops decandra* (1.8%) and *Aegialitis rotundifolia* (1.4%). Terrestrial tree taxa mainly comprise of Verbenaceae and Bombacaceae members (8.6%), Meliaceae (3.1%), *Thespesia populneoides* (2.6%), *Barringtonia* (2.5%), *Pinus* (1.8%), *Strombosia ceylanica* (1.7%), *Lumnitzera racemosa* (1.6%), *Careya arborea* (1.4%), *Elaeocarpus* (1.5%) and *Casuarina equisetifolia* (1.6%). Herbaceous taxa show dominance of Chenopodiaceae/ Amaranthaceae (5.7%), *Justicia* (2.5%), *Clerodendrum inerme* (2.4%), Rosaceae (2.4%), *Alternanthera* (1.9%), Poaceae (1.4%), Cyperaceae (1.9%) and *Derris trifoliata* (1.4%).

Non-pollen palynomorphs also show the dominance of *Dinocyst* sp. (20.8%) followed by *Pseudoschizaea* (13.8%) and *Arcella* (6.5%) in this zone.

4.7.2. B-II: 251–174 cm (2290–1600 cal yr BP)

B-II is characterized by an overall rise of mangroves and terrestrial tree taxa such as *Avicennia officinalis* (5.5%), *Sonneratia caseolaris* (4.3%), *Sonneratia apetala* (2.9%), *Avicennia marina* (2.9%), *Avicennia alba* (2.4%), *Acanthus ilicifolius* (3.9%), *Excoecaria agallocha* (2.3%), *Xylocarpus mekongensis* (2.2%), Rhizophoraceae members *Bruguiera cylindrica* (2.6%), *Ceriops decandra* (1.2%), and *Rhizophora apiculata* (1.0%) have also been recorded in this zone.

An increase in the diversity of terrestrial tree/shrub taxa has been observed with the dominance of Combretaceae (3.4%), *Casuarina equisetifolia* (3.3%), Palmae (2.5%), *Elaeocarpus* (2.1%), *Azardirachta indica* (2.1%), Sapotaceae (2.0%), *Careya arborea* (1.8%), *Hibiscus tiliaceus* (1.7%), Verbenaceae (1.7%), Bombacaceae (1.6%), *Pinus* (1.6%), Meliaceae (1.4%), *Syzygium* (1.4%), and *Strombosia ceylanica* (1.3%). Herbaceous taxa mainly comprise of *Caesalpinia crista* (3.5%), *Acacia* (3.4%), *Derris trifoliata* (3.0%), Cyperaceae (2.8%), Poaceae (2.2%), *Typha* (1.9%), Euphorbiaceae (1.8%), *Clerodendrum inerme* (1.6%), Solanaceae (1.6%), and *Artemisia* (1.6%).

The non-pollen microfossils also show the abundance of both *Pediastrum boryanum* (12.2%), *Dinocyst* sp. (8.6%), *Bitectodinium* (8.3%), *Arcella* (7.8%), Fungal spores (7.4%), *Spiniferites* (6.8%), *P. simplex* (6.8%) and *Tetraploa* (6.1%).

4.7.3. B-III: 174–124 cm (1600–1110 cal yr BP)

B-III is characterized by a gradual fall of mangrove taxa diversity reflecting *Avicennia alba* (5.2%), *Acanthus ilicifolius* (3.9%), *Sonneratia caseolaris* (3.6%) and *Xylocarpus mekongensis* (1.8%). Terrestrial taxa mainly comprise *Azardirachta indica* (5.8%), *Verbenaceae* (3.7%), *Lumnitzera racemosa* (3.6%), *Casuarina equisetifolia* (2.6%), *Dalbergia spinosa* (2.9%), *Strombosia ceylanica* (2.1%), *Palmae* (1.7%), *Syzygium* (1.6%) and *Combretaceae* (2.2%).

The open vegetation taxa are characterized by a strong representation of *Poaceae* (5.5%) with relatively fluctuating peaks of *Euphorbiaceae* (5.1%), *Caesalpinia crista* (4.0%), *Alternanthera* (3.5%), *Liliaceae* (3.4%), *Derris trifoliata* (1.8%), *Asteraceae* (1.5%), *Cyperaceae* (1.6%), and *Typha* (1.5%). Among non-pollen microfossils, increased percentage values of *Pediastrum* (12.4%), Fungal spores (19.6%), *Botryococcus* (6.1%), *Nebela* (8.1%), and Foraminiferal linings (10.5%) have been recorded all through the biozone.

4.7.4. B-IV: 123–74 cm (1110–650 cal yr BP)

B-IV shows an increased value of mangrove taxa mainly represented by *Avicennia marina* (4.6%), *Avicennia officinalis* (4.2%), *Sonneratia caseolaris* (3.7%), *Sonneratia apetala* (3.5%), *Xylocarpus mekongensis* (2.9%), *Conocarpus erectus* (2.6%), *Excoecaria agallocha* (2.4%), *Avicennia alba* (2.4%), *Rhizophoraceae* members *Bruguiera cylindrica* (1.9%), and *Rhizophora apiculata* (1.6%), *Aegiceras corniculatum* (1.9%), *Acanthus ilicifolius* (1.8%), and *Aegialitis corniculatum* (1.7%). The terrestrial tree and herbaceous taxa also show higher diversity than B-III, reflecting the increased values for *Casuarina equisetifolia* (3.2%), *Hibiscus tiliaceus* (2.6%), *Meliaceae* (2.6%), *Combretaceae* (2.4%), *Azardirachta indica* (2.3%), *Malvaceae* (2.2%), *Careya arborea* (1.7%), *Bombacaceae* (1.6%), *Elaeocarpus* (1.6%). Herbaceous taxa show presence of *Alternanthera* (4.4%), *Rosaceae* members (2.9%), *Clerodendrum inerme* (2.5%), *Liliaceae* members (2.5%), *Justicia* (2.2%), *Solanaceae* (2.2%), and *Euphorbiaceae* members (1.9%). Non-pollen microfossils with the abundance of *Selaginella* spores (14.0%), fungal spores (9.8%), *Tetraploa* (8.9%) and *Bitectodinium* (8.7%) are well represented in this zone. A constant high and low abundance of *Pseudoschizaea*, *Botryococcus*, and *Cyclopyxis* is also observed in zone B-III and B-IV.

4.7.5. B-V: 73–20 cm (650–180 cal yr BP)

The transition to biozone B-V is marked by a decline in the diversity and abundance of mangrove taxa with dominance of only *Ceriops decandra* (4.7%) and *Conocarpus erectus* (4.5%). A fall in abundance as compared to B-IV has been observed for *Sonneratia apetala* (2.55), *Sonneratia caseolaris* (0.5%), *Aegialitis rotundifolia* (1.4%), *Bruguiera cylindrica* (0.1%), *Excoecaria agallocha* (2.0%), *Xylocarpus mekongensis* (1.0%), *Avicennia marina* (1.2%), *Avicennia officinalis* (2.0%), and *Avicennia alba* (2.1%). The terrestrial tree taxa show low values for the tree taxa along with major peaks for *Coccos* (4.5%), *Casuarina equisetifolia* (4.2%), *Strombosia ceylanica* (3.9%), and *Palmae* (2.5%). Terrestrial shrubs were mainly represented by *Malvaceae* members (2.3%). However, herbaceous and open ground vegetation comprises of high percentage of *Cyperaceae* (6.7%), *Acacia* (4.2%), *Liliaceae* (3.7%), *Typha* (3.7%), *Asteraceae* (3.1%) and *Solanaceae* (2.8%). The non-pollen microfossils display a dominance of *Tetraploa* (17%), *Spiniferites* (8.9%), *Dinocyst* sp. (8.4%), and foraminifera linings (7.7%) followed by high to low peaks for *Arcella* (6.9%), and *Cyclopyxis* (6.3%). However, *Pseudoschizaea*, fungal spores, *Nebela*, and *Selaginella* spores show a decline in abundance in the zone.

4.7.6. B-VI: 19–0 cm (180 cal yr BP–Present)

Biozone B-VI is distinguished by higher recorded values for mangrove taxa as compared to zone B-V represented by *Xylocarpus mekongensis* (3.9%), *Aegialitis rotundifolia* (3.6%), *Avicennia marina* (3.0%), *Avicennia alba* (2.3%), *Rhizophora apiculata* (2.1%), *Ceriops decandra*

(2.1%), *Conocarpus erectus* (2.0%) are the dominant one across the biozone. The terrestrial tree taxa also display high abundance of tree/shrub taxa pollen reflecting moderate to low peaks for *Strombosia ceylanica* (4.0%), Meliaceae (2.6%), *Azardirachta indica* (2.5%), Verbanaceae (2.4%), Sapotaceae members (2.4%), *Lumnitzera racemosa* (2.2%), *Dalbergia spinosa* (1.9%), *Cocos* (1.7%), *Hibiscus tiliaceus* (1.7%), and Combretaceae members (1.7%). Herbaceous taxa include dominance of *Acacia* (4.2%) followed by Solanaceae members (2.6%), *Alternanthera* (2.4%), Chenop/Ams (2.3%), Rosaceae members (2.3%), Poaceae (2.2%), Cyperaceae (2.0%), and *Typha* (2.0%). Among the non-pollen microfossils *Pediastrum boryanum* (10.7%), *Spiniferites* (7.7%), foraminifera linings (7.6%), *Nebela* (7.1%), and *Cyclopyxis* (6.0%) show high values in this zone.

4.8. Pollen Accumulation Rate (PAR) and Semi-Quantitative Indices

Pollen accumulation rate (PAR) estimates of the major pollen groups obtained from the two sites show a similar trend in response to late Holocene climatic events (Figure 5).

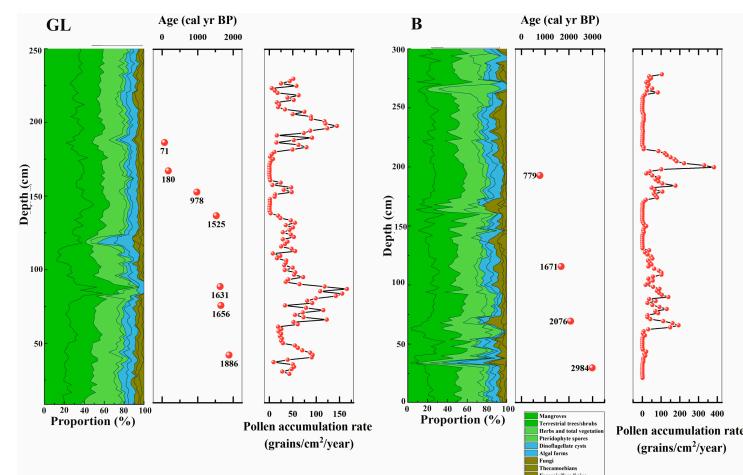


Figure 5. Summary palynomorph percentage diagram with calibrated radiocarbon age (cal yr BP) and pollen accumulation rate (PAR) for cores GL and B.

The PAR estimates show variable values throughout the sediment core with both high/low pollen concentrations in the same interval. Maximum and minimum pollen accumulation rates (PAR_{max} and PAR_{min}) observed in the GL and B sediment cores have been presented in Table 3. Maximum PAR (166.04 grains/cm²/year) in GL core was estimated at around 1725.9 cal yr BP whereas the minimum value for PAR (0.32 grains/cm²/year) was observed at around 170.3 cal yr BP. However, for the B sediment core the maximum PAR (382.77 grains/cm²/year) has been observed at 804.5 cal yr BP and minimum PAR (0.077 grains/cm²/year) at 2864 cal yr BP (Figure 6).

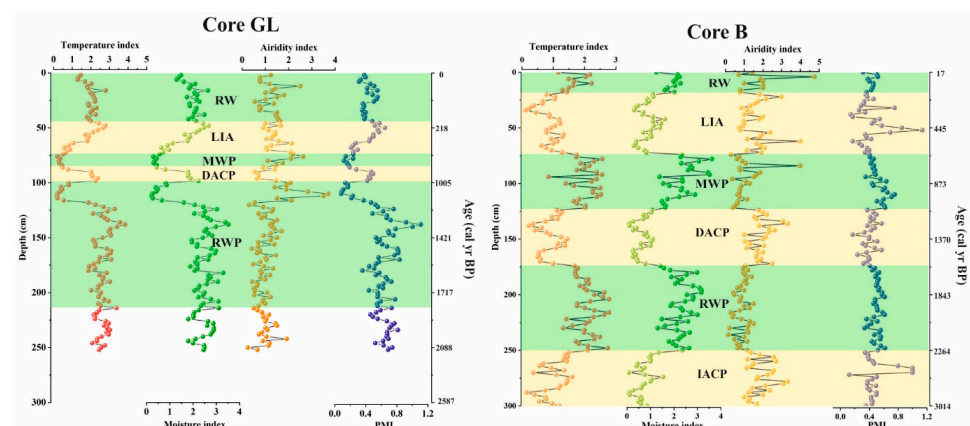
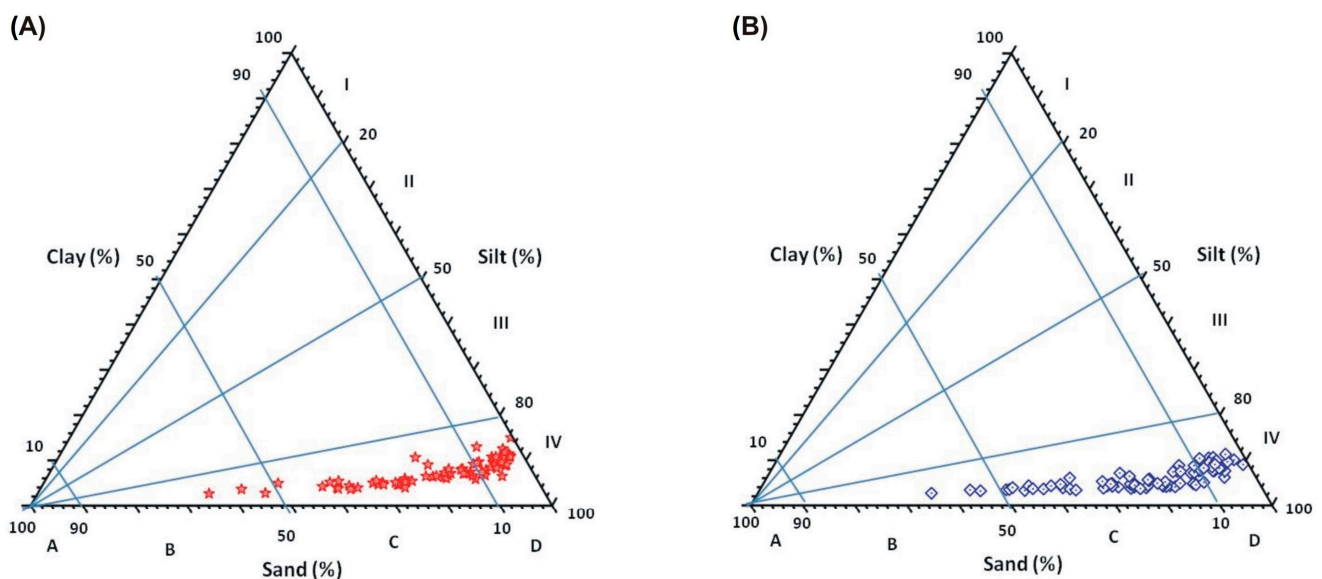


Figure 6. Temperature (T), moisture (M), aridity (A), and palynomarine index (PMI) for core GL and B.

Table 3. Maximum and minimum pollen accumulation rate (PAR) for sediment cores from Gogulanka (GL) and Boddu Venkatapalem (B) along the SE coast of India.

S No.	GL Core	PAR _{max} (Grains/cm ² /Year)	PAR _{min} (Grains/cm ² /Year)	Climate Zone
1.	GL-V	144.526 (40 cal yr BP)	5.33 (10 cal yr BP)	Current Warm Period
2.	GL-IV	79.3 (70 cal yr BP)	0.32 (170 cal yr BP)	Little Ice Age
3.	GL-III	48.04 (1070 cal yr BP)	6.82 (770 cal yr BP)	Medieval Warm Period
4.	GL-II	12.21 (1130 cal yr BP)	0.48 (1510 cal yr BP)	Dark Ages Cold Period
5.	GL-I	166.04 (1720 cal yr BP)	7.67 (1670 cal yr BP)	Roman Warm Period
B Core				
1.	B-VI	104.4 (17 cal yr BP)	22.03 (80 cal yr BP)	Current Warm Period
2.	B-V	14.22 (180 cal yr BP)	0.11 (290 cal yr BP)	Little Ice Age
3.	B-IV	382.77 (800 cal yr BP)	7.03 (650 cal yr BP)	Medieval Warm Period
4.	B-III	20.57 (1370 cal yr BP)	0.15 (1480 cal yr BP)	Dark Ages Cold Period
5.	B-II	193.62 (2230 cal yr BP)	17.66 (1900 cal yr BP)	Roman Warm Period
6.	B-I	30.93 (2290 cal yr BP)	0.077 (2860 cal yr BP)	Iron Age Cold Period

Core GL shows a $T_{\max}$ (maximum temperature index) value of 3.83 around 1650 cal yr BP whereas a $T_{\min}$ (minimum temperature index) value of 0.19 is observed at 1450 cal yr BP (Figure 7). Core B shows a $T_{\max}$ value of 2.78 around 1870 cal yr BP and 1960 cal yr BP whereas a $T_{\min}$ value of 0.12 is observed at 308.1 cal yr BP. The maximum moisture index ($M_{\max}$) value of 3.52 in core GL is also observed around 1650 cal yr BP along with the minimum moisture index ($M_{\min}$) of 0.22 around 1450 cal yr BP. However, Core B shows the maximum moisture index ($M_{\max}$) value of 3.62 around 680 cal yr BP, and a minimum moisture index ($M_{\min}$) value of 0.08 around 2560 cal yr BP. Core GL shows $A_{\max}$ (maximum aridity index) value of 3.70 around 1400 cal yr BP whereas $A_{\min}$ (minimum aridity index) value of 0.25 is observed at 2000 cal yr BP. Core B shows $A_{\max}$ value of 4.75 around 50 cal yr BP whereas $A_{\min}$ value of 0.15 is observed at 2110 cal yr BP.

**Figure 7.** Pejrup ternary diagram, Hydrodynamic state of (A) GL and (B) B sediment core.

Palynomarine index (PMI) shows the amount of marine incursion in the estuarine ecosystem. The maximum marine index ($PMI_{\max}$) value of 1.11 in core GL is also observed

around 1650 cal yr BP along with the minimum marine index (PMI_{min}) of 0.08 around 1400 cal yr BP. However, Core B shows the maximum marine index (PMI_{max}) value of 1.13 around 460 cal yr BP, and a minimum marine index (PMI_{min}) value of 0.12 around 2590 cal yr BP (Figure 6).

5. Discussion

5.1. Sediment Grain-Size Variation and Hydrodynamics

Sedimentological parameters play a crucial role in understanding the hydrodynamics and depositional environment. The sediment cores mainly consist of sand and silt, with proportions ranging from 89 to 97% for the B core and from 85 to 97% for the GL core. These sediment compositions were plotted on a ternary diagram (Figure 7) as proposed by Pejrup [51] (1988) to evaluate the hydrodynamic conditions at both study sites. The energy gradient, from low (clay-dominated) to high (silt-dominated) levels, is illustrated by four hydrodynamic groups in the Pejrup diagram. Group I represent very calm hydrodynamic conditions, Group II indicates relatively calm conditions, Group III represents relatively turbulent conditions, and Group IV indicates very turbulent conditions. The ternary diagram shows that the sediments predominantly fall within Group IV, indicating that they were deposited under very turbulent conditions, which facilitated the deposition of coarser sediments at both study sites (Figure 7).

5.2. Vegetation Dynamics in Response to Late Holocene Climatic Events

During the late Holocene, the vegetation in the region was a typical mangrove forest dominated by taxa such as *Sonneratia apetala*, *Excoecaria agallocha*, *Conocarpus erectus*, *Avicennia marina*, *Acanthus ilicifolius*, and *Barringtonia* along with the terrestrial arboreal taxa dominated by *Holoptelea*, *Meliaceae*, *Lagerstroemia*, *Sapotaceae*, *Myrtaceae*, *Casuarina*, and *Malvaceae* in the hinterland. The core B was taken from close to river mouth where it can be influenced by the sea level changes, whereas the GL core was taken from the upstream side and dominated by terrestrial taxa.

5.2.1. 3010–2290 cal yr BP (Iron Ages Cold Epoch)

Overall low abundance and diversity of mangrove and terrestrial tree pollen with dominance of salt marsh and herbaceous taxa may be related to the 2.8 kyr event, also known as the Iron Ages Cold Epoch (IACE; 3000–2400 cal BP [52], which is well-established global event with lower solar irradiance (the Homeric Minimum solar minimum centered on 2760 cal BP). There was an abrupt rise in ^{14}C and the associated decline in monsoon activity, particularly for the period around 2350 and 2800 cal yr BP [53]. Further south, in the Mediterranean region and in North Africa, the climate during the Iron Age Cold Epoch seems to have become drier, but not so dry as it is today [54–57].

5.2.2. 2290–1600 cal yr BP (Roman Warm Period)

The increase in the diversity and abundance of mangrove and upland taxa pollen in the palynological record marks the onset of the Roman Warm Period, which lasted from approximately 2200 to 1500 cal yr BP [58]. Periods of increased precipitation in the study area coincide with wetter conditions at Lonar Lake and higher precipitation in the NW Himalaya, indicating a stronger monsoon across the Indian subcontinent. This period aligns with the Roman Warm Period, known for its globally warm and humid climate [58,59]. Additionally, evidence from the mudflats of Diu Island shows a stronger Indian Summer Monsoon (ISM) between 2000 and 1800 cal yr BP [60]. A magnetic study of core sediments from Chilika Lagoon also indicate a weakening of the ISM from the mid to late Holocene, with a period of strengthened monsoon between 2000 and 1000 cal yr BP [61].

5.2.3. 1600–1110 cal yr BP (Dark Ages Cold Period)

A gradual decline in mangrove diversity with only remnants of *Avicennia*, *Sonneratia*, *Acanthus*, and *Xylocarpus* along with the loss in abundance and diversity of terrestrial tree

and herbaceous taxa pollen, marks the transition from the Roman Warm Period (RWP) to the Dark Ages Cold Period (DACP), which began around 1460 cal yr BP and involved a temperature fall to 1 °C below the 1950–1980 mean [62]. Higher values of *Cheno/Ams*, *Poaceae*, and *Cyperaceae* pollen concentration with low abundance of terrestrial shrubs and other herbaceous taxa point to a drier climatic condition which is also evidenced by a higher aridity index. Archaeological research has revealed a significant event 1410 cal BP when a series of summers failed to occur, leading to repeated crop failures and societal stress across Asia, Europe, and Central America [63]. This event marked the beginning of a period of climatic variability that aligns with the Dark Ages Cold Period (DACP). The DACP is known to be a consequence of the North Atlantic ice-rafting event (Bond Event 1) around 1400 years ago. The timing of the DACP varies, especially in Europe. In Iberia, it occurred between 1500 and 1000 years ago [58]. In Andean Peru, a cool and wet DACP, ending between 1250 and 950 cal yr BP, is indicated by higher lake levels [64] and glacier expansion [65], which hindered agriculture due to low temperatures [66]. Similarly, China experienced cool conditions from 1700 to 1150 cal yr BP [67]. In Japan and the northwest Pacific Islands, the period from 1700 to 1300 cal yr BP, corresponding to the DACP, is known as the Kofun cold stage and was associated with lowered sea levels [68].

5.2.4. 1110–650 cal yr BP (Medieval Warm Period)

Re-emergence of mangrove diversity along with terrestrial tree and herbaceous taxa could be related to a gradual increase in temperature up to the tolerance temperature range for the mangroves and tree taxa. This late Holocene warming may be associated with the Medieval Warm Period (MWP; 1050–650 cal yr BP). During this warm and humid phase, a reduction in *Cheno/Ams*, *Poaceae* and *Cyperaceae* with lower aridity index also indicates a decline in the herbaceous community. Persistent presence of pteridophyte spores especially *Selaginella* along with the fungal remains also points to a warm and wet climate. Also known as the Little Climatic Optimum, the MWP is usually defined as a warmer-than-present period that endured for ~400 years in most parts of the world. In almost every part of the world, evidence has been reported for a period between 1200 and 800 cal yr BP, that was warmer than the period before or that after [69,70].

5.2.5. 650–90 cal yr BP (Little Ice Age)

The decline in the diversity of mangroves with a low abundance of true mangroves along with a lower concentration of tree taxa such as *Palmae* and *Casuarina* marks the transition between the MWP and the Little Ice Age. This transition to a period of rapid cooling has been named as the 1300 AD (650 cal yr BP) event, to emphasize its importance to an understanding of climatic, environmental, and societal evolution within the last millennium [71]. The 1300 AD event was the most rapid cooling period of ~100 years that led to the replacement of MWP conditions with conditions by Little Ice Age (LIA) conditions [72]. Dash et al., 2022 [62] identified a significant impact of the LIA from 553 to 100 cal yr BP through the analysis of core sediments from Anshupa Lake. These minor climatic fluctuations during the LIA are consistent with a study by Sinha et al., 2011 [73] that examined $\delta^{18}\text{O}$ values in Central India, showing variability in the ISM and changes in precipitation patterns. Additionally, evidence of a cold and dry climate with a weakened summer monsoon around 800 cal yr BP, likely corresponding to the LIA, has been observed in peat from Benital, Badanital, and Din Gad (Lesser Himalayan lakes).

5.2.6. 90 cal yr BP–Present (Current Warming)

Rejuvenation of mangroves and tree taxa with a lower diversity indicates that the earth-surface temperatures have risen gradually within the past 200 years or so, marking a distinct period of recent warming. This warming phase in comparison to the MWP is likely the result of the human enhancement of the greenhouse effect, and strategies to reduce greenhouse-gas emission and deforestation, hence the plant diversity observed in the pollen record is lower in comparison to the MWP phase. These climatic conditions are also shown

by a remarkable increase in the temperature and moisture index, which indicates a gradual increase in moisture availability after 100 cal yr BP. However, several spikes in the aridity index are also observed due to a gradual shift of climate toward high seasonality conditions. Similar changes have been reported in China from multiple paleoclimate proxy datasets e.g., pollen assemblages [74] (Yi et al., 2003), ice cores [75], and phenological data [76].

5.3. Regional Climatic Variability

Palaeoclimate analysis at the Godavari Delta uncovered a cold period between 3010 and 2290 cal yr BP, characterized by salt marsh and herbaceous vegetation in the region. In the Bay of Bengal (BoB), offshore from the Godavari River mouth, monsoonal data reveal a more negative shift in *Globigerinoides ruber* $\delta^{18}\text{O}$ records and no decline in monsoonal precipitation during the IACP, suggesting ongoing freshwater discharge into the BoB [30]. Similar $\delta^{18}\text{O}$ patterns from Lonar Lake indicate reduced precipitation in Central India [77]. Sinha et al., 2018 [53] noted a decrease in ISM variability around 2800 years ago based on increased $\delta^{18}\text{O}$ values and reduced solar activity recorded in the Kadapa cave in peninsular India. Enhanced monsoonal precipitation between 250 and 450 cal AD is supported by various studies: a sedimentary record from Upshi in the Northwest Himalaya (showing strong ISM from 2700 to 1800 cal yr BP) [78]; organic and inorganic geochemical analyses and pollen data from Lonar Lake in Central India (indicating a strong Southwest Summer Monsoon from 3900 to 1900 cal yr BP) [77]; and data from Kukkal Lake in South India (showing a strong Southwest Summer Monsoon between 3200 and 1800 cal yr BP) [79], as well as biotic proxy records from Pookude Lake in South India (showing a strong Southwest Summer Monsoon from 3900 to 1900 cal yr BP) [80]. Higher salinity in the BoB during the Dark Ages Cold Period (DACP) coincides with minimum monsoonal winds in the Arabian Sea [81,82] and decreased monsoonal precipitation in Central and North India and the Northwest Himalaya, indicating widespread drought across the Indian subcontinent. The late Holocene climate warming during the Medieval Warm Period (MWP, 900–1300 cal yr BP) in the study region aligns with findings from other Indian subcontinent studies, such as those by Sinha et al., 2007 [83] in Central India, Singh et al., 2015 [84] in the Ganga Basin, Dutt et al., 2018 [85] and Singh et al., 2020 [86] in the Northwest Himalaya, Naidu et al., 2020 [87] in the BoB, and Gupta et al., 2005 [88] in the western Arabian Sea. The limited climate variation during the Little Ice Age (LIA) is consistent with $\delta^{18}\text{O}$ studies from Central India documenting ISM variability and changes in precipitation [73]. Cold and dry conditions with a weak summer monsoon around 800 years ago were also noted in Benital, Badanital, and Din Gad peat (Lower Himalayan lakes), which may correspond to the LIA [89–91]. Different proxies can interpret the same climatic events in various ways due to their unique methodologies, timescales, and the specific environmental signals they capture. Pollen data from sediment cores show changes in vegetation and runoff deposited in lakes, estuaries and oceans, offering clues to long-term regional climate changes. Different proxies respond to climate variables differently based on local conditions. For example, corals in tropical regions are sensitive to sea surface temperatures, while ice cores from polar areas reflect atmospheric composition. A warming event may show strong signals in coral data but could be muted in ice core records. A combination of coherent climate signals and high dating accuracy ensures that proxy records provide reliable and meaningful insights into past climate conditions. These criteria are essential for creating robust climate reconstructions that inform our understanding of historical climate variability and guide predictions for future climate scenarios [92].

5.4. Global Climatic Variability

The globally recognized IACP, occurring between 2850 and 2250 cal yr BP, was characterized by an unexpected cold climate in the North Atlantic region [93]. Raspopov et al., 2000 [94] reported a significant shift to cooler and drier conditions around 2400 cal yr BP. Additionally, a warming trend and improved monsoonal climate (strong ISM) between approximately 1700 and 1500 cal yr BP align with the RWP, which was globally noted

from around 2500 to 1600 cal yr BP [95]. The RWP is identified as a time of warmth in the circum-North Atlantic region [96], potentially caused by solar influences or internal North Atlantic variability [7]. The increased rainfall during the RWP also correlates with higher solar insolation and a northward shift of the Inter-Tropical Convergence Zone (ITCZ) during that period [97,98].

Following this, a reduction in monsoonal precipitation, indicated by a decrease in the values and diversity of terrestrial taxa between 1500 and 960 cal yr BP, aligns with the DACP. Singh et al., 2020 [86] found weak monsoonal precipitation during 1500–1000 cal yr BP in the NW Himalaya, which parallels the transition from Late Antiquity to the Early Middle Ages in Europe, a time marked by significant human migrations [99]. The DACP is believed to be a consequence of the North Atlantic ice-rafting event (Bond Event) around 1400 years ago, during the period of sea ice expansion (1550–1185 cal yr BP in Europe) [18,100]. Singh et al., 2020 [86] linked low solar activity during this time to a negative phase of the North Atlantic Oscillation (NAO) and/or El Niño-Southern Oscillation (ENSO), which contributed to cooler conditions in the Northern Hemisphere [18,101].

Furthermore, the late Holocene warm and humid phase from 1050 to 650 cal yr BP, likely associated with the MWP, coincided with intensified monsoonal precipitation and a northward shift of the ITCZ [97]. Gupta et al., 2005 [88] identified stronger south-west monsoon winds during the MWP from *Globigerina bulloides* records in the northwest Arabian Sea, attributed to high solar activity. MWPs are recognized globally between 1210 and 800 cal yr BP [102] and are primarily associated with changes in the intensity of the Thermohaline Circulation in the North Atlantic and influenced by ENSO-modulated solar insolation [103]. Hence, global climate variability is a complex interplay of natural and anthropogenic factors that affect the Earth's climate system. Understanding these dynamics is critical for anticipating climate change impacts, informing policy decisions, and implementing effective adaptation and mitigation strategies. The interconnectedness of global climate systems means that changes in one area can have far-reaching effects, highlighting the importance of comprehensive climate monitoring and research.

6. Conclusions

The high-resolution pollen record from the Godavari River delta, India reflects a centennial-scale (100 yr) climatic cyclicity in the southeast coast of India during the last 3000 years. Climate changes were short events (~200–400 yr) and led to three relatively cold intervals alternated with three rather warm periods. The study shows that the RWP occurred around 2200–1500 cal yr BP, after the first cold phase of the Sub-Atlantic era (2920–2200 cal yr BP). The beginning of the MWP around 960 cal yr BP marked the end of the Dark Ages, a subsequent cold era lasting from 1500 to 960 cal yr BP. After that, the recent warming (100 cal yr BP to the present) succeeded the LIA (550–100 cal yr BP). Palynological results from Coringa mangroves also provide insight into the response of mangrove ecosystems to these climatic changes during the late Holocene which was enhanced by human influences. The study emphasizes the ability of pollen analyses to assess short climatic changes with high-resolution sampling. However, lack on modern pollen analog data for the region was the major limitation in the study that can be added in future research work. To improve this approach, additional research on pollen indices calibration with contemporary pollen-vegetation databases and its application to other prehistoric pollen spectra is required.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/quat7040053/s1>, Figure S1: Complete pollen diagram for core GL; Figure S2: Complete pollen diagram for core B.

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