Article

Diatom response in different climatic zones from west coast of India

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Abstract

Coastal margins and their ecological setting are one of the magnificent landforms on globe. The complex interaction among the different biotic and abiotic components through ages has addressed that due to climatic changes the coastal regions, one of the pioneer regions, have been getting affected and this may continue in the future also. The role of microfossils through ages has helped in delineating the past climatic manifestations and global changes and amongst them diatoms also provide a valuable tool for inferring past climate and ecological variability in the dynamic coastal system. In the study, a modern set of 77 samples from different climatic zones along the west coast of India has been studied to gain knowledge about the present-day climate status and record environmentally susceptible diatoms to form a modern analogue for coastal settings. The study shows various associations of planktic and benthic diatoms that hitherto provide precious information about the diatoms and their relation to the climatic regions and ecological status. The change in the frequency of planktic and benthic diatoms inculcate the water levels, pH, salinity changes, tidal variability and trophic status. Hence, the study aims to provide a robust database on diatoms for the various climatic zones from the west coast of India and would inevitably fill knowledge gap in terms of primary productivity for broad implications. The study also aims to provide background for transfer-based function for the reconstruction of long-term palaeoclimatic records for the transition zone of terrestrial and oceanic realms.

Keywords

Diatom, microfossils, primary productivity, coastal settings, marine-brackish

INTRODUCTION

In the present global climate change scenario, the primary focus is to understand the climatic processes through time and its probable effects on ecology and human culture. In recent years, interest in climate change has increased due to multi-facet reasons. The amount of scientific literature on climate change has increased in tandem, and the rate at which significant articles presenting the findings of climate study are published now in an unimaginable pace than what was done few years back. Presently, the climate manifestations are explored using a broad variety of data types, using multi-proxy records such as ice, lake sediment, pollen/spore, diatoms, dinoflagellate cysts, nannofossils, foraminifera, tree rings, palaeosol, geomorphology and archaeological evidence (Bradley, 1999). Recently, the public interest in the topic has increased, as scientific understanding of the causes of climate change has expanded. The people living

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today may witness notable increases in the earth's temperature and sea level, along with decreases in snow cover, sea ice, land ice sheets, glaciers, permafrost, rise of tropical storms and changes in precipitation patterns in many parts of the world at various latitudes and longitudes (IPCC, 2007; Wiltshire et al., 2015). In case the effect of greenhouse gases stabilise in the coming decades, the alterations at current levels would last for centuries and accelerate (Anderson et al., 2007). Climate change can force plant and animal species beyond their geographically feasible ranges, and cause their localised or global destruction, and in the coming future many species are anticipated to suffer this fate as the temperature warms, forcing cold-tolerant species to go to refugia at ever-higher altitudes until they are extinct (Delcourt & Delcourt, 2004; Montoya & Raffaelli, 2010).

Understanding the types of proxy data and the techniques applied in their analysis is the initial step to study previous climates (Bradley, 1999). It is important to recognise the challenges and presumptions with the proxy so that it can be utilised effectively. With this context, it could potentially be able to combine many lines of data into a comprehensive picture of past climatic changes and evaluate ideas regarding the origins of climate change (Bradley, 1999).

It is often observed that the response of vegetation either macro or micro communities (trees to algae) vary, and may possibly represent either critically dependent or least responsive to changes in rainfall and temperature. Changes in climate and resource structure are frequently time transgressive, and reflect lags between climate data and biotic response. It is possible that the local conditions and changes may not always adhere or be closely related to global patterns (Anderson et al., 2007; Davis & Botkin, 1985; Singhvi & Kale, 2010). The lack of long-term data on palaeoclimatic conditions continues to make it obscure to anticipate future climatic change, and the instrumental records are insufficiently low (usually less than 100 years) to make regional predictions of the size and pace of upcoming climatic manifestations (Weckström et al., 2017). The climate change scenario is witnessed in response to biotic community, terrestrial, coastal or marine realms. However, the coastal dynamic to climate change is manifold.

Coastal ecosystems are dynamic systems lying between the land and the ocean and have wide effect in terms of natural disasters and human activities, for example, climate adversities, sea level changes, subsidence, sediment discharge, eutrophication and acidification (Li et al., 2018). The typical examples of coastal environments include mangroves, salt marshes, coral reefs, beaches, estuaries and coastal wetlands and these were all included in the Ramsar Convention's definition of coastal ecology (Ramsar Convention Secretariat, 2010) as an integral part of sea and land mixed habitats. The coastal ecosystem offers vital benefits that include direct supplies like food and biomaterials, wildlife conservation, carbon sequestration, protection from storm surges and many more to count (Li et al., 2018). In comparison to the terrestrial ecosystems, coastal wetlands have a relatively modest surface area, but they are among the most prolific ecosystems in terms of productivity (Li et al., 2018). Vegetated zones and tidal streams serve as important habitats for many terrestrial and marine species, offering a wide range of wild animals refuge and food supplies, resulting in high biodiversity and distinctive food webs. In order to precisely measure past climatic changes and biotic responses, palaeoecological records of terrestrial such as pollen and tree rings, plant macrofossils (Birks & Birks, 2006) and aquatic (such as diatoms) biota are becoming more and more relevant (Smol et al., 1991; Kilham et al., 1996; Thakur et al., 2019).

Diatoms have been recognised as one of the useful proxies for limnological fluctuations and climate change in the food web (Kilham et al., 1996; Smol & Cumming, 2000; Smol & Stoemer, 2010; Smol et al., 1991). They are microscopic, unicellular algae that have a siliceous cell wall (frustule), making them unique for a variety of applications and serve as a unique proxy for climate change since they are sensitive to a wide range of ecological states. The variations in species abundance within the sediment interval can be used to infer past changes in water chemistry, precipitation and temperature (Smol & Stoemer, 2010; Mutshinda et al., 2013b). These species serve as reliable indicators of the lake's level, nutrient availability and other ecological variables. They respond to a variety of parameters including precipitation, sun light and wind speed along with upwelling and erosion processes (Wiltshire et al., 2015). They respond rapidly to shifting environmental conditions and are sensitive to a number of biogeochemical components. Any aquatic environment, including ponds, rivers, streams, lakes and coastal areas (such as lagoons, deltas and estuaries), is home to them. The distribution of diatoms is one of the helpful markers in environmental reconstruction on eutrophication, extreme climates, lake acidification and climatic manifestations (Smol & Stoemer, 2010). Diatoms are subject to various climate effects. Diatom species and their growing regions are impacted by changes in the frequency and severity of droughts and floods. Climate also affects the circulation patterns and thermal stratification of lakes and oceans, which change the diversity of diatom species (Bigler & Hall, 2002; Bigler et al., 2002). Their distributions in older sediments (fossils) reveal details on the environment, ecology and climate that prevailed during the past time. The physical, chemical and biological characteristics of the aquatic ecosystem are revealed by the diatom assemblages in the surface sediments. Diatoms are utilised in rapid environmental change as they are widely disseminated, immobile, tiny, covered in siliceous material and well preserved in sediments. The effects of freshwater inflows, sea level change and nutrient availability are all particularly subtle on coastal habitats (Finkl & Makowski, 2017). Understanding the present-day diatom response in the coastal ecosystem with varying climatic zones such as humid, sub-humid to semi-arid regions is essentially required for delineating deep time inferences for climate change. The previous studies mostly focussed on sedimentology, tectonics, water quality, elemental studies but the biotic response, that is, primary productivity based on diatom assemblages, their composition and distribution patterns that are preserved in the sediments and the relationship between these assemblages and climatic changes have not yet been discussed. Climatically, India has presently a diverse climate as per the Koppen-Geiger classification. To establish the changes in the diatom assemblage in different climatic zones in surface sediments, the west coast of India is one of the pioneering coastal domains. By comparing the two coastline regions of India, we can see that the east coast is mostly restricted to a tropical savannah climate, whereas the west coast includes tropical monsoon, tropical savannah, arid steppe hot and arid desert hot climatic regions (Figure 1) according to Koppen-Geiger climate classification (Beck et al., 2018).

India has more than 7,500 square kilometres of coastline and is very vulnerable to sea-level changes due to climatic manifestations. The Western Coastal Plains span from the Arabian Sea to the Western Ghats between Gujarat and Kerala extending ~1400 km in length, and width ranging from 10 to 80 km. The east coast extends ~1500 km in length. The major features comprise sand beaches, coastal sand dunes, mudflats, lagoons, alluvial tracts, estuaries, lateritic platforms and residual hills.

Surface sediment assessment has received great attention around the world since it is a unique way to assess ecological conditions due to their spatial-temporal accumulations and climatic signatures (Bigler & Hall, 2002; Brush, 2009; Crosta et al., 2012; Costa-Böddeker et al., 2016; Finlayson, 2018; Ip et al., 2004; Manoj et al., 2020; Nodine & Gaiser, 2014). We examined the spatial diatom

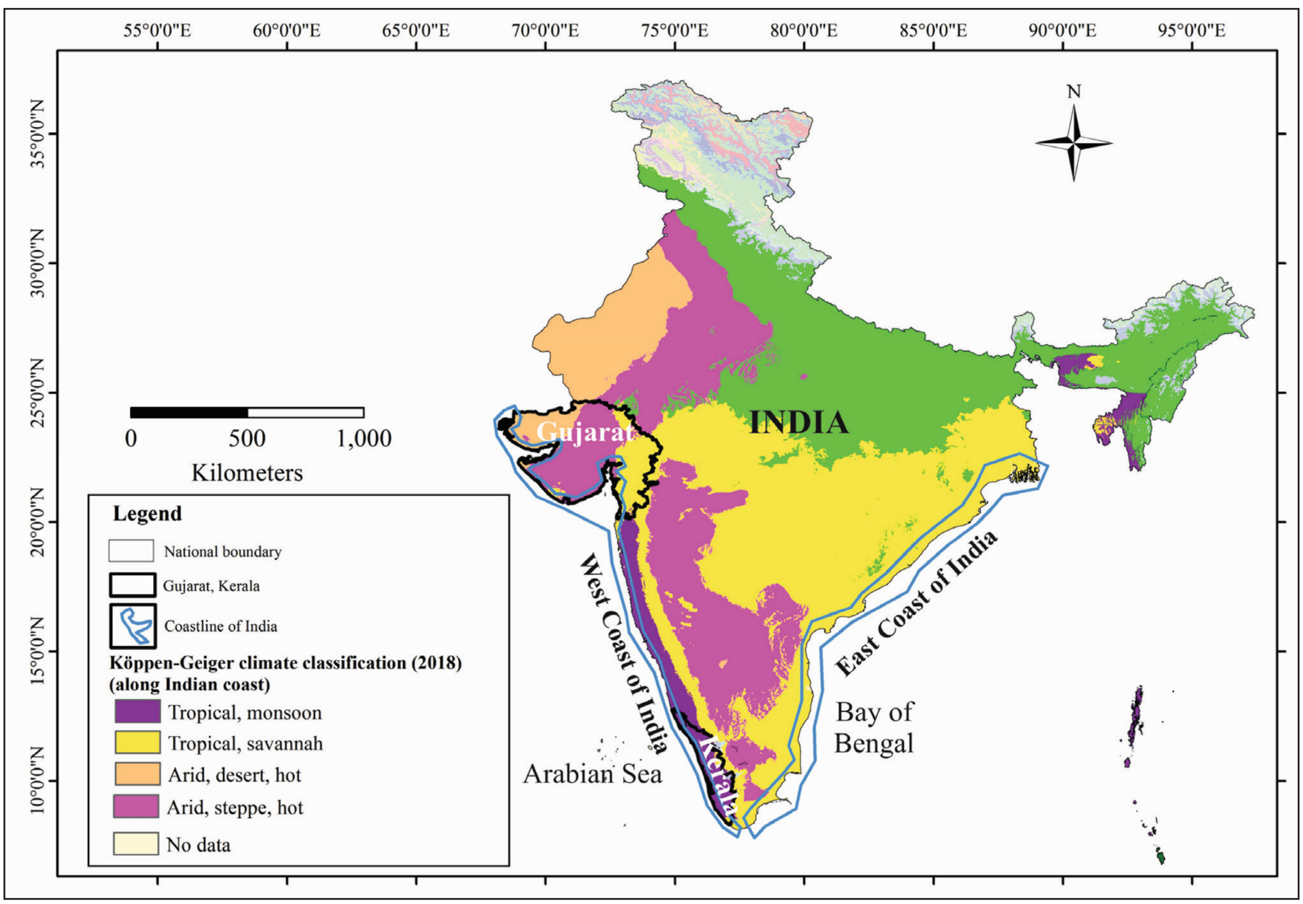

Figure 1. The different climatic regions along the west coast of India. Source: Beck et al. (2018).

composition and abundance in surface sediments from various climatic zones of western coastal settings in order to gauge the current ecological status of India's west coast.

MATERIALS AND METHODS

For the diatom analysis, 77 surface sediments were processed using HCl (35%) and H_2O_2 (30%) to remove carbonates and organic matter. The samples were collected from Vembanad coastal wetland (22), Dhadhar estuary (20), Sabarmati estuary (15), and Harshad estuary (20) comprising different climatic regions. The samples were neutralised properly by subsequent addition of distilled water followed by decantation. After neutralisation, 1 ml sample is taken in a dropper and spread uniformly and dried on the hot plate at 150˚C temperatures. The dried diatom slides were mounted with the suitable mountant for final study (Battarbee, 1986; Battarbee & Kneen, 1982; Renberg, 1990) and the taxonomic identification was done using various literatures (Bahls et al., 2018; Denys, 1991–1992; Desikachary, 1989; Dixit et al., 1992; Hustedt, 1930; John, 2012; Karthick et al., 2013; Krammer & Bertalot, 1986–1991; Simonsen, 1979; ; Smol & Stoemer, 2010). The slides were scanned under Olympus BH2 microscope (60X/100X in oil immersion) and the diatoms were photographed using DP-25 camera. Based on the abundance of the diatoms, at least 300–500 frustules were counted per sample.

Study Area

Vembanad Coastal Wetland: The Vembanad coastal wetland (Ramsar site) is one of the largest tropical estuary and lies on the southwest coast of India between 9°00' and 10°40'N latitude and 76°00' and 77°30'E longitude that is presently located in the humid tropics, has a semidiurnal tidal cycle and receives generally consistent temperatures between 21°C and 36°C (Figure 2). The region receives average precipitation of 3,200 mm per year surrounded by marshes and is recognised for endemism-rich ecological habitats (Babeesh et al., 2016; Remani et al., 2010).

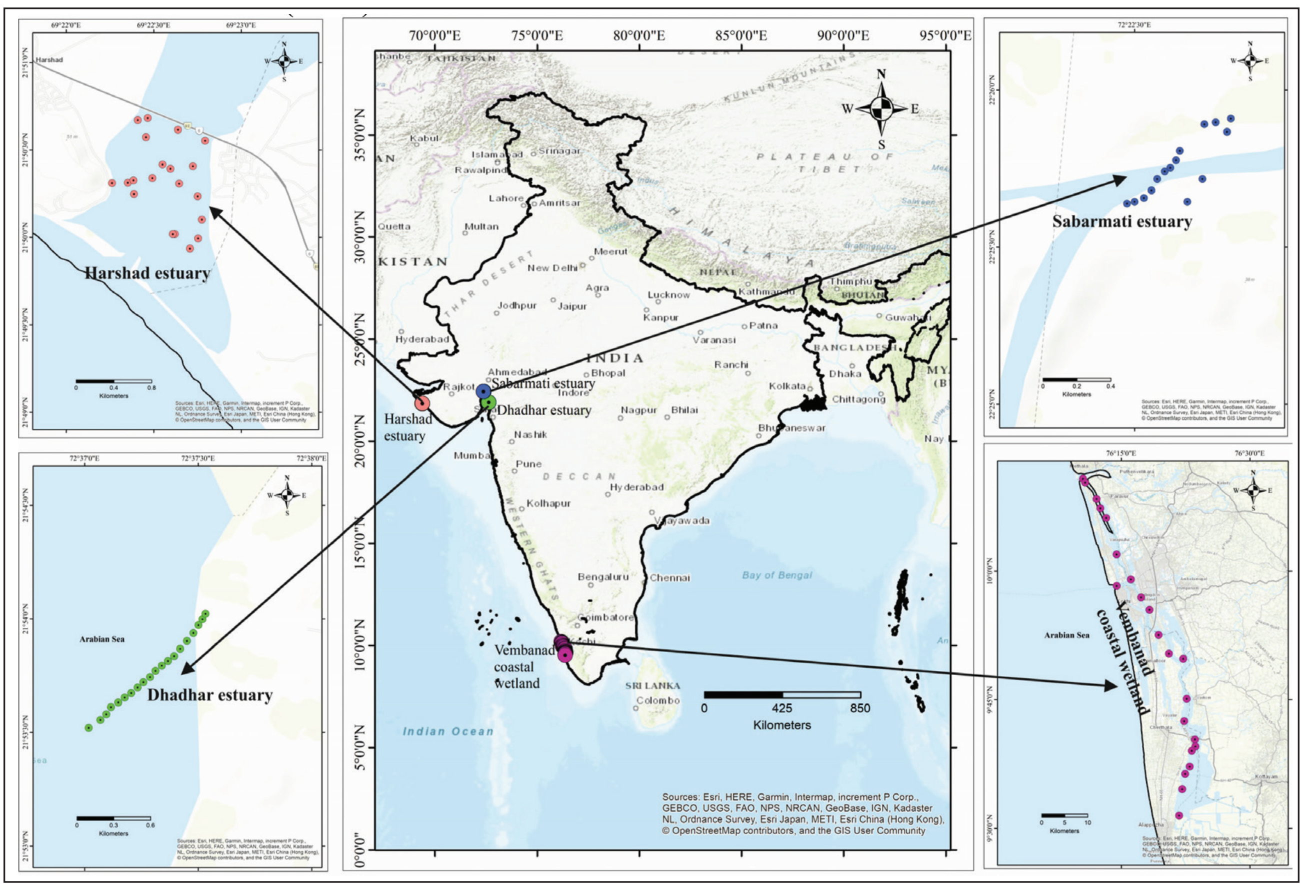

Figure 2. Location map of study area along west coast.

Dhadhar Estuary: The Dhadhar River drains the region between the rivers Mahi and Narmada and has its source close to Shivrajpur at 22°30'N latitude and 73°45'E longitude in the Aravalli range (Figure 2). The channel flows southwest and debouches into the Gulf of Cambay close to Gandhar with its tributaries Vishwamitri River on the right bank and Rupa Khadi, Rartgav and Bukhi Rivers from the left bank. The present day Dhadhar River represents a misfit channel (Raj, 2007). Climatically the basin has hot, dry summer, a mild winter and a humid monsoon season. The annual precipitation averages ~900 mm and most of the rainfall is received from SW monsoon.

Sabarmati Estuary: With its source in Rajasthan, the Sabarmati River normally runs in a south-westerly direction through the Gujarat Alluvial Plains before coming to confluence with the Gulf of Khambhat and finally culminating into Arabian Sea (Sridhar et al., 2014). The Sabarmati River is a monsoon-dominated seasonal river that flows across the semi-arid western India and goes dry after the monsoon (Figure 2). The Sabarmati is a seasonal river in a semi-arid climate zone that receives a range of rainfall (450–800 mm). The major tributaries of Sabarmati River are Wakal, Sei, Majham, Harnav, Hathmati and Watrak. With its origin in Rajasthan, the Sabarmati River normally runs in a south-westerly direction (Sridhar et al., 2014).

Harshad Estuary: Between Porbandar and Dwarka on the western Saurashtra coast, in latitudes N 21°49.25' to 21°51.75' and longitudes E 69°22.15' to 69°24.00', is the Harshad estuary (Meda stream) (Figure 2). When freshwater from terrestrial sources is not available, the estuary stays a creek (sea inlet), but during the summer monsoon season, it transforms into a lagoon with a high-water stand (Lakhmapurkar & Bhatt, 2010; Thakur et al., 2019). The estuary mostly exhibits saline and fresh water interactions with diverse environmental contexts of coastal landforms during the monsoon season, that is, mudflats, tidal flats, coastal sand shoals, mangrove swamps, etc. are all found in the intertidal, subtidal and supratidal zones. The present-day Harshad estuary is a mesotidal setting characterised by strong wave and moderate tidal energies.

RESULTS

The distribution of diatoms in the various climatic regions of Sabarmati, Harshad, Dhaddhar, and Vembanad along India's west coast is used as a biological proxy in the present study to ascertain the primary productivity. The frequency of the diatoms was analysed using the TILIA ver.1.7 software that is used to generate the diatom frequency range chart and cluster analysis for each location. For Vembanad coastal wetland (5 zones), Dhadhar estuary (4 zones), Sabarmati estuary (3 zones) and Harshad estuary (4 zones) were identified with CONISS cluster analysis based on dominance and sub-dominance of diatom frequency (Grimm, 1987, 2000).

Vembanad Coastal Wetland

In the present study based on the diatom analysis, five ecological zones are identified (Figure 3 and Plate 1).

Zone I (G-16 to G-22): It is marked by 18 to 25 distinct diatom genera with frequencies ranging from 321 to 833, respectively. It is marked by high abundance of brackish and freshwater planktic diatoms, namely *Cyclotella*, *Thalassiosira* and *Aulacoseira.* The low to moderate occurring planktic diatoms include *Stephanodiscus*, *Actinocyclus*, *Actinoptychus*, *Triceratium*, *Campylodiscus*, *Biddulphia*, *Hyalodiscus* and *Discostella*. The benthic diatoms chiefly include *Nitzschia*, *N. panduriformis*, *N. claussi*, *Tabellaria*, *Diploneis*, *Navicula*, *Ulnaria ulna*, *Eunotia* and *Pinnularia*. The frequency of low to moderate benthic diatoms comprise *Cocconeis*, *Gomphonema*, *Amphora*, *Bacillaria*, *Gyrosigma*, *Achnanthes* and *Caloneis*

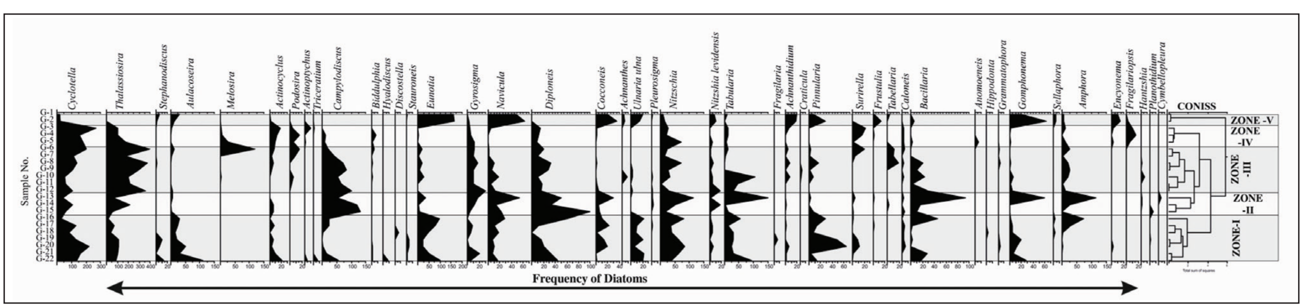

Figure 3. Frequency distribution range chart and CONISS cluster analysis of Vembanad coastal wetland.

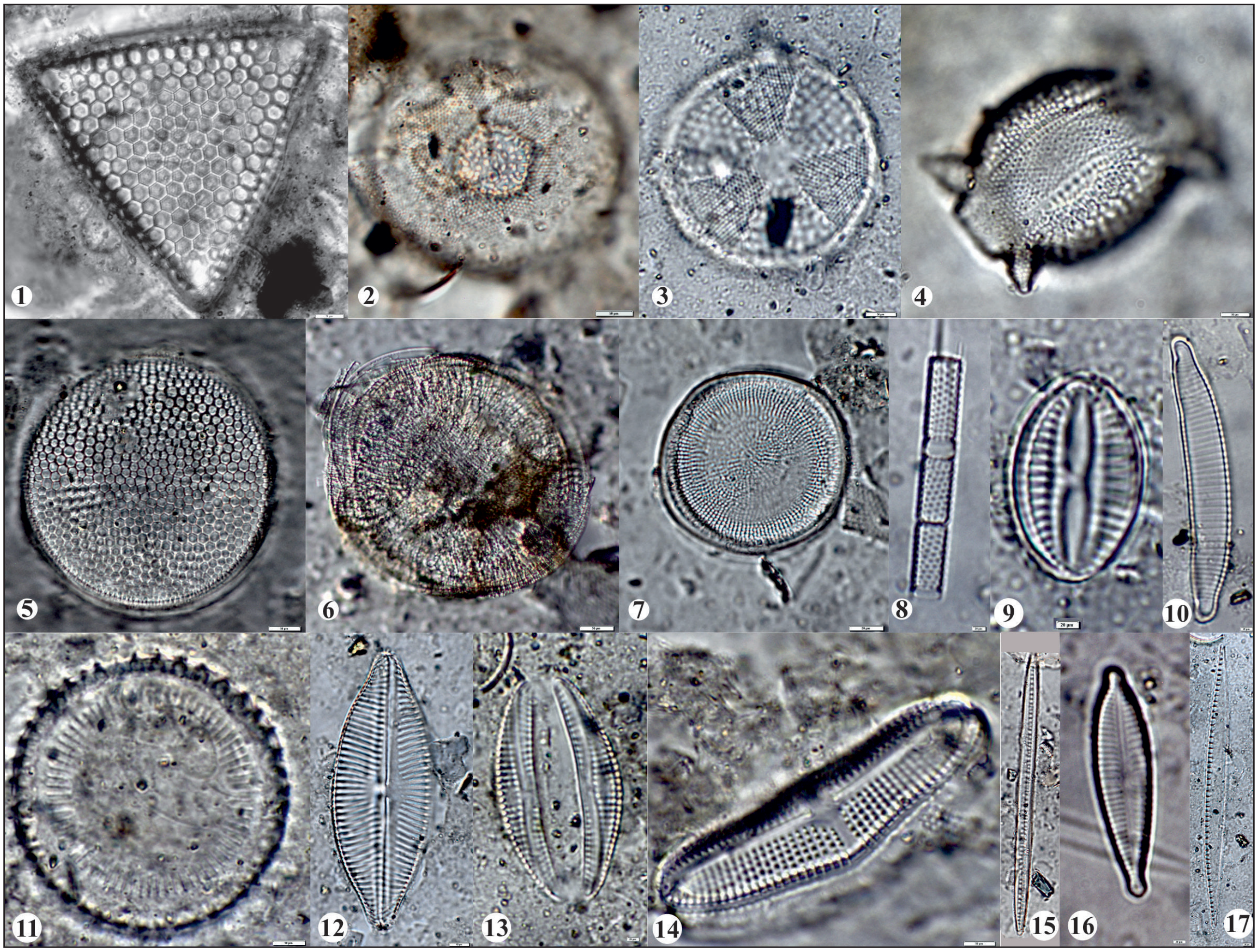

PLATE 1. Diatom flora of Vembanad coastal wetland: 1) *Triceratium favus*; 2) *Hyalodiscus sp*.; 3) *Actinoptychus sp*.; 4) *Biddulphia sp*.; 5) *Thalassiosira devious*; 6) *Campylodiscus clypeus*; 7) *Actinocyclus normanii*; 8) *Aulacoseira granulata*; 9) *Diploneis smithii*; 10) *Eunotia incisa*; 11) *Cyclotella striata*; 12) *Navicula cryptocephala*; 13) *Amphora veneta*; 14) *Achnanthes brevipes*; 15) *Bacillaria paradoxa*; 16) *Gomphonema parvulum*; 17) *Nitzschia amphibian*; Scale bar = 50 micron.

while the infrequent forms are *Surirella*, *Planothidium*, *Pleurosigma*, *Fragilaria*, *Sellaphora*, *Frustulia*, *Encyonema*, *Achnanthidium*.

Zone II (G-13 to G-15): The diatoms species comprise 18 to 22 genera with frequency ranging from 458 to 910, respectively. It is dominated planktic form *Thalassiosira*, *Campylodiscus*, *Cyclotella* with low frequency of *Aulacoseira* and *Actinocyclus*. The benthic form is dominated by *Diploneis* and *Nitzschia* followed by *Tabularia*, *Amphora*, *Bacillaria* and *Navicula*. The low frequency diatoms are represented by *Eunotia*, *Gomphonema* and *Gyrosigma*. Diatoms showing their occurrence in this zone are *Pleurosigma*, *Achnanthidium*, *Craticula*, *Pinnularia*, *Surirella*, *Frustulia*, *Tabellaria*, *Caloneis*, *Hantzshia*, *Planothidium* and *Cymbellopleura*.

Zone III (G-6 to G-12): It is represented by 16 to 24 diatom taxa while the frequency varies from 416 to 842, respectively. This zone is again represented by high planktic diatoms over the benthic ones. The major planktic diatom comprise *Thalassiosira* followed by *Cyclotella*, *Campylodiscus* with extremely low turnout of *Podosira*, *Actinocyclus*, *Aulacoseira*, *Biddulphia*, *Stephanodiscus* and *Melosira*. The benthic diatoms are chiefly represented by *Tabularia*, *Nitzschia*, *Diploneis*, *Gyrosigma*, *Bacillaria*, *Amphora*, *Eunotia*, *Navicula*, *Nitzschia levidensis*, *Pinnularia* and *Tabellaria* in accordance of their decreasing abundance. The low turnout of benthic diatoms recorded are *Cocconeis*, *Achnanthes*, *Ulnaria ulna*, *Pleurosigma*, *Achnanthidium*, *Craticula*, *Surirella*, *Caloneis*, *Grammatophora*, *Gomphonema* and *Hantzshia*.

Zone-IV (G-3 to G-5): The distinct diatom taxa varies from 17 to 21 genera while the frequency ranges from 406 to 546 in this zone. The planktic diatom are extremely high over the benthic ones. The major planktic diatoms are *Cyclotella* and *Thalassiosira* while the low frequency comprise *Actinocyclus*, *Melosira*, *Podosira*, *Campylodiscus*, *Actinoptychus*, *Biddulphia*, *Aulacoseira* and *Triceratium*. The benthic forms include *Nitzschia*, *Diploneis*, *Surirella*, *Fragilariopsis*, *Tabularia*, *Amphora*, *Gyrosigma*, *Navicula*, *Cocconeis*, *Nitzshia levidensis*, *Achnanthidium*, *Frustulia*, *Caloneis*, *Bacillaria*, *Anomoeneis*, *Gomphonema* and *Encyonema*.

Zone-V (G-1 to G-2): Zone-V comprises diatom with 21 and 22 representative taxa with frequency of 408 and 504. The present zone is represented by very high benthic diatom assemblage over the planktic. The major benthic diatom is represented by Eunotia followed by Navicula, *Cocconeis*, *Gomphonema*, *Achnanthidium*, *Pinnularia*, *Ulnaria ulna*, *Nitzschia*, *N. levidensis* and *Encyonema*. The diatom with infrequent occurrence comprises *Stauroneis*, *Achnanthes*, *Pleurosigma*, *Tabularia*, *Frustulia*, *Tabellaria*, *Bacillaria*, *Sellaphora* and *Fragilariopsis*. The planktic diatom recorded with moderate counts includes *Aulacoseira* and *Cyclotella* while the sporadic occurrence consists of *Stephanodiscus*, *Melosira* and *Actinocyclus*.

Dhadhar Estuary (Figure 4 and Plate 2)

Zone-I (DDH-G19 and DDH-G20) comprises 17 and 8 distinct diatom genera with frequencies 382 and 258 frustules. The frequently occurring diatom in this zone is Nitzschia followed by *Surirella*, *Gyrosigma*, *Pinnularia*, *Amphora*, *Fragilaria*. Few other diatoms recorded in DDH-19 include *Cyclotella*, *Cocconeis*, *Synedra ulna*, *Frustulia*, while they are absent in DDH-G20 (Figure 4 and Plate 2). The lowest record of diatoms comprises *Thalassiosira*, *Biddulphia*, *Diploneis*, *Gomphonema*, *Cymbella* and *Planothidium*.

Zone-II (DDH-15 to DDH-18) shows diatoms varying from 9 to 16 genera with frequencies ranging from 135 to 280, respectively. The commonly occurring diatoms according to frequency include *Surrirella* and *Pinnularia*. The other diatoms variable frequencies are *Gyrosigma*, *Nitzschia*, *Cocconeis*, *Amphora* and *Navicula*. The sporadically occurring diatoms comprise *Cyclotella*, *Aulacoseira*, *Actinocyclus*, *Coscinodiscus*, *Synedra ulna*, *Tabellaria*, *Bacillaria*, *Rophalodia* and *Planothidium*.

Zone-III (DDH-G5 to DDH-G14) represents 12–20 type of differentiating diatom taxa with frequencies varying from 143 to 396 frustules, respectively. The diatoms are recorded in variable counts but the frequently occurring are *Surirella*, *Pinnularia*, *Amphora*, *Nitzschia*, *Navicula*, *Cocconeis*, *Gyrosigma*, *Diploneis*, *Mastogloia*, *Fragilaria* and *Rophalodia*. The planktic diatoms include *Thalassiosira*, *Cyclotella*, *Actinocyclus*, *Aulacoseira* in low counts. The diatoms showing their occurrence comprise *Achnanthidium*, *Frustulia*, *Melosira*, *Coscinodiscus*, *Biddulphia*, *Tabularia*, *Craticula*, *Amphiprora* and *Encyonema*.

Zone-IV (DDH-G1 to DDH-G4) comprises 16 to 23 types of diatom taxa with frequencies varying from 368 to 761 frustules, respectively. The zone shows variable distribution of diatom. The most commonly occurring diatoms in frequencies include *Pinnularia* followed by *Nitzschia*, *Surrirela*, *Gyrosigma*, *Achnanthidium*, *Amphora*, *Navicula*, *Achnanthes*, *Cocconeis*. Among the planktic diatom, *Thalassiosira* is recorded to be highest with low turnout of *Cyclotella* and *Actinocyclus*. The infrequent occurring diatoms comprise *Cymbella*, *Synedra ulna*, *Diploneis*, *Pleurosigma*, *Craticula*, *Grammatophora*, *Sellaphora*, *Rophalodia*, *Melosira*.

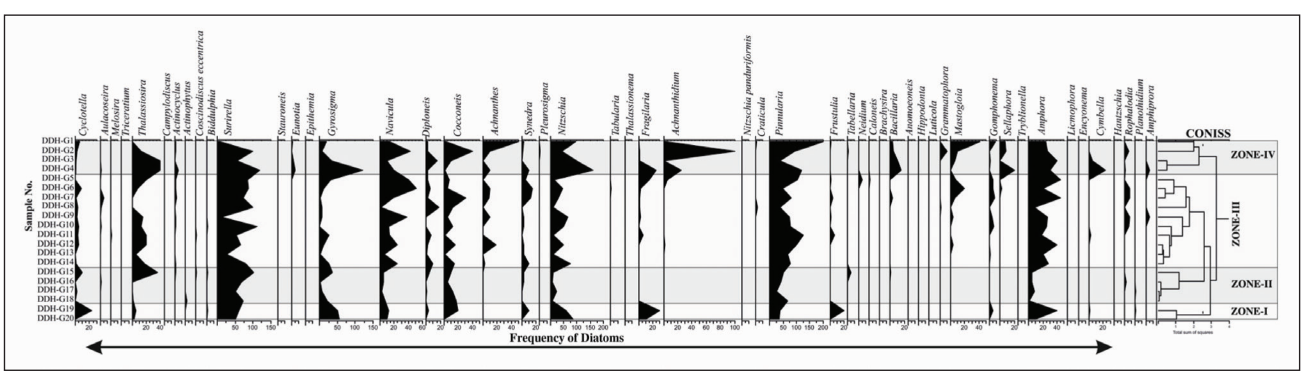

Figure 4. Frequency distribution range chart and CONISS cluster analysis of Dhadhar estuary.

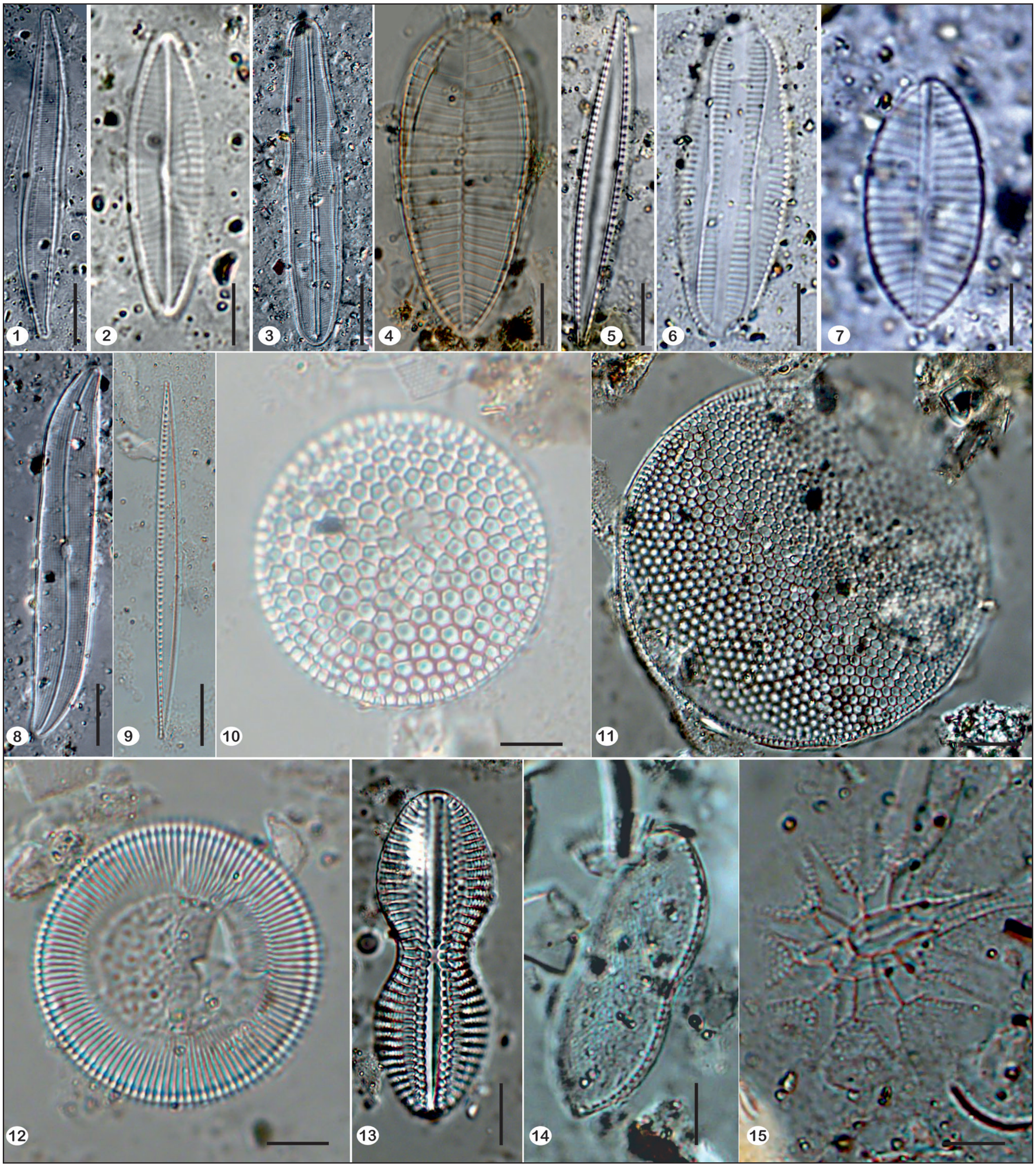

PLATE 2. Diatom flora of Dhaddhar: 1) *Nitzschia reversa*; 2) *Navicula sp*.; 3) *Pinnularia sp*.; 4) *Surirela tenera*; 5) *Nitzschia agnita*; 6) *Amphora veneta*; 7) *Planothidium sp*.; 8) *Gyrosigma eximium*; 9) *Nitzschia linearis*; 10) *Thalassiosira baltica*; 11) *Thalassiosira sp*.; 12) *Cyclotella ocellata*; 13) *Diploneis crabo*; 14) *Nitzschia levidensis*; 15) *Asteromphalus sp*.; Scale bar = 5 micron.

Sabarmati Estuary

In the Sabarmati coastal region, three zones were identified based on the CONISS cluster analysis (Figure 5 and Plate 3).

Zone-I (SB-10 to SB-15): the diatom taxa recorded ranged from 11 to 25 genera with 412 to 476 cell counts. The major representative diatoms were *Navicula* followed by *Nitzschia*, *N. panduriformis*, *Achnanthes*, *Pinnularia*, *Achnanthidium*, *Fragilaria*, *Amphora*. The low records of diatoms comprised of Cyclotella, Thalassiosira, Biddulphia, *Campylodiscus*, *Actinocyclus*, *Melosira*, *Triceratium*, *Aulacoseira*, *Mastogloia*, *Surirella*, *Gyrosigma*, *Luticola*, *Pleurosigma*, *Craticula*, *Rophalodia*, *Neidium*, *Sellaphora*, *Bacillaria*, *Hantzschia*, *Tryblionella*, *Planothidium*, *Frustulia*, *Diploneis*, *Eunotia*, *Grammatophora*, *Cocconeis*, *Epithemia*, *Synedra ulna*, *Anomoeneis*, *Licmophora*, *Encyonema*, *Gomphonema* and *Cymbella*. The coastal-marine diatoms recorded were *N. panduriformis*, *Thalassiosira*, *Biddulphia*, *Campylodiscus*, *Actinocyclus*, *Triceratium* and *Mastogloia*.

Zone-II (SB-3 to SB-9) comprised *Navicula* amongst the highest recorded diatom. There were 16–23 diatoms genera and species recorded in this zone with frequencies ranging from 347 to 957 (Figure 5 and Plate 3). The other diatom taxa recorded were *Nitzschia*, *Pinnularia*, *Frustulia*, *Diploneis*, *Neidium*, *Sellaphora*, *Eunotia*, *Synedra ulna*, *Achnanthes*, *Achnanthidium* and many others to account. The planktic diatoms include *Cyclotella* and *Aulacoseira* with low turnout of Thalassiosira species.

Zone-III (SB-1 and SB-2) recorded 20 and 22 diatoms taxa with 574 and 805 cell counts. The frequently occurring diatoms included *Navicula*, *Nitzschia*, *Pinnularia*, *Gomphonema*, *Synedra ulna*, *Diploneis*, *Frustulia*, *Achnanthidium* and *Surirella*. Among the planktic diatom, *Cyclotella* is common; however, *Aulacoseira* and Thalassiosira were occurring in low counts. The low and sporadic diatoms occurring in this zone are *Campylodiscus*, *Craticula*, *Luticola*, *Eunotia*, *Tryblioneella*, *Amphora*, *Epithemia* and many others to count.

Harshad Estuary

Zone-I (HS-01 to HS-06): This zone comprises variety of benthic and planktic form of diatoms. From this zone, the highest frequency 1,187 diatom frustules were recorded in HS-G6 and lowest frequency 495 frustules were recorded form HS-G2 (Figure 6 and Plate 4). *Amphora* shows the diverse counting but highly recorded diatom in the range of this zone. Besides that some benthic diatoms such as *Navicula*, *Diploneis*, *Grammatophora*, *Cocconeis*, and *Pinnularia* ranges from 0 to 180 frustules. In this zone, average count of diatom, such as *Achnanthidium*, *Achnanthes and Plannothidium was* also recorded. On the other hand, *Encyonema*, *Licmophora*, *Surirella*, *Frustulia*, *Bacillaria*, *Anomoeoneis*, *Mastogloia*, *Gyrosigma* were also recorded but their frequency was very low. In planktic forms of diatoms different diversities were also recorded but in very low frequency, such as *Thalassiosira*, *Cyclotella*, *Aulacoseira*, *Biddulphia* and *Melosira*.

Zone-II (HS-07 to HS-11): This zone comprises high diversity of benthic and planktic diatoms among the entire zone and this ranges from 55–1,154 with 10 to 30 distinct taxa. *Diploneis* was recorded in highest frequencies in this zone. Planktic form also shows low to moderate frequency in this zone with *Thalassiosira* occurring in high abundance (396 frustules). The other benthic diatoms were also recorded in high abundance in HS-07 which include *Pinnularia*, *Nitzschia*, *Grammatophora*, *Navicula* and *Cocconeis* in this zone. However, in HS-09 *Achnanthidium* was recorded as highest; besides, in HS-16-07, 08 and 10 very low frequency was recorded. Although this zone also comprises other benthic diatoms but in very low frequency and moderate count such as *Gyrosigma*,

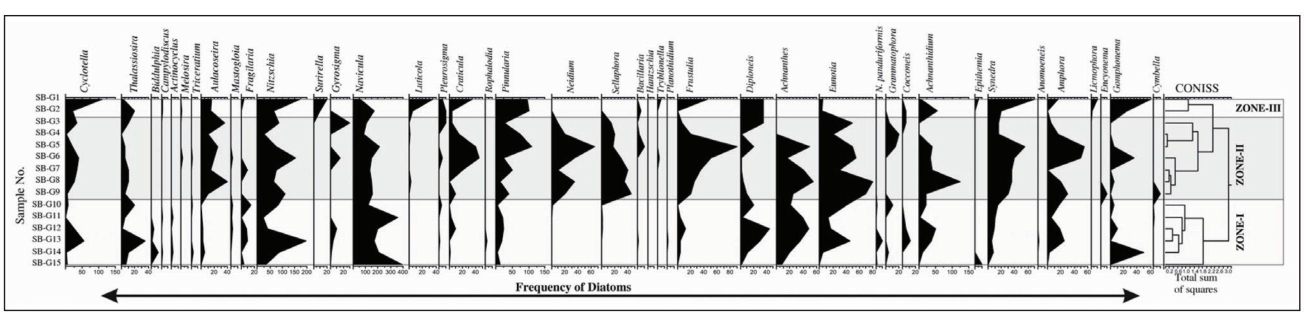

Figure 5. Frequency distribution range chart and CONISS cluster analysis of Sabarmati estuary.

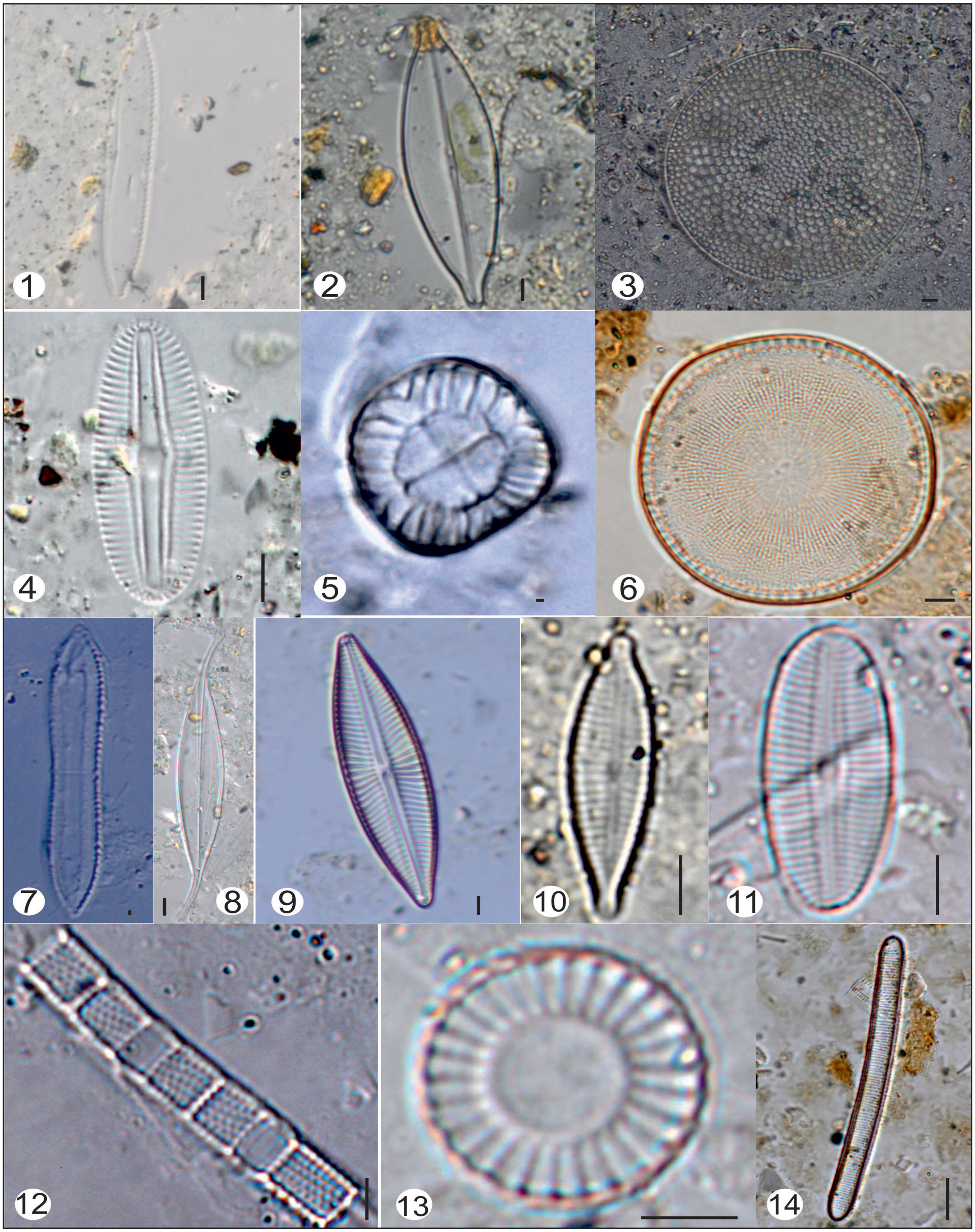

PLATE 3. Diatom flora of Sabarmati: 1) *Nitzschiz palea*; 2) *Craticula cuspidate*; 3) *Thalassiosira sp*.; 4) &5) *Diploneis litoralis*; 6) *Campylodiscus sp*.; 7) *Actinocyclus normanii*; 8) *Tryblionella gracilis*; 9) *Nitzschia reversa*; 10) *Navicula viridula*; 11) *Gomphonema parvulum*; 12) *Aulacoseira granulate*; 13) *Cyclotella meneghiniana*; 14) *Eunotia bilunaris*; Scale bar = 5 micron.

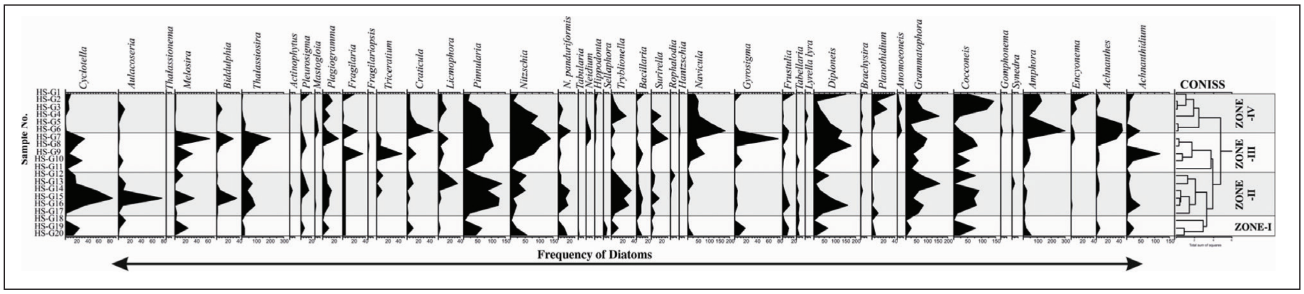

Figure 6. Frequency distribution range chart and CONISS cluster analysis of Harshad estuary.

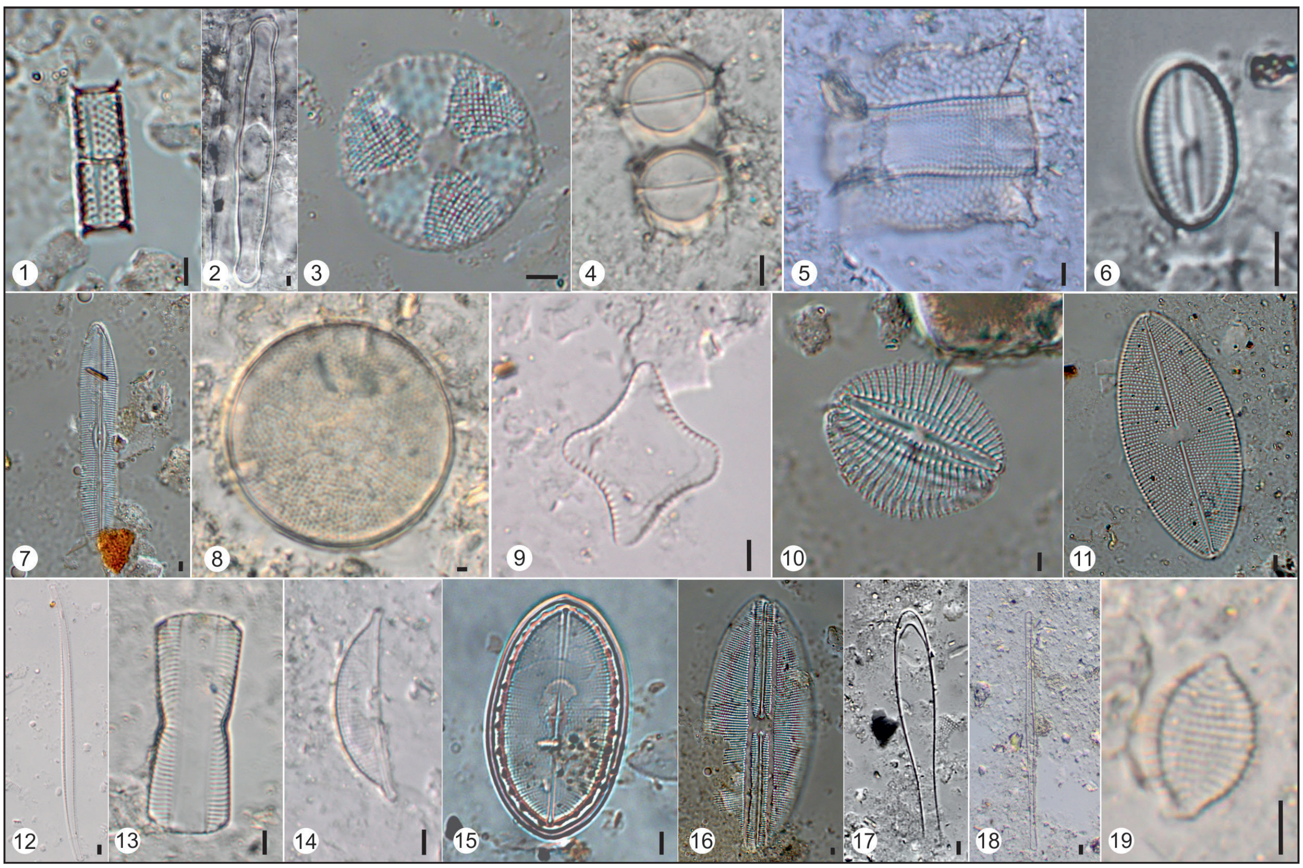

PLATE 4. Diatom flora of Harshad: 1) *Aulacoseira granulata*; 2) *Grammatophora sp.*; 3) *Actinoptychus senarius*; 4) *Melosira varians*; 5) *Biddulphia pulchella*; 6) *Diploneis ovalis*; 7) *Caloneis alpestris*; 8) *Actinocyclus normanii*; 9) *Biddulphia penitens*; 10) *Rhopalodia gibberula*; 11) *Aneumastus sp.*; 12) *Nitzschia reversa*; 13) *Pinnularia* (girdle view); 14) *Amphora sp.*; 15) *Cocconeis placentula*; 16) *Lyrella lyra*; 17) *Licmophora sp.*; 18) *Nitzschia sp.*; 19) *Raphoneis sp.*; Scale bar = 5 micron.

Triceratium Achnanthes, *Fragillaria*, *Licmophora*, *Surirella*, *Plannothidium*, *Plagiogramma*, *Bacillaria*, and *Frustulia*. *Melosira*, *Cyclotella*, *Biddulphia*; *Aulacoseira was* also recorded from this zone but in low count. The lowest record of diatoms in this zone is observed in HS-11 with only 55 cell counts.

Zone-III (HS-12 to HS-18): In this zone, a variety of benthic and planktic frustules were counted ranging from lowest (48) in HS-18 to highest in HS-15 (772 frustules). The zone shows *Pinnularia* as the highest recorded benthic diatom. The other diatoms recorded in good numbers include *Grammatophora*, *Diploneis*, *Cocconeis*. The other benthic diatoms recorded in low to moderate frequencies include *Nitzschia*, *N. panduriformis*, *Tryblionella*, *Achnanthidium*, *Amphora*, *Licmophora*. The infrequent occurring diatoms comprise *Fragillaria*, *Surirella*, *Frustulia*, *Triceratium*, *Pleurosigma*, *Bacillaria*, *Tabellaria*. The planktic form *Cyclotella* and *Thalassiosira* were recorded in moderate frequency in this zone while other planktic diatoms such as *Biddulphia*, *Melosira* and *Aulacoseira* were sporadically recorded in this zone.

Zone-IV (HS-19 to HS-20): In the present zone, the diatom taxa include 28 and 19 genera while the frequency is 488 and 325 frustules, respectively. The zone shows low-to-moderate diatom frequency. *Pinnularia* is amongst the frequently recorded diatom followed by *Cocconeis* and to lesser extent were *Diploneis*, *Nitzschia*, *Grammatophora*, *Amphora*, *Navicula*, *Achnanthidium*. The isolated occurring diatoms comprise *Tryblionella*, *Achnanthes*, *Gyrosigma*, *Pleurosigma*, *Licmophora*, *Nitzschia panduriformis*, *Bacillaria*, *Encyonema* and *Tabellaria*. *Cyclotella* is the commonest planktic diatom while *Melosira*, *Aulacoseira* just showed their occurrence in the zone.

DISCUSSIONS

Climate change has brought far-reaching consequences due to present day global warming and posed worldwide threat to terrestrial as well as coastal environments. The wetlands, lakes, coasts, estuaries, deltas have divulged into variety of threats due to climate manifestations and affected the ecological settings to a great extent. The west coast of India with different climatic regimes from tropical monsoon to semi-arid and arid is also strongly affected by climate change scenario since past to present and will be continuing in future also. Hence, the coastal margin along the west can play a key role in understanding the dynamics of continental and marine climatic trends. The west coast of India represents highly dynamic environment and ecosystem that is continuously undergoing pronounced changes through the Holocene to the present time (Babeesh et al., 2016; Chamyal & Merh, 1995; Lakhmapurkar & Bhatt, 2010; Pant & Juyal, 1993; Raj, 2007; Sridhar et al., 2014; Thakur et al., 2019).

In this article, the diatom groups and their zonations reflect changes in water salinity, sea water intrusion, limnic character, water depth and trophic status, which can be related to climatic changes, sea-level fluctuations and anthropogenic responses (Bigler & Hall, 2002; Birks et al., 2001, Li et al., 2018). The diatoms indicate alteration between fresh, brackish and marine environments, reflecting the interaction of rainfall and sea level (Smol et al., 2010).

The Vembanad wetland, Kerala coast shows dominance of *Thalassiosira* and *Cyclotella* with moderate to low abundance of *Campylodiscus*, *Eunotia*, *Diploneis*, *Nitzschia*, *Navicula*, *Tabularia*, *Bacillaria*, *Gomphonema*, *Pinnularia* and *Amphora*. The high abundance of the planktic diatoms indicates that the region is confined with high water columns. This may be because of the high monsoonal periods existing in this tropical region. The frequent tidal influence in the region also shows mixing of salt and freshwater regimes creating variable micro-environments in the wetland with assortment of fresh, brackish and marine settings. Along with these taxa there are numerous diatom genera whose occasional presence is also marked in the coastal wetland. It is found that the dominance of *Cyclotella* and *Thalassiosira* reflect sites with more salt-tolerant environment and indicate pelagic, marine phytoplankton ecology. These results have also been confirmed from the Congo basin deep sea sediments core reflecting various climatic shifts for 190 ka (Hatin et al., 2017). It is found that Aulacoseira spp. requires heavy silicified cells to attain high frequencies and a high sinking rate, and turbulence to maintain their presence in the water column (Bradbury, 1975; Chen et al., 2014) and are more competitive in the low light circumstances brought by turbulent waters. The abundance of *Tabellaria* spp. flourishes in electrolyte-poor, oligotrophic, circumneutral or slightly acidic waters (Taylor et al., 2007). It is commonly observed that species from genera like *Diploneis*, *Amphora* and *Campylodiscus* are generally more diverse in marine, coastal, or brackish habitats and this has also been confirmed from the present study. These findings are also evidenced from the findings of Lake Ohrid and Lake Prespa (Levkov & Williams, 2012).

It can be observed that in Dhadhar estuary again the benthic community is dominated by representatives of the genera *Pinnularia*, *Surirella*, *Nitzschia*, followed by *Gyrosigma*, *Amphora*, *Navicula*, *Cocconeis* and *Thalassiosira* (planktic). Many other sporadic forms with very low counts also exist in the region. The Dhadhar estuary along the Gujarat coast shows one of the oldest mangrove deposit in this regions. The well-preserved diatom in the mangrove region is believed to be one of the key factors in the sediments. This may be due to the humic acids accumulating in the submerged leaf litter along with pelagic sediments. Many times, it is observed that high tannin concentrations may prevent benthic diatoms from colonising the surface sediments, even though leaf litter does not always have a beneficial enrichment effect on them (Lee, 1999). The association of benthic diatoms recorded in Mecherchar Jellyfish Lake corroborates the present findings with the dominance of raphid pennate genera like *Pinnularia*, *Surirella*, *Amphora*, *Nitzschia*, *Caloneis*, *Diploneis*, *Lyrella* and *Navicula* (Smol & Stoemer, 2010).

In the Sabarmati estuarine complex, the highest record of diatoms comprise *Navicula* spp., and *Nitschia* spp., with low-to-moderate turnout of *Pinnularia*, *Eunotia*, *Achanathidium*, *Synedra*, *Amphora*, *Frustulia*, *Diploneis* and *Cyclotella* (planktic). The study suggests that the high dominance of benthic forms suggests shallow water levels in the estuarine complex. The coastal setting of Sabarmati is well known for its archaeological significance due to climatically-driven past. The diatoms from the present analogue may hitherto throw light on the propounding rich diatom diversity from the region. The past climatic manifestations in this region may be derived from the diatoms in terms of salinity changes, water levels, river influx, run-off related changes and many more to account. It has been found in studies that eutrophication was primarily evidenced by the appearance of *Stephanodiscus* species, in tracking the ecological history of the Thames archaeological sites as far back as the Middle Ages. The reconstruction of paleosalinity were produced from archaeological assemblages, and the presence of freshwater and marine species in historical sediments revealed that the Thames was tidal in downtown London throughout the Roman period (Smol & Stoemer, 2010). The changing pH because of climate change such as warming has been recorded in many parts of the world such as Austrian Tyrol, Baffin Island in the Canadian Arctic and many other cores bear direct relationship to changing climate with diatom assemblage. The species of *Navicula*, *Eunotia*, *Fragilaria*, *Frustulia*, *Achnanthidium* have been associated with changes in pH either as acidic or alkaline environments (Smol & Stoemer, 2010; Van Dam et al., 1994). The high abundance and diversity of *Nitzschia* taxa indicate varying ranges of subsaline and hyposaline conditions in the coastal environments.

The Harshad estuary diatoms comprise *Pinnularia*, *Diploneis*, *Grammatophora*, *Amphora*, *Cocconeis*, *Nitzschia*, , *Navicula*, *Achnanthidium* and *Achnanthes* as benthic genera while the planktic forms are dominated by *Thalassiosira*, *Cyclotella* and *Melosira*. The sporadic diatoms also comprise many taxa but with extremely low counts. The Harshad estuary is a typical example of tidal estuary with microenvironments reflecting micro, meso and supra tidal settings. The diatom assemblages clearly show a transition from marine–brackish diatoms along with mixed diatom community dominated by freshwater and salt-tolerant freshwater taxa (Manoj et al., 2020; Nodine & Gaiser, 2014; Smol & Stoemer, 2010).

From the present modern analogue there is no longer any doubt that climatic changes brought on by global warming pose a threat to the environment, especially wetlands (inland and coastal), estuary, lagoon, deltas, lakes, human wellbeing and socio-economic systems globally. Despite an increase in the amount of limnological and ecological studies from various climate regimes globally, there is still insufficient information to adequately describe the spatial and temporal patterns of climatic change at decadal to millennial scales, particularly for periods prior to the late Holocene (Chen et al., 2014; IPCC, 2007; Singhvi & Kale, 2010). The mechanisms connecting diatoms, lake hydrochemistry and climate are frequently poorly understood, as are numerous other types of inferences made from diatoms. Fossil diatoms have been utilised in numerous research works to chart past variations in lake water salinity. Few have reconstructed lake-level variations and other climate-related factors using changes in the relative abundance of planktic versus benthic diatoms, as well as other diatom alterations. Presently, multivariate techniques and qualitative assessments are incorporated in contemporary diatom studies to directly or indirectly reconstruct past climate conditions (Smol & Stoemer, 2010). Most of the studies related to climate and palaeoclimatic studies using diatoms have been from European and American barring a few from Indian sector.

The diatom assemblage from surface sediment aims to provide interaction among their 'chosen' environmental conditions and can be a valuable tool for calibration set, or 'training set' (Birks & Birks, 2006; Bopp, 2005; Hatin et al., 2017; Smol & Stoemer, 2010). These diatoms are valuable tool for reconstruction of long-term climatic changes with the aid of transfer function (Gasse et al., 1995; Zou et al., 2021) although the knowledge on this domain is very limited in Indian context.

Hence, to improve our knowledge on the palaeoclimatic inferences prior to instrumental records, proxy data serve as a major feedback.

CONCLUSION

The different climatic regimes in the present study provide valuable background information for the long-term geological and ecological status based on the diatom assemblages. The diatom assemblage in various climates reflects the character of present-day environment that inculcates the physiography, chemistry, geological and biogeochemical cycling. The variation in the diatom association combats the environmental and ecological conditions for their growth and silica mitigation to record the freshwater runoff, salt water intrusion, water chemistry, human interferences and more possible reasons to account. Thus, the modern diatoms helps to anticipate our present-day environment as they prefer fresh, brackish and marine environments and in down core studies they can be valuably assessed for climatic reconstruction during the geological past. Hence, understanding the variability of the climate system and its relationship with forcing mechanisms, diatoms can be an optimistic approach.

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REFERENCES

Anderson, G. A., Maasch, K. A., & Sandweiss, D. H. (2007). *Climate change and cultural dynamics: A global perspective on Mid-Holocene Transitions*. Academic Press.

Babeesh, C., Achyuthan, H., Sajeesh, T. P., & Ramanibai, R. (2016). Spatial distribution of diatoms and organic matter of the lake floor sediments, Karlad, North Kerala. *Journal of the Palaeontological Society of India*, *61*(2), 239–247.

Bahls, L., Boynton, B., & Johnston, B. (2018). Atlas of diatoms (Bacillariophyta) from diverse habitats in remote regions of western Canada. *PhytoKeys*, *105*(25), 1–186.

Battarbee, R. W. (1986). Diatom analysis. In B. E. Berglund (Ed.), *Handbook of Holocene palaeoecology and palaeohydrology* (pp. 527–570). Wiley and Sons.

Battarbee, R. W., & Kneen, M. J. (1982). The use of electronically counted microspheres in absolute diatom analysis. *Limnology and Oceanography*, *27*, 184–188.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Nature Scientific Data*, *5*, 180214. https://doi.org/ 10.1038/sdata.2018.214

Bigler, C., & Hall, R. I. (2002). Diatoms as indicators of climatic and limnological change in Swedish Lapland: a 100-lake calibration set and its validation for paleoecological reconstructions. *Journal of Paleolimnology*, *27*, 97–115.

Bigler, C., Isabelle, L., Sylvia, P., Birks, H., & Hall, R. I. (2002). Quantitative multiproxy assessment of long-term patterns of Holocene environmental change from a small lake near Abisko, northern Sweden. *The Holocene*, *12*, 481–496.

Birks, H. H., & Birks, H. J. B. (2006). Multi-proxy studies in palaeolimnology. *Vegetation History Archaeobotany*, *15*, 235–251.

Birks, H. H., Peglar, S. M., Boomer, I., Flower, R. J., Ramdani, M., & Abdelzaher, H. M. A. (2001). Palaeolimnological responses of nine North African lakes in the CASSRINA Project to recent environmental changes and human impact detected by plant macrofossil, pollen, and faunal analyses. *Aquatic Ecology*, *35*, 405–430.

Bopp, L., Aumont, O., Cadule, P., Alvain, S., & Gehlen, M. (2005). Response of diatoms distribution to global warming and potential implications: A global model study. *Geophysical Research Letters*, *32*, L19606.

Bradbury, J. P. (1975). Diatom stratigraphy and human settlement in Minnesota. *Geological Society of America Special Papers*, *171*, 1–74.

Bradley, R. S. (1999). *Paleoclimatology: Reconstructing climates of the quaternary* (2nd ed.). Academic Press Limited.

Brush, G. S. (2009). Historical land use, nitrogen, and coastal eutrophication: A paleoecological perspective. *Estuaries and Coasts*, *32*, 18–28.

Chamyal, L. S., & Merh, S. S. (1995). The quaternary formation of Gujarat. *Memoir Geological Society of India*, *32*, 246–257.

Chen, X., Li, Y., Metcalfe, S., Xiao, X., Yang, X., & Zhang, E. (2014). Diatom response to Asian monsoon variability during the Late Glacial to Holocene in a small treeline lake, SW China. *The Holocene*, *24*(10), 1369–1377.

Costa-Böddeker, S., Thuyên, L. X., & Schwarz, A. (2017). Diatom assemblages in surface sediments along nutrient and salinity gradients of Thi Vai Estuary and Can Gio Mangrove Forest, Southern Vietnam. *Estuaries and Coasts*, *40*, 479–492. https://doi.org/10.1007/s12237-016-0170-5

Crosta, X., Romero, O. E., Ther, O., & Schneider, R. R. (2012). Climatically-controlled siliceous productivity in the eastern Gulf of Guinea during the last 40,000 yr. *Climate of the Past*, *8*, 415–431.

Davis, M. B., & Botkin, D. B. (1985). Sensitivity of cool-temperature forests and their fossil pollen record to rapid temperature change. *Quaternary Research*, *23*, 327–340.

Delcourt, P. A., & Delcourt, H. R. (2004). *Prehistoric Native Americans and ecological change: Human ecosystems in Eastern North America since the Pleistocene*. Cambridge University Press.

Denys, L. (1991–1992). *A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. I. Introduction, ecological code and complete list* [Professional Paper 1991/2 No. 246]. Ministerie van Economische Zaken, Jennerstraat 13:1040, Brussel.

Desikachary, T. V. (1989). *Marine diatoms of the Indian Ocean region*. Madras Science Foundation.

Dixit, S. S., Smol, J. P., Kingston, J. C., & Charles, D. F. (1992). Diatoms: Powerful indicators of environmental change. *Environmental Science and Technology*, *26*, 22–33.

Gasse, F., Juggins, S., & Khelifa, L. B. (1995). Diatom-based transfer functions for inferring past hydrochemical characteristics of African lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *117* (1–2), 31–54.

Finkl, C. W., & Makowski, C. (Eds). (2017). *Coastal wetlands: Alteration and remediation*. Springer.

Finlayson, C. M., Milton, G. R., Prentice, R. C., & Davidson, N. C. (2018). *The wetland book*. Springer Netherlands.

Grimm, E. C. (1987). CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computational Geosciences*, *13*(1), 13–35.

Grimm, E. C. (1990). TILIA and TILIA.GRAPH, PC spreadsheet and graphics software for pollen data. *INQUA, Working Group on Data-handling Methods Newsletter*, *4*,5–7.

Hatin, T., Crosta, X., Le Hérissé, A., Droz, L., & Marsset, T. (2017). Diatom response to oceanographic and climatic changes in the

Congo fan area, equatorial Atlantic Ocean, during the last 190ka BP. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *469*, 47–59.

Hustedt, F. (1930). *Bacillariophyta (Diatomae)*. In A. Pascher (Ed.), *Die Su¨sswasser-Flora Mitteleuropas* (pp. 1–466). O. Koeltz.

Ip, C. C. M., Li, X. D., Zhang, G., Farmer, J. G., Wai, O. W. H., & Li, Y. S. (2004). Over one hundred years of trace metal fluxes in the sediments of the Pearl River Estuary, South China. *Environmental Pollution*, *132*, 157–172.

IPCC. (2007). Summary for policymakers. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds), *Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change* (pp. 1–18). Cambridge University Press.

John, J. (2012). *Diatoms in the Swan River Estuary, Western Australia: Taxonomy and ecology*. Koeltz Scientific Books.

Karthick, B., Hamilton, B., & Kociolek, J. P. (2013). *An illustrated guide to common diatoms of Peninsular India*. Gubbilabs.

Kilham, S. S., Theriot, E. C., & Fritz, S. C. (1996). Linking planktonic diatoms and climate in the large lakes of the Yellowstone ecosystem using resource theory. *Limnology and Oceanography*, *41*, 1052–1062.

Krammer, K., & Lange-Bertalot, H. (1986–1991). Bacillariophyceae. In H. Ettl, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds), *Süsswasserflora von Mitteleuropa* (Vol 2(1–3)). Gustav Fischer Verlag.

Lakhmapurkar, J., & Bhatt, N. (2010). Geo-environmental appraisal of the Meda Creek, Saurashtra, Gujarat. *Journal Geological Society of India*, *75*, 695–703.

Lee, S. Y. (1999). The effect of mangrove leaf litter enrichment on macrobenthic colonization of defaunated sandy substrates. *Estuarine, Coastal and Shelf Science*, *49*, 703–712.

Levkov, Z., & Williams, D. M. (2012). Checklist of diatoms (Bacillariophyta) from Lake Ohrid and Lake Prespa (Macedonia), and their watersheds. *Phytotaxa*, *45*, 1–76.

Li, X., Bellerby, R., Craft, C., & Widney, S. E. (2018). Coastal wetland loss, consequences, and challenges for restoration. *Anthropocene Coasts*, *1*, 1–15. https://doi.org/10.1139/anc-2017-0001

Manoj, M. C., Srivastava, J., Uddandam, P., & Thakur, B. (2020). A 2000 year multi-proxy evidence of natural/anthropogenic influence on climate from the southwest coast of India. *Journal of Earth Science*, *31*(5), 1029–1044.

Montoya, J. M., & Raffaelli, D. D. (2010). Climate change, biotic interactions and ecosystem services. *Philosophical Transactions of the Royal Society*, *365*, 2013–2018. https://doi.org/10.1098/rstb.2010.0114

Mutshinda, C. M., Troccoli-Ghinaglia, L., Finkel, Z. V., Muller-Karger, F. E., & Irwin, A. J. (2013). Environmental control of the dominant phytoplankton in the Cariaco basin: A hierarchical Bayesian approach. *Marine Biology Research*, *9*, 246–260.

Nodine, E. R., & Gaiser, E. E. (2014). Distribution of diatoms along environmental gradients in the Charlotte Harbor, Florida (USA) Estuary, and its watershed: Implications for bioassessment of salinity and nutrient concentrations. *Estuaries and Coasts*, *37*, 864–879.

Pant, R. K., & Juyal, N. (1993). Late quaternary coastal instability and sea-level changes: New evidences from Saurashtra coast, Western India. *Zeischrift fur Geomorphologie*, *37*, 29–40.

Raj, R. (2007). Late Pleistocene fluvial sedimentary facies, the Dhadhar River basin, Western India. *Quaternary International*, *159*(1), 93–101.

Ramsar Convention Secretariat. (2010). Coastal management: Wetland issues in integrated coastal zone management. *Ramsar handbooks for the wise use of wetlands* (4th ed., Vol. 12). Ramsar Convention Secretariat.

Remani, K. N., Jayakumar, P., & Jalaja, T. K. (2010). Environmental problems and management aspects of Vembanad Kol Wetlands in South West Coast of India. *Nature Environment and Pollution Technology*, *9*(2), 247–254.

Renberg, I. (1990). A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Paleolimnology*, *12*, 513–522.

Simonsen, R. (1979). The diatom system: Ideas on phylogeny. *Bacillaria*, *2*, 9–72.

Singhvi, A. K., & Kale, V. S. (2010). Paleoclimate studies in India: Last ice age to the present (IGBP-WCRP-SCOPE-Report Series: 4). *Proceedings of Indian Science Academy*, *4*, 1–41.

Smol, J. P., & Cumming, B. F. (2000). Tracking long-term changes in climate using algal indicators in lake sediments. *Journal of Phycology*, *36*, 986–1011.

Smol, J. P., & Stoermer, E. F. (2010). *The diatoms: Applications for the environmental and earth sciences*. Cambridge University Press.

Smol, J.P., Walker, I.R. & Leavitt, P.R. (1991). Paleolimnology and hindcasting climatic trends. *Verhandlungen des Internationalen Verein Limnologie*, *24*, 1240–1246.

Sridhar, A., Chamyal, L. S., & Patel, M. (2014). Palaeoflood record of high-magnitude events during historical time in the Sabarmati River, Gujarat. *Current Science*, *107*(4), 675–679.

Taylor, J. C., Harding, W. R., & Archibald, C. G. M. (2007). *An illustrated guide to some common diatom species from South Africa* [Report number: TT282/07]. Water Research Commission.

Thakur, B., Seth, P., Sharma, A., Pokharia, A. K., Spate, M., & Farooqui, S. (2019). Linking past cultural developments to palaeoenvironmental changes from 5000 BP to present: A climate-culture reconstruction from Harshad estuary, Saurashtra, Gujarat, India. *Quaternary International*, *507*(1–2), 188–196.

Van Dam, H., Mertens, A., & Sinkeldam, J. (1994). A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. *Netherlands Journal of Aquatic Ecology*, *28*, 117–133.

Weckström, K., Saunders, K., Gell, P., & Skilbeck, G. (Eds). (2017). *Applications of palaeoenvironmental techniques in Estuarine studies* (*Developments in paleoenvironmental research*, Vol. 20). Springer.

Wiltshire, K. H., Boersma, M., Carstens, K., Kraberg, A. C., Peters, S., & Scharfe, M. (2015). Control of phytoplankton in a shelf sea: Determination of the main drivers based on the Helgoland Roads Time Series. *Journal of Sea Research*, *105*, 42–52.

Zou, Y., Wang, L., He, H., Liu, G., Zhang, J., Yan, Y., Gu, Z., & Zheng, H. (2021). Application of a diatom transfer function to quantitative paleoclimatic reconstruction: A case study of Yunlong Lake, Southwest China. *Frontiers in Earth Science*, *9*, 700194.