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Multiple stressors impacting the corals on the Malvan Marine Sanctuary, Central West coast of India

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Coral reefs are formed by hard corals or Scleractinians, a tiny multicellular invertebrate animal that belongs to the phylum Cnidaria. They are some of the oldest animals on the planet; they have been surviving on the Earth by building limestone ($CaCO_3$) reef structures. They are one of the most ancient, dynamic, highly sensitive, complex, biologically diverse, highly productive, magnificently beautiful ecosystems on the Earth and mostly found in the tropical coastal environment between 30°N and 30°S latitudes which constitute half of the world's coastlines (Veron, 2000). Coral reefs support millions of people worldwide through services like fisheries and tourism (Hoegh-Guldberg *et al.* 2019). Unfortunately, extent of coral reefs has plummeted significantly globally, and are facing a high risk of extinction due to rapid climate change and intensive human disturbances (Hughes *et al.* 2018). The global average temperature has been rising alarmingly during the past few decades (Lough *et al.* 2018), wherein the past consecutive five years, turned out as the warmest years in the modern record. The year 2016 was the hottest on record in 136 years by breaking the previous record in 2015, 2014 (Lough *et al.* 2018).

Elevated Sea Surface Temperature (SST) induced thermal stress is a major threat to reef building corals, which causes of mass coral bleaching events (Brainard *et al.* 2018). Coral bleaching events occur when surface waters become warm and remain high for more than 28 days, expels the photo-symbiont of the coral colony due to thermal stress (Eakin *et al.* 2019). The loss of the symbiotic single-celled dinoflagellate Symbiodiniaceae or Zooxanthellae cause bleaching of the corals and leads to starvation and, ultimately, death of the corals. The frequency of coral bleaching events and mortalities have increased since late 1970 and affected coral reefs at a regional scale. Globally, mass coral bleaching occurred during 1997-1998, 2010 and 2015-2016, the extreme climate change events El Nino Southern Oscillations (ENSO) events have occurred in tropical oceans, which also raised sea surface temperature (SST) in the Indian Seas (Eakin *et al.* 2019). Moreover, compound effect of frequent thermal stress events driven coral bleaching and growing human pressure could overwhelm the ability of coral reefs to recover after the bleaching events (Van Hooidonk et al. 2016). Furthermore, recent studies have projected that coral reefs will decline by 70-90% relative to their current abundance by 2050 under the 'business-as-usual scenario' (Beyer et al., 2018; Hoegh-Guldberg et al., 2018).

Coral reefs in Indian water harbour a total of 585 Scleractinian species belonging to 108 genera and 23 families (De et al. 2020), however, Indian reefs are also subjected to mass coral bleaching, pollution, disease outbreak and coastal development activities (De et al. 2017). There are three main types of reefs found in India-Fringing reef (Andaman & Nicobar Islands 1021.46 km^2, Gulf of Kutch 352.50 km^2, Gulf of Mannar, 75.93 km^2); Barrier reef (Gulf of Mannar, Andaman & Nicobar Islands); Atoll (Lakshadweep Islands, 933.7 km^2) (DOD & SAC, 1997). Apart from these three main types, there are other types, such as patch reefs, with low coral generic diversity. Presence of corals was also reported along the Central-West coast of India (Malvan, Angria Bank, Goa & Netrani Islands). The Malvan (Marine) Wildlife Sanctuary is located along the central west coast of India and spread over 29.122 km^2 area. The Malvan coral reef harbor some of the important and beautiful corals species, i.e., *Porites* spp. and *Turbinaria mesenterina, Goniopora* sp., *Goniastrea* sp., *Plesiastrea* sp., *Leptastrea* sp., *Coscinaraea* sp., *Cyphastrea* sp., and *Pseudosiderastrea tayamai,* which is an IUCN 'Near threatened' species. Along with the corals, coral-associated vividly colourful fishes are the habitant of this reef, which attracts a large number of enthusiastic tourists for SCUBA tourists in Malvan. To the economic point of view, Malvan coral reef provides livelihood opportunities to the local populations by fisheries and recreational tourism (De *et al.* 2020).

Although the Malvan (Marine) Wildlife Sanctuary was designated in 1987, unfortunately, the implementation of regulation has been on paper (Rajagopalan, 2008). The accordance of Sanctuary status to this region has always

Malvan coral habitat

Malvan corals

been opposed by the local fishermen because of their apprehension that they would be denied access to their traditional fishing ground. The coral reef in the Malvan is impacted by intensified fishing and rapid coastal development (pollution, tourism, habitat loss) along with global impacts (e.g., climate-related coral bleaching). Corals in Malvan has been undergoing severe bleaching events and associated coral mortality in recent years because of elevated sea surface temperature triggered by climate change. During 2014, 15% of coral colonies were affected by bleaching (De *et al.* 2015). Further, the prevalence of coral bleaching increased drastically to 70.93% during December 2015, with a mortality of about 8.38% (Raj *et al.* 2018). Additionally, a different type of coral diseases like white syndrome and the coral tumor was observed in Malvan (Hussain *et al.* 2017). In addition to this, an increased abundance of bio-eroding sponges was observed in the reef, which overgrowing on different live corals species (Mote *et al*. 2019).

In the Malvan coast, tourism and fishing are the main sources of income for the local fishermen. However, both these activities pose a serious threat to the recovery and resilience of corals. In recent times, Malvan has witnessed an increase in pocket-friendly SCUBA tourism, although it has improved the local economy, but, a large number of tourist (mostly untrained) on a relatively small coral habitat has resulted in mass breaking and detachment of fragile coral colonies due to trampling and boat anchoring, which are already in severe stress due to coral bleaching (De *et al.* 2020).The cumulative impact of coral bleaching, coral diseases, and tourist trampling causes coral degradation in this region during the last few years, which could lead to local scale extinction of some coral species. The loss of corals would cause detrimental impact to the local's livelihood as they depend on fisheries and dive tourism. Therefore, it is important to carry out capacity building for the local community, and stringent implementation of conservation measures along with reef restoration measures (Nanajkar et al. 2019) for the protection and sustainability of the coral habitats along the Malvan Marine Sanctuary.

Malvan recreational diving activities

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Hydroclimate variability during the last two millennia and imprints of forcing factors: A study from western India



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Abstract

Although, the teleconnection of Indian Summer Monsoon (ISM) with El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) has been attempted using instrumental records, the association of ISM with these climate variables is yet to be resolved. The present study aims to investigate the ISM variability during last two millennia from western India with specific emphasis on the effects of climate variables and natural forcing factors on ISM. The study suggested the discrepancy in the Little Ice Age (LIA) climate detected between the peninsular India and other Indian records thereby emphasizing the possible role of Intertropical Convergence Zone (ITCZ) position in controlling the monsoon oscillation over Indian subcontinent.

1. Introduction

The Asian monsoon system is a crucial component of atmospheric circulation that controls the global climate system and impacts the socio-economic status of several countries. The Asian monsoon being an integral part of global climate demands a better understanding of past climate in order to estimate the response of monsoon in the upcoming changing climatic trends. The Asian Monsoon system consists of Indian Summer Monsoon (ISM) and East Asian Monsoon (EAM) which in spite of being independent of each other they happen to interact [1]. ISM is intertwined with the Indian weather system and socio-economy, any marginal alteration in ISM can manifest dire consequences over the Indian subcontinent and its nearby regions.

The ISM progression over the Indian subcontinent is monitored by ITCZ which drastically migrate towards north and south during boreal summer and winter thereby inducing summer and winter precipitation over Indian subcontinent [2]. The moisture laden winds over Indian landmass are brought by the thermal contrast between the Indian subcontinent and the northern Indian ocean during June-August leading to > 70% rainfall [3]. Generally, the ITCZ gets established in the Core Monsoon Zone[4].

Later, the gradual retreat of the ITCZ towards southward reverses the pressure gradient resulting in Northeast monsoon (NEM) over SE India (Tamil Nadu coast and Southern Andhra Pradesh) during October-December [5]. The winter precipitation caused by the Western Disturbances (WD) principally affects the North-Western India from December to February. The moisture for the WD is generally brought from the Black Sea, the Mediterranean and North Atlantic region associated with the extratropical frontal system moving eastward towards the Himalayan region[3].

The recent instrumental records and the paleoclimatic evidences suggest a teleconnection of ISM with other modes of climate variables such as El Nino Southern Oscillation (ENSO), Total Solar Irradiance (TSI), Indian Ocean Dipole (IOD), North Atlantic oscillation (NAO) and ITCZ [6]. As the ISM variability is a manifestation of latitudinal changes in the position of ITCZ, the western India witnessing the ISM rainfall as a function of ITCZ migration thereby providing an ideal platform to address climate as a function of ISM changes for the last two millennia.

Perhaps the availability of the proxy providing high resolution climatic cues elevated the possibility to address the last millennium. However, the restriction of the proxies to go beyond last few centuries limited the observations and the first millennium remained less understood. Globally, the last two millennia has been identified as Roman Warm Period (RWP: 2500-1450 yr BP), Dark Ages Cold Period (DACP: 1450-1050 yr BP), Medieval Warm Period (MWP: 1050-650 yr BP), Little Ice Age (LIA: 650-100 yr BP) and Modern Warming (MW: 100 yr BP- Present). Substantial information on the climate perturbation during MWP-LIA has been ascribed as a consequence of several factors such as the solar and volcanic activity, Ocean circulation, land-use changes, ocean-atmospheric processes and solar-oceanic feedbacks [3], [6]. However, limited studies have been attempted to address the climate of the first millennium (RWP and DACP) [7]. The limited understanding and lack of assessment between the climate of first millennium with the last raises a need to address the response of ISM during last two millennia. The present study aims to reconstruct the hydroclimate variation for the western India using multiproxy approach.

2. Study Area

The Saurashtra coastline of western Gujarat consists of various segments with diverse geologic and geomorphic evolutions accompanied by distinct assemblage of erosional and depositional landforms[8]. The southern Saurashtra coast is marked by 40–50 m vertical cliffs of miliolite limestone. The northeast of Diu Island consists of extensive tidal flats. The region is deprived of any perennial streams but some of the seasonal rivers flowing in this area (Dhantravardi, Raidi, Rupen, Malan, Rawal and Machhundri) are sluggish with little carrying capacity and almost disappear in the tidal flats before reaching the sea. The Saurashtra peninsula witnesses mean annual rainfall of ~600 mm with majority of rainfall during the ISM . The mean maximum and minimum temperatures are 34°C and 19°C respectively .The mudflats

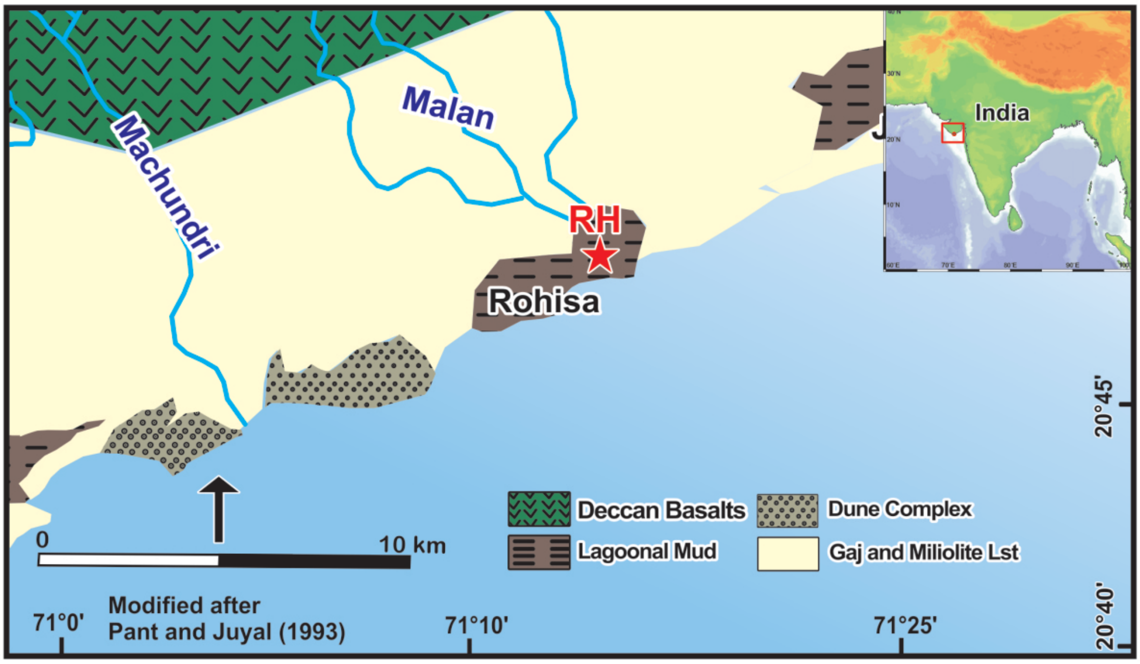

Figure 1. Map showing geology near the Rohisa active mudflat region of southern Saurashtra [60]. The region is drained by a seasonal river Malan. The red star indicates core collection site.

near Rohisa village of southern Saurashtra coast, Gujarat, Western India receive sediment during high tides while the seasonal river Malan leads to the detrital contribution. Geologically, the area consists of Deccan trap basalt of upper cretaceous period while the coastal plains are fringed by Quaternary deposits consisting of milliolite limestone, oyster beds, alluvial valley fills, aeolianites and coastal deposits (Fig.1).

3. Material and methods

A sediment core of ~60 cm raised from the active mudflats of Rohisa (20°48'59.1" N; 71°13'30.0" E), Western India to investigate the ISM variability for the last two millennia (Fig. 1). The sediment core was subsampled at 2 cm interval and analysed for several geochemical proxies. Samples were dried (at 80°C), crushed and homogenised using agate mortar and ~ 0.3 gm of sediment aliquot was subjected to closed digestion (in Thermo Microwave digestion system) using concentrated acids (HCl, HF and HNO_3). The major and trace elements were measured by aspirating the acid digested sample solutions in the ICP-AES (JobinYvon 38S) and (Thermo-X series2) respectively. The analytical precision and accuracy were monitored continuously using NOVA and MAG which were better than 5%[12]. The total organic carbon and nitrogen in the mudflat sediments were estimated in samples using the NC analyzer (FISONS model NA 1500). The crushed homogenised bulk sediment samples were decarbonated with 0.1 N HCl to remove the inorganic fraction and ~15-20 mg of sample was packed in tin capsules and measured for total organic carbon (TOC) and total nitrogen (TN) with the elemental analyser. The CN analyser calibration was done using Low Organic Soil Sample (LOSS), Batch no. 647582814 as a reference material containing 1.65 and 0.14 % carbon and nitrogen respectively[13]. The core was chronologically supported by AMS radiocarbon dating of organic carbon fraction along with ^{210}Pb and ^{137}Cs dating of bulk sediment. The details of the chronology has been discussed elsewhere.

4. Result and discussions

The coastal sediments receive organic material either from autochthonous or allochthonous sources. The TOC though serves as productivity indicator, but it is also prone to degradation. Thus, copper and nickel (normalised by Al_2O_3) being associated with organic carbon by organometallic complexes, acts as a proxy to organic carbon productivity[15]. In addition to Cu/Al_2O_3 and Ni/Al_2O_3, $Ba/A_{12}O_3$ also act as a potential proxy for the *in-situ* productivity [16]. The TOC degradation within the water column and sediment water interface is carried by aerobic microorganisms that utilises ambient dissolved oxygen (both from overlying and interstitial waters) while the extensive biological productivity can lead to oxygen depletion in the water column as a result of continued TOC degradation. Such deficiency in the ambient oxygen in the sediment-water interface and the water column leads to anoxic or euxinic conditions which can be deciphered using redox sensitive elements such as V, Co, Cr and Ni (normalised by Al_2O_3)[15].

The provenance of TOC can be identified based on the TOC/TN ratios (wt %) as the TOC in tidal flat/estuarine sediment is governed by indigenous plants and organic material transported through rivers or tidal current [17]. Generally, the TOC/TN for terrestrial C3 vascular plant material and C4 grasses are >12 [18] and >30 [19] respectively while lower plants such as the phytoplankton and the bacteria shows low [20] values i.e. <10 and 4–6 respectively[18], [19]. In the study area, the detrital contribution is a function of ISM variability resulting in activation of seasonal rivers. The detrital proxies such as TiO_2 and Al_2O_3 can be used as an indicator of improved hydrological conditions. Additionally, the global hydrogeochemical cycle of elements is primarily controlled by chemical weathering [21] while its intensity is governed by temperature and precipitation of the source region [22]. The elemental variation of Mg/Al and Ti/Al has been inferred as a chemical weathering indicator which gets enriched under warm and humid climatic conditions. The multiproxy approach on the sediment core raised from the mudflats of Rohisa likely reveals centennial to millennial scale drier climatic trends.

4.1 The first millennium

High TiO_2/Al_2O_3 and MgO/Al_2O_3 with TOC/TN > 12 between 1969 and 1546 cal yr BP can be attributed to intense weathering and terrestrially derived organic carbon. A simultaneous improvement in the *in-situ* productivity has been indicated by TOC and Al_2O_3 normalised Ba, Cu and Zn. Generally, the high TOC associated with productivity leads to the prevalence of oxygen deficient conditions which has been demonstrated by enriched values of V, Co, Cr and Ni normalised by Al_2O_3(Fig. 2). The high productivity and enhanced weathering suggest warm and wet climate as a result of ISM intensification. Globally, the time period corresponds to RWP and which has been associated with solar maxima. The ISM strengthening during RWP in the present study is in agreement with the observations made on the $\delta^{18}O$ isotope based speleothem study from the Sahiya caves, Uttarakhand [23], geochemical proxy based study on relict [24] and active mudflats [12] of Gujarat. The weathering proxy declined during 1590-1506 cal yr BP and later it remained consistently high till 800 cal yr BP. Additionally, after 1500 yr BP, the region witnessed oxic conditions as indicated by low redox sensitive elements. The marginal decline in weathering during 1590-1506 yr BP plausibly underscored DACP event with reduced ISM followed by its intensification during MWP. The reduced ISM with the onset of MWP in the present study is in agreement with the central India [25], lesser Himalaya [26] and Arabian Sea [27] records demonstrating possible occurrence of the DACP event with a declining ISM. Nevertheless, the MWP has witnessed ISM strengthening and the observations corroborated well with the northern Indian Ocean and Indian continental [6] records. But the culmination of MWP has been observed as weak ISM period [3].

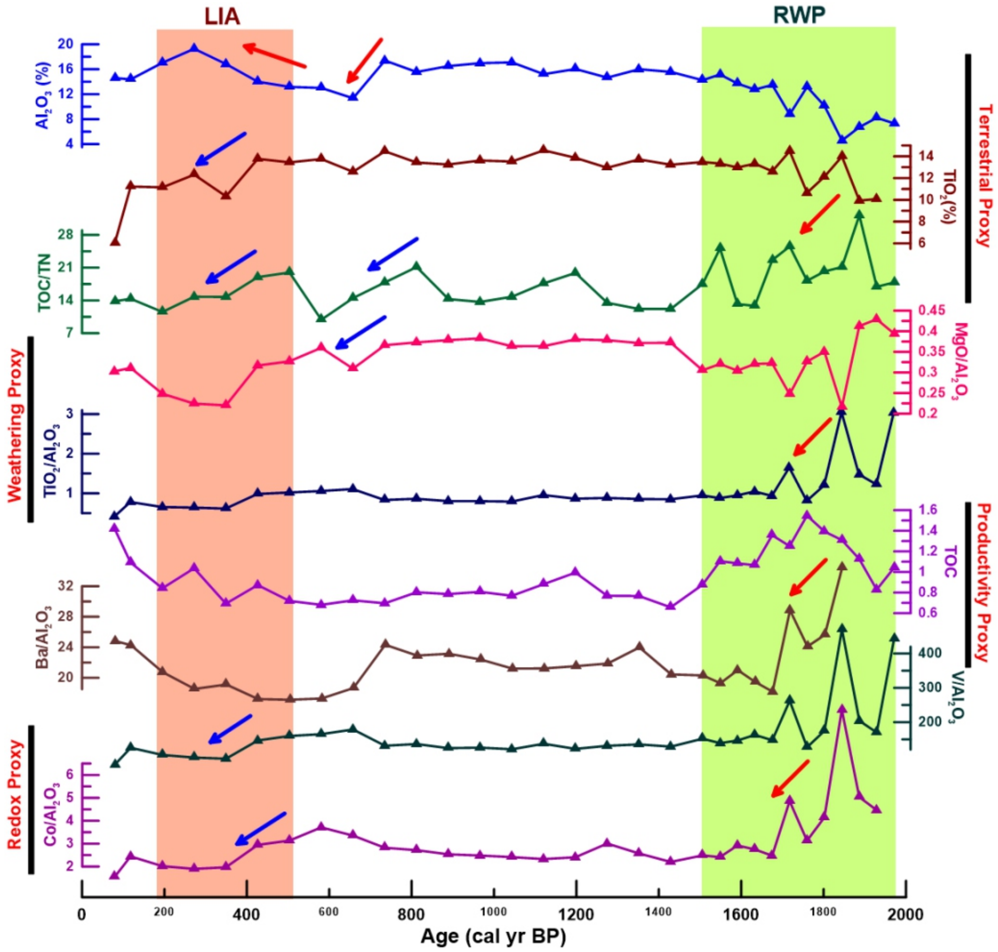

Figure 2. Improved hydrological conditions observed during RWP. Reduced weathering and productivity while marginal increase in the Al_2O_3 suggests wet and cool climate.

4.2 The last millennium

Reduced weathering (TiO_2/Al_2O_3 and MgO/Al_2O_3) and productivity proxies (TOC and Ba/Al_2O_3) along with declining TiO_2 during 503-193 cal yr BP implies reduction of warming in the climate (Fig. 2). However, marginal increase in the Al_2O_3 underscored possible improvement in the hydrological conditions due to monsoon. The reduction in the warming suggests ISM weakening but the improved hydrological conditions suggest possible strengthening of monsoon. The possible improved monsoon in the study area is in concordance with multiproxy approach at the Narmada valley, mainland Gujarat [28]. ISM weakening during LIA has been claimed by the present study based on reduced weathering and productivity which in agreement with the previous records from Indian subcontinent [3]. However, the monsoon activity during LIA implied by the marginal increase in Al_2O_3 underpinning the possible occurrence of winter precipitation. This can be attested by the fact that though the region presently is destitute in receiving winter precipitation but the palynological evidence during mid-late Holocene period demonstrated improved winter precipitation over Gujarat [29]. Thus, the possible strengthening of winter precipitation during LIA might have led to cool and wet climate in the study area. The improved weathering and *in-situ* productivity but lack of detrital flux during the last 190 cal yr BP demonstrated a climate warming corresponding to MW period. Last two century climate warming has been attested by the glacier retreat with punctuated advancement in the Himalayan region post-1795 AD after the termination of LIA [30]. Further, the instrumental data revealed an increase of 0.5°C in the All India mean annual temperature between 1901 and 2003 AD [31] and reduction in ISM rainfall since 1960s onwards [32] thereby supporting the claim of climate warming during last two centuries in the present study and other high resolution records.

4.3 The Little Ice Age (LIA)

Globally, the LIA has been associated with the cold winters and glacial advancement [33]. In the Indian subcontinent, several paleoclimatic continent and marine archives have delineated the climate of LIA as a function of ISM changes [3], [6]. The oxygen isotopic investigation on speleothem from Dharamjali cave, Kumaun Himalaya demonstrated wet climate spanning from ~1440 to 1880 AD and suggested the position of ITCZ over the cave during wet climates [35]. Similarly, another isotope based study on speleothem from Chulerasim cave, Kumaun Lesser Himalaya, showed a wet phase during the LIA (1590-1850 AD) followed by a comparatively dry phase after 1850 AD [36]. The prevalence of cool and moist LIA has been demonstrated by the pollen and diatoms study on peat deposit from the Pinder valley, Higher Himalayas [37]. Similarly, the paleoclimate reconstruction from the Wah Shikhar Cave, northeast India also suggested monsoon intensification during the onset of LIA [38]. A palynological investigation from Darjeeling Himalaya demonstrated monsoon enhancement from 1367 to 1802 AD [39]. LIA has been recorded as a wet climate in the northern and northeast Indian region however, a distinct scenario has been observed in the continental records from the peninsular region and the Arabian Sea. The isotopic study from Jhumar Cave, central India [40] and Arabian sea [41] suggested ISM intensification during the 17th century. Low productivity and low denitrification from the northeast [42] and eastern [43] Arabian sea has been ascribed during LIA (1400-1700 AD) thereby demonstrating weak ISM. The stable isotope (Carbon and Oxygen) based rainfall reconstruction on the speleothem from Uttar Kannada district, Karnataka identified 1666 AD and 1900 AD as the highest and lowest rainfall respectively[44]. A multiproxy study conducted on the sediment from Pookode Lake, Kerala, Southern India indicated an overall warm and dry conditions during 6200-420 yr BP interrupted by short wet phases (during BC 4000-BC300 AD, 800-1200 AD and 1570-1860 AD) [45]. Oxygen isotope study on two foraminiferal species extracted from eastern Arabian Sea sediment core provided evidences of centennial dry events at ~1500, ~1100, ~850 and ~500 yrs BP [46]. Similar dry episodes have also been registered in the form of reduced varve thickness and low Ti/Al in varved sediments [47] and enriched foraminiferal $\delta^{18}O$ in a sediment core from N. Arabian Sea [48]. Weak monsoon during LIA preceded by monsoon strengthening during MWP has also been recognised from the oxygen isotope-based study on speleothem from Andaman [49]. A foraminiferal study on a sediment core from western Arabian Sea demonstrated low *G. bulloides* abundance during 1500-1800 AD demonstrated reduced ISM [50]. The northern Indian region witnessed wet climate while most of the peninsular region might have witnessed dry climate[6].

4.3.1 Role of Intertropical Convergence Zone (ITCZ)

Generally, dry climate associated with weak ISM has been observed during LIA from the peninsular India [6]. However, wet climate has been claimed as a result of improved winter precipitation from northern and northeast India [6]. In the present study, marginal improvement in the terrestrial contribution with no major change in the weathering proxies underscored winter monsoon activation. In the present scenario, only the southward migration of the ITCZ can cause winter monsoon influence associated with the WD. The possibility of ITCZ southward migration is in agreement with the reduction of Titanium concentration in the sediment core (Fig.3d) raised from the Cariaco Basin [51]. The southward migration of the ITCZ has been associated with gradual increase in the El Nino variability. The comparison of the Ti concentration with the red colour intensity of Peruvian lake [52] indicated increased El Nino events (Fig.3e). Thus, the present study attests the southward migration of ITCZ during LIA leading to winter precipitation due to enhanced WD caused by negative phase of NAO in the study area [14] which is also in agreement with the other global records [53]. Thus, the ITCZ played a crucial role in establishing an inhomogeneous climate during LIA over the Indian subcontinent.

4.3.2 Forcing mechanisms

Though the global climate for the Holocene period has been controlled by three major natural forcing factors viz. orbital, solar and volcanic forcing. The last two millennia have been primarily influenced by solar and volcanic forcing. Nevertheless, there has been some impacts of anthropogenic induced forcing such as Green House Gases (GHGs), vegetation cover, stratospheric ozone during last few centuries as a result of complex feedback mechanism [54]. But its impact has been observed more towards last two centuries. Thus, the present study attempts to investigate the influence of solar and the volcanic forcing. The ^{10}Be in ice cores from Greenland and Antarctica along with the global ^{14}C tree ring record for the last millennium suggested ~400-year long period of elevated solar activity peaked at ~1000 AD which later declined rapidly ~1350 AD and remained low till 1850 AD [55]. The persistent solar activity in the former corroborated with the warm phase of MWP from 950 to 1250 AD. The subsequent period of reduced solar activity corresponded well with the cold period of LIA [55]. In the present study, the reduced weathering (Fig.3b) and productivity (Fig.3c) during LIA are in agreement with the reduced Total Solar Irradiance (TSI) (Fig.3g) implying weak ISM. A consistently high TSI during 1300-800 cal yr BP is comparable with the productivity proxy variations indicating stable monsoonal conditions during MWP. The high TSI and stable productivity during MWP are in agreement with the enhanced temperature recorded by the GISP2 (Greenland ice core) (Fig.3f). The conspicuous reduction in GISP2 temperatures with the termination of MWP supports the observation of reduced productivity and weathering of the present study. While the marginal increase in the detrital proxy (Fig.3a) demarcates the possible influence of monsoon in the region thereby underscoring the prevalence of winter precipitation. The variations in the productivity and weathering proxies as a function of ISM changes triggered by solar forcing are in agreement with global and Indian records [3], [6].

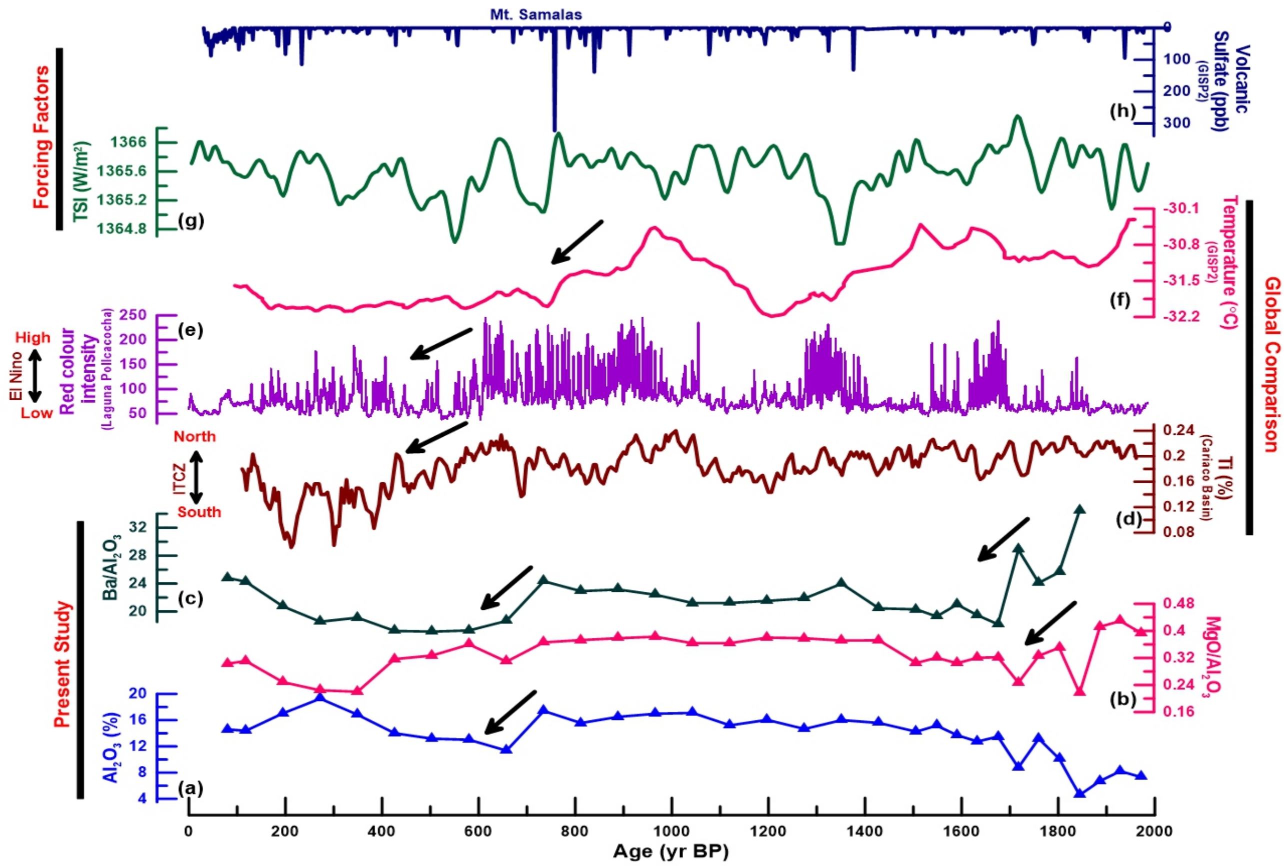

Figure 3. Geochemical proxies (a-c) were compared with (d) Cariaco Basin [51], (e) Peruvian lake [52], (f) GISP2 reconstructed Temperature [61], (g) Total Solar Irradiance (TSI) [55] and (h) GISP2 Volcanic Sulfate [62].

The role of volcanic forcing on climate has been extensively studied [6], [54]. In the last 850 yr, no less than 12 significant eruptions have been documented with more frequency recorded during LIA [54]. Study on the growth of ice cap from Arctic, Canada and Iceland demonstrated repeated volcanic explosions during the 15th century that triggered the cold climate of LIA [56]. The volcanic eruption of 1258 AD (Mt. Samalas) is considered to be one of the largest eruption in last 7000 yr BP [57] which ejected sulfate aerosols ~260±60 Tg that dispersed in both the hemispheres underscoring low latitude eruption [58].

A simultaneous occurrence of reduced weathering and productivity with the volcanic eruptions recorded in the GISP2 ice core (Fig.3h) demonstrates a possible role played by the volcanoes in controlling the ISM thereby triggering climate perturbations. The volcanic eruption not only influenced the ISM but has also affected the global temperature as seen from the reconstructed temperature from GISP2 ice core. Additionally, with the volcanic eruption of 1258 AD (~690 cal yr BP), a conspicuous decline in the weathering and productivity is seen which possibly demarcates the termination of MWP and the onset of the LIA. Thus, the cooling temperature during LIA possibly resulted due to the 1258 AD volcanic eruption which is possibly associated with the Mt Samalas eruption episode [14], [57], [59].

5. Conclusion

A warm and wet climate during RWP and MWP interspersed with dry climate during DACP has been proposed in the present investigation as a result of varying ISM which is in agreement with the regional and global studies. The strengthening of winter monsoon coupled with southward migration of ITCZ led to a cool and wet climate during LIA. The climate for LIA was broadly in agreement with the records of northern India but a contrasting scenario (i.e. dry climate) has been observed in peninsular India. The present study has assessed the potential role of ITCZ migration coupled with the possible influence of ocean-atmospheric processes that led to the inhomogeneous climate over the Indian subcontinent during LIA. The present study emphasis the fact that the last two millennia has been significantly influenced by the solar forcing and volcanic eruption. Further, the 1258 AD volcanic eruption has been the possible factor triggering global cooling leading to the onset of LIA.

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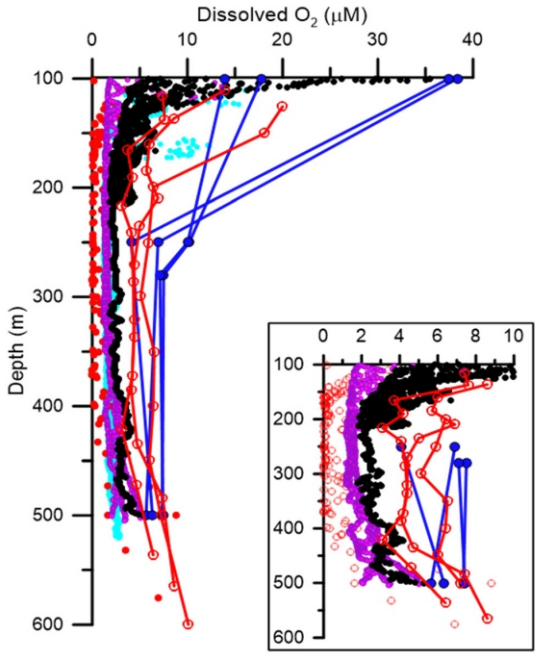
Research Highlights

A revisit to the regulation of oxygen minimum zone in the Bay of Bengal

Occurrence of intense oxygen minimum zone (OMZ) is known in the Bay of Bengal (BoB), but it has been recently reported to have become more acute and is at its tipping point. Here, we show that the intensification of OMZ to acute condition is a random and short-term rather than perennial phenomenon based on re-evaluation of old and recent information in the BoB. Short-term modifications in dissolved oxygen (DO) in the OMZ are caused by balance among physical forcings: salinity stratification, occurrence of cyclonic (CE), and anticyclonic eddies (ACE). Our analysis reveals that `acute OMZ' is only a transient phenomenon in the Bay since the dynamic periodic physical forcings, particularly ACEs, do not allow it to become a dead zone.



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