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Review on Indian Summer Monsoon (ISM) Reconstruction since LGM from Northern Indian Ocean

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ABSTRACT

Indian summer monsoon (ISM) is critical to understand the global hydrological and carbon cycles and acts as a major driving force of earth's climate system. Paleoclimatic evidences however, suggests episodic weakening and intensification of ISM in the past since its initiation. The weather system and socio-economy of Indian subcontinent depends on the ISM strength; thus, it is important to comprehend the centennial and millennial scale variability of ISM on northern Indian Ocean. The paper attempts to review the response of two basins in the northern Indian Ocean (Arabian Sea and Bay of Bengal) towards changing ISM intensities since Last Glacial Maximum (LGM). Further, we also tried to reconcile the knowledge gaps that need to be addressed in the paleoclimatic reconstruction of ISM from marine records which will reinvigorate modelers and policy makers to have prospects of amended predictions with imperative and robust strategies.

Keywords: ISM, LGM, northern Indian Ocean, Sea Surface Temperature, Holocene, GEOTRACES

INTRODUCTION

A large-scale sea breeze that originates due to significant difference between the temperatures on land and ocean is termed as Monsoon. The term 'Monsoon' has been coined from Arabic word 'Mausam', which stands for season, first witnessed by Arab sailors navigating through the Arabian Sea, who observed a persistent wind reversal every year during the same time. Monsoon is generally associated with dry (NE winds) or wet (SW or Indian Summer Monsoon-ISM) weather. The Indian Ocean differs from other global oceans due to its unique characteristics and noticeable behavioural pattern with changes in the strong monsoonal winds over the ocean. The strong differential land-ocean thermal contrast leads to seasonal reversing of wind system and regulates monsoonal circulation which influences weather pattern between

30°N and 30°S over the Indian, Asian and African landmasses (Schott and McCreary, 2001). The initiation of the Indian Monsoon system with its peak intensity around 5 Ma (Molnar *et al.*, 1993) has been attributed to the upliftment of the Tibetan Plateau during the late Miocene (10-8 Ma) (Niitsuma and Naidu, 2001). The Arabian Sea records and the windblown dust in the loess plateau of China suggested the commencement of ISM occurred at ~8 Ma.

The ISM is responsible for heat and moisture transport from tropical to higher latitude regions across the equator (Clemens *et al.*, 2003). During boreal summer, the monsoonal winds blows from ocean towards the land and are intense, wet and southwesterly (SW), whereas, during boreal winter, the monsoonal winds are cold, dry and northeasterly (NE) blowing from land to sea. ISM is also associated with the migration of the Intertropical Convergence Zone (ITCZ)- a narrow latitudinal zone of low pressure of wind convergence near equator (Chao and Chen, 2001; Gadgil, 2003). During boreal summer, ITCZ shifts north of the equator and the winds blow across the equator to reach ITCZ, inducing strong SW monsoon winds. During boreal winter, the ITCZ shifts south of equator with winds blowing from north across the equator to reach ITCZ, generating strong NE monsoon winds (Fig. 1).

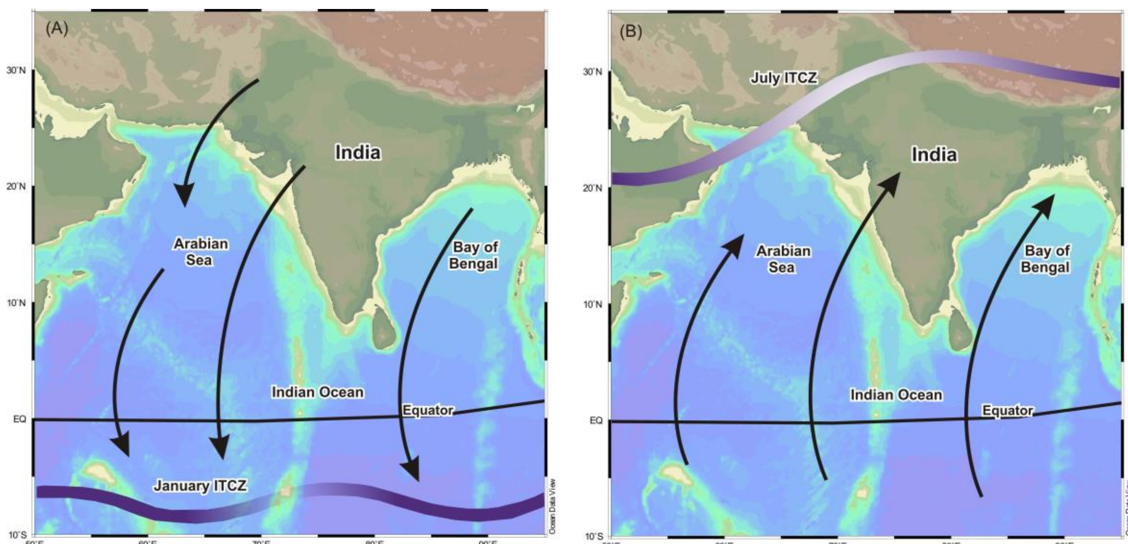

Fig. 1: Migration of Intertropical Convergence Zone (ITCZ) during (A) winter monsoon and (B) summer monsoon.

ISM is an important phenomenon of Asian monsoon system which causes >70% rainfall on the Indian subcontinent (Warrier and Shankar, 2009) with huge impacts on Indian socio-economic status (Roy and Collins, 2015). The teleconnection linking of ISM with El Nino Southern Oscillation (Maity and Kumar, 2006), Total Solar Irradiance (Agnihotri *et al.*, 2002) Indian Ocean Dipole (Abram *et al.*, 2009), North Atlantic osicllation (NAO) (Menzel *et al.*, 2014) and ITCZ (Saraswat *et al.*, 2013) have strengthened the implications of ISM. Abrupt variations in ISM with extreme drought and flood events in last few decades are the major impediment that reinvigorated various paleoclimatologists to understand the ISM fluctuations since Last Glacial Maxima (LGM) till present (Agnihotri *et al.*, 2003; Singh *et al.*, 2006; Tiwari *et al.*, 2006) to develop understanding for the present global climatic perturbations and modelling the future changes. Therefore, various paleoclimatic archives such as marine sediments (Bhushan *et al.*, 2001; Saraswat *et al.*, 2012; 2013; Banerji *et al.*, 2017), lake sediments (Juyal *et al.*, 2009;

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Dixit *et al.*, 2014; Prasad *et al.*, 2014), peats (Sukumar *et al.*, 1993; Hong *et al.*, 2003; Rühland *et al.*, 2006), speleothems (Sinha *et al.*, 2005; Yadava and Ramesh, 2005; Fleitmann *et al.*, 2007) and corals (Ahmad *et al.*, 2011) at varying temporal resolution have been investigated for the reconstruction of ISM during the late Quaternary. Though, there have been extensive studies on late Quaternary ISM reconstruction from marine and terrestrial records, there remains a lacuna in comparative study based on impacts of ISM intensity on the two distinct basins of northern Indian Ocean. In the present review, we expound a general framework for addressing the influence of ISM strength on the Arabian Sea, the Bay of Bengal, the Andaman Sea and the equatorial Indian Ocean since LGM.

GLACIAL- INTERGLACIAL RECORDS OF ISM

Both the Arabian Sea and the Bay of Bengal in the northern Indian Ocean respond differently under changing influence of ISM. The reconstruction of ISM based on oxygen isotopes of foraminifera of various sediment cores from the northern Indian Ocean during LGM suggests ISM weakening resulted in warmer sea surface temperature (SST) for Arabian Sea due to reduced upwelling, while enhanced salinity observed in the Bay of Bengal caused by declining continental influx (Prell *et al.*, 1980).

The Arabian Sea

The Arabian Sea is a highly productive region strongly linked with monsoon system and accompanied by shift in ITCZ (Clemens *et al.*, 1991). The sediment trap study from the Arabian Sea shed light on enhanced biological productivity during ISM (Prahl *et al.*, 2000; Wakeham *et al.*, 2002). The primary productivity for the Arabian Sea varied as a function of change in monsoon intensity on Milankovitch and Holocene time scales. The reconstructed paleo-productivity for the past 135 ka from the northern and eastern Arabian Sea suggest large variations during glacial-interglacial periods. Intensification of ISM during interglacial period with increased wind velocities caused strengthened upwelling resulting into high productivity at the northern Arabian Sea. But during glacial periods, the intensified NE monsoon led to mixed layer deepening causing high productivity in the eastern Arabian Sea (Ivanova *et al.*, 2003). Similar observations of enhanced productivity during LGM from the eastern Arabian Sea has been described as a result of nutrients shoaling due to enhanced convective mixing led by intensified NE monsoon (Ishfaq *et al.*, 2013). On the contrary, reduced overhead productivity witnessed during glacial interglacial transition following which enhanced productivity occurred during Holocene as evidenced by the geochemical proxies for the sediment core retrieved from the eastern Arabian Sea (Agnihotri *et al.*, 2003).

The large scale differential heating of landmass and Indian Ocean along with complex dynamics of ocean atmosphere system of Indian Ocean controls the atmospheric circulation associated with ISM (Kessarkar *et al.*, 2013). The reconstructed upwelling history and monsoon circulation from the western Arabian Sea based on pollen and upwelling foraminifera suggested stronger ISM during interglacial period (Prell and Campo, 1986). This is in agreement with the investigation on reconstruction of SST derived from Mg/Ca in combination with calcification temperature of the planktonic foraminiferal species for the last 20 ka from the western Arabian Sea made by Saher *et al.* (2007). The study claimed improved ISM with weakening of NE monsoon winds during interglacial periods while weak ISM with enhanced cooling by NE monsoon winds during LGM.

Plethora of paleoclimate studies using trace elemental geochemistry of the marine sediments revealed variations in chemical weathering (Tripathy *et al.*, 2014), paleo-productivity (Agnihotri *et al.*, 2003), paleo-redox conditions (Pattan and Pearce, 2009) and its implications on changing monsoon. Temporal variations of the trace elements from the Arabian Sea as a function of changing monsoonal intensity, atmospheric circulation and hydrographic conditions during last 25000 years by Sirocko *et al.* (2000) has been reported based on sediment core from western Arabian Sea. Weakening of ISM during LGM with high dust discharge from the north-westerly winds has been observed by Sirocko *et al.* (2000). A multi proxy study on a sediment core raised from the western Arabian Sea suggested that the low calcareous productivity could be due to the favoring of silicate over carbonate productivity as a function of ISM strengthening (Tiwari *et al.*, 2010).

In the Arabian Sea, the depth of Aragonite Compensation Depth (ACD) (250-700 m) generally falls within the Oxygen Minimum Zone (150-1250 m). Above conditions in the Arabian Sea are sustained by overhead productivity, carbon respiration within the water column and sediments and water mass ventilation thereby causing an interconnection between aragonite preservation and intensity of OMZ (von Rad *et al.*, 1999). However, in the present-day conditions, aragonite preservation is poor in the Arabian Sea due to the occurrence of intense OMZ environment (Naidu *et al.*, 2014). To study the relationship between ACD and Antarctica Intermediate Water (AAIW) ventilation in the Arabian Sea, Naidu *et al.* (2014) estimated aragonite contents and pteropods abundance in a sediment core within the oxygen minimum zone of the eastern Arabian Sea. Compared to present day condition, deepening of ACD in the eastern Arabian Sea persisted during glacial period and stadials (Heinrich events) as suggested by enhanced aragonite content and pteropod abundances. Such changes in ACD result as a function of declining local monsoon driven productivity accompanied by improved ventilation caused by intrusion of glacial AAIW (Naidu *et al.*, 2014). Thus, the ISM intensity directly influences the overhead productivity in the western Arabian Sea. But the NE monsoonal wind intensification during LGM in the eastern Arabian Sea documented ACD deepening which lead to enhanced productivity and better preservation of aragonite and pteropods.

The Bay of Bengal and the Andaman Sea

The Bay of Bengal witnessed sedimentation since early Miocene and is known to have archived paleoclimatic signatures experienced in various catchment regions of different fluvial sources such as Himalaya, peninsular regions, Andaman group of islands and Myanmar (Sarin *et al.*, 1979; Fontugne and Duplessy, 1986). Unlike the Arabian Sea, the Bay of Bengal and the Andaman Sea is highly influenced by riverine influx and sediment (2000 million tons/year) from the Himalayan and Indian peninsular rivers (Chauhan and Vogelsang, 2006) and rainfall during ISM (Govil and Naidu, 2011). The Bay of Bengal is known to experience extensive river discharge during ISM with strongly stratified surface layer causing abrupt decline in surface salinity of the order of 4 psu in the northern Bay of Bengal (Wyrtki, 1973). The past (~32 kyr) sea surface salinity and temperature reconstruction based on paired measurement of planktonic foraminiferal Mg/Ca and $\delta^{18}O$ in a sediment core from western Bay of Bengal was studied by Govil and Naidu (2011). The study demonstrated ~3.2°C cooler SST of the Bay of Bengal during LGM. But low salinity during Bolling-Allerod (B-A) event signified the onset of intensified ISM. Similarly, the Holocene also suggested strong ISM with enhanced freshwater discharge in the region (Govil and Naidu, 2011). Likewise, ISM weakening/strengthening during LGM/

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Holocene as a consequence of low/high freshwater influx in the northern Bay of Bengal has been evidenced from foraminiferal $\delta^{18}O$ (Kudrass *et al.*, 2001). Although, sediment sources to the Bay of Bengal has been dominated by both Higher and Lesser Himalaya, on million year time scale, but the source of sediment has remained nearly consistent since Miocene (Bouquillon *et al.*, 1990; France-Lanord, 1993). Evidence of changing provenance of sediment as a function of changing climate on millennial timescale has been extensively addressed (Ahmad *et al.*, 2005; Clift *et al.*, 2008; Rahaman *et al.*, 2009). The isotopic study of the sediment from western Bay of Bengal revealed ISM weakening and expansion of glaciation over Higher Himalaya that reduced the erosion rate over the Himalaya resulting in relatively lower $^{87}Sr/^{88}Sr$ and higher ε_{Nd} during LGM (Tripathy *et al.*, 2011).

The sediment records of the Andaman Sea indicate low riverine flux and cooler SST during LGM and Younger Dryas with subsequent warmer SST and enhanced riverine influence from Irrawaddy river during B-A and early Holocene as suggested by $\delta^{18}O_{sw}$ (Rashid *et al.*, 2007). Based on stable carbon and oxygen isotopic variation of the planktonic foraminifera from a deep sediment core in the Andaman Sea indicated increased salinity/ decrease temperature during glacial period attributed to cooling event or sudden decline in fresh water flux as recorded from $\delta^{18}O$. Simultaneous enrichment in $\delta^{13}C$ values during glacial periods is an indicative of enhanced productivity due to NE monsoon intensification in the Andaman Sea (Ahmad *et al.*, 2000). Weak ISM resulted in low fresh water influx to the Bay of Bengal and Andaman Sea which lead to increase in SST and overhead productivity during LGM. With the re-establishment of ISM during B-A event and Holocene, high fresh water influx with depleted SST has been witnessed by the Bay of Bengal and Andaman Sea.

The equatorial Indian Ocean

A low salinity tongue formed by the inflow of low salinity surface water from the Bay of Bengal to the eastern Arabian Sea is largely driven by the higher sea level in the Bay of Bengal than in the Arabian Sea (Mahesh and Banakar, 2014). To assess absolute sea surface salinity changes during the last glacial period, Mahesh and Banakar (2014) collected two cores along a north–south transect in the eastern Arabian Sea. Based on paired measurement of $\delta^{18}O$ and Mg/Ca in surface dwelling planktonic foraminifera, suggested decrease in intensity of ISM resulted in low freshwater discharge in the Bay of Bengal during the last glacial period.

A technique of studying the abundance ratio of unsaturated alkenones in phytoplankton preserved in sediments has recently developed in past few decades (Prahl and Wakeham, 1987). The paleotemperature record based on alkenone and oxygen isotopes in foraminifera from Maldives inferred high salinity during glacial stages characterized by increased evaporation and/or decreased precipitation, is attributed to enhanced dry NE winds and/or reduced SW monsoon (Rostek *et al.*, 1993). Unlike other paleoclimatic records from the Arabian Sea, enhanced primary productivity was observed during the glacial periods while interglacial periods witnessed low productivity as attributed to increased convective overturning due to stronger NE monsoon winds (Rostek *et al.*, 1993). Similar observation of enhanced productivity during LGM in the equatorial Indian Ocean was suggested by (Punyu *et al.*, 2014) based on marine productivity indicators such as phytol, brassicasterol and organic carbon. Such enhanced productivity during LGM is combined impact of intensified inter-monsoon Wyrtki Jets and NE winds which triggered the nutrients levels in the photic layer (Punyu *et al.*, 2014). Study based on redox sensitive and productivity proxies from the equatorial Indian Ocean demonstrated occurrence of anoxic bottom water conditions during LGM. The anoxic conditions at sediment-water interface is due to concurrent occurrence of both poorly ventilated bottom waters and high surface productivity (Chandana *et al.*, 2017). Conversely, the oxygen isotopes of planktonic foraminifera from the equatorial Indian Ocean suggested strengthening of NE wind during early deglacial period instead of LGM (Tiwari *et al.*, 2005). Based on Mg/Ca on planktonic foraminifera from the equatorial Indian Ocean for the SST reconstruction of last 137 kyr, it has been observed that SST was 2.1°C cooler during LGM compared to the present (Saraswat *et al.*, 2005). On comparing the equatorial Indian Ocean SST with Antarctic δD and Greenland δ^{18}O records, presence of major high-latitude cooling/warming events in the equatorial Indian Ocean is noticed (Saraswat *et al.*, 2005). Based on these studies, it can be suggested that the equatorial Indian Ocean is characterized by high SSS and overhead productivity accompanied by low SST during LGM lead by strengthened NE monsoon winds during LGM.

HOLOCENE RECORDS OF ISM

Holocene period is known to have witnessed great fluctuations in ISM precipitation. The wind reversal associated with the ISM and winter monsoon results in a unique environment with upwelling, large freshwater influx and a seasonal bottom water anoxia (Agnihotri *et al.*, 2008) thereby leading to enhanced phytoplankton productivity in the eastern Arabian Sea (Parab *et al.*, 2006). The Arabian Sea is known to witness bacterially mediated denitrification in the suboxic conditions which in turn depends on the surface productivity. Sediment record of past 700 yr from the eastern Arabian Sea revealed reduced denitrification during 1750 to 1650 AD (Little ice age) associated with low upwelling as a result of reduced ISM (Agnihotri *et al.*, 2008). However, increased productivity with depleted sedimentary δ^{15}N for the last 150 years (the Anthropocene) resulted due to the dilution by isotopically lighter nitrogen supply from the land (Agnihotri *et al.*, 2008). Likewise, the study of other productivity proxies ($\delta^{13}C_{org}$, $\delta^{13}C_{ruber}$ and OC) from the eastern Arabian Sea also suggests enhanced productivity since 7 ka as a result of increase in upwelling intensity/ winter convective mixing (Naik *et al.*, 2014). Temporal variation of high resolution terrigenous contribution in the eastern Arabian Sea suggests monsoon intensification during 9.5 and 9.1 ka followed by monsoon weakening events recorded at 8.2, 7.0, 5.5 and 3.5 ka (Thamban *et al.*, 2007).

Exploring the Holocene records from equatorial region of the Indian Ocean is skeptical, but the continental shelf of Sri Lanka can be examined to have better understanding of the paleoceanographic processes for the Holocene. The southeastern coast of Sri Lanka is mainly affected by winter monsoon, as it is the shadow region for ISM and thus archives winter monsoon variability. Investigation based on sediment cores from coastal estuaries and lagoons underscored the climate aridification intervals from 7.3-6.7, ~4.0-3.0 and ~1.1-0.5 ka interspersed with semi-arid conditions from ~6.2-4.6 ka, and short-wet intervals of ~6.5-6.2 ka and ~3.0-1.5 ka. Statistical similarity between Indian winter monsoon and Indian summer monsoon variability suggests control of similar forcing mechanism (Ranasinghe *et al.*, 2013).

Summary and outlook

Over the last several decades, the paleoclimatic and paleoceanographic understanding for the northern Indian Ocean since LGM has expanded. Such extensive and pioneering studies provide an excellent portrayal of ISM variability since LGM. The past climate variability as a

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function of ISM intensification from several paleorecords on different time scales from northern Indian Ocean indicate ISM weakening during glacial periods such as LGM (~23 ka) and Younger Dryas (~12.5 ka) interrupted by ISM strengthening post LGM (~ 17 ka). The temporal variability of ISM during Holocene suggested monsoon strengthening during early Holocene (~10 ka) followed by gradual weakening towards mid- late Holocene (~8-4 ka).

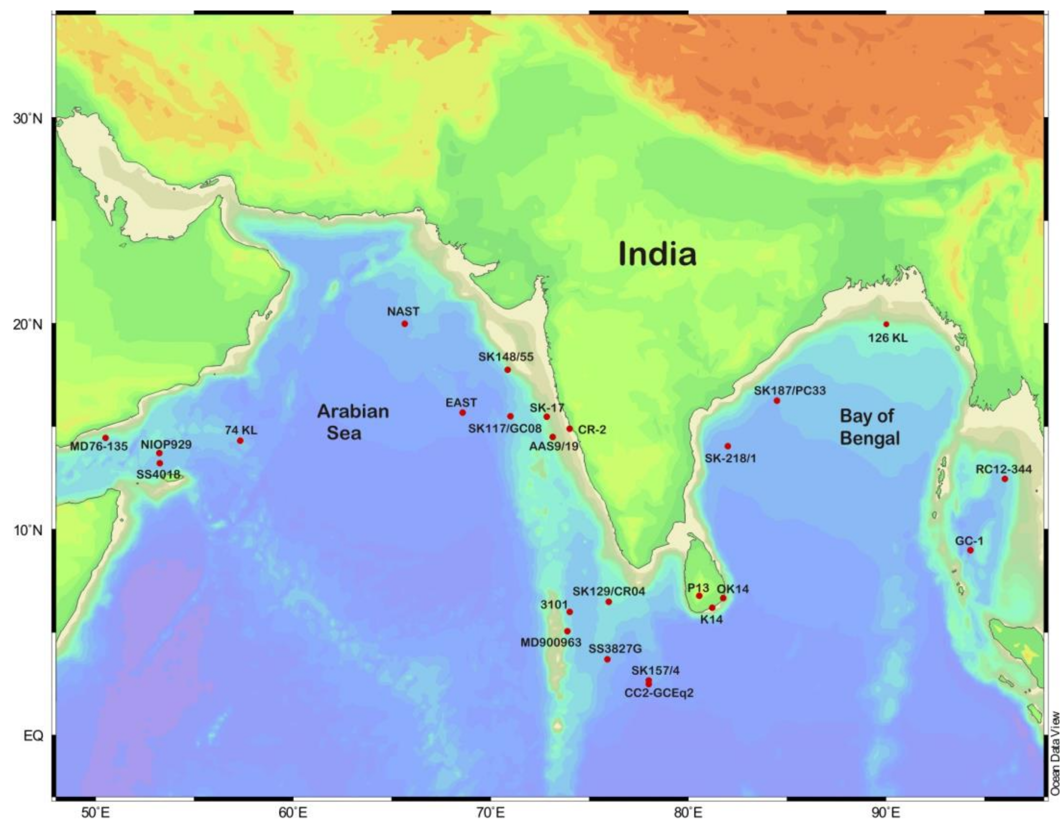

Fig. 2: Location of the cores discussed in the paper is represented by filled circles.

The observation based on various studies primarily opines two concepts of the past ISM variability in the northern Indian Ocean: a) the productivity variation in the Arabian Sea, and b) the change in SST/salinity in the Bay of Bengal, as a function of the ISM intensity during glacial-interglacial periods. The western Arabian Sea witnessed high productivity due to enhanced upwelling driven by improved ISM intensity during interglacial period whereas the eastern Arabian Sea experienced high productivity during LGM due to mixed layer deepening caused by intensified NE monsoon. Similar to eastern Arabian Sea, the Andaman Sea also witnessed enhanced productivity during LGM triggered by NE monsoon intensification. But, during B-A event and Holocene low salinity signified improved ISM with enhanced freshwater influx in the Bay of Bengal and the Andaman Sea, while low temperatures during LGM invokes ISM weakening in the region. In the equatorial Indian Ocean, dry NE winds and reduced ISM resulted in high salinity in the region during glacial period. Further, a combined impact of intensified inter-monsoon Wyrtki Jets and NE winds triggered productivity during LGM near central equatorial Indian Ocean.

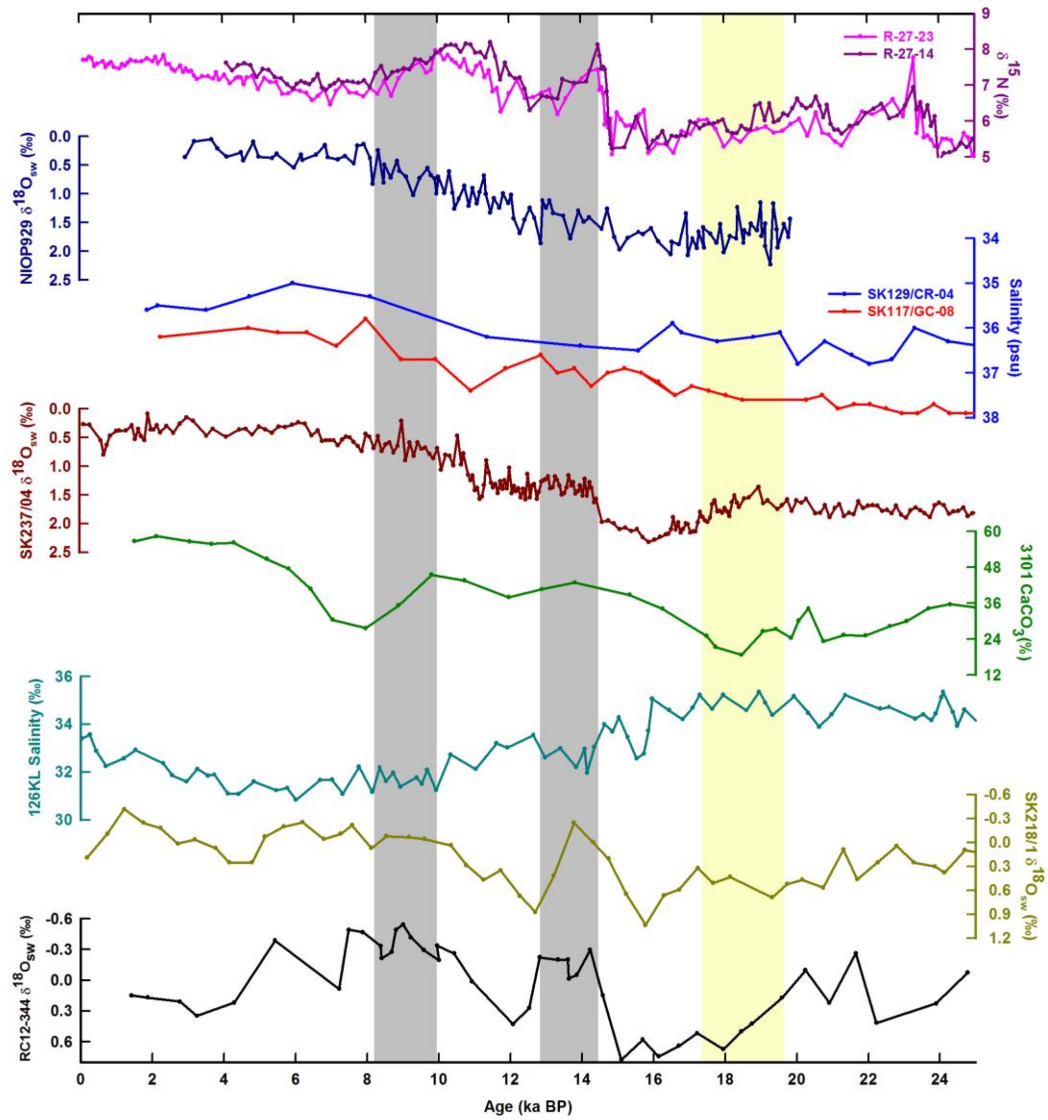

Fig. 3: Reconstructed high resolution paleomonsoon records from the northern Indian Ocean for the last glacial-interglacial transition. RC27-14, RC27-23 $\delta^{15}N$ (Altabet *et al.*, 2002); NIOP929 $\delta^{18}O_{sw}$ (Saher *et al.*, 2007); SK129/CR-04 & SK117-GC-08 (Mahesh and Banakar, 2014); SK237-GC04 $\delta^{18}O_{sw}$ (Saraswat *et al.*, 2013); 3101 (Agnihotri *et al.*, 2003); SK218/1 (Govil and Naidu, 2011); 126KL Salinity (Kudrass *et al.*, 2001); RC12-344 (Rashid *et al.*, 2007). Gray band in the plot represents ISM strengthening and yellow band indicative of ISM weakening.

Emphasis is being made on paleoclimatic and paleoceanographic reconstruction of the Arabian Sea, the Bay of Bengal and the Andaman Sea. However, the intermixing zone of the

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Arabian Sea and the Bay of Bengal near the equatorial region with limited studies still remains an enigma and needs to be addressed in terms of the oceanographic processes since LGM. Further it has also been observed that past climate bracketing the major events of last few centuries for the northern Indian Ocean is the major impediment in the compilation of data for rapid climate change of late Holocene and future climate changing trends. Therefore, century scale reconstruction can be attained using other coastal and continental proxies for better outlook of ISM, its interlinked processes and its association with global climate change.

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Table-1: Details of the cores discussed in the study

S. No.	Study	Latitude (°N)	Longitude (°E)	Core
1.	Saher *et al.* (2007)	13.70	53.25	NIOP929
2.	Tiwari *et al.* (2010)	13.21	53.26	SS4018
3.	Prell and Van Campo (1986)	14.45	50.52	MD76-135
4.	Sirocko *et al.* (2000)	14.32	57.35	74 KL
5.	Ivanova *et al.* (2003)	20.00	65.67	NAST
6.	Thamban *et al.* (2007)	17.75	70.87	SK 148/55
7.	Ivanova *et al.* (2003)	15.67	68.58	EAST
8.	Ishfaq *et al.* (2013)	15.48	72.85	SK117-GC08
9.	Mahesh and Banakar (2014)	15.49	71.02	SK117/GC08
10.	Mahesh and Banakar (2014)	6.49	75.98	SK129/CR04
11.	Naidu *et al.* (2014)	15.25	72.97	SK 17
12.	Agnihotri *et al.* (2008)	14.90	74.00	CR-2
13.	Naik *et al.* (2014)	14.50	73.14	AAS9/19
14.	Rostek *et al.* (1993)	5.07	73.88	MD900963
15.	Tiwari *et al.* (2005)	3.70	75.91	SS3827G
16.	Punyu *et al.* (2014)	2.48	78.00	CC2-GCEq2
17.	Saraswat *et al.* (2005)	2.67	78.00	SK 157/4
18.	Agnihotri *et al.* (2003)	6.0	74.00	3101
19.	Ranasinghe *et al.* (2013)	6.21	81.22	K14
20.	Ranasinghe *et al.* (2013)	6.68	81.77	OK-14
21.	Ranasinghe *et al.* (2013)	6.77	80.58	P13
22.	Govil and Naidu (2011)	14.04	82.00	SK218/1
23.	Tripathy *et al.* (2011)	16.27	84.50	SK187/PC33
24.	Kudrass *et al.* (2001)	19.97	90.03	126 KL
25.	Ahmad *et al.* (2000)	9.00	94.28	GC-1
26.	Rashid *et al.* (2007)	12.46	96.04	RC12-344

Table-2: Inferences derived from previous studies

Study	**Core Site**	**Inference**
Saher *et al.* (2007)	western Arabian Sea	Negative calcification temperature during glacial period indicative of weaker ISM.
Sirocko *et al.* (2000)	western Arabian Sea	ISM weakening during Last Glacial Maxima (LGM).
Ishfaq *et al.* (2013)	eastern Arabian Sea	Enhanced productivity ($CaCO_3$ and C_{org} fluxes) during LGM due to intensified NE monsoon.
Thamban *et al.* (2007)	eastern Arabian Sea	High resolution terrigenous contribution during early Holocene suggests intensified ISM.
Rostek *et al.* (1993)	equatorial Indian Ocean	Stronger NE monsoon winds led to enhanced productivity (unsaturated alkenones) during LGM.
Tiwari *et al.* (2006)	equatorial Indian Ocean	Increased strength of Indian Ocean Equatorial Westerlies (IEW) resulted high productivity ($CaCO_3$) during Holocene
Kudrass *et al.* (2001)	northern Bay of Bengal	Holocene witnessed strong ISM with enhanced freshwater influx as exhibited by depleted $\delta^{18}O$

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