The Indian Monsoon and North Atlantic Tele-climatic Controls upon the Arabian Sea High Salinity Water Variability into the Equatorial Indian Ocean during the Last Glacial-Interglacial Transition

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May 10, 2024
This manuscript has been submitted for publication in Paleoceanography and Paleoclimatology journal. It is currently under the process of peer review and will probably modify somewhat before it gets accepted. If accepted, the final version of the manuscript will be available via the "Peer-reviewed Publication DOI" link on the EarthArXiv page.

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Abstract

Paleosalinity reconstructions of the subsurface Equatorial Indian Ocean (EIO) has been carried out using the Mg/Ca and δ¹⁸O records of sub Mixed Layer (ML) dwelling planktonic foraminifera *T. sacculifer* (w/s) from a sediment core SK-312/12 spanning over the last 44 kyr. An assessment of temporal variability in the Arabian Sea High Salinity Water (ASHSW) influx into the EIO during the last glacial-interglacial transition has been obtained. The results provide clear evidence of increased ASHSW influx during the cold glacial period caused by its enhanced formation over the northern AS as a result of intensified North-East Monsoon (NEM) activity. Conversely, a decrease in the ASHSW influx during the warm interglacial period took place as a result of reduced ASHSW production, following an intensification in the South-West Monsoon (SWM) activity. The Heinrich events (H2 and H3) mark distinct signatures of North Atlantic tele-climatic variability resulted by concurrent increases in the NEM activity. The present study is thus unique to report a maiden record of the Indian Monsoon and the North Atlantic tele-climatic controls upon the temporal production and equatorward distribution of ASHSW during the past geologic time periods. The study also acknowledges the ASHSW as an additional marker of the North Atlantic tele-climatic influence over the tropical Indian Oceanic paleoclimate as a maiden historic report.
Keywords: Arabian Sea High Salinity Water (ASHSW), North-East Monsoon (NEM), South-West Monsoon (SWM), North Atlantic, Heinrich, Glacial-Interglacial

Plain Language Summary

Seawater salinity records of subsurface (around 50-90 m water depth) Equatorial Indian Ocean (EIO) was reconstructed during the last 44 kyr. The salinity at the particular oceanic depth is actually contributed by the Arabian Sea High Salinity Water (ASHSW), which originates over the northern Arabian Sea of the Indian Ocean. Enhanced equatorward distribution of the ASHSW essentially depends upon its production at the source region, which is controlled by the Indian Monsoonal Variabilities. While the North East Monsoon (NEM) promotes its enhanced production, the South West Monsoon (SWM) tends to reduce it. The variability observed in the paleosalinity record, thus, represents the variable influence of the Indian Monsoon Strength upon the distribution of ASHSW into the EIO. The records also reveal an additional tele-climatic influence of the North Atlantic climate towards enhancing the ASHSW production through intensifying the NEM activity during the cold paleoclimatic periods named Heinrich 2 (~24 kyr ago) and heinrich 3 (~30-32 kyr ago).
1. Introduction

The Arabian Sea High Salinity Water (ASHSW) is one of the highly saline water masses present in the northern Arabian Sea (AS) over the tropical Indian Ocean (IO) (Han, 1999). The northern AS usually receives a relatively less amount of precipitation from the Indian Monsoon System (IMS) compared to its lower meridional latitudes. The origin of ASHSW is associated with the increase in density of the surface ocean over the northern AS, resulting from intense surface cooling coupled with increased evaporation over precipitation induced by the cold-dry winter monsoon winds (Kumar and Prasad, 1999). After its formation, the core of ASHSW undergoes convective spreading southwards within the upper ~100m depth (Han, 1999), observing a large scale spatiotemporal variability caused by the seasonally changing monsoonal strength and the subsequent changes in the upper oceanic circulations across the tropical IO (Joseph and Freeland, 2005; Prasad and Ikeda, 2002). Present-day water mass studies provide clear evidence of the movement of the ASHSW into the subsurface Equatorial Indian Ocean (EIO), reaching further into the Bay of Bengal (BoB), by the eastward flowing Indian Monsoon Current (IMC) during the summer and fall seasons (Han and McCreary Jr., 2001; Vinayachandran et al., 1999). The production and distribution of the ASHSW across the EIO, is thus intricately linked with the northern Arabian sea surface temperature (SST), wind speed and the upper oceanic circulations of the northern IO, primarily driven by the Indian monsoonal strength variability.
The ASHW produces a potential influence on the regional hydrography and the oceanic biogeochemistry (Zhang et al., 2020) with a significant control upon the intensity and extent of the AS Oxygen Minimum Zone (OMZ), and the bioavailability of nitrogen, which leads to critical changes in the ecological and biogeochemical conditions of the subsurface ocean (Lachkar et al., 2019). Ventilation of high saline Arabian Gulf water has reportedly caused a more than 40% increase in the volume of suboxic waters in the upper ocean of the northern AS, leading to strong intensification of the Oxygen Minimum Zone (OMZ), where the volume of suboxic water has increased by ~5% under 1°C of surface oceanic warming (Lachkar et al., 2019). Salinity variations within the upper ocean also produce vital modifications to the surface oceanic circulations, vertical thermal structure (Fedorov et al., 2004), stratification and heat budget of the upper ocean along with the surface evaporation-precipitation (Maes and O’Kane, 2014).

Paleoclimatic records suggest that the tropical IO has undergone an average SST reduction by 1.5–2.5 °C during the last glaciaion noticing a maximum drop of 3–4 °C during the Last Glacial Maximum (LGM) (Saraswat, 2011; Sonzogni et al., 1998). Study from the eastern AS has indicated the coldest SST (∼ 27°C) during the Marine Isotopic Stage (MIS) 2, and a highest sea surface salinity (∼37.5 ‰) existing for most of the last glacial period, within the 50 ka record. Additionally, the intensity of SWM reached its peak during the Holocene (∼8 ka), marking a ~1 °C
cooling in the SST and a 0.5 ‰ reduction in the sea-surface salinity (Banakar et al., 2010). Thermal variability of tropical IO paleoclimate has distinctly lead to an intensification (reduction) of the south-west monsoon (SWM) (north-east monsoon (NEM)) during the warm climatic periods, but, a contrary reduction (intensification) during the cold ones (Böll et al., 2015; Hong et al., 2018). An intricate link of ISM upon the production and spatial distribution of ASHSW has been well acknowledged from contemporary climatic studies. However, a consequent variability in the ASHSW has not been addressed in the entire history of paleoclimate reconstructions carried out across the tropical Indian Ocean. The matter has developed a significant gap in understanding the joint response of ASHSW to the tropical Indian Ocean paleoclimatic dynamics. It also places a black-spot on the fundamental contributions of ASHSW upon the biogeochemical evolution of the regional upper oceanic hydrodynamics.

The present study is a maiden attempt to investigate the temporal variability of ASHSW influx into the upper EIO during the last glacial-interglacial transition. The study highlights the principal controls of IMS and North Atlantic teleclimatic variability as the major drivers of production and spatial distribution of ASHSW during the past climatic periods.

2. Location and Hydrographic Settings

A sediment core (SK-312/12; 0.0068°N, 65.0048°E and 3750m water depth) situated in a small basin around 300 km south of the transect between the Bao-
Chuan fracture zone and the Carlsberg ridge, from the western central EIO, (Fig. 1) has been taken for this study. A westward flowing South Equatorial Current (SEC), an eastward flowing Indian Monsoon Current (IMC) and a strong western boundary Somali Current (SC) predominate the surface ocean during the South-West Monsoon (SWM) season (Divakar Naidu and Malmgren, 1999). Whereas, the North-East Monsoon (NEM) current flows westward across the basin, carrying the fresher Bay of Bengal (BoB) water into the studied region (Schott et al., 2009). The subsurface ocean below the Mixed Layer (ML) is primarily ventilated by the ASHSW with in the upper 100m water depth (Han and McCrea Jr., 2001; Vinayachandran et al., 1999), whereas, the SubAntarctic Mode Water-Antarctic Intermediate Water (SAMW-AAIW) is the principal contributor to the EIO thermocline along with minor contributions from the Indonesian Through Flow (ITF) (You, 1998). Contributions from terrestrial and riverine inputs are clearly insignificant into the studied region.

3. Material and Methods

3.1. Sample Collection & Processing

Sediment core SK-312/12 was collected from the western central EIO (section 2, Fig. 1) during the GEOTRACES cruise ORV Sagar Kanya in May, 2014. The core was sub-sampled at 1cm interval. Around 30-40 g of bulk sediment from alternate sections were processed to separate the foraminifers from the sediment fraction using hydrogen peroxide (50%, Emplura) and sodium hexa-
Fig. 1: Simplified representation of surface (solid lines) and subsurface (dashed lines) water mass circulations (modified after Han and McCreary Jr., 2001; Schott et al., 2009; You, 1998; Vinayachandran et al., 1999) over EIO at core SK-312/12 (0.0068°N,65.0048°E) (red dot).


The red and green solid lines represent the surface ocean circulations during the south-west monsoon and the north-east monsoon periods respectively.

metaphosphate (10%, w/V) solutions to remove the organics and the clay particles respectively. The solution was ultra-sonicated and sieved through 63μm sized sieve set. The remaining foraminifers were cleaned using ultrapure (Milli-
Q) water, collected in beakers and kept in an oven at ~45°C for complete drying. The dried foraminifers were then sieved through specific size ranges of 150 µm, 250 µm, 355 µm and 425 µm and finally collected into separate vials.

3.2. Chronology

Around 10 mg of cleaned and well preserved foraminifera shells of *Globigerinoides ruber* (*G. ruber*) and *Trilobatus sacculifer* (*T. sacculifer*) were picked up in sub equal amounts from 250-425 µm size fraction for the radiocarbon dating of the surface ML. The samples along with the International Inter comparison carbonate reference standards for radiocarbon (FIRI-C and IAEA C-2) and blank (IAEA-C1) were graphitised using the CHS (Carbonate Handling System) sample processing unit coupled with the AGE-3 Graphitisation unit. Additionally, Primary standards (NBS Oxalic acid-1, NBS Oxalic acid-2), reference standards (FIRI-E, VIRI-R, VIRI-U and IAEA-C6) and blank (Anthracite) were graphitised under the EA (Elemental Analyser) unit coupled with the AGE-3 Graphitisation unit. The graphitized samples were pressed into aluminium targets with copper pins using automated pressing equipment. Radiocarbon measurement was done at PRL AURiS (Physical Research Laboratory Accelerator Unit for Radioisotope Studies (AURiS, Ahmedabad, India), using a compact 1 MeV Accelerator Mass Spectrometer (AMS) (Bhushan et al., 2019a, 2019b).
Radiocarbon ages obtained were normalized and corrected for isotopic fractionation as per standard method (Stuiver et al., 1998; Stuiver and Polach, 1977). The radiocarbon ages were further calibrated with respect to the MARINE20 Calibration curve (Heaton et al., 2020) with a modern reservoir age (ΔR) of -54 ± 65 yr (Dutta et al., 2001; Southon et al., 2002) under the R package “Bacon” (Blaauw and Christeny, 2011) and the Bayesian calendar age chronology was obtained (Table S1). The sedimentation rate of this core varies between 1.1–3.5 cm/ka with an average sedimentation rate of ~ 1.9 cm/ka.

3.3. Oxygen isotopic and Mg/Ca analyses

The planktonic foraminifera species *Trilobatus sacculifer* (*T. sacculifer*) (w/s) typically survives with an average depth (Apparent calcification Depth, (ACD$_{T. sac (w/s)}$)) of ~50 to 80m with in the oceanic water column, across the equatorial regions (Hollstein et al., 2017; Sagawa et al., 2012). The present study, therefore, uses *T. sacculifer* (w/s) as the appropriate proxy to reconstruct the paleo salinity records from the particular sub ML depth over the EIO, which is essentially governed by the ASHSHW influx (Fig. 2).
Fig. 2: Present-day annual mean temperature and salinity profile of upper oceanic water column over core SK-312/12 location (WOA 2018). The zone of ‘Salinity Maximum’ (grey shaded) observed between the water depth of around 50-90 m is essentially caused by the Arabian Sea High Salinity Water (ASHSW) influx into the subsurface Equatorial Indian Ocean (EIO) (Refer Fig. S1). $ACD_{T.\ sacculifer\ (w/s)}$ represents the Apparent Calcification Depth or the Apparent Living Depth of $T.\ sacculifer\ (w/s)$ with in the EIO water column.

Around 50-100 $\mu$g of cleaned unfragmented shells of $T.\ sacculifer\ (w/s)$ (250-355 $\mu$m) were selected from each analysis section. Individual shells were crushed to homogenisation prior to analysis. Isotopic analysis was carried out using the Delta V Isotope Ratio Mass Spectrometer coupled with an automated carbonate preparation device, Kiel IV facility at SILICA lab, IISER Kolkata (Table S2). The CaCO$_3$ standard Z-CARARA (procured from Physical Research Laboratory, Ahmedabad, India) was run as internal and check standard, calibrated via NBS-
18 ($\delta^{18}O = -23.2 \pm 0.1\%$) produced an external precision of $\pm 0.05\%$ (1$\sigma$) (Pillai et al., 2017).

Around 25 numbers of cleaned and unfragmented *T. sacculifer* (w/s) (250-350 $\mu$m) shells were picked up under microscope. Samples were cleaned in successive steps following the protocol developed by Barker et al. (2003), the method for foraminiferal Mg/Ca analysis. Elemental analysis for Ca, Mg, Al, Fe and Mn were carried out with the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) facility at Geosciences division, Physical Research Laboratory, Ahmedabad, India. The international reference limestone standard BCS-CRM 393 (ECRM 752-1) was run after every five samples during the course of the measurement, where a mean value of Mg/Ca = 3.68 $\pm$ 0.01 mmol/mol was obtained against the international consensus value of 3.75 mmol/mol (Greaves et al., 2005) producing an analytical accuracy and precision of $\pm 0.018$ and $\pm 0.004$ respectively. The average ratios of contaminant phases, i.e. Al/Ca, Fe/Ca and Mn/Ca were present well below 0.1 mmol/mol. This clearly assures the efficiency of cleaning method, and the insignificant contributions of Mg into the foraminiferal Mg/Ca records from the clay contaminations, the syn-sedimentary and post-depositional Mn-oxide precipitates, and Mn-rich carbonate coatings, which can potentially overestimate the paleotemperature reconstructions.
3.4. Paleotemperature and paleosalinity reconstructions

Paleotemperature was reconstructed using the species-specific Mg/Ca vs T equation given by Hollstein et al., 2017, as:

\[
\text{Mg/Ca (mmol/mol) = 0.24} \times \exp(0.097T)
\]  

(1)

(where T (°C) stands for temperature), having a standard deviation of ±1.0°C (Anand et al., 2003; Bemis et al., 1998).

The seawater oxygen isotopic record \((\delta^{18}O_{\text{SW}})\) was obtained using the relationship,

\[
T (\text{°C}) = 17 - 4.52 (\delta^{18}O_{\text{Carb}} - \delta^{18}O_{\text{SW}}) + 0.03 (\delta^{18}O_{\text{Carb}} - \delta^{18}O_{\text{SW}})^2
\]  

(2)

given by (Erez and Luz, 1983). The \(\delta^{18}O_{\text{Carb}}\) represents the oxygen isotopic ratio of the foraminiferal carbonate of \(T. \text{sacculifer (w/s)}\), i.e., \(\delta^{18}O_{T. \text{sac (w/s)}}\). The \(\delta^{18}O_{T. \text{sac (w/s)}}\) and \(\delta^{18}O_{\text{SW}}\) are represented in ‰ with respect to VPDB (Vienna Peedee Belemnite) and VSMOW (Vienna Standard Mean Ocean Water) respectively (Table S2).

The paleo \(\delta^{18}O_{\text{SW}}\) record was corrected for the Global Ice Volume (GIV) effect following Waelbroeck et al., 2002. Paleosalinity \((S_{\text{SW}})\) was reconstructed using the \(S_{\text{SW}} \sim \delta^{18}O_{\text{SW}}\) relationship:

\[
\delta^{18}O_{\text{sw}} (VSMOW) = -8.89 + 0.27 \times S_{\text{SW}}
\]  

(3)

given by Srivastava et al., 2007, where S represents the salinity of seawater expressed in terms of Practical Salinity Unit (PSU) (Table S2).
4. Results and discussions

Considering a below Mixed Layer Depth (MLD) habitat for *T. sacculifer* (w/s) (Hollstein et al., 2017), the average core-top paleotemperature record (from five core-top sections spanning the Holocene) obtained using eq (1) has been matched with the present-day average temperature recorded at the MLD (Fig. 2) over the SK-312/12 core location (World Ocean Atlas 2018). Both the records are in good agreement with in the analytical uncertainty of ±1.0°C, confirming the appropriateness of the choice of the paleotemperature equation (1).

The paleosalinity record ($S_{SW}$) obtained shows a variability ranging from 32.01‰ to 37.51‰ with a mean of 34.34‰. The $S_{SW}$ shows distinct trends of variations throughout the core record; (i) an increase during MIS2 upto the Last Glacial Maximum (LGM), (ii) a constant decrease during the Holocene and (iii) salinity peaks during the Heinrich 3 (H3) and Heinrich 2 (H2) events (Fig. 2).

Subsurface water mass circulations in the present-day EIO certainly suggest that the salinity at the MLD over the SK-312/12 region is essentially governed by the ASHSW influx, only. As mentioned earlier, variations in the equatorial influence of the ASHSW is intricately linked to its convective source water formation and distribution, primarily caused by the IMS variability. While, the north-east monsoon (NEM) plays the fundamental role in the formation of dense, highly saline surface water in the northern AS, the south-west monsoon (SWM) imparts
Fig 3: Comparison of paleosalinity ($S_{SW}$) with Indian Monsoon System (IMS) strength variability, along with other proxy records of $T$. sacculifer (w/s). (a) $\delta^{13}$C records of Baoan peat cellulose (from the southeastern edge of the Tibetan Plateau) representing the ISM strength variability (Hong et al., 2018). (b) Paleosalinity record, (c) paleotemperature record, (d) oxygen isotopic record of seawater (with out Global Ice Volume (GIV) correction) and (e) oxygen isotopic record of $T$. sacculifer (w/s) from sub ML depth over core SK-312/12.

A critical contribution by providing a limited precipitation supply into this region. The IMS has witnessed a noted variation in its strength during different paleoclimatic periods.
Fig. 3 represents the variations in the nature of IMS during the last glacial-interglacial transition period, as obtained from δ¹³C records of Baoan peat (Hong et al., 2018). The study clearly depicts increased SWM (counteractively reduced NEW) conditions during the warm interglacial, but reduced SWM (increased NEM) activities during the cold glacial periods. An increase in the SWM strength during the Holocene would subsequently lead to an increase in precipitation and fresh water supply into the northern AS, resulting in freshening and reduction of surface water density over the region. The process would essentially cause a reduction in the magnitude of ASHSW formation. Conversely, an increase in the NEM activity during the glacial period would enhance the formation of ASHSW through increase in surface water density driven by increased cooling and evaporation over precipitation of the surface ocean produced by the north-east monsoonal winds.

5. North Atlantic climatic tele-connection

Distinct increases in paleo S_SW record are also observed during the Heinrich event, H2 and H3 (Fig. 3). The Heinrich events are short spanned 1-2 kyr cold climatic events characterized by massive iceberg discharges (Bond et al., 1993). A number of studies have shown clear evidence of global tele-climatic response of Heinrich events, marked over the tropical paleoclimatic records (Behl and Kennett, 1996; Bharti et al., 2022; Peterson et al., 2000) including the Indian Ocean (Schulz et al., 1998). The IMS has noticeably undergone phases of weakened SWM an
enhanced NEM activities during the H2 and H3 events (Deplazes et al., 2014).

Increases in $S_{SW}$ record during the H2 and H3 can thus clearly be brought about by intensified NEM causing an increase in ASHSW influx into the subsurface EIO following its enhanced production over the northern AS during the subsequent periods. The observed outcomes thereby, provide a first time accountability of the ASHSW as an additional marker of the North Atlantic climatic tele-connection over the tropical Indian Ocean paleoclimate.

6. Conclusions

An assessment of temporal variability in ASHSW influx into the EIO has been carried out through paleosalinity reconstruction of sub ML oceanic depth using the planktonic foraminifera species $T. sacculifer (w/s)$. The results confirm a clear control of IMS over the temporal production and equatorial distribution of ASHSW during the last glacial-interglacial transition. The study also produces strong evidence of North Atlantic tele-climatic controls over the ASHSW variability during the cold Heinrich events, H2 and H3. An increased ASHSW influx into the EIO during the cold glacial periods were caused by its enhanced formation over the northern AS, driven by the NEM intensification. Conversely, a decrease in the equatorial spread of ASHSW was observed during the Interglacial warming, essentially caused by intensification of SWM resulting a subsequent reduction in the production of ASHSW over the northern AS. The present study is a maiden report that accounts the IMS and North Atlantic tele-
climatic variability controls upon the production and equatorward distribution of ASHSW during the past geologic time periods. The study also acknowledges the ASHSW as an additional marker of North Atlantic tele-climatic variability over the tropical Indian Ocean paleoclimate.

Credit authorship contribution statement

Sanjit Kumar Jena: Sample preparation, original manuscript preparation, data curation, visualisation; Ravi Bhushan: Manuscript review, editing and supervision; Partha Sarathi Jena: Data processing; Nisha Bharti: Methodology; A. K. Sudheer: Formal Analysis; Prasanta Sanyal: Formal Analysis; Ajay Shivam: Formal analysis, software; Ankur J Dabhi: Formal analysis, software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to express their thankfulness to the Director, Physical Research Laboratory, Ahmedabad, for his kind support in funding the logistical requirements for this work. We are grateful to the Ministry of Earth Science (MoES), India for providing and funding for the ship time. We truly acknowledge the contributions of the Captain, Crew members and all participants of
the ORV Sagar Kanya Cruise SK-312/12 during the period of cruise and sampling.

**Supplementary Figure**

Figure S1: Temperature-Salinity (T-S) records of major water masses circulating across the upper and intermediate Indian Ocean.

![Characteristic Temperature-Salinity (T-S) records of the major water masses existing across the upper and intermediate Indian Ocean at present. BBW- Bengal Bay Water, ASHSW- Arabian Sea High Salinity Water, IEW- Indian Equatorial Water, SICW- South Indian Central Water, ITF- Indonesian Through Flow, RSPGIW- Red Sea-Persian Gulf Intermediate Water, AAIW- Antarctic Intermediate Water, IIW- Indonesian Intermediate Water (Emery, 2001; Kumar and Prasad, 1999). The grey ‘square’ represents the temperature-salinity record of the ORV Sagar Kanya Cruise SK-312/12 over the period of sampling.](image-url)
‘Salinity Maximum’ zone observed between ~50-90 m depth over the SK-312/12 water column (Fig. 2).

Inference: The T-S record of the ‘Salinity Maximum’ zone observed within the SK-312/12 upper water column (Fig. 2) represents the closest order of approximation with that of the ASHSW record (Fig. S1), thus, suggesting the primary influence of the latter upon the corresponding depth of oceanic ventilation over the studied region.

Data availability

All supporting data will be made available in ‘Pangaea’ repository following the acceptance of the manuscript.

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