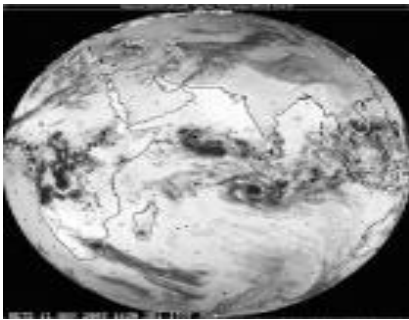


The Late-Pleistocene sedimentation history in the Eastern Arabian Sea: Climate- Weathering-Productivity linkage

**Thesis submitted to the Department of Marine Sciences, Goa
University, Taleigao Plateau, Goa, India, for the degree of
Doctor of Philosophy in Marine Science**



Ms. Anjali R. Chodankar

**Research Supervisor
Dr. Virupaxa K. Banakar**

2004

**National Institute of Oceanography, Donapaula, Goa,
India**

Goa University, Taleigao Plateau, Goa, India

Contents

<i>Certificate of the candidate</i>	<i>i</i>
<i>Certificate of the research supervisor</i>	<i>ii</i>
<i>Acknowledgements</i>	<i>iii</i>
<i>Summary of the work</i>	<i>iv</i>
<i>Abbreviations used</i>	<i>viii</i>
1. Introduction	
1.1. Palaeoclimatology	01
1.2. History of Ice-Age	04
1.3. Oceanographic setting of the Arabian Sea	06
1.4. Study area	10
1.5. Previous work	12
2. Objectives	16
3. Material	17
4. Methods	
4.1. Sediment texture analysis	21
4.2. Grain-size distribution	22
4.3. Calcium carbonate analysis	23
4.4. Sedimentary stable isotope measurements	
4.4.1. <i>Calcite oxygen & carbon isotopes</i>	24
4.4.2. <i>Organic matter and carbon, nitrogen isotopes</i>	29
4.5. Sedimentary alkenone extraction and analysis	30
4.6. Estimation of scavenged-Al and particulate-Mn	31

5. Results	
5.1. Oxygen-isotope age-models and chronology	32
5.2. Sedimentation rates	38
5.3. Sediment texture	39
5.4. Time-series record of sedimentary inorganic components	
5.4.1. <i>Calcium carbonate</i>	42
5.4.2. <i>Oxidised-Mn and scavenged-Al</i>	45
5.5. Time-series record of sedimentary organic components	
5.5.1. <i>Organic carbon and total nitrogen</i>	46
5.5.2. <i>Alkenones</i>	47
5.5.3. <i>Organic carbon-isotopes</i>	47
5.5.4. <i>Sedimentary nitrogen-isotopes</i>	48
5.6. Time-series record of calcite carbon-isotopes	49
6. Discussion	
6.1. $\delta^{18}\text{O}_{\text{G.saccullifer}}$, surface salinity & monsoons	53
6.2. Silicate detritus and summer monsoon rains	67
6.3. Past-monsoon driven productivity fluctuations	
6.3.1. <i>The controversy</i>	74
6.3.2. <i>Biogenic-calcite & productivity</i>	76
6.3.3. <i>Sedimentary organic matter and productivity</i>	79
6.4. Eastern Arabian Sea productivity vis-à-vis global climate	86
6.5. Denitrification and past productivity	87
7. Conclusions	91
8. References	94
Appendix	109

Statement

As required under the University Ordinance 0.19.8 (vi), I state that the present thesis entitled “The late Pleistocene sedimentation history in the Eastern Arabian Sea: Climate-Weathering-Productivity linkage”, is original contribution and the same has not been submitted on any previous occasion. To the best of my knowledge, the present study is the first comprehensive work of its kind for the area mentioned.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Anjali R. Chodankar
(Alias Anjali Y. Volvaiker)

Certificate

This is to certify that the thesis entitled “The Late Pleistocene sedimentation history in the Eastern Arabian Sea: Climate-Weathering-Productivity linkage”, submitted by Mrs. Anjali R. Chodankar (Alias Anjali Y. Volvaiker) for the award of the degree of Doctor of Philosophy in Marine Sciences is based on original studies carried out by her under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any universities or institutions.

Dr. Virupaxa K. Banakar
Research Guide
Geological Oceanography Division
National Institute of Oceanography
Donapaula, Goa, India.

August 2004.

Acknowledgements

First of all I wish to thank the National Institute of Oceanography for providing me an opportunity to work for this thesis while I was working as a Project Trainee. It is indeed a great gesture from this esteemed institution, which supports several young students who wish to improve their qualification while working for various scientific programs on contract. The former director Dr. E. Desa was kind enough to permit me to register for the Ph.D. and to utilize the facilities. The friendly and supporting attitude of several NIO-members has helped me to accomplish this work.

No words would express my deep sense of gratitude to Dr. Virupaxa Banakar, who has been more a guide than a simple supervisor. He not only introduced me to this fascinating subject of palaeoclimate but also guided me efficiently throughout. He has been a smiling source of inspiration and a tough taskmaster.

The encouragement and support by senior colleagues Drs. Parthiban, Nigam, Pattan, Savita Kerkar, Ramaiah, Marathe, Divakar Naidu and Mudholkar and my friends Hilda, Rajani, Avina, Anjelina, Ranjita, Velina, Poonam, Usha etc, while on cruise for sampling and in lab for analytical work gave me lot of strength to accept challenges in advanced marine research work. I sincerely thank Drs. N. B. Bhosle, M. V. S. Guptha and A. L. Paropkari for patiently reading the draft thesis and constructive suggestions. The discussions with Dr. Satish Shetye were of great help.

The help of professors Tadamichi Oba, M. Yamamoto, and Dr. T. Kuramoto of the Hokkaido University, Japan in obtaining the stable isotope and organic component data and Dr. V. Ramaswami in obtaining grain-size data on laser particle analyzer is sincerely acknowledged. Dr. B. Chakraborty helped me to take the final prints of this thesis.

When the part of this work was selected (out of over 1100 papers submitted) for the International Young scientists Global Climate Change Conference-2003 at Trieste, Italy as one of the fifty invited papers by the START Secretariat (USA), it was a nice feeling and exciting experience to present this work in front of several experts in the field. I sincerely thank the START for that opportunity. I gratefully acknowledge the EMR, CSIR, New Delhi for awarding me with SRF.

The encouragement and guidance by my co-supervisor Prof. U. M. X. Sangodkar of the Goa University and the FRC member Dr. N. H. Hashimi, and time-to-time administrative and scientific guidance by Prof. G. N. Nayak, HOD of Marine Sciences, Goa University were of great help.

Last but not least, the sustained love and support of my parents, husband Ritesh, uncles, aunts, brothers, sisters, and in-laws gave me energy to complete this work. Although just few months old, my young daughter lovely Eesha did not trouble me much while finalizing the thesis and has been additional source of energy for me in pursuing the challenging tasks of oceanographic science.

Anjali R. Chodankar.

Summary

This thesis is aimed to understand the response of the Indian monsoons and associated biogeochemical processes in the Eastern Arabian Sea (EAS) to the past climate change. The EAS bordering the western coast of India is an important region to understand the past climate variation because the region has been shown to contain valuable sedimentary records relating to evidences of regulating glacial-interglacial climate. However, the palaeoclimate studies from this region are very limited unlike the western part of the basin. The role of low-latitude tropical oceans gains importance in global climate change as the southern high-latitude oceans failed to provide unambiguous evidences for regulating the glacial-interglacial climate. Few intriguing observations such as the Indian Monsoons providing important feedback for global climate change, Arabian Sea hosting high productivity and intense denitrification, and the past changes in the Indian Monsoons correlating with the northern high latitude Dansgaard-Oeschger type rapid climate fluctuations render the Arabian Sea as one of the very significant oceanic areas for understanding the feedbacks for the past climate change.

The EAS is a complex and dynamic water body experiencing intense summer monsoons with well-defined precipitation gradient along the west coast of India. The moderate to high productivity, intense oxygen minimum zone, higher accumulation of organic matter and terrigenous input from the Deccan Rivers characterize the EAS. Another peculiar feature of this region is the presence of low-salinity tongue developed due to inflow of the low salinity water from the Bay of Bengal along the western continental margin of India. The structure of the low-salinity tongue is determined by the relative intensity of the Poleward Coastal Currents (PCC) and the northern Arabian Sea high salinity water, which in turn are dependent upon the summer monsoon intensity and evaporation-precipitation balance in the region. In addition, the previous studies related to the monsoon driven productivity changes in the Arabian Sea have yielded contrasting results. In that, the Western Arabian Sea sediments have recorded interglacial high productivity while the eastern region sedimentary records have indicated glacial high productivity. Those studies were relying mostly on individual proxy records. If one has to comprehensively understand the climate forcing on marine regime, it is necessary to look in to the complex interlinks of the multitudes of marine processes. This can be

achieved only by studying strictly paired multiple proxies from the intact sediment repository. Therefore, the objectives of the thesis are centered on a theme of comprehensive understanding of the EAS response to the past climate change utilizing multi-proxy investigations, which are listed in Chapter 2.

Three sediment cores were collected from different water depths (200 m - 2500 m) in the EAS covering northern and southern region. The sediment texture was determined using standard pipette analyses and the sediment grain-size parameters were obtained using the Laser Particle Analyzer. The calcium (for carbonate estimation), scavenged-Al and -Mn were analyzed on Perkin-Elmer ICP-AES. All the above measurements were carried-out at the Geological Oceanography Division of the National Institute of Oceanography, Goa. The upper mixed layer dwelling planktonic foraminifera *G.sacculifer* tests were picked under the microscope from the sub-sections (2 cm intervals) of the >4 m long sediment cores. These *G. sacculifer* tests were utilized to measure the oxygen and carbon isotopes and the sedimentary organic-carbon and nitrogen isotopes were measured on stable isotope Mass-Spectrometry facility of the Hokkaido University, Japan. The *G.sacculifer* $\delta^{18}\text{O}$ variation with the core depth was tuned to the SPECMAP to obtain the chronology for the cores.

The thesis is divided into eight chapters, viz., 1) Introduction 2) Objectives 3) Materials 4) Methods 5) Results 6) Discussion 7) Conclusions and 8) References. The Chapter 1 describes the evolution and development of the palaeoclimatology, oceanographic and climatic settings of the study region, previous studies and unresolved climate related controversies existing for the region. The Chapters 3 and 4 are devoted to provide the details of samples and the methods used for obtaining the required data. In the Method section a brief description of the instrumentation and principles also are given. The Chapter 5 lists the results obtained and several age versus data plots. In this chapter the details of age-model and chronology are also included. The discussions and interpretations in light of the previous studies are presented in Chapter 6 with the support of few schematic models and figures. This chapter also contains a brief note on the EAS productivity vis-à-vis the past global climate scenario. The important observations and the interpretations with respect to the climate forced past changes in the Indian monsoons, coastal current intensity, Deccan River strength, marine productivity and denitrification are presented as Conclusions in the Chapter 7. Most of the relevant references available until date are cited in the text at appropriate places and

are listed in the Reference Chapter. At the end of the thesis, the raw data is included as an Appendix.

The continental shelf core covers the Holocene-Last Glacial Period, where as, the two deep-water continental slope cores encompass over 100,000 years sedimentation history enabling me to explore the impact of the climate change on the EAS region both on high-resolution (for Holocene-Last Glacial Period) and on low resolution (Glacial-Interglacial). In the present study a first-time attempt is made to reconstruct the past variation in the summer monsoon intensity utilizing the changes in the characteristic salinity structure of the EAS (i.e., the low-salinity tongue). The global ice-volume corrected (residual)- $\delta^{18}\text{O}_{G.sacculifer}$ contrast between the northern- and the southern-cores from deep-EAS is used as a tool for reconstructing the past salinity structure of the low-salinity tongue or the variation in the PCC. It is evident from the fluctuations in the time-series record of the residual- $\delta^{18}\text{O}_{G.sacculifer}$ contrast that a definite linkage exists between the intensity of the summer monsoons and the changes in the surface salinity gradient in the EAS due to variation in the PCC. Significant weakening of the summer monsoons during the LGM and intensification during the last warm period (Marine Oxygen Isotope Stage 5) compared to the Holocene is evidenced by the respectively increased and decreased north-south salinity gradients within the low-salinity tongue of the EAS. The disappeared low-salinity tongue during the LGM is interpreted as due to the reduced alongshore pressure gradient resulting from the broken communication between the EAS and the Bay of Bengal. The salinity gradient reconstruction also exhibits high amplitude fluctuations within 4 to 5 ky temporal-band suggesting general instability in the Indian summer monsoons.

The present study demonstrates higher productivity during the Last Glacial Period when the summer monsoons were significantly weaker and winter monsoons stronger. This is in contrast to the observation made in the western Arabian Sea in general and Oman upwelling cell in particular. The multi-proxies from a single deep-water core of the study region provide convincing evidences to propose the glacial high-productivity hypothesis. It is proposed that, a) the collapse of the inter-basin communication between the high salinity Arabian Sea and the low salinity Bay of Bengal weakened the mixed layer stratification, b) the weakened mixed layer stratification led to the increased deep-water nutrient injection in to the photic-zone, and c) the glacial intensification of the winter winds provided adequate limiting micro-nutrient 'iron' derived from the lateritic and basaltic soils of the Deccan region. All the above might have

culminated in increasing the marine productivity during the coldest climate of the Last Glacial Period. This part of the present study is the salient feature of the thesis and appears to support the newly emerging evidences of glacial high productivity in regulating the global climate.

The intense OMZ in the Arabian Sea is believed to induce significant denitrification, which is the source for nitrous oxide. The record of the past 100 ky water column denitrification is reconstructed utilizing the sedimentary $\delta^{15}\text{N}$. Interestingly, the EAS denitrification record superimposes the previously published records from the western, central, and northeastern Arabian Sea both in timing and amplitude of variation. This homogeneity in the past $\delta^{15}\text{N}$ across the entire basin having significantly different modern productivity patterns is puzzling. Secondly, reduced denitrification during the last glacial period when the productivity was higher than the Holocene warranted new explanation. An attempt is made in the present thesis to provide reasonable mechanism for the above de-coupling of the productivity and denitrification in the glacial-EAS. The glacial intensification of the winter winds is invoked to have forced effective ventilation of the EAS-thermocline feeding the OMZ due to intensified deep winter mixing, thus satisfying the increased demand of oxygen during elevated productivity period. The deep-winter mixing is evident in the modern times and responsible for the ventilating the Arabian Sea thermocline. The enhanced glacial productivity on one hand and increased supply of the oxygen to the OMZ-depth due to increased ventilation during the coldest winters of the glacial time appear to have forced the observed decoupling of those intimately related processes. The cross-basin homogeneity in the temporal-trends of the denitrification could be explained by intense horizontal mixing of both thermocline and mixed layer due to vigorous seasonally reversing circulations in the basin.

Finally it is concluded that, the studied sediment cores effectively preserve the records of past variation in biogeochemical processes in response to the climate forced changes in the Indian monsoon system. The past changes in the salinity structure of the low-salinity tongue in the EAS could be a faithful proxy for the summer monsoon reconstructions. The glacial-high productivity and low denitrification may provide new insight to understand the global climate change on glacial-interglacial time-scale. Thus the present work brings out the interlink between the climate forcing-monsoon system-weathering-productivity recorded in the sediments of the Eastern Arabian Sea with well-defined clarity thus achieving the objectives of the proposed work.

Although the work presented here provides comprehensive understanding of the linkage between the past-climate, Indian monsoons, continental weathering and marine productivity, but may not answer all the complex questions related to oceanic response to climate change, as the subject in itself is extremely vast. However, the above observations/interpretations may be important to explain the glacial-low and interglacial-high atmospheric $p\text{CO}_2$. In that, if the biological pump was weak in the glacial southern oceans, then the tropical productivity must have to be increased to account for the reduced glacial atmospheric- CO_2 . One of such regions may be the Eastern Arabian Sea!

(The thesis contains around 125 pages, is supported by 29 composite figures, two cartoons, four tables, inserted at appropriate places in the text, over 150 references to the previous works, and one appendix)

Abbreviations used in this thesis

EAS	Eastern Arabian Sea (The study region in western Indian Margin)
BOB	Bay of Bengal (The main low-salinity water source to the EAS)
LGP	Last Glacial Period (Immediate past cold event spanning 24Ka-11Ka)
LGM	Last Glacial Maximum (Immediate past coldest earth surface ~18Ka)
E-P	Evaporation minus Precipitation (Indicator of moisture balance)
ASHSW	Arabian Sea High salinity Water (Forms in northern Arabian Sea)
PCC	Poleward Coastal Current (BOB low-salinity water tongue in EAS)
SMC	Summer monsoon Currents (Flow towards equator & east or BOB)
WMC	Winter Monsoon Currents (Flow towards Arabian Sea from BOB)
MIS	Marine Oxygen Isotope Stage (Defines the climate events)
LAD	Last Appearance Datum (Time or depth of disappearance of any species from sedimentary record)
Ky	Thousand Years (Time unit used for Quaternary)
Ka	Thousand Years Before Present (Unit of time in to the past)
Ma	Million Years Before present (Unit of time in to the past)
YTT	Youngest Toba Tuff (A mega eruption in Indonesia around 72 Ka. Believed to have global impact and used as a key-point in late Quaternary chronology)
OM	Organic Matter (Sediment component derived largely from the biological activity in the upper ocean)