

**COUPLING BETWEEN THE NORTH INDIAN  
OCEAN AND THE MONSOONS**

**(A MODEL BASED STUDY OF THE THERMAL STRUCTURE CYCLING  
IN THE CENTRAL ARABIAN SEA)**

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**BY**

**RABINDRA KUMAR NAYAK**

**NATIONAL INSTITUTE OF OCEANOGRAPHY  
COUNCIL OF SCIENTIFIC AND INDUSTRIAL RESEARCH  
DONA PAULA. GOA. INDIA**

**2005**

*to my parents*

## **CERTIFICATE**

This is to certify that the thesis entitled “**Coupling between the North Indian Ocean and the Monsoons**” submitted by **Mr. Rabindra Kumar Nayak** for the award of the degree of Doctor of Philosophy in Physics is based on his original studies carried out by him under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

Place: Dona Paula

Date:

**Dr. S. R. Shetye**

Research Guide

Director

National Institute of Oceanography

Dona Paula-403 004, Goa, India.

## STATEMENT

As required under the University ordinance 0.19.8 (vi), I state that the present thesis entitled “**The coupling between the North Indian Ocean and the Monsoons**” is my 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 from 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.

R. K. Nayak

*National Institute of Oceanography, Goa*

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# Synopsis

The ocean plays a significant role in determining the Earth's climate and weather through its interaction with the atmosphere. Since it is the radiation from the Sun heating the Earth that drives motion in both these fluids, an understanding of climate and weather, and how they evolve, necessarily requires an understanding of how energy is transported within, and exchanged between, the ocean and the atmosphere. The Indian Ocean is a unique environment having very special dynamics and thermodynamics due to its small size and geographical location (i.e. a tropical basin having no connection with the northern polar seas). The near-surface circulation of the North Indian Ocean (NIO) is driven by the seasonally reversing winds associated with the monsoons. The NIO in turn provides the moisture and energy to drive the summer monsoon. Hence, the ocean and the atmosphere are coupled — they work together to create the monsoon system.

The Arabian Sea of the NIO is an active region of the air-sea interaction processes and plays a major role in driving the monsoon system over the Indian subcontinent. Two important issues about the Arabian Sea have to be noted. (1) The annual evolution of the near-surface layer thermal structure undergoes a unique biannual cycle: the temperature decreases during the monsoonal periods (winter and summer) and it increases during the inter-monsoonal periods (spring and autumn). This is in contrast to the annual march of the near-surface layer thermal structure over most of the world oceans, which do not undergo a summer cooling. (2) The central Arabian Sea is a region of net heat gain across the air-sea interface over a year. It is thus of interest to determine how the heat is transported and ultimately removed from the region.

At small time scales as well as on an annual cycle, the heat budget is a delicate balance between various concurrent processes, namely heat exchange at the surface, turbulent mixing, and horizontal and vertical advection. To quantify these processes, time-series of high frequency observations of both the atmosphere and the ocean are required. Such data, over a full annual cycle, have been lacking for a long time, and the numerous studies carried out in the past to examine the above two issues have been based on climatologies. Thus, there has been some uncertainties regarding the role of local air-sea interaction versus ocean processes in the observed annual evo-

lution of upper ocean properties and the heat balance of the Arabian Sea as a whole. Recently, a field study of moored-array observations was carried out in the central Arabian Sea at (61.5° E, 15.5°N) during October 1994 to October 1995 under the US Joint Global Ocean Flux Studies (JGOFS) programme with the aim of quantifying the contributions of various processes to the annual evolution of the upper ocean thermal structure. An accurate, year-long, high frequency, concurrent time-series data of atmospheric-forcing fluxes and upper ocean response thus became available.

In the recent past, these data were used to describe the temperature evolution and to estimate the contribution of the various terms of the heat budget. The difficulty with such an approach is that all processes are at work simultaneously. Its success thus rely on accurate observation of each process. A concurrent fruitful approach is to use a model, to predict explicitly each process. The observations are used to force the model as well as to constrain or validate its predictions.

A critical feature of the above time-series, is that the high frequency data is essentially available at a single point. The vertical dimension is thus strongly privileged. This naturally calls for the use of a one dimensional mixed-layer physics model. To account for horizontal and vertical advection, such a model has to be forced with the estimates of the corresponding contributions.

In view of the above, this thesis has three goals. The first goal is to achieve a proper simulation of the seasonal cycle of the upper ocean thermal structure in the central Arabian Sea at the location of JGOFS moored-array observations. For this an upper-ocean thermodynamical model will be forced with atmospheric fluxes at the surface and advective heat fluxes will be prescribed in order to correct the prediction. The second goal is to use the model simulation to achieve a diagnostic of the processes contributing to the seasonal heat budget. The third goal is to examine the sensitivity of the thermal structure to auxiliary parameters that are not generally accounted for (these include salinity and biomass concentration), and to various surface forcing fluxes: momentum fluxes (wind stress), heat fluxes (fluxes of solar radiation and infrared radiation, and turbulent latent and sensible heat fluxes).

After presenting the introduction of the thesis in chapter 1, a brief overview of the ocean-atmosphere coupled system with emphasis on the NIO, the background knowledge for the present study, is presented in chapter 2.

The data and methods used in the thesis is described in chapter 3. To examine the role of various intervening processes in controlling the upper ocean thermal structure in the central Arabian Sea, a 1-D mixed-layer model based on turbulent closure scheme is forced by atmospheric fluxes and advective heat fluxes over the one-year period of the JGOFS time-series starting from

mid-October 1994 in the central Arabian Sea at (61.5°E & 15.5°N). Atmospheric forcing data are available from the moored array observations. The horizontal advective contributions at the study location are available from two different sources. The first estimate is based on local *in situ* measurements. The second estimate is based on optimally interpolated satellite SST field and *in situ* currents. The vertical velocity, as in all oceanography problem, poses a challenge. Two possible approaches have been considered for the diagnostic analysis. In the first approach, the model was used to predict the temperature profile (using atmospheric fluxes and estimates of horizontal and vertical advection). In the second approach, the observed temperature profiles (and atmospheric fluxes and estimates of horizontal advection) were used to force the model in order to predict the vertical velocity.

Several numerical experiments, using the above two approaches, are described in chapter 4. Besides the main experiments, several additional experiments were also performed for two purposes: (i) to support the analysis of the results obtained from the main experiments, and (ii) to examine the role of auxiliary parameters (salinity and biomass) in the seasonal evolution of upper-ocean temperature. The model-based heat-budget analysis for the four monsoon seasons: winter, spring, summer, and autumn has been carried out in chapter 5.

The thesis is concluded by summarizing the results, and by describing outlines of some future research areas where the present study can help. The following are the important conclusions of the thesis.

(1) Vertical advection is an important process, as important as atmospheric fluxes and horizontal advection, throughout the year in controlling the upper ocean thermal structure and the heat budget of the central Arabian Sea.

(2) The general trends of ML deepening and SST cooling in the central Arabian Sea during the NE monsoon are due to buoyancy driven convective entrainment mixing, whereas the trends of ML deepening and SST cooling during the SW monsoon are due to both wind driven mixing and buoyancy driven convective mixing. However, the observed trends of ML and SST during the whole year can only be reproduced when all the intervening process are accounted for: advection together with atmospheric fluxes.

(3) Ocean dynamics plays a primary role in controlling the thermodynamics of the upper ocean in the central Arabian Sea, whereas salinity and phytoplankton biomass concentration evolution do not have a significant control over the thermal structure.

(4) Some results of the present study have their validity limited by the uncertainties in Fischer-based horizontal advective heat fluxes. The deployment of a four/five mooring system to quantify



the contributions of horizontal variability is believed not to be satisfactory as far as quantitative estimation is concerned. The information obtained from the central mooring in combination with satellite altimeter imagery proves to be at least as good, and may be better.

At the end of this thesis, we do not know whether the conclusions obtained for the central Arabian Sea are still valid in other parts of the Arabian Sea. This issue still remains an open question. This can be answered by achieving similar model-based diagnostic studies or by carrying out a basin scale study using a 3D model.

This model can be used for studies similar to those presented in this thesis to understand the eastern and southeastern Arabian Sea, where time-series observation were carried out during the Arabian Sea Monsoon Experiment (ARMEX) during 2002–2003.

Thermodynamics of the ocean influences the biogeochemical system of the ocean environment. Another perspective is to couple a biogeochemical model to an upper ocean thermodynamical model to perform a simulation of carbon and nitrogen fluxes along an annual cycle in the central Arabian Sea.

# Chapter 1

## Introduction

The ocean plays a significant role in determining the Earth's climate and weather through its interaction with the atmosphere. Since it is the radiation from the Sun heating the Earth that drives motion in both these fluids, an understanding of climate and weather, and how they evolve, necessarily requires an understanding of how energy is transported within, and exchanged between, the ocean and the atmosphere. The Indian Ocean (see Fig. 1.1) is a unique environment having very special dynamics and thermodynamics due to its small size and geographical location (i.e. a tropical basin having no connection with the northern polar seas). The near-surface circulation of the North Indian Ocean (NIO) is driven by the seasonally reversing winds associated with the monsoons. The NIO in turn provides the moisture and energy to drive the summer monsoon. Hence, the ocean and the atmosphere are coupled — they work together to create the monsoon system. A brief overview of this system is presented in sections 2.1 and 2.2.

The Arabian Sea, the western half of the NIO (see Fig. 1.2), is an active region of air-sea interaction processes and plays a major role in driving the monsoon system over the Indian subcontinent. Two important issues about the Arabian Sea have to be noted. (1) The annual evolution of the near-surface layer thermal structure undergoes a unique biannual cycle: temperature decreases during the monsoonal periods (winter and summer) and increases during the inter-monsoonal periods (spring and autumn). This is in contrast to the annual march of the near-surface thermal structure in most of the world ocean, which do not undergo summer cooling. (2) The central Arabian Sea is a region of net heat gain across the air-sea interface over a year. It is thus of interest to determine how the heat is transported and ultimately removed from the region.

At small time scales as well as on an annual cycle, the heat budget is a delicate balance between various concurrent processes, namely heat exchange at the surface, turbulent mixing, and horizontal and vertical advections. To quantify these processes, high-frequency time-series obser-

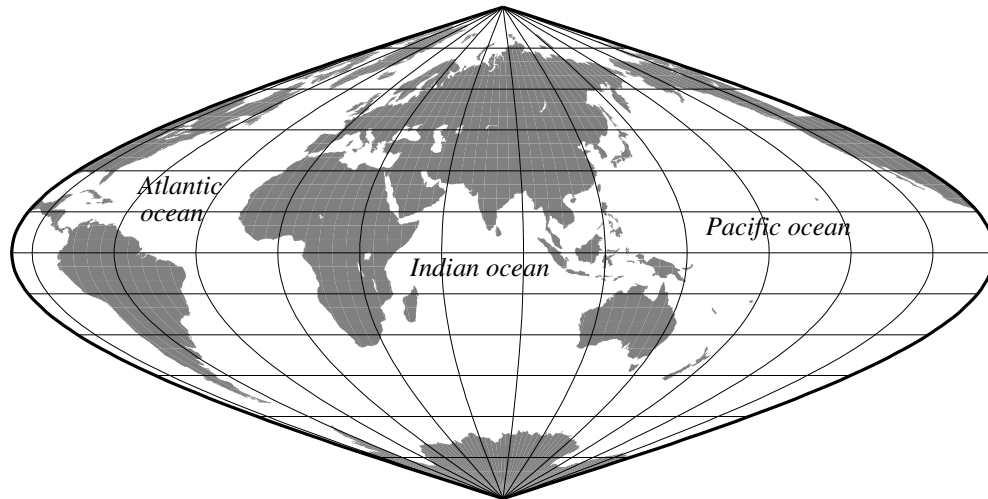


Figure 1.1: The geography of the Indian Ocean. The zonal extent of the Indian Ocean is much less than that of the Pacific or the north Atlantic. Its southern boundary is arbitrary, but is chosen to distinguish it from the Antarctic, or southern, Ocean. Unlike the Pacific and the Atlantic, the Indian Ocean is bounded in the north by Asia; this makes it a tropical basin. This has profound consequences for the meteorology and oceanography of this region: the land-ocean contrast forces seasonally reversing winds, the monsoons, over the north Indian Ocean, unlike in the north Atlantic or the north Pacific.

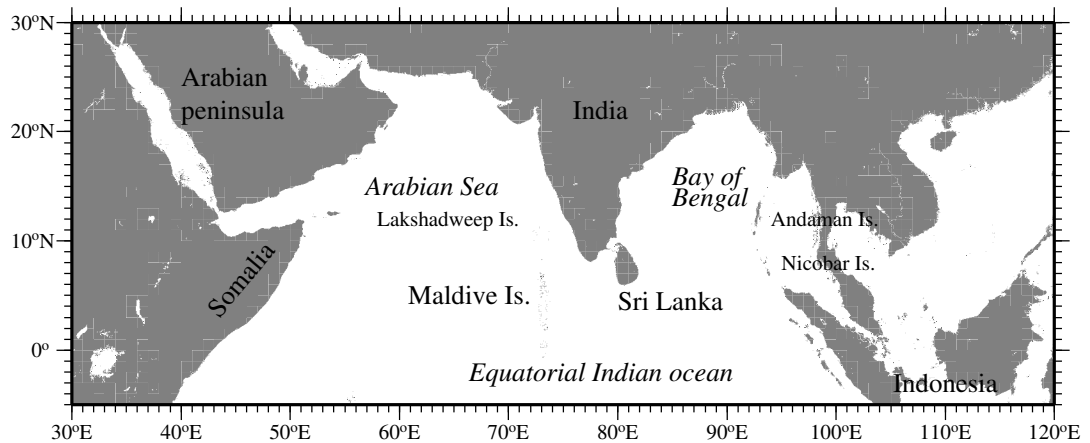


Figure 1.2: The domain of the North Indian Ocean (NIO). The Indian subcontinent divides the NIO into two semi-enclosed tropical basins, the Arabian sea and the Bay of Bengal.

variations of both atmosphere and ocean are required. Such data, over a full annual cycle, have been lacking for a long time, and the numerous studies carried out in the past to examine the above two issues have been based on climatologies (see section 2.2.2). Thus, there has been some uncertainty regarding the role of local air-sea interaction versus ocean processes in the observed annual evolution of upper ocean properties and the heat balance of the Arabian Sea as a whole.

Recently, a field study was carried out during October 1994 to October 1995 in the central Arabian Sea as a part of the US Joint Global Ocean Flux Studies (JGOFS) programme with the aim of quantifying the contributions of various processes (surface forcing, horizontal and vertical advective processes) to the annual evolution of upper ocean thermohaline structure in the Arabian Sea (see Fig. 1.3). The location of the moorings, centred at (61.5° E and 15.5°N) was selected for its proximity to the climatological axis of the atmospheric Findlater Jet (Findlater [1]) (the area of strongest surface forcing) and for its distance from the complicating effects of the coast. An array of five moorings was deployed, forming a square of approximately 50 km on a side with a fifth mooring located in the centre. Surface meteorological and sub-surface oceanographic instrumentation mounted on the central mooring yielded the first concurrent, high-quality record of atmospheric forcing and upper-ocean response over a monsoonal cycle (Weller et al. [2] and Weller et al. [3]). Three of the four corner moorings provided temperature profiles over most of the study period. Using the same time-series, Fischer et al. [4] estimated the heat fluxes due to horizontal advection in the upper 125 m layer using the current measurements on the central mooring and the horizontal temperature gradient estimated from the combinations of all mooring data.

These data were used to describe the temperature evolution and to estimate the contribution of the various terms of the heat budget (Weller et al. [3]; Fischer et al. [4]). The difficulty with such an approach is that all processes are at work simultaneously. Its success thus relies on accurate observation of each process. An alternative approach is to use a model to predict explicitly each process. The observations are used to force the model as well as to constrain or validate its predictions.

A critical feature of the above time-series is that the high-frequency data are essentially available at a single point. The vertical dimension is thus strongly privileged. This naturally calls for the use of a one-dimensional mixed-layer physics model. To account for horizontal and vertical advection, such a model has to be forced with estimates of the contributions of these processes.

In view of the above, this thesis has three goals. The first goal is to achieve a proper simulation of the seasonal cycle of the upper ocean thermal structure in the central Arabian Sea at the location

of JGOFS moored-array observations. For this an upper-ocean thermodynamical model will be forced with atmospheric fluxes at the surface and advective heat fluxes will be prescribed in order to correct the prediction. The second goal is to use the model simulation to achieve a diagnostic of the processes contributing to the seasonal heat budget. The third goal is to examine the sensitivity of the thermal structure to auxiliary parameters that are not generally accounted for (these include salinity and biomass concentration), and to various surface forcing fluxes: momentum fluxes (wind stress), heat fluxes (fluxes of solar radiation and infrared radiation, and turbulent latent and sensible heat fluxes).

The thesis is divided into five chapters (including this introduction). A brief overview of the ocean-atmosphere coupled system (with emphasis on the NIO), the background knowledge for the present study, will be presented in chapter 2. (A reader desirous of going straight to the new results may skip this chapter.) The data and methods used in the thesis will be described in chapter 3. Several numerical experiments are carried out to simulate the thermal structure at the moored-array location. These experiments and their results form the subject of chapter 4. The heat-budget analysis (based on our simulations) are presented in chapter 5. The final chapter provides concluding remarks.

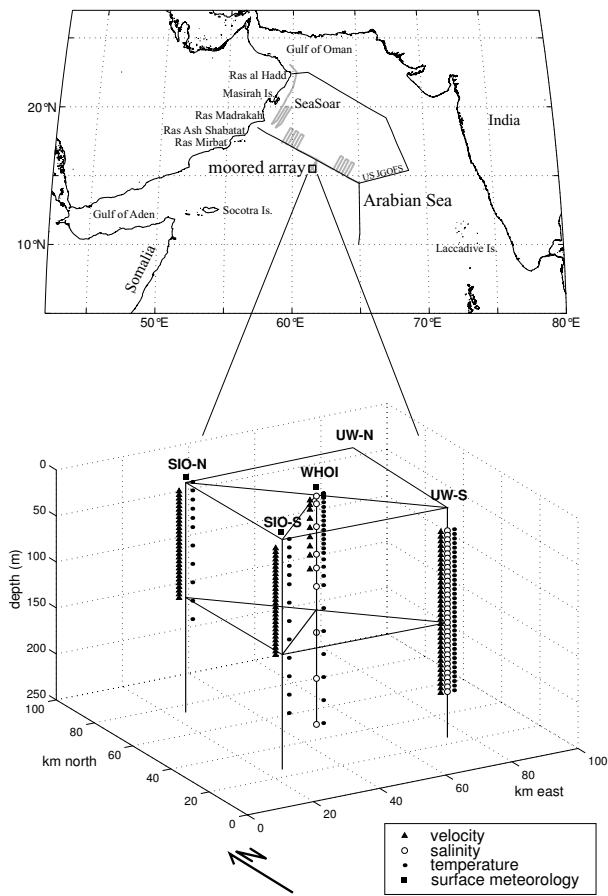


Figure 1.3: Location of Arabian sea moored-array observations during October 1994 to October 1995 (adopted from Fischer et al. [4])