# Modelling and observations of upwelling along the southwest coast of India and its intrusion into the Bay of Bengal, during summer monsoon

**Mary Swapna George**

Dissertation for the degree of Philosophiae Doctor (PhD)
in Physical Oceanography

Geophysical Institute
University of Bergen
Norway

Submitted: October 2014

Dissertation date: 19 January 2015

# Acknowledgements

All thanks and praises to God Almighty who enabled me to complete my thesis.

I am extremely grateful to my main supervisor Ola M. Johannessen and co-supervisor Laurent Bertino for their patient support and guidance, without which this thesis would have never materialized.

My sincere thanks to Dr. Ajith K. Joseph for his continuous support and assistance during my research. Valuable comments and suggestions from Dr. P. V. Joseph and Dr. Annette Samuelsen are greatly acknowledged.

I am grateful to Trond Mohn C/O Frank Mohn AS as well as Nansen Scientific Society and Nansen Centre, India (through INDO-MARECLIM project), for the funding received to carry out this research work.

Thanks to François and Knut-Arild for the help I received from them in setting up HYCOM. I thank the wonderful co-operative group of colleagues and friends at the Nansen Center, Bergen and also acknowledge all my colleagues at Nansen Centre, India. Heartfelt thanks to my friends in Bergen for their cheerful company and nice memories, which made life easier in a city so far away from home. Tusen takk Susan and Rajuchayan!

Nisha and Sajini, without your prayers and support I wouldn´t have made it. Thank you both for always being there for me, especially during the stressful times when it all seemed lost.

Finally but most importantly, none of this would have been possible without the love and patience of my family. I thank Daddy, Mummy and Chachu for their goodwill, encouragement, blessings and prayers. Thanks also to my dear cousins for their constant support and prayers.

# Preface

This thesis titled "**Modelling and observations of upwelling along the southwest coast of India and its intrusion into the Bay of Bengal, during summer monsoon**" is submitted for the degree of Philosophiae Doctor (PhD) in Physical Oceanography at the Geophysical Institute, University of Bergen, Norway. The work was carried out at Mohn-Sverdrup Center, Nansen Environmental and Remote Sensing Center (NERSC), Bergen and also during the last one and half year, at the Nansen Environmental Research Centre India (NERCI), Kochi, India. The thesis consists of an introductory part, where the motivation for this work is presented – giving a brief review of the previous papers dealing with the thesis topics, a summary of the three papers and conclusions - followed by the three papers, which forms the main thesis work. The three papers of my thesis are the following:

**Paper I** Validation of a hybrid coordinate ocean model for the Indian Ocean, **George, M. S.**, L. Bertino, O. M. Johannessen and A. Samuelsen, *Journal of Operational Oceanography*, 2010, 3(2), 25-38

**Paper II** Upwelling along the southwest coast of India during summer monsoon: Observations and Modelling, **George, M. S.**, L. Bertino, A. Samuelsen, K. A. Joseph and O. M. Johannessen, to be submitted

**Paper III** Modelling and observational study of the intrusion of Cold Pool into the Bay of Bengal in association with the summer monsoon, **George, M. S.**, P. V. Joseph, K. A. Joseph, L. Bertino and O. M. Johannessen, to be submitted

The work was funded by a grant from Trond Mohn, c/o Frank Mohn AS and a grant of CPU time from the Norwegian Supercomputing project NOTUR was also used. Grants from Nansen Scientific Society and EU-FP7 project no. 295092, INDO-MARECLIM were used while working at NERCI.

# Contents

# Abstract

Coastal upwelling regions are among world´s most productive areas, with high levels of primary productivity and fishery potentials. The southwest coast of India is a classic example of such an upwelling system during the boreal summer monsoon. By using a numerical model based on the Hybrid Coordinate Ocean Model (HYCOM) and observational data sets, this upwelling along the southwest coast of India and the associated Cold Pool that forms during summer monsoon are examined in detail. In the first paper, the model was validated for the north Indian Ocean using available *in situ* and satellite observations. The model simulation of the circulation patterns of the north Indian Ocean matched well with the observations. The surface and subsurface features were also simulated well by the model. Therefore it was concluded that it could be further used as a tool to study the upwelling system and its associated characteristics. Paper 2 analyses the interannual variability of upwelling along the southwest coast of India during a period of ten years from 2001 to 2010. The strong monsoon winds over the Indian Ocean have an impact on the circulation of the region. The alongshore component of the wind along the southwest coast of India strengthens during the summer monsoon. The influence this alongshore wind stress has on the upwelling along the coast is examined and found to be having a moderate correlation with the observed cooling. The study also implied the importance of remote forcing on determining the variability of upwelling in the region. The Summer Monsoon Current (SMC) carries a part of upwelled cold waters that form along the southwest coast and the locally upwelled waters from the southern tip of India into the Bay of Bengal. The final paper addresses this Cold Pool intrusion into the Bay of Bengal. During the break phases of Indian summer monsoon, the surface winds shifts southward and becomes stronger south of India and Sri Lanka. We examine a new hypothesis that enhanced open ocean upwelling occur in the Cold Pool region during these break phases, owing to the wind pattern and the study confirmed that this hypothesis is true. The analyses from the papers also proved the potential of HYCOM model to be developed into a forecasting tool for the study region.

# List of publications

1. **George, M. S.**, L. Bertino, O. M. Johannessen and A. Samuelsen (2010), Validation of a hybrid coordinate ocean model for the Indian Ocean. *Journal of Operational Oceanography*, 3(2), 25-38
2. **George, M. S.**, L. Bertino, A. Samuelsen, K. A. Joseph and O. M. Johannessen, Upwelling along the southwest coast of India during summer monsoon: Observations and Modelling. to be submitted
3. **George, M. S.**, P. V. Joseph, K. A. Joseph, L. Bertino and O. M. Johannessen, Modelling and observational study of the intrusion of Cold Pool into the Bay of Bengal in association with the summer monsoon. to be submitted

# Introduction

Indian Ocean, the third largest and covering approximately one fifth of the world's ocean area is comparatively the less studied ocean than the Atlantic or Pacific. Nevertheless, it is physically the most complex system compared to other oceans, owing to its interactions with the monsoon system that affect the weather and climate of a considerably large area in the tropics (*Schott and McCreary*, 2001). Consequently it plays a major role in the resources (e.g. fisheries) and livelihood of billions of people inhabiting the area that comes under its influence. Even then, Indian Ocean was previously considered to have a less role in the climate variability. Until the recent decades, it was considered to have only a probable influence on the monsoon system (*Schott et. al*., 2009). Research in the past few years have shown that the Indian Ocean – especially its surface temperatures - has much more significant influence on the climate, in different timescales, not just within the region but on other areas of the globe as well (*Schott et. al*., 2009).

## The monsoon winds

The north Indian Ocean comes under the influence of seasonally reversing monsoon winds, the effects of which reaches up to the subtropics of the southern ocean. The large-scale temperature difference between the ocean and land (land warms up faster during summer and cools down faster during winter) causes the monsoon winds and these winds change their direction between summer and winter. Based on the wind direction, the seasons are named as southwest/summer monsoon and northeast/winter monsoon. During summer monsoon (June–September), the large-scale winds blow towards the warm land mass, from southwest direction (Fig. 1a) and during winter monsoon (November–February), the winds blow towards the ocean, from northeast direction (Fig. 1b). These seasonally reversing winds drive the ocean surface currents and cause a seasonal reversal in the major circulation pattern in the northern Indian Ocean (including both the Arabian Sea and the Bay of Bengal) (*Schott and McCreary*, 2001; *Haugen et al*., 2002a,b; *Shankar et al*., 2002; *Schott et al*., 2009).

The winds are much stronger during the summer monsoon and weaker during the transition periods (March–April and October). The Indian Ocean differs from other tropical oceans in one more aspect that it lacks sustained yearlong easterly winds along the equator.

The winds near equator have an easterly component only during the late winter/early spring, and have a semiannual westerly component during both inter-monsoons and a weak westerly annual mean.

## The northern Indian Ocean

The Indian peninsula splits the northern Indian Ocean into two basins; Arabian Sea in the west and Bay of Bengal in the east. Both are semi-enclosed basins, located in the same latitudinal belt and are forced by the monsoon winds. Nevertheless there are some striking differences between both the basins. The winds over the Arabian Sea are stronger than that over the Bay of Bengal, especially during summer monsoon. In the Arabian Sea, evaporation exceeds precipitation while in the Bay of Bengal precipitation exceeds evaporation. In addition, there is huge freshwater discharge into the Bay of Bengal from five of the world's largest rivers (Brahmaputra, Ganga, Irrawaddy, Godavari and Mahanadi). The river runoff into the Arabian Sea is meager compared to that into the Bay of Bengal. The total annual continental runoff into the Bay of Bengal is 2950 $km^3$ (*Sengupta et al*., 2006), runoff from Ganga and Brahmaputra being the fourth largest in the world; thus making the surface layer in the bay much fresher and stratified than that in the Arabian Sea.

After the onset of summer monsoon in June, as the wind becomes stronger, there is a decrease in the surface temperatures, with the Arabian Sea cooling rapidly (*Vinayachandran*, 2004), whereas surface temperatures in the Bay of Bengal remain above 28 °C (*Shenoi et al*., 2002). The tropical cyclones are more frequent in the Bay of Bengal than in the Arabian Sea, especially during the northeast/winter monsoon (*Srikanth et al*., 2012).

The inter-ocean exchange of thermocline waters in the Indian Ocean include: Agulhas leakage that transfers waters from Indian Ocean into the Atlantic Ocean; the transfer of Pacific waters into the Indian Ocean through the Indonesian Throughflow at around 12°S and through the Tassie Leakage south of Australia. Among this, the Indonesian Throughflow is the most significant and transports cold and fresh water into the Indian Ocean, with a mean flow of about 10 Sv (Sv = $10^6$ $m^3$/sec) with seasonal and inter-annual fluctuations (*Gordon et al*., 2010).

## Circulation in the northern Indian Ocean

In order to set my thesis topic in perspective, here in this section I have chosen to give a brief summary of the Indian Ocean circulation. The monsoon circulation of the Indian Ocean is extensively studied, using observational data as well as numerical models and the major surface circulation patters are well established (*Schott and McCreary*, 2001; *Shankar et al.*, 2002). Figure 1c, d gives a schematic representation of the circulation patterns in the Indian Ocean during summer and winter monsoons.

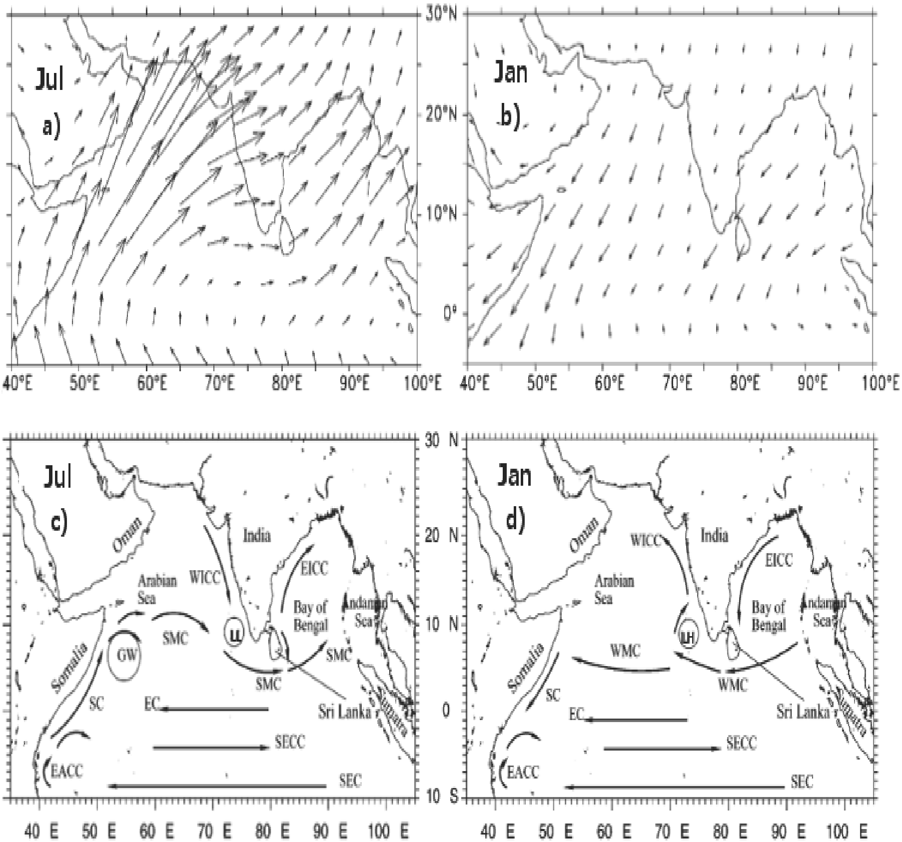


*Figure 1. Taken from Shankar et al., 2002. The climatological wind stress over northern Indian Ocean during a) July (summer monsoon); b) January (winter monsoon) and schematic representation of the circulation in the Indian Ocean during c) July (summer monsoon); d) January (winter monsoon). The prominent currents are: Somali Current (SC), Equatorial Current (EC), Summer Monsoon Current (SMC), Winter Monsoon Current (WMC), East India Coastal Current (EICC), West India Coastal Current (WICC), South Equatorial Counter Current (SECC), East African Coastal Current (EACC), South Equatorial Current (SEC), Lakshadweep high (LH), Lakshadweep low (LL) and Great Whirl (GW).*

The currents along the Indian coast, equator and south of equator are well defined. The circulation in the northern Indian Ocean is mainly dominated by large scale Ekman drift. This is more prominent during summer, particularly in the Arabian Sea, where the Ekman drift overwhelms the geostrophic flow, owing to the strong winds (*Shankar et al*., 2002). The currents are mainly eastward during summer and westward during winter seasons (*Tomczak and Godfrey*, 2001). A brief description of the current patterns is presented in this section.

In December the Winter Monsoon Current (WMC, Fig 1d) develops in the southeastern Bay of Bengal. It flows westward as a major current during January-April with its axis about 5°N. WMC peaks during February (*Shankar et al.*, 2002). The speed of WMC ranges from 0.3 m/s in the Bay of Bengal to 0.8 m/s in the western part of Sri Lanka (*Tomczak and Godfrey*, 2001). A part of WMC curves pole-ward and enter the southeastern Arabian Sea (*Shankar et al.*, 2002). In March WMC starts weakening and dissipates by April. In summer, Summer Monsoon Current (SMC, Fig 1c) replaces WMC. It starts building up in May flowing eastwards (*Shenoi et al.*, 1999a) and peaks during summer, with speeds in the range of 0.5-1.0 m/s. The SMC intrudes into the Bay of Bengal (*Vinayachandran et al.*, 1999) persisting till September and dissipating by October at the end of the summer monsoon period.

South of the equator, between 8°S and 16°S latitudes, South Equatorial Current (SEC) flows westward throughout the year, with speeds about 0.3 m/s (*Schott and McCreary*, 2001). At the western end it splits into two branches, one flowing northward and the other towards south, feeding to the coastal currents along the African coast. The South Equatorial Counter Current (SECC) flows eastward and lies between equator and SEC. It peaks during February with speeds ranging from 0.5-0.8 m/s in the west and lower speeds in the east (*Shenoi et al.*, 1999a; *Tomczak and Godfrey*, 2001).

The East African Coastal Current (EACC), which flows northward throughout the year and Somali Current (SC), which reverses its direction during monsoons are the two major currents along the African coast (*Schott and McCreary*, 2001). The westward flowing SEC feeds the EACC and the EACC flows northward and feeds into the eastward flowing current. The EACC reaches its peak in April-May with speeds reaching up to 2.0 m/s (*Tomczak and Godfrey*, 2001). The SC flows southward during winter (Fig. 1d) and northward during summer (Fig. 1c). Southward flow of SC starts in early December with speeds reaching up to 1.0 m/s and along with the EICC feeds into the SECC (*Schott and McCreary*, 2001; *Shankar et al*., 2002). During March-April, SC reverses its direction and is fed by EACC from south. In summer SC becomes the strong northward flowing jet in the Arabian Sea with the speeds reaching about 3 m/s (*Tomczak and Godfrey*, 2001). During this time of the year, two anticyclonic systems also develop associated with the SC - Great Whirl (GW) between 4°N and 10°N and Southern Gyre (SG) about 4°N.

The two major currents along the coast of India are the West Indian Coastal Current (WICC) and East India Coastal Current (EICC) (Fig. 1c,d). Along the west coast of India, WICC flows equator-ward during summer and pole-ward during winter (*Shetye et al.*, 1991; *Shenoi et al.*, 1999a). In April the WICC starts flowing equator-ward and peaks during summer, transporting high salinity water from the northern parts of Arabian Sea into the southwest coast of India. The flow dissipates by October and by December the pole-ward flow reaches its peak phase (*Shetye et al.*, 1991). The pole-ward flowing WICC is more organized and transports the low salinity water from Bay of Bengal (carried by EICC) to southeastern Arabian Sea.

The EICC flows along the east coast of India, equator-ward during October–December and pole-ward during February–May (*Shetye et al.*, 1993, 1996). During November, the equator-ward EICC peaks with speeds reaching 1.0 m/s (*Tomczak and Godfrey*, 2001). It turns around Sri Lanka and feeds into the WICC (which is in its initial pole-ward phase), transporting low salinity waters from Bay of Bengal. The reverse flow (pole-ward) starts by February and peaks in April (*Tomczak and Godfrey*, 2001). A detailed review on these two coastal currents and their intraseasonal variabilities could be found in *Shenoi*, [2010] and the references there within.

During winter, a well-defined high sea level forms off the southwest coast of India, which is known as Lakshadweep high (LH, Fig. 1d). It propagates westward as the season progresses (*Bruce et al.*, 1994). LH and the associated anticylconic circulation play an important role in the thermohaline structure of the region (*Shankar et al.*, 2002). During summer, a low in the sea level pattern replaces the LH and is known as Lakshadweep low (LL, Fig. 1c), which also propagates westward (*Shankar and Shetye*, 1997).

The transition periods between summer and winter monsoons occurs in April and October. A strong eastward flowing current, known as Wyrtki jet/Equatorial jet (*Wyrtki*, 1973) with speeds about 1.0 m/s occupies the equatorial Indian Ocean during the transition periods (figure not shown). The Wyrtki jet that forms during fall season are stronger than spring jet (*Schott and McCreary*, 2001).

## Upwelling along the southwest coast

The strong summer monsoon winds have a major impact on the ocean surface circulation of the region and its oceanographic characters (Fig. 1a). One such phenomenon is the upwelling during summer season. Upwelling along the south west coast of India during the southwest monsoon is a recurring phenomenon (Fig. 2).

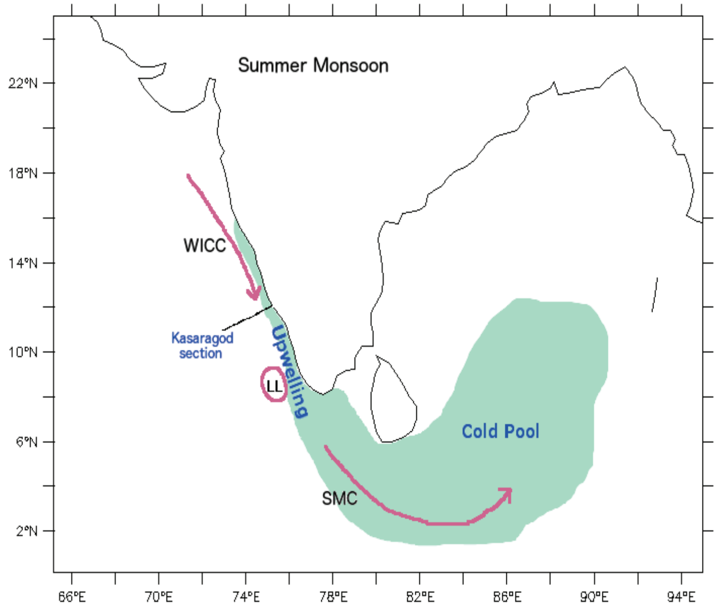


*Figure 2. Schematic representation of upwelling and its intrusion into the Bay of Bengal as the Cold Pool, during the southwest monsoon.*

During the pre-monsoon (April-May), the northern Indian Ocean is covered by warm surface waters. In the southeastern Arabian Sea, the Indian Ocean Warm Pool (IOWP) forms during this time and it has a critical impact on the development of southwest monsoon (*Joseph*, 1990; *Rao and Sivakumar*, 1999; *Kurian and Vinayachandran*, 2007). As the southwest monsoon sets in, these warm surface waters are replaced by upwelled cooler, oxygen depleted and nutrient rich subsurface waters (*Johannessen et al.*, 1987, Fig. 3). The uplift in the subsurface isolines (*Johannessen et al.*, 1987) and low sea levels (*Shankar and Shetye*, 1997) are also characteristics associated with this upwelling.

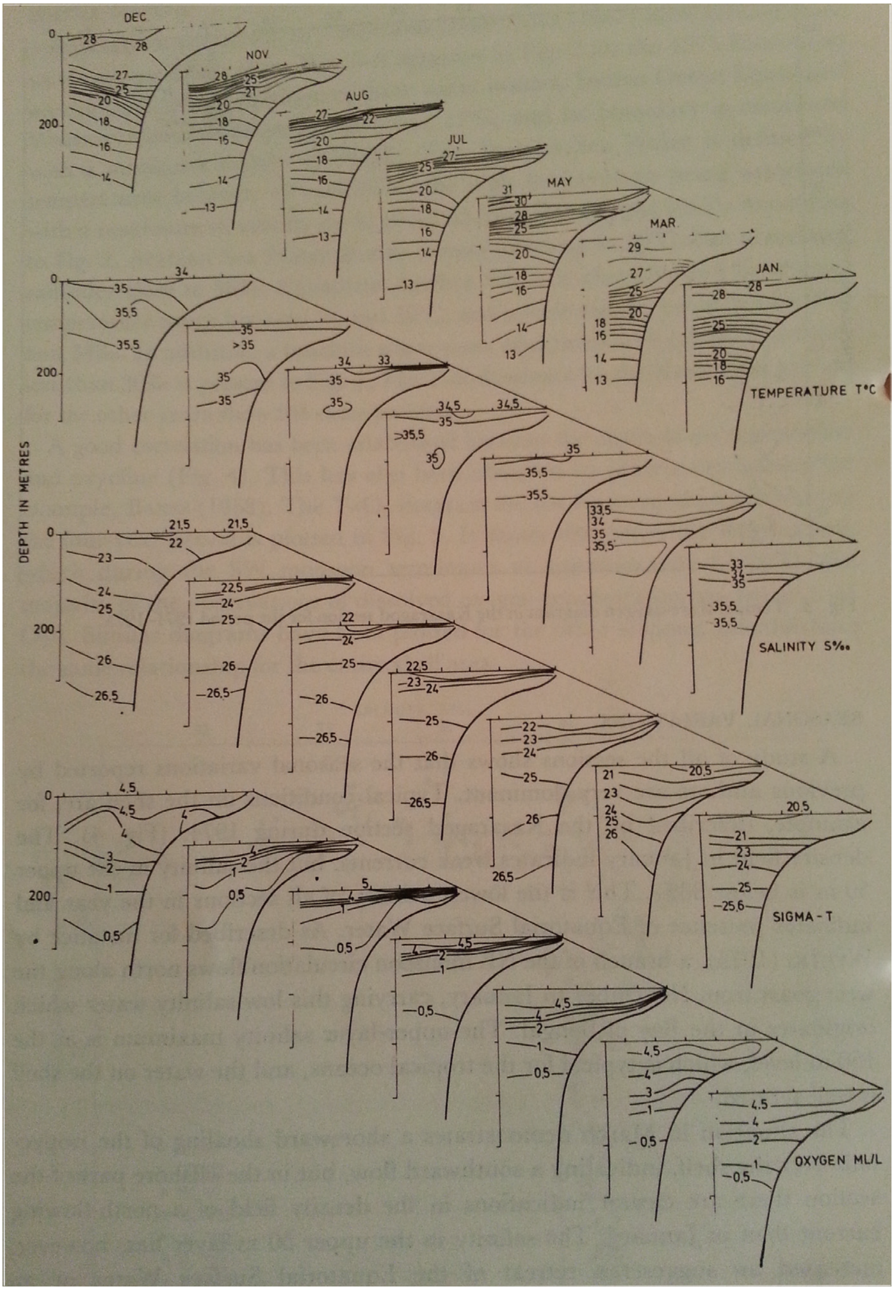


*Figure 3. Taken from Johannessen et al., (1987). Hydrographic fluctuations along the Kasaragod section (marked in Fig. 2) in the study during 1974, showing the shoaling of isolines, including the oxygen depletion over the shelf area, during the summer monsoon.*

Although the stronger monsoon winds set in only by June, the upwelling signals are seen in the deeper depths as early as February (*Shetye*, 1984; *Johannesen et al.*, 1987) probably caused by a Kelvin wave (*Shankar and Shetye*, 1997; *Haugen et al.*, 2002a,b), propagating from the Bay of Bengal around Sri Lanka and northward along the southwest coast of India (further commented in the later section). Later during June-July, the near surface divergence caused by the strong alongshore wind is the most important factor, which leads to the upwelling (*Shetye et al.*, 1985; *Johannessen et al.*, 1987; *Shetye and Shenoi*, 1988).

*Johannessen et al*., (1987) using hydrographic data (collected during a collaborative fishery project between Norway and India), described the features of the upwelling along the southwest coast of India. They observed a shoreward lift in isopycnals (Fig. 3) indicating a southward flow near to the coast. During the southwest monsoon, they observed the shoaling of isotherms, sharpening of the thermocline and penetration of low oxygen water (Fig. 3). The temperature structure at 10m (Fig. 4) from their observations also showed that the temperatures reduced to less than 23 °C much lesser compared to the offshore temperatures. The surface salinities were low which could be explained by runoff, the extent of which is only in the upper few meters (Fig. 4) as the salinities at 10m suggest. The upwelling was more prominent towards south of the study region. The strong winds prevailing during southwest monsoon enhances the southward current, which caused the shoaling of isolines and *Johanneseen et al*., (1987) concluded that the upwelling was not only associated with the local wind, but also with the large-scale monsoonal conditions which drives the anticyclonic circulation in the Arabian Sea. Other studies have also established the local wind forcing as the primary force responsible for the upwelling, especially caused by the alongshore component of the wind and the associated Ekman dynamics (*Shetye*, 1984; *Shetye et al*., 1985; *Shetye and Shenoi*, 1988; *Smitha et al*., 2008).

Along with the local forcing – strong along shore components of the wind – remote forcing also play a role in the upwelling along the coast. Several numerical modelling and observational studies have shown the importance of remote forcing by Kelvin & Rossby waves, which originates from the equatorial Indian Ocean

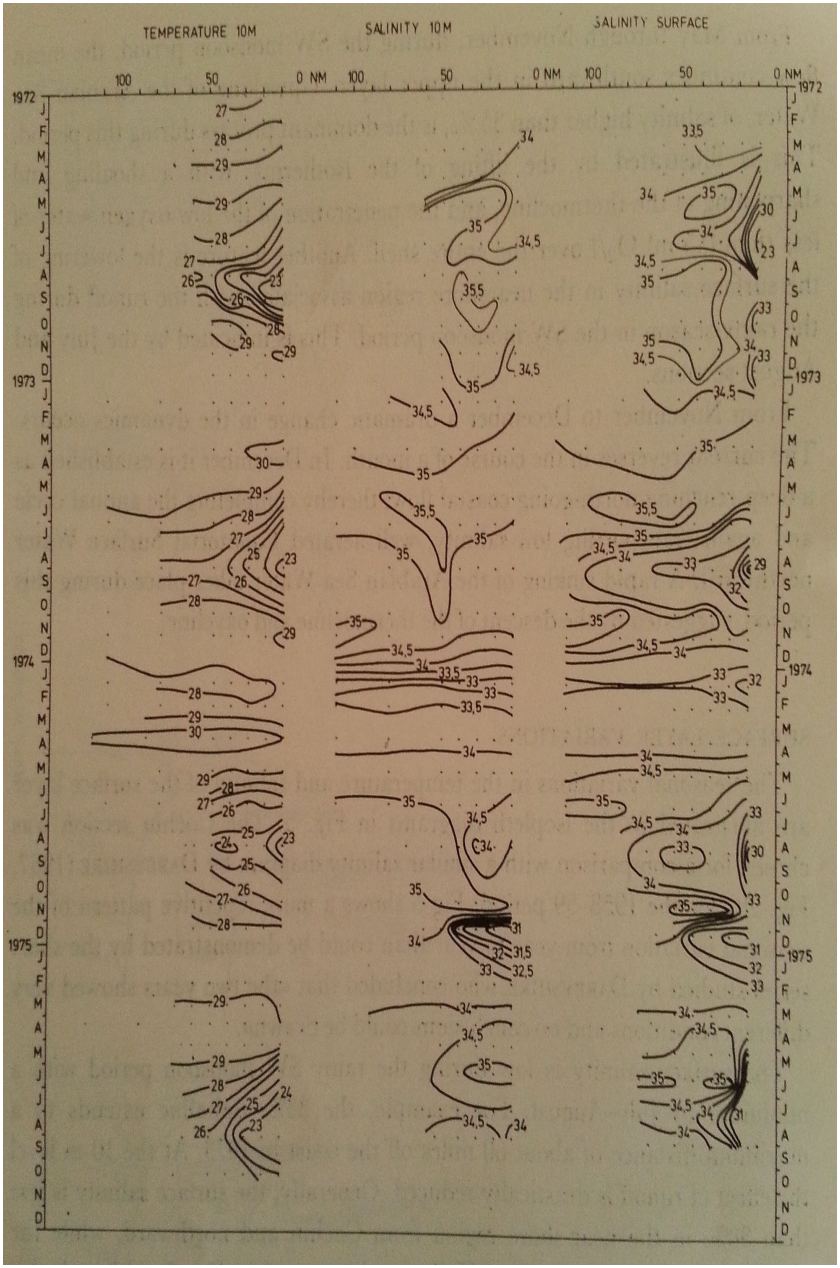


*Figure 4. Taken from Johannessen et al., (1987). Isopleth diagram for the Cochin section; temperatures at 10m, salinities at 0m and 10m showing the cooling induced by upwelling.*

(*McCreary et al.,* 1993; *Shankar and Shetye*, 1997; *Haugen et al*., 2002a,b; *Han and Webster*, 2002; *Rao et al.*, 2010). In the equatorial Indian Ocean, the zonal winds generate semi-annual sea level fluctuations (*Clark and Liu*, 1993), which triggers the equatorially trapped Kelvin waves. These Kelvin waves travel towards east, across the Indian Ocean, hits the Sumatra coast and then bifurcates; one part which gets trapped as coastal Kelvin wave along the coastal boundary of Bay of Bengal, and travels around Sri Lanka and enters the southwest coast of India (*Yu et al*., 1991; *McCreary et al.,* 1993; *Shankar and Shetye*, 1997; *Haugen et al*., 2002a,b; *Rao et al.*, 2010). They also trigger westward propagating Rossby waves off the eastern boundaries of both Bay of Bengal and Arabian Sea. However, *Gopalakrishna et al*., (2008) using XBT data in the Lakshadweep sea proposed that, in the southeastern Arabian Sea, the upwelling is influenced mostly by the remote forcing from the propagating coastal Kelvin waves from south Sri Lanka and the alongshore wind stress off the southwest coast of India than the equatorial forcing.

During May, the regions south of India starts cooling owing to coastal upwelling (*Luis and Kawamura,* 2002; *Vinayachandran et al*., 2003). *Rao et al.*, (2006a,b) using multi-year averaged Tropical Rainfall Measuring Mission (TRMM) Microwave Imagery (TMI) data showed a cold patch of water less than 26°C, off the southern tip of India and named it Mini Cold Pool. They showed that large positive wind stress curl in the region drives this upwelling, and suggested that local upwelling can happen off the southern tip of India. Using observational data *Smitha et al.*, (2008) also studied the upwelling conditions of the area. They concluded that the strong upwelling noted at the tip of India is primarily caused by the winds that are tangential to the coast.

The present status of the upwelling studies shows that the upwelling along the southwest coast of India can start as early as March, triggered by the coastally propagating Kelvin waves. During summer monsoon, the alongshore component of the strong winds take over and drives the upwelling along the coast and south of India and Sri Lanka, along with the large-scale circulation. *Haugen et al*., (2002a) showed that the there is a decrease in the intensity of upwelling during El Niño years, which was confirmed by *Jayaram et al*., (2010) using a satellite observation based study. However, it is not entirely clear, how much of the upwelling is caused by the local alongshore wind component; a topic which will be dealt with in Paper II of this thesis.

## Cold Pool in the Bay of Bengal

As mentioned earlier, strong monsoonal winds also drive the surface currents in the Indian Ocean. During the southwest monsoon, the Summer Monsoon Current, SMC (Fig. 1c) flows southeastward in the eastern Arabian Sea and it flows eastward around south of India and Sri Lanka. East of Sri Lanka, a part of the current turns eastward and flows into the Bay of Bengal. The SMC that brings the cool waters from the south of India and Sri Lanka into the southern Bay of Bengal plays a role in the salt/freshwater balance of the Bay of Bengal (*Vinayachandran et al*., 1999). *Joseph et al*., (2005) using TMI data, showed the existence of a large tongue of Cold water in the Bay of Bengal in the latitude belt of 3-10°N and named it the Cold Pool of the Bay of Bengal (Fig. 5).

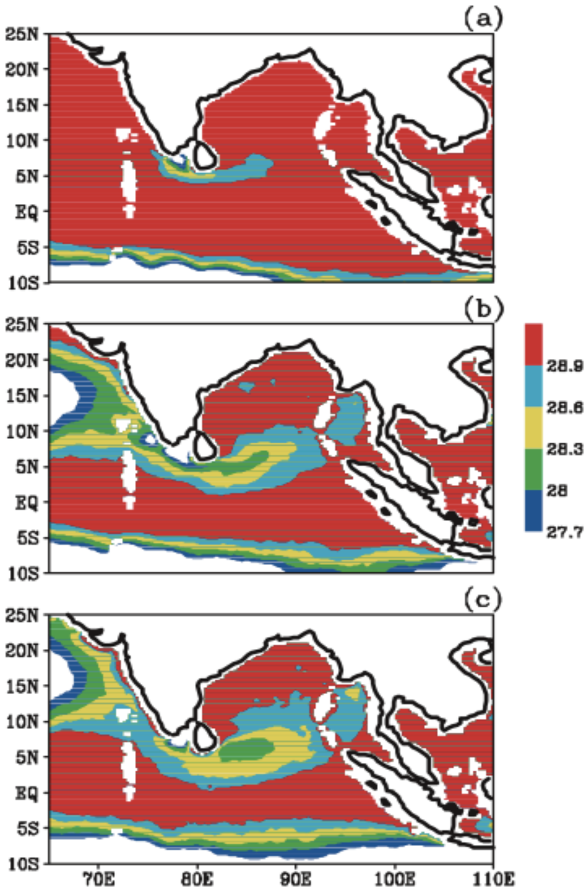


*Figure 5. Taken from Joseph et al., (2005). The composites (1998-2003) of SST (℃) from TMI during a) June, b) July and c) August.*

This cold pool lies in between two warm water region; one in the equator and other in the northern Bay of Bengal. From TMI observations they showed that from June to August the temperature of the Cold pool decreases and attributed it to the possibility of the spreading of upwelled waters formed along the southwest coast of India reaching this region, favoured by the strong SMC. The Cold Pool generates a strong gradient in the Bay of Bengal SST, which could play a role in the generation mechanisms of active monsoon convection over the Bay of Bengal (*Joseph and Sabin*, 2008). *Shankar et al*. (2007) also established that there exists a strong relationship between convection and the meridional gradient of SST in the Bay of Bengal.

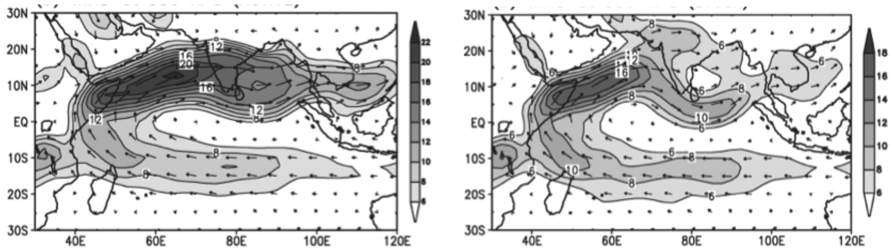


*Figure 6. Taken from Joseph and Sijikumar (2004). Figure shows the winds at 850 hPa from NCEP-NCAR data. Left panel shows the composite of winds during active phase of monsoon and right panel shows the same for break phase.*

Monsoon has active-break cycles. During the break cycles, there is enhanced wind stress curl over the Cold Pool area, southeast of Sri Lanka. We hypothesize that this will cause enhanced upwelling in the Cold Pool region, in addition to the advected waters carried into the area by SMC. Over the Indian Ocean, a strong cross-equatorial wind jet known as Low Level Jet (LLJ) exists in the lower levels of the atmosphere, during summer monsoon, with its core around 850 hPa (1.5 km in height). The existence of this jet was established by *Joseph and Raman* [1966] and later by *Findlater* (1969). *Joseph and Sijikumar* (2004) showed that there is a shift in the axis of the LLJ closely associated with the active-break cycle of the monsoon. The surface wind over the ocean around 10 m height also follows a similar pattern as seen in the ERA-Interim data (figure not shown).

*Joseph and Sijikumar* [2004] found that during active monsoon spells, the core of the LLJ passes through peninsular India between latitudes 12.5° and 17.5°N (Fig. 6, left) and is associated with a large area of strong convection in the Bay of Bengal and increased rainfall over the Indian subcontinent. They found that when the convection weakens over the Bay of Bengal, the LLJ turns clockwise over the Arabian Sea and during the break monsoon that follows, the LLJ bypasses India and flows south of India with its core lying between latitudes 2.5°N and 7.5°N. The break phase is characterised by decreased winds over India (and hence less rainfall over Indian subcontinent), Arabian Sea and Bay of Bengal and increased convection and rainfall south of India, along with enhanced wind and positive wind stress curl over the Cold Pool area.

Present state of art is that the Cold Pool of the Bay of Bengal is caused by the advection of the upwelled waters along the southwest coast of India that are carried into the south central Bay of Bengal by the SMC (Fig. 2). The Cold Pool generates a temperature gradient in the SST of the bay, which could influence the active-break cycle of the monsoon over India, through ocean-atmospheric interactions. The strong winds over the Cold Pool region, during the break periods cause positive wind stress over the area and there could be a possibility of open ocean upwelling in the region due to this curl and also potential Ekman pumping due to existence of eddies in the region – a new hypothesis we have investigated in Paper III of this thesis.

## Summary and conclusion of the thesis

The main objective of the thesis is to advance the knowledge of cold water upwelling along the southwest coast of India and the intrusion of this upwelled waters into the Bay of Bengal, including open ocean upwelling in the Cold Pool region, by an integrated approach using observations and modelling. I have addressed this aim with the following three papers summarized below including conclusions. In the papers, we have used *in situ* data both from satellite and Argo float ocean profiling data and also the HYbrid Coordinate Ocean Model (HYCOM), which is explained more in detail in Paper I.

### Paper 1. "Validation of a hybrid coordinate ocean model for the Indian Ocean"

The HYCOM model was set up at NERSC, Bergen for the Indian Ocean. The model was set up for the whole Indian Ocean, of which data of the north Indian Ocean was analysed in detail. A validation scheme was developed comparing the model with available observations. The model runs have been validated with many satellite and *in situ* observations including the data from the Argo floating profiles. The surface currents, surface temperatures, sea level anomalies, the subsurface temperature and salinity patterns were compared with observations. The model had warm waters, particularly in the sub surface region compared to observations. Even then it could simulate the surface currents, temperature and salinity patterns realistically. It was concluded from the validation results that the model gives a good comparison with the *in situ* and satellite data and can further be used to study the upwelling along the southwest coast of India and its intrusion into the Bay of Bengal as the Cold Pool during the summer monsoon.

**Paper 2. "Upwelling along the south-west coast of India during summer monsoon: Observations and Modelling"**

The upwelling along the southwest coast of India was studied by an integrated approach using both observations as well as an improved version of HYCOM. We examine the role of local forcing - alongshore wind component - in the upwelling along the coast. During summer monsoon, the strong monsoon winds along the south west coast of India causes upwelling of subsurface waters along the coast, these cold waters are carried by the strong summer monsoon ocean current around south of India and Sri Lanka into the Bay of Bengal. These upwelling and cold waters are well simulated realistically by HYCOM and compares well with TMI data. Thus a detailed analysis of influence of alongshore winds on the upwelling and inter-annual variability of the upwelling over the ten years from 2001 to 2010 is presented in the paper. In conclusion, we found that there is only a correlation of about 0.4-0.6 between the along shore wind and sea surface temperatures near the coast (both TMI and HYCOM) for certain years, thus implying that the alongshore wind stress can only explain 16-36% ($R^2$) of the upwelling that happens along the southwest coast of India. The study also implies that other remote forcing such as the large-scale wind driven circulation also plays an important role in the upwelling along the southwest coast of India.

**Paper 3. "Modelling and observational study of the intrusion of Cold Pool into the Bay of Bengal in association with the summer monsoon"**

The Cold Pool formed in the Bay of Bengal (due to the advection of the above said upwelled waters) is also a part of the upwelling that happens in the southern part of the north Indian Ocean. The Summer Monsoon Current (SMC) carries the upwelled cold waters into the Bay of Bengal during the summer monsoon season. These cold waters have an influence on the SST distribution in the Bay of Bengal. Also the strong winds along the southern part of India during the break cycles, which cause strong positive wind stress curl in the area, seem to have an influence in lowering the temperatures of the region. Thus the study focuses on intrusion of these cold waters into the Bay of Bengal region and its inter-annual variabilities in relation with the summer monsoon, specially looking into its relation with the break period wind pattern. We have tested a hypothesis that enhanced upwelling can occur in the Cold Pool region, owing to the positive wind stress curl that forms during the break period of the summer monsoon. Seven cases of break phases occurred during the ten years of study period were analysed in detail and in conclusion the results confirmed our new hypothesis.

## Future perspectives

Upwelling is very important for the fisheries. *Johannessen et al*., (1987) showed that during southwest monsoon, when the oxygen depleted water moved to the shelf, the anchovies migrated towards the south of study area. The upwelling during summer monsoon makes the area one of the most biologically productive regions and contributes to large fishery potential of India (*Madhupratap et al*., 1994, 1996, 2001). From operational point of view, its only the Indian National Centre for Ocean Information Services (INCOIS) at Hyderabad, India that gives a potential fishing zone information - based on satellite data - available to the fishermen. Through our model studies we have seen that the improved version of HYCOM is an useful tool which could be used as a forecasting tool. Our major future aims are to improve the knowledge of science of the area further and to test a data assimilative system along the southwest coast of India in small scale for short periods, which could be further developed and implemented as a forecasting system for the area.

# Bibliography


Bruce, J. G., D. R. Johnson, and J. C. Kindle (1994), Evidence for eddy formation in the eastern Arabian Sea during the northeast monsoon, *J. Geophys. Res.*, *99*(C4), 7651–7664.

Clark, A.J., Liu, X., 1993. Observations and dynamics of semiannual and annual sea levels near the eastern equatorial Indian Ocean boundary. Journal of Physical Oceanography 23 (2), 386–399.

Findlater, J. (1969), A major low level air current near the Indian Ocean during the northern summer. *Q. J. R. Meteorol. Soc.*, 95:362–380

Gopalakrishna, V.V., R. R. Rao, K. Nisha, M. S. Girishkumar, T. Pankajakshan, M. Ravichandran, Z. Johnson, K. Girish, N. Aneeshkumar, M. Srinath, S. Rajesh and C. K. Rajan (2008), Observed anomalous upwelling in the Lakshadweep Sea during summer monsoon season of 2005. *J. Geophys. Res.,* 113: C05001,doi:10.1029/2007JC004240.

Gordon, A., J. Sprintall, S. Wijffels, D. Susanto, R. Molcard, H. M. Van Aken, A. L. Ffield, W. de Ruijter, J. Lutjeharms, S. Speich and L. Beal (2010). Interocean Exchange of Thermocline Water: Indonesian Throughflow; "Tassie" Leakage; Agulhas Leakage. *Proceedings of OceanObs*, *9*.

Han, W., and P. J. Webster (2002), Forcing mechanisms of sea level inter-aannual variability in the Bay of Bengal, *J. Phys. Oceanogr.*, 32, 216 –239.

Haugen V E, Johannessen O M and Evensen G (2002a), Indian Ocean circulation. Part 1: Validation of the Miami Isopycnic Coordinate Ocean Model and Part 2: ENSO events during 1958–1998; *J. Geophys. Res.*, 107 (C5), p101029–101057.

Haugen, V. E., O. M. Johannessen, and G. Evensen (2002b), Mesoscale modeling study of the oceanographic conditions off the southwest coast of India, *Journal of Earth System Science.*, *111*(3), 321–337.

Johannessen, O. M., G. Subbaraju, and J. Blindheim (1987), Seasonal variations of the oceanographic conditions off the southwest coast of India during 1971 – 1975, *Fisk Dir. Skr Hav Unders*, 18, 247 – 261.

Joseph, P. V. And P. L. Raman (1966), Existence of low level westerly jet stream over Peninsular India during July. *Indian. J. Meteorol. Geophys.*, 17:407–410.

Joseph, P.V. (1990), Warm pool over the Indian Ocean and monsoon onset, *Trop. Ocean Atmos. Newsl.*, *Winter,* (53), 1-5.

Joseph, P. V. and S. Sijikumar (2004) Intra seasonal variability of the low-level jet stream of the Asian summer monsoon, *Journal of Climate*, 17, 1449 – 1458

Joseph, P. V., K. P. Sooraj, C. A. Babu and T. P. Sabin (2005) A Cold Pool in the Bay of Bengal and its interaction with the active–break cycles of monsoon, *CLIVAR Exchanges*, 10 (3), 10–12

Joseph, P. V. and T. P. Sabin (2008) An ocean–atmosphere interaction mechanism for the active break cycle of the Asian summer monsoon, *Clim Dynamics* 30, 553–566

Kurian, J., and P. N. Vinayachandran (2007), Mechanisms of formation of the Arabian Sea mini warm pool in a high-resolution Ocean General Circulation Model, *J. Geophys. Res*., 112, C05009, doi:10.1029/2006JC003631.

Luis, A. J and H. Kawamura (2002), A case study of the sea surface temperature-cooling dynamic near the Indian tip during May 1997, *J. Geophys. Res.*, 107 (C10), 3171, doi:10.1029/2000JC000778

Madhupratap, M., S. R. Shetye, K. N. V. Nair, and S. R. Sreekumaran Nair (1994), Oil sardine and Indian mackerel: their fishery, problems and coastal oceanography, *Curr. Sci.,* 66: 340 – 348.

Madhupratap, M., M., S. Prasanna Kumar, P. M. A. Bhattathiri, M. Dileep Kumar, S. Raghukumar, K. K. C. Nair, and N. Ramaiah (1996), Mechanism of the biological response to winter cooling in the north eastern Arabian Sea, *Nature,* 384: 549 – 552.

Madhupratap, M., K. N. V. Nair, T. C. G. P. Haridas, K. K. C. Nair, P. Venugopal, and M. Gauns (2001), Arabian Sea oceanography and fisheries of the west coast of India, *Curr. Sci.*, 81(4): 355–361.

McCreary, J. P., P. K. Kundu, and R. L. Molinari (1993), A numerical investigation of the dynamics, thermodynamics and mixed layer processes in the Indian Ocean, *Prog. Oceanogr.*, 31, 181 – 244, doi:10.1016/0079-6611(93)90002-U.

Rao, R. R., and R. Sivakumar (1999), On the possible mechanisms of the evolution of a mini-warm pool during the pre-summer monsoon season and the onset vortex in the southeastern Arabian Sea, *Q. J. R. Meteorol. Soc.*, 125(555 Part A), 787 – 809.

Rao, R. R., M. S. Girish Kumar, M. Ravichandran, B. K. Samala, and N. Sreedevi (2006a), Observed mini-cold pool off the southern tip of India and its intrusion into the south central Bay of Bengal during summer monsoon season, *Geophys. Res. Lett*., *33*, L06607, doi:10.1029/2005GL025382.

Rao, R. R., M. S. Girish Kumar, M. Ravichandran, B. K. Samala, and G. Anitha (2006b), Observed intraseasonal variability of mini-cold pool off the southern tip of India and its intrusion into the south central Bay of Bengal during summer monsoon season, *Geophys. Res. Lett*., *33*, L15606, doi:10.1029/2006GL026086.

Rao, R. R., Kumar, G., Ravichandran, M., Rao, A. R., Gopalakrishna, V. V., & Thadathil, P. (2010). Interannual variability of Kelvin wave propagation in the wave guides of the equatorial Indian Ocean, the coastal Bay of Bengal and the southeastern Arabian Sea during 1993–2006. *Deep Sea Research Part I: Oceanographic Research Papers*, *57*(1), 1-13.

Sengupta, D., G. N. Bharath Raj, and S. S. C. Shenoi (2006), Surface freshwater from Bay of Bengal runoff and Indonesian Throughflow in the tropical Indian Ocean, Geophys. Res. Lett., 33, L22609, doi:10.1029/ 2006GL027573.

Schott, F. A. and J. P. McCreary (2001), The monsoon circulation of the Indian Ocean. *Prog. Oceanogr.*, 51: 1,123.

Schott, F. A., S-P. Xie, J. P. McCreary (2009) Indian Ocean circulation and climate variability. *Rev Geophys.* 47. doi:10.1029/2007RG000245

Shankar, D. and S. R. Shetye (1997), On the dynamics of the Lakshdweep high and low in the southeastern Arabian Sea, *J. Geophys. Res.*, 102, 12,551 – 12,562, doi:10.1029/97JC00465.

Shankar, D., P. N. Vinayachandran, and A. S. Unnikrishnan. (2002), The monsoon currents in the north Indian Ocean, *Progr. Oceanogr.*, 52(1): 63–120.

Shankar, D., S. R. Shetye and P. V. Joseph (2007), Link between convection and meridional gradient of sea surface temperature in the Bay. *J. Earth. Syst. Sci.*, 116(5), p 385–406.

Shenoi, S. S. C., P. K. Saji, and A. M. Almeida (1999a), Near–surface circulation and kinetic energy in the tropical Indian Ocean derived from Lagrangian drifters, *J. Mar. Res.*, *57*(6), 885–907.

Shenoi, S. S. C., D. Shankar, and S. R. Shetye (2002), Differences in heat budgets of the near-surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon, *J. Geophys. Res.*, *Oceans (1978–2012), 107*(C6), 3052, doi:10.1029/2000JC000679, 2002.

Shenoi, S. S. C. (2010), Intra-seasonal variability of the coastal currents around India: A review of the evidences from new observations, *Indian Journal of Marine Sciences*, *39*(4), 489-496.

Shetye, S. R. (1984), Seasonal variability of temperature fields off the southwest coast of India, *Proc. Indian Acad. Sci. Earth Planet. Sci.*, 93, 399 – 411.

Shetye, S. R., S. S. C. Shenoi, M. K. Antony, and V. Krishna Kumar (1985), Monthly mean wind stress distribution along the coast of the North Indian Ocean, *Proc. Indian Acad. Sci. Earth Planet. Sci.*, 94, 129 – 137.

Shetye, S. R. and S. S. C. Shenoi (1988), Seasonal cycle of surface circulation in the coastal North Indian Ocean, *Proc. Indian Acad. Sci. Earth Planet. Sci.*, 97, 53 – 62.

Shetye, S. R., A. D. Gouveia, S. S. C. Shenoi, G. S. Michael, D. Sundar, A. M. Almeida, and K. Santanam (1991), The coastal current of western India during the northeast monsoon, *Deep-Sea Res. Part A*, *38*(12), 1517–1529

Shetye, S. R., A. D. Gouveia, S. S. C. Shenoi, D. Sundar, G. S. Michael, and G. Nampoothiri (1993), The western boundary current of the seasonal subtropical gyre in Bay of Bengal, *J. Geophys. Res.*, *98*(C1), 945–954.

Shetye, S. R., A. D. Gouveia, D. Shankar, S. S. C. Shenoi, P. N. Vinayachandran, D. Sundar, G. S. Michael and G. Nampoothiri (1996), Hydrography and circulation in the western Bay of Bengal during the northeast monsoon, *J. Geophys. Res.*, *101*(C6), 14,011–14,025.

Srikanth, L., M. Ramalingam, M. S. George, L. Bertino and A. Samuelsen (2012), A Study on the Influence of Oceanic and Atmospheric Parameters on Tropical Cyclones in the Bay of Bengal, *European Journal of Scientific Research*, *76*(1), 63-73.

Smitha, B. R., V. N. Sanjeevan, K. G. Vimalkumar and C. Ravichandran (2008), On the upwelling off the southern tip and along the west coast of India. Journal of Coastal Research, 24(4C), 95–102.

Tomczak, M., and J. S. Godfrey (2001), *Regional Oceanography: An Introduction*, 391 pp

Vinayachandran, P. N. and Toshio Yamagata (1998), Monsoon response of the sea around Sri Lanka: Generation of thermal domes and anticyclonic vortices. *Journal of Physical Oceanography*, 28, 1946 - 1960.

Vinayachandran, P. N., Yukio Masumoto, Tetsuya Mikawa and Toshio Yamagata (1999), Intrusion of the Southwest Monsoon Current into the Bay of Bengal, *Journal of Geophysical Research*, 104 (C5), 11,077 – 11,085.

Vinayachandran, P. N., P. Chauhan, M. Mohan, and S. Nayak (2003), Biological response of the sea around Sri Lanka to summer monsoon, *Geophys. Res. Lett.*, *31*, L01302, doi:10.1029/ 2003GL018533.

Vinayachandran, P. N. (2004), Summer cooling of the Arabian Sea during contrasting monsoons, Geophys. Res. Lett., 31, L13306, doi:10.1029/2004GL019961.

Wyrtki, K. (1973). An equatorial jet in the Indian Ocean. *Science*, *181*(4096), 262-264.

Yu, L., O'Brien, J.J., Yang, J., 1991. On the remote forcing of the circulation in the Bay of Bengal. *Journal of Geophysical Research*, 96 (C11), 20,449–20,454.