PhD Research Proposal

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SECTION 1. PROJECT TITLE & AIMS

1.1. Project Title

Flow Topography Interaction in the Northern Indian Ocean

1.2. Aims

The overarching theme for this research project is to explore the dynamics and generation mechanisms of island wakes and their resultant eddies in the Northern Indian Ocean as well as their response to large scale Indian Ocean variability events, such as the Indian Ocean Dipole Mode (IOD). This information will contribute to the growing body of literature that will be critical in predicting the impacts of climate change, pollution, and implementing sustainable fisheries management for the Indian Ocean and its surrounding nations.

It is with this understanding that the following research themes have been developed for this project and will be presented in the form of three journal articles and then compiled into a final thesis for submission as part of the candidature requirements –

Theme 1: What is the role of the monsoon on the island mass effect in the Northern Indian Ocean?

Theme 2: What are the dominant factors influencing the development of the island mass effect in the Northern Indian Ocean?

Theme 3: What is the relationship between the island mass effect and major climate modes such as ENSO and the Indian Ocean Dipole Mode?

SECTION 2. PROJECT MOTIVATION

Problem formalisation

Large scale forcing events, such as the El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) mode have a large impact on the global and regional climate regime. These events affect the variability in monsoonal rainfall and wind strength in the Indian Ocean and since two decades ago, ENSO was thought to be the primary forcing event for the region (Sreenivas et al. 2012). However, the increasing occurrence of intense IOD events in the last decade has prompted investigations into the extent of its influence on the Indian Ocean climate. In a climate change scenario, the periodicity and cycle of these forcing events might change, which will then feedback into the local climate through wind variability and eddies.

This study is motivated by the importance of island wakes in establishing localized biological productivity in the lee of islands, a phenomenon known as the "Island Mass Effect" (IME)(Doty & Oguri 1956). Island wakes represent a mechanism for the generation of eddies which result in upwelling, bringing nutrient rich water from the depths of the ocean to the surface (Caldeira et al 2002). The development of island wakes and their variablity have been documented in a diverse range of locations such as the Gran Canaria, the Carribean, Philippines, Hawaii and across the Pacific (Basterretxea et al. 2002, Cherúbin and Garavelli 2016, Pullen et al. 2008 and Gove et al. 2016) through the use of in-situ measurements and satellite observations. However, the various oceanic and atmospheric mechanisms which favour the formation of these coherent oceanic features are still under discussion and little is known about the life cycle of these structures and how they evolve over space and time. This has largely been due to most observations being reliant on satellite imagery such as the Moderate Resolution Imaging Spectrometer (MODIS) which is dependant on having cloud free vision of the ocean surface for measurements. The use of MODIS also means that one can only track wakes that are strong enough to generate chlorophyll blooms and may fail to capture weaker eddies of smaller spatial scales.

Thus, a detailed investigation into the generation mechanisms of these wake eddies and upwelling and how they respond to large scale forcing events like the IOD will contribute to advancements in predictability studies and support decision-making in fisheries management. This will be addressed through the combined use of field observations, satellite measurements and numerical modelling.

Significance

Many Indian Ocean fisheries are closely tied to eddies and upwelling variability so these features of physical oceanography have direct societal impacts. It is therefore important to understand these dynamics, their variability and their ecosystem impacts on time scales ranging from weeks to years. Quantifying these processes will be informative in predicting how these wake eddies and the upwelling associated with them might change in the future and, in particular, how they will respond to climate change and global warming.

SECTION 3. PROJECT BACKGROUND

General Background

Physical Setting: The Northern Indian Ocean

The general circulation of the Indian Ocean is the least well understood of all of the open ocean basins due to the paucity of oceanographic data, compared to the Atlantic and Pacific. This is compounded by the fact that the Indian Ocean surface and deep currents are more dynamically complex and variable compared to the other ocean basins, due to the influence of the reversing bi-annual seasonal monsoon winds. The South West Monsoon wind (SWM) blows from the southwest towards the northeast in the boreal summer (June-October) and the North East Monsoon (NEM) blows in the opposite direction during the boreal winter (December-April) (Schott & McCreary 2001). As a result of the monsoon wind forcing, all of the boundary current systems in the Northern Indian Ocean (NIO) reverse seasonally, driving upwelling circulations during the SWM and downwelling circulations during the NEM respectively (Schott & McCreary 2001; Shankar et al. 2002).

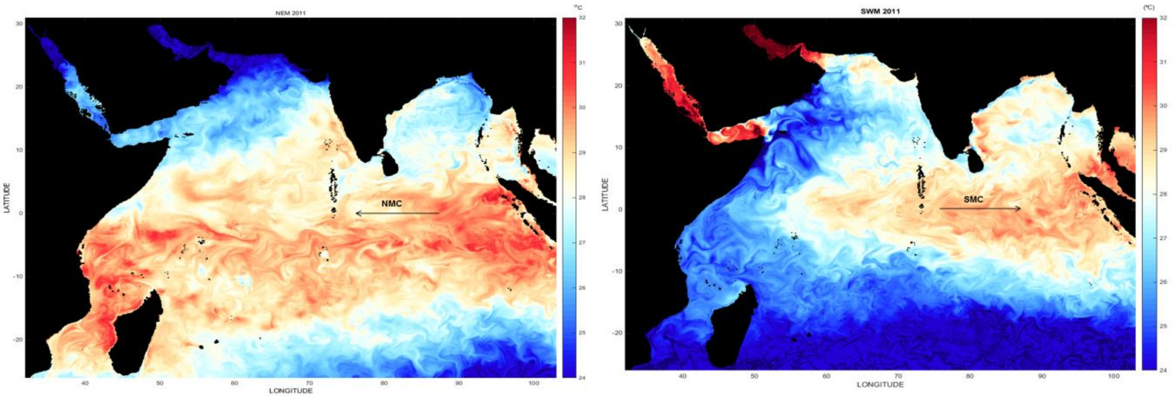

Figure 1: Sea surface temperatures in the Northern Indian Ocean during the NEM and SWM (Output generated from HYCOM).

During the NEM, the Northeast Monsoon current (NMC) flows from east to west, transporting lower salinity water (< 33 ppt) from the Bay of Bengal westwards (Figure 2; Schott & McCreary 2001).The East Indian Coastal Current (EICC) flows southward past Sri Lanka and merges with the NMC (Figure 2; Schott et al. 1994). The currents then flow around the clockwise Lakshadweep eddy and northward along the western Indian coastline as the WICC (Figure 2a; Schott & McCreary 2001; Vos et al. 2013).Conversely, during the SWM, the Southwest Monsoon Current (SMC) flows from west to east, transporting higher salinity water (~36.5 ppt) from the Arabian Sea eastwards (Figure 2b; Schott et al. 1994; Schott & McCreary 2001). The WICC in the Arabian Sea flows southwards along the west Indian coastline to join the eastward flowing SMC (Figure 2b; Schott et al. 1994; Schott & McCreary 2001). After passing the coast of Sri Lanka, the currents form an anti-clockwise eddy known as the Sri Lanka Dome located (83E, 7N) and (Figure 2b; Vinayachandran & Yamagata 1998). The western arm of this eddy drives a southward current along the eastern coast of Sri Lanka whilst the remainder flows northward along the eastern Indian coast and continues as the EICC (Figure 2;Vinayachandran & Yamagata 1998; Schott et al. 1994).

The island of Sri Lanka and the Maldives Islands occupy a unique location due to their position at the crossroads of water exchange between the Arabian Sea and the Bay of Bengal. Due to the sheer volume of water being transported by the major monsoon currents flowing against these islands, this interaction leads to the generation of recirculation features such as eddies.

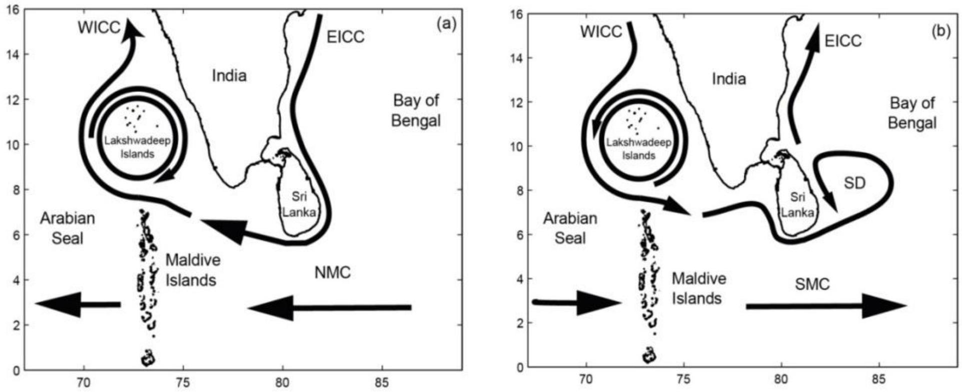

Figure 2: Circulation patterns in the Northern Indian Ocean (a) NMC flows from east to west and occurs during the NEM from December to April . (b) The SMC flows from west to east during the SWM from June and October (Vos et al. 2013) and the Sri Lanka Dome (SD) is observed only during the SWM.

Island wakes and the Island Mass Effect

The theoretical basis for the formation of islands wakes is analogous to the phenomenon of a 'Von karman vortex street', where a series of vortices detach from a cylindrical barrier when placed in a steady inertial flow environment. In a non-rotating frame and homogenous fluid with a steady unidirectional flow, the nature of flow downstream of a barrier (known as the 'wake') ranges from laminar to turbulent (Barton 2001). This flow is usually characterized by the Reynolds number defined as $Re = UD/\nu$ where U is the constant upstream flow speed, D is the horizontal scale of the barrier and ν is the coefficient of molecular viscosity. As the Reynolds number increases, the wake flow transitions from being viscous to inertial. Detachment of vortices occurs as a result of the frictional boundary layer separation in the inertial regime at moderate Reynolds numbers, estimated in the range of 40-1000. In similar fashion, the Island Wake Parameter developed by Wolanksi et al (1984) uses this concept to predict the likelihood of eddy formation and stability behind islands. Island wakes can be classified into two main categories based on their formation mechanism: oceanic wakes and atmospheric wakes. Oceanic wakes refer to eddies that are generated and shed by an oceanic flow around a barrier, such as an island or a headland. Alternatively, atmospheric wakes induce eddy formation through wind flow around an atmospheric barrier, such as a tall island, which generates wind shear in the lee.The "Island Mass Effect" (IME), refers to the enhanced primary production that occurs around oceanic islands in comparison to the surrounding waters and is the result of flow topography interaction around an island (Doty and Oguri 1956). There are several physical mechanisms that may create an IME: (1) strong tidal mixing around the island, which enhances vertical mixing locally (2) uni or bi-directional flow past the island that generates a wake often extending downstream (3) freshwater runoff or (4) local wind shear stirring the surface layer sufficiently to cause local upwelling. The IME has been observed in various case studies; Caldeira et al. (2002) reported the enrichment of planktonic biomass off the Madeira Island in the north eastern part of the Atlantic Ocean. Intensification of oceanic production around islands has also been reported off Barbados (Cowen & Castro 1994), the Sombrero and St. Croix Islands (Corredor et al. 1984), the Canary Islands (Basterretxea et al. 2002; Barton et al. 2004) and the Aldabra and Cosmoledo atolls (Heywood et al. 1990).

The Indian Ocean Dipole Mode

The IOD is a coupled ocean-atmospheric mode in the tropical Indian Ocean (Sreenivas et al. 2012). During positive IOD years, due to increased upwelling near the Sumatra coast, cooler sea surface temperatures (SST) are observed in the south eastern tropical Indian Ocean, while warmer SST are observed in the western tropical ocean. This leads to droughts over the Indonesian region and heavy rains and floods over East Africa. When the sign of the IOD reverses, these temperatures also swing to the opposite phase. During negative IOD years, the south eastern tropical Indian Ocean experiences enhanced downwelling and increased SST while cooler SST are observed in the western tropical ocean. The role of equatorial forcing has been shown to impact the eddy generation mechanism in the Bay of Bengal (Sreenivas et al. 2012) via coastal Kevin waves and the associated radiated Rossby waves.

SECTION 4. RESEARCH PLAN

There are three key research themes that will be addressed throughout this research project. Theme 1 investigates the monsoonal influence on the island mass effect around Sri Lanka and the Maldives; Theme 2 will address the elucidation of the dominant generation mechanism for island mass effect through the application of a sensitivity analysis while Theme 3 will establish the relationship between the IOD/ENSO events with the IME. Each of these research themes will be applied tothree specific locations (Figure 3) within the NIO region where the focus will be on the recirculation features unique to that area and developed into three separate journal papers.

The first paper will examine the upwelling dynamics along the southern coast of Sri Lanka and looks at the upwelling cell and how it responds to the monsoons and interannual variability events. The recirculation feature present is the product of flow convergence and remains ‘attached’ to the coastline. The second paper’s focus is on the Sri Lanka Dome which is similar to an attached headland eddy and its interannual variability and stability are compared over a 10 year simulation to see its response to IOD/ENSO events. Similarly, the monsoonal and interannual variability of the multiple wake eddies along the Maldivan coastlines forms the basis of the third paper.

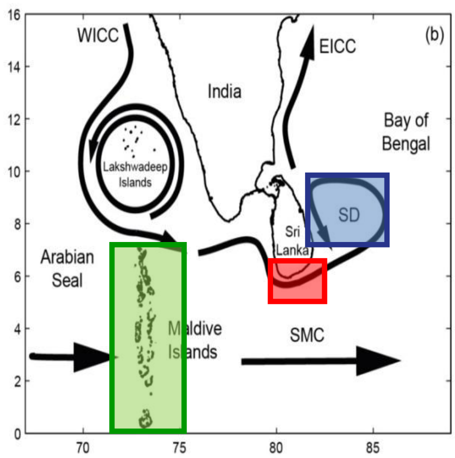

Figure 3: Study regions within the NIO. The red area is the southern coast of Sri Lanka and will form the basis for Paper 1. The blue area is the region of the Sri Lanka Dome

and will be examined in Paper 2. Lastly, the green region for the Maldives is the study location used in Paper 3.

Research Methodology

Model Configuration

These questions will be addressed by running idealized three-dimensional numerical simulations using the Regional Ocean Modelling System (ROMS) to deconstruct the acting forces on the upwelling cell and to quantify their relative contribution to upwelling. ROMS is a three-dimensional numerical ocean model based on the non-linear terrain following coordinate system of (Song & Haidvogel 1994). It solves the incompressible, hydrostatic, primitive equations with a free sea surface, horizontal curvilinear coordinates and a generalized terrain-following s-vertical coordinate that can be configured to enhance resolution at the sea surface or seafloor (Haidvogel et al. 2008). The model formulation and numerical algorithms are described in detail by (Shchepetkin & McWilliams 2005).The numerical model will use data from the following sources (Coastline Data (NOAA NGDC)(http://www.ngdc.noaa.gov/); Bathymetry(GEBCO)(http://www.gebco.net/data_and_products/gridded_bathymetry_data/); Boundary (HYCOM) (https://hycom.org/);Forcing Data such as wind and heat fluxes (ECMWF) http://apps.ecmwf.int/datasets/data/interim-full-daily/ and Tidal forcing (OSU Tidal Data Inversion) http://volkov.oce.orst.edu/tides/). The model will then be validated with field observations. Figure 4 summarizes the grid configuration for the current model domain.

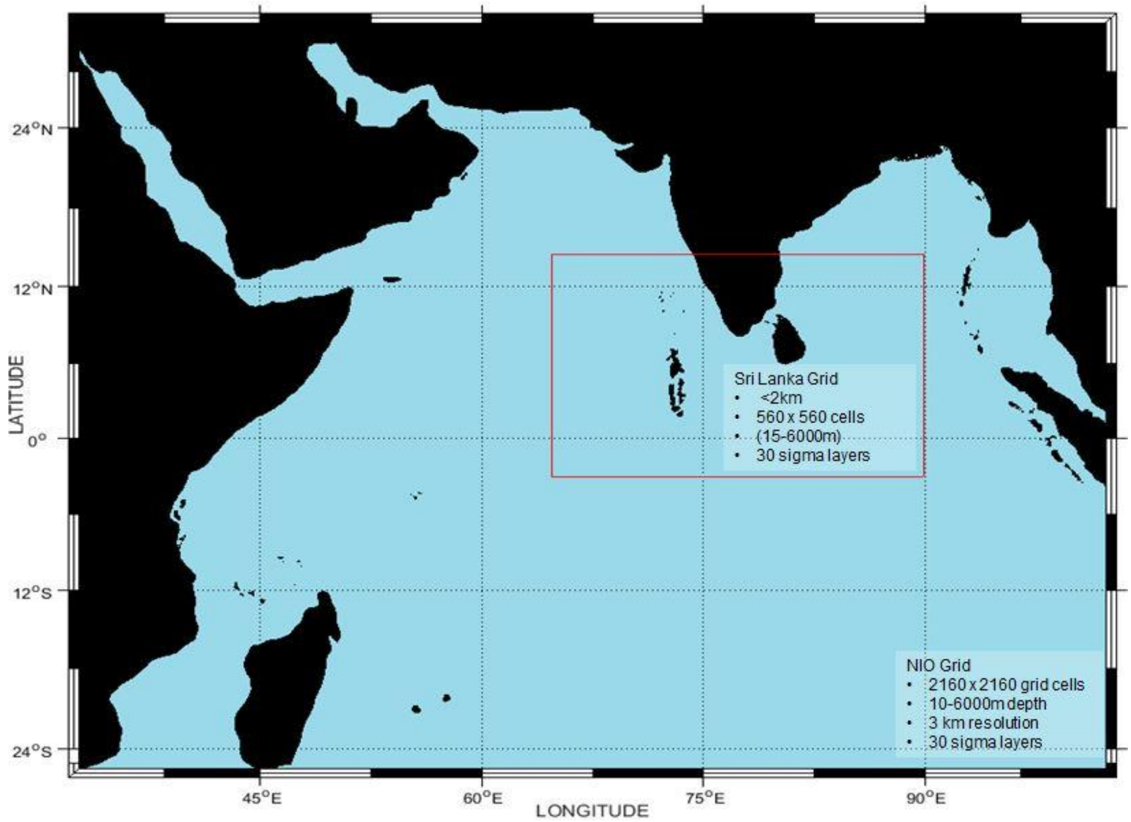

Figure 4: Grid configuration for Northern Indian Ocean model. The red box indicates the grid domain used for the preliminary model runs around Sri Lanka.

Sensitivity Analysis

Most eddy studies tend to focus on the sea surface and little is known about the vertical structures of the eddies in the region.A detailed understanding of the formation mechanisms for these recirculation features will be vital in evaluating the influence of Indian Ocean Dipole Mode upon them and how they will respond to a changing global climate in the future. Island wakes can be a product of wind stress, topographic forcing and oceanic flow, to name a few factors. We will look at the vertical structure of these wakes to see how the upwelling depth is modified under different conditions using a sensitivity analysis. There will also be a development of a workflow for reconstructing the vertical structure of island wakes.This paper will apply the methodology of Dong and McWilliams (2012) where an eddy data set will be identified from the numerical product and the eddy kinetic energy will also be calculated for each of the NIO wake eddies.

Identification of Indian Ocean Dipole Mode years

The IOD has the potential to impact eddy genesis due to the influence it has on the Rossby and Kevin waves (Sreenivas et al. 2012). This is because an IOD event induces anomalous remote winds in the NIO, creating variability in the sea level, which can affect the periodicity and intensity of Kevin waves (Chowdary & Gnanaseelan 2007; Aparna et al. 2012; Sreenivas et al. 2012). Sreenivas et al. (2012) showed that the observed annual cycle of coastal Kevin waves and their associated radiated Rossby waves play a prominent role in the evolution of mesoscale eddies in the Bay of Bengal. The IOD can also affect the Indian summer monsoon rainfall (ISMR) on its own and can weaken or strengthen the influence of ENSO on the ISMR (Ashok et al. 2001). Because of the existence of positive and negative events in the two major tropical climate phenomena, the influence on ISMR depends on the phase and amplitude of the IOD and ENSO (Ashok et al. 2001). Thus, the variability and intensity of the wake eddies could be altered due to the change in volume transport in the ocean from the freshwater input from the ISMR. This observation, along with the frequent occurrence of intense IOD events in the last decade has prompted investigations into whether the moving correlation between the IOD and the ISMR changes from decade to decade and in particular, its role in the weakening of the monsoon ENSO correlation (Ashok et al. 2001). In addition, monsoon surges have also been known to alter the development of island wakes as evidenced in the Philippines (Pullen et al. 2008). The IOD is commonly measured by an index that is the difference between SST anomalies in the western (50°E to 70°E and 10°S to 10°N) and eastern (90°E to 110°E and 10°S to 0°S) equatorial Indian Ocean. The index is called the Dipole Mode Index and will be used to identify positive and negative IOD years for comparison. The model runs will be conducted over a 10 year simulation period between 2006-2016 to study the variability in the recirculation features around Sri Lanka and the Maldives and account for IOD years based on the dipole mode index produced by (Saji et al. 1999). The methodology will be similar to that of Palastanga et al. (2006) who had previously established a link between low-frequency mesoscale eddy variability around Madagascar and the IOD where sea surface height (SSH) was used as a measurement of eddy activity, along with eddy kinetic energy.

Paper 1: Upwelling dynamics along the southern coast of Sri Lanka

Research Question: How does the island mass effect around the southern coast of Sri Lanka vary between the monsoons and interannually?

Research sub questions

- Elucidation of the three dimensional structure of the upwelling cell along the southern coast of Sri Lanka during the SWM and NEM
- What is the importance of shelf topography in contributing to the upwelling?
- At what depth does the upwelling start?
- What are the mechanisms for generating the upwelling?

During the SWM, increased chlorophyll concentrations were observed from MODIS imagery along the southern coast of Sri Lanka (Figure 2; Vinayachandran et al. 2004). These elevated chlorophyll concentrations are associated with high primary productivity and have been attributed to coastal upwelling, advection by the SMC and open ocean Ekman pumping (Vinayachandran et al. 2004; Vos et al. 2013). Chlorophyll concentrations appeared low during the NE monsoon, but feeding aggregations of blue whales along the southern coast indicated evidence of high productivity (Figure 2; Vos et al. 2013). This meant that upwelling along the southern coast was prevalent throughout the year, instead of being limited to the SWM as previously thought. Vos et al. (2013) proposed that the supporting mechanism for the upwelling during the NEM was due to flow convergence and flow curvature induced secondary circulation that reinforced the traditional mechanism of wind driven Ekman upwelling during the SWM. Their study also provided evidence for the importance of the Coriolis force on the circulation in the region and the formation of the Sri Lanka Dome. A similar case study for this type of upwelling was also observed along the northern shelf of Taiwan (Chang et al. 2010).

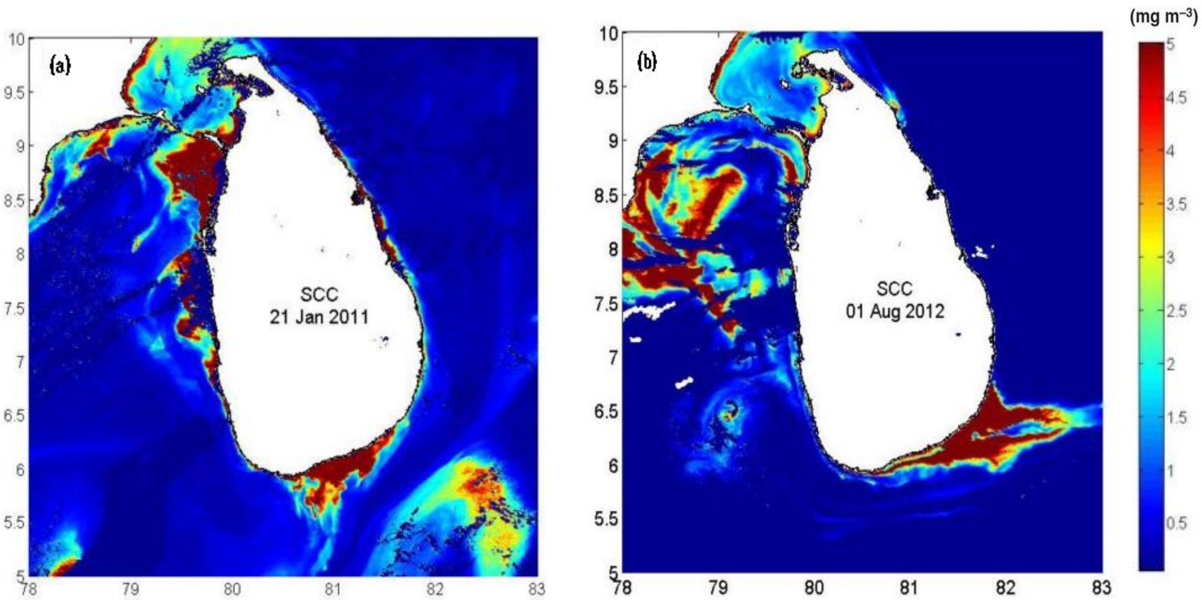

Figure 4: Surface chlorophyll concentrations (SCC) along the southern coast of Sri Lanka (a) during the NEM and during (b) the SWM (De Vos et al. 2013).

Paper 2: The generation mechanisms and the interannual variability of the Sri Lanka Dome

Research Question: What is the dominant generation mechanism of the Sri Lanka Dome and how will it respond to ENSO/IOD events?

Research Sub Question

- What is the interannual stability fo the Sri Lanka Dome?

Paper 3: Monsoonal and interannual varibaility for the wake circulation around the Maldives

The Maldives Islands are located to the south of India 73ºE and to the west of Sri Lanka and form a barrier to the NMC during the NEM (Sasamal 2007)**.** The channels through the Maldives have varying widths which allow equatorial water to flow through, creating wake eddies that develop off the islands, mixing stratified equatorial water. Sasamal (2006) has shown using MODIS derived chlorophyll-*a*data that theisland mass effect on the western coast responds to the NMC and the decay of the IME phenomena was observed along with the reduction in the westward flow from the NMC. . However, although the westward flow can be seen through the altimeter data, it does not always correspond to a significant chlorophyll plume e.g. March 2004 (Sasamal 2007). A potential question here is why the presence of these anticyclonic eddies does not always coincide with the occurrence of a chlorophyll plume. This could be related to the depth and extent of which these wake eddies produce upwelling. In addition, there has been a lack of characterization for this counterpart feature along the eastern coast during the SWM due to high cloud cover present in the MODIS imagery.

Research Question: How does the island mass effect around the Maldives vary between the monsoons and interannually?

Research Sub Questions

- What is the 3D structure of the recirculation features downstream of the Maldives?
- What is the extent of influence of the resultant IME along the Maldives?
- How will the eddy kinetic energy within these eddies vary on intraseasonal and interannual scales?

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