VARIABILITY OF SURFACE CIRCULATION AND BIOLOGICAL PRODUCTIVITY OF SOUTHERN INDIAN OCEAN IN REMOTE SENSING PERSPECTIVE

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I dedicate this thesis to my family and friends.

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ABSTRACT

The Indian Ocean has a unique geographic location that is not connected to the North Pole (blocked by the Asian Land mass at around 26°N) but it has a wide opening to the Antarctic Ocean. Therefore, the oceanic and atmospheric circulation of the Indian Ocean is significantly controlled by the processes occurring in the Southern Ocean region. In this study, a comprehensive analysis was carried out to derive information of the spatial and temporal variability of surface circulation, and biological productivity of the Southern Indian Ocean using the available remote sensing observations. The monthly multi-mission merged satellite altimeter data with a resolution of 1/3 x 1/3 degrees in latitude and longitude from Archiving, Validation and Interpretation of Satellite Oceanographic Data, Collective Localisation Satellites; France (AVISO) for the period of 1993-2010 were used to estimate the surface currents in this study. The biological productivity was analysed using the Chlorophyll-*a* (Chl-*a*) data from Sea Viewing Wide Field-of-View Sensor (SeaWiFS) from September 1997 until December 2010. The maps of seasonal circulation patterns and the Chl-*a* distribution were prepared and analysed. The Empirical Orthogonal Function analysis was carried out to identify the spatial and temporal modes of Chl-*a* variability of Southern Indian Ocean. Available in-situ oceanographic observations of currents were used to validate the accuracy of the estimated velocity field. The surface velocity field in the Southern Indian Ocean shows active circulations comprising of Agulhas Current, Agulhas Return Current and Antarctic Circumpolar Current. The seasonal Chl-*a* maps show high Chl-*a* concentration prevails in the coastal region of Africa, central region and south of Australia. At south of Africa, influence of coastal current is more significant than the climatic indices. Meanwhile, in the central region, large topographic barriers near Kerguelen Island play an important role in modulating the Chl-*a* concentration. In south of Australia, high Chl-*a* concentration along the west coast is related to Leuuwin Current eddies and land run-off. In this study, no significant relationship was found between the climate modes of El Nino Southern Oscillation (ENSO)/Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). The propagation of Antarctic Circumpolar Wave (ACW) also influences the mesoscale dynamics as well as the Chl-*a* distribution.

ABSTRAK

Lautan India mempunyai lokasi geografi yang unik dan ianya bersambung dengan Kutub Utara (disekat oleh daratan Tanah Asia di sekitar 26°U) tetapi mempunyai pembukaan yang luas ke Lautan Antartik. Oleh itu, peredaran lautan dan atmosfera Lautan Hindi dikawal dengan ketara oleh proses yang berlaku di bahagian lautan selatan. Dalam kajian ini analisis menyeluruh telah dijalankan untuk memperolehi keberubahan ruang dan masa bagi peredaran permukaan, dan produktiviti biologi Lautan Hindi Selatan menggunakan cerapan penderiaan jauh sedia ada. Gabungan data bulanan satelit altimeter pelbagai misi dengan resolusi 1/3 x 1/3 darjah dalam latitud dan longitud daripada arkib, pengesahan dan tafsiran data satelit oseanografi, pengumpulan penempatan satelit; Perancis (AVISO) bagi tempoh 1993 hingga 2010 telah digunakan untuk menganggarkan arus permukaan dalam kajian ini. Produktiviti biologi telah dianalisis dengan menggunakan data klorofil-*a* (Chl-*a*) daripada *Sea Viewing Wide Field-of-View Sensor* (SeaWiFS) mulai September 1997 hingga Disember 2010. Peta corak peredaran bermusim dan taburan Chl-*a* telah disediakan dan dianalisis. Analisis Fungsi Ortogon Empirikal telah dijalankan untuk mengenal pasti mod ruang dan masa keberubahan Chl-*a* Lautan Hindi Selatan. Cerapan oseanografi asal bagi arus telah digunakan untuk mengesah ketepatan medan halaju yang dianggarkan. Medan halaju permukaan di Lautan Hindi Selatan menunjukkan peredaran aktif yang terdiri daripada Arus Agulhas, Arus Pulangan Agulhas dan Arus Antartik Sirkumpolar. Peta bermusim Chl-*a* menunjukkan kepekatan Chl-*a* yang tinggi wujud di wilayah pantai Afrika, kawasan tengah dan selatan Australia. Di selatan Afrika, pengaruh arus pantai adalah signifikan daripada indeks iklim. Manakala di kawasan tengah, halangan topografi besar berhampiran Pulau Kerguelen memainkan peranan yang penting dalam memodulasi kepekatan Chl-*a*. Di selatan Australia, kepekatan Chl-*a* yang tinggi di sepanjang pantai barat adalah berhubung kait dengan pusaran Arus Leuuwin dan larian tanah. Dalam kajian ini, tiada hubungan yang signifikan ditemui antara mod iklim *El Nino Southern Oscillation* (ENSO)/*Indian Ocean Dipole* (IOD) dan *Southern Annular Mode* (SAM). Penyebaran *Antartic Circumpolar Wave* (ACW) juga mempengaruhi dinamik mesoskala serta taburan Chl-*a*.

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LIST OF SYMBOLS

CO^2	-	Carbon dioxide
E	-	East
g	-	gravity
HCO^{3-}	-	Hydrogen Carbonate
Km	-	Kilometer
Kg/m^3	-	Kilogram per meter cube
m	-	meter
m/s	-	meter per second
mg/m^3	-	milligram per meter cube
N	-	Geoid height
S	-	South
ζ	-	Sea surface dynamic topography

LIST OF ABBREVIATIONS

AASW	-	Antarctic Surface Water
ABW	-	Antarctic Bottom Water
ACC	-	Antarctic Circumpolar Current
ACW	-	Antarctic circumpolar wave
ADCP	-	Acoustic Doppler Current Profiler
AIW	-	Antarctic Intermediate Water
ARC	-	Agulhas Return Current
ARF	-	Agulhas Return Font
AVISO	-	Archiving, Validation and Interpretation of Satellite Oceanographic Data, Collective Localisation Satellites; France
AZ	-	Antartic Zone
CDW	-	Circumpolar Deep Water
Chl-*a*	-	Chlorophyll-*a*
ENSO	-	El Nino Southern Oscillation
ENVISAT	-	Environmental Satellite
EKE		Eddy Kinetic Energy
EOF	-	Empirical Orthogonal Function
ERS	-	European Remote Sensing
Fortran	-	FORmula TRANslation
HNLC	-	High Nutrient Low Chlorophyll
Jason	-	Joint Altimetry Satellite Oceanography Network
IGY	-	International Geophysical Year (IGY)
IOD	-	Indian Ocean Dipole
LC	-	Leeuwin Current

LCDW	-	Lower Circumpolar Deep Water
MSLA	-	Mean Sea Level Anomaly
Matlab	-	Matrix Laboratory
NADW	-	North Atlantic Deep Water
NASA		National Aeronautics and Space Administration
NSTF	-	North Subtropical Front
ODV	-	Ocean Data View
PF	-	Polar Front
PFZ	-	Polar Frontal Zone
Poseidon	-	Positioning Solid Earth, Ice Dynamics, Orbital Navigator
SAM	-	Southern Annular Mode
SAMW	-	Subantarctic Mode Water
SB	-	Southern Boundary
SeaWiFS	-	Sea Viewing Wide Field-of-View Sensor
SLA		Sea Level Anomaly
SST	-	Sea Surface Temperature
SORP	-	Southern Ocean Research Partnership
STF	-	Subtropical Front
SAF	-	Subantarctic Front
SSTF	-	Southern Subtropical Front
TOPEX	-	Topography Experiment
TZCF	-	Transition Zone Chlorophyll Front
UCDW	-	Upper Circumpolar Deep Water
WOCE	-	World Ocean Circulation Experiment

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the past 50 years, Antarctic Ocean (Southern Ocean) has been receiving much attention by marine researchers as it is playing significant role in regulating global climate system. Even though it is geographically remote, Antarctic Ocean influences the whole planet through its deep reaching overturning circulation (Rintoul *et al*., 2012). Thus, the southern hemisphere circumpolar oceanic belt maintains as the centre of ocean circulation.

Antarctic Ocean circulation is comprised by the broad Antarctic Circumpolar Current (ACC) which connects the three major oceans and serves as a principal pathway of exchange between these basins and controls the distribution of heat, salt, momentum and nutrients. ACC is the largest current system in the world oceans and recognized to be the dominant force for global overturning circulation (Mayewski, *et al*., (2009). The eastward flow of ACC is driven by strong westerly winds and it transport shallow and deep water parts.

Southern Ocean is also the formation region of important water masses of the world oceans. The Antarctic Bottom Water forms when the surface water moves southward and where it becomes more cold and salty enough to sink to the deep ocean. While some of it moves northward where water becomes warmer and fresher ultimately sinks on the northern side of ACC and spreads to the north forming Intermediate Antarctic Water. This pattern of two counter rotating cells is known as overturning circulation. The resulting global circulation redistributes heat and other properties, influencing patterns of temperature and rainfall over the globe.

Moreover, one of the important features of Antarctic Ocean is the Southern Hemisphere westerly wind field. Many of the large scale and regional changes in the physical aspect of the Southern Ocean have linked to changes in wind forcing, in particular Southern Annular Mode (SAM) which appears to dominate inter-annual variability of westerly winds in the Southern Ocean. Fogt and Bromwich (2006), stated that SAM can be defined as alternating pattern of strengthening and weakening of westerly winds with low pressure at high latitude while high pressure at mid latitude zone. Thus, SAM is essentially a zone of climate variability that encircles the South Pole and strongly influences zonal winds, sea ice formation, oceanic circulation and biological productivity (Bromwich *et al*., 2012)

Antarctic Ocean is the most biologically productive ocean and has unique marine ecosystem. Antarctic Ocean known as High Nutrient Low Chlorophyll region (HNLC), phytoplankton biomass is generally low, despite high concentrations of macronutrients, often ascribed to the lack of the micronutrient iron. The Southern Ocean food web is characterised by a keystone species, like Antarctic krill (Euphausia suberba). Furthermore, according to British Antarctic Survey in 2010, highlighted that Antarctic Krill’s population keep declining, Krill’s are very important food source to Antarctic food web and this decline could threaten the population of whales, seals and penguins.

Antarctic Ocean is one of the least sampled among the world oceans. Preliminary information on Antarctic Ocean has been obtained from the South Polar Cruises of UK research Vessel Discovery during 1930's where there are very few surface observations of temperature and salinity. Later, many international programmes like International Geophysical Year (IGY) expeditions, World Ocean Circulation experiment (WOCE), Southern Ocean Research Partnership (SORP) have enhanced the quality and quantity of oceanographic observations of the Antarctic region.

1.2 Problem Statement

Among the two polar oceans, Antarctic Ocean is well connected to the tropical region of the major oceans and hence even the slightest change in its physical processes in the circumpolar ocean propagates to the low latitudes through its circulation. This is due to the Antarctic Ocean circumpolar extent and has great oceanic surface area relative to the Northern Hemisphere. Thus, the present phase of climate change has drawn substantial amount of attention to the activities of Antarctica and physical processes in the Southern Ocean.

The Indian Ocean has a unique geographic location that is not connected to the North Pole (blocked by the Asian Land mass at around 26 °N) whereas; it has a wide opening to the Antarctic Ocean. Therefore, the oceanic and atmospheric circulations of the Indian Ocean are significantly influenced by the processes occurring in the Southern Ocean region. The distribution of heat, salt and other biogeochemical properties are closely related to horizontal and vertical circulations occurring in the circumpolar region.

Biological production of Antarctic Ocean is also affected by climate change since its food web is closely related physical aspects of the ocean, which have the potential to significantly alter the marine ecosystem. So, there are concerns about sustainability of marine ecosystem, especially with regard to species such as Patagonian toothfish and Antarctic krill. For instance, decrease in Antarctic krill can be related to reduction in ice cover and changes in westerlies. As the consequences the community of phytoplankton also affected as together with whale, penguin and seals populations. In order to understand the on-going climate change and associated changes in the biological resources, knowledge of physical processes occurring in the high latitudes is essential.

The recent advancement in satellite remote sensing has been providing time series observations of various oceanic parameters with greatest accuracy and fine resolution even for remote oceanic regions. Hence, realising the importance of Antarctic Ocean on the global climate system and biological resources system, a comprehensive investigation were carried out to understand the spatial and temporal variability of circulation and biological productivity of the Antarctic region of the Indian Ocean using the available remote sensing observations.

1.3 Research Questions

Research questions are the fundamental core of a research project and it is developed in order to fulfilled objectives of present study. Thus the research questions of this study are as follows:

(a) How to derive the spatial and temporal features of surface circulation of subantarctic region of the Indian Ocean?

(b) What is the method being used to determine the seasonal to inter-annual variability of biological productivity?

(c) What is the influence of climate modes on surface circulation and productivity?

(d) How is the surface circulation influence biological productivity of the study region?

1.4 Objectives of Research

The aim of this research is to identify the dynamics of ocean circulation on the biological productivity of the study region. Thus the objectives of the research are to:

(a) Derive the spatial and temporal features of surface circulation of Antarctic region of the Indian Ocean.

(b) Determine the seasonal to interannual variability of biological productivity of Southern Indian Ocean.

(c) Identify the influence of climate modes on surface circulation and productivity.

(d) Infer the influence of surface circulation on biological productivity in the Southern Indian Ocean.

1.5 Scope of Research

The present study intends to investigate the biological productivity of Southern Indian Ocean in relation to ocean circulations. The details of the study region, data and software are used are as follows:

(a) Area of Study

The area selected for present study covers between is 20˚E - 120˚E and 30˚S - 70˚S which includes southern region of Indian Ocean (Subantarctic sector).

(b) Data

In this study, satellite altimetry observation, in situ current data and Chlorophyll (Chl-*a*) data are used. The monthly multi-mission merged satellite altimeter data with a resolution of 1/3 X 1/3 degree in latitude and longitude is used in this study. The Sea Level Anomaly (SLA) produced by the Collect Localisation Satellites (CLS), France (AVISO, 2014*)*. The satellite altimetry data is obtained by integration of Topex/Poseidon-ERS and Jason-Envisat for the period of 1993 - 2010. The Chlorophyll-a (Chl-*a*) is obtained from Sea Viewing Wide Field-of-View Sensor (SeaWiFS) for the period of September 1997 - December 2010 are employed to determine the ocean productivity. The in-situ current observations Acoustic Doppler Current Profiler (ADCP) obtained from World Ocean Circulation Experiment (WOCE) cruise is also used to validate the accuracy of velocity estimations.

(c) Tools and Software

The present study involves dynamical computations and statistical analysis. The FORTRAN software is used to estimates the geostrophic velocity and Matlab software for EOF (Empirical Orthogonal Function) analysis. Mapping of surface currents and Chl-*a* were made using the Ocean Data View (ODV).

1.6 General Methodology

The general methodology of this study is shown in figure 1.1 which involved Research area identification where the study covers the subantarctic region of Indian Ocean as mentioned in Section 1.5. Next stage covers the data acquisition part, satellite altimeter data collected from AVISO, mean surface velocity, in-situ data and remotely sensed Chl-*a* (refer Section 1.5). Final phase of this study are results and analysis where importance given in analysing the spatial and temporal features of both surface circulation and biological productivity and relationship between both attributes are rectified.

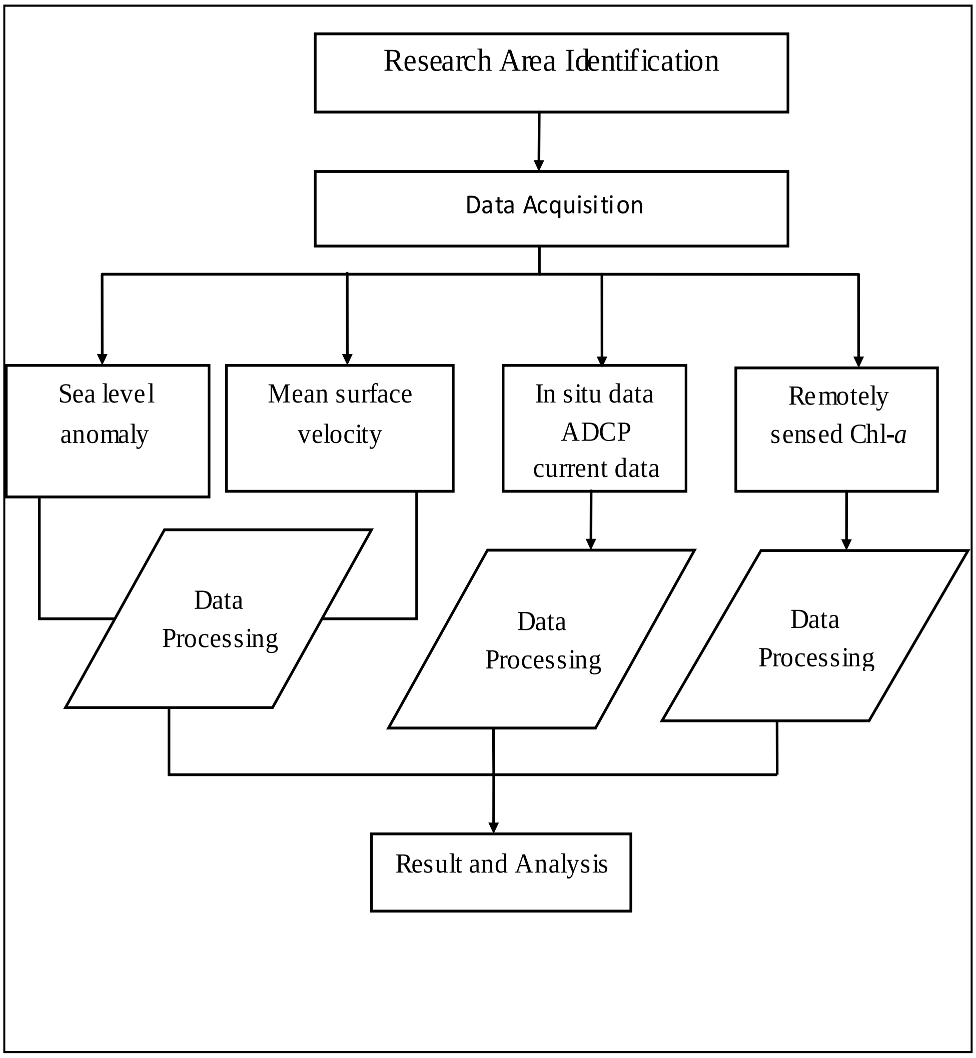

Figure 1.1 Overview of general methodology

1.7 Significance of Research

The present investigation on circulation of Southern Indian Ocean derived the spatial and temporal variations taking place in the surface currents of the Antarctic – subtropical regions of the Indian Ocean. The changes in the surface currents and physical processes in this region are very significant to understand the exchange of mass, heat, salt and momentum between Polar and tropical regions. Hence, it will give an insight to climate change occurring in the Antarctic region and its influence on the tropical regions.

Moreover, high latitude marine ecosystems contribute for more than 75% of the global ocean primary production, with the Southern Ocean as a major contributor. The sea level measurements by altimeter can reveal the ocean eddies whether it cold core eddies or warm core eddies near ocean surface. The cold core eddies are usually rich in dissolved nutrients which is required for the growth of phytoplankton and fish food. The existence of the phytoplankton attracts marine organism to assemble at the cold core eddies. Thus, ocean circulation patterns affect the distribution, productivity and resilience of fish stock. Fishing industry generates a huge income from high latitude fishing. Thus, outcomes of this study will be benefited for the optimum utilization of biological resources and maintaining sustainable marine ecosystem.

The surface circulation information through this study benefitted to support the marine operation and research by scientist since there is no study conducted on this particular study area. In offshore exploration, this would be helpful for engineers in monitoring the stresses on offshore structure and identifying area with minimum impact from strong current. This is because strong current may affect the platform structure and cause further damage in offshore exploration drilling activity and development processes.

1.8 Thesis Outline

This thesis consists of five chapters. Chapter 1 clarifies the main ideas of this research including the research background, description of the study area and also the tools and software that are being used to perform this research. Some justifications on the importance of carrying out this research are also being discussed. The aim and objectives of this research are pointed out in Section 1.4. Besides that, scope of the research is outlined in the Section 1.5 to understand the limitation of this research.

Chapter 2 provides review of earlier studies on the Antarctic Ocean with reference to Indian Ocean on first Section. Followed by brief description in atmospheric circulation of Antarctic Ocean comprising of Southern Annular Mode (SAM) and Antarctic Circumpolar Wave (ACW). Further discussion on Antarctic Ocean circulation in Section 2.4 and climate modes on Section 2.5. Besides, more insight into structure of zonation of Antarctic Circumpolar Current (ACC) which includes definition of all fronts and zones, correlation between the fronts and zone and its general characteristic. In Section 2.7 water masses of Antarctic Ocean was explained followed by biological productivity of the ocean on next Section. Finally details on the role of satellite altimetry in measuring the geostrophic current.

Chapter 3 give details on methodology used to carry out this research. It started with a flowchart to clarify the process of the data acquisition, data processing and visualization.

Chapter 4 discussed starts off with surface mean geostrophic velocity field, anomaly field, zonal current distribution and verification with in-situ ADCP current data. In second part, brief explanation on seasonal mean surface absolute geostrophic velocity and mean seasonal Chl-*a* concentration of Southern Indian Ocean. Moving on to the next Section, analysis of the time series map of EKE followed by overlaid geostrophic velocity field with Chl-*a* concentration and EOF analysis of Chl-*a*. Finally, thorough discussion on the output of this research is presented.

Chapter 5 give clear view on conclusion, recommendation, and limitation of this research.

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