# CLIMATE CHANGE AND POPULATION CONNECTIVITY OF LAKSHADWEEP ATOLLS

*by*

**ATHIRA PRASAD**

**(2013-20-120)**

**THESIS**

**Submitted in partial fulfillment of the**

**requirements for the degree of**

***B.Sc. – M.Sc. (Integrated) Climate Change Adaptation***

**Faculty of Agriculture**

**Kerala Agricultural University**

**ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH**

**VELLANIKKARA, THRISSUR – 680 656**

**KERALA, INDIA**

**2018**

# DECLARATION

I hereby declare that the thesis entitled **"Climate Change and Population Connectivity of Lakshadweep Atolls"** is a bonafide record of research work done by me during the course of research and the thesis has not been previously formed the basis for the award to me any degree, diploma, fellowship or other similar title, of any other University or Society.

Vellanikkara
Date: 11.12.18

**ATHIRA PRASAD**
(2013-20-120)

# CERTIFICATE

Certified that this thesis entitled **"Climate Change and Population Connectivity of Lakshadweep Atolls"** is a record of research work done independently by **Ms. Athira Prasad** (2013-20-120) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Place: Kochi
Date: 11.12.18

**Dr. Sreenath K.R.**
(Chairman, Advisory Committee)
Scientist,
Marine Biodiversity Division,
ICAR-Central Marine Fisheries Research Institute,
Kochi

# CERTIFICATE

We, the undersigned members of the advisory committee of **Ms. Athira Prasad** (2013-20-120), a candidate for the degree of BSc - MSc (Integrated) Climate Change Adaptation, agree that the thesis entitled **"Climate Change and Population Connectivity of Lakshadweep Atolls"** may be submitted by Ms. Athira Prasad, in partial fulfillment of the requirement for the degree.

**Dr. Sreenath K. R.**
(Chairman, Advisory Committee)
Scientist,
Marine Biodiversity Division,
ICAR-Central Marine Fisheries
Research Institute, Kochi

**Prof. Nameer P.O.**
(Member,Advisory committee)
Special Officer & Head
Academy of Climate Change
Education and Research
Vellanikkara, Thrissur

**Dr. Joshi K.K.**
(Member, Advisory committee)
Principal Scientist & Head,
Marine Biodiversity Division,
ICAR-Central Marine Fisheries
Research Institute, Kochi

**Dr. Grinson George**
(Member, Advisory committee)
Senior scientist,
Fishery Resources Assessment
Division
ICAR-Central Marine Fisheries
Research Institute, Kochi

**EXTERNAL EXAMINER**

H

# *ACKNOWLEDGEMENT*

*I would like to express my sincere gratitude to my mentor* ***Dr. Sreenath K.R.****, Scientist, Marine Biodiversity Division, Central Marine Fisheries Research Institute and Chairman of my advisory committee for his patience, motivation, and meticulous guidance throughout the period of my M.Sc. project work. He filled me with the qualities required for a researcher and made me more enthusiastic in the field of problem solving scientific research.*

*I must express my very profound gratitude to* ***Prof. Claire B. Paris****, Rosenstiel School of Marine and Atmospheric Science, University of Miami for the keen interest on my work, and the immense help in producing the results. I heartily thank* ***Dr. Ana C. Va****z and all the members of Paris Lab, University of Miami for the great support during my work.*

*I owe my deep gratitude to* ***Prof. Rupert Ormond*** *and International Society for Reef Studies (ISRS) for financial assistance in the form of ISRS graduate fellowship award.*

*I respectfully thank* ***Prof. Nameer P.O.,*** *Special officer, Academy of Climate Change Education and Research, KAU, Vellanikkara and* ***Dr. A. Gopalakrishnan,*** *Central Marine Fisheries Research Institute (CMFRI) to permit me to undertake this work. I extend my heartfelt thanks to* ***Dr. Joshi K.K.****, Principal Scientist and head of marine biodiversity division, Central Marine Fisheries Research Institute and member of my advisory committee for his scrupulous guidance, advices, valuable and timely suggestions given during my work. I express my thanks to* ***Dr. Grinson George,*** *Senior Scientist, Central Marine Fisheries Research Institute and member of my advisory committee for his constructive suggestions and constant motivation that guided me to complete this work.*

*I express my thanks to* ***Miss Krishna Priya ,*** *Teaching Associate, Academy of Climate Change Education and Research, for her whole hearted support during my whole college days. I would like to express my highest gratitude to My senior* ***Mr. Anand C. Babu*** *at a high level for laying out the foundation stone for my work at CMFRI. I am thankful to* ***Ms. Monalisa Sundar****, Research scholar, CMFRI, Kochi,* ***Dr. Phiros Shah****, Research Associate, CMFRI, Kochi and* ***Mr. Muhammad Shafeeque*** *Research Scholar, CMFRI, Kochi for their valuable help and support.*

*Let me thank* ***Ms. Shamiya Hasan, Ms.Haritha J., Ms. Aarathy G.S., Ms. Amitha J. Pai, Ms. Angel P. Sunny and Mr. Nidhish P. Madhu*** *for their help, support and generous care throughout the study.*

*I wish to express my obligations to* ***Alvin Anto, Aiswarya Mohan, Reshma Prasad, Asha Ravi, Varsha Soorej and Sethulakshmi, Sheeba B, Thobias P Antony and Aju K Raju*** *for their immense support during project work. I am thankful to* ***Academy of Climate Change Education and Research*** *for providing me the opportunity to complete the work. I am also grateful to all the staff for their support and help throughout the course of work.*

*I am greatly indebted to the Central Marine Fisheries Research Institute and the* ***Director*** *for providing all the amenities for the research programme. I am happy to thank all the* ***scientists, staff and workers of Marine Biodiversity Division*** *for their support and help. My heartfelt thanks and love to all my classmates of* ***Kauravas -2013,*** *for their support given to me during the whole college days.*

*Words are less to express my gratitude to my* ***Parents****, my sister* ***Aparna Prasad*** *and all my family members for being with me always, supporting and encouraging me in all of my endeavors. Their prayers and blessings were constant source of inspiration and guidance to me.*

**Athira Prasad**

# TABLE OF CONTENTS

# LIST OF FIGURES

# SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| SST | Sea Surface Temperature |
| IOD | Indian Ocean Dipole |
| ENSO | El-Nino Southern Oscillation |
| SSS | Sea Surface Salinity |
| CMFRI | Central Marine Fisheries Research Institute |
| IPCC | Intergovernmental Panel on Climate Change |
| EOF | Empirical Orthogonal Function |
| PC | Principal Component |
| CO2 | Carbon dioxide |
| PLD | Pelagic Larval Duration |
| MPA | Marine Protected Area |
| ONI | Oceanic Nino Index |
| MLD | Mixed Layer Depth |
| OND | October, November, December |
| TIO | Tropical Indian Ocean |
| IO | Indian Ocean |
| CCSM | Community Climate System Model |
| SMC | Summer monsoon Current |
| OMZ | Oxygen Minimum Zone |
| AIRI | All India Rainfall Index |
| SWM | South West Monsoon |
| ISMR | Indian Summer Monsoon Rainfall |
| HYCOM | Hybrid Coordinate Ocean Model |

| | |
|---|---|
| OSCAR | Ocean Surface Current Analysis Real-time |
| CMS | Connectivity Modelling System |
| ICOADS | International Comprehensive Ocean-Atmosphere Data Set |
| IHO | International Hydrographic Organization |
| SVD | Single Value Decomposition |
| Km$^2$ | kilometre |
| $^0$C | degree Celsius |
| % | Percentage |

# INTRODUCTION

# CHAPTER 1

# INTRODUCTION

Coral reefs are one of the oldest and extremely bizarre communities that function as a single unit. Despite the fact that coral reefs form only 0.2 per cent of marine environment, these are home to one-third of known marine species (Reaka-Kudla, 1997; 2001). Coral reefs are massive limestone structures built by the animals of Order: Scleractinia (Class Anthozoa) and other calcium carbonate secreting organisms including calcifying algae. Reefs are well known for high biological productivity and so they support the major marine life. They also act as the major carbon sink. In addition they are providing us with many pharmaceutically important products especially life saving drugs (Pillai, 1997). India's coral reef system comprises four major components viz., Andaman and Nicobar Islands, the Gulf of Kachchh, Lakshadweep Islands and the Palk Bay and Gulf of Mannar Biosphere Reserve. Lakshadweep Islands, a group of scattered coral reef islands in the Arabian Sea are the only atoll type of reefs in the territory of India (Jones, 1986).

We are on the verge of great shifts in climate. Multiple stresses on Asian coral reefs will result in loss of 30% corals within the next 30 years (IPCC, 2007). Increased sea temperature, chemical runoff from agriculture fields and other marine pollution were the stresses faced by most of the coral reefs. In addition, reduction in aragonite concentration due to climate change will also make corals more vulnerable (Gattuso et al., 1998). However, both climatic and non-climatic factors have various impacts on corals by increasing their vulnerability and decreasing resilience to temperature change (Buddemeier et al., 2004). According to IPCC (2007), a 2°C increase in sea surface temperature than that of 1990s will result in extinction of coral community.

The oceanic pH goes down, when the amount of dissolved CO2 increases and the availability of carbonate ions to calcifying organisms to form shells and skeletons may also decrease (Kleypas et al., 1999, 2005; Hoegh-Guldberg et al., 2007). Moreover, these changes will result in degradation of coral community bleaching and reef erosion. Water temperature, circulation patterns, water chemistry, sea level, the occurrence of tropical cyclones and El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events are some of the key global phenomena and environmental variables affecting coral reef ecosystems. These variables will affect the distribution of coral reef organisms, the structure of reef communities, and the function of key ecological processes such as population connectivity (Munday et al., 2009). Exposure factors like the increase in intensity of tropical cyclones will have the potential to damage coral reefs.

Cowen et al. (2000) described population connectivity as the exchange of individuals among geographically separated subpopulations. Both the ecological and evolutionary time scales connectivity is essential for the survival of marine metapopulations (James et al., 2002; Cowen and Sponaugle, 2009; Burgess et al., 2014). Population connectivity plays a domain role in community dynamics and structure, local and metapopulation dynamics, the resilience of populations to human exploitation, ecosystem responses to environmental changes, and genetic diversity (Cowen et al., 2007). Temperature, physical transport & dispersion, and dependent biological responses such as the pelagic larval duration (PLD), spawning timing, larval behavior, and mortality are the factors controlling the connectivity among marine metapopulations. The spatial scale of a population over which it is connected is determined by the pooled effect of these processes (Gawarkiewicz et al., 2007). The connectivity will vary highly across spatial and temporal ranges (Cowen and Sponaugle, 2009; Christie et al., 2010; Domingues et al., 2012). Knowledge on connection among corals reef regions are limited (Cowen et al., 2000; Sponaugle et al., 2002; Mora and Sale, 2002).

Climate change is likely to affect the scale of dispersal, thus considerably changing the patterns of biological connectivity in coral reef ecosystems (Munday et al., 2008). Andrello et al.(2015) suggested that climate change has a greater impact on connectivity and effectiveness of marine protected area (MPA) networks, and should receive more attention in future conservation planning and large-scale population dynamics. With this premises, the objectives of the present study are -

13

I. To assess climatic trends and variations in Lakshadweep waters.
II. To evaluate the possible effects of climatic change on larval connectivity between the reefs.

# REVIEW OF LITERATURE

# CHAPTER 2

# REVIEW OF LITERATURE

## 2.1 Climate Change

Climate change is a real phenomenon and is the biggest threat we are facing today. It can occur naturally or due to human activities. They have a greater role in refining the infrastructure and functioning of earth's water system. Its impact is faced by fragile mangrove swamps to great Arctic ice cover (IPCC, 2007). The change in intensity and frequency of precipitation patterns, sea level rise, ever elevating a number of extreme events such as cloudburst, tropical cyclones, droughts, floods etc are the outcome of changing climate (Hoegh-Guldberg and Bruno, 2010; Kundzewicz et al., 2014; Maikhuri et al., 2003). The earth is warming and is elevating the global temperature elevate to new levels. The warming which we are facing today is mainly attributed to the increased greenhouse gases (Dodman, 2009). The continual emission of greenhouse gas such as carbon dioxide, methane, chlorofluorocarbons will alter Earth's warming and modifies components of Earth's climate system (Boer et al., 2000). According to IPCC's 5th assessment report (2014), the greenhouse gas concentration in Earth's atmosphere reached 49 ± 4.5 Gt CO2 eq/year.

The ocean is an important carbon sink. The excess heat emission due to human activities had increased the amount of absorbance of heat by the world's Ocean (Reid et al., 2009). The adverse effect of climate change makes oceans more acidic and upsets the balance of a marine ecosystem. It also alters evaporation and precipitation cycles as well as broadly affecting the ocean chemistry, circulation, and ecosystems. Climate-driven warming impacts on biological productivity by reducing vertical mixing of seawater. Meehl et al. (2005) reported climate change as the primary cause of change in ocean circulation, precipitation pattern, sea level rise, increased intensity and frequency of storms. 40% of the sea level rise observed during the past 35 years was from warming of water.

16

### 2.1.1 ENSO

El Niño-Southern Oscillation (ENSO) is the strongest interannual climatic phenomenon occurring in the Pacific Ocean, which has significant global socio-economic and environmental impacts. ENSO has a greater effect on the ecology of tropical Pacific and global climate system. This phenomenon generally has two states: which is known as El Niño (warmer than normal central and eastern equatorial Pacific SSTs) and which is usually called as La Niña (cooler than normal SSTs of the same region) (Latif and Keenlyside, 2009). These two distinct phases repeat in every 2 to 10 years. The El Niño occurred during '2015-2016' is considered as one of the strongest El Niño event on record (Ineson et al., 2018). A convective loop formed due to the differential warming in the Pacific called as Walker Circulation strengthens during La Niña years and weakens during El Niño years (Power and Smith, 2007). ENSO is classified according to the onset time, propagation direction, periodicity, or the associated horizontal SST. Between central and eastern Pacific Ocean, there is a shift in SST anomaly.

ENSO induced sea surface temperature anomalies form a strong dipole pattern oriented along the zonal direction in the Indian Ocean in the coupled model, preventing the ENSO signals from reaching the Indian monsoon region (Achuthavarier *et al.*, 2012). The intensity of ENSO may vary with SST anomalies of Indian Ocean. Frauen and Dommenget (2012) suggested that the tropical Indian and Atlantic oceans influenced the dynamics and predictability of ENSO. Multi-decadal variations in the Pacific, Indian, and Atlantic Oceans have substantial ENSO components (Compo and Saedeshmukh, 2010).

Predicting an El Niño is a difficult process. There are several indices used to monitor ENSO event. The most commonly used indices are Niño 3.4 index and the Oceanic Niño Index (ONI) (Wolter and Timlin, 2011). One of the important factors to improve predictability of the East Asian climate during ENSO may be the atmosphere-ocean system in the Indian Ocean (Watanabe and Jin, 2002). Wu and Kirtman (2004) stated that ENSO state was stronger and occurred more frequently when the Indian Ocean SST in summer was relatively cold (warm),

17

whereas it is weaker and occurs less frequently when the Indian ocean is relatively warm (cold). In Indian Ocean, ENSO modulates the convective heating and Walker circulation over tropical Pacific and Indian Ocean.

One of the key components of the atmospheric bridge driving SST anomalies is Surface heat flux. Other than SST, atmospheric bridge also influences on the seasonal evolution of upper-ocean temperatures, salinity and mixed layer depth (MLD) (Alexander *et al.*, 2002). During the ENSO cycle, there is an active forcing happening on interannual variability in the Indian Ocean by wind stress and surface heat flux (Wu and Kirtman, 2004). It is able to describe a considerable part of the interannual variability in Indian ocean SST as the response to interannual fluctuations over the Pacific related to ENSO. The Indian Ocean region also exhibits ENSO-independent interannual variability. Large-scale SST anomalies may develop in the entire tropical and subtropical Indian Ocean with a time lag of about 4 months. The ENSO signal is carried into the Indian Ocean mainly through anomalous surface heat fluxes (Venzke et al., 2000).

Tropical Pacific imparts generous decadal climate inconstancy toward the western Indian Ocean and by suggestion, may constrain decadal changeability in different areas with robust ENSO teleconnections (Cole, 2000). An investigation done by Ashok et al. (2001) reported that depending on the amplitude and the stage of IOD and ENSO in the Indo-Pacific region, the IOD-actuated abnormal meridional circulation cell region is either countered or upheld to the ENSO-instigated anomalous circulation over the Indian region. According to Izumo et al. (2010) the quick demise of the Indian Ocean Dipole anomaly in November–December then induces a sudden collapse of anomalous zonal winds over the Pacific Ocean, which leads to the development of El Niño/La Niña.

Examinations of the Indian Ocean situation in the wider global context by (Allan *et al.*, 2003) provide strong evidence that 'protracted' El Niño and La Niña episodes result from interactions between quasi-biennial, if and quasi-decadal signals in the climate system. The situation in October-December (OND) also suggests that a propensity exists in the climate system for drought or flooding extremes to occur over central-eastern Africa to central Asia on quasi-biennial to decadal timescales and that this may particularly be manifested during 'protracted' El Niño and La Niña episodes. Major consequences for global teleconnection patterns, and thus have the potential to impact on both regional and remote climatic signatures.

ENSO has historically influenced the variability of both the IOD and the Asian monsoon (Abram *et al.*, 2008). According to Ihara et al. (2007), amid El Niño occasions, there is a noteworthy negative relationship between Indian south west monsoon and the zonal wind anomalies over the tropical Indian Ocean. There is a reversal in Indian monsoon– ENSO relationship when the Indian Ocean is decoupled from the atmosphere. The relationship between north Indian Ocean's surface wind, surface evaporation and SST had a strong linkage to this change (Wu and Kirtman, 2004). Recently Pokhrel et al. (2012) reported that a declining motion of anomalous Walker circulation is experienced during ENSO phase which diminishes the Indian summer monsoon while an elevating branch of anomalous Hadley circulation is associated with IOD phase resulting enormous rainfall during Indian summer monsoon.

Ihara et al., (2007) reported that the zonal wind anomalies and SST anomaly gradient over the equatorial Indian Ocean are used as indices that represent the condition of the Indian Ocean. There is only poor correlation between Indian summer monsoon rainfall and the index defined by the zonal wind anomalies. The linear reconstruction of Indian summer monsoon rainfall on the basis of a multiple regression from the Niño3 and this wind index better specifies the Indian summer monsoon rainfall than the regression with the only Niño3. During the typical El Niño (La Niña) event, easterly (westerly) anomalies are not induced until after boreal autumn, which is too late in the annual cycle to instigate strong dynamical coupling. ENSO events that develop early (i.e., before boreal summer) instigate a strong coupled response in the Indian Ocean. There is a strong linkage between Indian monsoon, Indonesian drought, and Indian Ocean climatic variability with the association and co-occurrence of ENSO failure of Indian Monsoon.

Warming in the Indian Ocean, which is a part of the El Niño signal, operates as a negative feedback mechanism to ENSO (Kug and Kang, 2006). The interactive feedback between the ENSO and the Indian Ocean holds the key to the rapid transition to an opposite phase (Kug et al., 2006). The studies conducted by Latif and Keenlyside (2009) concluded that there exists a large uncertainty in the response of ENSO to global warming. Some models simulate an increase in ENSO amplitude, while others a decrease and some virtually no change.

In a study conducted by Zinke et al. (2005) all coral records show clear teleconnections between the western Indian Ocean and the ENSO. The multi-proxy site analysis enables the detection of the covariance structure between individual records and climate modes such as ENSO. This method unravels shifts in ENSO tele-connectivity of the western and central Indian ocean on multi-decadal time-scales (after 1976). Strong ENSO forcing had a strong relationship with corals in Southwestern Indian Ocean (1880-1920, 1970 to present). In 1999, Hoegh-Guldberg explained the major coral bleaching experienced in the past decades had strong relationship with ENSO, especially in 1998.

### 2.1.2 Indian Ocean Dipole (IOD)

Indian Ocean Dipole (IOD) is a natural ocean-atmospheric coupled climatic variability occurring in tropical Indian Ocean region which causes many climatic extremes (Abram et al., 2007). Mostly, IOD are correlated with significant variation in rain and temperature in countries of Indian Ocean rim. A reduction in rainfall and warmer land surface anomalies were associated with positive IOD. There exists introduction of an anomalous anticyclonic circulation over eastern tropical and the subtropical Indian Ocean at lower levels during positive IOD (Ashok et al., 2003). During IOD, there exists a strong variability in troposphere above the Indian Ocean. The IOD is correlated with equivalent barotropic geopotential anomalies in the extra tropics while rossby waves determine the structure in southern hemisphere. (Saji and Yamagata, 2003). Ashok et al.,(2004) suggest that decadal modulation of the interannual IOD events are interpreted by the decadal IOD in the tropics.

Abram *et al.* (2008) used a coral oxygen isotope records which reveal that there is an increase in the frequency and strength of IOD events during the twentieth century, which is associated with enhanced seasonal upwelling in the eastern Indian Ocean. But there is no consensus on long-term variability of the IOD. Indian Ocean Dipole modulates the strength of the Walker circulation in autumn (Izumo et al., 2010). During the middle Holocene, IOD events were characterised by a longer duration of strong surface Ocean cooling along with drought which peaks later than expected by El Niño forcing alone (Abram et al., 2007).

Saji and Yamagata (2003) suggested that IOD events have the potential to occur independently even though they are often associated with an ENSO event. However the ENSO events co-occurring with IOD events were much stronger than non-co-occurring events. Izumo *et al.*, (2010) steered about the prediction of El-Niño before 14 months from the occurrence of negative IOD events with a simple forecast model. Hong et al. (2008) reported that, there existed a large difference in structure of occurrence and temporal evolution between IOD occurring with or without an ENSO event. In both negative and positive IOD events without ENSO, the wind anomaly in the eastern Indian Ocean seems to be responsible for the formation of sea surface temperature anomalies, while the anomaly in the western Indian Ocean seems to be the oceanic dynamical response to the anomaly in the east. During the peak phase of IOD events, the west early equatorial wind reverses their direction as easterlies. This time the western part has warm SST and Cool in the eastern side (Yamagata et al., 2004). The forcing of the off-equatorial Rossby waves, north of 10°S is directed by IOD which are mainly come from the anomalous Ekman pumping associated by IOD. Although, Rossby waves are dominantly forced by ENSO predominantly in the south of 10°S where the IOD activity is less (Rao and Behera, 2005).

The dipole modifies low-level winds and surface pressure, and grows in a positive feedback loop involving winds, surface pressure, and SST (Achuthavarier et al., 2012). IOD-monsoon connections imply that the socioeconomic impacts of projected future changes in Asian monsoon strength

21

may extend throughout Australasia (Abram et al., 2007). The Indian monsoon will get greatly impacted by a small change in IOD (Krishnaswamy et al., 2015). Thus, IOD plays a key role in modulating the Indian monsoon rainfall, and it also influences the correlation between the Indian Summer Monsoon Rainfall (ISMR) and ENSO (*e.g.* Ashok et al., 2001).

### 2.1.3 Salinity

Salinity has a great impact on marine biota. A small variation in salinity may severely affect marine biodiversity, abundance and alter the functioning of the ecosystem (Schallenberg et al., 2003). The balance between evaporation and precipitation resulted in variations in salinity and it is a sensitive indicator of climate change. Both remote forcing and ocean-atmospheric coupling apparently influence the salinity distribution in the Arabian Sea (Joseph and Freeland, 2005). Changes in ocean temperature and salinity patterns from global-warming induced increases in the Earth's hydrological cycle may weaken due to the intensified double-diffusive mixing (Johnson and Kearney, 2009).

Among the marginal seas of the Indian Ocean, the Bay of Bengal has low salinity compared to the Arabian Sea, due to the contrast in freshwater forcing of the two basins of Bay of Bengal (Vinayachandran and Kurian, (2008). According to Rostek et al., (1993) there is a reduction in the thickness of the near-surface mixed layer due to the incorporation of salinity effects. In the Bay of Bengal, this is very obvious, which builds up from June to July and becomes most prominent by February in the following year. It is found that horizontal advection of salinity is important during the summer monsoon season in western and eastern Arabian Sea and during winter in the south-eastern Arabian Sea. While in the Bay of Bengal it is throughout the year with the exception of pre monsoon season.

During August-September months there is a minimum salinity in the coast of north-west Bay of Bengal due to the influence of massive river outflow. In the coastal region of the north-western and south-eastern part of Arabian Sea and the northern Bay of Bengal, the seasonal variability of sea surface salinity was most prominent. (Rao and Sivakumar 2003). In the Bay of Bengal, the more saline

22

southern bay is separated by the low saline water of the North Bay Monsoon Current, which flows eastward in the northern Bay consequently plays an important role in the freshwater budget of the Bay of Bengal (Vinayachandran and Kurian, 2008). Vinayachandran and Nanjundiah (2009) used Community Climate System Model (CCSM 2.0) which marked low salinity in the east and high salinity in the west from the monsoon-driven seasonal sea surface salinity (SSS) pattern in the Indian Ocean.

Due to the differences in hydrological forcing, the annual average of sea surface salinity in the Arabian Sea and the Bay of Bengal shows contrasting distributions (Rao and Sivakumar 2003). The high salinity Arabian Sea Water circulates along with the Summer Monsoon Current (S-MC) from the Arabia Sea into the Bay of Bengal (Rixen et al., 2011). During winter-spring time along the western margin of India the northward flowing coastal currents advect the low-salinity Bay of Bengal water into the Eastern Arabian Sea and produce a distinct low-salinity tongue. Its strength is determined by the freshwater flux to the bay during summer monsoons. Although we can understand the past variations in the Indian Summer Monsoon from the salinity-gradient in the eastern Arabian Sea low-salinity tongue (Chodankar et al., 2005).

Du and Zang (2015) suggested that the IOD induces variation in SSS can be captured using satellites like SMOS (Soil Moisture and Ocean Salinity) and Aquarius. They added an increase of SSS farther to the south occur during the upwelling Rossby wave. Hay et al., (2006) calculated past salinity from reconstructed chlorine content of the ocean. He found that in the past, higher salinities for the world ocean have profound significances for the thermohaline circulation. Durand et al. (2007) revealed that in southeastern Arabian Sea, there is a strong impact between the runoff distribution and the India–Sri Lanka passage on the realism of the salinity simulated in the area at seasonal timescales. According to Rixen et al. (2011). In the times of global warming the mechanism maintaining oxygen concentration above the threshold of nitrate reduction in the OMZ of the Bay of Bengal could be the reduced propagation of oxygen-depleted high salinity Arabian Sea Water into the Bay of Bengal. While comparing with the coupled model simulations of the North Atlantic Ocean, Indian Ocean's interannual variability of SSS is around five fold larger Vinayachandran and Nanjundiah (2009).

In the Indian Ocean, significant SST anomalies appear only during IOD years. SSS anomalies for ENSO years are much weaker than during IOD years. The SSS anomalies are existing as two zonal bands. This includes positive salinity anomalies south of the equator and negative salinity anomalies to the north of the equator. Kültz (2015) reported that euryhaline fishes inhabit to the environment with variable salinity which has a wide range of salinity tolerance. They are able to control dynamic changes in osmoregulatory strategy with an evolutionary advantage with adaptive radiation from the speedy changing climate.

### 2.1.4 Sea Surface Temperature

Chang et al. (1997) proposed that there is an unstable thermodynamic ocean-atmospheric interaction between wind-induced heat fluxes and Sea Surface Temperature (SST) which results from the decadal variation in the tropical SST dipole. A positive correlation of SST was found between tropical Pacific and Northern Tropical Atlantic while the correlation is negligible in Tropical Pacific and South Atlantic. Towards the end of a season, combined with the substantial tenacity of SST in both Oceans, there is a seasonal mean relationship result from the relatively strong monthly relationship (Uvo et al., 1998).

Along with the strong ENSO teleconnection to the western Indian Ocean and alternative regions, the tropical Pacific could force decadal climate variability (Cole et al., 2000). The Tropical Pacific Sea Surface Temperature is closely correlated with the interannual variation of the Indian monsoon. Clark et al. (2000) found a positive correlation between SST and monsoon rainfall in the tropical Indian Ocean while SST has a negative correlation on All India Rainfall Index (AIRI) in subsequent autumn in the northern Indian Ocean. However, a strong correlation (0.53) is found among the summer AIRI and the preceding December–February Arabian Sea SST. There is also a strong relationship between the variability of the Indian monsoon and Indian Ocean sea surface temperature (SST) variability including analysis of potential long-lead predictions of Indian rainfall by regional SST and the influence of ENSO and decadal variability on the stability of the relationships. A strong influence is exerted by sea surface temperature (SST) anomalies in the Eastern Equatorial Pacific Ocean and the Arabian Sea on withdrawal and length of rainy season prior to the climate shift In the post-climatic shift period, there is an influence of Indian Ocean SST on withdrawal of Indian Summer Monsoon and also, a decrease in upper troposphere temperature gradient over the main Monsoon regions (Sabeerali, 2012).

Munday *et al.* (2009) suggested that an increase in ocean temperature is expected to speed up the larval development, which in turn reduces the pelagic duration and also promotes reef-seeking behaviour. A small rise in temperature is likely to enhance the number of larvae surviving the pelagic phase while reduced reproductive output and an increased larval mortality rate may result from increase in temperature. Sheppard et al. (2002) reveals that in the central Indian Ocean reef of Chagos, there is an increase in herbivores and detritivores and reduction in species dependent on corals. The data on SST shows that the mean SST has risen to 0.65°C since 1950. In Chagos, the critical sea surface temperature causing larval mortality was 29°C.

Recently, coral reefs have experienced an extraordinary decline as the world's oceans continued to warm (Cacciapaglia and Van, 2016). During 1998, approximately 42% of reefs bleached to some extent with 18% strongly bleached while 54% of reefs bleached to some extent in 2002 with 18% strongly bleached. Change in the natural nutrient environment of coral reduces their tolerance to light and heat stress. Modeling done by Berkelmans et al. (2004) on the relationship between bleaching and maximum SST occurring over any 3-day period (max3d SST) specifies that a 1°C rise would increase the bleaching rate of reefs from 50% to 82%, while a 2°C increase would increase the rate to 97% and a 3°C increase to 100%. These results suggest that even to a small increase in temperature coral reefs are profoundly sensitive and are likely to suffer large declines in the absence of acclimatization/adaptation.

Based on the new coral records Nurhati et al. (2001) suggests that in the central tropical Pacific low-frequency SST and salinity variations are measured by different sets of dynamics and that recent hydrological trends in this region may be related to anthropogenic climate change. Cacciapaglia and van (2016) predicted that turbidity will protect some coral species more than others from climate-change-associated thermal stress.

McNeil et al. (2004) predicted that with the future ocean warming, there would be an increase in annual mean calcification rate of coral which outpace pre industrial rate about 35% by 2100. (Ainsworth et al., 2016) found that a small increase in local temperature of 0.5°C in near-future result in loss of ability to mitigate thermal tolerance which may increase the rate of degradation of the Great Barrier Reefs. Obura (2005) identifies three concepts of 'thermal protection', 'thermal resistance' and 'thermal tolerance' on affecting coral-zooxanthellae holobiont and reef vulnerability to thermal stress previously termed 'resistance to bleaching'. Analysis of archive sea-surface temperature (SST) data by Purkis and Riegl (2005) confirmed that there is at least a partial link between El Niño Southern Oscillation (via Indian Ocean Zonal Mode) and the area was subject to recurrent and cyclic temperature anomalies at a frequency. Wooldridge et al. (2005) suggested that in future beyond 2050, the persistence of hard coral reefs capes will be profoundly reliant on the coral's ability to increase their upper thermal bleaching limit by 0.1°C per decade and the management of algal biomass proliferation during an inter-disturbance interval.

Studies say that bleaching is not only affecting the reef health, and coral diseases but also the breakdown of reef framework by bioeroders, and the loss of critical habitat for associated reef fishes and other biotas (Baker et al., 2008). Palumbi et al., (2014) reciprocally transplant the corals between the reef sites experiencing distinctive temperature regimes and tested succeeding physiological and gene expression profiles to conclude the mechanism of temperature tolerance. Heat tolerance and the reflectance in gene pattern are also contributed by local acclimatization and fixed effects, such as adaptation.

### 2.1.5 Precipitation and Monsoon

The Indian Monsoon, the largest monsoon system on earth drives Precipitation over India. The differential seasonal diabatic heating of Asia and the Indo-Pacific Ocean plays a key role in the change in Indian Monsoon (Reuter et al., 2013). The meteorological records on Indian Ocean Monsoon Rainfall are available generally less than 100 years long. The increase in Sea Surface Temperature (SST) in the Indian Ocean results in the decrease in monsoon rainfall over the past century (Burns et al., 2002). According to Shukla and Huang (2016), ISM predictability from monthly to seasonal scales is mainly contributed by the pre-monsoon Arabian Sea conditions.

Since the link between Indian Monsoon and global warming is far unknown, Reuter et al.(2013) implies that an increase in global warming doesn't make changes in South Indian Monsoon rainfall. While the seasonal atmospheric flow during the monsoon seasons in Southeast Asia and global warming show varying degree of fuzziness. As a result of Climate change, a delay of 15 days in the onset of Southeast Asian Monsoon is predicted in near future. (Loo et al., 2015).

Seth et al. (2013) projected that with the response to anthropogenic activities the global monsoon is predicted to increase in precipitation, intensity, area. He had found a redistribution of rainfall from early to late monsoon season. Gupta et al. (2003) suggests that there is a persistent link between the North Atlantic region and Asian monsoon. Krishnan and Sugi (2003) found that inter-decadal fluctuation of Pacific Ocean sea surface temperature (SST) have a coherent inverse relationship on the Indian monsoon rainfall during the last century. A decreased summer precipitation in the western North Pacific is associated with the enhanced precipitation over the Arabian in summers (Conroy and Overpeck, 2011).

Meehl and Washington (1993) found an increase in the surface temperatures and evaporation with greater mean precipitation in the south Asian summer monsoon region. Association with the land and Ocean temperature in the monsoon region, a trend of increased interannual variability of Indian Monsoon is

27

observed. During SW monsoon, the high salinity Arabian Sea Water circulates from the Arabia Sea into the Bay of Bengal circulates along with the Summer Monsoon Current. May (2004) revealed an increase in the intensity of heavy rainfall events in the near future with a large increase over the tropical Indian Ocean and Arabian Sea, Pakistan and Northwest India as well as in Northeast India, Myanmar, and Bangladesh.

During the last four decades, the IOD and the El Niño/Southern Oscillation (ENSO) have complementarity effect on the interannual variability of the Indian Summer Monsoon Rainfall (ISMR). If the ISMR–ENSO correlation is high (low), then the ISMR–IOD correlation is low (high) (Ashok et al., 2001).

Shukla and Huang (2016) suggest Indian summer Monsoon have a major connection with El Niño-Southern Oscillation (ENSO). Krishnan and Sugi (2003) analyzed that, the vulnerability to drought is more in Indian Monsoon when El Niño events coincide during warm phases of the Pacific interdecadal variability on the contrary when La Nina events occur during cold phases of the Pacific interdecadal variability, wet monsoons are more likely to prevail. Ihara et al. (2007) reveals that the Indian summer monsoon rainfall and the zonal wind anomalies have a significant negative association over the equatorial Indian Ocean during El Niño events. Levine and Turner (2012) say that through the development of Somali Jets, ENSO is feeding back to the monsoon.

## 2.2 Coral Connectivity

### 2.2.1 Seasonal and annual pattern of current system in the Northern Indian Ocean

Indian Ocean has a complex wind as well as circulation patterns (Wyrtki 1973). The results from the studies conducted by Mojgan et al. (2017) says that the trend of wind speed is reduced from 1981 to 2015 while there is a considerable change in wind patterns. Also, there is a noticeable increase in sea surface temperature is observed over Indian Ocean. This phenomenon confirms the effects of global warming and the Current patterns in the Indian Ocean. Shape of land masses as well as configuration of ocean bed was affecting the ocean currents. The major climatic factors affecting current system are wind patterns, temperature and salinity (Shetye et al., 1994).

Indian Ocean is extremely differing from other ocean because of its land locked pattern by Indian sub continent. Also, monsoon winds in these regions had peculiar effect on Indian Ocean. The major northern Indian Ocean currents are southwest monsoon currents, northeast monsoon current, Equatorial counter current, Somali Current. Prior to the arrival of monsoon, Indian Ocean becomes warmer among the world oceans (Clemens et al. 1991). This time, the Somali current will reverse its direction (Schott, 1983). Compared to other oceans, the presence of winter and summer monsoon winds changes flowing direction of Northern Indian Ocean currents twice a year.

The monsoon currents are open ocean currents which seasonally reverse its pattern between Bay of Bengal and Arabian Sea (Eigenheer and Quadfasel, 2000). This seasonal reversal in the surface circulation results in nutrient rich upwelling in Arabian Sea along its coast (Murtugudde et al., 2007). These currents extend over Somalia to eastern Bay of Bengal. During May to September, the south west monsoon currents flow eastward while the north east monsoon currents move westward during the month of November to February. The NE monsoon current is primarily geotropic current regulated by Ekman drift (Shankar et al., 2002). They first develop around Sri Lanka and moves eastward and during December to March in their mature phase, they flow to westward towards southern Bay and form two branches in Arabian Sea. One of these currents move around Lakshadweep high. On the other hand, South west monsoon develop around southern bay during May then during its matured period they reach at Arabian Sea and finally join with Somali Current. They move eastwards and south east wards around Lakshadweep low then to Sri Lanka and finally reach Bay of Bengal (Shetye et al., 1994).

Ocean currents have greater importance in climate studies. Different ocean current data are available now a day (e.g. OSCAR, HYCOM GOMl0.04, HYCOM GLBa0.08, AVISO DUACS, and Pacific ROMS-CoSiNE). We can

29

access ocean current data from Satellite and modeled datasets. Among satellite data OSCAR provides high resolution current data approximately 37 km at equator (Sikhakolli et al, 2013). While, there are modeled data available that have more resolution than satellite data. HYCOM is a near real time global model having resolution about 9 km (Winther and Evensen, 2006). HYCOM is more accurate and had similar resolution that of satellite (Barth et al., 2008). Joseph and Ravichandran (2012) validated 0.25 x 0.25 HYCOM model with buoy data and concluded that HYCOM perform well in reproducing zonal current data in equatorial region.

### 2.2.2 Occurrence and extent of life history stages and pelagic larval duration in corals

In Lakshadweep waters around 12 family and 130 species of scleractinian corals were reported (Pillai and Jasmine, 1989, Rajasuriya et al., 2002). Acropora and Porites were the most dominant coral species in Lakshadweep waters (Nobi et al., 2014). Pelagic larval duration (PLD) is an important component while studying larval connectivity which determines rate of dispersal. Larval dispersal had a key ambiguity in connectivity study. PLD varies with species to species. In case of close proximity island, if the spawned larvae are moving with shorter surface current it will increase connectivity between the islands while, on the other hand, decreases connectivity with distant islands. Pelagic larval duration, movement of larvae, its survival and competency will significantly influence the connectivity of larvae (Paris et al., 2007). According to the model developed by (Black, 1993) the larvae are assumed to be settled if they attain competent before flushed from the source reef.

### 2.2.3 Studies on pattern of larval connectivity between reefs elsewhere in the world

Connectivity usually refers to ‘‘the demographic linking of local populations through the dispersal of individuals among them as larvae, juveniles or adults’’. Larval connectivity is a whole life process (Pineda et al., 2007). The study of larval connectivity among corals is more dynamic and complex.

Knowledge on connectivity pattern will be helpful in planning efficient spatial management strategy for marine ecosystem and conservation (Mayorga-Adame et al., 2017). Connectivity among larvae is inherently driven with the help of some physical and biological factors. The physical environmental conditions such as current speed and direction, salinity and temperature are the factors determining the arrival patterns to the reefs. The biological factors that affect connectivity are competency period, swimming behavior, larval dispersal distance & duration, health & abundance of source population and availability of downstream habitat. Distance between archipelago and local oceanographic variables also influences larval connectivity (Knittweis et al., 2009). Across different reefs, the length of average connectivity varies significantly (Thomas et al., 2014). Coral bleaching and acidification will also impact connectivity by increased fragmentation of reef habitat (Munday et al., (2009). Different studies suggest that, population connectivity had a fundamental role in resilience and management strategies as well as local and metapopulation dynamics (Hastings and Harrison, 1994; Botsford et al., 2009). Paris et al. (2007) revealed that change in population connectivity may occur by self-recruitment impacted from larval behavior. Munday et al. (2009) used a biophysical model, which says that the reduced Pelagic Larval Duration (PLD) have a greater effect on connectivity patterns and are depends on the distribution of suitable habitats for settlement.

Scientific knowledge on behavior of dispersal has improved from recent empirical studies. An efficient approach to examine role of circulatory pattern in larval transport and connectivity between reefs is by using computer based simulations (Kendall et al., 2016). Generally hydrodynamic model is used to predict the dispersal patterns. But it lacks some information on larval biology. We can estimate the potential connectivity by simulating the larval transport among source and destination (Kendall et al., 2016).

Local population dynamics of corals were first modeled by Hughes (1984) and then Roughgarden et al. (1985). Treml et al. (2008) followed eulerian advection approach for modeling coral larval dispersal between reefs. The elements of larval dispersal matrices can be identified by tracking larval particles from biophysical circulation modeling (Botsford et al., 2009). Using six microsatellite markers, Nakajima et al. (2009) predicted that Acropora digitifera had connectivity of 5-25 km apart. Almany et al. (2009) mentioned that, the decrease in distance between reefs make more connectivity. According to Buston et al. (2012), there will be a fivefold decrease in probability of successful dispersal over 1 km between populations. In 2013, Paris et al. (2007) developed a Connectivity Modelling System (CMS) which can be used for tracking different floating particles in ocean. This model is highly recommended for larval monitoring and other migration. Kaplan et al. (2016) developed an R package 'ConnMatTools' for studying uncertainty about connectivity between larvae. They tried three techniques *viz*. natural chemical markers, artificial chemical markers, and parentage analysis for estimating connectivity. These techniques had a great contribution in future connectivity studies. Kendall et al. (2016) estimated future larval connectivity using Hybrid Coordinate Ocean Model (HYCOM) which results decreased connectivity with change in current pattern and also predicted poor connectivity with reduced PLD.

### 2.2.4 Influence of climate on coral larval transport

The amount of larval dispersal varies among and within species. Some larvae disperse within a little distance while others took 100s of kilometers. Climate change had the potential to affect larval transport and dispersal (Munday et al., 2008). Climate change will alter circulatory patterns of currents which carry the coral larvae from source to destination. Rate of larval development increases with increase in sea surface temperature that in turn results in decreased PLD and early reef seeking behavior (Munday et al., 2009). Greater the increase in temperature, a major expected change will influence reproductive phenology (e.g., shift in the spawning season) and results larval mortality (e.g., changes in the exposure to lethal temperatures) (Lett et al., 2010). While judging individual response, there is shift in abundance and distribution of corals with the impact if temperature (Harley et al., 2006). This may also acts on connectivity and dispersal patterns by modifying reproductive output, swimming behavior, larval transport, and mortality (Lett et al., 2010). Gerber et al., (2014) confirms a reduction in functional connectivity through reduction in potential dispersal from change in ocean climate. He has also suggested more closely spaced protected area to overcome spatial scale reduction in connectivity due to climate change.

Change in nutrient availability will also affect growth of coral larvae. An investigation conducted by Koop et al., (2001) stated that, the increase in nitrogen content will suppress the larval growth and subjected to mortality while, increase in phosphorus enhanced the larval settlement.

# MATERIALS AND METHODS

# CHAPTER 3

# MATERIAL AND METHODS

## 3.1 Study Area

The study was conducted in a region of the south eastern Arabian Sea constituting the waters around the Lakshadweep atolls i.e., 69° W, 7° S, 77° E, 15° N Grid. Lakshadweep is an archipelago with hundred thousand of islands, located 225 to 450 km away from southwest coast of India (Mallik, 2017). Lakshadweep coast extends to 132 km (Venkataraman, 2008) and consists of 35 islands of which 11 are inhabited. Minicoy, Agatti, and Amini are the chief islands which built up by corals having fringing type reefs very close to their shores. Lakshadweep is the only atoll type reef in India having 107 species of hard corals (George & Jasmine, 2015) with lagoon of 4,200 $km^2$. It has over 101 species of birds (Pande et al. 2007), 603 species of marine fishes, 52 species of crabs, 82 species of seaweed, 2 species of lobsters, 12 species of bivalves, 48 species of gastropods Venkataraman and Wafar, 2005; Apte, D. 2009). The island has a tropical humid climate and plentiful seasonal rainfall.

The Lakshadweep Sea or Laccadive Sea is a warm sea, bordering India (including its Lakshadweep islands), Sri Lanka, and the Maldives. Lakshadweep Sea has clear water, excellent coral reefs with diverse fishes, white sand beaches with coconut trees. It is located about 400 kilometres from the west coast of India, with majority of the islands lying to the north of the 9° navigation channel except southern island, the Minicoy which lies in the north of the Maldives. The sea surface temperature is quite constant over the year, with an average of 26–28 °C during the summer season and 25 °C during winter. In the centre and northern part of the sea, the salinity is 34‰ (parts per thousand) and in the south it is about 35.5‰. The direction of wind throughout the year in Lakshadweep sea is mostly north-west. Higher wind speed experienced during summer monsoon ranges from 5-8 m/s (Prakash *et al.*, 2015).

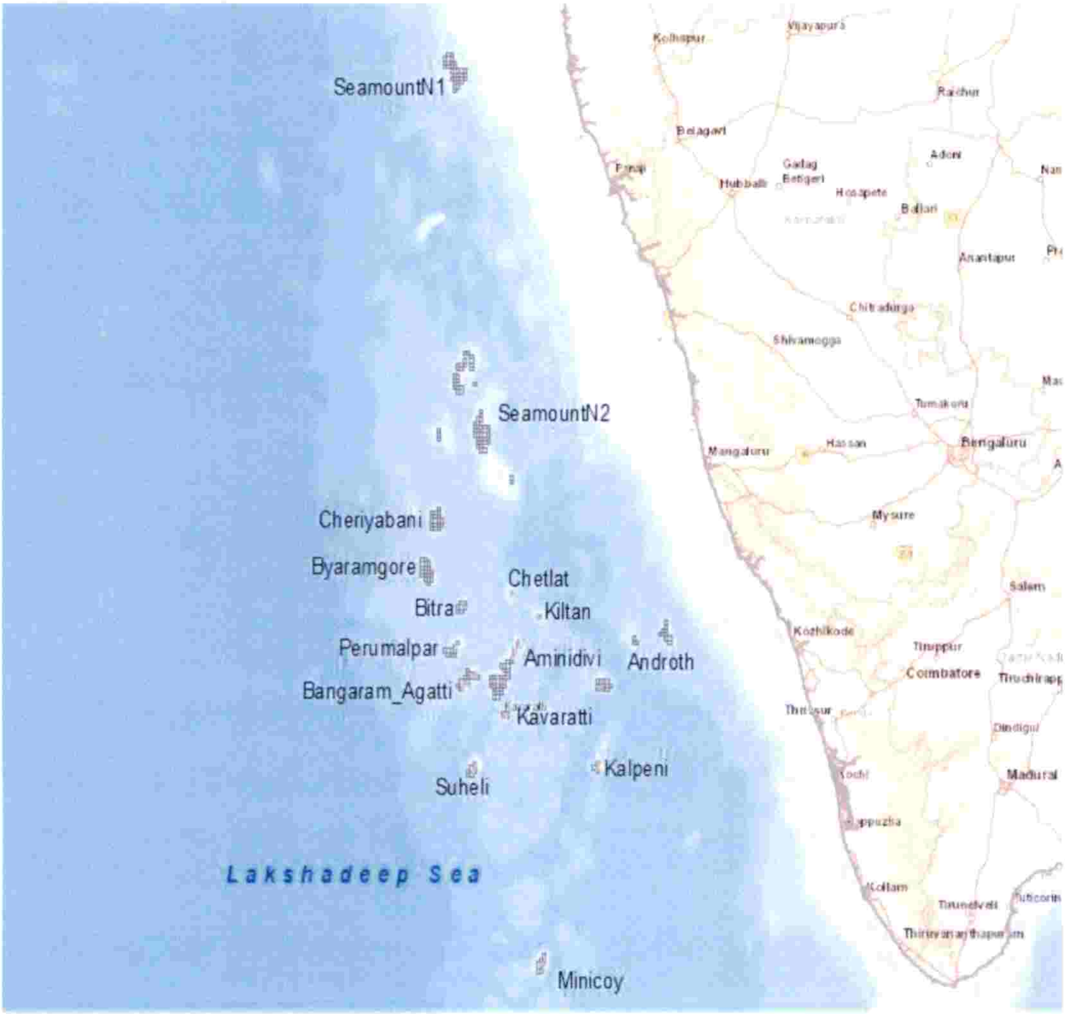

**Figure 1: Location map of the study area**

## 3.2 Collection and Compilation of Data

Reef data throughout Lakshadweep archipelago were collected from Millenium coral Reef mapping project (Andrefouet et al., 2006). The reef data were divided in 4 km x 4 km raster using Qgis 3.3.3 to create the habitat module of the reef. The reefs were divided based on bathymetry from General Bathymetric Chart of the Oceans (GEBCO); (http://www.gebco.net) to find the connectivity of deep and shallow Acropora species. Acroporids were highly studied as well as dominant species in this archipelago usually occur between 0 to 15m depth. Based on the data of the reef area, each cell of the grid was assigned a percentage of the reef. To find the local connectivity, the nodes were again subgrouped based on different islands in this region. Due to the low resolution in this area, we consider some of the small islands together as a single polygon (for example Bangaram with Agatti and Kadamat with amini) and also considered three seamounts for the study and named as seaN1 and seaN2 for the two northern seamounts and seaS1 for the southern one. The current data were collected from Hybrid Coordinate ocean model (HYCOM-Global 1/12 degree horizontal resolution) (Bleck, 2002). The CMS was coupled to the Global HyCOM in the Laccadive Sea to predict the probability of dispersal and connectivity of Acroporids in the region from 2015-2018. Particles were released from each spawning sites on and around full moon days of april and march using three dimensional velocity field.

## 3.3 Trend Analysis

### 3.3.1 Mann Kendall analysis

A comparison of the trend of SST in the marginal seas surrounding India was performed. Monthly $1^0$ latitude-longitude gridded hundred year data of Sea Surface Temperature (SST) from 1913 to 2012 were gathered from International Comprehensive Ocean - Atmosphere Data Set (ICOADS) (Woodruff *et al.*, 2011). Mann Kendall trend analysis has been performed to find the trend of SST. It is a non parametric test which helps to find the trend in a time series. Data were processed using 'ncdf4' package in R. IHO's standard has been followed to find the limits of the Oceans (IHO 1953, 2001). All the statistical analysis were performed using R ver 3.4.2 (R core, 2017). 'Kendall' (McLeod, 2005) and 'Trend' (Pohlert, 2016) packages were also utilised. The SST climatology of each sea has been plotted separately as Box plots using R. To know the monotonicity of the trend, Seasonal Mann Kendall test has been also performed. Mapping and spatial demarcation by clipping the data were performed in ArcGIS ver 9.3 software. Inverse Distance Weighting (IDW) using ArcGIS 9.3 has been used to interpolate the results to find spatial variation. 25 year SST climatology data for different quarters of the century as well as 25 years Kendall's trend value for different quarters of the century were plotted.

37

### 3.3.2 Empirical orthogonal functions

Empirical orthogonal functions (EOFs) are powerful and sophisticated techniques that are used to determine the dominant patterns of sea surface temperature (SST) variance in Northern Indian Ocean. EOF is a numerical computation based on a statistical theory which is widely used in climate studies in order to understand various spatial and temporal patterns in a climate system. It is possible to find underlying teleconnections using EOF analysis. If the EOF mode explains more than 50% variance at the centre of action then there exists a real teleconnection. The main objective of EOF is to attain decomposition of a continuous space-time fields into its some orthogonal modes or functions, which represents the changeability in the spatio-temporal pattern of original dataset. In this study EOF is used to identify the patterns in the spatio-temporal trend of sea surface temperature and salinity.

We can express time series data as:

$$D(m,n)=\sum_{i=1}^{P} \quad A_i(n)F_i(m)$$

where, m is the spatial dimension and n is the temporal dimension, $A_i$ is the temporal amplitude and $F_i$ is the eigenfunction.

We can achieve EOF analysis through singular value decomposition (SVD) method. Before applying SVD, we should remove spatial and temporal means from the dataset, which helps to extract spatial features like fronts, gyre and temporal variability.

We can decompose any matrix $D_{m\times n}$as:

$$D = USV^T$$

Here, U and V are the orthogonal matrices and S is the diagonal matrix. We get EOF or spatial patterns from each column of U while, V provides principal component related to which indicates the average time series. The 140 years data from January 1870 to December 2017 data of SST has been collected from HadISST1 (Rayner et al., 2003) imagery having $1^0$ resolution and sea surface salinity data of 114 years were collected from EN4.2.0 (Good et al., 2013). .

### 3.3.3 Time series analysis

To understand the underlying forcing of the data over time, time series graphs of average SST, SST anomaly, IOD and ENSO have been plotted. Using Multivariate ENSO index, years of strong El Niño and La Niña events were identified. Similarly, the positive and negative IOD events were also identified using Dipole Mode Index.

## 3.4 Population Connectivity

The simulation of larval connectivity of Lakshadweep atolls has been done using Connectivity Modelling System (CMS; Paris et al., 2013), an individual based which track movement of particles in the ocean. It is a probabilistic, Lagrangian framework based open source biophysical model coupled with GIS-based habitat, biological module, and local or regional currents. CMS uses output from HYCOM and track movement of larvae with time.

Our study has been conducted on Acroporids which are dominant species in this archipelago. They usually occurs between 0 to 15m depth. They spawn around march and april in this region (Jasmine et al., 2013; Howells et al. 2014, Kaplan et al. 2016). Acroporids are fast growing and are more resistant to environmental changes (Renema et al., 2016). Therefore resilience based works are easy to implement on acroporids. We have simulated the connectivity of coral (Acroporids) larvae for the months March and April of 2015 to 2018 in two climate scenarios *viz.*, 1. the current scenario with pelagic larval duration of 100 days and mortality of 50 days and 2. the climate change scenario with pelagic larval duration of 60 days and mortality of 30 days. We have used graph theory which will help us to understand the main linkage between the islands. For this study, a total of 1831 coral reef polygons were developed with 4km nodes and were used as the source and sink zone. Particles were released randomly from each nodes and they were tracked and their individual positions were recorded every year. Additionally, the dispersal and settlement of particles on suitable habitat with specified biological parameters were examined in both the scenarios. If the larvae in the simulation failed to reach suitable habitat, they will continue to move. The simulated particles are allowed to settle to the suitable habitat once competency period has reached.

The released particles includes biological parameters such as mortality, PLD, competency period, and settling on the coral substrate. The available data on PLD of Acroporid species indicates that they ranges from ~3.5 to 140 days (Ayre and Hughes, 2000; Baird 2001; Baums et al. 2005). This will vary geographically. In this study the maximum PLD of 100 days is considered for a normal scenario (Conolly & Baird, 2010; Munday et al., 2009; O'Connor et al., 2007). Full moon peak spawning was simulated by releasing planulae over 11 days following a Gaussian distribution. The planula's competency period was set from 4-100 days, with an exponential mortality of 50 days half-life. CMS Lagrangian dispersal kernels, connectivity matrices, and network analyses were carried out using Matlab R2018a.

# RESULT AND DISCUSSION

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Trend of Sea Surface Temperature

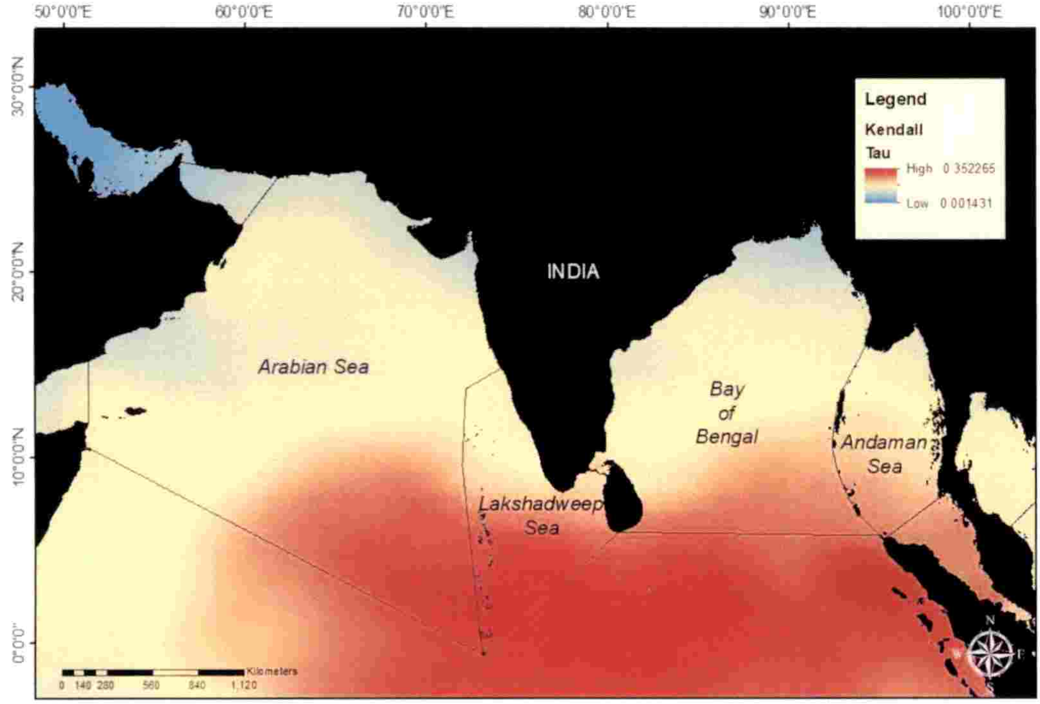

**Figure 2: 100 year SST trend of northern Indian Ocean by Mann Kendall test.**

A general indication of hundred year SST trend from 1913 to 2012 of northern Indian Ocean is represented in the Fig. 2. The interpolated map showed a maximum positive trend around the study area. Most of Laccadive sea is showing very high trend over these years. Thus, the high positive trend due to rise in temperature explains an unusual heating experience over the past few decades.

Among the four marginal seas of India, Lakshadweep sea is experiencing more fluctuation in SST which stresses the corals of these area and makes them more vulnerable. Such an increase in SST makes the coral undergo severe bleaching. Persistent increase in SST due to climate change would affect the survival of Lakshadweep corals threatening the extermination of the atolls from

42

the face of the earth. Heron et al (2016) has observed that 2016 was the warmest year on record. Later, World Meteorological Organisation reported 2015, 2016 and 2017 as the warmest years of Earth. Nevertheless, 2017 was the warmest without the occurrence of El Niño.

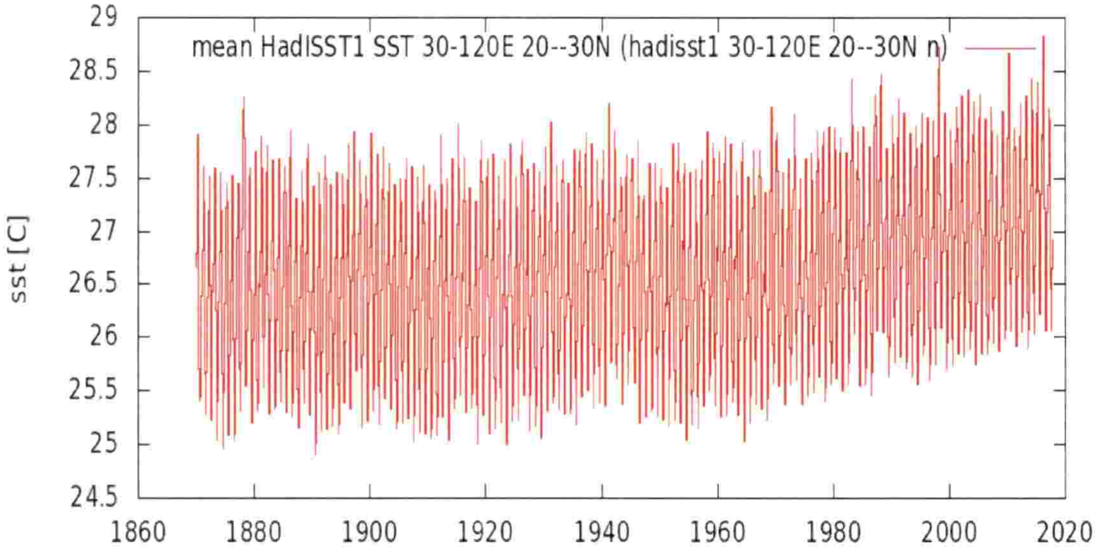

**Figure 3**: **Time series map of average SST over northern Indian Ocean from 1870 to 2017.**

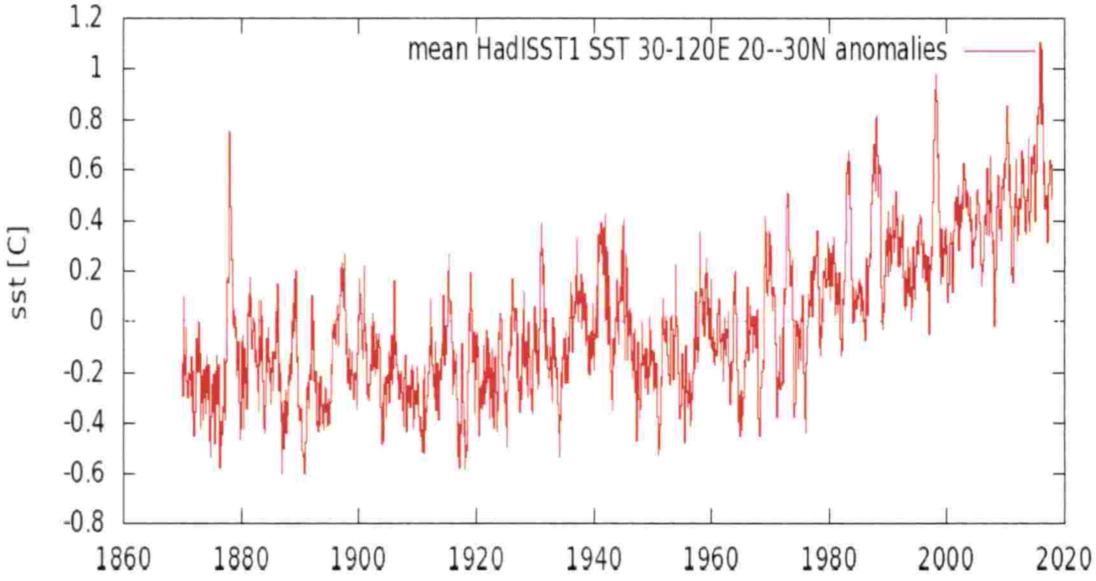

**Figure 4**: **Time series map of average SST anomalies from 1870 to 2017.**

43

Analysis of time series data of sea surface temperature in the Northern Indian Ocean (fig. 3 and 4) indicates a linearly increasing pattern of SST trend after 1960s. An increase of $1.5^{0}$C in SST was experienced during the past century. The current average temperature observed from the graph was around $28.75^{0}$C which can shoot above $29^{O}$C within a decade.

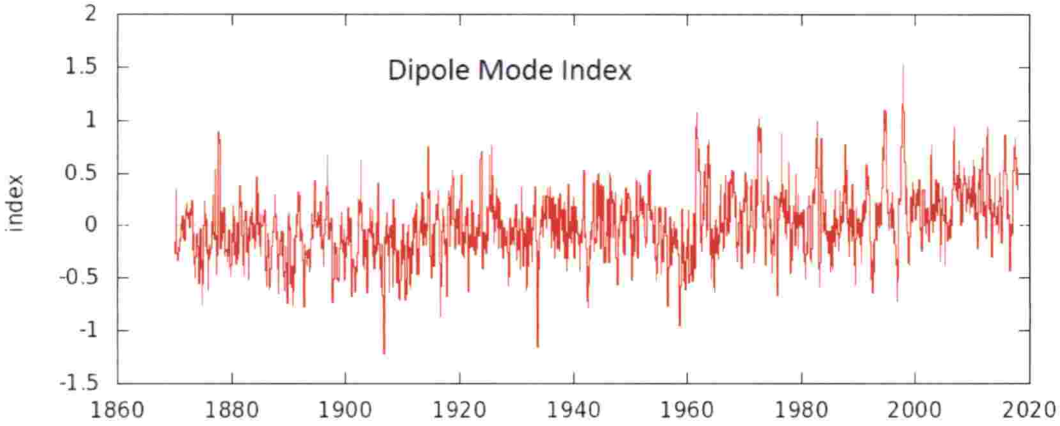

Figure 5: Temporal representation of IOD index

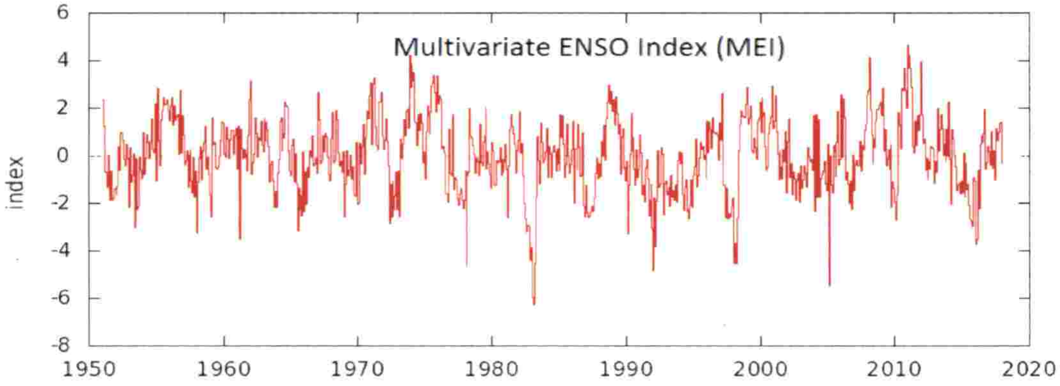

Figure 6: temporal representation of ENSO index

In order to understand the impact of ENSO (fig. 5) and IOD (fig.6) on Indian Ocean SST, temporal representation of ENSO and IOD events were performed. In the fig. 5, the positive values represent the warm ENSO phase (El Niño) and negative values represent the cold ENSO phase (La Niña). A large scale teleconnection was evident from the results. The El Niño of 1998 and 2016 were the highest ranked event on the decade. Several mass bleaching events were reported in these years among the study area.

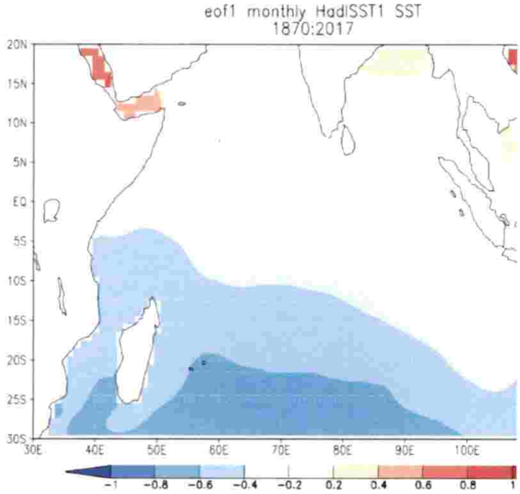

**Figure 7.a: First spatial mode EOF1 of SST from 1870-2017**

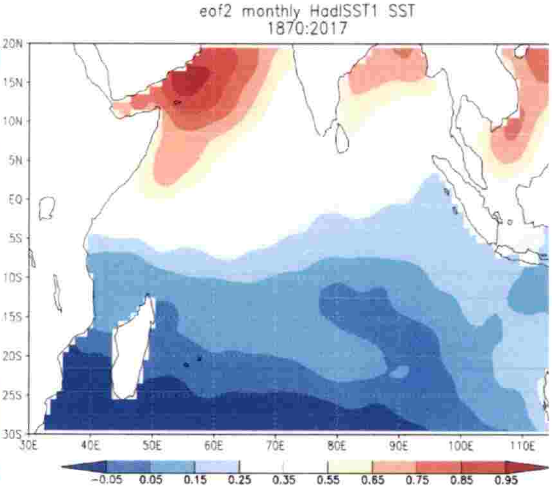

**Figure 7.b: Second spatial mode EOF2 of SST from 1870-2017.**

EOF analysis has indicated that above 80 % of variability was explained by EOF1 and EOF2. In the spatial map produced EOF1 (figure 7.a) is showing weak dipole pattern at the northern latitudes against the southern. However, EOF2 (figure 7.b) clearly shows a strong positive mode along the Oman coast and Bay of Bengal while there is strong negative trend towards the southwest side of Indian Ocean.

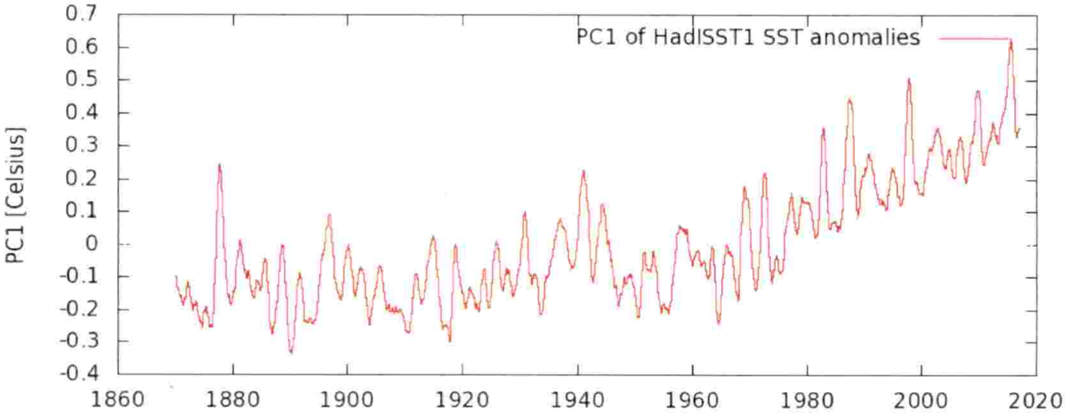

**Figure 8: PC1 of SST anomaly**

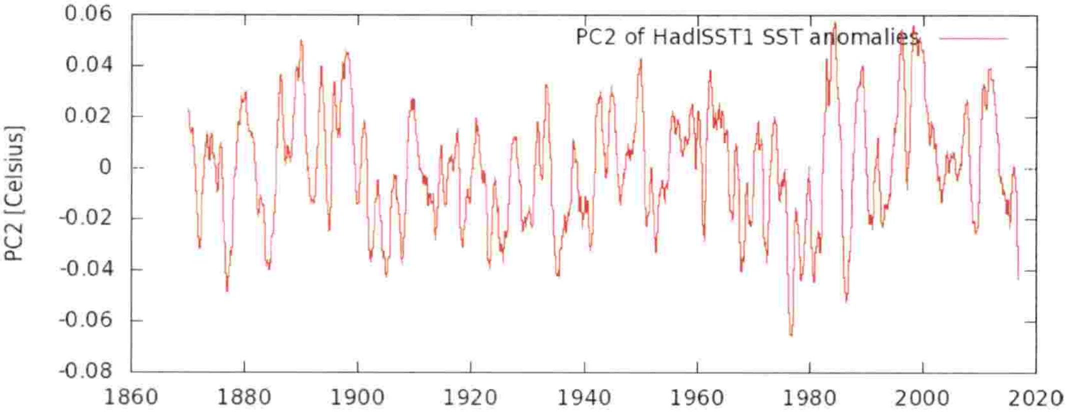

**Figure 9: PC2 of SST anomaly**

The major axis showed a SST anomaly fluctuating from -0.3°C to +0.6°C . The variation of SST has comparatively increased and showed linearly increasing trend after 1960s (fig. 8). PC2 also showed variation but there is a lack of trend. A strong influence of El Niño and La Niña was evident from PC2 (fig. 9). After two consecutive La Niña during 1974 to 1976, northern Indian Ocean was badly affected by El Niño teleconnection around 1978. Later, the frequency of El Niño had increased and the years 1992 to 1994 appeared as a three consecutive El Niño years. This led to abnormal positive trends around these years. The massive El Niño event which led to the first mass coral bleaching experienced by the world during 1997-1998 is clear from PC2 graph. Moreover, other El Niño events which led to significant but lesser mass coral bleaching events during 2010 and 2015-2016 years are also evident from PC2 graph.

## 4.2 Trend analysis of Salinity

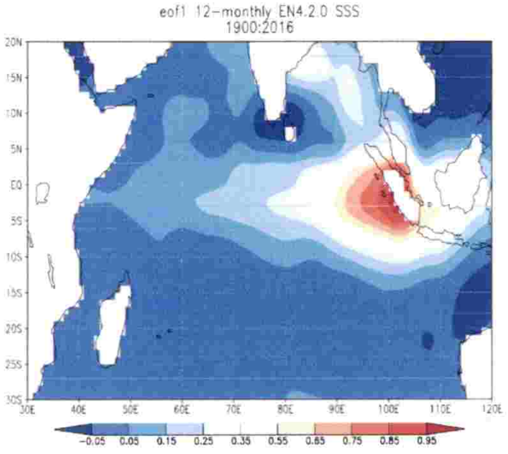

**Figure 10.a: First spatial mode EOF1 of SSS from 1900 to 2016**

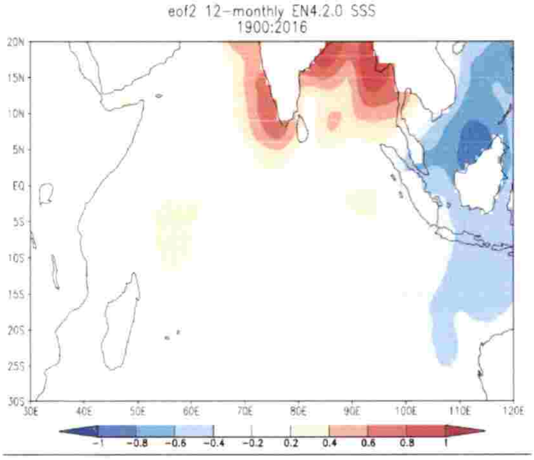

**Figure 10. b: Second spatial mode EOF2 of SSS from 1900 to 2016.**

An analysis of Empirical orthogonal function of SSS has been performed to understand the contrasting trend among the Indian Ocean. The figures 10.a and 10.b, represents the first and second EOF mode and its temporal amplitude of the salinity. The data for past 116 years explains 90 % of the variation. In the case of salinity, the EOF1 itself shows two prominent modes. One is towards southern India and other near to Indonesian islands along the equator. The positive anomaly around Sumatra Indonesian region was greatly influenced by the positive IOD events along with El Niño teleconnection.

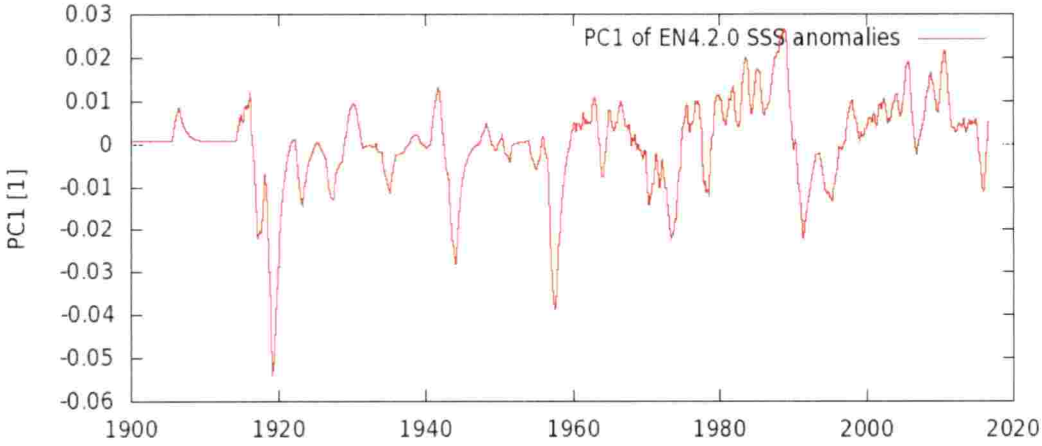

**Figure 11: First temporal mode PC1 of SSS anomaly**

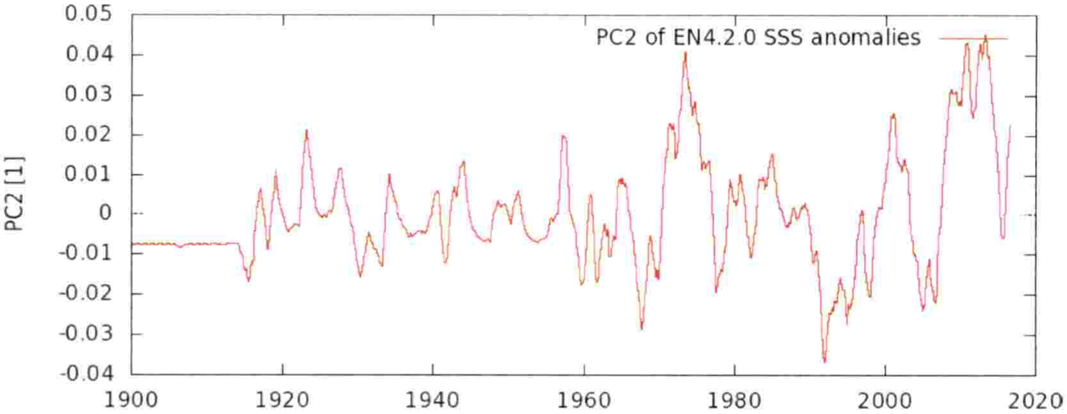

**Figure 12: second temporal mode PC2 of SSS anomaly.**

The Fig.11 represents the majority of variance of SSS and the fig.12 represents the subsequent greatest SSS variation. In the last two decades as compared to average salinity for this century, salinity has been staying on the higher side. In PC1 SST shows a high correlation with the incidence of IOD events. This is evident from the drop of SSS in 1920.

## 4.3 Connectivity among the reefs

The modularity (fig. 13) in the former scenario with a PLD of 100 days and mortality of 50 days indicates that the regional self-recruitment is high in most of the reefs. There is a good connectivity between each reefs and all the reefs shows high potential to act as sources and sinks. The rate of self-recruitment is high in these regions. The SeamountN2 had high betweenness centrality which means they are used frequently as the critical node for dispersal. Therefore SeamountN1 have a key ecological role in larval dispersal of this region. They act as both source and sink for Lakshadweep acroporids in all of the studied years.

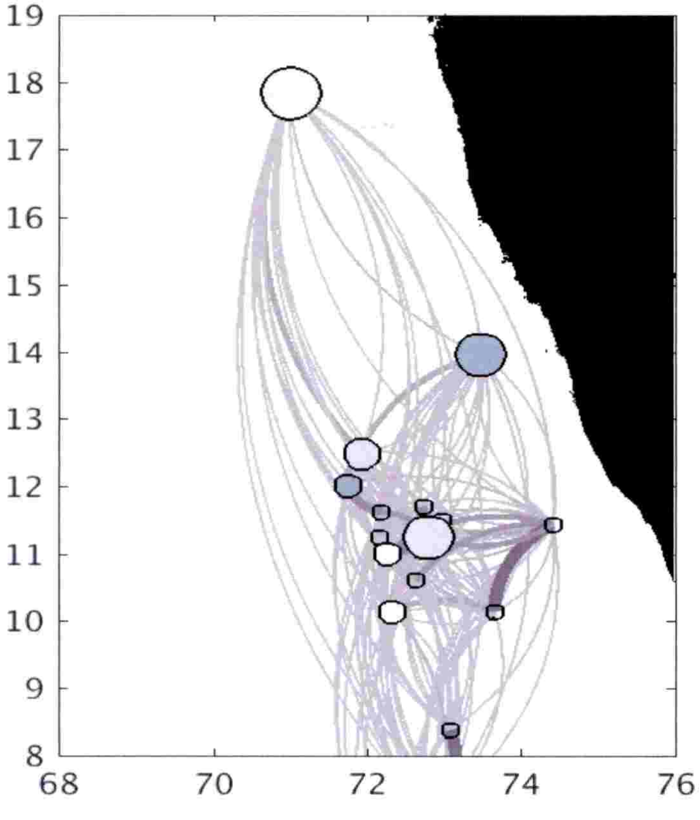

**Figure 13: Modularity of Lakshadweep Acroporids 2015 - 2018.**

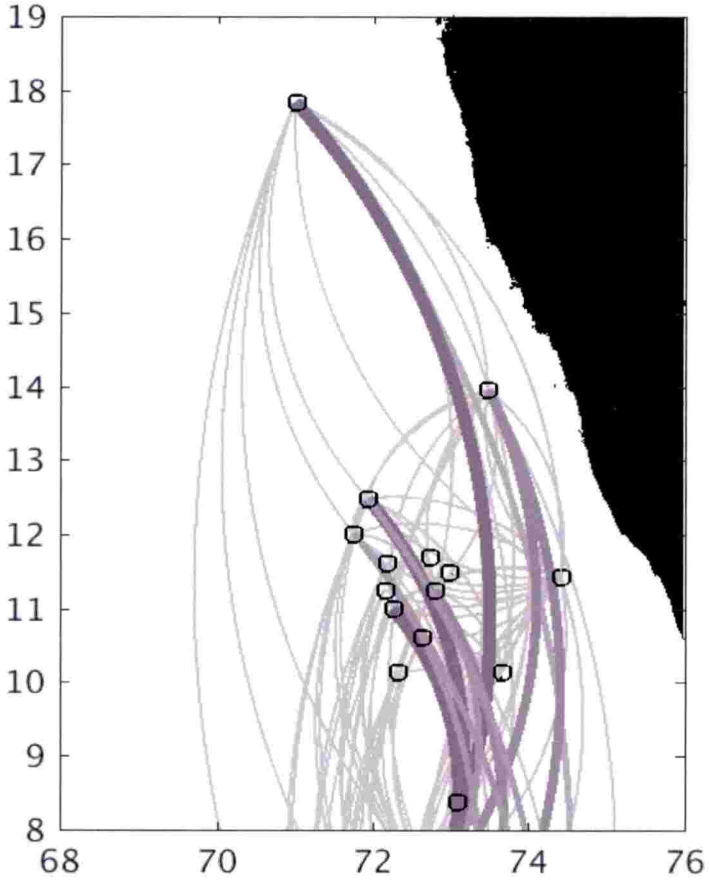

**Figure 14: Modularity of Lakshadweep Acroporids with respect to climate change.** Vertices represent islands; edges represent larval exchanges (clockwise along arc); size of the vertex indicates the proportion of regional self-recruitment; shade indicates the betweenness centrality (darker shades indicate higher values). The thickness of the edge represents the probability of migration.

Oceans absorb more heat from the atmosphere which leads to an increase in the SST. The coupled ocean atmospheric phenomena enhances this effect. When temperature increases, the metabolic rate of larvae also increases which in turn hastens the larval development. This will also likely to increase mortality rate of larvae and decrease the pelagic larval duration. This can finally affect the connectivity between the reefs. Thus the connectivity patterns changes. In such cases, some of the larvae may not be able to reach new reefs. If there is an intermediate reef, new connectivity pattern will be formed. Absence of reefs acting as a sink will results in the death of that larvae. Fig. 14 shows the pattern of connectivity with respect to climate change. The result revealed a southward migratory pattern of larvae. Also the regional self-recruitment of most studied reefs has declined with climate change.

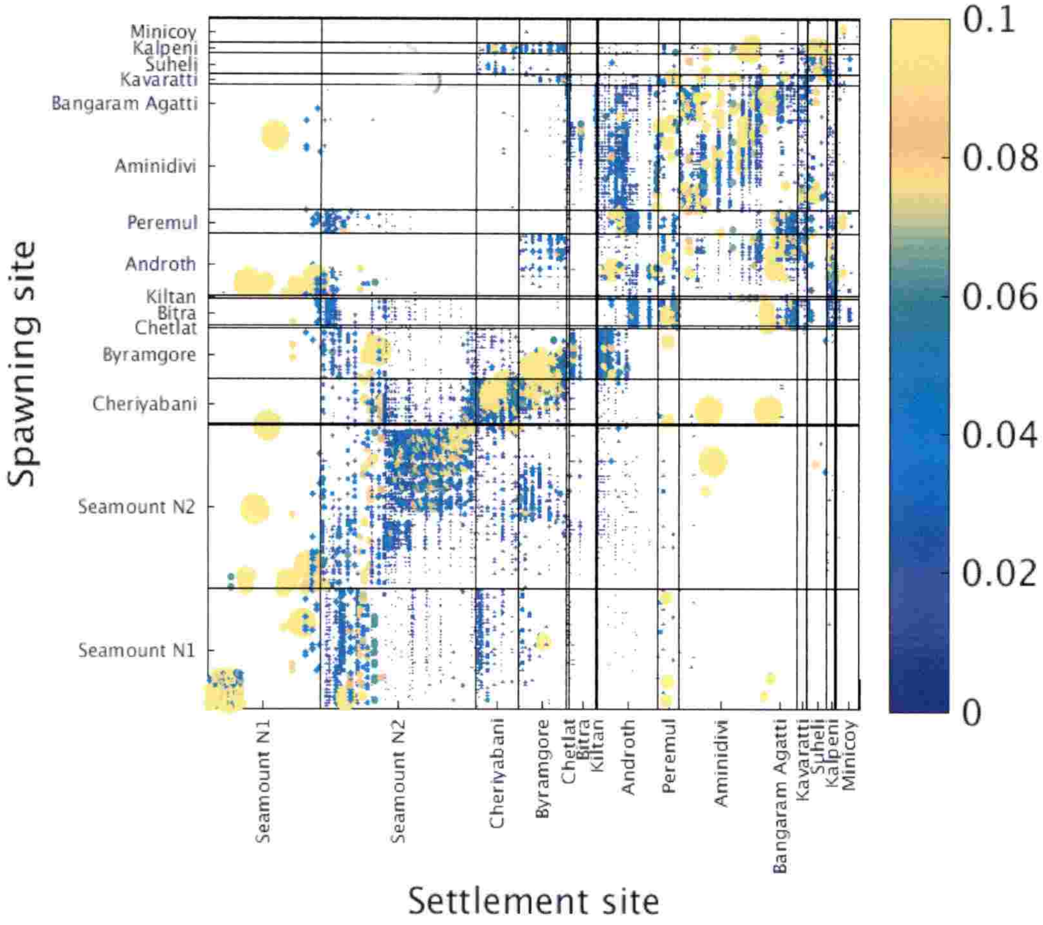

**Figure 15: Connectivity matrix of Acroporids with respect to climate change**

High migratory pattern is evident when we simulated larval connectivity with PLD of 60 days and mortality of 30 days. Marked shift in the connectivity network has been found between the reefs. Acroporid larvae from most of the reef shows a trend of southward movement with a migratory pattern compared to actual connectivity. From the network it is evident that most of the Lakshadweep islands are receiving larvae from Maldives islands in the later scenario. Also the regional self-recruitment shows a decreasing pattern with climate change. The two seamounts in the northern part of Lakshadweep is an active source and sink for acroporids, but this has been observed to be getting decreased with the warming. Therefore, conservation based decisions should be required for this regions.

Minicoy Island is isolated from Indian territory at the south with the presence of nine degree channel. Our results says that Minicoy receives some larvae from most of the southern reefs while they are not sharing larvae with any of the northern islands.

For the past few years, the frequency of occurrence of cyclone has been increased around the study region and the corals are facing huge damages. Combined effect of ocean warming with climate variability and the exposures like cyclonic event will change the dispersal pattern and decreases the recruitment capacity of these region. Being an island with much tourism activities like scuba diving and snorkelling, Lakshadweep atolls may also be affected by human impacts along with the climate impact. Together these stressors can amplify the death of bleached corals in these areas. Comparatively, reefs of SeamountN1 and SeamountN2 may be less affected due to the lack of human activities except fishing.

The local current pattern had a dominant role in larval dispersal and transport to some extent. Indian ocean is oceanographically unique compared to other oceans with the presence of southwest and northeast monsoon circulation, and the dispersal pattern of larvae will be significantly affected. During this time there is an occurence of Lakshadweep low and high (Shetye, 1998). This quasi stationary cyclonic circulation could control the pattern of dispersal. March - April are the transition period of Monsoon circulation. This is the time where spawning of most acropora corals occurs in this region. Therefore, all the behaviour of monsoon including their onset and the offset could sway the connectivity and dispersal pattern of larvae.

Knowledge on larval connectivity should be given importance while demarcating conservation areas especially the sanctuaries and protected areas. Wood et al. (2012) shows that the central indian ocean corals have greater influence on Eastern Indian Ocean ie., the Indonesian corals and they are highly capable of sharing larvae each other. High gene flow will increase the connectivity and promote resilience of the reef. Hence the importance to take conservation related decisions are high. A holistic understanding of the nature and limits of the resilient reefs in this area had a key role in conservation programs and management decisions.

Hughes et al. (2003) suggested that, rather than disappearing, corals will change with the climate change through adaptation or migration. Hence connectivity study is important to maintain population resilience under climate change. Evaluation of the ecological changes and the impact of climate change on the connectivity between the reefs will help in taking important decisions during the interpretation and implementation of resilience-based management and designation of Marine Protected Areas. Severe bleaching were reported in the studied areas as an aftermath of climate change and some were recovering slowly (Vinoth et al., 2012). Therefore identifying the the resilient reefs and understanding the connectivity of these region is an effective ways for protecting the sensitive coral reefs.

# SUMMARY

# CHAPTER 5

# SUMMARY

Larval connectivity study of coral is a young science which is still at the preliminary stage around the world. Corals are sensitive organisms which need particular temperature, salinity and clear shallow water. Any small stress to these organisms makes them highly vulnerable. Analysis on the 140 years SST data showed increase pattern of SST over Indian Ocean. EOF analysis of SST and salinity shows effects of teleconnection from ENSO and IOD events. These two natural phenomena showed a greater influence on SST and SSS of Indian Ocean. Knowledge on the climatic variability around the Lakshadweep reefs can help in predicting the future bleaching events and make the coral reef managers prepared.

The study concludes with the depiction of an alarming rate of increase in the climatic variables in the Lakshadweep Sea. Both SST and salinity has showed an increasing trend in the region. Amid the fear of frequent bleaching event in the future, the study also evaluates the threat of the increase in temperature on the population connectivity among the reefs of Lakshadweep. It is concluded that many of the isolated reefs will be impacted heavily with a decreased exchange of genetic material by the way of larvae and recruitment, a strong bleaching event sparked by the global climatic phenomenon like El Niño or IOD can wipe out such reefs. Also, Lakshadweep reefs have the potential to exchange larvae with nearby Maldives reefs. Therefore these reefs could acts as source for Lakshadweep reefs.

No reef is an island. The larval connectivity information should be given importance while demarcating conservation areas especially the sanctuaries and protected areas. Evaluation of the impact of climate change on the connectivity between the reefs will help in taking important decisions during the interpretation and implementation of resilience based management tools in a coral reef. From our results seamount 1 can be used for resilience based management because they are exchanging larvae with most of the reefs with high betweenness centrality.

Compared to other reefs in Indian Ocean, Lakshadweep have no protected area other than Pitti. Therefore our study suggests more protection in these areas.

# CHAPTER 6

# REFERENCES

Abram, N. J., Gagan, M. K., Liu, Z., Hantoro, W. S., McCulloch, M. T. and Suwargadi, B. W. 2007. Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch. *Nature*. 445(7125): 299.

Abram, N. J., Gagan, M. K., Cole, J. E., Hantoro, W. S. and Mudelsee, M. 2008. Recent intensification of tropical climate variability in the Indian Ocean. *Nature Geoscience*. 1(12): 849.

Achuthavarier, D., Krishnamurthy, V., Kirtman, B. P. and Huang, B. 2012. Role of the Indian Ocean in the ENSO–Indian summer monsoon teleconnection in the NCEP Climate Forecast System. *Journal of Climate*. 25(7): 2490-2508.

Ainsworth, T. D., Heron, S. F., Ortiz, J. C., Mumby, P. J., Grech, A., Ogawa, D. and Leggat, W. 2016. Climate change disables coral bleaching protection on the Great Barrier Reef. *Sci*. 352(6283): 338-342.

Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N. C. and Scott, J. D. 2002. The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. *Journal of Climate*. 15(16): 2205-2231.

Allan, R. J., Reason, C. J. C., Lindesay, J. A. and Ansell, T. J. 2003. Protracted'ENSO episodes and their impacts in the Indian Ocean region. *Deep Sea Research Part II: Topical Studies in Oceanography*. 50(12-13): 2331-2347.

Almany, G. R., Connolly, S. R., Heath, D. D., Hogan, J. D., Jones, G. P., McCook, L. J., Williamson, D. H. 2009. Connectivity, biodiversity conservation and the design of marine reserve networks for coral reefs. *Coral Reefs*.

Andrello, M., Mouillot, D., Somot, D. S., Thuiller, W. and Manel, S. 2015. Additive effects of climate change on connectivity between marine

57

protected areas and larval supply to fished areas. *Diversity and Distributions.* 21: 139-150.

Andrefouet et al. 2006. Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space, Proceedings of 10th International Coral Reef Symposium, 1732-1745.

Apte, D. (2009). Opisthobranch fauna of Lakshadweep Islands, India, with 52 new records to Lakshadweep and 40 new records to India: part 1. Journal of the Bombay Natural History Society, 106(2), 162.

Ashok, K., Guan, Z. and Yamagata, T. 2001. Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophysical Research Letters.* 28(23): 4499-4502.

Ashok, K., Guan, Z. and Yamagata, T. 2003. Influence of the Indian Ocean Dipole on the Australian winter rainfall. *Geophysical Research Letters.* 30(15).

Ashok, K., Chan, W. L., Motoi, T. and Yamagata, T. 2004. Decadal variability of the Indian Ocean dipole. Geophysical Research Letters. 31(24).

Ayre, D. J., & Hughes, T. P. 2000. Genotypic diversity and gene flow in brooding and spawning corals along the Great Barrier Reef, Australia. Evolution, 54(5), 1590-1605.

Baird, A. H. 2001. The ecology of coral larvae: settlement patterns, habitat selection and the length of the larval phase (Doctoral dissertation, James Cook University).

Baker, A. C., Glynn, P. W. and Riegl, B. 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, coastal and shelf science.* 80(4): 435-471.

Baums, I. B., Miller, M. W., & Hellberg, M. E. 2005. Regionally isolated populations of an imperiled Caribbean coral, Acropora palmata. Molecular ecology, 14(5), 1377-1390.

Barth, A., Alvera-Azcárate, A. and Weisberg, R. H. 2008. Benefit of nesting a regional model into a large-scale ocean model instead of climatology. Application to the West Florida Shelf. *Continental Shelf Research*. 28(4-5): 561-573.

Berkelmans, R., De'ath, G., Kininmonth, S. and Skirving, W. J. 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. *Coral reefs*. 23(1): 74-83.

Black, K. P. 1993. The relative importance of local retention and inter-reef dispersal of neutrally buoyant material on coral reefs. *Coral reefs*. 12(1): 43-53.

Bleck, R. 2002. An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates, Ocean Modelling, 4 (1), 55-88.

Boer, G. J., Flato, G. and Ramsden, D. 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century. *Climate dynamics*. 16(6): 427-450.

Botsford, L. W., White, J. W., Coffroth, M. A., Paris, C. B., Planes, S., Shearer, T. L., Jones, G. P. 2009. Connectivity and resilience of coral reef metapopulations in marine protected areas: Matching empirical efforts to predictive needs. *Coral Reefs*.

Buddemeier, R. W., Kleypas, J. A. and Aronson, R. B. 2004. Potential contributions of climate change to stresses on coral reef ecosystems. Coral reefs and global climate change. Pew Center on Global Climate Change, Virginia, USA.

Burgess, S. C., Nickols, K. J., Griesemer, C. D., Barnett, L. A., Dedrick, A. G., Satterthwaite, E. V., and Botsford, L. W. 2014. Beyond connectivity: how empirical methods can quantify population persistence to improve marine protected-area design. *Ecological Applications,* 24(2): 257-270.

Burns, S. J., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A. and Mangini, A. 2002. A 780-year annually resolved record of Indian Ocean monsoon

59

precipitation from a speleothem from south Oman. *Journal of Geophysical Research: Atmospheres*, 107(D20), ACL-9.

Buston, P. M., Jones, G. P., Planes, S and Thorrold, S. R. 2012. Probability of successful larval dispersal declines fivefold over 1 km in a coral reef fish. *Proceedings of the Royal Society B: Biological Sciences*.2011.204.

Cacciapaglia, C. and Van Woesik, R. 2016. Climate-change refugia: shading reef corals by turbidity. *Global change biology*. 22(3): 1145-1154.

Chang, P., Ji, L. and Li, H. 1997. A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature*. 385(6616): 516.

Chodankar, A. R., Banakar, V. K. and Oba, T. 2005. Past 100 ky surface salinity-gradient response in the Eastern Arabian Sea to the summer monsoon variation recorded by δ18O of G. sacculifer. *Global and Planetary Change*. 47(2-4): 135-142.

Christie, M. R., Tissot, B. N., Albins, M. A., Beets, J. P., Jia, Y., Ortiz, D. M. and Hixon, M. A. 2010. Larval connectivity in an effective network of marine protected areas. *PloS one*, 5(12): e15715.

Clark, C. O., Cole, J. E. and Webster, P. J. 2000. Indian Ocean SST and Indian summer rainfall: Predictive relationships and their decadal variability. *Journal of Climate*. 13(14): 2503-2519.

Clemens, S., Prell, W., Murray, D., Shimmield, G. and Weedon, G. 1991. Forcing mechanisms of the Indian Ocean monsoon. Nature, 353(6346), 720.

Cole, J. E., Dunbar, R. B., McClanahan, T. R. and Muthiga, N. A. 2000. Tropical Pacific forcing of decadal SST variability in the western Indian Ocean over the past two centuries. *Sci*. 287(5453): 617-619.

Compo, G. P. and Sardeshmukh, P. D. 2010. Removing ENSO-related variations from the climate record. *Journal of Climate*. 23(8): 1957-1978.

Connolly, S.R. and Baird, A.H., 2010. Estimating dispersal potential for marine larvae: dynamic models applied to scleractinian corals. Ecology, 91(12), pp.3572-3583

Conroy, J. L. and Overpeck, J. T. 2011. Regionalization of present-day precipitation in the greater monsoon region of Asia. *Journal of Climate*. 24(15): 4073-4095.

Cowen, R. K., Lwiza, K. M. M., Sponaugle, S., Paris, C. B. and Olson, D. B. 2000. Connectivity of marine populations: open or closed?. Sci. 287: 857–859.

Cowen, R. K., Gawarkiewicz, G., Pineda, J., Thorrold, S. R. and Werner, F. E. 2007. Population connectivity in marine systems: an overview. *Oceanogr.* 20: 14-21.

Cowen, R. K. and Sponaugle, S. 2009. Larval dispersal and marine population connectivity. *Annu. Rev. Mar. Sci.* 1: 443-466.

Dodman, D. 2009. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and urbanization*. 21(1): 185-201.

Domingues, C. P., Nolasco, R., Dubert, J. and Queiroga, H. 2012. Model-derived dispersal pathways from multiple source populations explain variability of invertebrate larval supply. *Plos One*. 7(4): e35794.

Du Y and Zhang Y. 2015. Satellite and Argo observed surface salinity variations in the tropical Indian Ocean and their association with the Indian Ocean dipole mode. *Journal of Climate*. 28(2): 695-713.

Durand, F., Shankar, D., de Boyer Montégut, C., Shenoi, S. S. C., Blanke, B. and Madec, G. 2007. Modeling the barrier-layer formation in the southeastern Arabian Sea. *Journal of Climate*. 20(10): 2109-2120.

Eigenheer, A. and Quadfasel, D. 2000. Seasonal variability of the Bay of Bengal circulation inferred from TOPEX/Poseidon altimetry. *Journal of Geophysical Research: Oceans*. 105(C2): 3243-3252.

Frauen, C. and Dommenget, D. 2012. Influences of the tropical Indian and Atlantic Oceans on the predictability of ENSO. *Geophysical Research Letters*. 39(2).

61

Gattuso, J. P., Frankignoulle, M., Bourge, I., Romaine, S. and Buddemeier, R. W. 1998. Effect of calcium carbonate saturation of seawater on coral calcification. *Global and Planetary Change*. 18(1): 37-46.

Gawarkiewicz, G., Monismith, S., and Largier, J. 2007. Observing larval transport processes affecting population connectivity: progress and challenges. *Oceanography*. 20(3): 40-53.

Gerber, L.R., Mancha-Cisneros, M.D.M., O'connor, M.I. and Selig, E.R., 2014. Climate change impacts on connectivity in the ocean: Implications for conservation. Ecosphere, 5(3), pp.1-18.

George, R. M., & Jasmine, S. 2015. Scleractinian coral diversity in Indian reefs, their threats and conservation.

Good, S. A., M. J. Martin and N. A. Rayner, 2013. EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates, *Journal of Geophysical Research: Oceans*. 118: 6704-6716.

Gupta, A. K., Anderson, D. M. and Overpeck, J. T. 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature*. 421(6921): 354.

Harley, C. D., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J., Thornber, C. S. and Williams, S. L. 2006. The impacts of climate change in coastal marine systems. *Ecology letters*. 9(2): 228-241.

Hastings, A., & Harrison, S. 1994. Metapopulation dynamics and genetics. Annual Review of Ecology and Systematics, 25(1), 167-188.

Hay, W. W., Migdisov, A., Balukhovsky, A. N., Wold, C. N., Flögel, S., & Söding, E. 2006. Evaporites and the salinity of the ocean during the Phanerozoic: Implications for climate, ocean circulation and life. Palaeogeography, Palaeoclimatology, Palaeoecology, 240(1-2), 3-46.

Heron, S. F., Maynard, J. A., Van Hooidonk, R., & Eakin, C. M. 2016. Warming trends and bleaching stress of the world's coral reefs 1985–2012. Scientific reports, 6, 38402.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and freshwater research*. 50(8): 839-866.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E.,Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K. and Knowlton, N.2007. Coral reefs under rapid climate change and ocean acidification. *Sci*. 318: 1737–1742.

Hoegh-Guldberg, O. and Bruno, J. F. 2010. The impact of climate change on the world's marine ecosystems. Sci. 328(5985): 1523-1528.

Hong, C. C., Lu, M. M. and Kanamitsu, M. 2008. Temporal and spatial characteristics of positive and negative Indian Ocean dipole with and without ENSO. *Journal of Geophysical Research: Atmospheres*. 113(D8).

Howells, E.J., Abrego, D., Vaughan, G.O. and Burt, J.A., 2014. Coral spawning in the Gulf of Oman and relationship to latitudinal variation in spawning season in the northwest Indian Ocean. Scientific reports, 4, p.7484.

Hughes TP. 1984. Population dynamics based on individual size rather than age: a general model with a reef coral example. *Am. Nat*. 123: 778–95.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B., Kleypas, J. and Lough, J.M., 2003. Climate change, human impacts, and the resilience of coral reefs. science, 301(5635), pp.929-933.

Ihara, C., Kushnir, Y., Cane, M. A. and Victor, H. 2007. Indian summer monsoon rainfall and its link with ENSO and Indian Ocean climate indices. *International Journal of Climatology*. 27(2): 179-187.

Ineson, S., Balmaseda, M. A., Davey, M. K., Decremer, D., Dunstone, N. J., Gordon, M. and Weisheimer, A. 2018. Predicting El Niño in 2014 and 2015. *Scientific reports*. 8(1): 10733.

International Hydrographic Organization, IHO, 1953: Limits of Oceans and Seas. International Hydrographic Organization, Special Publication No 23, 3rd Edition, IMP, Monégasque - Monte-Carlo, hdl:10013/epic.37175.d001

IPCC AR4 WG2. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. 2007. Climate Change 2007: Impacts, Adaptation and

Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland: 151.

Izumo, T., Vialard, J., Lengaigne, M., de Boyer Montegut, C., Behera, S. K., Luo, J. J., Cravatte, S., Masson, S. and Yamagata, T. 2010. Influence of the state of the Indian Ocean Dipole on the following year's El Niño. *Nature Geoscience*. 3(3): 168.

James, M. K., Armsworth, P. R., Mason, L. B. and Bode, L. 2002. The structure of reef fish metapopulations: modelling larval dispersal and retention patterns. *Proc. R. Soc. Lond B.* 269(1505): 2079-2086.

Jasmine, S., Sreenath, K.R., Ranjith, L. and Kingsly, H.J., 2013. Mass spawning of Scleractinian corals in the Lakshadweep Archipelago. CMFRI Newsletter, (136), pp.6-6.

Johnson, G. C. and Kearney, K. A. 2009. Ocean climate change fingerprints attenuated by salt fingering?. *Geophysical Research Letters*. 36(21).

Jones, S. 1986. Lakshadweep-General features and some considerations. Marine Fisheries Information Service, Technical and Extension Series, 68: 1-6.

Joseph, S. and Freeland, H. J. 2005. Salinity variability in the Arabian Sea. *Geophysical research letters*. 32(9).

Joseph, S. and Ravichandran, M. 2012. Validation of 0.25 ox 0.25 o Indian Ocean HYCOM.

Kaplan, D. M., Cuif, M., Fauvelot, C., Vigliola, L., Nguyen-Huu, T., Tiavouane, J. and Lett, C. 2016. Uncertainty in empirical estimates of marine larval connectivity. *ICES Journal of Marine Science*. 74(6): 1723-1734.

Keith, S.A., Maynard, J.A., Edwards, A.J., Guest, J.R., Bauman, A.G., Van Hooidonk, R., Heron, S.F., Berumen, M.L., Bouwmeester, J., Piromvaragorn, S. and Rahbek, C., 2016. Coral mass spawning predicted by rapid seasonal rise in ocean temperature. Proc. R. Soc. B, 283(1830), p.20160011.

Kendall, M. S., Poti, M. and Karnauskas, K. B. 2016. Climate change and larval transport in the ocean: Fractional effects from physical and physiological factors. *Global Change Biology.*

Kleypas, J. A., R. W. Buddemeier, D. Archer, J.-P. Gattuso, C. Langdon, and B. N. Opdyke. 1999. Geo-chemical consequences of increased atmospheric carbon dioxide on coral reefs. *Sci*. 284: 118-120.

Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L. and Robbins, L.L. 2005. Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research. *Report of a workshop held*. 18: 20.

Knittweis, L., Kraemer, W. E., Timm, J. and Kochzius, M. 2009. Genetic structure of Heliofungia actiniformis (Scleractinia: Fungiidae) populations in the Indo-Malay Archipelago: Implications for live coral trade management efforts. *Conservation Genetics.*

Koop, K., Booth, D., Broadbent, A., Brodie, J., Bucher, D., Capone, D., and Hoegh-Guldberg, O. 2001. ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis of results and conclusions. *Marine pollution bulletin*. 42(2): 91-120.

Krishnan, R. and Sugi, M. 2003. Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. *Climate Dynamics*. 21(3-4): 233-242.

Krishnaswamy, J., Vaidyanathan, S., Rajagopalan, B., Bonell, M., Sankaran, M., Bhalla, R. S. and Badiger, S. 2015. Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. *Climate Dynamics*. 45(1-2): 175-184.

Kug, J. S. and Kang, I. S. 2006. Interactive feedback between ENSO and the Indian Ocean. *Journal of climate*. 19(9): 1784-1801.

Kug, J. S., Li, T., An, S. I., Kang, I. S., Luo, J. J., Masson, S. and Yamagata, T. 2006. Role of the ENSO–Indian Ocean coupling on ENSO variability in a coupled GCM. *Geophysical research letters*. 33(9).

Kültz, D. 2015. Physiological mechanisms used by fish to cope with salinity stress. *Journal of Experimental Biology*. 218(12): 1907-1914.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P. and Muir-Wood, R. 2014. Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journa*l. 59(1): 1-28.

Latif, M. and Keenlyside, N. S. 2009. El Niño/Southern Oscillation response to global warming. *Proceedings of the National Academy of Sciences*. 106(49): 20578-20583.

Lett, C., Ayata, S. D., Huret, M. and Irisson, J. O. 2010. Biophysical modelling to investigate the effects of climate change on marine population dispersal and connectivity. *Progress in Oceanography.*

Levine, R. C. and Turner, A. G. 2012. Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases. *Climate dynamics*. 38(11-12): 2167-2190.

Loo, Y. Y., Billa, L. and Singh, A. 2015. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*. 6(6): 817-823.

Maikhuri, R. K., Rao, K. S., Patnaik, S., Saxena, K. G. and Ramakrishnan, P. S. 2003. Assessment of vulnerability of forests, meadows and mountain ecosystems due to climate change. *ENVIS Bulletin*. 11(2): 1-9.

Mallik TK. 2017. Coral atolls of Lakshadweep, Arabian Sea, Indian Ocean. MOJ Eco Environ Sci. 2(2):68–83

May, W. 2004. Simulation of the variability and extremes of daily rainfall during the Indian summer monsoon for present and future times in a global time-slice experiment. *Climate Dynamics*. 22(2-3): 183-204.

Mayorga-Adame, C. G., Batchelder, H. P., & Spitz, Y. 2017. Modeling larval connectivity of coral Reef organisms in the Kenya-Tanzania Region. Frontiers in Marine Science, 4, 92.

McLeod, A. I. 2005. Kendall rank correlation and Mann-Kendall trend test. R Package Kendall.

McNeil, B. I., Matear, R. J. and Barnes, D. J. 2004. Coral reef calcification and climate change: The effect of ocean warming. *Geophysical Research Letters*. 31(22).

Meehl, G. A., & Washington, W. M. 1993. South Asian summer monsoon variability in a model with doubled atmospheric carbon dioxide concentration. Science, 260(5111), 1101-1104.

Meehl, G. A., Washington, W. M., Collins, W. D., Arblaster, J. M., Hu, A., Buja, L. E., Strand, W. G. and Teng, H. 2005. How much more global warming and sea level rise?. *Sci*. 307:1769-1772.

Mojgan, G. M., Mehdi, M. M. and Reza, B. M. 2017. The Trend of Changes in Surface Wind in the Indian Ocean, in the Period from 1981 to 2015, Using Reanalysis Data, NCEP/NCAR. *Open Journal of Marine Science*. 7(04): 445.

Mora, C. and Sale, P. F. 2002. Are populations of coral reef fish open or closed?. *Trends Ecol. Evol.* 17(9): 422-428.

Munday, P. L., Kingsford, M. J., O'Callaghan, M. and Donelson, J. M. 2008. Elevated temperature restricts growth potential of the coral reef fish Acanthochromis polyacanthus. *Coral Reefs*. 27(4): 927-931.

Munday, P. L., Leis, J. M, Lough, J. M., Paris, C. B., Kingsford, M. J., Berumen, M. L. and Lambrechts, J. 2009. Climate change and coral reef connectivity. Coral Reefs. 28(2): 379-395.

Munday, P. L., Leis, J. M., Lough, J. M., Paris, C. B., Kingsford, M. J., Berumen, M. L. and Lambrechts, J. 2009. Climate change and coral reef connectivity. *Coral Reefs*. 28(2): 379-395.

Murtugudde, R., Seager, R. and Thoppil, P. 2007. Arabian Sea response to monsoon variations. *Paleoceanography*. 22(4).

Nakajima, Y., Nishikawa, A., Isomura, N., Iguchi, A. and Sakai, K. 2009. Genetic connectivity in the broadcast-spawning coral Acropora digitifera analyzed by microsatellite markers on the Sekisei Reef, Southwestern Japan. *Zoological science*. 26(3): 209-215.

Nobi, E. P. and Kumar, P. D. 2014. Environmental characteristics of tropical coral reef-seagrass dominated lagoons (Lakshadweep, India) and implications to resilience to climate change. *Environmental earth sciences*. 72(4): 1025-1037.

Nurhati, I. S., Cobb, K. M. and Di Lorenzo, E. 2011. Decadal-scale SST and salinity variations in the central tropical Pacific: Signatures of natural and anthropogenic climate change. *Journal of Climate*. 24(13): 3294-3308.

Obura, D. O. 2005. Resilience and climate change: lessons from coral reefs and bleaching in the Western Indian Ocean. *Estuarine, Coastal and Shelf Science*. 63(3): 353-372.

O'Connor MI, Bruno JF, Gaines SD, Halpern BS, Lester SE, Kinlan BP, Weiss JM (2007) Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. Proc Nat Acad Sci USA 104:1266–1271

Palumbi, S. R., Barshis, D. J., Traylor-Knowles, N. and Bay, R. A. 2014. Mechanisms of reef coral resistance to future climate change. *Sci*. 344(6186): 895-898.

Pande, S., Sant, N. R., Ranade, S. D., Pednekar, S. N., Mestry, P. G., Kharat, S. S., & Deshmukh, V. 2007. An ornithological expedition to the Lakshadweep archipelago: Assessment of threats to pelagic and other birds and recommendations. Indian Birds, 3(1), 2-12.

Paris, C. B., Chérubin, L. M. and Cowen, R. K. 2007. Surfing, spinning, or diving from reef to reef: effects on population connectivity. *Marine Ecology Progress Series*. 347: 285-300.

Paris, C. B., Helgers, J., Van Sebille, E. and Srinivasan, A. 2013. Connectivity Modeling System: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. *Environmental Modelling & Software*. 42: 47-54.

Pillai, C. S. G. and Jasmine, S. 1989. The coral fauna of Lakshadweep. CMFRI Bulletin Marine living resources of the union territory of Lakshadweep An Indicative Survey With Suggestions For Development. 43: 179-195.

Pillai, G. C. S. 1997. A brief resume of research and understanding of the reef corals and coral reefs around India. In Proc. Regional workshop on the Conser. Sustain. Manag. Coral Reefs (pp. 13-21).

PiNeDa, J., Hare, J. A. and Sponaugle, S. U. 2007. Larval transport and dispersal in the coastal ocean and consequences for population connectivity. *Oceanography*. 20(3): 22-39.

Pohlert, T. 2016. Non-parametric trend tests and change-point detection. CC BY-ND, 4.

Pokhrel, S., Chaudhari, H. S., Saha, S. K., Dhakate, A., Yadav, R. K., Salunke, K., Mahapatra, S. and Rao, S. A. 2012. ENSO, IOD and Indian Summer Monsoon in NCEP climate forecast system. *Climate dynamics*. 39(9-10): 2143-2165.

Power, S. B. and Smith, I. N. 2007. Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed?. *Geophysical Research Letters*. 34(18).

Prakash, S., Mitra, A.K., Momin, I.M., Rajagopal, E.N., Basu, S., Collins, M., Turner, A.G., Rao, K.A. and Ashok, K., 2015. Seasonal intercomparison of observational rainfall datasets over India during the southwest monsoon season. International Journal of Climatology, 35(9), pp.2326-2338.

Purkis, S. J. and Riegl, B. 2005. Spatial and temporal dynamics of Arabian Gulf coral assemblages quantified from remote-sensing and in situ monitoring data. *Marine Ecology Progress Series*. 287: 99-113.

Rajasuriya, A., Zahir, H., Muley, E. V., Subramanian, B. R., Venkataraman, K., Wafar, M. V. M. and Whittingham, E. M. M. A. 2002. Status of coral reefs in South Asia: Bangladesh, India, Maldives, Sri Lanka. In *Proceedings of the Ninth International Coral Reef Symposium*. 2: 2841-845.

R Core Team , 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

69

Rao, R. R. and Sivakumar, R. 2003. Seasonal variability of sea surface salinity and salt budget of the mixed layer of the north Indian Ocean. *Journal of Geophysical Research: Oceans*. 108(C1): 9-1.

Rao, S. A. and Behera, S. K. 2005. Subsurface influence on SST in the tropical Indian Ocean: Structure and interannual variability. *Dynamics of Atmospheres and Oceans*. 39(1-2): 103-135.

Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res. (Atmospheres)*. 108(14): 2-1

Reaka-Kudla, M. L. 1997. The global biodiversity of coral reefs: a comparison with rain forests. Biodiversity II: Understanding and protecting our biological resources, 2: 551.

Reaka-Kudla, M. L. 2001. Known and unknown biodiversity, risk of extinction and conservation strategy in the sea. In Waters in peril. *Springer*, Boston, MA: 19-33.

Reid, P. C., Fischer, A. C., Lewis-Brown, E., Meredith, M. P., Sparrow, M., Andersson, A. J. and Brix, H. 2009. Impacts of the oceans on climate change. *Advances in marine biology*. 56: 1-150.

Renema, W., Pandolfi, J.M., Kiessling, W., Bosellini, F.R., Klaus, J.S., Korpanty, C., Rosen, B.R., Santodomingo, N., Wallace, C.C., Webster, J.M. and Johnson, K.G., 2016. Are coral reefs victims of their own past success?. Science advances, 2(4), p.e1500850.

Reuter, M., Kern, A. K., Harzhauser, M., Kroh, A. and Piller, W. E. 2013. Global warming and South Indian monsoon rainfall—lessons from the Mid-Miocene. *Gondwana Research*. 23(3): 1172-1177.

Rixen, T., Ramachandran, P., Lehnhoff, L., Dasbach, D., Gaye, B., Urban, B. and Ittekkot, V. 2011. Impact of monsoon-driven surface ocean processes on a coral off Port Blair on the Andaman Islands and their link to North Atlantic climate variations. *Global and Planetary Change*. 75(1): 1-13.

Rostek, F., Ruhlandt, G., Bassinot, F. C., Muller, P. J., Labeyrie, L. D., Lancelot, Y. and Bard, E. 1993. Reconstructing sea surface temperature and salinity using δ18O and alkenone records. Nature. 364(6435): 319.

Roughgarden J, Iwasa Y, Baxter C. 1985. Demographic theory for an open marine population with space-limited recruitment. *Ecology*. 66: 54–67

Sabeerali, C. T., Rao, S. A., Ajayamohan, R. S. and Murtugudde, R. 2012. On the relationship between Indian summer monsoon withdrawal and Indo-Pacific SST anomalies before and after 1976/1977 climate shift. *Climate dynamics*. 39(3-4): 841-859.

Saji, N. H. and Yamagata, T. 2003. Possible impacts of Indian Ocean dipole mode events on global climate. *Climate Research*. 25(2): 151-169.

Schallenberg, M., Hall, C. J., & Burns, C. W. 2003. Consequences of climate-induced salinity increases on zooplankton abundance and diversity in coastal lakes. *Marine ecology progress series*. 251: 181-189.

Schott, F. 1983. Monsoon response of the Somali Current and associated upwelling. *Progress in Oceanography*. 12(3): 357-381.

Seth, A., Rauscher, S. A., Biasutti, M., Giannini, A., Camargo, S. J. and Rojas, M. 2013. CMIP5 projected changes in the annual cycle of precipitation in monsoon regions. *Journal of Climate*. 26(19): 7328-7351.

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

Sheppard, C. R., Spalding, M., Bradshaw, C. and Wilson, S. 2002. Erosion vs. recovery of coral reefs after 1998 El Niño: Chagos reefs, Indian Ocean. *AMBIO: A Journal of the human environment*. 31(1): 40-48.

Shetye, S. R., Gouveia, A. D. and Shenoi, S. S. C. 1994. Circulation and water masses of the Arabian Sea. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, 103(2): 107-123.

Shetye, S.R., 1998. West India coastal current and Lakshadweep high/low. Sadhana, 23(5-6), pp.637-651.

Shukla, R. P. and Huang, B. 2016. Interannual variability of the Indian summer monsoon associated with the air–sea feedback in the northern Indian Ocean. *Climate dynamics*. 46(5-6): 1977-1990.

Sikhakolli, R., Sharma, R., Basu, S., Gohil, B. S., Sarkar, A. and Prasad, K. V. S. R. 2013. Evaluation of OSCAR ocean surface current product in the tropical Indian Ocean using in situ data. *Journal of earth system science*. 122(1): 187-199.

Sponaugle, S., Cowen, R. K. Shanks, A., Morgan, S. G., Leis, J. M., Pineda, J., Boehlert, G. W., Kingsford, M. J., Lindeman, K. C., Grimes, C. and Munro, J. L. 2002. Predicting self-recruitment in marine populations: biophysical correlates and mechanisms. *Bull. Mar. Sci.* 70(1): 341-375.

Thomas, C. J., Lambrechts, J., Wolanski, E., Traag, V. A., Blondel, V. D., Deleersnijder, E. and Hanert, E. 2014. Numerical modelling and graph theory tools to study ecological connectivity in the Great Barrier Reef. *Ecological Modelling*.

Treml, E. A., Halpin, P. N., Urban, D. L. and Pratson, L. F. 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. *Landscape Ecology*. 23(1): 19-36.

Uvo, C. B., Repelli, C. A., Zebiak, S. E. and Kushnir, Y. 1998. The relationships between tropical Pacific and Atlantic SST and northeast Brazil monthly precipitation. *Journal of Climate*. 11(4): 551-562.

Venkataraman, K., & Wafar, M. V. M. 2005. Coastal and marine biodiversity of India.

Venkataraman, K. 2008. Coastal and marine wetlands in India. In Proceedings of the Taal2007: the 12th World Lake Conference (pp. 392-400).

Venzke, S., Latif, M. and Villwock, A. 2000. The coupled GCM ECHO-2. Part II: Indian ocean response to ENSO. *Journal of Climate*. 13(8): 1371-1383.

Vinayachandran, P. N. and Kurian, J. 2008. Modeling Indian Ocean circulation: Bay of Bengal fresh plume and Arabian Sea mini warm pool. *In Proceedings of the 12th Asian Congress of Fluid Mechanics*. 18-21.

Vinayachandran, P. N. and Nanjundiah, R. S. 2009. Indian Ocean sea surface salinity variations in a coupled model. *Climate dynamics*. 33(2-3): 245-263.

Vinoth, R., Gopi, M., Kumar, T.T.A., Thangaradjou, T. and Balasubramanian, T., 2012. Coral reef bleaching at Agatti Island of Lakshadweep atolls, India. Journal of Ocean University of China, 11(1), pp.105-110.

Watanabe, M. and Jin, F. F. 2002. Role of Indian Ocean warming in the development of Philippine Sea anticyclone during ENSO. *Geophysical research letters*. 29(10): 116-1.

Winther, N. G. and Evensen, G. 2006. A hybrid coordinate ocean model for shelf sea simulation. *Ocean Modelling*. 13(3-4): 221-237.

Wood, S., Paris, C.B., Ridgwell, A. and Hendy, E.J., 2014. Modelling dispersal and connectivity of broadcast spawning corals at the global scale. Global Ecology and Biogeography, 23(1), pp.1-11.

Woodruff, S.D., S.J. Worley, S.J. Lubker, Z. Ji, J.E. Freeman, D.I. Berry, P. Brohan, E.C. Kent, R.W. Reynolds, S.R. Smith, and C. Wilkinson, 2011: ICOADS Release 2.5: Extensions and enhancements to the surface marine meteorological archive. Int. J. Climatol., 31, 951-967 (doi:10.1002/joc.2103)

Wolter, K. and Timlin, M. S. 2011. El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI. ext). *International Journal of Climatology*. 31(7): 1074-1087.

Wooldridge, S., Done, T., Berkelmans, R., Jones, R. and Marshall, P. 2005. Precursors for resilience in coral communities in a warming climate: a belief network approach. *Marine Ecology Progress Series*. 295: 157-169.

Wu, R. and Kirtman, B. P. 2004. Understanding the impacts of the Indian Ocean on ENSO variability in a coupled GCM. *Journal of climate*. 17(20): 4019-4031.

Wyrtki, K. 1973. Physical oceanography of the Indian Ocean. In The biology of the Indian Ocean. *Springer*, Berlin, Heidelberg:18-36

Yamagata, T., Behera, S. K., Luo, J. J., Masson, S., Jury, M. R. and Rao, S. A. 2004. Coupled ocean-atmosphere variability in the tropical Indian Ocean. Earth's Climate: The Ocean–Atmosphere Interaction, *Geophys. Monogr.* 147: 189-212.

Zinke, J., Pfeiffer, M., Timm, O., Dullo, W. C. and Davies, G. R. 2005. Atmosphere–ocean dynamics in the Western Indian Ocean recorded in corals. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. 363(1826): 121-142.

# CLIMATE CHANGE AND POPULATION CONNECTIVITY OF LAKSHADWEEP ATOLLS

By

**ATHIRA PRASAD**

**(2013-20-120)**

ABSTRACT OF THE THESIS
Submitted in partial fulfilment of the requirement
For the degree of
***B.Sc.-M.Sc. (Integrated) Climate Change Adaptation***
Faculty of Agriculture
Kerala Agricultural University, Thrissur

**ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH**
VELLANIKKARA, THRISSUR – 680656
KERALA, INDIA
2018

75

# ABSTRACT

Lakshadweep is the only atoll type reefs in the territory of India. Since Indian Ocean is the warmest among tropical oceans, Indian corals reefs are vulnerable to the impact of climate change. Coral connectivity helps in maintaining the resilience capacity of sensitive coral reefs. However, shifts in global temperature will strongly influence the period of larval duration and hence the connectivity between the reefs. This study utilised the Mann Kendall trend analysis and Empirical Orthogonal Formula to study the trend of sea surface temperature and salinity over the region. Current study revealed a warming trend of sea surface temperature of Lakshadweep waters. Empirical orthogonal function indicates opposite temperature and salinity modes in the Indian Ocean region which encompasses the Lakshadweep waters. Spatio temporal dipoles identified are surmised to be due to the influence of global climatic phenomenon like El Niño and Indian Ocean Dipole. The study also tries to understand the relationship between larval connectivity and climate. Our findings implies that climate change has a significant influence on larvae and in turn affecting the journey to their corresponding settlement reef. Resilient reefs act as the source for seeding the bleached or destroyed reefs by larval dispersal. Knowledge on the changes of larval connectivity between the reefs can help in taking important decisions during the interpretation and implementation of resilience based management tools in a coral reef. Identifying the pattern of settlement and population connectivity supports in making new Marine Protected areas.