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Air-Sea Interactions And Ocean Dynamics In The Southwest Tropical Indian Ocean

Jessica Maureen Burns
University of South Carolina

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AIR-SEA INTERACTIONS AND OCEAN DYNAMICS IN THE SOUTHWEST TROPICAL INDIAN OCEAN

by

Jessica Maureen Burns

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Accepted by:
Subrahmanyam Bulusu, Director of Thesis
Venkat Lakshmi, Reader
Alexander Yankovsky, Reader
Cheryl L. Addy, Vice Provost and Dean of the Graduate School
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ABSTRACT

The Southwest Tropical Indian Ocean (SWTIO) features a unique, seasonal upward lift of the thermocline, which is known as the Seychelles-Chagos Thermocline Ridge (SCTR; 55°E-65°E, 5°S-12°S). It is known that a high correlation exists between the depth of the thermocline and sea surface temperature (SST; a key ingredient for tropical cyclogenesis). With a particular focus on 2012/2013, this study reveals the dynamic properties of the SCTR that play an important role in the modulation of tropical cyclones in the SWTIO. Phenomena including Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) are also well correlated to cyclogenesis through changes in the thermocline of the SCTR. More tropical cyclones form over the SWTIO when the thermocline is deeper, which has a positive relation to the arrival of downwelling Rossby waves originating in the southeast tropical Indian Ocean due to the anomalous effects of IOD.

In addition to influencing cyclogeneis over the SCTR region, remote processes such as IOD and ENSO are also the primary drivers of the SCTR interannual variability with respect to both ocean temperature and salinity. Thus, this study also explores how temperature and salinity with depth, as well as at the surface, in the SCTR change with the climatic events in a given year. Although ENSO is known to have a stronger impact on SST south of the SCTR (10°S-15°S), this study reveals the stronger impact of ENSO on sea surface salinity (SSS) in the SCTR.
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CHAPTER 1
INTRODUCTION

A. Study Region: Seychelles-Chagos Thermocline Ridge and the Southwest Tropical Indian Ocean

Unlike the neighboring Pacific and Atlantic Oceans, the Indian Ocean does not feature strong equatorial upwelling due to the tropical westerlies that dominate over the region. Instead, large open-ocean upwelling is isolated to the Southwest Tropical Indian Ocean (SWTIO) where the transition from northerly to westerly winds over the region generate strong Ekman pumping throughout most of the annual cycle [Figure 1.1; Hermes and Reason, 2009a; Hermes and Reason, 2009b]. This upwelling region, bound by 55°E-65°E and 5°S-12°S, has been named the Seychelles-Chagos thermocline ridge (SCTR) after the islands it sits between, and shares many similarities with other important open-ocean upwelling regions such as the Costa Rica Dome [Umatani and Yamagata, 1991]. This region in particular is important to the seasonal and climate dynamics of the Indian Ocean because of the sea surface temperature (SST) anomalies in this region caused by the seasonal upwelling of colder subsurface waters [Schott and McCreary, 2001]. This SCTR is also an important region for air-sea interactions because of its strong connection between the depth of the thermocline and SST and its close proximity to the equator where the atmosphere is already sensitive to SST variations [Manola et al., 2015].
B. Tropical Cyclones in the Southwest Tropical Indian Ocean

In the SWTIO, tropical cyclone season is from November through April. On average, about 15 tropical storms form over the SWTIO and move across the Indian Ocean basin. The storms ultimately pose a major threat to the Indian Ocean rim countries, especially eastern Africa. Over the SWTIO, most of the tropical storms that later develop into tropical cyclones are formed between the latitudinal belt of 5°S-10°S [Vialard and Duvel, 2008]. The SCTR overlaps this active tropical cyclone band. This region is an important region for air-sea interaction and is unique in that the variability of the subsurface ocean processes can influence the cyclogenesis.

C. El Nino Southern Oscillation and Indian Ocean Dipole

A positive Indian Ocean Dipole (IOD) event is identified by a negative SST anomaly in the tropical eastern Indian Ocean and a positive SST anomaly in the tropical western Indian Ocean [Saji et al., 1999]. During the peak phase of an IOD event, the equatorial winds reverse direction from westerlies to easterlies when the SST is cool in the east and warm in the west. During a positive IOD event, in the subsurface level, the thermocline rises in the east due to upwelling and deepens in the central and western parts [Yamagata et al., 2004]. El Niño Southern Oscillation (ENSO) is an equatorial Pacific climate scale phenomenon that impacts the atmosphere and ocean globally [Murtugude et al., 2002; Du et al., 2009; Kumar et al., 2014; Rao et al., 2002]. Rossby waves generated off the west coast of Australia following an ENSO or IOD event propagate across the southern Indian Ocean [Masumoto and Meyers, 1998] arriving
several months later at the SCTR region and suppressing the thermocline; altering SCTR oceanic dynamics.

In this thesis, chapter two examines the relationship between the dynamics of the SCTR in SWTIO and tropical cyclones with a particular focus on austral summer of 2012/2013. In the austral summer of 2012/2013, seven named tropical cyclones developed in the SWTIO during cyclone season, including intense tropical cyclone ‘Anais’, preceding the typical tropical cyclone season in October. This chapter discusses the role of Rossby waves, triggered by IOD and ENSO events, on TC activity. Additionally, the mixed layer depth (MLD), isothermal layer depth (ILD), and barrier layer thickness (BLT) are examined to relate the evolution of the barrier layer and the mixed layer dynamics in the SCTR region and along the cyclone tracks to the intensity of these storms.

Chapter three discusses the variability of the SCTR dynamics in connection with ENSO and IOD. ENSO and IOD have been linked to influencing parameters such as SST, sea surface salinity (SSS), sea surface height (SSH), and surface wind patterns over the SCTR region. Looking over a larger time frame, this study explores how the SCTR responds to ENSO and IOD events.

Lastly in chapter four, the major findings of this research are summarized. The methods of this research can be implemented to other regions, for example, the Sri Lanka dome. These further research ideas are also discussed in Chapter four.
Figure 1.1: Climatological surface winds and 0–300m average ocean temperature in Jan–Feb. (The Seychelles–Chagos thermocline ridge (SCTR) is in the box area). The thick black arrows indicate the surface flow induced by wind that promotes upwelling and leads to the SCTR formation. The arrows marked SEC and SECC indicate the south equatorial current and south equatorial countercurrent. [Figure modified from Vialard et al., 2009]
CHAPTER 2
TROPICAL CYCLONE ACTIVITY OVER THE SOUTHWEST TROPICAL INDIAN OCEAN


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ABSTRACT

The Southwest Tropical Indian Ocean (SWTIO) is a key region for air-sea interaction. Tropical cyclones (TCs) regularly form over the SWTIO and subsurface ocean variability influences the cyclogenesis of this region. Tropical cyclone days for this region span from November through April, and peak in January and February during austral summer. Past research provides evidence for more tropical cyclone days over the SWTIO during austral summer (December–June) with a deep thermocline ridge than in austral summer with a shallow thermocline ridge. We have analyzed the Argo temperature data and HYbrid Coordinate Ocean Model (HYCOM) outputs while focusing on the austral summer of 2012/2013 (a positive Indian Ocean Dipole (IOD) year and neutral El Niño Southern Oscillation (ENSO) year) when seven named tropical cyclones developed over the SWTIO region. This study reveals that climatic events like IOD and ENSO influence the cyclonic activity and number of TC days over the SWTIO. We ascertain that the IOD events have linkages with the Barrier Layer Thickness (BLT) in the SWTIO region through propagating Rossby waves, and further show that the BLT variability influences the cyclonic activity in this region.

2.1 INTRODUCTION

In the Southwest Tropical Indian Ocean (SWTIO), tropical cyclone season is from November through April. On an average, about 15 tropical storms form over the SWTIO and move across the Indian Ocean basin, and ultimately pose a major threat to the Indian
Ocean rim countries, especially in eastern Africa. A recent report for the 2012/2013 TC season [RSMC, 2015] suggested that, although only one TC crossed over land, many of the cyclones were close enough to affect inhabited lands, and Haruna even claimed victims on the island of Madagascar.

Over the SWTIO, most of the tropical storms that later develop into tropical cyclones (TCs) are formed between the latitudinal belt of 5°S–10°S [Vialard et al., 2009]. The Seychelles-Chagos Thermocline Ridge (SCTR), bounded by 55°E–65°E and 5°S–12°S, overlaps this active tropical cyclone band. Although the main upwelling region of the SCTR is between 55°–65°E and 5°–12°S, the upwelling extends as far east as 80°E. This SCTR region is an important region for air-sea interaction and is unique in that the variability of the subsurface ocean processes can influence cyclogenesis [Hermes and Reason, 2009b]. The strong connection between the depth of the thermocline and Sea Surface Temperature (SST) in the SCTR region, and its proximity to the equator where the atmosphere is already sensitive to variations in SST, suggests that the SCTR is an important region for not only air-sea interaction but also variations in tropical circulations [Manola et al., 2015]. Variations in the SCTR affect cyclogenesis over the SWTIO because the thermocline is shallowest from December to June (austral summer), a period that overlaps with the cyclone season [Xie et al., 2002; Hermes and Reason, 2009a; Manola et al., 2015]. Cyclogenesis over this region is also impacted by atmospheric stability, which in turn is influenced by SST [Annamalai et al., 2003; Hermes and Reason, 2009a]. Hermes and Reason [2009b] provided the evidence for more observed tropical cyclone days over SWTIO during austral summers of deep thermocline ridge than those with a shallow thermocline ridge. The reason is that when the ridge is
dynamically made-up of a deeper mixed layer, it experiences heightened SST, which is a key ingredient for cyclogenesis [Hermes and Reason, 2009b]. Additionally, the deep thermocline suppresses the feedback to the SST as upwelling of cooler subsurface waters is restrained. The inhibition of mixing at the base of mixed layer prevents the cooler waters from mixing to the surface and lowering of SST. During austral summer, the SCTR features a SST range between 28.5°C and 30°C, which makes the atmosphere sensitive to small changes in SST [Vialard et al., 2009]. This SST range is unusual for a quasi-permanent upwelling region. Most upwelling regions similar to the SCTR (e.g., eastern tropical Pacific) have SSTs much below 28.5°C resulting from cold thermocline waters brought to the surface under the influence of anticyclonic wind stress curl field during austral summer [McCreary et al., 1993]. However, on a seasonal time scale, the vertical advection by way of upwelling has little effect on the mixed layer temperature or SSTs so during upwelling times the colder water below does not significantly cool the water at the surface through vertical advection [Halkides and Lee, 2009].

The Barrier Layer (BL) is defined as the layer between the thermocline and the halocline. BL formation is an important parameter for surface heat exchange and thus heat content in the ocean. The stratification due to the vertical distribution of salinity may affect heat exchange between the ocean and atmosphere, thus affecting cyclogenesis. Balaguru et al. [2012] demonstrated that in parts of the tropical Pacific, Atlantic, and the northern Indian Ocean basins, salinity stratified BLs in the upper ocean influence TC intensification. The same study also demonstrated that in tropical ocean basins, typically, the intensification rate of TCs is about 50% higher over the BL regions than in regions without BLs. The occurrence of a salt-stratified BL causes stratification that reduces
This study focuses on austral summer of 2012/2013 when seven named TCs developed over the SWTIO during cyclone season, including the occurrence of the intense TC ‘Anais’, preceding the typical tropical cyclone season, in October. Usually, the cyclone season in the SWTIO does not begin until November and there are only on average 5 named cyclones and 10 tropical storms per season [Vialard et al., 2009]. We explore the impacts of IOD and ENSO events on the formation of TCs and their intensification in the SWTIO region. The archived data of tropical storms and their paths from 1982 through 2013 were downloaded from Unisys Weather and Typhoon Warning Center (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/shindex.php).

Primarily, Argo observations of salinity and temperature along with HYCOM simulations are used to examine the influence of the SWTIO region on cyclone formation and intensity in this region. All analyses are performed on the extended SCTR upwelling region (55°–80°E and 5°–12°S), unless otherwise specified. Correlating the dynamics of the SCTR region with tropical cyclone activity will hopefully provide an insight to cyclone formation and intensity in this region and ultimately lead to more accurate cyclone intensity and track forecasts.

2.2 DATA AND METHODOLOGY

A. Data Sources

The tropical cyclone days and their location data and surface winds data used in this study were downloaded from the Joint Typhoon Warning Center (JTWC) best track
data set for the Southern Hemisphere [Chu et al., 2002]. Additionally, track information and hurricane data for the 2012/2013 SWTIO TC season were obtained from Unisys Weather and the National Aeronautics and Space Administration's (NASA) past years Hurricane/Tropical Cyclone news archive. Whenever the JTWC issues a warning, the Regional and Mesoscale Meteorology Branch (RAMMB) estimates TC intensities based on winds and temperature every 6 h [Sampson and Schrader, 2000]. Only the TCs over the SWTIO basin (i.e., 40–90°E and 0–40°S) were considered in this study. In addition, the World Meteorological Organization (WMO) defines tropical cyclones in the SWTIO as having maximum sustained winds near the center exceeding 33 ms$^{-1}$, therefore only cases that met this criterion were considered for estimating the TC days for the purpose of this study. Oceanic Niño Index (ONI) region 3.4 values were obtained from the National Weather Service Climate Prediction Center [Wolter and Timlin, 1993, 1998]. Dipole Mode Index (DMI), a measure of IOD intensity, data were obtained from The State of the Ocean Climate webpage (stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php). The DMI is defined as the difference in SST anomaly between the south-eastern Indian Ocean (90° E–110° E and 10° S–0°) and the western Indian Ocean (50° E–70° E and 10° S–10° N) [Saji et al., 1999].

Argo floats drift within the ocean and typically retrieves salinity and temperature in the water column. The Argo SST data were obtained from the Asian Pacific Research Center (APDRC). APDRC takes the raw data from the Argo profiles and grids them into 1°×1° resolutions using optimal interpolation. APDRC also applies the raw data horizontal binning and vertical interpolation, where the data are interpolated onto standard depth levels.
In this study, we used a data assimilative version of the HYbrid Coordinate Ocean Model (HYCOM). HYCOM is extensively described in Bleck [2002], Chassignet et al. [2003], and Metzger et al. [2014]. The model has a nominal horizontal resolution of 1/12° and 41 hybrid layers in the vertical. It is isopycnal in the open stratified ocean, and makes a smooth transition to a terrain following ($\sigma$) coordinate in coastal waters using the layered continuity equation. The HYCOM system uses the Navy Coupled Ocean Data Assimilation (NCODA) system [Cummings and Smedstad, 2013] for data assimilation. NCODA uses the model forecast as a first guess in a three-dimensional variational scheme and assimilates available satellite altimeter observations, satellite and in-situ SST as well as available in-situ vertical temperature and salinity profiles from CTDs, Argo floats and moored buoys. The outputs of profiles of salinity and temperature were interpolated to calculate the mixed layer depth (MLD), isothermal layer depth (ILD), and barrier layer thickness (BLT).

The European Centre for Medium-Range Weather Forecasts (ECMWF) provides an archive of meteorological data. In this study, we utilized the ECMWF’s monthly mean 10 m wind and monthly mean 850 hPa relative vorticity. In addition, we used the monthly mean 700 hPa and 500 hPa relative humidity (RH), monthly mean 850 hPa and 500 hPa air temperature, and monthly mean horizontal and meridional components of the 200 hPa and 850 hPa wind vectors to compute atmospheric parameters known to influence cyclogenesis (discussed in the methodology section).

Daily sea surface height anomaly (SSHA) data for 2010–2015 were obtained from Archiving Validation and Interpretation of Satellite Oceanographic data (AVISO) (http://www.aviso.oceanobs.com) [Ducet et al. 2000]. This product, a representation of
SSH relative to the 1993–2012 mean sea level, is produced by merging altimetry measurements from several satellites including Ocean Topography Experiment (TOPEX)/Poseidon, Jason, European Remote Sensing Satellite (ERS-1/2), and Environmental Satellite (Envisat). In this study, the AVISO altimetry data were used to observe Rossby wave propagation across the SWTIO basin.

Monthly precipitation (P) data were obtained from the Tropical Rainfall Measuring Mission (TRMM) [Hoffman et al., 2007] product 3B42 version 7. The data are produced from a combination of rain gauge and satellite data and are available on a 0.25° × 0.25 ° grid.

B. Methodology

To find the MLD, we used the variable density criterion method as described in Felton et al. [2013] where Δσ is the density change from the surface to the MLD base:

\[
\Delta \sigma = \sigma_i(T_0 + \Delta T, S_0, P_0) - \sigma_i(T_0, S_0, P_0)
\]

The term \( \sigma_i(T_0 + \Delta T, S_0, P_0) \) accounts for the presence of thermal inversion since it is the density equal to the change in temperature from the surface while salinity and pressure are constant as at sea surface. The \( \sigma_i(T_0, S_0, P_0) \) term is the surface \( \sigma_i \) value. Each location was searched to find the depth where the density changed by an amount equivalent to a change in temperature of 0.5°C from the surface, and this depth was then defined as the MLD.

For both MLD and ILD, linear interpolations of the HYCOM data were used to obtain the approximate depth. The ILD is defined as the depth where the temperature is ±0.5°C from the surface temperature \( T_z - T_o = 0.5 \), where \( T_o \) is the surface temperature.
and $T_z$ is the temperature at depth, $z$. The BLT is then calculated by taking the difference between the ILD and MLD (BLT=ILD-MLD).

Gray [1968, 1979] proposed vertical wind shear, mid-tropospheric R.H., and mid-tropospheric thermal instability to be among the atmospheric parameters influencing cyclogenesis. The mid-tropospheric R.H. is computed by taking the difference between the R.H at 700 hPa and 500 hPa (mid-tropospheric R.H. (%) = R.H\textsubscript{700 hPa} - R.H\textsubscript{500 hPa}). The mid-tropospheric instability is computed as the air temperature at 850 hPa minus the air temperature at 500 hPa (mid-tropospheric instability = T\textsubscript{850 hPa} - T\textsubscript{500 hPa}). The vertical wind shear (m s\textsuperscript{-1}) is computed using the vector wind speed at 200 hPa and 850 hPa where $u$ is the zonal component of the wind speed and $v$ is the meridional component of the wind speed:

$$\text{Vertical wind shear (m s}^{-1}) = \sqrt{(u_{200 \text{ hPa}} - u_{850 \text{ hPa}})^2 + (v_{200 \text{ hPa}} - v_{850 \text{ hPa}})^2}$$

To examine the relationship between ENSO and number of TCs and ENSO and number of TC days in the SWTIO from 1981-2013 we needed to standardize the data for the different phases of ENSO. To do this we took the mean number of TCs during neutral years, subtracted out the long-term mean of TCs and divided by the standard deviation. We did this for each phase of ENSO for both TCs and TC days.

2.3 RESULTS AND DISCUSSION

A. 2012/2013 Cyclonic Activity in the Southwest Tropical Indian Ocean

Tropical cyclone days for the SWTIO span from November through April, with an average of 15 tropical storms and named cyclones that track across the basin. In the 2012/2013 season, there were seven named tropical cyclones (Figure 2.1a; Anais
The tracks of these cyclones are displayed in Figure 2.1b. All the cyclones started within a few degrees of the equator in the SCTR region or just south of the region and traveled poleward. The most intense cyclone was at the end of January going into February with the cyclone in December and the cyclone in October followed closely behind (Table 2.1). The 2012 positive IOD event may have influenced the intensity and variability of these TCs through the propagation of downwelling Rossby waves.

Generally, winds north of the equator are westerly while winds south of the equator are easterly. However, during positive IOD years, the normal equatorial westerly winds weaken and eventually reverse direction to easterly. This wind anomaly and associated Ekman pumping generate off-equatorial Rossby waves that propagate westward and act to deepen the thermocline; thus warming the SST in the western part of the Indian Ocean [Gnanaseelan et al., 2008; Chowdary et al., 2009]. Figure 2.2 shows the wind anomalies plotted over SST anomalies for the peak months during the 2012 positive IOD. This IOD event is unique in that the IOD peaked in August and September (Figure 2.2). The early peak may be attributed to the quick weakening and reversal of the westerly trade winds north of the equator. Strong westerlies near the equator can create unfavorable conditions for the negative dipole [Vinayachandran et al., 2009]. However, if the westerlies quickly weakened, earlier than usual, this would allow the negative dipole to form and peak earlier than usual off the west coast of Sumatra. In Figure 2.2 it is seen that by August 2012 the trade winds immediately north of the equator were already anomalously easterly and beginning to weaken and return to their normal
westerly flow. As these winds further weaken and reverse back, the thermocline deepens [Vinayachandran et al., 2009], and the negative dipole decays. Since the IOD had an early peak, the region of the 2012/2013 TC cyclone tracks in the SWTIO experienced warmer SST earlier than usual (Figure 2.2) in the month of October. As a result, we see TC occurrence earlier (October) than the typical start of the TC season (November), and an earlier peak in TC season as well, with 4 of the 7 cyclones of the 2012/2013 season occurring in the months of January and February.

For the 2012/2013 TC season, most of the TCs formed east of the major upwelling zone of the SCTR, in the 60–80°E longitude range. In Figure 2.3, we see the Rossby wave enters the SWTIO in mid-2012 (dashed black line). The Rossby wave propagates at an estimated speed of 25 cm s\(^{-1}\). With this speed, the high SSH anomalies reach the 60–80°E longitude range by late 2012 and early 2013 (dashed red and white lines), coinciding with higher TC activity. As the Rossby waves reach the SCTR region and deepen the thermocline heat content increases in the western part of the Indian Ocean, thus supporting TC development. According to the National Oceanographic Data Center (NODC) [Levitus et al., 2012] the mean 0–700 m layer total heat content (THC) in the South Indian Ocean for the months of July–September 2012 was 2.6 \(\times 10^{22}\) J. For the months of October–December 2012 the THC was 3.2 \(\times 10^{22}\) J. THC for January–March 2013 was 3.4 \(\times 10^{22}\) J, and for April–June 2013 the THC decreased again to 2.3 \(\times 10^{22}\) J. The spike in total heat content during the October–March period agrees with the Rossby waves propagating westward across the Indian Ocean basin and reaching the 60–80°E longitude range within 4–6 months.

Figure 2.4 shows that all of the cyclones developed in areas of SST of
approximately 28°C and died in areas of SST varying between 24° and 26°C. Unlike other seasons, March had no tropical cyclone activity. Gray [1968] proposed many preconditions of oceanic and atmospheric parameters for the cyclogenesis including a threshold of SST above 26°C, high low-level relative vorticity, low vertical wind shear, high midtropospheric relative humidity, and high midtropospheric thermal instability. Since SSTs in this SCTR region were warm enough during March 2013 (Figure 2.4), the absence of any tropical cyclone activity during this month is likely a result of an unfavorable atmospheric condition. During March 2013, there was high vertical wind shear (Figure 2.5), which might have torn any developing storm apart. In addition, there was also low relativity humidity (Figure 2.5), thus dry layers could have also suppressed any cyclone development.

B. Evolution of Barrier Layer and Mixed Layer Dynamics

Salinity stratification in the ocean results in a difference between the ILD and MLD, creating a BL, which is important in regulating surface heat exchanges [Felton et al., 2014]. The thickness of this BL varies seasonally in this region (Figure 2.6). Since the BL is important in regulating surface heat exchanges, it also may play a role in the formation of TCs in the SWTIO. As TCs pass over BLs, SST cooling decreased due to reduced efficiency in vertical mixing [Balaguru et al., 2012]. This reduction in SST cooling then strengthens TCs through changes in air-sea heat transfers.

Chowdary et al. [2009] explains that Rossby wave induced surface warming results from downwelling Rossby waves pushing the thermocline downward resulting in a deeper thermocline thus creating a thicker BL and contributing to surface warming.
Since the IOD events result in the propagation of upwelling and downwelling Rossby waves, they would thus influence the BLs. Figure 2.7 shows the relationship between the DMI of each month during peak IOD (August–December) and the BLT 4 months, 5 months, and 6 months later. Significant correlation exists up to 4–5 months (not significant at 6 month lag, Figure 2.7). This suggests that the impact of the IOD on BLT extends beyond the peak months of the IOD, up to about 5 months (i.e., into the year after the IOD events). This is plausible as, for example, during the peak of positive IOD events, the warming SST increases convective activities which induces more rainfall, increases stratification, strengthens Surface Temperature Anomalies (SSTA) and further enhances the BLT. Additionally, the higher SSTAs feedback to strengthen the zonal winds which further enhances the downwelling during these events.

The BL may inhibit entrainment and maintain higher SSTs favoring cyclogenesis, but atmospheric conditions are also very important for cyclogenesis. Figure 2.8 examines how BLT may correlate to atmospheric conditions important for cyclogenesis over a 4 year period. During, January 2010 to December 2013 the thicker the BLT is, the higher the vertical wind shear is. This would result in a competition of favorable conditions for cyclogenesis since thicker BLs may help inhibit entrainment and maintain high SSTs but high vertical wind shear negatively influences cyclogenesis by tearing the storm apart. The midtropospheric stability would also result in cyclogenesis competition during these years. For TC formation, higher thermal instability in the midtroposphere is essential, but associated with high instability is a lower BLT during 2010–2013. With regard to vorticity in atmospheric winds, the relationship between low level vorticity and BLT seems to be more variable (Figure 2.8).
Results from Mainelli et al. [2008] support the idea that the upper ocean thermal structure is important in TC intensity changes. While IOD events and Rossby waves may influence BLs, feedback between the storm and the BL may also exist. Figure 2.9 examines the subsurface ocean structure by showing the evolution of MLD (blue line), the mixed layer temperature (MLT, red line) and the BLT (black line) for the three cyclones out of the seven TCs in 2012/2013. In the first two cases (Felleng and Gino), the BL thickens along the tracks. In the case of ‘Imelda’, we do not see this happening (Figure 2.9). The TC Imelda was a long lasting storm and instead of traveling southward, the storm tracked westward for a while, before turning southward. Therefore, most of the storm track (where BLT is spatially averaged) was in the SCTR upwelling region where subsurface dynamics differ.

In all three cases of TCs, we observe something different with regard to the BLT and intensity of the cyclone. In the first two cases (Felleng and Gino), at the start of the cyclones, BL thickens along the tracks and at the same time the TC intensity increases. During Felleng, as its intensity peaks, we see a short leveling of the BLT then an increase again. In the case of Gino, we just see a leveling of the BLT after the storm peaks in intensity. In the case of Imelda the BLT remains constant throughout the cyclone life and we observe 2 peaks in intensity. The large variability between these results suggests that the BLT alone does not significantly influence storm intensity.

C. Role of ENSO and IOD Events on the SWTIO Cyclonic Activity

Preexisting studies have been done to examine TC activity over the SWTIO. However, the use of different data sets have resulted in varying results amongst these
studies. A recent study by Astier et al. [2015] used primarily TC data from the Meteo-France RSMC La Réunion database. However, when a TC was included in the JTWC database and not in the RSMC’s database, Astier et al. [2015] added that TC to their database. Astier et al. [2015] used the years 1981–2013 as their study period and excluded all TCs in the Mozambique Channel arguing that TC activity in this area may be different than TC activity in the rest of the SWTIO. They also focused only on peak TC season months (January–March). We obtained our TC data from the JTWC database for 1981–2013. We considered the entire SWTIO (some Mozambique Channel TC eventually cross into the main SWTIO region and vice versa) and considered the entire TC season since some of the most intense TC cyclones occur outside of the peak TC months.

Since there are different numbers of El Niño (10 years total), La Niña (11 years total) and Neutral years (11 years total) during the 1981–2013 time period, we standardized the data by subtracting the long-term mean (mean for 1981–2013 period) from the mean of each ENSO phase and dividing by the long-term standard deviation (standard deviation for 1981–2013 period). Both the number of TCs and TC days were plotted to see if there was a difference between the number of TCs and the duration the TCs were lasting. During neutral years, the mean number of TCs and the mean number of TC days is approximately 0.7 standard deviations above the long-term total mean of TC (Figure 2.10). Both El Niño and La Niña years experience below average number of TCs and TC days (Figure 2.10). In addition to more cyclones occurring during the neutral years, the TC season also lasted longer and began earlier during neutral years as well. During the months of September, October and May the TCs occurred during neutral years.
(Figure 2.11a) but not during years of positive or negative ENSO phase. However, this may also be a result of a 1 year smaller sample size for El Niño years during our study period or simply too small of sample sizes for all three categories to be statistically accurate.

With regard to the neutral phase of ENSO, Astier et al. [2015] concluded that neutral years seem to have high variability in TC activity. Although the TC days may be variable during these years, more TC days do still occur during neutral years in comparison to the positive and negative phases of ENSO (Figure 2.10). While they concluded that cyclogenesis seems to be less favored during La Niña years, we also conclude that there seems to be less TC activity during La Niña years. For the positive ENSO phase, Astier et al. [2015] concluded that there is competition between favorable and unfavorable conditions for cyclogenesis. During El Niño years, cyclogenesis would be favored because of higher SST, higher humidity, and vorticity [Kuleshov et al., 2009]. However, the equator-ward shift of the subtropical jet creates wind shear, which can suppress the storm formation, in the areas where TCs typically form (10°–20°S) [Heureux and Thompson, 2006]. Although they noted low TC activity being associated with El Niño years, overall their study concluded that there is no clear linear relationship between ENSO and TC activity. However, when looking at just the positive phase of ENSO, we do see a statistically significant correlation between the positive phase of ONI and the number of TCs ($r = -0.78$, $p = 0.008$) and TC days ($r = -0.75$, $p = 0.012$) (Figure 2.12). As the ONI index increases, the number of TCs and TC days decreased.

There seems to be a less clear pattern with regard to IOD events and the mean number of TCs each month (Figure 2.10b). Some months, years of positive IOD events
have the largest mean number of TCs while other months' neutral or negative IOD years seem to (Figure 2.10b). These inconsistent results may be due to the timing of the downwelling and upwelling Rossby waves (associated with IOD events) reaching the SCTR region. On the other hand, it could be due to skewed data since the sample size for the positive IOD, neutral, and negative IOD are different. With regard to intensity, we also do not observe any obvious pattern. The year 2012 was a positive IOD and we see the highest number of storm systems for most of the intensity categories during the 2012/2013 TC season (Figure 2.13). However, the year 2011 was also a positive IOD and this was not the case. A difference in the strength or the peak month of the IOD events may have resulted in the inconsistent results for those 2 years. The 2010 negative IOD year showed the least amount of tropical systems for each of the intensity categories and also produced no TCs with an intensity greater than 43 m/s or 85 kt (Figure 2.13). However, to draw the conclusion that negative IOD events result in less intense TCs, more negative IOD years data would be needed for the analysis.

With regard to the intensity of the IOD event and TC activity, there seems to be no direct correlation between the DMI of a year and the number of TC days in the same year (figure not shown). However, a 4–5 month lag relationship exists between the DMI of a year and the number of TC days (Figure 2.14). In Figure 2.14, the DMI and TC days during 2003 and 2013 are correlated against each other at zero lag and then at subsequent month lags. The DMI of 2012 would be setting the stage for the 2012/2013 cyclone season, with a 4–5 months lag between the peak DMI for 2012 (August–September) and the peak in TC season (January–February 2013) (Figure 2.15). This lag is due to the approximate time it takes for downwelling Rossby waves generated at the periphery of
the colder SST band off southern Sumatra coast during positive IOD events to propagate westward across the SWTIO ocean basin. It takes approximately 4–6 months for downwelling Rossby waves to reach about 60–80ºE (the region where most TCs form in the SWTIO, Figure 2.3).

**2.3 SUMMARY AND CONCLUSIONS**

In this study, we examined how phenomena like IOD and ENSO events impact the variability of TCs in the SWTIO. We found that there seems to be a negative linear correlation between the positive phase of ENSO and TC days in the SWTIO while neutral ENSO years seem to have more TC activity than other years. We also analyzed how Rossby waves associated with IOD events may influence BL and thus TCs. The BLT was correlated to atmospheric conditions important for cyclogenesis over a 4 year period and results showed that during this 4 year period midtropospheric instability and vertical wind shear values that may be unfavorable to TCs are associated with thicker BLs favoring TC formation. The BLT along the cyclone tracks were also studied to see if the BL along the cyclone tracks could influence the storm intensity. However, the large variability between these results suggested that the BLT alone does not significantly influence storm intensity.

In summary, we examined the relationship between the properties of the SCTR region and TCs in the SWTIO, while focusing on the 2012/2013 TC season. The year 2012 was a positive IOD year and a neutral ENSO year. In the SWTIO, on average, neutral years experienced higher number of TCs. Therefore, the lack of an ENSO event in 2012 may have played a role in the number of TC days during that season. With regard to
IOD, we established that there is a 4–5 month lag correlation between DMI index and number of TC days in the SWTIO region. This lag time is attributed to the traveling time of Rossby waves (4–6 months) across the IO basin to the SCTR region. Therefore, the occurrence of a positive Indian Ocean Dipole in 2012 possibly influenced the number of TC days in that season through downwelling Rossby waves. As the Rossby waves propagated westward, they deepened the thermocline and thickened the BL resulting in enhanced warming at the surface, and increased cyclogenesis in early 2013. Although we now have a better understanding of the dynamics that influenced the active 2012/2013 TC season, still more research is needed to see if these findings hold true for other seasons as well. In addition, other impacts of these climate phenomena (beyond the enhancement of surface warming) and their relation to TCs also need to be explored.
**Table 2.1:** 2012/2013 Tropical Cyclone Dates, Times, Location, Intensity, and Daily Barrier Layer Thickness Along Cyclone Track

<table>
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<tr>
<th>TC</th>
<th>Date</th>
<th>Time (UTC)</th>
<th>Location</th>
<th>Intensity (kt)</th>
<th>BLT (m)</th>
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<td>115</td>
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<tr>
<td></td>
<td>1/30</td>
<td>1800</td>
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<td>105</td>
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<tr>
<td></td>
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This table provides details on the dates, times, locations, intensities, and daily barrier layer thickness for various tropical cyclones from 2012/2013.
Figure 2.1: (a) Distributions of tropical storms and named tropical cyclones during 2012–2013 Tropical Cyclone Season in the Southwest Tropical Indian Ocean basin. The dashed red line represents precipitation rate (mm h$^{-1}$). (b) The 2012/2013 cyclone season seven named tropical cyclone tracks in the SWTIO. The black dashed circle is the SCTR region.
**Figure 2.2:** Argo monthly interannual SST anomalies for August–November 2012 using Argo data for a period of 2005–2014. Monthly mean ECMWF interannual wind anomalies are superimposed. Wind interannual anomalies were calculated with a base period of 1992–2013. The black boxes denote the south-eastern IO (90° E–110° E and 10° S–0°) and the western IO (50° E–70° E and 10° S–10° N), the regions of SST anomalies used to define the dipole mode index [Saji et al., 1999]. The black lines are the 2012/2013 TC season TC tracks.
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CHAPTER 3
VARIABILITY OF THE SEYCHELLES-CHAGOS THERMOCLINE RIDGE DYNAMICS IN CONNECTION WITH ENSO AND INDIAN OCEAN DIPOLE


**ABSTRACT**

Remote processes, such as El Niño- Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), are primary drivers of the Seychelles–Chagos thermocline ridge (SCTR) interannual variability with respect to ocean temperature and salinity. Although salinity variability in this region is understudied, previous studies have separated out effects of El Niño and IOD on sea surface temperature (SST) anomalies and concluded SST changes due to IOD are primarily associated with the southward advection of warmer equatorial water. Likewise, SST changes due to El Niño are associated with the suppression of clouds over the Indian Ocean. Although ENSO is known to have a stronger impact on SST south of the SCTR (10°S–15°S), this study finds that the ENSO has a stronger impact on sea surface salinity (SSS) in the SCTR. This study further explores how the surface and subsurface salinity and temperature in SCTR varies throughout the year in response to ENSO and IOD separate and co-events using long-term Simple Ocean Data Assimilation (SODA) reanalysis records. Our SSS results from the SODA reanalysis are compared and found to be consistent with soil moisture active passive derived SSS observations for both a positive and negative IOD year.

**3.1 INTRODUCTION**

During El Niño and Indian Ocean Dipole (IOD) co-occurrence years, basin-wide Indian Ocean warming has been observed and this results in changes in the surface wind pattern of the eastern Indian Ocean [Chowdery and Gnanaseelan, 2007]. This alteration
of surface wind patterns in the eastern Indian Ocean produces anomalous Ekman downwelling through which the suppression of the regional thermocline generates downwelling Rossby waves that propagate westward suppressing the Seychelles–Chagos Thermocline Ridge (SCTR; an open-ocean upwelling region located 55°E–65°E and 5°S–12°S). During El Niño and IOD co-occurrence years, meridional advection and enhanced vertical ocean-side processes have resulted in anomalous warming of the surface waters [Murtugudde et al., 2000; Du et al., 2009]. Xie et al. [2002] observed sea surface temperature (SST) anomalies in the SCTR region of up to 0.6 °C due to changes in thermocline depth caused by anomalous downwelling Rossby waves. Another study done by Rao et al. [2002] showed that SST variability in the Indian Ocean is controlled by El Niño-Southern Oscillation (ENSO), whereas IOD predominately controls the subsurface variability in this region.

Kumar et al. [2014] separated out the effects of El Niño and IOD on SST anomalies in the SCTR region through observational estimates and model-derived surface layer heat budget analyses. This study concluded that the changes in SST due to El Niño are associated with the suppression of clouds over the Indian Ocean as a whole, while changes in SST due to IOD are primarily associated with the southward advection of warmer equatorial water. While Kumar et al. [2014] concentrated on identifying the separate physical processes associated with ENSO and IOD affecting the SST in thermocline region, this study focuses on determining which regions are most effected by ENSO and IOD co-occurring years, and during which portions of the year, these regions are most impacted. The subsurface temperature anomalies and mixed layer salinity anomalies associated with El Niño, La Niña, and IOD years were addressed in a model
study [Jenson, 2007]. The model showed weak warm anomalies in the SCTR region during El Niño and larger warm anomalies in the SCTR during IOD events [Jenson, 2007]. In addition, this study also found that surface salinity anomalies were small and negative for El Niño, La Niña, and IOD events in our region of interest [Jenson, 2007].

In addition to examining the SST of combined and separated events, we also examine sea surface height (SSH), the thermocline, and salinity variability in the ocean, including sea surface salinity (SSS) in response to ENSO and IOD. Very few studies have focused on salinity with depth in response to these climatic events.

### 3.2 Data and Methodology

**A. Data Sources**

Dipole Mode Index (DMI) measures IOD intensity. The DMI is defined by difference in SST anomaly between the south-eastern Indian Ocean (90°E–110°E and 10°S–0°) and the western Indian Ocean (50°E–70°E and 10°S–10°N) [Saji et al., 1999]. For this study, the SST DMI data set derived from HadISST data set was obtained from the Japan Agency for Marine-Earth Science and Technology web page.

The Oceanic Niño Index (ONI) is one measure of ENSO. The ONI values used in this study were obtained from the National Weather Service Climate Prediction Center web site. The ONI values of the National Weather Service Climate Prediction Center were calculated as the three-month rolling mean of ERSST.v4 SST anomalies in the Niño 3.4 region (5°N–5°S and 120°W–170°W) based on centered 30-year base periods, updated every five years.

The Simple Ocean Data Assimilation (SODA) reanalysis is produced from a
general ocean circulation model, driven by surface forcing, and corrected based on direct observations \([Carton and Giese, 2008]\). SODA v2.2.4 is obtained from Asian Pacific Data Research Center at a monthly temporal resolution and a 1/2° spatial resolution, which spans from 1950–2010. This study utilizes monthly averaged SST, SSS, and SSH over a 50-year period (1960–2009). The model is based on Parallel Ocean Program physics. It consists of both gridded variables for the global ocean as well as derived fields.

**B. Methodology**

In this study, we use salinity derived from NASA’s soil moisture active passive (SMAP), which was launched on January 31, 2015. The monthly SMAP data Version 2.0 \([Meissner and Wentz, 2016]\) during April 2015–June 2016, obtained from Remote Sensing Systems, Santa Rosa, CA \([Meissner and Wentz, 2016]\), is used in this study. A comparison with ARGO for monthly 1° averages found a global RMS of 0.26 psu (personal communication with Dr. Thomas Meissner, Remote Sensing Systems).

In this study, we classified all the years between 1960–2009 as a positive IOD year if the three-month running mean DMI value was above a 0.5 value for three consecutive months, a negative IOD year if the three-month running mean DMI value was below a −0.5 value for three consecutive months, and all other years as neutral. We classified all the years between 1960–2009 as positive ENSO year if the three-month running mean ONI value was above a 0.5 value for three consecutive months, a La Niña year if the three-month running mean ONI value was below a −0.5 value for three consecutive months, and all other years as neutral. Once all years were classified as
positive IOD, negative IOD, or neutral IOD and La Niña, El Niño, or neutral years, the years were further classified as a positive IOD/El Niño year, positive IOD/La Niña year, negative IOD/El Niño year, negative IOD/La Niña year, positive IOD-only year, negative IOD-only year, El Niño-only years, La Niña-only year, or a neutral year. The results of which years fell under each category are summarized in Table 3.1.

In order to examine how each season may be impacted by ENSO and IOD events, we broke each year into quarters [January February March (JFM), April May June (AMJ), July August September (JAS), and October November December (OND)]. Since there are different numbers of years that fell under each category (Table 3.1), we standardized the quarterly data by subtracting the long-term quarterly means (mean for 1960–2009 period) from the mean of each quarter year and then divided the difference by the long-term quarterly standard deviations (standard deviation for 1960–2009 period). The quarterly standard scores for each year were then grouped into their categories (Table 3.1) and then averaged to get the mean standard score for each category. The standardization of each parameter indicates how many standard deviations above or below the observation is from the mean.

### 3.3 Results and Discussion

#### B. A Surface Response to ENSO and IOD on SCTR

IOD usually starts around May–June and peaks between August–October. ENSO events develop during March–June and reach peak intensity during the months December–April. Based on the 50 years between 1960 and 2009, when a positive IOD event occurs, 67% of the time, an El Niño event also occurs that year while only 33% of
the time either a La Niña or a neutral ENSO year also occurs (Table 3.1). When a positive IOD event occurs, co-occurrence with a La Niña is more common (eight events) than co-occurrence with an El Niño (three events), however, negative IOD is also frequently seen during neutral ENSO years (ten events) (Table 3.1). In this study, we focus on two of the more common combinations, the negative IOD/La Niña (eight years) and the positive IOD/El Niño (ten years).

Since previous studies have found that ENSO has a stronger impact between the latitudes 10°S–15°S and IOD seems to have a stronger impact between 5°S–10°S [Kumar et al., 2014; Rao and Behera, 2005; Yu et al., 2005], we have chosen to examine these regions as well as the SCTR in response to different ENSO and IOD phases. Through the displacement of the warm pool in the Western Pacific and its associated atmospheric convection over thousands of kilometers, El Niño is able to disrupt weather globally [Vialard and Duvel, 2008]. Most regions of the Indian Ocean experience a warming in response to surface heat flux perturbations prompted by the El Niño event [Vialard and Duvel, 2008]. The SCTR region seems to be among one of those regions. During all four quarters of the year, all three regions have above average SSTs during El Niño-only years (Figure 3.1). Because of the overlap between the three regions (particularly the SCTR and IOD region) and the smoothing involved in the 1/2° resolution of the SODA reanalysis, it is not surprising that all three regions have nearly identical anomalies.

With regards to IOD, generally, the wind pattern during neutral years is characterized by westerly winds north of the equator and easterly winds south of the equator. However, when a positive IOD event occurs, the normal equatorial westerly winds weaken and reverse direction to easterly winds. This wind anomaly and associated
Ekman pumping generate off-equatorial Rossby waves, which propagate westward deepening the thermocline and thus warming the SST in the western part of the Indian Ocean [Gnanaseelan et al., 2008]. During negative IOD years, the winds north of the equator remain westerly while the winds south of the equator weaken and eventually become westerly. Therefore, during negative IOD years, the Rossby waves are upwelling favorable resulting in a shoaling of the thermocline, which cools the subsurface temperatures and reduces the magnitude of heat content in the upper ocean. In agreement with these previous studies, negative IOD years have below average SST in all three regions for most of the year, but particularly during IOD months (Figure 3.2). In addition, during the IOD months of positive IOD years, the SST in all three regions is above average (Figure 3.1). Again, the identical anomalies are not surprising considering the overlap of the regions and the smoothing involved in the 1/2° resolution of the SODA reanalysis.

When El Niño events co-occur with a positive IOD event, the SST is still above average for all three regions during the last three quarters of the year. During the AMJ period, during positive IOD-only years, SST is below average in all three regions, but during El Niño-only years, SST is above average for all three regions during the AMJ period. When the two events co-occur, the SST is above average by almost half a standard deviation. This supports Rao et al. [2002] conclusion that ENSO has more influence on SST than IOD. Since the SST is above average in all three regions for most of the year during La Niña-only years and below average for most of the year in all three regions during negative IOD-only years, we would expect that when the two events co-occur the SST would be above average for most of the year in all three regions. However,
the SST is below average suggesting that the negative IOD might have more influence on SST than the La Niña.

The upwelling and downwelling Rossby waves associated with negative and positive IOD, respectively, do not only influence SST in the Southwest Indian Ocean, but also SSH. As mentioned above, during positive IOD years, the normal equatorial westerly winds weaken and eventually reverse direction to easterly winds. This wind anomaly and associated Ekman pumping generate off-equatorial Rossby waves that propagate westward increasing SSHs in the western part of the Indian Ocean upon their arrival [Gnanaseelan et al., 2008]. During negative IOD dipole years, the opposite is true and the Rossby waves are upwelling favorable. Thus, we see above average SSHs during positive IOD years and below average SSHs during negative IOD years (Figures. 3.1 and 3.2).

Although IOD generally peaks in August and September, the SSHs seem to be more influenced during the OND period. This is a result of the timing of the Rossby waves reaching the SCTR region. It takes approximately four to five months for downwelling Rossby waves to propagate westward and reach the SCTR region. Therefore, although the IOD is starting around May/June and peaking around August/September, the Rossby waves are taking a few months to travel across the Indian Ocean, reaching the SCTR region at the end of the year thus influencing the SSHs during the last quarter of the year.

All three regions seem to have a less clear response to ENSO in regards to SSH (Figures. 3.1 and 3.2). However, during positive IOD and El Niño co-occurring years, SSHs are slightly below average in all three regions during the middle of the year and
above average during the start and end of the year (Figure 3.1). During negative IOD and La Niña co-occurring years, the opposite is true. SSHs are slightly above average in all three regions during the middle of the year and below average during the start and end of the year (Figure 3.2).

A comparison of Argo versus SMAP (Figure 3.3) is provided to show the accuracy of SMAP in our region of interest. In the Southwest Tropical Indian Ocean (SWTIO) region, the mean difference between Argo SSS and SMAP SSS for 15 months is between 0 and 0.5 psu; having a standard deviation of about 0.2. The spatial SSS maps of the SWTIO using SMAP (Figure 3.4) are for three months of an El Niño/Positive IOD year (2015) and the same three months in an El Niño/ Negative IOD year (2016). During the month of April, May, and June, the salinity in the SCTR region is 0.02, 0.14, and 0.01 psu higher, respectively, during the El Niño/ Positive IOD year than during the El Niño/ Negative IOD year. Theses difference in SSS of the SCTR region between the two years is smaller than the accuracy of SMAP and these results contradict the idea that lower SSS values are observed in the western Indian Ocean during Positive IOD years because of the enhanced convection over the western Indian Ocean diluting the surface waters with fresh water rainfall [Saji et al., 1999]. However, the results of the SMAP analysis are consistent with our SODA analysis where the SSS in the SCTR during April, May, and June of the El Niño and Positive IOD years is slightly above average (0.13 standard deviations above the mean). During negative IOD years, above average SSS is observed in all three regions for most of the year (Figure 3.2). Contrary to this, during positive IOD years, below average SSS is observed in all three regions for most of the year (Figure 3.1). Therefore, surprisingly, the SCTR and IOD regions seem to be most influenced by
El Niño and La Niña events. During La Niña years, the SSS is below average in these two regions for all quarters of the years except JAS (Figure 3.2). During El Niño years, the SCTR and IOD regions experience below average SSS during JAS and all three regions experience above average SSS in OND (Figure 3.1). This suggests that although ENSO has a stronger impact in SST between the latitudes 10°S–15°S [Kumar et al., 2014; Rao and Behera, 2005; Yu et al., 2005]; this may not be the case for SSS.

B. Influence of ENSO and IOD on SCTR

Previous studies have found that ENSO-only events have had little influence on the thermocline. Our results seem to agree since the temperature anomalies with depth during La Niña-only years and El Niño-only years are very small (Figure 3.5). This signifies that regardless the ENSO event, as long as no IOD event is also co-occurring, the thermocline will not be influenced. On the other hand, previous studies have found that IOD events do influence the thermocline as a result of the off-equatorial Rossby waves that propagate westward and act to deepen the thermocline [Gnanaseelan et al., 2008]. During positive IOD-only years, temperature is anomalously warm in the SCTR region from 50–150 m, particularly during last few months of the year (Figure 3.5). During negative IOD events Rossby waves are upwelling favorable, shoaling the thermocline, and thus we see cold temperature anomalies during the end of the year from 50–100 m during IOD-only years (Figure 3.5).

Although SST can be influenced by interannual variability with El Niño contributing to basin wide warming and La Niña contributing to basin wide cooling, SSS anomalies in the Indian Ocean during El Niño and La Niña events are smaller in
magnitude and shorter in duration [Vinayachandran and Nanjundiah, 2009]. Chowdery and Gnanaseelan [2007] used SODA to look in depth at the variability between SSS and IOD and ENSO events. This study also uses SODA to cover a large period of time but instead of limiting ourselves to the surface, we examine the variability of salinity with depth during ENSO, IOD, and neutral years. We find that contrary to temperature, subsurface salinity does seem to be influenced by ENSO-only events.

While during negative IOD years, positive salinity with depth anomalies occur down to 80 m throughout much of the year, during positive IOD years, positive salinity with depth anomalies seem to occur down to the same depth (Figure 3.6). During the first half of La Niña years, salinity with depth is similar to that of El Niño years. However, for the second half of the year, positive anomalies are observed up to 100 m depth during El Niño years while negative anomalies are observed up to 50 m depth during La Niña years (Figure 3.6). This results in a similar salinity with depth structure for negative IOD/ La Niña years and positive IOD/ El Niño years for the early months of the calendar year. However, around the peak months of IOD and the start of ENSO peak months, the salinity in the upper 50 m layer of the SCTR region begins to become lower than usual during Positive IOD/ El Niño years.

### 3.4 Summary and Conclusions

In general, based on the study period of 1960–2009, both the SST and SSH in the SCTR, ENSO, and IOD region during different quarters of the year are influenced by ENSO-only, IOD-only, and ENSO and IOD co-occurring events. Previous studies have concluded that ENSO has more of an influence on SST than IOD. However, in this study,
for the case of negative IOD/ La Niña, the negative IOD might have more of an influence on SST than the La Niña. The SSS in these regions also seem to be influenced by IOD and ENSO events. Although Rao and Behera [2005] and Yu et al. [2005] found that ENSO has a stronger impact in SST between the latitudes 10°S–15°S, this study found that the SSS in the SCTR and IOD regions seem to be most influenced by El Niño and La Niña events.

With respect to IOD, we found that during negative IOD years, above average SSS is observed and during positive IOD years, below average SSS is observed. These results were compared to spatial SMAP SSS plots of the SWTIO for an El Niño/positive IOD year and an El Niño/negative IOD year. With SMAP confirming our analyzed SODA reanalysis results, we hope that remote sensing systems, such as SMAP and SMOS, will be able to provide more insight on ENSO and IOD influence with respect to salinity.

This is, as far as we know, the first study that analyzes how the subsurface salinity in SCTR varies during different months of the year in response to ENSO and IOD separate and co-events. With regards to salinity in the ocean with depth, during La Niña (El Niño)-only years, salinity down to 100 m seems to be much lower (higher) for the second half of the year. During negative (positive) IOD-only years, the salinity down to 100 m appears greater (lower) at all depth during all the months. IOD events seem to be the dominant influence on salinity during peak IOD months of co-occurring event years. Thus, the end of the year of Negative IOD/La Niña years have anomalously high salinity down to about 100 m and the end of the year of Positive IOD/El Niño years have anomalously low salinity down to about 100 m.
Table 3.1: Different IOD and ENSO Phase Years

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<tr>
<th>Year</th>
<th>Negative IOD/Neutral ENSO</th>
<th>Positive IOD/Neutral ENSO</th>
<th>Negative IOD/Neutral ENSO</th>
<th>Positive IOD/Neutral ENSO</th>
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<th>Neutral IOD/Neutral ENSO</th>
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Figure 3.1: Mean of standardized SODA SSH, SSS, and SST data for the SCTR (green), IOD influenced region (red), and ENSO influenced region (blue) for the period 1960–2009 during positive IOD and El Niño years (left column), positive IOD-only years (middle column), and El Niño-only years (right column) broken up into four three month periods.
Figure 3.2: Mean of standardized SODA SSH, SSS, and SST data for the SCTR (green), IOD influenced region (red), and ENSO influenced region (blue) for the period 1960–2009 during negative IOD and La Niña years (left column), negative IOD-only years (middle column), and La Niña-only years (right column) broken up into four three month periods.
Figure 3.3: Standard deviation of the difference between Argo SSS and SMAP SSS (average from April 2015–June 2016). Contours represent the mean of the difference between Argo SSS and SMAP SSS (April 2015–June 2016).
Figure 3.4: Monthly SMAP SSS for an El Niño/Positive IOD year (April–June 2015; left column) and an El Niño/Negative IOD year (April–June 2016; right column). Black boxes: SCTR region (5°S–12°S and 50°E–80°E), and the average salinity of the box for each month is displayed above each subplot.
Figure 3.5: SODA temperature anomalies with depth averaged over the SCTR region (5°S–12°S and 50°E–80°E) for (a) negative IOD and La Niña years, (b) negative IOD-only years, (c) La Niña-only years, (d) positive IOD and El Niño years, (e) positive IOD-only years, (f) El Niño-only years, and (g) Neutral IOD and neutral ENSO years.
Figure 3.6: SODA salinity anomalies with depth averaged over the SCTR region (5°S–12°S and 50°E–80°E) for (a) negative IOD and La Niña years, (b) negative IOD-only years, (c) La Niña-only years, (d) positive IOD and El Niño years, (e) positive IOD-only years, (f) El Niño-only years, and (g) Neutral IOD and neutral ENSO years.
CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

This research focused on how ENSO and IOD events impact the variability of cyclogenesis in the SWTIO and how these events influence the ocean dynamic properties of the SCTR, located in the SWTIO. The results display a negative linear correlation between the positive phase of ENSO and TC days in the SWTIO while neutral ENSO years seem to have more TC activity than other years. With regard to IOD, we established that there is a 4–5 month lag correlation between Dipole Model Index (DMI) and number of TC days in the SWTIO region. This lag time is attributed to the traveling time of Rossby waves (4–6 months) across the IO basin to the SCTR region. As the Rossby waves propagated westward, they deepened the thermocline and thickened the BL resulting in enhanced warming at the surface.

In addition to studying how remote processes such as ENSO and IOD influence cyclogenesis in the SCTR region, this study also explored how temperature and salinity with depth as well as at the surface in the SCTR change depending on climatic events in a given year. Although ENSO is known to have a stronger impact on SST south of the SCTR (10°S-15°S), the results of this research revealed that the ENSO has a stronger impact on sea surface salinity (SSS) in the SCTR.
4.2 Future Work

Because ENSO and IOD events influence the SCTR region in the SWTIO, it should not be dismissed that these climatic events have the potential to influence other, smaller, oceanic features of the Indian Ocean. For example, the Sri Lanka Dome. East of Sri Lanka, in the Northern Indian Ocean, a dome develops during the Southwest Monsoon season (June-September) and the dome is referred to as the Sri Lanka Dome (SLD). It is a seasonal dome that first appears around May, matures in July and decays around September. The formation of the dome is associated with the strong cyclonic wind stress curl east of Sri Lanka. Similar to the research presented in this thesis, a future study should encompass how the structure and dynamics of the SLD responds to the climatic events of ENSO and IOD as well as decadal changes of the SLD.

As mentioned above, the SLD develops during the SW monsoon in response to the cyclonic curl in the local wind field. Vinayachandran and Yamagata [1998] describe that the upward Ekman pumping induced by the cyclonic curl brings cooler waters to the near surface. They also explain the decay of the dome around September after the arrival of Rossby waves that are associated with the reflection of the Spring Wyrtki jet at the eastern boundary of the ocean [Vinayachandran and Yamagata, 1998].

The decadal variability the SLD may be experiencing may be linked to recent changes in the oceanic heat content (OHC) of the Indian Ocean. A study done by Vialard [2015], proposes that the Pacific Ocean may be dropping in temperature because the heat absorbed by the Pacific Ocean is transported to the Indian Ocean. Trade winds over the Pacific accumulate warm water in the western Pacific Ocean that creates high pressure on the Pacific side of the Indonesian Throughflow. Reed [2015] noted that there has been an
observed increase in trade winds since the beginning of the twenty-first century. This high pressure on the Pacific side of the Indonesian Throughflow creates a gradient that drives flow from the Pacific Ocean into the Indian Ocean [Vialard, 2015]. The enhanced flow in combination with the anomalous high SST in the Pacific Ocean ultimately resulted in an abrupt increase of heat content in the Indian Ocean [Reed, 2015]. Although decadal changes of the SLD may be a result of the increased heat content, the variability of the SLD may be due to changes in climatic events (if IOD and ENSO influence the SLD).

Preliminary results suggest that if ENSO events and/or IOD affect salinity and temperature in the SLD region, they may affect salinity most at shallower depths and temperature mostly around the 100 m depth. In addition, and in regards to decadal changes of the SLD, the atmospheric parameters including the wind shear and the mid-tropospheric relative humidity over the SLD region have been increasing over the decades. Preliminary results also allude to changes in the chlorophyll-a concentration over this region throughout the decades.
REFERENCES

Annamalai, H., R. Murtugudde, J. Potemra, S.-P Xie, P. Lui, and B. Wang (2003),
Coupled dynamics over the Indian Ocean: Spring initiation of the zonal mode,

Astier, N., M. Plu, and C. Claud (2015), Association between tropical cyclone activity in

Balaguru, K., P. Chang, R. Saravanan, L. R. Leung, Z. Xu, M. Li, and J. Hsieh (2012),
Ocean barrier layers' effect on tropical cyclone intensification. *Earth Atmos. 

Bleck, R. (2002), An oceanic general circulation model framed in hybrid isopycnic-

Carton, J.A, and B.S Giese (2008), A reanalysis of ocean climate using simple ocean data

simulations with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the


Meissner, T., and F. Wentz (2016), Remote Sensing Systems SMAPL3 monthly sea
surface salinity on 0.25 deg grid Version 2.0 validated release, Remote Sens. Syst.

Metzger, E. J., et al. (2014), US Navy operational global ocean and Arctic ice prediction
systems, Oceanography, 27(3), 32–43.


Masumoto, Y., and G. Meyers (1998), Forced Rossby waves in the southern tropical

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

variability in the tropical Indian Ocean with a special emphasis on the Indian

Reed, C. (2015), Tracking the missing heat from the global warming hiatus, Eos, 96,

RSMC (2015), Review of recent (2012-2015) main activities and achievements at RSMC
La Reunion, edited by RSMC La Réunion, pp 1–8, World Meteorological
Organization (WMO), Geneva, Switzerland.


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