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Kaitlyn E. Colna
University of South Florida, kcolna11@gmail.com

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Latitudinal Position and Trends of the Intertropical Convergence Zone (ITCZ) and its Relationship with Upwelling in the Southern Caribbean Sea and Global Climate Indices

by

Kaitlyn E. Colna

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
Marine Science
with a concentration in interdisciplinary and physical oceanography
College of Marine Science
University of South Florida

Major Professor: Frank Muller-Karger, Ph.D.
Don Chambers, Ph.D.
David Enfield, Ph.D.

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DEDICATION

I dedicate this thesis to all of those in my life who have provided me with support and encouragement. First, I dedicate this thesis to my family and friends who are and have always been my biggest support system, without them I would not be who I am or where I am today. The dedication my parents have provided to my education and success is a direct result of who I am today. I am so thankful to have such involved, supportive, dedicated, and proud parents. I owe my successes to how they raised me and their unwavering support in everything I do. I'd also like to dedicate this thesis to my sister who has been proud, supportive, and someone to confide in as well as a source of comic relief during stressful times. To my grandparents, whose support, encouragement, and involvement in my life and education has helped shape who I am. Additionally, I would like to thank my boyfriend for his support, encouragement, and dedication to me and my education. I could not have done it without him by my side. I also dedicate this thesis to my long time best friend Alyssa, thank you for being my best friend since as long as I can remember and providing me with support, positivity, and encouragement in everything I do. To my friend Megan, I am glad I had a friend to experience a graduate school with. Thank you for all of the studying help, support, and involvement in both my personal and educational life. Finally, I would like to thank Dr. Ajoy Kumar from Millersville University, without his direct personal influence and investment in my collegiate education and research experiences, I would not be where I am today. Thank you all for support, encouraging, and being there for me during my graduate school career, you all have influenced me and made me who I am today. I am eternally grateful for all of you and dedicate this thesis to you.

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ABSTRACT

The Intertropical Convergence Zone (ITCZ) is a feature that results from the ocean-atmosphere interactions in the tropics around the world. The ITCZ is characterized by surface wind convergence, tall storm clouds, and it forms a belt of high time-averaged precipitation around the globe. The ITCZ undergoes seasonal migrations between 5°S and 15°N roughly following the subsolar point on Earth with the seasons, with a mean annual position located slightly above the Equator, between 2° and 5°N.

This study tested the hypothesis that there was a northward shift in the median position of the ITCZ in the first decade of the 2000's relative to the 1900's. This hypothesis has been posed in the literature given a weakening in the intensity of the Trade Winds observed in the southern Caribbean Sea during the first decade of the 2000's, with concomitant ecological impacts due to weakening in coastal wind-driven upwelling. The hypothesis was tested by analyzing variations in the monthly latitudinal position of the ITCZ over the Atlantic Ocean relative to the median position computed for the period 1987-2011. The position of the ITCZ was derived from satellite-derived ocean surface wind measurements collected from 1987 to 2011. A Mann-Kendall analysis and a Monte Carlo simulation were used to test for trends in the median cross-basin latitudinal position of the ITCZ. The study included an analysis of regional changes across the tropical central Atlantic (50°W to 15°W), the Western Atlantic (50°W to 30°W), and the Eastern Atlantic (30°W to 15°W) within the tropics. The results show a

slight southward trend in the median position of the ITCZ over the central Atlantic and also in the Eastern Atlantic in the first decade of the 2000's relative to the 1990's. While this trend is barely significant, it is likely simply due to interannual variation in the average annual position of the ITCZ.

The data were also examined for the timing and persistence of a double ITCZ in the Atlantic. The double ITCZ over the Atlantic appeared every year in February or March, with the largest separation between the northern and southern branches of the ITCZ observed in June and July.

The possible effects of changes in the average latitudinal position of the ITCZ on the upwelling in the Cariaco Basin (southeastern Caribbean Sea off Venezuela) were also examined. Anomalies of the median of the latitudinal position of the ITCZ in the Atlantic were compared with anomalies of in-situ temperature collected during the 1990's and the first decade of the 2000's by the CARIACO Ocean Time-Series program and with anomalies of satellite SST (from the Advanced Very High Resolution Radiometer satellite; AVHRR) from 1995 to 2016. Correlation analysis were performed between anomalies of water temperatures at various depths and anomalies of satellite SST with anomalies of the monthly mean ITCZ position with lags up to 3 months for the time series, and also just for the Cariaco basin upwelling months (December-April).

For the whole Cariaco time series there were no significant correlations between the anomalies of the ITCZ position and anomalies in subsurface temperatures in the Cariaco Basin. However, during the upwelling period, the central Atlantic and Western Atlantic ITCZ position anomalies were directly correlated with Cariaco Basin temperature anomalies with no-lag (r = 0.20), and the central and Eastern Atlantic ITCZ position anomalies were inversely correlated with Cariaco Basin temperatures (r ~ -0.22 to -0.28) with ITCZ leading Cariaco temperatures by 3 months. However, these correlations were low, indicating that other factors than the position of ITCZ latitudinal position play bigger role on the Cariaco basin upwelling variability.

Interannual variability in oceanographic and meteorological characteristics of the Atlantic Ocean are expected as a result of large-scale changes in other regions of the world, including due to changes such as the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). Six oceanic-atmospheric variables are used to monitor ENSO over the tropical Pacific, while the AMO is determined by monitoring SST over the Atlantic. Correlations with lags of up to ± 6 months were conducted with those climate indices and the anomalies of the median monthly latitudinal position of the ITCZ. Significant direct correlations with ENSO (Multivariate ENSO Index) were seen in the Atlantic and Western Atlantic (r = 0.15), with ENSO leading the position of the ITCZ anomalies by 3 months. This implies that within three months after an El Niño event (warm ENSO anomaly in the Pacific) the ITCZ over the mid-Atlantic and Western Atlantic Ocean tends to shift to a more northerly position. The AMO also had a direct influence on the anomalies of the ITCZ position (r = 0.13) in the Central and the Western Atlantic, with the AMO leading ITCZ anomalies by 1 month (i.e. a warming of the North Atlantic led to a northward shift in the ITCZ one month later). Correlations between AMO and the ITCZ anomalies in the Eastern Atlantic were also direct but with no lag. Although significant, these correlations were low.

An inverse correlation (~ -0.35) was found between ENSO and anomalies of water temperature of the Cariaco Basin. ENSO lagged ocean temperature anomalies by 3 to 4 months for both the whole Cariaco time series and for the upwelling months of CARIACO data. Correlations with AMO were direct (~ 0.4); for the whole time series AMO led Cariaco

temperature anomalies by 3 months, but for the upwelling months AMO lagged Cariaco temperature anomalies by one month.

GENERAL INTRODUCTION

The interaction between the ocean and the atmosphere influence biogeochemistry, ecology, and climate of the Earth (Waliser and Gautier, 1993; Lietzke et al., 2001). The Intertropical Convergence Zone (ITCZ) is one feature of this interaction. The ITCZ is a zonal band of atmospheric convection that can be characterized by the convergence of the northern and southern Trade Winds, tall storm clouds, and maximums in time-averaged precipitation over the tropical oceans (Lietzke et al., 2001; Wang and Wang, 1999; Henke et al., 2012; Schneider et al., 2014). The ITCZ migrates seasonally between 5°S and 15°N, with a mean position between 2°N and 5°N (Waliser and Jiang, 2014; Waliser and Gautier, 1993). There have been reports of a separate well-organized band of clouds in the Southern Hemisphere. This double ITCZ has typically been observed in the Pacific Ocean from late February to early May, but is most common in March (Waliser and Gautier, 1993; Henke et al., 2012). In this study we examine the variability in the median cross-basin latitude of the ITCZ in the tropical Atlantic Ocean, including the regular, annual development of a double ITCZ, over the period 1987-2011.

The ITCZ is important due to its effects on biogeochemical and ecological processes on a local scale. Changes in the position of the ITCZ can result in changes in processes like wind-driven upwelling, coastal salinities, and biological productivity. An area that is strongly affected by changes in the intensity of the Trade Winds is the Cariaco basin, located in the southeastern Caribbean Sea. The Cariaco Basin was examined intensively as part of the CARIACO Ocean Time-Series program between 1995 and 2017, with the CARIACO Station located at 10.50° N, 64.66 °W. Geological, biogeochemical, and ecological processes in the Cariaco basin are seasonal, with an important coastal upwelling during December-April due to the seasonal intensification of the Trade Winds (Taylor et al., 2012). Additionally, when the Trade Winds relax, the Cariaco Basin experiences its rainy season (Taylor et al., 2012). Seasonal changes in the latitudinal position of the ITCZ have important implications for tropical ecosystems (Cvijanovic and Chiang, 2013). This includes the Cariaco Basin and its upwelling and rainy season. The Trade Winds intensify and the ITCZ is in its southern position during the Northern Hemisphere summer causing the Cariaco Basins upwelling season (Taylor et al., 2012). Then, when the Trade Winds relax, the ITCZ is in its northern position during the summer hemisphere summer and the Cariaco Basin experiences their rainy season (Taylor et al., 2012). The characteristics of the ITCZ have also been linked to climate, and to processes like El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) (Enfield and Mayer, 1997).

The chapters in this thesis aim to explore the seasonality and decadal-scale variations in the ITCZ, and provide insights into the relationship between the ITCZ and processes occurring at global as well as local scales. The chapters are organized as outlined below.

Chapter 1: Latitudinal Position and Trends of the Intertropical Convergence Zone of the Atlantic Ocean

This chapter examined the median latitudinal position of the ITCZ over the Atlantic Ocean and trends between the 1990's and the first decade of the 2000's. A preliminary examination of satellite imagery suggested that there was more variability in the position of the ITCZ in the Eastern Atlantic Ocean and the regional analyses sought to characterize these differences. The Atlantic Ocean was split into three basins (Atlantic basin, Western Atlantic basin, and Eastern Atlantic basin). Wind convergence was used to track the latitudinal position of the ITCZ over the Atlantic Ocean from 1987 to 2011 every 0.25° of longitude; these were averaged in each of the three basins. Long term trends in the latitudinal position of the ITCZ were examined using a Mann-Kendall (MK) trend test conducted over the entire time series and over two sub-periods (1987 – 1999 and 2000 – 2011).

Chapter 2: Relationship between the Position of the Atlantic Intertropical Convergence Zone and Upwelling in the Southeastern Caribbean Sea

Chapter 2 describes an analysis designed to determine if the variability on the latitudinal position of the ITCZ over the Atlantic Ocean is related to variability on the upwelling process in the Cariaco Basin, using sea temperatures as a proxy for upwelling intensity. In-situ ocean temperature measurements at various depth intervals in the Cariaco Basin and satellite sea surface temperature (SST) extracted at the Cariaco basin were used to study this relationship. The in-situ temperature measurements were collected as part of the CARIACO Ocean Time-Series program from 1995 to 2017. Monthly mean satellite SST data were derived from data collected by the Advanced Very High Resolution Radiometer (AVHRR, 1 km pixel resolution) from 1996 to 2016. SST time series were derived by calculating an average in a 10 by 10 pixel area around the CARIACO Time Series station (10.50° N, 64.66 °W). Another objective was to characterize the relationship between the ITCZ over the Atlantic Ocean and two climate indices, namely ENSO and the AMO. Data for these indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Division (PSD) of the Earth System Research Laboratory (ESRL). The Multivariate ENSO Index (MEI) was used as the ENSO data set.

Each chapter has its own results and conclusions sections. A final section summarizing the conclusions is presented at the end of the thesis.

CHAPTER ONE

Latitudinal Position and Trends of the Intertropical Convergence Zone of the Atlantic Ocean

1. Introduction

Ocean-atmosphere interactions in the tropics influence climate around the Earth (Waliser and Gautier, 1993; Lietzke et al., 2001). An integral part of the tropical ocean-land-atmosphere system is the Intertropical Convergence Zone or ITCZ (Figure 1.1). The ITCZ is a zonal band of atmospheric convection in the tropics that is characterized by the convergence of surface winds, tall storm clouds, and a maximum in time-averaged precipitation (Lietzke et al., 2001; Wang and Wang, 1999; Henke et al., 2012; Schneider et al., 2014). The position and strength of the ITCZ is controlled by the convergence of the northern and southern Trade Winds (Schneider et al., 2014). The ITCZ effectively defines the meteorological equator between about 2° and 5°N. The ITCZ migrates seasonally between about 5°S and 15°N as a result of changes in the heat-flux balance between hemispheres, following the position of the sun over the tropics (Waliser and Jiang, 2014; Waliser and Gautier, 1993). The lack of symmetry about the equator is due to the influence of the larger land mass coverage in the northern hemisphere (Folland et al., 2002). In this study, I examine the variability in the median latitudinal position of the ITCZ over the Atlantic Ocean.

While the median position of the ITCZ is in the northern hemisphere, a separate, well organized band of clouds has also been observed in the southern hemisphere in the Pacific Ocean from late February to early May, most commonly in March (Waliser and Gautier, 1993; Henke et al., 2012). These previous studies, however, did not quantify how the double ITCZ varied in time, other than identifying the presence in a particular month. Grodsky and Carton (2003) and Hasternath and Lamb (1978) found a double ITCZ in the Atlantic Ocean. I examine the timing of appearance and disappearance of the ITCZ in the Atlantic Ocean, and its geographical shift along the seasons.

Changes in the latitudinal position of the ITCZ reflect seasonal and longer-term meteorological and oceanographic changes in the tropics (Haug et al., 2001; Black et al., 2004; Peterson et al., 2000). The position of the ITCZ also affects many biogeochemical and ecological ocean processes in the tropics, in addition to ocean physics (Taylor et al., 2012). Physical processes like equatorial and coastal wind-driven upwelling, vertical mixing and stability, rainfall, and riverine inputs, are related to the location of the ITCZ, and these processes influence coastal and ocean interior nutrient cycles, biological productivity, and biodiversity (Folland et al., 2002).

While the factors that cause variability in the annual position of the ITCZ have been the focus of much research (Waliser et al., 1993, Lietzke et al., 2001; Wang and Wang, 1999, Schneider et al., 2014), the variability in the position of the ITCZ over time has not yet been well documented. Practical indices to gauge the position of the ITCZ do not exist. The motivation of the present study were decadal-scale changes observed by Taylor et al. (2012) in the hydrography and ecology of the Southeastern Caribbean Sea. These were attributed to changes in the annual median latitudinal position of the ITCZ over the Atlantic Ocean. The CARIACO Ocean Time-Series Program, which collected data in the southern Caribbean Sea at 10.50° N, 64.66 °W between 1995 and 2017, recorded weaker coastal upwelling in the southeastern Caribbean Sea in the 2000's compared to the 1995 – 1999 period. Taylor et al. (2012) concluded that a more northerly ITCZ may be related to these changes, which were associated with a decrease in the intensity of the Trade Winds over the southern Caribbean Sea. This decreased the intensity of upwelling in the Cariaco Basin, with substantial ecological consequences that included changes in the biodiversity and production of the phytoplankton, zooplankton, fisheries, and the composition of particulate carbon flux to the bottom of the sea.

In this study I tested the hypothesis posed by Taylor et al. (2012) that the ITCZ in the Atlantic Ocean shifted northward during the period 2000 – 2011. To track the position of the ITCZ in the Atlantic Ocean, after testing several methods, I used the maximum of the monthly wind convergence at the ocean surface as observed by satellites between 1987 and 2011.

2. Data and Methods

2.1 Data

Preliminary estimates of the ITCZ location using cloud height and rain estimates were performed using monthly mean cloud height and precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM). We used version 7 of the 3A25 TRMM product (Adler et al., 2009), distributed by the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory (JPL PO-DAAC). These observations, gridded to 0.5 degree x 0.5 degree cells, gave noisy estimates of the location of the ITCZ across the ocean, and led to the testing of algorithms to trace the ITCZ using satellite-derived wind observations.

Monthly satellite-derived ocean wind observations were obtained from the JPL PO-DAAC and were derived under the Cross-Calibrated Multi-Platform (CCMP) project. The data collected was a part of the Making Earth Science Data Records for Use in Research Environments (MEaSUREs) project. The dataset combines calibrated satellite surface winds, referenced to a height of 10 meters above sea level, from a series of different sensors (NASA/GSFC/NOAA, 2009). These included the Special Sensor Microwave Imager (SSM/I), Special Senor Microwave Imager Sounder (SSMIS), Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), Tropical Rainfall Measuring Mission TRMM Microwave Imager (TRMM TMI), Quick Scatterometer (QuikSCAT), SeaWinds, and WindSat (NASA/GSFC/NOAA, 2009). The ocean wind monthly time series spans from July 1987 to June 2011. Observations were gridded to a spatial resolution of 0.25° x 0.25° (NASA/GSFC/NOAA, 2009). The u-component and v-component of the wind were used in the convergence computation of the wind vectors to trace the position of the ITCZ. Wind observations were reported in units of meters per second (NASA/GSFC/NOAA, 2009).

Additionally, SST data from the Atlantic Warm Pool was analyzed. Dr. Sang-Ki Lee from the Atlantic Oceanographic and Meteoroidal Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA) provided SST data averaged over the Atlantic Warm Pool region (5°N - 30°N, 100°W - 40°W) from 1854 to 2015. From this time series, climatologies and anomalies were computed.

2.2 Methods

2.2 a) Preliminary ITCZ estimates

The TRMM cloud and rain estimates helped visually trace the ITCZ over the global ocean, but extracting an average latitude for each 0.5 degree longitudinal cell of the gridded product was not straight-forward. The cloud product showed very tall clouds at widely different latitudes across the tropics. Thus, estimates of the location of the ITCZ across the ocean extracted with the band of maximum cloud height across the Atlantic Ocean were noisy. The rain product also revealed noisy estimate of the location of the ITCZ across the ocean. I did not use the TRMM product further for the analyses described below since the wind convergence fields instead yielded a better-defined ITCZ product (Figure 1.1).

2.2 b) Measuring the location of the ITCZ

IDL™ and Matlab™ routines were developed in-house to calculate the surface ocean wind convergence time-series to identify the location of the ITCZ for the time period 1987 – 2011. Since the ITCZ is defined by strong convergence of the Northern and Southern Trade Winds, the first step in tracking the position of the ITCZ was to compute wind convergence for each month in the time series (Figure 1.2a). Convergence is the negative of divergence, so the u and v wind components of the wind were used in the divergence routine of Matlab™, via the following equation.

$$Divergence\ (i,j) = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)_{i,j} \approx \left(\frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y}\right)_{i,j} = \frac{u_{(i+1)} - u_{(i-1)}}{2\Delta x} + \frac{v_{(j+1)} - v_{(j-1)}}{2\Delta y}$$

Where $\frac{\partial u}{\partial x}$ represents the change of the u-component of the wind in the x direction, and $\frac{\partial v}{\partial y}$ is the change of the v-component of the wind in the y direction.

Since this study wants to look at convergence to track the position of the ITCZ, for convenience, divergence was multiplied by -1 so that convergence areas have positive values and divergence have negative values (Figure 1.2a). Once wind convergence was computed at 0.25 x 0.25 degree resolution, the approach was to record the latitude of the ITCZ in the Atlantic Ocean at every 0.25° of longitude by tracing the maximum in wind convergence across each longitude. The algorithm to search for the main ITCZ location (hereafter called the "principal ITCZ") was focused between the boundaries of -10° south and 20° north. Although the principal ITCZ was normally located in the Northern Hemisphere, in rare occasions during February or March portions of the principal ITCZ was located in the Southern Hemisphere (Figure 1.5a). These boundaries were defined after examining the entire time series to ensure the elimination of strong convergence at higher latitudes not related to the ITCZ. The boundaries helped to eliminate outlier data related to transient wind convergence features in more temperate latitudes.

The original wind convergence calculations, Figure 1.2a, were noisy. To further clean the data and locate maximum wind convergence, several additional steps were taken as follows.

- Step 1. Each monthly image of wind convergence was spatially smoothed by applying a running mean filter in order to get a more pronounced pattern of convergence and divergence to locate the ITCZ (Figure 1.2b). Each pixel value was averaged with the values of the pixels around it (3 x 3 pixel averages; Figure 1.2b).
- Step 2. An adaptive low-pass filter known as "wiener2" in Matlab™ was applied to the previously spatially smoothed data (Figure 1.2c). Low-pass filters are the best method for smoothing climate data (D. Chambers, personal communication, February 23, 2015). This was done in addition to the spatial smoothing because the spatial smoothing did not allow patterns of convergence to be easily identified, and the data along the coastlines was still problematic for tracking the ITCZ. Just applying the "weiner2" filter without the spatial smoothing (Figure 1.2d) had similar results than with the spatial smoothing alone, in which the patterns of convergence still were not as distinct as needed in order to easily identify patterns of convergence. This specific filter was applied in order to identify gradients that occurred over larger spatial scales. This filter blends the strong values of convergence along the coastline into the values in the nearby ocean to eliminate the individual large data points along the coastline, since these strong convergence points affect the ability of the program to properly track the ITCZ. Additionally, the "weiner2" filter is a linear filter, such that where the variance in the data is large little smoothing

occurs, but where the variance is small more smoothing is applied, this allows for a more distinct patterns of convergence and divergence to be revealed.

- Step 3. The function ‘findpeaks’ of Matlab™ finds all local maxima. This function was executed at each 0.25° longitude to find the latitudes with maximum convergence (Figure 1.2e). Once the local maxima were found for each 0.25° longitude, the largest convergence values (i.e. biggest peaks) for each 0.25° longitude was kept and used as the position of the ITCZ. The process of using the largest peak to characterize the ITCZ was done both for the principal ITCZ and also for the southern branch of the ITCZ when the double ITCZ occurs.

After producing a smoothed map of convergence, the ITCZ was identified using a threshold. This threshold was determined by examining the distribution of the wind convergence data for the entire time series (Figure 1.3). Convergence values greater than the threshold were indicative of the ITCZ, since the ITCZ is characterized by strong convergence. A threshold of 0.6 s^{-1} of convergence was used as indicative of the principal ITCZ. To eliminate outliers, a cubic regression of the latitudinal position of the convergence peaks (y) against the basin wide longitudes (x) was applied, and the residuals examined for all of the longitudes for each month in the time series (Figure 1.4). The functions “polyfit” and “polyval” in Matlab™ were used with a polynomial to the third degree to perform the cubic regression and compute the residuals via the equations below.

$$p = polyfit\ (x, y, n)$$

Where *x* is the longitude and *y* is the convergence peaks, and n is the degree of the polynomial (we used n = 3). The polyfit equations returns p, the coefficients for a polynomial of degree n =3 that is a best fit (via a least squares sense) for the data in *y* (convergence peaks)

$yfit\ = polyval\ (p, x)$

Where x is the longitude and p is the output from the polyfit equation. The polyval function returns *yfit*. The value of the polynomial of degree n = 3 evaluated at *x* (i.e. longitude).

$residuals =\ y -\ yfit$

Where *y* is the convergence peaks and *yfit* is the output from the polyval function.

Figure 1.4a depicts the original values and the cubic fit of the data. Values with residuals exceeding ± 4° latitude compared to the cubic regression fit were eliminated (Figure 1.4b). The regression was performed separately for each month in the time series.

The process to extract the latitudinal location of the "southern ITCZ", the southern branch of the double ITCZ in the Atlantic (Figure 1.5b), was the same outlined above for the principal ITCZ. The only two differences were: a) the latitudinal boundaries were from the equator to -15° south, and b) it used a smaller threshold of 0.3 s^{-1} of convergence as indicative of the southern ITCZ. Previous studies explain that the southern branch of the double ITCZ is weaker than its northern hemisphere counterpart (Henke et al., 2012; Grodsky and Carton, 2003; Lietzke et al., 2001; Waliser and Jiang, 2014, Waliser and Gautier, 1992).

The previous methods created a time series of the monthly position of the ITCZ every 0.25° longitude from 1987 to 2011 for the width of the entire Atlantic Ocean. From this time series, the position of the ITCZ was quantified for three zonal segments (Figure 1.6): the entire central Atlantic basin (50°W to 15°W; Figure 1.6a), the Western Atlantic (50°W to 30°W; Figure

1.6b), and the Eastern Atlantic (30°W to 15°W; Figure 1.6b). We did not extend the analyses farther to the west or east to avoid artifacts detected near the landmasses. Figure 1.1 illustrates these artifacts: west of 50°W the wind convergence product consistently showed a maximum tracing the coastline of northeastern South America and, east of 15°W it traced the coastline of Africa in the Gulf of Guinea. Even though these artifacts may be a real convergence feature, it is probably not connected to the ITCZ and for the purposes of this research is artificial. We therefore set artificial longitudinal limits to the analyses and focused on the central Atlantic Ocean, as described above.

In each of the three zonal segments of the Atlantic, medians (instead of means) were used to spatially average the ITCZ within each of the three zonal segments; this was to minimize the influence of outliers. From the monthly time series in each region, climatologies and anomalies of the ITCZ latitudinal position were calculated. Climatologies were computed first by taking all of the data in the time series for one of the 12 months in a year and averaging it to determine what the average latitudinal position of the ITCZ is for that month. This was done for all 12 months (i.e. averaging all of the data for January across the time series to get an average position of the ITCZ in the month of January; see equation below). Climatologies show the normal values (i.e. typical latitudinal position of the ITCZ) for each month. Once climatologies were computed, anomalies were calculated. An anomaly measures the deviation of a value from the normal or expected value. Anomalies are computed by taking the time series data and subtracting it from the climatological value for that month (i.e. if your time series date is July of 1987 then take the latitudinal position of the ITCZ in July of 1987 and subtract the climatological position of the ITCZ in July to obtain the anomaly value for that date). How to compute climatologies and anomalies are further explained in equation form below.

$$Climatology\ (m) = \frac{\sum_{i=1}^{n} x_i\,(m)}{n}$$

Where m is the month, n is the number of data points, and x is the latitudinal position of the ITCZ. (Note: “i” is the year in which the first data value occurs and n is the year where the last data value occurs)

$$Anomaly\ (d) = x_d - climatology(m)$$

Where d is the date (month, year), x_d is the latitudinal position of the ITCZ for that date, and climatology (m) is the climatolgocial position of the ITCZ for the month in d.

2.2 c) Mann-Kendall Trend Test

Significance of trends or shifts in the monthly anomalies of the median meridional position of the ITCZ were examined using two methods. The first was the Mann-Kendall (MK) trend test. The MK test determines whether median values tend to increase or decrease over time and estimates the significance of the change (Mann, 1945; Kendall, 1955). The test involves the MK test statistic (S), number of data points (n), data values (x_i and x_j), sign function ($sgn\ (x_j - x_i)$), variance (V), number of groups (m), number of observations in the group (t), test result (H), and the normal test statistic Z_s (Mann, 1945; Kendall, 1955). These variables were calculated using the following equations:

$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$, where *sgn* is the sign of the expression:

$$sgn(x_j - x_i) = \begin{cases} +1, if\ (x_j - x_i) > 0 \\ 0, if\ (x_j - x_i) = 0 \\ -1, if\ (x_j - x_i) < 0 \end{cases}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k\,(t_k - 1)(2t_k + 5)}{18}$$

$$Z_S \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & if\ S < 0 \end{cases}$$

The method of Fatichi (2009) was applied to test the null hypothesis of the absence of a trend in the median meridional position of the ITCZ with an alpha level (α) of 0.05 (95% confidence interval). The *H, Z_s,* and p-values were used as follows: if H is equal to zero, there is not enough evidence to reject the null hypothesis; if Z_s is a positive/negative value, this indicates an increasing/decreasing trend; a p-value less or equal than 0.05 was considered significant (Mann, 1945; Kendall, 1955).

The MK test was executed using anomaly values for each section of the Atlantic basin and for the 1987 to 2011 (24 year) time frame. To test the hypothesis of Taylor et al. (2012) that the ITCZ shifted northward in the 2000's compared to previous years, the MK test was also two time windows within this period (i.e. 1987 to 1999 and 2000 to 2011) and for all three sectors defined in the Atlantic basin.

2.2 d) Monte Carlo test

To see if the trends determined by the Mann-Kendall test were still significant using another approach, I also performed a Monte Carlo test based on a colored noise model applied to the autocovariance of the residuals relative to the trend fit with least squares.

The Monte Carlo test takes a time series and fits a bias plus a trend model to the time series via an ordinary least squares to provide uncertainty estimates (Chambers et al., 2016). Using this method, the effective degrees of freedom (i.e. the number of parameters estimated subtracted from the number of statistically independent observations) are estimated (Chambers et al., 2016). From the effective degrees of freedom, the corrected uncertainty can be determined.

The Monte Carlo simulation was based on residuals of a simulated time series that has a similar autocovariance to the true residuals (Chambers et al., 2016). An auto-regression (AR) model was used to impose correlations to an initial random time series. AR(p) models estimate values (y) at some time (t) based on p earlier times scaled by coefficients that had correlations (see equation below; Chambers et al., 2016)

$$y = a_1 y(t-1) + a_2 y(t-2) + a_3 y(t-3) + \cdots + a_p y(t-p) + \varepsilon(t)$$

Where $\varepsilon(t)$ is random noise with a prescribed variance and a is the coefficient determined via the Yule-Walker algorithm.

The Yule-Walker algorithm (see equation below; Chambers et al., 2016) determines the coefficients based on the one-sided autocovariance, meaning that negative lags are treated the same as positive lags in the computation.

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_p \end{bmatrix} = \begin{bmatrix} R_0 & R_1 & \cdots & R_{P-1} \\ R_1 & R_0 & \cdots & R_{P-2} \\ \vdots & \vdots & \ddots & \vdots \\ R_{P-1} & R_{P-2} & \cdots & R_0 \end{bmatrix}^{-1} \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ \vdots \\ R_p \end{bmatrix}$$

$$\sigma_\varepsilon^2 = R_0 - \sum_{k=1}^{p} a_k R_k$$

Where R_0 is the autocovariance at lag = 0, R_1 is the autocovariance at lag = 1, etc., and σ_ε^2 is the standard deviation of the random noise needed to match the covariance at lag = 0.

For this time series, the coefficients from an AR(1) model were used and 1,000 different colored noise models were created in order to have the covariance to lag-1 matches of the original residuals. Trends are fit to the simulated residuals and the standard deviation of the sample trends is then used as the standard error for the uncertainty of the trend. Uncertainties were scaled to 90% and 66% confidence for this study.

3. Results

3.1 Climatology

Medians of the cross-basin climatological zonal location of the ITCZ position show the expected seasonality of this feature (Figure 1.7, 1.8). The principal ITCZ was closest to the equator on average during January-April (~ 4°N), with the minimum latitude in March. The principal ITCZ typically reached its northernmost position during July-September (~11°N, Figure 1.8). In the Western Atlantic Ocean, the ITCZ maintains a northerly position for a longer period (from July to October; standard error = 0.19° latitude; Figure 1.8). In the Eastern Atlantic Ocean the ITCZ undergoes a shorter northward excursion (July-August; standard error = 0.16; Figure 1.8). The average standard error across the three basins is as follows: 0.17 for the Atlantic, 0.21 for the Western Atlantic, and 0.17 for the Eastern Atlantic. In October, the standard error in the Western Atlantic is 0.19 and in the Eastern Atlantic is 0.12, indicating a difference in the Eastern and Western Atlantic compared to the annual ranges for the basin (0.21° latitude and 0.17° latitude respectively). These standard errors indicate that there is a difference in position between the basins for the principal ITCZ. The southern branch of the double ITCZ is present climatologically from December to August (Figure 1.8) and it will be discussed in more detail in section 3.3.

3.2 Long term trends of the Atlantic ITCZ

Figure 1.9 illustrates the trends of the principal ITCZ. There was a generally positive northward trend of the principal ITCZ for the entire time series in the Eastern Atlantic (Figure 1.9a). From 1987 to 1999, there are relatively smaller anomalies than in the following decade (2000 to 2011; Figure 1.9a). In the Atlantic Ocean from 1987 to 1999, there was a positive northward trend (Figure 1.9b, i). Despite the two large negative anomalies in 1996 and 1999 observed in the primary ITCZ across the Atlantic, the overall trend was a slight northward movement (Figure 1.9b, i). In the Western Atlantic, there was larger variability (Figure 1.9b, ii). Throughout the time period, large positive anomalies seemed to drive the northward trend (Figure 1.9b, ii). The Eastern Atlantic anomaly time series for 1987-1999 also has large variability (Figure 1.9b, iii). Overall there are more positive anomalies throughout resulting in the increasing trend (Figure 1.9b, iii).

Figure 1.9c shows the anomaly time series from 2000 to 2011. The negative decreasing trends in the Atlantic and Eastern Atlantic sector are significant. First, the median across the entire central Atlantic Ocean showed less variability than in the previous decade except after 2008 with a large negative anomaly 2009 (Figure 1.9c, i). Variability in the Eastern Atlantic was similar as that seen across the basin. The negative anomalies of 2009 accentuated the record, leading to the overall decreasing trend observed (Figure 1.9c, ii).

The Mann-Kendall test was conducted using monthly anomalies from the median position of the ITCZ for the three areas of the Atlantic and also for the separate time periods (entire series and the two separate decades). The Mann-Kendall test has a 66% confidence interval. Trends were discovered at various levels of significance (significant ($p=0.10$), very significant ($p=0.05$), and highly significant ($p=0.01$)) in each of the three basins of the Atlantic Ocean (Tables 1.1 and 1.2).

From 1987 to 2011, the test shows a significant positive trend in the Eastern Atlantic Sub-basin in which the median latitude of the ITCZ increased by 0.38° (43 km) over the 24 year period (Table 1.1a, $p<0.05$). For the sub time period from 1987 to 1999 (12 years), all three basins had a significant positive northward trend: 0.33° (37 km) across the Atlantic Ocean; 0.42° (47 km) in the Western Atlantic; and 0.41° (46 km) in the Eastern Atlantic (Table 1.1b, $p<0.1$).

The period from 2000 to 2011 (11 years) showed a significant negative trend of 0.60° (67 km southward) in the Atlantic (Table 1.1c, $p<0.1$). A highly significant negative trend of 0.73° (81 km southward) over the 11 year time period was observed in the Eastern Atlantic (Table 1.1c, $p<0.01$).

In addition to the Mann-Kendall trend test, the Monte Carlo test was conducted using monthly anomalies from the median position of the ITCZ for the three areas of the Atlantic and also for the separate time periods (entire series and the two separate decades) to see if this test produced the same results. The Monte Carlo test was performed at both the 90% confidence interval and using the 1 sigma (66%) confidence interval, which is the level used by the Mann-Kendall test for significance (Table 1.2). The increasing/decreasing trends discovered using the Monte Carlo test are the same as discovered with the Mann-Kendall test (i.e. increasing in Eastern Atlantic from 1987 to 2011, increasing in Atlantic/Western Atlantic/Eastern Atlantic from 1987 to 1999, and decreasing in the Atlantic/Eastern Atlantic from 2000 to 2011; Table 1.2), but only at the 66% confidence interval. In addition, the latitudinal increase or decrease (in degrees) between the two tests differs slightly by 0.0° to 0.05°, but this is well below the level of significance. However, if a 90% confidence test is used to judge significance (Table 1.2), there are no significant shifts in the latitudinal position of the ITCZ.

3.3 Double ITCZ variability

The double ITCZ is a feature in which a second zonal band of weaker maximum wind convergence appears in the Southern Hemisphere. This study found a double ITCZ present seasonally in the Atlantic Ocean. The northern branch was discussed in detail above, in section 3.1. The climatology of the southern branch of the double ITCZ shows that it was present from December to August (Figure 1.8). From December – March, the southern branch of the double

ITCZ is near the equator (~2°S), with the northernmost latitude occurring in December (Figure 1.8). The southernmost position is reached from June to August (~4°S to 5°S), with the southernmost latitude occurring in August for the West Atlantic and in July for the Atlantic and Eastern Atlantic. In the Western Atlantic Ocean, the southern branch of the double ITCZ is located slightly more to the north than in the eastern part of the basin (Figure 1.8).

I found a southern branch of the ITCZ every year, but the strength and timing of the southern branch showed interannual variability (Table 1.3). The southern branch of the double ITCZ seems to first appear in the Western Atlantic off the coast of South America, and extends eastward across the Atlantic basin with time. Typically, the southern branch forms in December or January (Figures 1.8 and 1.10a, Table 1.3). In 2005 and 2008, the southern branch formed in November (Table 1.3). In 1999, the southern branch of the double ITCZ did not form until February (Table 1.3). In the early months of the southern branch development it is very close to or is part of the primary ITCZ (Figure 1.10b). The largest separation between the northern and southern branches of the double ITCZ was seen mainly in June and July (Figure 1.10c). The southern branch of the double ITCZ often lasted through August (Table 1.3).

3.4 Atlantic Warm Pool and the Cariaco Basin

Since section 3.2 disproved the hypothesis of Taylor et al. (2012) that the ITCZ was moving northward in the first decade of the 2000's, this study posed a new hypothesis that warming SST's in the Atlantic were the underlying cause for the changes observed by Taylor et al. (2012) in the Cariaco Basin. The Mann-Kendall test of the AWP data revealed that there was a highly significant ($p<0.01$) increasing trend of SST in the Atlantic Warm Pool by 0.29°C over the 11 year period from 2000-2011. This result leads to the conclusion that warming Atlantic

Ocean waters during the time period of the Taylor et al. (2012) study could be the cause of the changes that Taylor et al. (2012) observed in the Cariaco Basin.

4. Discussion

4.1 Seasonality of the ITCZ

The overall seasonal pattern of the ITCZ in the Atlantic Ocean is well known. Our results are consistent with the findings of other studies (e.g., Chiang et al., 2002; Waliser et al, 1993; Waliser and Jiang, 2014; Henke et al., 2012; Schnieder et al., 2014). The seasonality of the ITCZ shows differences between the eastern and western sectors of the Atlantic Ocean. In the eastern sector of the Atlantic Ocean, the northern branch of the ITCZ is more north than the western sectors ITCZ from February to August. Additionally, in the southern branch of the ITCZ, the western Atlantic ITCZ is more southern than the eastern Atlantic ITCZ (i.e. closer to the equator) between April and August. These spatial differences can be attributed to the SST gradient that exists across the Atlantic Ocean. The Atlantic features a warm pool (AWP) in the west and an equatorial cold tongue that is strongest in the east (Lin, 2007). The AWP is a large body of warmer waters that spans the Gulf of Mexico, Caribbean Sea, and the Western tropical Atlantic and that reaches it maximum in September (Wang, 2014; Wang et al., 2006; Wang and Enfield, 2001). The equatorial cold tongue develops due to wind-driven upwelling in the Eastern Atlantic, and lasts from June to September (Hasternath and Lamb, 1977; Mitchell and Wallace, 1992; Xie and Carton, 2004; Caniaux et al., 2011). The equatorial cold tongue and the ITCZ are related via annual cycles of solar radiation and SST (Wang and Wang, 1999). The annual variations on solar radiation favor the equatorial cold tongue to vary in phase with the annual cycle of the Southern

Hemisphere SST. This in-phase variation in turn favors the placement of the warmer SST and the ITCZ into the Northern Hemisphere (Wang and Wang, 1999).

4.2 Trends of the ITCZ and their implications

Several studies have sought to test whether there are long-term trends in the average position of the ITCZ. Servain et al. (2014) studied the ITCZ in the tropical Atlantic Ocean (60°W to 15°E) from 1964 to 2012 using SST and surface winds. They concluded that there was no significant long term trend of the mean ITCZ position for that period. I found two small but significant trends in the latitudinal position of the ITCZ over the Atlantic Ocean (50°W to 15°E) from 1987 to 2011; those trends were significant at the 66% confidence level but not at the 90% confidence level. There were positive northward changes in the ITCZ latitudinal location ranging from 0.33° to 0.42° for the period 1987-1999 in all the sub-basins, and for the period 1987-2011 for the Eastern ITCZ (Table 1.2). These trends are in the range of the northward shift of the ITCZ seen during the mid-Holocene (0.25±0.38°; McGee et al., 2014). Negative southward changes in the ITCZ latitudinal location were found for the period 2000 to 2011 for the Atlantic and the Eastern Atlantic (-0.60 and -0.73, respectively); these changes are within the expected variability of the ITCZ, McGee et al. (2014) discovered a southward shift of the ITCZ during the Heinrich Stadial 1 time frame 15,000 -18,000 years ago (-0.61±0.47°). The changes in the position of the ITCZ found in this study are within the expected variability of the position of the ITCZ.

These trends can have implications for ecosystems in the region. For example, the Trade Winds drive coastal upwelling in the southeastern Caribbean Sea, including the Cariaco Basin. Decreased Northeast Trade Wind intensity is typically associated with an increasingly northward position of the ITCZ in the Atlantic Ocean (Taylor et al., 2012). Diminished upwelling in the

Cariaco Basin can cause a decline in primary production (Taylor et al., 2012). The changes observed by Taylor et al. (2012) in the Cariaco Basin were hypothesized to be due to a northward shift in the position of the ITCZ. However, this study disproved this hypothesis and instead suggests that the changes Taylor et al. (2012) observed were actually due to warming Atlantic Ocean waters.

Servain et al. (2014) detected a warming trend of SST's in the Atlantic off of Western Africa from 1968 to 2012 that is also consistent with an increase in SST's in the entire northern Atlantic after 1972 (Thompson et al.; 2010). In this study, the Mann-Kendall test of the AWP data during the first decade of the 2000's revealed that there was a highly significant ($p<0.01$) increasing trend of SST in the Atlantic Warm Pool by 0.29°C over the 11 year period from 2000-2011. This result and the results of Servain et al. (2014) and Thompson et al. (2010) provide further evidence that warming Atlantic Ocean waters may be the reason for the observed Cariaco Basin changes in the study by Taylor et al. (2012).

Between 2000 and 2011, I observed a negative (southward) trend in the position of the ITCZ by 0.73° (81 km) over the Eastern Atlantic. It is not clear what the implications of a southward shift in the ITCZ in the eastern Atlantic would be. A southward shift could be due to a number of causes, such as for example changes in the equatorial cold tongue. A warmer than normal Eastern Atlantic could result in a decreased northward displacement (i.e. a southward shift) of the ITCZ. A study by Tokinaga and Xie (2011) discovered an upward trend in their equatorial zonal SST difference index (∇SST_{EQ}) since the 1950's. This trend represents a weakening of the equatorial cold tongue (i.e. warmer than normal equatorial cold tongue). The warmer trends of SST in the equatorial cold tongue are coupled with a long-term relaxation in the equatorial trade winds. When the trade winds relax, they suppress upwelling and lead to intensified SST warming in the eastern equatorial Atlantic. Consistent with the warming of SST in the eastern equatorial Atlantic are changes in cloud cover and precipitation (i.e the ITCZ). Specifically, the zonal band of cloud cover is along the western edge of the equatorial cold tongue in the eastern Atlantic indicating a southward shift of the ITCZ position. Tokinaga and Xie (2011) further explain that recent couple Global Climate Model (GCM) experiments have shown that a southward shift of the ITCZ weakend the meridional SST gradient in the 20th century.

The Monte Carlo test was also performed at two confidence intervals (90% and 66%) in addition to the Mann-Kendall test to see if the trends were significant using both tests. Both tests produced increases and decreases in the latitudinal position of the ITCZ that were similar in magnitude (i.e. differences ranging between 0° and 0.05°). Despite this similarity, at the 90% confidence interval, the trends that were significant using the Mann-Kendall test were not significant using the Monte Carlo test. The trends were not significant because their rate of uncertainty was greater than the rate of increasing or decreasing latitude, for example in the Eastern Atlantic from 1987 to 2011 the rate of increase was 0.38° while the uncertainty was 0.48°. However, when the confidence interval was reduced to the 1-sigma value (i.e. 66% confidence interval), the trends were significant. Although these trends were significant at these intervals, the confidence is not high. Despite these differences, the Mann-Kendall test and the Monte Carlo test at 66% confidence interval determined the following trends of the ITCZ with time: ITCZ is moving northward over the whole time series in the Eastern Atlantic and from 1987 to 1999 in all three basins, and the ITCZ is moving southward from 2000 to 2011 in the Atlantic and Eastern Atlantic.

Taylor et al. (2012) examined seasonal and long-term changes in several physical, chemical, and biological oceanographic variables based on CARIACO data. They speculated that decadal strengthening and a northward trend in the ITCZ caused the changes observed in the local marine ecosystem of the southern Caribbean Sea between the last decade of the 1990's and the first decade of the 2000's. The diminished upwelling, warmer surface waters, and an increase in ocean stratification led to a decrease in the nutrient supply to surface waters of the Cariaco Basin. The effects propagated through the food web, leading to fewer sardine abundance and contributing to a collapse of this fishery in the region. However, the Taylor et al. (2012) study was not clear on its computation of the trend in the latitudinal position of the ITCZ. In fact, Taylor et al. (2012) mentioned shifts in the latitudinal position of the ITCZ of approximately 800 km over a 10 year period which is out of the realm of possibility based on wind convergence being the fundamental factor to measure the ITCZ's location. This study did not find a significant increasing northward trend of the ITCZ over the Atlantic in the decade of the 2000's, but rather small a decreasing (southward) trend of the ITCZ over the Atlantic from 2000 to 2011. Our results reject the hypothesis proposed by Taylor et al. (2012) that there was a northward trend in the position of the ITCZ.

4.3 Atlantic Ocean double ITCZ

Several studies have detected a double ITCZ exists in the eastern Pacific Ocean (i.e. Henke et al., 2012; Lietzke et al., 2011; Gu et al., 2005; Waliser and Gautier, 1993, etc.). Zhang (2001) concluded that there is no double ITCZ in the Atlantic from January through April because SST's are symmetrical about the equator during this time. Grodsky and Carton (2003) and Hasternath and Lamb (1978), found a double ITCZ in the Atlantic from January through about August. By June, the southern ITCZ branch is completely separated from the northern branch. Our results show that this southern branch forms as early as December in some years.

The formation of the double ITCZ has been described in previous studies (i.e. Grodsky and Carton, 2003) as being closely related to the intensity of the equatorial cold tongue. A strong cold tongue diminishes convection in the overlying atmosphere (Grodsky and Carton, 2003). The equatorial cold tongue develops in May-June as a result of intensified divergence in the upper water column forced by the stronger trade winds blowing along the Equator (Grodsky and Carton, 2003). After July, convection decreases as the ocean cools down in the Western Atlantic, causing the southern ITCZ to dissipate (Grodsky and Carton, 2003).

I found a double ITCZ every year. The feature was stronger in some years and weaker in others based on the strength of the wind convergence. The interannual variability of the dITCZ can be explained by the year to year differences in SST, specifically in the cold tongue which provides the split between the northern and southern convergence zones that create each branch of the double ITCZ, and the variation in the strength of the wind convergence itself.

4.4 Future research

Future research on the ITCZ should focus on quantifying the intensity of the ITCZ, and exploring the linkages between various meteorological and oceanographic parameters and features of the ITCZ. Some examples include: comparing the ITCZ to the meridional location of the SST maximum, comparing the relationship between the ITCZ over the western Atlantic and the strength of the Atlantic Warm Pool, and the relationship between the position of the ITCZ and rainfall in northeast Brazil. Additionally, further research on the double ITCZ in the Atlantic should be conducted since most double ITCZ studies indicate that a double ITCZ is only prevalent in the Eastern Pacific and that the double ITCZ created by Global Climate Models in other basins are not accurate. On the other hand, there are some studies, including this one, which discovered a legitimate double ITCZ in the Atlantic. The ITCZ should also be compared to climate indices to determine if they have an impact on one another. As climate changes, some of these linkages may be expressed more strongly as effects on regional ecosystems. Additionally, studies similar to this should be conducted for longer time periods and also for the Atlantic and Pacific Oceans to better test the conventional wisdom about northward propagation due to the Northern Hemisphere warming.

5. Conclusion

The ITCZ is a feature of the interaction between the tropical atmosphere and the ocean. The Atlantic Ocean ITCZ has seasonal and long term trends that have been the subject of numerous studies over the years. The monthly climatology of the ITCZ shows a strong seasonal cycle, with this area of convection migrating towards higher latitudes through August, and moving southward towards a latitude minimum in March.

The latitudinal position of the ITCZ for the 1987 – 2011 timeframe was examined using the convergence features observed in satellite-derived wind fields. We compared the median meridional position of the ITCZ for two periods (1987 – 1999 and 2000 – 2011) to see if the ITCZ moved northward during the latter time period compared to the earlier time period.

A Mann-Kendall (MK) test revealed significant trends in the median meridional position of the ITCZ. A slight but significant northward position of the ITCZ was observed, including 0.38° (43km) in the East Atlantic (30°W to 15°W) from 1987 to 2011; 0.33° (37km) over the Atlantic (50°W to 15°W) from 1987 to 1999; 0.42° (47km) over the Western Atlantic (50°W to 30°W) from 1987 to 1999; and 0.41° (46km) over the Eastern Atlantic (30°W to 15°W) from

1987 to 1999. The northward displacement in the ITCZ over the Western and Eastern Atlantic were slightly larger than range of variability documented in earlier studies for the ITCZ, or ~0.3° for the mid-Holocene. A slight southward trend in the ITCZ position was seen from 2000 to 2011. In the Atlantic (50°W to 15°W) the ITCZ decreased by 0.60° (67km) and in the Eastern Atlantic (30°W to 15°W) the ITCZ decreased by 0.73° (81km). A Monte Carlo test was also performed at 90% and 66% confidence intervals to see if the significant trends discovered using the Mann-Kendall test were still significant using another method. It was determined that at 90% confidence interval, the trends were not significant, but were significant at the 66% confidence interval. Despite these differences, both tests produced similar increases and decreases in the latitudinal position of the ITCZ. While confidence using the Monte Carlo test is not high at 66%, it still reveals significant trends in the ITCZ.

The larger increasing and decreasing trends in this study could be due to several factors including changes to the SST gradient across the basin as a result of the Atlantic warm pool (west) and the equatorial cold tongue (east). The extent of the effect of a northward or southward moving ITCZ in the Atlantic Ocean was not examined in this study, but should be explored in future studies.

A Southern hemisphere branch of the ITCZ in the Atlantic Ocean was observed in the wind convergence climatology and time series. The double ITCZ forms in the Western Atlantic off the coast of South America in December-February, and extends eastward over the ocean through about July and August. By June-July the southern ITCZ is completely separate from the northern branch. The southern ITCZ forms as a result of the north-south gradient in SST across the equator due to the equatorial upwelling cold tongue developing in the Eastern Atlantic

Ocean. The cold tongue is the result of intensified divergence along the equator and two convergence zones on each side of the equator.

Shifts in the strength of the ITCZ and formation of the double ITCZ can have important implications for ocean-atmosphere interactions around the globe (i.e. upwelling, rainfall, weather, climate, etc.). Understanding these linkages requires further study of the ITCZ. Meteorological, oceanic, biogeochemical, and marine ecosystem parameters should be studied locally in order to identify how the ITCZ's variability affects them. The local and regional changes observed in the southern Caribbean Sea are more likely the result of an overall warming of the entire tropical and temperate Atlantic, as an underlying cause for a weakening of the Trade Winds and local upwelling. External forces that act on the ITCZ, such as climate indices, should also be the subject of future research.

6. Tables and Figures

6.1 Tables

Table 1.1. Mann-Kendall trend test results for ITCZ anomalies calculated with median averages for a) the entire time series, b) from 1987 to 1999, and c) from 2000 to 2011. Where NS means no significance, * is significant (p≤0.1), ** is very significant (p≤0.05), and *** is highly significant (p≤0.01).

a) Whole Time Series: 1987 – 2011

Basin	**Normalized Test Statistic (Z)**	**p-value**	**Significance**
Atlantic Principal (50 W to 15 W)	1.57	0.12	NS
Western Atlantic Sub-basin Principal (50 W to 30 W)	1.21	0.23	NS
Eastern Atlantic Sub-basin Principal (30 W to 15 W)	2.22	0.03	**

b) First Sub-Time Period: 1987 – 1999

Basin	**Normalized Test Statistic (Z)**	**p-value**	**Significance**
Atlantic Principal (50 W to 15 W)	1.74	0.08	*
Western Atlantic Sub-basin Principal (50 W to 30 W)	1.69	0.09	*
Eastern Atlantic Sub-basin Principal (30 W to 15 W)	1.94	0.05	*

c) Second Sub-Time Period: 2000 – 2011

Basin	**Normalized Test Statistic (Z)**	**p-value**	**Significance**
Atlantic Principal (50 W to 15 W)	-1.99	0.05	*
Western Atlantic Sub-basin Principal (50 W to 30 W)	-0.23	0.82	NS
Eastern Atlantic Sub-basin Principal (30 W to 15 W)	-2.78	0.005	***

Table 1.2. Significant long-term trends in the position of the ITCZ with the respective increases and decreases with time over the three Atlantic Ocean basins (Atlantic, Western Atlantic, and Eastern Atlantic) determined by the Mann-Kendall and Monte Carlo test. Significance is shown as * significant (p≤0.1), ** very significant (p≤0.05), and *** highly significant (p≤0.01). Only significant trends from Table 1 are presented here.

(Time Period) Basin	**Monte Carlo Trend ± 90% confidence (per Time Period)**	**Monte Carlo Trend ± 66% confidence (per Time Period)**	**Mann-Kendall Trend**
(1987 to 2011)			
Eastern Atlantic	0.38° ± 0.48° / 24 years	0.38° ± 0.28° / 24 years**	0.38° / 24 years**
(1987 to 1999)			
Atlantic	0.34° ± 0.48° / 12 years	0.34° ± 0.28° / 12 years*	0.33° / 12 years*
Western Atlantic	0.43° ± 0.48° / 12 years	0.43° ± 0.28° / 12 years*	0.42° / 12 years*
Eastern Atlantic	0.41° ± 0.48° / 12 years	0.41° ± 0.28° / 12 years**	0.41° / 12 years*
(2000 to 2011)			
Atlantic	-0.55° ± 0.46° / 11 years	-0.55° ± 0.26° / 11 years**	-0.60° / 11 years*
Eastern Atlantic	-0.75° ± 0.46° / 11 years	-0.75° ± 0.26° / 11 years***	-0.73° / 11 years***

Table 1.3.

Months with a double ITCZ from July 1987 to June 2011. Months presenting double ITCZ are marked with an 'X'; nd: no data available.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	nd	nd	nd	nd	nd	nd	X					
1988	X	X	X	X	X	X	X					X
1989	X	X	X	X	X	X	X	X				X
1990	X	X	X	X	X	X	X					
1991	X	X	X	X	X	X	X					
1992	X	X	X	X	X							X
1993	X	X	X	X	X	X	X					X
1994	X	X	X	X	X	X	X	X				X
1995	X	X	X	X	X	X	X	X				
1996	X	X	X	X	X	X	X	X				
1997	X	X	X	X	X							
1998	X	X	X	X	X	X	X					
1999	X	X	X	X	X	X	X	X				
2000	X	X	X	X	X	X	X					
2001	X	X	X	X	X	X	X	X				
2002	X	X	X	X	X	X	X	X				X
2003	X	X	X	X	X	X	X	X				X
2004	X	X	X	X	X	X	X	X				
2005	X	X	X	X	X	X	X	X			X	
2006	X	X	X	X	X	X	X	X				
2007	X	X	X	X	X	X	X	X				X
2008	X	X	X	X	X	X	X	X			X	
2009	X	X	X	X	X	X	X	X				X
2010	X	X	X	X	X	X	X	X				
2011	X	X	X	X	X	X	nd	nd	nd	nd	nd	nd

6.2 Figures

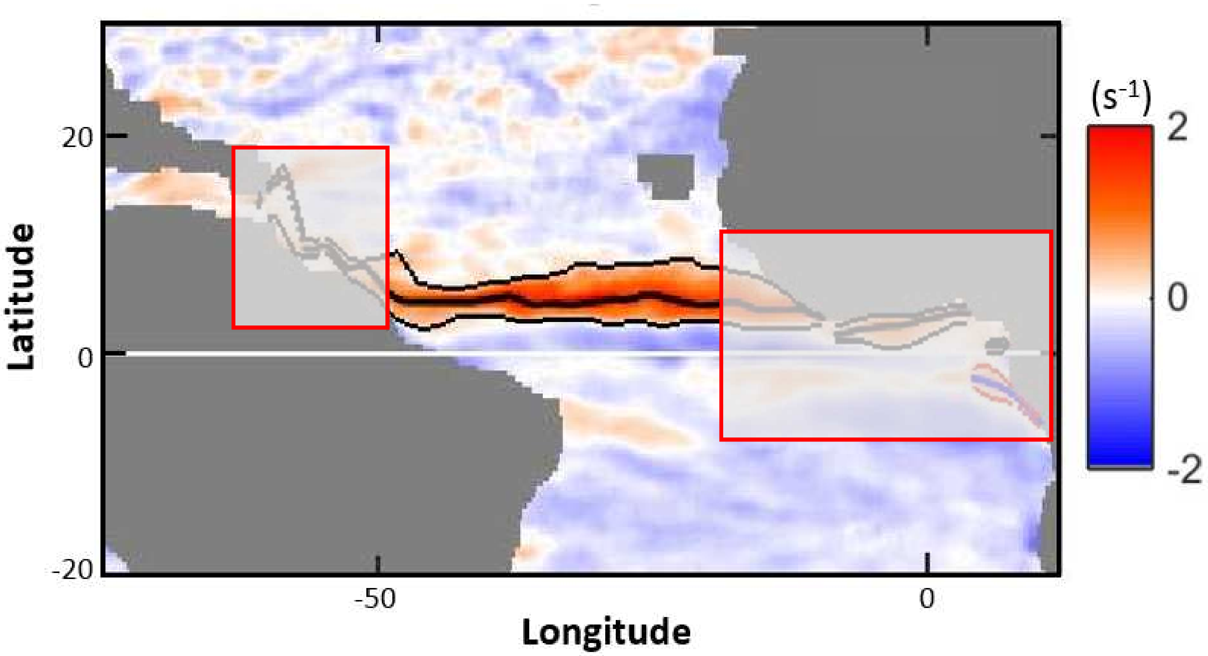
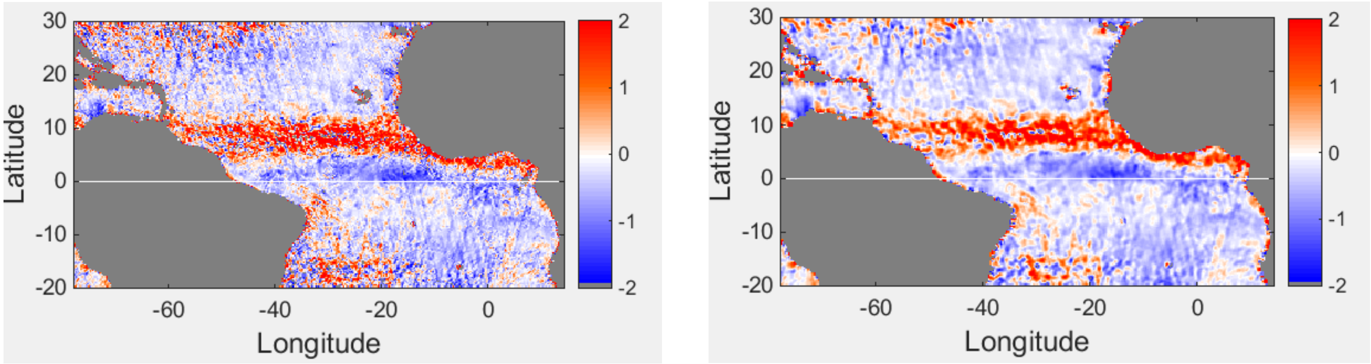


Figure 1.1. Monthly climatological average median position (thick black line) of the ITCZ in the Atlantic Ocean plotted against wind convergence (red) for December of 2001. The thin black lines denote the width of the ITCZ. Locations west of about 50°W and east of about 15°W (shaded boxes outlined in red) are in error and should be ignored; this is shown here to illustrate the artifact caused in the wind convergence field caused by the lack of satellite wind observations over land.

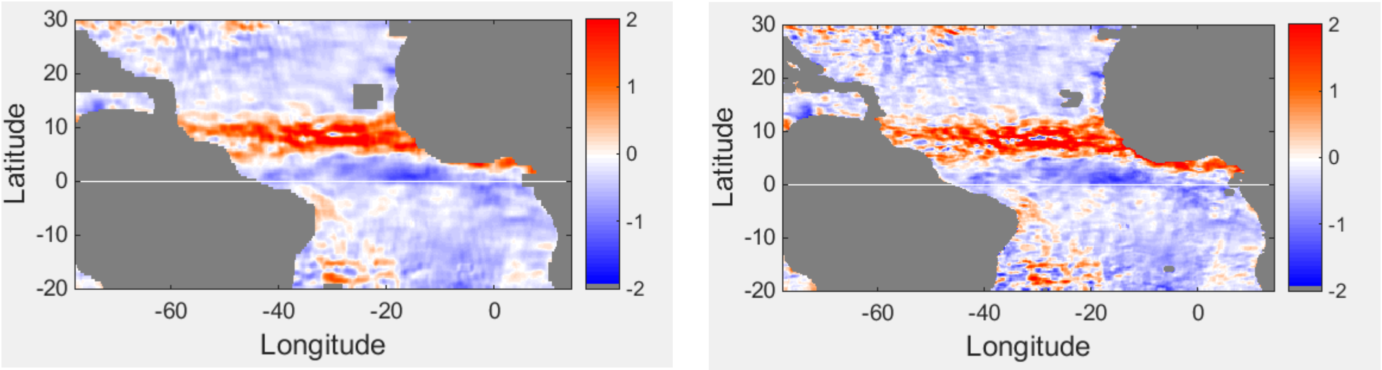


a) Wind convergence data

b) Spatial smoothing via a running mean

c) Low-pass filter (weiner2)

d) Just weiner2 filter (no spatial smoothing)



e) Finding maximum wind convergence along each 0.25 degrees of longitude

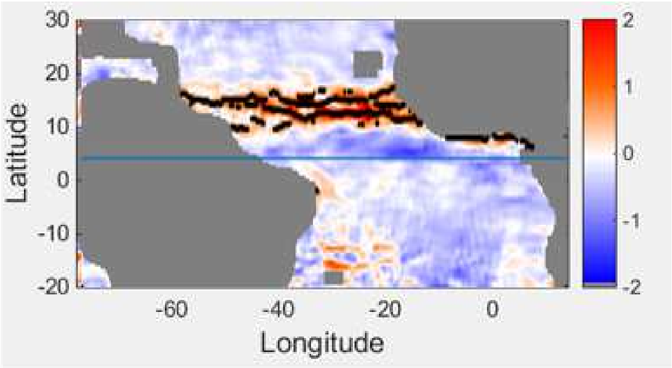


Figure 1.2. Results from steps in the algorithm to compute wind convergence and measure the location of the ITCZ as follows: a) wind convergence data (where convergence is in red), b) spatial smoothing using a running mean, c) low-pass "weiner2" filter, d) if just the "weiner2" filter and not the spatial smoothing was applied to the data, and e) wind convergence maximum (illustrated by black dots).

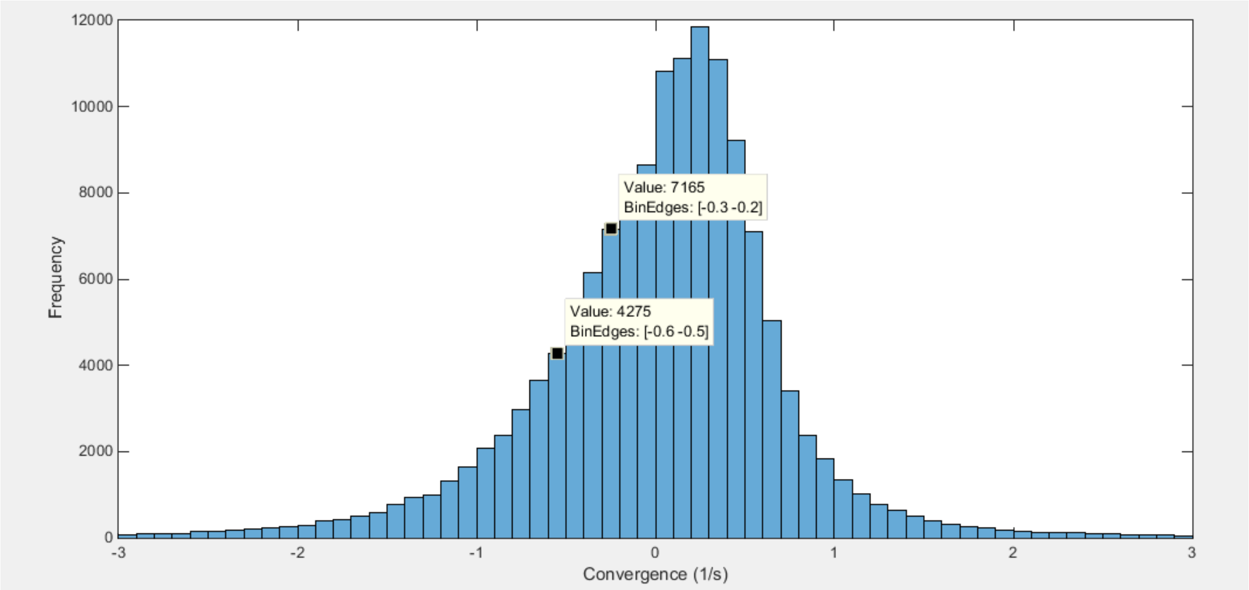
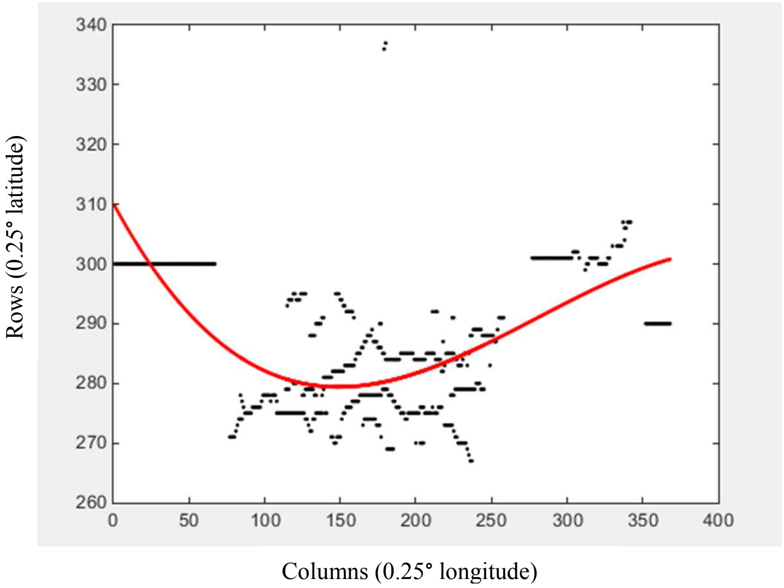


Figure 1.3. Histogram of the wind convergence data, for the entire time series, that determined the wind convergence threshold. (Note: histogram uses negative values as convergence).

a) Original values with the fit



b) Residuals

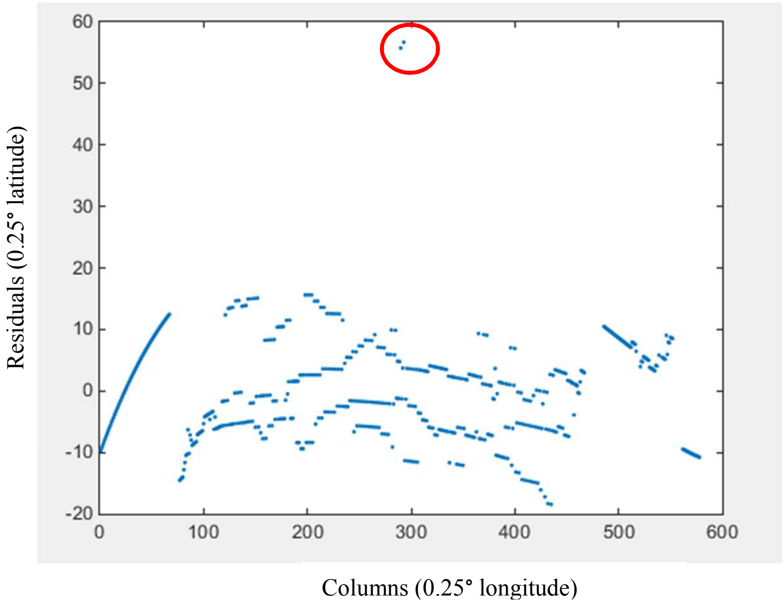
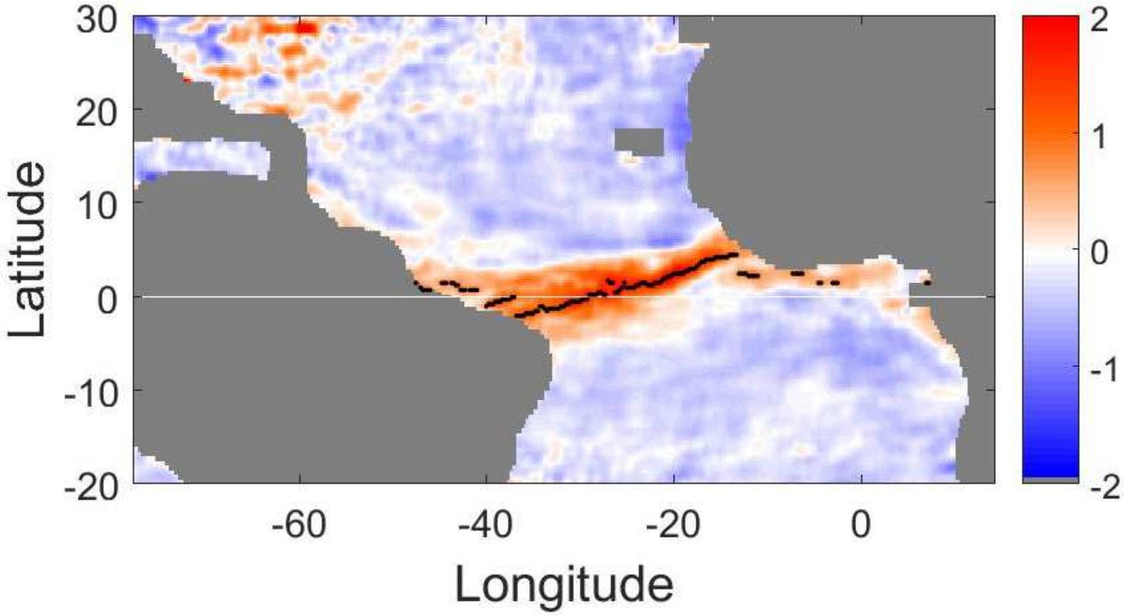


Figure 1.4. An example of the cubic regression results from July of 1987 to depict how cubic regressions are used to eliminate outliers. Where a) depicts the original values (black dots) and the cubic fit of those values (red line), and b) is the residuals (blue dots) and the red circle indicate the outliers. Residuals exceeding ± 4° latitude were eliminated. (Note: The axes are listed as rows and columns because the algorithm computes everything by columns and rows in order to properly locate maximum convergence, then columns and rows are converted back to longitude and latitude at the end (1° = 4 rows or 4 columns). The longitudes with data range from ~ -60° and end at ~15°, and the latitudes range from ~ -6° to ~ 12°).

a) Position of the principal ITCZ in February of 1991



b) Position of the principal ITCZ and the southern ITCZ in June of 1994

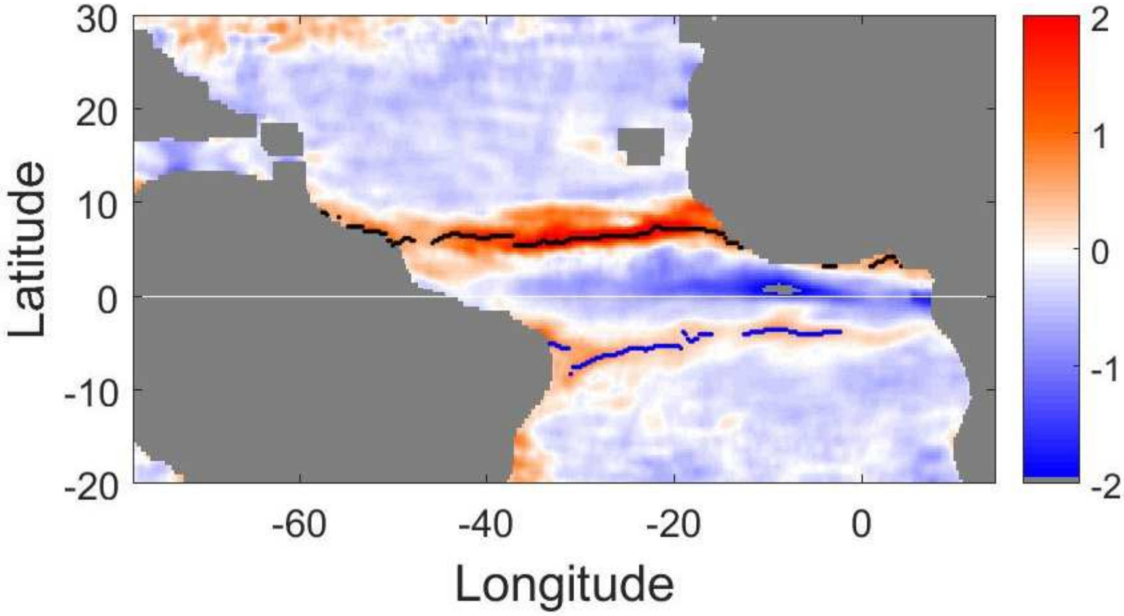
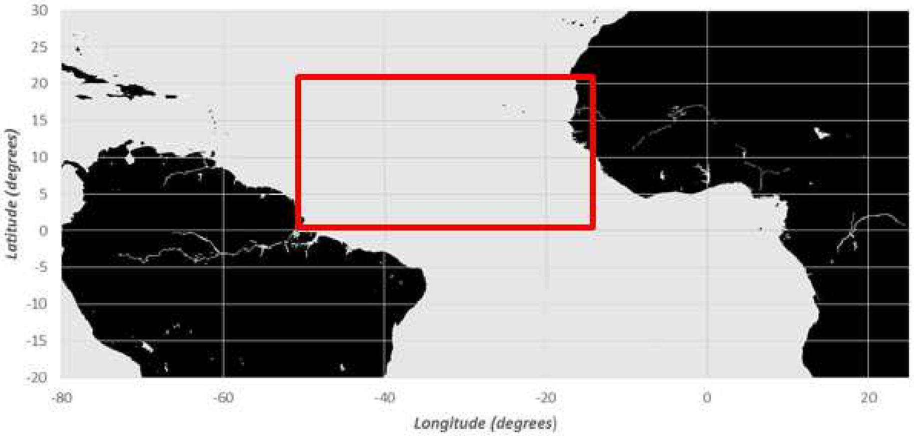


Figure 1.5. Monthly average median position (black line) of the ITCZ in the Atlantic Ocean plotted against wind convergence (red) for: (a) February of 1991, and (b) June of 1994. This is shown to illustrate the rare occurrence of portions of the principal ITCZ in the southern hemisphere (a), and the presence of the southern branch of the Atlantic ITCZ (b). The red color is wind convergence, the black line is the principal ITCZ, and the blue line is the southern branch that appears during a double ITCZ.

a) Central Atlantic



b) Western and Eastern Atlantic

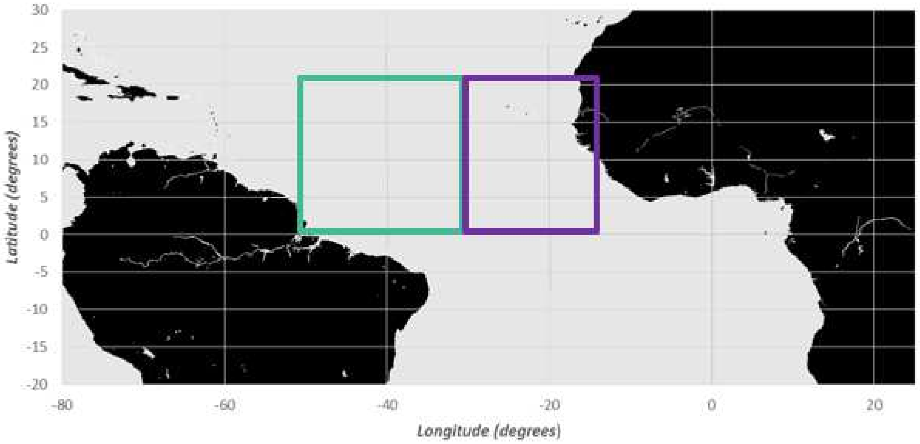


Figure 1.6. The three zonal segments of the Atlantic Ocean basin defined by longitude: a) is the central Atlantic (red box), b) shows the separation of the Western (green box) and Eastern (purple box) Atlantic.

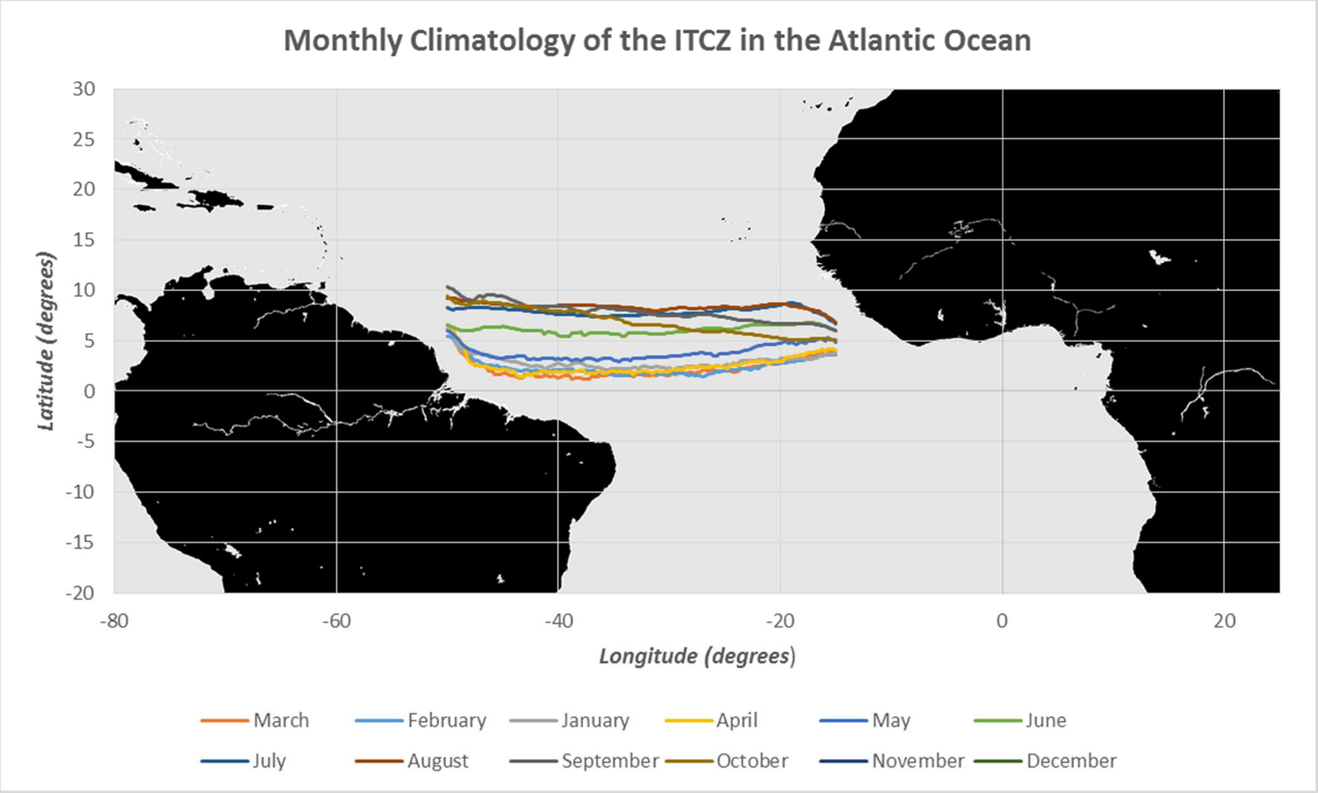


Figure 1.7. Monthly climatology of the Atlantic Ocean ITCZ median position every 0.25° of longitude from 50°W to 15°W calculated from 1987 to 2011. Data to the west and east of this region was removed to eliminate the artifacts caused by land as showed in Figure 1.1.

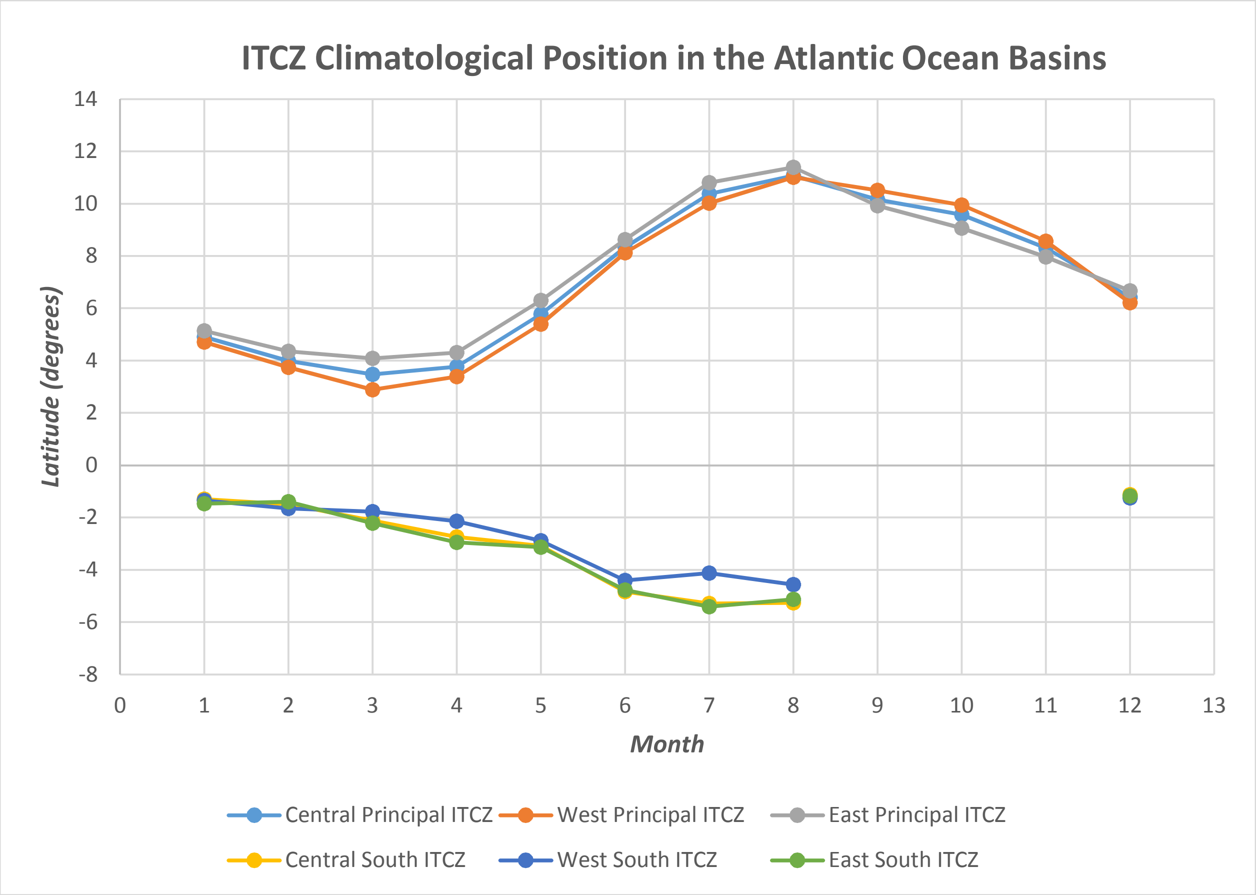
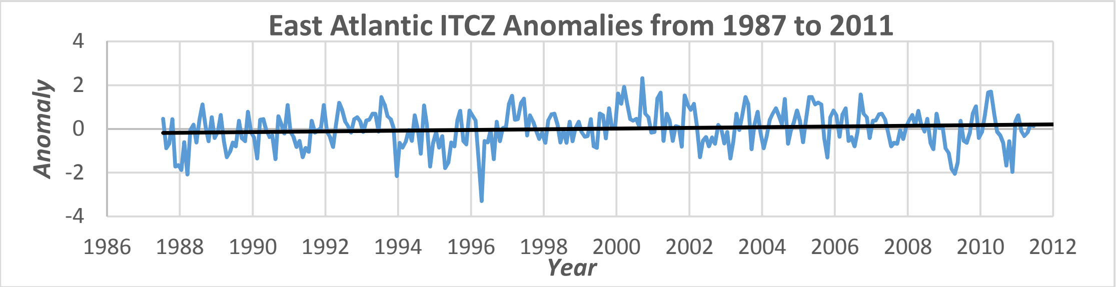
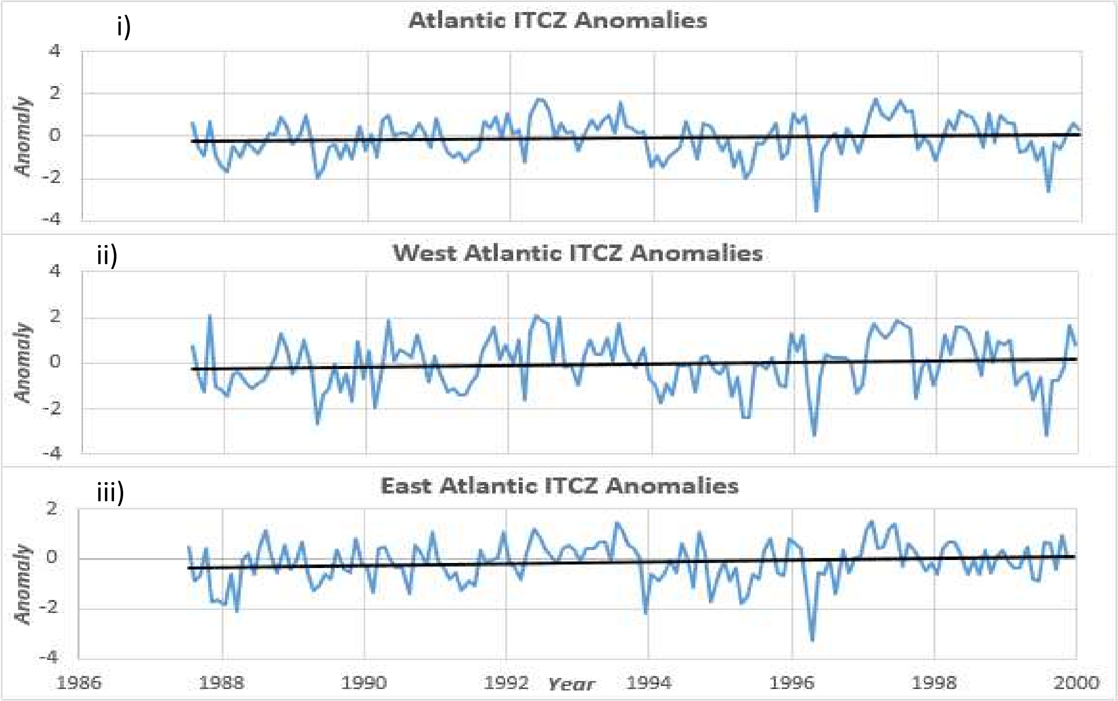


Figure 1.8. Monthly climatological position of the northern and southern branches of the ITCZ calculated with median averages from the entire time series (1987 to 2011).

a) ITCZ anomaly time series for significant trends of the entire time series: 1987 to 2011



b) ITCZ anomaly time series for significant trends of the first sub time period: 1987 to 1999



c) ITCZ anomaly time series for significant trends of the first sub time period: 2000 to 2011

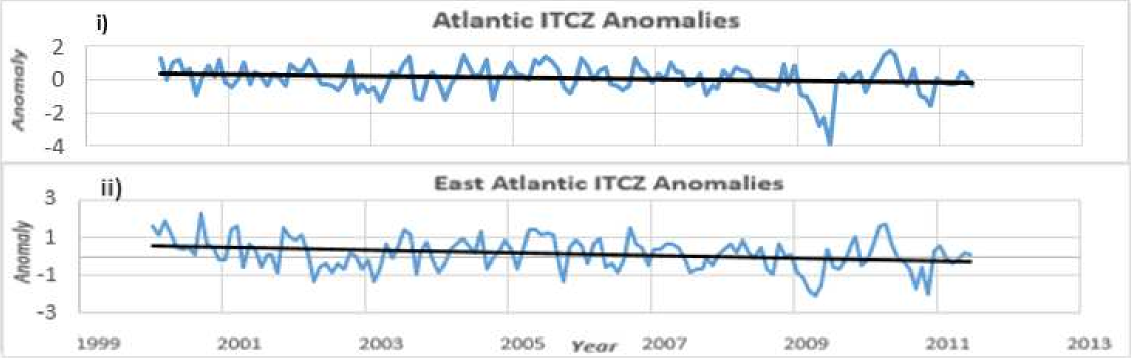
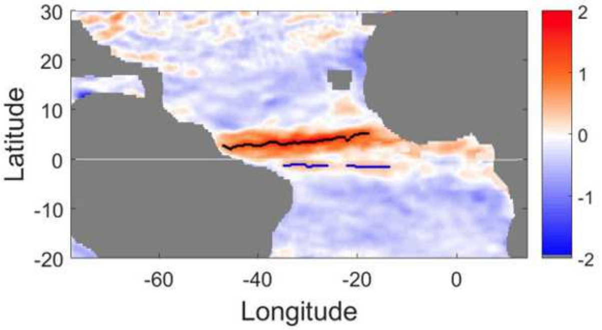
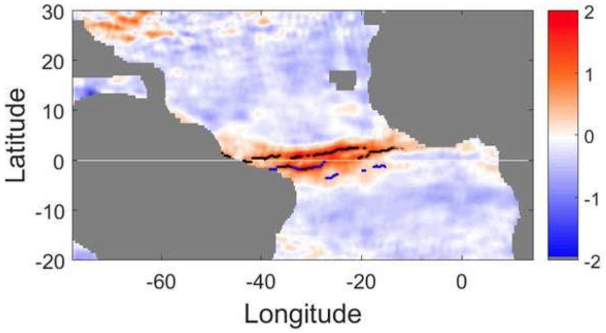


Figure 1.9. Anomaly time series for significant trends of the ITCZ for: (a) the entire time series from 1987 to 2011, (b) the first sub time period from 1987 to 1999, and (c) the second sub time period from 2000 to 2011. The blue lines represent the anomaly values and the black line is the trend line for each figure.

a) The double ITCZ forming in December of 2002



b) Merged northern and southern branches of the double ITCZ in February of 1994



c) Separated northern and southern branches of the double ITCZ in June of 1994

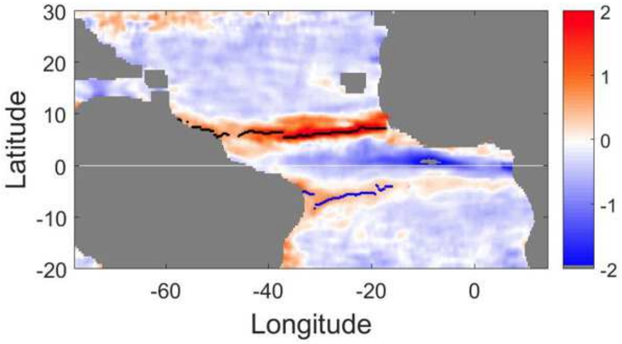


Figure 1.10. Monthly average position (black line) of the ITCZ in the Atlantic Ocean plotted against wind convergence (red) for: (a) December of 2002, (b) February of 1994, and (c) June of 1994. This is shown to illustrate the merged position of the northern and southern branches of the double ITCZ in the early months of the year (Figure a) and the separation of the branches during later months of the year (Figure b). The red color is wind convergence, the black line is the principal ITCZ, and the blue line is the southern branch that appears during a double ITCZ.

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CHAPTER TWO

Relationship between the Position of the Atlantic Intertropical Convergence Zone (ITCZ) and Upwelling in the Southern Caribbean Sea

1. Introduction and Background

1.1 Introduction

The Cariaco Basin, located in the southern Caribbean Sea (10.50° N, 64.66 °W), has a paleoclimate record that has been used to develop a chronology of climate change spanning over 600,000 years (see Black et al., 2007; and references therein). The sediments accumulating in the Cariaco Basin are the result of two interacting processes (Lorenzoni et al., 2012; Taylor et al. 2012). One is phytoplankton production in the overlying water column, which fluctuates with coastal upwelling strength. Another process is river runoff and terrigenous sediment input, which are modulated by rainfall. Both processes are directly linked to seasonal changes in ocean-atmosphere interactions, including those that lead to the formation and variability in the Intertropical Convergence Zone (ITCZ).

The ITCZ is a zonal band of atmospheric convection within the tropics caused by solar heating of surface ocean waters. Converging surface winds, tall storm clouds, and maximum mean precipitation all characterize the seasonal latitudinal migration of the ITCZ (Lietzke et al., 2001; Wang and Wang, 1999; Henke et al., 2012; Schneider et al., 2014). The latitudinal position of the ITCZ and its strength are determined by the position of the sun over the tropics and geographic, oceanographic, and atmospheric processes that affect the convergence of the southern and northern Trade Winds (Schneider et al., 2014). Biological and ecological processes in the tropics are affected by some of these same processes (Folland et al., 2002; Taylor et al., 2012). Changes in wind-driven upwelling, vertical mixing/stability, and riverine inputs are affected by the factors that control the seasonal migration of the ITCZ (Peterson et al., 2000; Haug et al., 2001).

Of interest is whether it is possible to make some inferences about the magnitude of biological production of organic particulate matter in terms of the characteristics and location of the ITCZ, in order to help the interpretation of the paleoclimate signals contained in the sediments accumulating at the bottom of the Cariaco Basin. Coastal upwelling occurs in the southern Caribbean Sea when the Northeast Trade Winds intensify over this area, i.e., when the ITCZ is in its southern position during the Northern Hemisphere winter months (and also shortly before and after it reaches its most southern position). The rainy season in the southern Caribbean occurs when the ITCZ is in its northern position during the Northern Hemisphere summer months (Richards, 1975; Muller-Karger et al., 1989; Muller-Karger and Aparicio, 1994; Black et al., 1999; Peterson et al., 2000; Lorenzoni et al., 2012). The study of the seasonal migration of the ITCZ location can therefore help in understanding change in tropical ecosystems (Cvijanovic and Chiang, 2013).

This study had two objectives. The first was to assess whether interannual variability in upwelling in the Cariaco Basin, measured using in situ water column temperature and satellite-derived sea-surface temperature as proxies of upwelling, is related to variability in the latitudinal position of the ITCZ in the Atlantic Ocean. The second was to evaluate whether interannual variability of the position of the Atlantic Ocean ITCZ is related to global-scale phenomena, specifically as characterized by the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) indices.

1.2 Background

In November 1995, the CARIACO Ocean Time-Series Program was established in a collaboration between U.S. and Venezuela investigators to understand the causes of temporal variations in the amount and type of sediments that settle through the water column (Muller-Karger et al., 2000; Lorenzoni et al., 2012). The observations reveal significant changes in the physical, chemical, and biological properties of the southern Caribbean Sea between the 1990's and the first decade of the 2000's. This led to the hypothesis that a more northern location of the ITCZ in the 2000's compared to the decade of the 1990's might have driven these changes (Taylor et al., 2012). The argument was that the processes underlying a change in the average annual position of the ITCZ to a more northerly location also caused a weakening in the intensity of the Trade Winds, and therefore in upwelling intensity in the Southern Caribbean Sea.

What would cause shifts in the average latitudinal position of the ITCZ? Are these changes related to larger-scale, global processes? The ITCZ is a large-scale feature that spans the circumference of the globe. Therefore, it should reflect changes in other large global-scale phenomena, such as those that are characterized by climate indices. Climate indices that may be relevant in the tropical Atlantic Ocean are the ENSO and the AMO. ENSO variability is evident in the variation of wind, rain, and sea surface temperature (SST) fields over the tropical eastern Pacific Ocean. The warm ENSO phase is typically known as *El Niño* and the cool phase as *La Niña*. The AMO tracks the average sea surface temperature of the North Atlantic. The AMO also has a warmer and a cooler phase (Knight et al., 2006; Enfield et al., 2001). The phases of the AMO modify the large-scale atmospheric circulation over North America. This modification to the circulation involves additional (less) precipitation over the central/western United States during the cold (warm) phases of the AMO (Oglesby et al., 2011). Additionally, Enfield et al. (2001) found that precipitation and discharge from the Mississippi River decreases (increases) east of the Rockies during the warm (cool) phase of the AMO.

Earlier studies suggest that 50 – 80% of the Atlantic SST variability is statistically related to ENSO (Enfield and Mayer, 1997). In the Atlantic, a decrease in the Northeast Trade Wind intensity is observed approximately 1 season (~ 1 to 3 months) after the peak of El Niño in the Pacific Ocean (Enfield and Mayer, 1997). Carton et al. (1996) and Xie and Carton (2004) show that warmer SST in the Atlantic occurs a few months after the peak of the warm phase of ENSO (El Niño) in the Pacific Ocean, and that this is associated with a northward average displacement of the tropical Atlantic ITCZ. Wang (2007) discovered that the Caribbean Low-Level Jet (CLLJ), a maximum easterly zonal wind in the lower troposphere of the Caribbean, is inversely related with Caribbean SST anomalies and also has an opposite relationship with ENSO in the winter and summer. For SST anomalies in the Caribbean, warm (cold) SST anomalies correspond to low (high) sea level pressure that weakens (strengthens) the CLLJ (Wang, 2007). The inverse ENSO relationship in the winter involves a weak (strong) CLLJ being associated with warm (cold) SST anomalies in the tropical Pacific. In the summer, the relationship is that a strong (weak) CLLJ corresponds with warm (cold) SST anomalies in the tropical Pacific. This opposite relationship between ENSO and the CLLJ is caused by ENSO teleconnections in which ENSO induces negative (positive) sea level pressure anomalies in the subtropical North Atlantic in the winter (summer; Wang, 2007)). During El Niño, the Caribbean Low-Level Jet (CLLJ) is stronger which causes more upwelling (Shieh and Colucci, 2010). The warm phase of AMO has also been associated with a northward shift of the ITCZ, leading to increased rainfall and a northward cross-equatorial wind anomaly over the tropical Atlantic Ocean (Knight et al., 2006; Häkkinen et al., 2011). When the AMO is in the cool phase, the opposite tends to occur and the ITCZ in the Atlantic shifts to a more southward position (Knight et al., 2006).

2. Data and Methods

2.1 Data

2.1 a) Wind Data

Monthly satellite-derived ocean wind observations from July 1987 to June 2011 were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory (JPL PO-DAAC). The Cross-Calibrated Multi-Platform (CCMP) wind vector analysis product dataset combines calibrated satellite ocean surface winds referenced to a height of 10 meters above sea level, in a grid with at a spatial resolution of 0.25° x 0.25°. The gridded data incorporates observations from different remote sensing sensors, i.e., the Special Sensor Microwave Imager (SSM/I), Special Senor Microwave Imager Sounder (SSMIS), Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), Tropical Rainfall Measuring Mission TRMM Microwave Imager (TRMM TMI), Quick Scatterometer (QuikSCAT), SeaWinds, and WindSat. The u-component and v-component of the wind vector were used to calculate the wind convergence (refer to section 2.2 b in Chapter 1 for the methods and equation to calculate convergence), and the maximum in convergence in the tropical Atlantic Ocean was found mathematically and used to trace the position of the ITCZ (Figure 2.1).

2.1 b) In-situ Cariaco Basin temperature data

Cariaco in-situ temperature data were obtained from CTD (Conductivity, Temperature and Depth profiler) monthly profiles at the CARIACO Ocean Time Series station (10.50°N, 64.67°W) from 1995 to 2012. The time frame for the in-situ data used was 1995 to 2012, to match the time period of the ITCZ analysis from the satellite data. The CARIACO project was initiated in October 1995 and the satellite data for ITCZ analyses was available only through late 2011.

Temperatures in the surface waters of the Cariaco basin area are affected by upwelling and by other processes such as wind turbulence, summer stratification, stratification due to fresh water input, etc., which also undergo seasonal variation. During the weak upwelling and/or rainy season, near-surface temperatures do not always reflect the intensity of upwelling in the Cariaco area. Temperatures were averaged at different depth intervals and analyzed to determine the depth interval that better reflects the temperature fluctuations that were related to the changes in the position of the ITCZ. In order to find the optimal index of upwelling, in-situ temperature profile data were thus averaged over several depth intervals (i.e., 0 – 10 m, 10 – 25 m, 1 – 20 m, 1 – 30 m, and 5 – 10 m). Monthly time series, long-term monthly averages (climatologies), and anomalies relative to the climatologies were calculated for each depth interval.

2.1 c) Satellite sea surface temperature (SST) data

High-resolution infrared satellite images collected by the Advanced Very High Resolution Radiometer (AVHRR, 1 km pixel resolution) were used to construct monthly SST means over the period of 1995 to 2016 for the Caribbean Sea. Images were collected by a ground-based L-band antenna located at the University of South Florida (St. Petersburg, Florida, U.S.A.). AVHRR images contain false cold pixels as a result of cloud contamination; to improve data quality a cloud filter was implemented, similar to that of Hu et al. (2009), for each satellite pass. The cloud filter was implemented based on the standard deviations of a weekly climatology derived for each pixel (Rueda-Roa and Muller Karger, 2013) and on a temporal median constructed with passes from ± three days from the pass to be cleaned (Rueda-Roa personal communication, September 2016). A monthly SST time series (1995 - 2016) was calculated by averaging 10 by 10 pixels around the CARIACO Time Series station at 10.50 °N, 64.66 °W. Monthly SST climatologies and anomalies were subsequently calculated.

2.1 d) El Niño Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO) data

The ENSO index was obtained from the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Division (PSD) of the Earth System Research Laboratory (ESRL). The ENSO data set used was the Multivariate ENSO Index (MEI). The MEI monitors ENSO based on six observed variables over the tropical Pacific Ocean (Wolter, 2015). These variables include sea-level pressure, u and v component of the surface wind, SST, surface air temperature, and total cloudiness fraction of the sky (Wolter, 2015).

The AMO index was also obtained from the NOAA-PSD-ESRL. The AMO data was calculated by computing a weighted average of the Kaplan SST data set (5 degrees latitude x 5 degrees longitude) from the NOAA ESRL over the North Atlantic. The time series that was obtained from the NOAA-PSD-ESRL was de-trended, this is important for this study because we are only interested in the decadal variation. The trend was removed over the entire period (1856 to 2016). The degrees of freedom for the AMO where calculated using autocovariance (degrees of freedom – 1). The ENSO and AMO datasets were shortened to the years from 1987 to 2011 to match the time frame of the wind convergence data.

2.2 Methods

2.2 a) Estimation of the ITCZ latitudinal location

The location of the ITCZ between 1987 and 2011 was estimated using wind convergence fields derived over the tropical Atlantic Ocean (Figure 2.1). Wind convergence fields produced a better-defined ITCZ than satellite-derived cloud height and rain products. Cloud and rain estimates from the Tropical Rainfall Measurement Mission (TRMM) also were initially used to trace the ITCZ over the global ocean. Extracting an average latitude for each 0.5 degrees longitude from the TRMM cloud height data was not straight forward, because very tall clouds, scattered at widely different latitudes across the tropics, led to noisy estimates of the position of the ITCZ across the Atlantic Ocean. TRMM products were therefore used for a visual trace of the ITCZ, but not for further quantitative analysis. We used the ITCZ trace derived from the wind convergence product (see Section 2.2 b in Chapter 1). Wind convergence was computed as described in Chapter 1 section 2.2.b.

Time series of the latitudinal position of the ITCZ in the Atlantic Ocean were derived for three areas (Figure 2.2): the entire basin (50°W to 15°W), the West Atlantic (50°W to 30°W), and the East Atlantic (30°W to 15°W). These sub-basins were examined separately given earlier findings that the largest SST variability is experienced in the eastern equatorial Atlantic Ocean (Carton et al., 1996). This variability is due to the occasional transport of warmer water to the eastern Atlantic from the western Atlantic, when Trade Winds relax, causing a regional warm event (Carton et al., 1996). The spatial analyses did not extend further west or east because of artifacts in the computation of the convergence related to the lack of wind measurements over or near land (Figure 2.1). Wind convergence followed the coastline of South America west of 50°W. Additionally, the ITCZ was too far south along the African coast east of 15°W.

2.2 b) Comparison of ITCZ position and Cariaco Basin temperature anomalies

The possible links between the ITCZ position in the various regions of the tropical Atlantic and water temperatures in the CARIACO basin were examined using a cross-correlation analysis. Correlations with lags up to 3 months were examined for the entire time series of the

ITCZ position anomalies for each region and in-situ and satellite SST anomalies from the CARIACO Time-Series station. A separate analysis was done just for the months of upwelling in the Cariaco Basin (December to April) since the upwelling season in the southern Caribbean Sea coincides with intensifying Trade Winds, leading to the hypothesis that ocean temperatures and the ITCZ would be more likely to be correlated during the upwelling season..

2.2 c) Comparison of ITCZ and climate indices anomalies

Monthly anomalies of ITCZ position for the three regions were compared to the ENSO MEI and the AMO index using a cross-correlation analysis. Correlations were examined using lags up to 6 months. The analysis sought to determine whether changes in climate indices lead changes in the ITCZ position, or if the ITCZ position has some effect on those climatic indices. Possible relationships between climate indices and ocean temperatures during the upwelling season in the Cariaco Basin (December to April) were also examined. The analysis focused on short-term variability in the indices and the ITCZ rather than multidecadal oscillations

3. Results and Discussion

3.1 Southeastern Caribbean temperatures and the latitudinal position of the ITCZ

3.1 a) Time series: All months during 1995-2012

The ITCZ is an important feature of the interaction between the atmosphere and the oceans. One way to study this relationship is to examine the correlation between parameters that influence ocean-atmosphere interactions (e.g., the ITCZ, climate indices, and SST). The correlation between the ITCZ and ocean temperatures in different regions has been characterized in several studies (e.g. Folland et al., 1986; Citeau et al., 1989; Waliser and Gautier, 1993; Wang and Wang, 1999; Xie and Carton, 2004; Foltz et al., 2011; Gulev et al., 2013; Servain et al., 2014). These studies explain that SST cycles interact with and regulate the north-south excursions of the ITCZ. More specifically, that the ITCZ position corresponds to the warmer hemisphere and that warmer (cooler) SST anomalies to the north are associated with a northward (southward) movement of the ITCZ.

The satellite SST represents the skin temperature of the ocean (perhaps the upper 10 microns of the ocean; Kearns et al., 2000). The in-situ temperature measurements in this study ranged in depths from 10 to 30 m. Since satellite SST and in-situ temperatures represent different depths, their correlations with wind data could be expected to be different. Alvera-Azcárate et al. (2011) explained that satellite SST and in-situ temperature may differ since each can be affected by various factors such as sensor or platform type, a bias at a specific platform, etc. It is most likely that the difference in the depth at which the measurements are taken cause the differences. A study by Stramma et al. (1986) confirms this by explaining that satellite SST is subject to diurnal warming patterns. Ship-based observations and other in-situ temperatures measurement techniques often miss these warming patterns since they measure temperature at greater depths, i.e., not just the surface. In addition, random noise could also cause the differences in correlations between in-situ and satellite SST measurements.

In situ temperature anomalies from the CARIACO Ocean Times Series (1995-2012) had no statistically significant correlation with the anomalies of the ITCZ position in any of the tropical Atlantic areas, for any lags tested (Figure 2.3a, 2.3b, and 2.3c, left panels). The lagged correlations between the in-situ temperature time-series anomalies and ITCZ position anomalies were different for the satellite SST measurements, this may due to the factors mentioned previously. However, in this case, these differences are not different statistically. There was a weak correlation between shallow temperature anomaliess and the ITCZ latitude anomalies in the Eastern Atlantic sub-basin. There, the correlation was weakly negative, but significant with $p<0.1$ when the ITCZ over the Eastern Atlantic led SST by 3 months (i.e. SST increased or decreased three months after the ITCZ migrated south or north, respectively).

3.1 b) Upwelling season

Since variability in the upwelling strength in the Cariaco Basin has important consequences for the regional ecology and fisheries, cross-correlations were tested only for the Cariaco Basin temperature time series during the upwelling season (December to April, Figure 3 right). For this period, in-situ Cariaco temperature anomalies were significant with no lag and with the ITCZ anomalies leading temperature anomalies by 3 months in the Atlantic and Western Atlantic regions. However, the most significant ($p<0.1$) correlation with the anomalies of the ITCZ position in the Atlantic and Western Atlantic regions was with no lag (Figures 2.3a, 2.3b, right panels). This may imply that during winter-spring the position of the ITCZ is related to the upwelling intensity in Cariaco (SST); for example, negative anomalies of the ITCZ position (ITCZ closer to the equator) corresponded to negative anomalies of SST (stronger upwelling). This could be due to the inverse relation between the latitudinal ITCZ position and the Trade Wind intensity in the Cariaco area, which has been found in earlier works (Muller-Karger et al., 2004; Goni et al., 2006; Taylor et al., 2012).

The Eastern Atlantic ITCZ anomalies had an inverse correlation leading Cariaco Basin temperature anomalies by 3 months (i.e. upwelling temperatures at Cariaco decreased or increased 3 months after the ITCZ had positive (north) or negative (south) anomalies, respectively; Figure 2.3a and 2.3c, right panel). The entire Atlantic saw this same correlation but to a lesser extent, while the correlations for the Western Atlantic are weak. This suggests that the whole Atlantic correlation (Figure 2.3a) is due to the eastern sector. Additionally, the inverse correlation in the Eastern Atlantic may imply that anomalies in the position of the Eastern Atlantic ITCZ during the northern autumn, are inversely related to the upwelling strength at Cariaco during the northern winter.

The correlations found in this study were generally low, this means that a direct cause-effect relationship between the ITCZ and upwelling in the Cariaco basin does not necessarily exist. The more likely explanation for low correlations is that other non-related variability is masking the hypothesized relationship since this study related remote ITCZ behavior to upwelling and the behavior may be responding to other air-sea interactions and not reflect well what is happening near the Cariaco Basin. Additional research outside the scope of this thesis would need to be done to examine other possible relationships and factors. Research such as the remote effects of ENSO and the AMO on subsidence over northern South America that affects rainfall, runoff, turbidity, and stratification, would be beneficial to further examine possible relationships and factors. For example, a northward moving ITCZ could be associated with less rainfall over South America leading to changes in SST through turbidity or other mechanisms in the river plume regions, controlled by unrelated precipitation over northern South America.

3.1 c) Mechanisms responsible for the relationship between Cariaco surface temperatures and the ITCZ

Taylor et al. (2012) proposed that a northward trend of the ITCZ over the 1996-2010 period diminished the upwelling strength causing progressively weaker nutrient supply to the surface. This would have affected the local marine ecosystem of the Cariaco Basin. However, my results on ITCZ trends (see Chapter 1) don’t support this hypothesis. I saw no northward trend of the ITCZ between 1995 and 2012, but the AWP data indicated that waters were warming by 0.29°C between 2000 and 2011 which may be the underlying cause for the changes to the marine ecosystem in the Cariaco Basin that Taylor et al. (2012) observed. On the contrary, there was a slight southward trend of the ITCZ over the Atlantic, particularly in the Eastern Atlantic, during the first decade of the 2000's (2000 to 2011; see Chapter 1 Section 3.2, and Table 1c and Figure 9c,ii in Chapter 1).

Could a southward trend in the position of the ITCZ lead to weaker upwelling in the southern Caribbean Sea, and indeed to a warmer Caribbean Sea? Or perhaps more likely, are other processes at work that produce the unexpected relationship? Fluctuations in SST are often related to changes in ocean circulation (Bjerkness, 1964). Tropical North Atlantic meridional SST gradients are associated with ocean circulation (Zebiak, 1993). The ITCZ is bound by subtropical gyres to the north and south (Arbuszewski et al., 2013); these subtropical gyres affect both SST and atmospheric variability (Bjerkness, 1964). Thus, variations in the North Atlantic gyre could be one explanation for the 3-month-lagged inverse relationship between Cariaco SST and the ITCZ in the Atlantic and the Eastern Atlantic. Other explanations for the 3-month-lagged inverse relationship could be a northward moving ITCZ could be associated with less rainfall over South America. This could lead to an effect on SST through turbidity or other mechanisms in the river plume regions, controlled by unrelated precipitation over northern South America. Additionally, the advection of water masses affects the position of temperature gradients in the north Atlantic, as the basin adjusts to changes in the wind stress curl (Wu and Liu, 2005). Reductions in speed and intensity of the thermohaline circulation in the North Atlantic may cause the ITCZ to shift southward (Brown and Johnson, 2005). However, the inverse delayed correlation found in this study does not necessarily mean that a cause-effect relationship between the ITCZ and upwelling in the Cariaco basin exists. These patterns will require further study that are outside the scope of this thesis.

3.2 Climate indices relationship with the latitudinal position of the ITCZ

3.2 a) ENSO

The ENSO MEI has significant positive correlations with the ITCZ latitudinal position anomalies over the Atlantic and the Western Atlantic Ocean when ENSO variations preceded changes in the ITCZ position anomalies by 0 to -6 months (Figure 2.4a). Maximum correlations in this study were with an ENSO three-month lead before the ITCZ position anomalies. There were no significant correlations with the ITCZ position anomalies in the Eastern Atlantic. As seen in the relationship between the ITCZ and Cariaco temperatures, the correlations between the ITCZ and climate indices also reveal that correlations with the Eastern Atlantic ITCZ seem to typically be different than the correlations observed with the Central and Western Atlantic ITCZ. Despite these observations, the correlations observed between ENSO and the ITCZ are still low (<0.15), this suggests that the results are not conclusive of a direct relationship, or that other processes are masking that relationship. Additionally, the difference between ENSO leading the ITCZ by 3 months and the no-lag relationship (0 months) is minute. This small difference makes it difficult to determine if there is any difference between the significant correlations at those lags.

Several studies have documented the role that ENSO plays in the tropical Atlantic Ocean (e.g. Enfield and Alfaro, 1999; Enfield and Mayer, 1997; Xie and Carton, 2004; Marullo et al., 2010; Munnich and Neelin, 2005). Enfield and Mayer (1997) conclude that during an El Niño event, the intensity of the Northeast Trade Winds over the Atlantic decreases, from Northwest Africa to the Caribbean, with a lag of 1 to 3 seasons (1 season is ~ 3 months). In this study the maximum correlation was with a lag of 3 months (or 1 season). This implies that during El Niño and within three months after an El Niño event (warm ENSO anomaly in the Pacific) the ITCZ over the Western Atlantic Ocean tends to shift to a more northerly position). The results from this study support previous work that indicates that warmer ENSO anomalies in the Pacific affect the Western Atlantic ITCZ by shifting its position northward three months later and during El Niño.

Enfield and Alfaro (1999) further discovered that in the winter, both the CLLJ winds and the position of the ITCZ favor weaker upwelling (the positive correlations in Figure 2.4). Although the correlations between the ITCZ and ENSO in the Western Atlantic were significant, these correlations were small (Figure 2.4a). ENSO explained less than 3% of the variability of the ITCZ latitudinal position over the Atlantic Ocean. This again points to the fact that other factors may play a role in the relationship observed between ENSO and the ITCZ. For example, during the December-January-February (DJF) season, the 200 millibar velocity potential anomalies indicate convergence aloft which suppresses convection over South America (Mestas-Nuñez & Enfield 2001; Fig. 9b). This relationship indicates a disruption of the Walker circulation which is not directly related to the ITCZ, yet it affects the river plume regions (Mestas-Nuñez & Enfield 2001). This is an example of a process that can affect the Cariaco Basin that has nothing to do with the ITCZ, but can affect the sediment and mask the impacts of the ITCZ on Cariaco Basin.

3.2 b) AMO

The ITCZ latitude anomalies over both the Atlantic and the Western tropical Atlantic basins showed highest direct correlations with the AMO changes occurring one month earlier (Figure 2.4b). While for the Eastern tropical Atlantic ITCZ anomalies the response was instantaneous (maximum with no lag), but it was still felt one month after the AMO (Figure 2.4b). Positive or negative phases of the AMO are related to the ITCZ position by the presence of warmer or cooler waters in the tropical North Atlantic that lead to increased or decreased convective activity in the atmosphere (Elder et al., 2014). In this work, a positive AMO phase (warmer anomalies) caused a small northerly shift in the ITCZ position, which was contemporaneous in the Eastern Atlantic ITCZ, and one month later in the Western Atlantic ITCZ. Previous studies have also indicated that a warmer AMO is related to a more northerly ITCZ position (Knight et al., 2006; Elder et al., 2014).

3.3 Climate indices relationship with Cariaco basin temperatures

3.3 a) ENSO

There were inverse correlations between Cariaco near-surface temperature anomalies and the ENSO index (Figure 2.5a), with ENSO lagging Cariaco Basin temperature anomalies (Figure 2.5a, left) by -1 to 6 months, and a maximum correlation with ENSO at 3-4 months later than Cariaco temperature anomalies. When analyzing only the upwelling months of the Cariaco temperatures (December-April), correlations with ENSO were also maximum and inverse with ENSO changes occurring three to four months after Cariaco Basin temperature anomalies (Figure 2.5a, right), but correlations were significant only for the lagged period 1 to 6 months.

Ham et al. (2013) found an inverse teleconnection between tropical Atlantic SST anomalies and ENSO. Positive SST anomalies in the tropical Atlantic during the boreal spring preceded negative ENSO (La Niña) events during the next boreal winter, which is around 9 months later. Once the warming in the tropical Atlantic is observed, La Niña frequently starts in the Northern Hemisphere summer-fall months following El Niño. This may be due to warmer SST's in the Atlantic, but also is due to the internal oscillatory behavior of the tropical Pacific. Wang et al. (2011) found similar results, but with a lag from 5 to 13 months. The results here may suggest teleconnections at an even shorter lag of 3-4 months, but other factors (like the oscillations in the Pacific) may also play a role.

3.3 b) AMO

Surface temperatures in the Cariaco Basin have long-term fluctuations that reflect the SST fluctuations in the tropical Atlantic. This was evident in this study by the direct correlations between the Cariaco surface temperatures anomalies and the AMO index. For the whole-time series, correlations between Cariaco basin temperature anomalies and AMO were direct and significant for lags between -6 to +4 months, with maximum correlations with AMO leading the Cariaco temperature anomalies by 2-3 months (Figure 2.5b left). When analyzing only the upwelling months, correlations were also direct and significant between lags of -6 to +5, but the maximum correlation was with AMO lagging Cariaco Basin temperature anomalies by one month (Figure 2.5b right). This lag is most likely due to the fact that there is hysteresis built into the system, with a negative SST anomaly in this tropical upwelling area preceding any major change of the entire northern Atlantic system.

The significant correlations along a wide range of lags between AMO and Cariaco temperatures indicate similar seasonal forcing for the sea surface temperatures from both the North Atlantic and the southern Caribbean Sea, as well as feedbacks between those areas. Findings from Kilbourne et al. (2008) and other studies (i.e. Delworth and Mann, 2000; Vellinga and Wood, 2002) concluded that hemispheric temperatures variations (like that of the North Atlantic SST anomalies) are related to the AMO. Schmidt et al. (2004) explains that western waters from the Atlantic subtropical gyre circulates through the Caribbean Sea before it is transported to the North Atlantic via the Gulf Stream. Around 20-40 Sverdrup’s (Sv) of Atlantic water passes through the Caribbean (Nof, 2000). The flow of water from the Tropical Atlantic to the Caribbean Sea might explain in part the leading correlations of AMO two-three months earlier than Cariaco temperature. Also, a warmer AMO forces a more northerly position of the ITCZ (Fig. 4b), which would cause weaker Trade Winds over the southern Caribbean and weaker upwelling. While in general the AMO index affected two-three months later the temperatures measured at the Cariaco area, winter temperatures from Cariaco during the upwelling season, seem related to one month later AMO index. Similarly, this can be in part related to the water circulation from the Caribbean Sea to the North Atlantic via the Gulf Stream.

3.4 Results and discussion summation

The latitudinal position of the ITCZ is weakly correlated with both Cariaco sea temperatures and global climate indices. Similarly, climate indices and Cariaco sea temperatures are also have a weak correlation. These results indicate that there is a slight linkage between upwelling in the Cariaco Basin and the ITCZ position and climate indices.

Ocean temperatures averaged over different depth intervals in the Cariaco Basin all had similar correlations with the ITCZ position and with climate indices. When just the upwelling season was evaluated, there was a non-lagged correlation with the ITCZ position anomalies in the Atlantic and Western Atlantic, while in the Eastern Atlantic the ITCZ amonalies led Cariaco temperature anomalies by 3 months.

When examining the relationship between climate indices and the ITCZ, it was determined that in the Atlantic and Western Atlantic ENSO led the ITCZ position anomalies by 3 months and that the AMO led the ITCZ position anomalies by 1 month. However, there were no correlations between ENSO and the anomalies of the ITCZ position in the Eastern Atlantic, and correlations between the Eastern Atlantic ITCZ anomalies and AMO were higher with no-lag. These results indicate that correlations for the Eastern Atlantic ITCZ were typically different from the results seen for the ITCZ of the Central and Western Atlantic basins. These differences may possibly be due to the Eastern Atlantic experiencing stronger equatorial upwelling compared to the Western Atlantic, since the Eastern Atlantic is the eastern boundary of the ocean basin. Additionally, the majority of correlations in this study were low. This means that these relationships discussed in this paper are present but other process may be involved in the relationship between the ITCZ and Cariaco Basin temperatures and also between the ITCZ and climate indices.

The results found in this study may suggest that other non-directly related factors may also play a role in the relationships discussed. For example, during the Northern Hemisphere winter there is convergence over northern South America during the peak of El Niño. This convergence produces subsidence and causes a decrease in rainfall. This is why northern South America experiences less rainfall during the Northern Hemisphere winter immediately following the peak warming in the Pacific that occurs about 2 months earlier (Mestas-Nuñez and Enfield, 2001). When this happens, the Amazon is at its driest affecting runoff to the Caribbean and the ITCZ through rainfall suppression during the Amazon wet season (Mestas-Nuñez and Enfield 2001). These results from Mestas-Nuñez and Enfield (2001) suggest that there are other remote processes that are involved in the relationship between ENSO and the Cariaco Basin that are independent of the ITCZ and therefore outside the scope of this study.

Additionally, in the paper by Mestas-Nuñez and Enfield (2001), they describe the difference between patterns in tropospheric variability associated with ENSO and non-ENSO (which includes the AMO) forcing over northern South America. Their paper looked at atmosphere-ocean interactions that differ from the processes discussed previously in this paper. The parameters examined were convergence and divergence patterns in the 200 hPa velocity potential. They concluded that the tropospheric patterns between the ENSO and non-ENSO forcing were very different. Over northern South America, where El Niño indicates convergence aloft the non-ENSO warm phase indicates divergence at 200 hPa. At 500 hPa, El Niño shows downward motion (i.e. consistent with convergence at higher levels) while warm non-ENSO shows stronger upward motion. Based on these results, they concluded that at the lower latitudes, ENSO and non-ENSO have opposite impacts on regional climates. The results and conclusions of Mestas-Nuñez and Enfield (2001) suggest that there are other remote process involved in the relationship between the ITCZ and climate indices (i.e. runoff that affects the surface water characteristics that impact the Cariaco Basin) other than the parameters examined in this study.

3.5 Future Studies

Ocean temperatures, the ITCZ, and climate indices are related. They define the variability of the tropical Atlantic Ocean. Changes in these parameters help understand impacts on local and regional climate, precipitation, and other characteristics (i.e. upwelling, primary productivity, etc.). For example, land processes result in runoff and land processes also affect the ITCZ so examining land processes may be an important aspect of future research. Future studies should focus on the mechanistic linkages between the ITCZ and SST, and between the ITCZ and climate indices, in order to better understand how local and regional parameters are affected by larger scale ocean-atmosphere features.

4. Conclusions

The ITCZ is a feature of the interaction between the atmosphere and the ocean. This interaction has important implications for local, regional, and global climate around the world. In the Atlantic Ocean, the ITCZ is linked to variability of temperatures in the southeastern

Caribbean Sea temperature and climate indices. Temperatures anomalies from in-situ and satellite SST measurements in the Cariaco Basin were examined via cross-correlations with lags of up to 3 months to examine the relationship with anomalies of the latitudinal position of the ITCZ.

No statistically significant correlations between Cariaco Basin in-situ temperature anomalies and the ITCZ anomalies were found in any of the tropical areas for any of the lags tested. However, there was a significant weak, negative correlation found in the Eastern Atlantic when the ITCZ anomalies led SST anomalies by 3 months. Additional correlations were found when just the upwelling months of the Cariaco time series, from December to April, were cross-correlated with the ITCZ position. In the Atlantic and Western Atlantic, there was a significant small, positive correlation between the ITCZ position anomalies and Cariaco Basin temperature anomalies with no-lag. On the other hand, in the Eastern Atlantic there was a weak, inverse correlation with the ITCZ anomalies leading Cariaco Basin temperature anomalies by 3 months.

Significant correlations were also found to exist between the ITCZ and climate indices, specifically ENSO and the AMO. Significant direct correlations were found, with ENSO leading the ITCZ position anomalies in the Atlantic and Western Atlantic by 3 months. There were no significant correlations with ENSO and the ITCZ anomalies in the Eastern Atlantic. The AMO had significant correlations with the anomalies of the ITCZ in each of the tropical areas examined. In the Atlantic and Western Atlantic, anomalies of the position of the ITCZ were affected by the AMO changes taking place 1month earlier. But, in the Eastern Atlantic, the ITCZ position anomalies were correlated with the AMO with no-lag and with a 1 month lag.

When correlations were examined for ENSO and the AMO with temperatures anomalies in the Cariaco Basin, the results were similar. Significant correlations between ENSO and

Cariaco Basin temperature anomalies occurred with ENSO lagging temperature anomalies in the southern Caribbean by 3 to 4 months for the whole time series and the upwelling season. However, the AMO had different correlations for the whole time series and the upwelling season. For the whole time series significant correlations occurred with the AMO lagging Cariaco Basin temperature anomalies by 2 to 3 months. During the upwelling season, the correlation between the AMO and ocean temperature anomalies is stronger, and shows a faster linkage of about 1 month (i.e. the AMO changes occur 1 month after temperature anomalies in the southern Caribbean).

The correlations found in this study were small which implies that a direct cause-effect relationship between (1) the ITCZ and upwelling in the Cariaco Basin and (2) the ITCZ and climate indices might not necessarily exist. However, these small correlations may suggest that other remote process may also be involved in the relationships. These relationships and patterns require further research that is outside the scope of this thesis.

The ITCZ, ocean temperatures, and climate indices all interact and affect one another. The relationship between these parameters affects local and regional climate, meteorology, biogeochemistry, and marine ecosystems. An important area of research is the relationship between these processes so that local regions can prepare for changes they may observe (i.e. atypical drought or rainy seasons, changes in upwelling intensity, and changes in primary productivity).

5. Figures

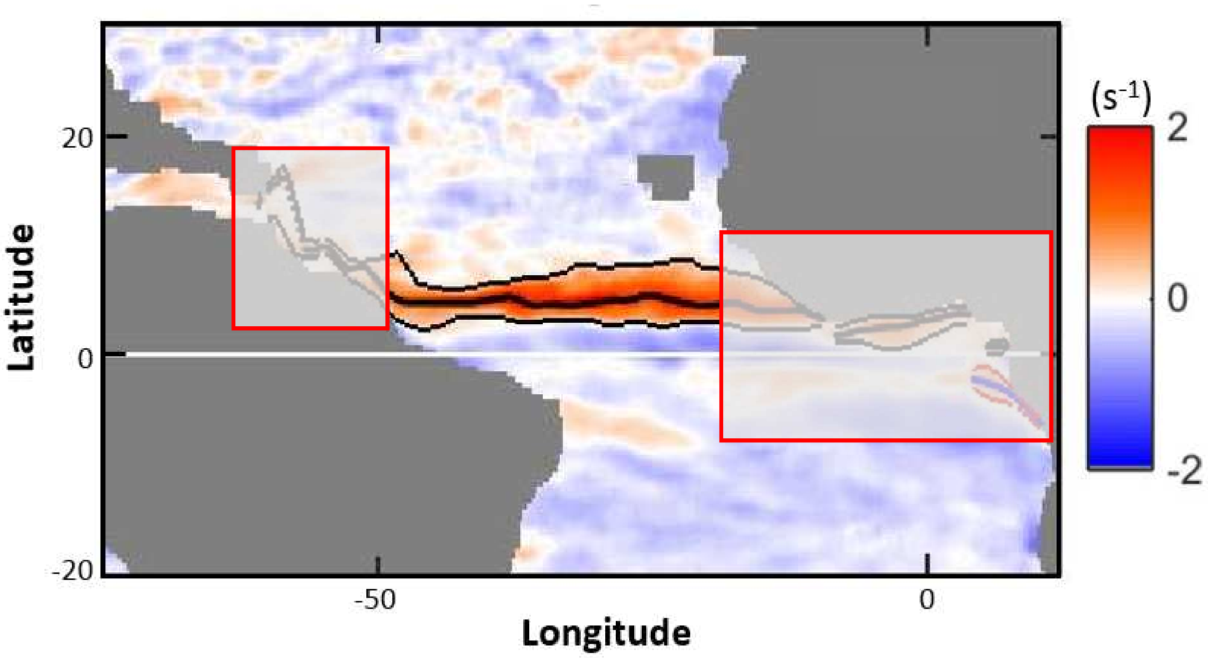


Figure 2.1. Position of the Intertropical Convergence Zone (ITCZ) in the Atlantic Ocean for December of 2001 (thick black line) and its latitudinal width (thin black lines marking a threshold ≥ 0.6 s^{-1} of stronger winds toward the north and south). Background: wind divergence (red/blue) for the same month. Wind divergence was calculated from ocean surface wind vectors obtained from the NASA Cross-Calibrated Multi-Platform (CCMP) wind vector analysis product. Longitudes west of about 50°W and east of about 15°W (shaded boxes outlined in red) were excluded from the analysis because the convergence field contain artifacts derived from the lack of satellite wind over land.

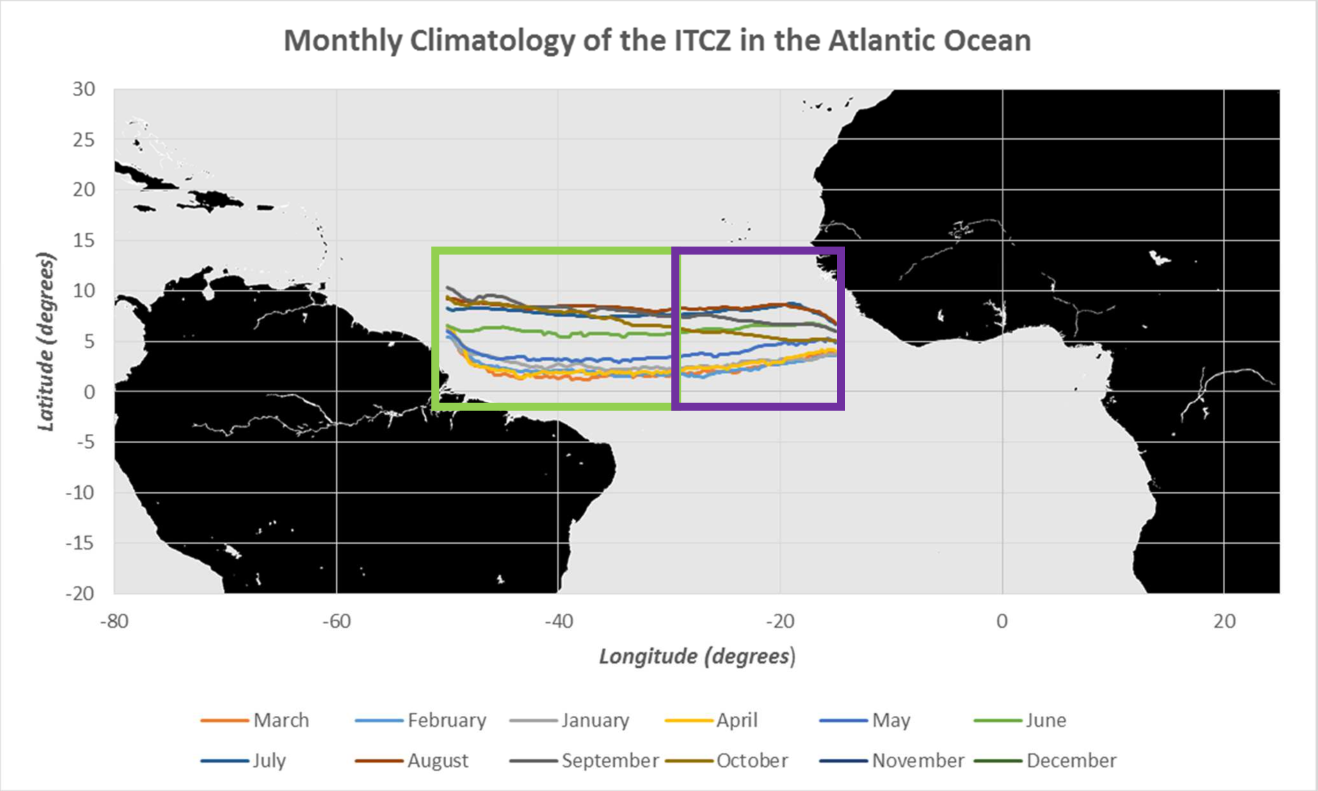
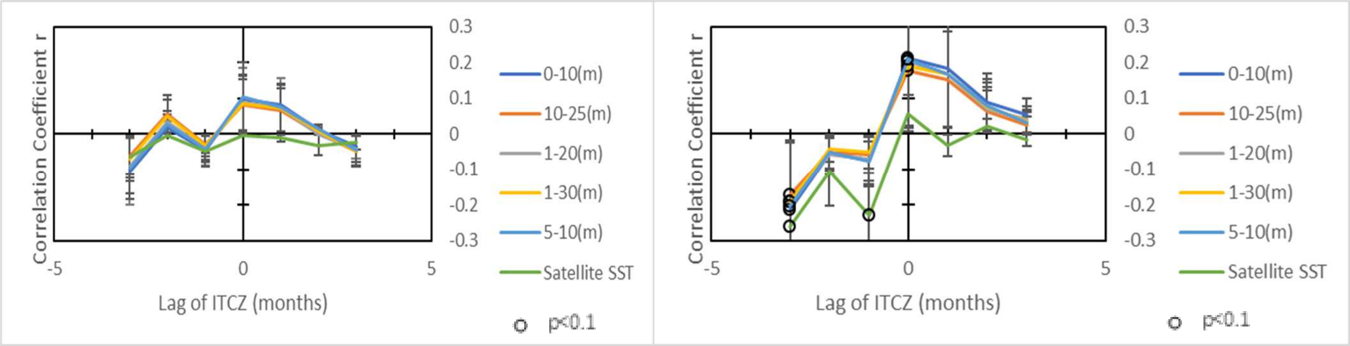
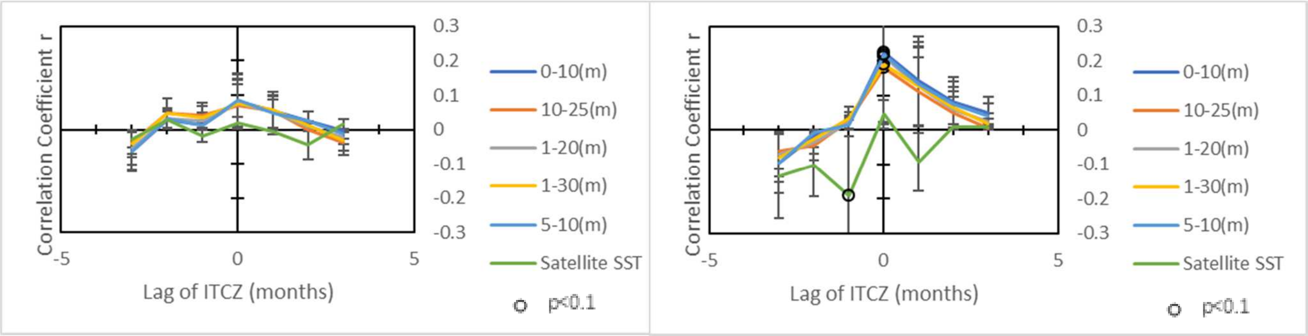


Figure 2.2. Monthly climatologies of the Atlantic Ocean ITCZ latitudinal position between 50°W to 15°W derived from average monthly wind divergence fields computed between 1987 and 2011. Boxes represent the areas of the Atlantic used to calculate the median of the ITCZ latitude over time. The green is the Western Tropical Atlantic Sub-basin, the purple is the Eastern Tropical Atlantic Sub-basin, and the green and the purple areas together are used to represent the median latitudinal position over the Tropical Atlantic.

(a) Correlation coefficient (r) for ocean temperatures and the Atlantic ITCZ



(b) Correlation coefficient (r) for ocean temperatures and the Western Atlantic ITCZ



(c) Correlation coefficient (r) for ocean temperatures and the Eastern Atlantic ITCZ

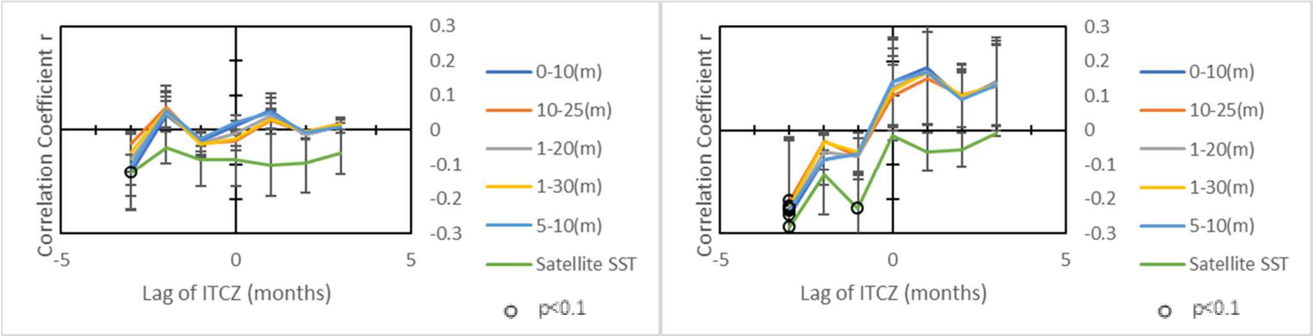
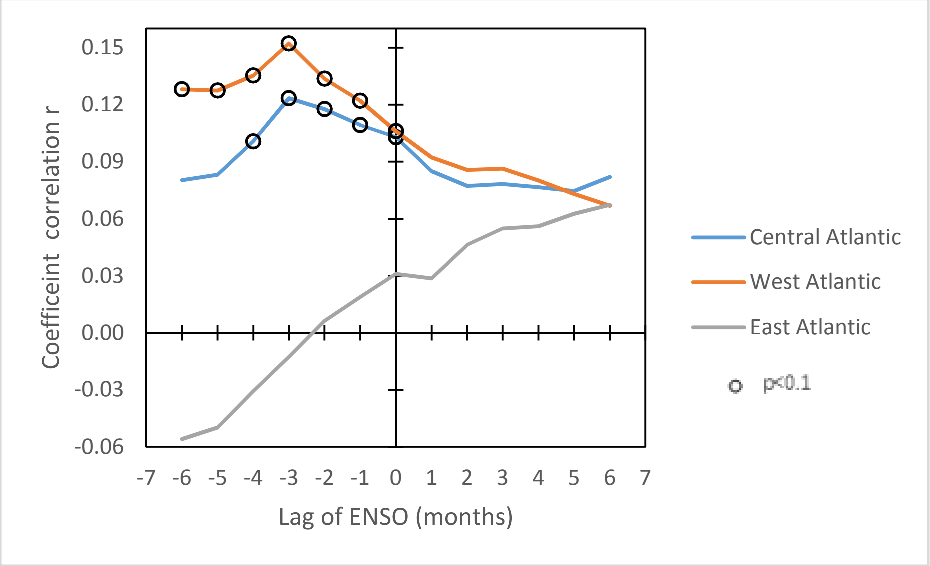


Figure 2.3. Correlation Coefficient (r) values for the comparison between sea temperatures anomalies from the Cariaco Basin and the ITCZ latitudinal position anomalies (median) over the (a) the Atlantic, (b), the Western Atlantic, and (c) the Eastern Atlantic Ocean with lags of ± 3 months. (Left) correlations with the entire CARIACO time series. (Right) correlations with only the Cariaco Basin upwelling season months (December to April). Significant correlations ($p \leq 0.1$) are highlighted with a black circle and the 90% confidence interval is illustrated with the gray error bars. In situ temperature from the CARIACO Time Series station (10.50° N, 64.66 °W) were averaged over several depth ranges shown in the graphs, Sea Surface Temperature (SST) was averaged over a box of 10 x 10 pixels around the CARIACO Time Series station.

(a) ENSO correlations with the ITCZ



(b) AMO correlations with the ITCZ

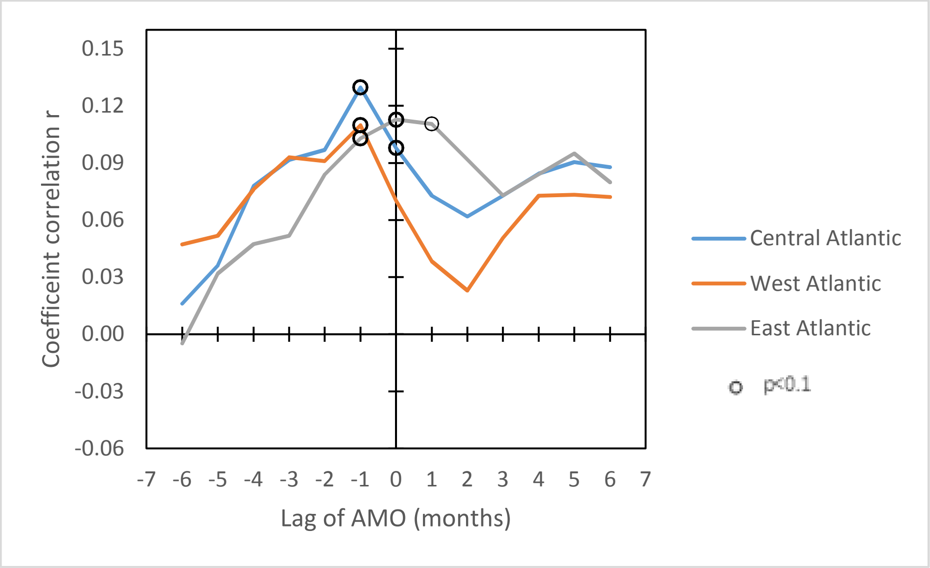
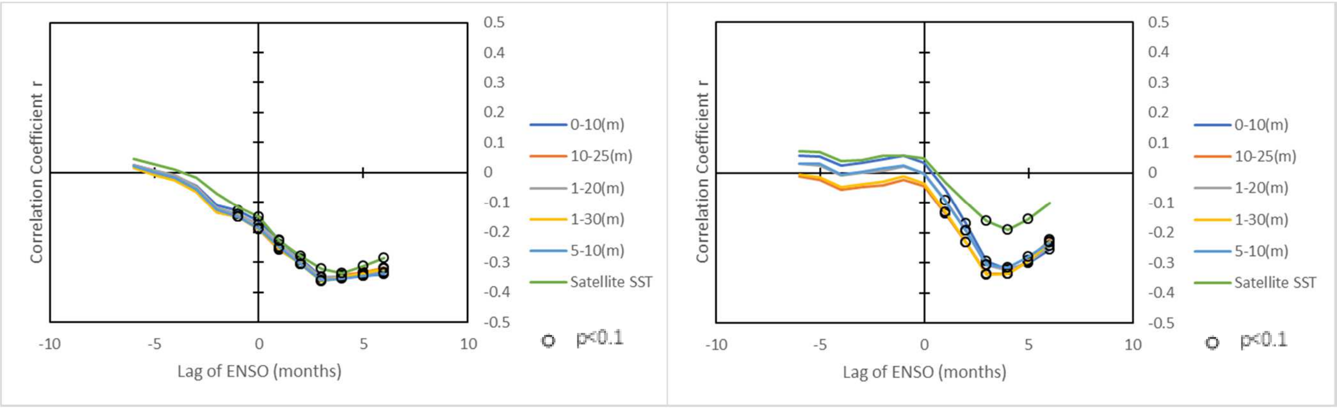


Figure 2.4. Correlation Coefficient (r) values for (a) El Niño Southern Oscillation (ENSO) and (b) Atlantic Multidecadal Oscillation (AMO) climate indices compared to the ITCZ latitudinal anomalies for the three Atlantic Ocean basins with lags of ± 6 months.

a) Correlation coefficient (r) for ENSO lagging in-situ ocean temperatures



b) Correlation coefficient (r) for AMO lagging in-situ ocean temperatures

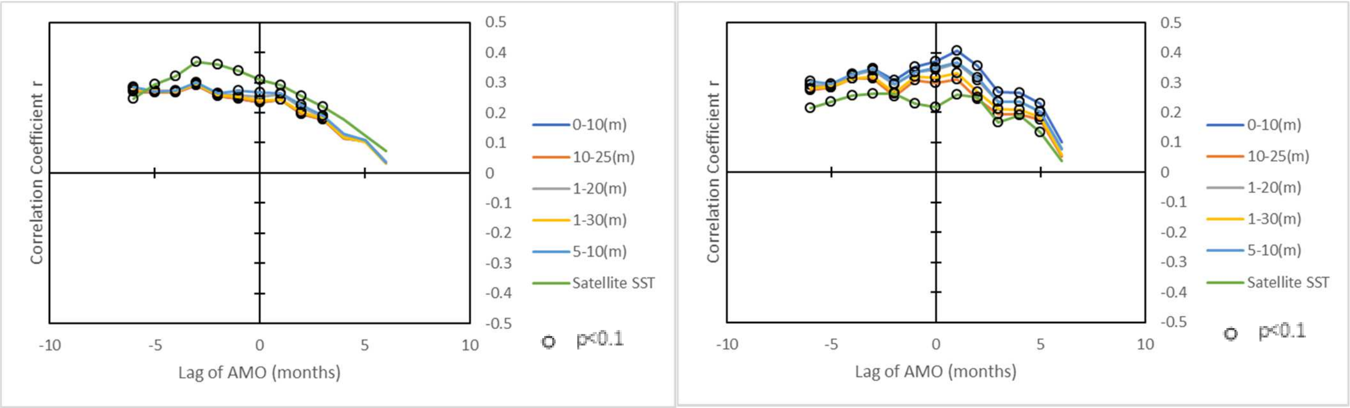


Figure 2.5. Correlation Coefficient (r) values for Cariaco in-situ sea temperatures anomalies correlated with (a) ENSO and (b) AMO climate indices with lags of ± 6 months for (left) the whole time series and (right) during the Cariaco basins upwelling season (December to April).

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GENERAL CONCLUSIONS

The ITCZ is a feature in the tropics that is the result of the interaction between the atmosphere and the ocean. Seasonally, the ITCZ moves towards higher latitudes through August, when it reaches its northernmost extent. It then moves southward through March, when it typically reaches a minimum latitude. In this study, the position of the ITCZ was determined between 1987 and 2011 using satellite-derived wind convergence fields. The median meridional position of the ITCZ was compared for two time periods (1987 to 1999 and 2000 to 2011) to determine if the ITCZ moved northward during the latter time period compared to the earlier time period to test a hypothesis proposed by Taylor et al. (2012) that the ITCZ was moving northward in the first decade of the 2000's.

Mann-Kendall (MK) and Monte Carlo tests were performed to determine significant trends in the latitudinal position of the ITCZ. MK tests suggest that there have slight changes in the average position of the ITCZ position over time. For example, just for the period 1987-1999, there was a northward shift of 0.33° (37km) over the central Atlantic (50°W to 15°W), 0.42° (47km) over the Western Atlantic (50°W to 30°W), and 0.41° (46km) over the Eastern Atlantic (30°W to 15°W) from1987 to 1999. The MK tests revealed that after that, from 2000 to 2011 there was a southward trend in the ITCZ position by 0.60° (67km) in the central Atlantic, and by 0.73° (81km) in the Eastern Atlantic. The Monte Carlo test found these trends to be significant at the 66% confidence interval, but not significant at the 90% confidence interval.

A Southern Hemisphere branch of the ITCZ was observed in the wind convergence climatology and time series of the ITCZ in the Atlantic Ocean. This double ITCZ forms near the coast of South America in the Western Atlantic in December – February, and extends eastward over the ocean until July – August. The southern branch of the ITCZ is completely separate from its northern branch counterpart by June – July. The southern branch of the ITCZ is the result of the north-south gradient in SST that exists across the equator due to the equatorial upwelling cold tongue that develops in the East Atlantic.

This study rejected the hypothesis that the ITCZ position shifted northward during the first decade of the 2000's relative to the 1990's. Shifts in trends and strength of the ITCZ, as well as the formation of the double ITCZ, can have important implications for ocean-atmosphere interactions around the world. The local and regional changes observed by Taylor et al. (2012) in the southern Caribbean Sea are more likely to be the result of an overall warming of the entire tropical and temperate Atlantic Ocean causing weaker Trade Winds and local upwelling.

In-situ and satellite ocean temperature measurement anomalies from the CARIACO Ocean Time-Series Program in the Cariaco Basin were examined via a cross-correlation analysis with anomalies of the latitudinal position of the ITCZ. There were no statistically significant correlations between the ITCZ position anomalies and in-situ temperature anomalies in the Cariaco Basin, but there was a weak inverse correlation between the ITCZ position anomalies and sea surface temperature (SST) anomalies in the Eastern Atlantic, with the ITCZ anomalies leading SST anomalies by 3 months (i.e. SST increased or decreased 3 months after the ITCZ moves north or south respectively). For the months when upwelling occurs in the Cariaco basin (December- April), the central and Western Atlantic had small, positive, significant correlations between the ITCZ anomalies and Cariaco Basin temperature anomalies with no-lag. There was an inverse correlation between Cariaco Basin temperature anomalies and ITCZ position anomalies in the Eastern Atlantic, with ITCZ position anomalies leading by 3 months.

Significant correlations were found between the ENSO MEI index and the ITCZ latitudinal position anomalies in the central and Western Atlantic, with the ENSO MEI index leading the ITCZ position anomalies by 3 months. There was no significant correlation between ENSO MEI and ITCZ position anomalies in the Eastern Atlantic.

The ITCZ position showed a significant correlation with the intensity of the variability in the AMO. The position of the ITCZ anomalies in the central and Western Atlantic lagged the AMO by 1 month. The Eastern Atlantic was correlated with the AMO with no-lag and when the ITCZ position anomalies lagged the AMO by 1 month.

ENSO MEI was found to lag Cariaco Basin temperature anomalies by 3 to 4 months for the whole time series and during the upwelling season. The Cariaco Basin temperature anomalies lagged the AMO by 2 to 3 months. When just the upwelling season was evaluated, the correlation was stronger and faster, with a lag of only 1 month.

My results lead me to the conclusion that the changes observed in the southern Caribbean Sea are more likely the result of an overall warming of the entire tropical and temperate Atlantic, as an underlying cause for a weakening of the Trade Winds and local upwelling. Changes to the position and strength of the ITCZ (and the double ITCZ in the Atlantic Ocean) need to be studied further to understand how the variability of the ITCZ affects local and regional processes (i.e. weather, climate, rainfall, upwelling, etc.). The ITCZ, SST, and climate indices all tell different stories. The relationship between the ITCZ, SST, and climate indices has important impacts on local weather and oceanographic changes, including ecological changes. Monitoring these features with satellite observations is important, since these changes impact resources in the region. Studies like these should be continued to derive operational indices of potential impacts of changes in the ITCZ that the public can use.

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ABOUT THE AUTHOR

The author of this thesis, Kaitlyn E. Colna, is originally from southern New Jersey. She attended Millersville University for her undergraduate schooling where she was a double major and received two Bachelor of Science degrees (Meteorology, Ocean Sciences and Coastal Studies with a Physical Oceanography concentration) in 2014. Her research experience began when she received the Rachel Carson Biology Field Scholarship in the summer of 2011 to take a course in Wallops Island Virginia at the Marine In 2013, she completed a Research Experience for Undergraduates (REU) internship at Penn State University where she worked under Dr. Ray Najjar in the Department of Meteorology conducting research on the changes in salinity in Biscayne Bay, Florida. Additionally, at Millersville University, she conducted an independent study project under Dr. Ajoy Kumar in which she studied environmental changes for a section of the east coast from Virginia to New Jersey. She presented this research at the Ocean Sciences Meeting in Honolulu, HI in February of 2014.

In August of 2014, she began to pursue her Masters of Science degree in Marine Science at the University of South Florida. During her time at there, she received two fellowships: the University Graduate Fellowship for the 2014 – 2015 school year, and the Sanibel-Captiva Fellowship for the 2015 – 2016 school year. Her position as a Graduate Research Assistant allowed her to complete the research in this thesis using meteorological and oceanographic data and relating it to regional and global parameters. She will graduate from the University of South Florida in May of 2017 with her Master of Science degree. Kaitlyn E. Colna is a young scientist whose hard work in her schooling and research endeavors is represented in this thesis.