Influence of ENSO on Tropical Cyclones in North Atlantic in a high-resolution climate model

by

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Table of Contents

List of Tables & Figures ........................................................................................................... 4
Tables ........................................................................................................................................ 4
Figures....................................................................................................................................... 4
Acknowledgements .................................................................................................................. 6
Abstract ................................................................................................................................... 7
1. Introduction ........................................................................................................................ 8
2. Data, method of analysis and model ...................................................................................... 17
   2.1 Observational Data .......................................................................................................... 17
   2.2 Method of analysis ........................................................................................................... 17
   2.3 Model ............................................................................................................................... 20
3. Results .................................................................................................................................. 26
   3.1 Mean state and variability ............................................................................................... 26
      a. SST ................................................................................................................................. 26
      b. Tropical cyclone density .............................................................................................. 26
      c. Tropical Cyclone Movement ...................................................................................... 27
      d. Environmental factors ............................................................................................... 28
   3.2 ENSO-Tropical Cyclone Relationship .......................................................................... 29
      a. SST ................................................................................................................................. 30
      i. Observations .................................................................................................................. 30
      b. Tropical Cyclones ....................................................................................................... 31
      i. Observations .................................................................................................................. 31
   3.3 Environmental factors important for ENSO-TC relationship ....................................... 34
      a. Vertical wind shear ........................................................................................................ 34
b. Relative Humidity .................................................................37

c. Precipitation.................................................................39

4. Conclusion ........................................................................63

Appendix...............................................................................67

A.1 Glossary........................................................................67

A.2 Tables ............................................................................69

A.3 Figures............................................................................73

References............................................................................77
List of Tables & Figures

Tables

Table 1.1 – ENSO influence on TC development 13
Table 2.1 – Observational ENSO years 20
Table 2.2 – Model ENSO years 21
Table 3.1 - General TC movement in sub-basins 41
Table 3.2 – El Niño influence on TC development in sub-basins 42
Table 3.3 - La Niña influence on TC development in sub-basins 43
Table A.1 - Stages of tropical cyclone development by speed 71
Table A.2 - Environment modes 72
Table A.3 – Observational datasets 73
Table A.4 – List of GFDL climate coupled models 74

Figures

Figure 1.1 – Tropical Cyclone Development 14
Figure 1.2 – Tropical Cyclone Development Model 15
Figure 2.1 – North Atlantic Sub-basins 22
Figure 2.2 – Standardized Niño3.4 Index (Observations) 23
Figure 2.3 – Standardized Niño3.4 Index (Model) 24
Figure 3.1 - Monthly climatology of tropical cyclone activity 44
Figure 3.2 - Climatology of SST 45
Figure 3.3 – Standard Deviation of SST 46
Figure 3.4 – Climatology of Tropical Cyclones 47
Figure 3.5 – Standard Deviation of Tropical Cyclones 48
Figure 3.6 – Tropical Cyclone Movement 49
Figure 3.7 – Climatology of Vertical Wind Shear
Figure 3.8 – Standard Deviation of Vertical Wind Shear
Figure 3.9 – Climatology of Relative Humidity
Figure 3.10 – Standard Deviation of Relative Humidity
Figure 3.11 – Climatology of Precipitation
Figure 3.12 – Standard Deviation of Precipitation
Figure 3.13 - Percentage of tropical cyclones for track types
Figure 3.14 – ENSO composites of SST
Figure 3.15 – ENSO composites of tropical cyclones
Figure 3.16 – ENSO composites of vertical wind shear
Figure 3.17 – ENSO composites of relative humidity
Figure 3.18 – ENSO composites of precipitation
Figure A.1 – Gradient Wind Shear Balance
Figure A.2 – Atlantic Meridional Mode
Figure A.3 – Madden Julian Oscillation
Figure A.4 – North Atlantic Oscillation
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Abstract

The tropical cyclones in the North Atlantic are known to cause intense damage and loss of property over United States. Thus, it is important for coupled climate models to simulate and predict the tropical cyclones. It is widely known that the El Niño-Southern Oscillation (ENSO) affects the tropical cyclone activity in the North Atlantic. In this study, the ability of the coupled climate model, the flux-adjusted version of Geophysical Fluid Dynamics Laboratory’s Forecast Oriented Low Ocean Resolution model, FLOR-FA, to simulate the relationship between ENSO and tropical cyclone activity in the North Atlantic in general and in the sub-basins is explored. FLOR-FA model successfully simulates the observed teleconnection between ENSO and tropical cyclones with reduced activity during El Niño and enhanced activity during La Niña in the North Atlantic. The model also captures the effect of ENSO on the environmental factors important for ENSO and the tropical cyclone relationship such as sea surface temperature, vertical wind shear, relative humidity and rainfall consistent with observations. During El Niño, the model simulates strong vertical wind shear, low relative humidity and reduced intensity of rainfall that creates unfavorable conditions for tropical cyclone activity. Further, weak vertical wind shear, high relative humidity and increased intensity of rainfall is simulated during La Niña leading to favorable conditions for the tropical cyclone activity. Despite some of the model’s inconsistencies compared to observations, the FLOR-FA model has better simulation of tropical cyclones and factors that affect tropical cyclone development, and therefore will aid in better prediction of the tropical cyclone occurrences in the North Atlantic.
1. Introduction

The impact of tropical cyclones on land has been historically monitored to provide early warnings to the general public to prepare for possible disasters caused by these tropical cyclones. Recent hurricanes, such as Hurricane Katrina (2005) and Hurricane Sandy (2012) have left people in the state of homelessness, debt and loss. Epidemiological studies have shown that the tropical cyclones lead to spread of infectious diseases, food shortages, fatality and injury in inflicted communities (Shultz et al., 2005). The likelihood of global tropical cyclone activity and intensity is also projected to increase in the future (Delworth et al., 2012; Hill and Lackmann, 2011; Knutson et al., 2010; Mann and Emanuel, 2006) increasing the possibility that communities in the path of tropical cyclones will be more vulnerable to these disasters. For these reasons, it is important to have a better understanding of the factors that affect tropical cyclones, in order to improve our ability to predict their occurrence and trajectory, and provide early warnings to the public.

A tropical cyclone is a low-pressure system that has a structure of spiraling bands and a maximum wind speed of 23 miles per hour or greater. They develop between the Tropic of Cancer (23°N) and Tropic of Capricorn (23°S) excluding the equatorial regions (Ashmore, 2008). For a tropical storm to develop, sea surface temperature must be at least 26°C for a depth of at least 50 meters. In addition, low vertical wind shear (less than 10 m/s) between the sea surface and the upper troposphere is required for the development of the tropical cyclone to develop.

Tropical cyclones form at a distance of at least 500 kilometers from the equator so that there is a significant amount of Coriolis effect present to favor a
near gradient wind balance to occur\(^1\). In the absence of the Coriolis force, the low pressure of the cyclonic disturbance cannot be sustained. The formation of a tropical cyclone usually occurs in a quick-cooling atmosphere with a height that is nearly unstable to moist convection (Fig. 1.1). Thunderstorm activity in this region allows for the heat from the sea surface to rise. This results in a rise in humidity near the mid-troposphere (5 km), which then warms the air. The condensation of water vapor, due to the increase of the sea surface, then promotes thunderstorm activity (Gray, 1968; Gray, 1979).

Tropical cyclone develops from weak near-surface tropical disturbances with relatively slow translational speeds\(^2\) (Peng et al., 2012). These disturbances may form from traces of fronts or mesoscale convective complexes\(^3\) that drift into the tropical regions (Ashmore, 2008; Gray, 1968; Gray, 1998) and should be associated with low-level convergence (with increasing surface pressure) and upper-level divergence (with decreasing surface pressure), in addition to whirlwind rotation or wind shear (Ashmore, 2008; Gray, 1968) (Fig. 1.2). These developing disturbances which turn into tropical cyclones have higher relative humidity at 500-hPa (~5,500 meters above sea-level) than those that do not develop into tropical cyclones (Peng et al., 2012).

In this study, the variability of tropical cyclones in the North Atlantic basin is investigated due to its important implications for United States. Several climate modes of variability are known to affect the North Atlantic tropical cyclone activity by altering basin-wide circulation patterns, thereby changing atmospheric steering currents and vertical wind shear for tropical cyclones (Colbert and Soden, \(^1\) Gradient Wind Balance - see Appendix for definition

\(^2\) See Table A.1 for translational speeds that relate to stages of TC development

\(^3\) Mesoscale Convective Complexes - see Appendix for definition
The climate modes of variability are the Atlantic Meridional Mode (AMM), Madden-Julian Oscillation (MJO), North Atlantic Oscillation (NAO)\(^4\) and the El Niño-Southern Oscillation (ENSO) (Colbert and Soden, 2012; Knutson et al., 2010; Kossin et al., 2010).

The AMM exhibits strong variability on interannual to decadal timescales. It affects sea surface temperature, vertical wind shear and surface air pressure in the North Atlantic, which in turn affects the tropical cyclones in the North Atlantic. AMM is also shown to affect the North Atlantic tropical cyclone development by shifting the location of the Intertropical Convergence Zone (ITCZ) (Foltz et al., 2011).

The MJO is a tropical disturbance that spreads eastward around the global tropics with a cycle on the order of 30-60 days. It causes patterns of tropical and extra-tropical precipitation, atmospheric circulation (e.g. Walker circulation\(^5\) patterns) and surface temperature, which further affect the tropical cyclone development in the North Atlantic (Gottschalck et al., 2005).

The NAO is an atmospheric teleconnection\(^6\) pattern in the North Atlantic that is measured by the surface sea-level pressure (SLP) between the Subtropical High\(^7\) and Sub-Polar Low\(^8\). Phases of NAO are associated with basin-wide

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\(^4\) Figs A.2, A.3 and A.4 show illustrations of first three climate modes.

\(^5\) Walker Circulation - see Appendix for definition

\(^6\) Teleconnection - see Appendix for definition of

\(^7\) The Subtropical High is one of several regions of semi-permanent high atmospheric pressure located over the oceans between 20° and 40° of latitude in both the Northern and Southern hemispheres of the Earth.

changes in the intensity and location of the North Atlantic jet stream and tropical cyclone tracks (NOAA, 2015). It is also related to large-scale modulations of zonal and meridional heat and moisture transport, temperature and precipitation patterns over the eastern North Atlantic to the western and central Europe (NOAA, 2015).

The El Niño-Southern Oscillation is associated with changes in the variability of the sea surface temperature (SST) and sea level pressure (SLP) over the eastern, western and central tropical Pacific. The warm phase of ENSO is called El Niño and it is characterized by anomalously high sea surface temperature and low sea level pressure in the eastern Pacific. The cold phase of ENSO is referred to as La Niña and is associated with anomalously low sea surface temperature and high sea level pressure in the eastern Pacific (Gray, 1984; Larkin and Harrison, 2001). ENSO is known to influence the atmospheric circulation and weather patterns on interannual to decadal timescales in turn affecting the variability of the tropical environmental systems around the world. (Colbert and Soden, 2012; Larkin and Harrison, 2001; Sasaki et al., 2014; Wang and Chan, 2002; Wang and Fiedler, 2006; Wang et al., 2014). ENSO is also shown to modulate the tropical cyclone activity over the Indian, Pacific and Atlantic Oceans (Bell et al., 2014; Camargo et al., 2007).

In this study, the focus is on the effect of ENSO on the tropical cyclone activity in the North Atlantic basin. During the warm phase of ENSO, tropical cyclone activity over the North Atlantic is reduced and it is increased during the cold phase of ENSO (Bell et al., 2014; Colbert and Soden, 2012; Kim et al.,

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8 The Subpolar Low is an area of semi-permanent low atmospheric pressure located at 60ºN and 60ºS latitude that maintains cool, wet weather. It is formed from the collision of cold air masses from higher latitudes and warmer air masses from lower latitudes. Ibid.
ENSO is known to affect the tropical cyclone activity over the North Atlantic via changes in vertical wind shear, relative humidity and precipitation (Bell et al., 2014; Sasaki et al., 2014; Wang et al., 2014).

Vertical wind shear has been identified as one of the main environmental factors that affects the tropical cyclones over the North Atlantic (Goldenberg et al., 2001; Gray, 1968). The absence of strong vertical wind shear increases the likelihood of tropical cyclone genesis. Strong wind shear can inhibit the initial development of tropical cyclones and continue to suppress the cyclone formation (Goldenberg et al., 2001; Gray, 1968; Gray, 1998; Wang et al., 2014). Strong vertical wind shear can also weaken or diminish a developed tropical cyclone by separating the upper and lower regions of a convective cell, further leading to the replacement of air currents within the convective cell (Ashmore, 2008; Gray, 1968). During El Niño events, vertical wind shear is enhanced in the North Atlantic suppressing the tropical cyclone development, whereas vertical wind shear is reduced in La Niña years favoring tropical cyclone activity (Goldenberg et al., 2001; Goldenberg and Shapiro, 1996).

Relative humidity is also shown to affect tropical cyclone activity within the convective cell (Bell et al., 2014). When relative humidity increases, tropical cyclone genesis enhances via deep convection (Bell et al., 2014; Peng et al., 2012). It also contributes to fluctuations in the tropical cyclone activity during the two ENSO phases (Camargo et al., 2007; Wang et al., 2014). High relative humidity in the North Atlantic enhance the potential for tropical cyclone genesis during La Niña (Camargo et al., 2007; Peng et al., 2012).

Convective cell - see Appendix for definition.
Intense rainfall is necessary for tropical cyclone development (Peng et al., 2012). ENSO affects rainfall intensity over the North Atlantic by changing the intensity of rainfall over the Atlantic through the Walker circulation (Sasaki et al., 2014). During El Niño, the Atlantic branch of Walker circulation is enhanced with reduced precipitation in the equatorial Atlantic creating unfavorable conditions for tropical cyclones. During La Niña, the Atlantic branch of Walker circulation is weakened, resulting in increased precipitation in the equatorial Atlantic (Sasaki et al., 2014) and thus favoring tropical cyclones.

The aforementioned studies document the observed North Atlantic tropical cyclone activity and its relation to ENSO (Table 1.1). Since climate models are used in the prediction of tropical cyclones, it is important to investigate the ability of models to capture the observed tropical cyclone activity and its teleconnections. Since ENSO is the most predictable climate signal, the ability of GFDL coupled climate model to simulate the ENSO-tropical cyclone relationship is assessed. Further, the observed mechanism through which ENSO affects the North Atlantic tropical cyclone activity is also explored in the model. Thus, the main objectives of this thesis are,

1. The simulation of the North Atlantic tropical cyclones in the coupled climate model is explored.
2. The ability of the model to capture the observed relationship between the ENSO and tropical cyclone activity in the North Atlantic is analyzed.
3. The environmental factors in the North Atlantic (such as vertical wind shear, relative humidity and precipitation) through which ENSO might affect the regional tropical cyclone activity are investigated in the model.
Table 1.1 shows ENSO affects on TC activity and environmental factors in the North Atlantic Basin.

<table>
<thead>
<tr>
<th>ENSO Phase</th>
<th>North Tropical cyclone activity</th>
<th>SST</th>
<th>Vertical Wind Shear</th>
<th>Moisture Content</th>
<th>Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Niño</td>
<td>Reduced</td>
<td>Warm in the eastern Pacific and cold in the North Atlantic</td>
<td>Strong</td>
<td>Low</td>
<td>Reduced</td>
</tr>
<tr>
<td>La Niña</td>
<td>Enhanced</td>
<td>Cold in the eastern Pacific and warm in the North Atlantic</td>
<td>Weak</td>
<td>High</td>
<td>Enhanced</td>
</tr>
</tbody>
</table>
Figure 1.1 shows the development of tropical cyclone above the (1) warm sea surface in (2) a moist atmosphere with (3) low vertical wind shear. (AOML, 2014)
Figure 1.2 shows graphical model of a vertical cross-section of the air circulation, clouds, and precipitation associated with a hurricane. Red arrows show movement from low pressure and blue arrows show movement from high pressure. (Image Copyright: Michael Pidwirny).
2. Data, method of analysis and model

2.1 Observational Data

SST data is derived from the United Kingdom Met Office Hadley Center’s HadISST version 1.1 (Rayner and Coauthors, 2003). SST data spans from 1870-2013 and is available at spatial resolution of $1^\circ \times 1^\circ$. Observed tropical cyclone densities are obtained from best track datasets from the U.S. National Hurricane Center (HURDAT2) & Joint Typhoon Warning Center (JTWC Best Track Data) (Knapp et al., 2010).

Precipitation data from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Lab’s Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997). CMAP data spans from 1979 - present day, and is available at a spatial resolution of a $2.5^\circ$ latitude $\times$ $2.5^\circ$ longitude global grid. NASA’s Modern-era Retrospective Analysis for Research and Applications (MERRA) is used for zonal and meridional winds and relative humidity (Rienecker and Coauthors, 2011). MERRA data spans from 1979 - present day. It is available at a spatial resolution of $0.5^\circ$ latitude $\times$ $0.5^\circ$ longitude. The observational analysis in this study is performed over the period of 1979-2013$^{10}$.

2.2 Method of analysis

The regional characteristics of tropical cyclone activity are best understood by separating the North Atlantic basin into six sub-basins. The sub-basins (Fig. 2.1) are defined as follows:

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$^{10}$ See table A.3 for observation dataset information
1) The Caribbean & Central America include the region, 85°W-50°W and 10°N-20°N. We have named this sub-basin Caribbean.

2) The Gulf of Mexico, The Bahamas, Florida, Cuba and the Turks & Caicos are established from 100°W-50°W and 20°N-30°N. This region is known as Trops.

3) The Southern US Coast, Georgia to Delaware covers 85°W-50°W and 30°N-40°N. This sub-basin has been named US South.

4) The Northeastern US and Canadian coast represents 70°W-50°W and 40°N-60°N. We call this sub-basin US NE.

5) The eastern part of the Atlantic main development region represents 50°W-0°W and 10°N-25°N. This sub-basin is known as E.MDR.

6) The rest of the North Atlantic Basin is mostly ocean and ranges from 50°W-0°W and 25°N-60°N. We have named this sub-basin Open Ocean.

To understand the effect of ENSO on the tropical cyclones and the associated environmental factors, composites of tropical cyclone density, sea surface temperature (SST), relative humidity, precipitation and vertical wind shear are constructed for different phases of ENSO. The composites are constructed for warm and cold phases of ENSO based on the standardized Niño3.4 index (Fig. 2.2).

The Niño3.4 index is the well-known measure of the state of ENSO. The Niño3.4 index is defined as the area-averaged SST anomalies over the domain 5°N - 5°S and 170°W-120°W. The standardized Niño3.4 index is constructed by dividing the Niño3.4 index time series by its standard deviation (SD) and is shown in Fig. 2.2. The El Niño years are chosen as the years with the standardized
Niño3.4 greater than +1.0 SD. La Nina years are those with the standardized Niño3.4 less than -1.0 SD (Table 2.1).

Tropical cyclone density was calculated based on the algorithm in Zhao et al., 2009. Data is measured in six-hour increments. The following conditions must be fulfilled for potential cyclones to be identified. The relative vorticity\(^\text{11}\) at 850-hPa (1,457 meters above sea level) must have a maximum that exceeds \(3.5 \times 10^{-5}\) s\(^{-1}\) are in regions of 6º x 6º latitude and longitude. Sea level pressure must have a local minimum within a span of 2º latitude and longitude from the vorticity maximum. This is established as the center of the storm. The local maximum surface wind speed is then recorded at the lowest model level. The local maximum mean temperature between 300hPa and 500 hPa (9,164m and 5,574m) defines the warm core. Its distance from the storm center must not surpass 2º, and its temperature must be at least 1°C warmer than the local average.

After creating a database of potential storm images through the identification process, a tropical cyclone track analysis is performed to connect these images. For analysis, tropical cyclones in each image must be within a distance of 400 km. If there are no tropical cyclones, the trajectory is considered to have stopped. If there are a few present, the closest storm is selected and associated with the initial storm trajectory. If there are many possibilities, tropical cyclones located to the west and pole-ward of the current location is selected. It is required that the tropical cyclone track must sustain itself and have a maximum surface wind speed greater than 15.3 m/s for at least three days.

\(^{11}\) See Appendix
2.3 Model

In order to capture tropical cyclones on regional scales, a model with high resolution in atmosphere and land is imperative. The NOAA Geophysical Fluid Dynamic Laboratory (GFDL) developed the model used in this study. It is a flux-adjusted version of Forecast-oriented Low Ocean Resolution (FLOR) version of GFDL’s Coupled Model version 2.5 (Vecchi et al., 2014). The high-resolution coupled climate model, FLOR, was built (with the intention to create a seasonal-to-decadal forecast system for regional climate impacts) with high resolution in land and atmosphere components of the coupled model. FLOR-FA is the flux-adjusted version of FLOR. In FLOR-FA, climatological adjustments were applied to the FLOR model’s fluxes (momentum, enthalpy and freshwater) that are passed from atmospheric model to ocean model. This was performed to reduce the biases in the model by ensuring that the model’s long-term climatology\textsuperscript{12} of SST and surface wind stress are closer to the observational estimates over 1979-2012. Flux adjustment was performed to explore the hypothesis that the improvements to the mean climate simulation would lead to improvement in tropical cyclone simulations and thus lead to improved forecasts of basin-wide and regional tropical cyclone activity\textsuperscript{13}.

The data spanning for 100 years from the simulation of FLOR-FA is used in this study to understand the teleconnection between the tropical cyclones in the North Atlantic and ENSO. El Niño and La Niña years in the model are determined in the same way as in observations. The Niño3.4 index from the model is shown in Fig. 2.3. There are 14 El Niño years and 16 La Niña years as listed in Table 2.2.

\textsuperscript{12} Climatology- see Appendix for definition
\textsuperscript{13} See Ensemble Forecasting in Appendix
Table 2.1 shows the El Niño years and La Niña years used in observational study.

<table>
<thead>
<tr>
<th>El Niño Years</th>
<th>La Niña Years</th>
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<td>1982</td>
<td>1988</td>
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<td>2010</td>
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<td>2009</td>
<td>2011</td>
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Table 2.2 shows the El Niño years and La Niña years from FLOR-FA coupled model.

<table>
<thead>
<tr>
<th>El Niño Years</th>
<th>La Niña Years</th>
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<td>7</td>
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</table>
Figure 2.1 – Division of North Atlantic Basin by sub-basins: (1) The Caribbean, (2) Trops, (3) US South, (4) US NE, (5) E.MDR, and (6) Open Ocean. The dashed box represented the main development region (20°W-80°W; 10°N-20°N). (Source: NOAA National Hurricane Center, Miami, Florida)
Figure 2.2: August-September-October (ASO) seasonal anomaly of standardized Niño3.4 time series (see text for definition of Niño3.4 index).
Figure 2.3 – ASO seasonal anomaly of standardized Niño3.4 based on 100-year simulation of FLOR-FA.
3. Results

3.1 Mean state and variability

We first explore the ability of the model to simulate the mean state and variability of SST, tropical cyclone density and the environmental factors important for ENSO-tropical cyclone relationship. The peak months for tropical cyclone development in the North Atlantic are August, September and October (ASO), as seen in Fig. 3.1 and thus all the analysis in this work is based on this period.

a. SST

The FLOR-FA model successfully simulates the mean state of SST in the Pacific and Atlantic Oceans compared to observations (Fig. 3.2). The model shows warm SSTs in the western Pacific and the equatorial, as seen in observations. However, the model SST is slightly warmer than observations in the West and East Pacific and the tropical Atlantic. We then investigate the standard deviation of SST to evaluate the ability of the model to simulate the variability in SST (Fig. 3.3). Observations suggest enhanced variability in the tropical Pacific Ocean. The model effectively simulates SST variability, but it shows slightly enhanced variability in the central Pacific compared to observations. In addition, the model also shows less variability in the tropical Atlantic compared to observations.

b. Tropical cyclone density

Observed climatology of tropical cyclone density suggests high tropical cyclone activity in the North Atlantic over the main development region, Caribbean, Gulf of Mexico and southern coast of US. The increase of tropical
cyclones in the main development is also seen in Fig. 3.1. The model simulates observed climatology of tropical cyclone activity well, however, tropical cyclone activity is not as pronounced as in observations in some regions, such as Gulf of Mexico and the main development region. The model also shows greater tropical cyclone activity near the Lesser Antilles than in observations.

The ratio of tropical cyclone densities in the North Atlantic sub-basin (Table 3.1) is used to understand the climatological distribution of tropical cyclone densities in the North Atlantic Basin. This table is calculated based on climatology of tropical cyclone density (Fig. 3.4). Most tropical cyclones are concentrated in the Open Ocean and the fewest tropical cyclones pass through the US South and Caribbean. The model shows similar results as observations, suggesting that the model effectively simulates tropical cyclone movement as seen in observations.

The standard deviation of tropical cyclone density in the observations and model is investigated (Fig. 3.5). The observations suggest increased variability in the tropical cyclone activity over the Caribbean, Gulf of Mexico, E.MDR and the Open Ocean. The model simulates the overall pattern of variability well except that it shows less activity over these regions compared to observations.

c. Tropical Cyclone Movement

In the North Atlantic basin, tropical cyclone genesis typically occurs in the MDR and tropical cyclones tend to have different track patterns. Based on Colbert & Soden’s description of track movements (Colbert and Soden, 2012), the tropical cyclone tracks are classified into one of the three categories (Fig. 3.6):

1. Straight-moving (SM) tropical cyclones stay below 25ºN until they cross 80ºW and threaten the U.S. Gulf Coast and the western Caribbean Sea.
2. Re-curving landfall (RCL) tropical cyclones cross 70ºW north of 25ºN or cross 65ºW north of 40ºN and threaten the U.S. East Coast.

3. Re-curving ocean (RCO) tropical cyclones do not cross either coastal boundary but go north of 25ºN and re-curve into the open ocean.

Table 3.1 shows the general pattern of tropical cyclone movement. Most tropical cyclones form and travel through the E.MDR and Open Ocean, showing that the majority of tropical cyclones are RCO tropical cyclones. There are fewer RCL tropical cyclones, which originate in the E.MDR and travel toward Trops, NE US, and US South. The least amount of tropical cyclones are SM tropical cyclones that form in the E.MDR and travel through the Caribbean.

d. Environmental factors

We examine the ability of the model to simulate the mean state of vertical wind shear, relative humidity and precipitation during the ASO period. Observed climatology shows enhanced vertical wind shear in the northwest of the North Atlantic basin (over the northern United States) in the main development region (Fig. 3.7(a)). In the main development region, vertical wind shear in the model is slightly weaker than in observations (Fig. 3.7(b)). The model also simulates the high variability for vertical wind shear in the lower latitudes of the basin (Fig. 3.8 (b)), but the enhanced variability shifts over Central America and away from the main development compared to observations (Fig. 3.8(a)).

We then investigate the mean state of relative humidity in the North Atlantic during ASO in observations and the model (Fig. 3.9). Observations suggest high relative humidity values in the main development region. The model has realistic
simulation of relative humidity except that the values are slightly higher. We further analyze the variability of relative humidity. In observations, relative humidity deviates most in the Caribbean and near the equator (Fig. 3.10(a)), which is not reflected in the model (Fig. 3.10(b)). In the model, relative humidity varies less compared to observations.

Finally, we analyze the mean state of precipitation in the Pacific and Atlantic Oceans in observations and the model (Fig 3.11). Observed climatology shows enhanced precipitation in the equatorial Pacific and the equatorial Atlantic. Although the model has realistic simulation of observed mean precipitation, it simulates weaker rainfall in the convective zones over the equatorial oceans compared to observations.

We then investigate the variability of precipitation in the North Atlantic as seen in observations (Fig. 3.12(a)) and in the model (Fig. 3.12(b)). In both model and observations, enhanced variability is seen in the equatorial Pacific, Caribbean, and North Atlantic main development region.

### 3.2. ENSO-Tropical Cyclone Relationship

Tropical cyclones respond to different phases of ENSO in the North Atlantic, Pacific and Indian Oceans. In the North Atlantic, the effects of ENSO on the tropical cyclones are through the changes in SST, vertical wind shear, relative humidity and precipitation (Bell et al. 2014, Kossin et al. 2010, Wang et al. 2014). In the North Atlantic, tropical cyclone development is reduced during El Niño events. During La Niña events, tropical cyclone genesis is enhanced (Bell et al. 2014). In addition to genesis, ENSO also affects the movement of the tropical cyclone tracks by changing deep-steering flow of wind, as reflected in Fig. 3.13 (Colbert and Soden, 2012). The occurrence of straight-moving tropical cyclones is enhanced during La Niña. During El Niño, most tropical cyclones re-curve into
the ocean, and most tropical cyclones re-curve onto land during La Niña. In this study, the sensitivity of tropical cyclones to the different phases of ENSO is explored in observations. Further, the ability of coupled model (FLOR-FA) to capture the observed ENSO-TC relationship in the North Atlantic will be examined using the data from model simulation.

a. SST

i. Observations

In observations, we explore the relation between ENSO and the North Atlantic tropical cyclone activity by analyzing the observed SST and tropical cyclone densities during El Niño and La Niña phases. The number of years included in each of these composites is shown in Table 2.1.

The SST composite (Fig. 3.14(a)) depicts the state of the tropical Pacific associated with El Niño with positive SST anomalies in the eastern to central Pacific and negative SST anomalies in the western Pacific Ocean. The SST composite for La Niña (Fig. 3.14(b)) displays negative SST anomalies in the central to eastern Pacific and positive SST anomalies over the west Pacific.

ii. Model

In order to explore the ability of the current coupled models to simulate the observed ENSO-tropical cyclone relationship in the North Atlantic basin, a 100-year long simulation of the FLOR-FA coupled climate model with high-resolution atmosphere and land components is examined. Composites of SST and tropical cyclone density from the model simulation are constructed in the same way as in observations. The number of model years used for each composite is given in Table 2.2.
The composites of SST for El Niño and La Niña suggest that the model is successful in simulation of SSTs associated with ENSO events compared to observations. During El Niño events, the SST of the equatorial Pacific is anomalously warm (Fig. 3.14(c)) while during La Niña events, the SST in the equatorial Pacific is cold (Fig. 3.14(d)). However, there are minor inconsistencies in the simulation of ENSO-related SSTs between the model and the observations. For El Niño, the model (Fig. 3.14(c)) captures slightly higher anomaly in the equatorial Pacific compared to observations (Fig. 3.14(a)). The enhanced SST anomaly in Niño3.4 region is stronger in the model than in observations. The model also does not capture the enhanced anomalies in the Atlantic Ocean. For La Niña, the reduced SST anomaly in the Niño3.4 region is stronger in the model (Fig. 3.14(d)) than in observations (Fig. 3.14(b)).

b. Tropical Cyclones

i. Observations

To understand the ENSO-TC teleconnection in the North Atlantic basin, composites of tropical cyclone density associated with the two phases of ENSO are examined. During El Niño events, tropical cyclone density is reduced (Fig. 3.15(a)), suggesting that fewer tropical cyclones are formed during El Niño. However, during La Niña, tropical cyclone density over the North Atlantic is enhanced (Fig. 3.15(b)). This suggests that tropical cyclones are more likely to occur in the North Atlantic Basin during a La Niña event than in an El Niño event.

We further examine the effect of ENSO on the tropical cyclone densities over sub-basins (refer to Section 2 on details of sub-basins). During El Niño, a large number of tropical cyclones occur in the E.MDR and Open Ocean sub-basins (Table 3.2). Table 3.2 suggests that fewer tropical cyclones are
concentrated in the NE US, Trops, Caribbean and US south during El Niño consistent with the reduced anomalies in Fig. 3.15(a). During La Niña, all sub-basins show relatively increased concentration of tropical cyclones. The tropical cyclone densities in the Caribbean, Trops and E.MDR sub-basins show dramatic increase from El Niño to La Niña (Table 3.2). This is also seen in Fig. 3.15(b) where there are enhanced tropical cyclone density anomalies over these regions. There are fewer tropical cyclones in the US South, NE US and Open Ocean (Table 3.2).

From Table 3.2, it is also possible to infer the tropical cyclone track movement in the North Atlantic Basin for each ENSO phase. During El Niño, most tropical cyclones form in the Main Development Region, followed by the Atlantic Open (Open Ocean). This indicates that more tropical cyclones re-curve into the ocean (RCO) during an El Niño event and, fewer tropical cyclones re-curve onto land (RCL) and reach the Northeastern US (NE US). Fewest tropical cyclones are straight-moving (SM) tropical cyclones. They pass through the Trops, the Caribbean and the US South sub-basins.

Tropical cyclones travel on different tracks during La Niña than El Niño. A majority of tropical cyclones are SM tropical cyclones. They travel through the E.MDR and passing through the Caribbean and the Trops. Fewer tropical cyclones re-curve into the ocean (RCO), after forming in the E.MDR and traveling through the Open Ocean and NE US. The least amount of tropical cyclones re-curves onto the land (RCL), passing over the US South (Table 3.2).

**ii. Model**

The model simulated tropical cyclone density associated with El Niño and La Niña are also shown in Fig. 3.15. Similar to observations, the model simulates
reduced tropical cyclone density in the North Atlantic basin during El Niño. Tropical cyclone density anomalies are reduced in the main development region and extends into the Caribbean basin and the US coast (Fig. 3.15(c)). During La Niña, enhanced tropical cyclone density anomalies are present in the Caribbean and western part of the main development region (Fig. 3.15(d)). Above-normal tropical cyclone density anomalies are also found in the Gulf of Mexico, along the US Coast and in the Mid-Atlantic Ocean but are relatively weaker compared those in Caribbean basin.

Although, model successfully simulates the ENSO-related tropical cyclone density, there are inconsistencies between the model and the observations. For El Niño, reduced anomalies are stronger in the model (Fig. 3.15(c)) than the observations (Fig 3.15(a)). In the observations, the most reduced anomaly is in the Mid-Atlantic and near the Lesser Antilles. However in the model, the most reduced anomaly extends over the main development region to the Caribbean and over the southern US coast. This shows that inhibition of tropical cyclones is enhanced in the model than in observations during El Niño. For La Niña, the signal for enhanced anomalies is also stronger in the model (Fig 3.15(d)) than in the observations (Fig 3.15(b)). The enhanced anomaly in the main development region in the observations is slightly shifted westward in the model. Enhanced anomalies are also seen over the midlatitudes of the Atlantic, which are absent in observations.

The relation of tropical cyclones in the sub-basin for different phases of ENSO is also explored. During El Niño, the model simulates a reduced number of tropical cyclones in all the North Atlantic sub-basins. During La Niña, the model results suggest that most tropical cyclones form in the Caribbean and Trops.
Fewer tropical cyclones travel through the US South, the Open Ocean and NE US. The model fails to simulate the enhanced tropical cyclone density in the E.MDR compared observations during La Niña.

Table 3.3 is also used here to examine the movement of tropical cyclone tracks in each sub-basin for ENSO phases. During El Niño events, tropical cyclones in the model are more likely to re-curve into the Atlantic Ocean (RCO). Most of the tropical cyclones travel through the Northeastern US (NE US) and the mid-Atlantic Ocean (Open Ocean). Fewer tropical cyclones are likely to make landfall (RCL) and travel through the southern US and southern Caribbean (US South and Caribbean). The least amount of tropical cyclones travel through Trops, and thus fewer of these tropical cyclones are straight-moving (SM).

### 3.3 Environmental factors important for ENSO-TC relationship

ENSO modulates the environmental factors that affect the development of tropical cyclones in the North Atlantic Basin. Some of these factors are vertical wind shear, relative humidity and precipitation. In this section, we explore the ability of coupled model to simulate the effect of ENSO on these three environmental factors, which are important for the ENSO-TC relationship in the North Atlantic. For each environmental variable, we show observational results to compare with the model simulation.

a. *Vertical wind shear*

   i. *Observations*

   Vertical wind shear has been identified as one of the main factors that affect the tropical cyclone development in the North Atlantic basin (AOML, 2014;
Ashmore, 2008; Bell et al., 2014; Camargo et al., 2007; Hill and Lackmann, 2011). Tropical cyclones develop in atmospheres where vertical wind shear is low. Strong vertical wind shear not only inhibits the development of incipient tropical cyclones, but also weakens developed tropical cyclones (Camargo et al., 2007).

Composites of vertical wind shear are shown for El Niño and La Niña to understand the effect of ENSO on vertical wind shear (Fig. 3.16). During an El Niño, there are high values of vertical wind shear in the North Atlantic in the main development region and thus suppression of formation of tropical cyclones during El Niño (Fig. 3.15(a)). For La Niña, the composite of vertical wind shear is almost the opposite of El Niño. There are low values of vertical wind shear below 20ºN and thus favoring tropical cyclones development in the main development region (Fig. 3.15(b)).

We also explore the effect of ENSO on vertical wind shear in the North Atlantic sub-basins by analyzing the data shown in Fig. 3.16. During El Niño, there are enhanced anomalies in the Caribbean, E.MDR, NE US, US South and northern Open Ocean sub-basin (Fig 3.16(a)). According to Fig. 3.15(a) and Table 3.2, reduced number of tropical cyclones are concentrated in the Caribbean, NE US, Trops, and US south during El Niño consistent with the enhanced anomalies of vertical wind shear in these sub-basins.

During La Niña, there are reduced vertical wind shear anomalies in the Caribbean, E.MDR and NE US sub-basins (Fig. 3.16(b)), reflecting favorable conditions for tropical cyclone development in these sub-basins. This is consistent with enhanced tropical cyclone density anomalies in these regions in La Niña years relative to El Niño years (Table 3.2). Relatively enhanced anomalies of
vertical wind shear are found in the Open Ocean and Trops sub-basins (Fig. 3.16(b)), consistent with fewer tropical cyclones occurring in the US South, NE US and Open Ocean (Table 3.2).

**ii. Model**

We also investigate the model’s ability to simulate the observed effect of ENSO (as described in Section 3.3a) on these environmental factors that are relevant for ENSO-TC relationship. For vertical wind shear, model results are similar to observations for both ENSO phases with reduced wind shear during El Niño and enhanced wind shear during La Niña in the main development region. However, for El Niño, the strength of the anomalies in the model (Fig. 3.16(c)) is stronger than those in observations (Fig. 3.16(a)), especially in the main development region and in higher latitudes. Thus, the model creates less favorable conditions for the formation of tropical cyclones relative to observations.

The composite of vertical wind shear during La Niña in the model is also different compared to observations. In the model, the reduced vertical wind shear anomaly does not extend to the east of the main development region (Fig. 3.16(d)) as in observations. This may be the reason for the lack of model simulation of enhanced tropical cyclone density anomalies in the E.MDR sub-basin during La Niña (Fig. 3.15(d)). Although the weak vertical wind shear in the Caribbean is successfully simulated in the model, the reduction of vertical wind shear anomalies in the Southern US, Gulf of Mexico and main development region is not as pronounced as observations. This is also reflected in the simulation of weaker tropical cyclone density in these regions in the model (Fig. 3.15(d)) where most of the tropical cyclones occur.
b. Relative Humidity

i. Observations

ENSO influences tropical cyclone formation in the North Atlantic by changing relative humidity in the North Atlantic (Wang et al., 2014). Relative humidity is important for tropical cyclone development in the North Atlantic as it contributes to thunderstorm development in the tropical cyclone region (Camargo et al., 2007; Peng et al., 2012). High relative humidity reflects high moisture content in the atmosphere, which is shown to favor tropical cyclone activity in the North Atlantic (Bell et al., 2014).

We examine the composites of relative humidity in the North Atlantic basin during El Niño and La Niña to understand the effect of ENSO on relative humidity through which it modulates the tropical cyclone activity. During El Niño, there are anomalously low values of relative humidity around the Caribbean and main development region (Fig. 3.17(a)), where tropical cyclones are least likely to develop (Fig 3.15(a)). During La Niña, high values of relative humidity are present over the Caribbean and near Central America, contributing to the development of tropical cyclones. These enhanced anomalies weaken but extend through the Northern Caribbean and main development region (Fig. 3.17(b)). There are anomalously low values over the United States and at high latitudes of the North Atlantic Basin (Fig. 3.17(b)), where very few tropical cyclones are present (Fig. 3.15(b)).

We further explore relative humidity in the North Atlantic sub-basins during El Niño and La Niña years. In El Niño event, most of the Open Ocean and the NE US sub-basins have lower enhanced anomalies, consistent with reduced tropical cyclone densities (Table 3.2). The reduced relative humidity is seen in the
Caribbean, Trops, and E.MDR sub-basins consistent with the formation of fewer tropical cyclones in these regions (Table 3.2). During La Niña, there are enhanced relative humidity anomalies in the Caribbean and E.MDR sub-basins (Fig. 3.17(b)) favoring tropical cyclone activity (Fig. 3.15(b) and Table 3.2). Reduced anomalies are found in the US South and NE US basins, where the fewest tropical cyclones occur (Table 3.2).

**ii. Model**

We then explore the ability of the model to simulate relative humidity compared to observations. For El Niño, anomalously low values of relative humidity are present over the main development region, the Caribbean and the mid-Atlantic (Fig. 3.17(c)) consistent with observations creating less favorable conditions for tropical cyclone activity. For La Niña, anomalously high values are found in the main development region, in the lower Caribbean and Central America, similar to observations. The increased relative humidity conditions associated with La Niña favors tropical cyclone activity in these regions (Fig. 3.17d).

We then investigate relative humidity in the North Atlantic sub-basins to identify the differences between the model and observations. During El Niño, there are reduced anomalies of relative humidity anomalies over the Caribbean, E.MDR and parts of the Open Ocean (Fig. 3.17(c)). The reduced humidity conditions during El Niño suppress the formations of tropical cyclones especially in the E.MDR where they tend to occur more often. During La Niña, there are enhanced anomalies over the E.MDR, Caribbean, and a majority of Open Ocean sub-basins (Fig. 3.17(d)). The enhanced anomaly is higher in the Caribbean, where most tropical cyclones form (Table 3.3).
c. Precipitation

i. Observations

Intense rainfall is required for tropical cyclone development (Peng et al., 2012). ENSO affects precipitation intensity over the North Atlantic by modifying the intensity of the Walker circulation over the Atlantic (Sasaki et al., 2014). We investigate the effect of ENSO on rainfall in the North Atlantic through which it might modulate the tropical cyclone activity.

During El Niño events, there is an increase of precipitation in the equatorial Pacific Ocean (Fig. 3.18(a)). El Niño is associated with reduced rainfall anomalies in the North Atlantic, creating less favorable conditions for tropical cyclones. There are enhanced rainfall anomalies in most of the regions over the North Atlantic Ocean and over the continental United States, favoring tropical cyclone progression (Fig. 3.18(a)). The reduced rainfall anomalies in the Caribbean and Central America tend to suppress tropical cyclone development.

La Niña is associated with anomalous decrease of precipitation in the equatorial Pacific Ocean (Fig. 3.18(b)). In the North Atlantic, Fig. 3.18(b) shows enhanced rainfall anomalies over the main development region, the Caribbean and the Gulf of Mexico, where large number of tropical cyclones are concentrated (Fig. 3.15(b)). There are relatively low precipitation values over parts of the US and in the Atlantic Ocean, where less tropical cyclone activity is seen (Fig. 3.15(b)).

We then investigate the rainfall intensity in the North Atlantic sub-basins. During El Niño, there are reduced anomalies of precipitation in the Caribbean, the E.MDR and Trops sub-basins (Fig. 3.18(a)). The least amount of tropical cyclones
occurs in these sub-basins (Table 3.2). Enhanced precipitation anomalies are found in the Open Ocean and NE US sub-basins, creating a more favorable condition for tropical cyclone movement. Reduced tropical cyclone anomalies are found in these sub-basins, especially in the Open Ocean (Table 3.2).

During La Niña, there are enhanced precipitation anomalies in the Caribbean, E.MDR and Trops (Fig. 3.18(b)), favoring enhanced tropical cyclone densities in these sub-basins (Table 3.2). Precipitation anomalies are slightly reduced in the Open Ocean and NE US (Fig. 3.18(b)), where the least amount of tropical cyclones occurs (Table 3.2).

ii. Model

We then investigate the model’s ability to simulate the ENSO-related precipitation compared to observations. During El Niño events, there is an anomalous increase of precipitation in the equatorial Pacific Ocean in the model (Fig. 3.18(c)) similar to the observations (Fig. 3.18(a)). Increased rainfall values are present over the United States and favor the tropical cyclone activity (Fig. 3.15(c)) and low precipitation values are found in the Caribbean, which suppress tropical cyclone development in this region. However, these reduced rainfall anomalies in Caribbean are not as strong as in the observations (Fig 3.18(c)). During La Niña, there is an anomalous decrease of precipitation in the equatorial Pacific Ocean in the model (Fig. 3.18(d)) similar to the observations (Fig. 3.18(b)). In the North Atlantic, high precipitation values over the main development region, The Caribbean and the Gulf of Mexico, tend to favor tropical cyclone activity in these regions (Fig. 3.15(d)).

We further investigate precipitation in the North Atlantic sub-basins. During El Niño, there are reduced anomalies of precipitation in the Caribbean and
parts of the E.MDR (Fig. 3.18(c)). Few tropical cyclones occur in these sub-basins (Table 3.3). Enhanced precipitation anomalies are found in the US South, NE US, and Trops sub-basins. With the exception of the Trops sub-basin, most tropical cyclones are concentrated in the US South and NE US sub-basins (Table 3.3). During La Niña, there are enhanced precipitation anomalies in all of the sub-basins, especially in the Caribbean and Trops (Fig. 3.18(d)). Most of the tropical cyclones form in these sub-basins (Table 3.3). The model does not capture the reduced anomalies in the NE US and parts of the US South as in observations (Fig. 3.18(b)), creating more favorable conditions for tropical cyclone development in the model than in observations.
Table 3.1 - Concentration of tropical cyclone tracks in the six sub-basins relative to the entire basin for observations and model.

<table>
<thead>
<tr>
<th></th>
<th>Caribbean</th>
<th>Trops</th>
<th>US South</th>
<th>NE US</th>
<th>E.MDR</th>
<th>Open Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBS</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td>Model</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table 3.2 – Frequency of tropical cyclone densities during ENSO events from observational data. The sub-basin sum was divided by the North Atlantic basin sum for each basin: The first row shows El Niño frequencies and the second row La Niña frequencies. The last row shows concentration of tropical cyclone tracks in the sub-basin relative to the entire basin.

<table>
<thead>
<tr>
<th>OBS</th>
<th>Caribbean</th>
<th>Trops</th>
<th>US South</th>
<th>NE US</th>
<th>E.MDR</th>
<th>Open Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Niño</td>
<td>-0.15</td>
<td>-0.14</td>
<td>-0.19</td>
<td>-0.05</td>
<td>-0.005</td>
<td>-0.03</td>
</tr>
<tr>
<td>La Niña</td>
<td>0.41</td>
<td>0.18</td>
<td>-0.09</td>
<td>-0.02</td>
<td>0.15</td>
<td>-0.05</td>
</tr>
<tr>
<td>SB/NA Basin</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td>MODEL</td>
<td>Caribbean</td>
<td>Trops</td>
<td>US South</td>
<td>NE US</td>
<td>E.MDR</td>
<td>Open Ocean</td>
</tr>
<tr>
<td>-----------</td>
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<td>------------</td>
</tr>
<tr>
<td>El Niño</td>
<td>-0.2</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.05</td>
<td>-0.2</td>
<td>-0.03</td>
</tr>
<tr>
<td>La Niña</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.02</td>
<td>-0.003</td>
<td>0.03</td>
</tr>
<tr>
<td>SB/NA Basin</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 3.3 - Frequency of tropical cyclone densities during ENSO events using model data. The sub-basin sum was divided by the North Atlantic basin sum for each basin: The first row shows El Niño frequencies and the second row La Niña frequencies. The last row shows concentration of tropical cyclone tracks in the sub-basin relative to the entire basin.
Figure 3.1 – Monthly climatology of tropical cyclone activity area-averaged in the main development region. Tropical cyclone activity peaks during the ASO.
Figure 3.2 – ASO Climatology of SST (°C) for (a) observations and (b) FLOR-FA coupled model in the Pacific and Atlantic Oceans. The dashed line represents the main development region.
Figure 3.3 – ASO Standard deviations of SST (°C) for (a) observations and (b) FLOR-FA coupled model in the Pacific and Atlantic Oceans. The dashed line represents the main development region.
Figure 3.4 – ASO Climatology of tropical cyclone (TC) Density in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.5 – ASO Standard Deviation of Tropical Cyclone Density in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.6 – Tropical cyclones categorized by movement in North Atlantic Basin. The green track shows straight-moving (SM) tropical cyclones, which travel through sub-basins: E.MDR, Caribbean and Trops. The red track shows tropical cyclones that re-curve onto land (RCL), which travel through sub-basins: E.MDR, Trops, US South, and US NE. The blue track shows tropical cyclones that re-curve into the ocean (RCO), which travel through sub-basins: E.MDR and Open Ocean. Grey area represents the entire main development region. (Colbert and Soden, 2012)
Figure 3.7 – ASO Climatology of Vertical Wind Shear (m/s^{-1}) in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.8 – ASO Standard Deviation of Vertical Wind Shear (m/s$^{-1}$) in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.9 – ASO climatology of relative humidity values (%) in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.10 – ASO standard deviation of relative humidity values (%) in the North Atlantic Basin for (a) observations and (b) model. The dashed line represents the main development region.
Figure 3.11 – ASO Climatology of Precipitation (mm/day$^{-1}$) for (a) observations and (b) model in the Pacific and Atlantic Oceans. The dashed line represents the main development region.
Figure 3.12 – ASO Standard Deviation of Precipitation (mm/day$^{-1}$) for (a) observations and (b) model in the Pacific and Atlantic Oceans. The dashed line represents the main development region.
Figure 3.13 - Percentage of tropical cyclones for track types: straight moving (SM), re-curving making landfall (RCL), and re-curving into the ocean (RCO) for each ENSO phase and the non-ENSO phase (Neutral). The values in parentheses show the number of tropical cyclones included in the frequency distribution for each phase (Colbert and Soden, 2012)
Figure 3.14 – Composites of SST anomalies (°C) in the Pacific and Atlantic Oceans for (a) El Niño (b) La Niña for observation, (c) El Niño and (d) La Niña for model. The dashed line represents the main development region.
Figure 3.15 – Composites of tropical cyclone densities in the North Atlantic Basin for (a) El Niño (b) La Niña for observation, (c) El Niño and (d) La Niña for model. The dashed line represents the main development region.
Figure 3.16 – Composites of vertical wind shear (m/s\(^{-1}\)) in the North Atlantic Basin for (a) El Niño (b) La Niña for observation, (c) El Niño and (d) La Niña for model. The dashed line represents the main development region.
Figure 3.17 – Composites of relative humidity anomalies (%) in the North Atlantic Basin for (a) El Niño (b) La Niña for observation, (c) El Niño and (d) La Niña for model. The dashed line represents the main development region.
Figure 3.18 – Composites of precipitation anomalies (mm/day\(^{-1}\)) in the Pacific and Atlantic Oceans for (a) El Niño (b) La Niña for observation, (c) El Niño and (d) La Niña for model. The dashed line represents the main development region.
4. Conclusion

The main objective achieved in this study is to investigate tropical cyclone activity in the North Atlantic and its relationship with ENSO in observations and the coupled climate model, FLOR-FA. For this purpose, we first analyzed the ability of the coupled model to capture the mean state and variability in the tropical cyclone activity, SST and the environmental factors relevant to the ENSO-TC relationship. We focus on the ASO season, as the tropical cyclone activity in the North Atlantic tropical cyclone activity peaks during these months.

The model simulates high tropical cyclone activity in the North Atlantic, especially over the northern Caribbean, Florida and the main development region during ASO consistent with observations. Although the model replicates ASO climatology as in observations, tropical cyclone activity is not as strong in regions such as the Gulf of Mexico and the main development region. The model also has better simulation of variability in tropical cyclone activity over the Caribbean, Gulf of Mexico and the main development region but is slightly weaker than observations. Further, the model successfully represents the mean and variability of the environmental factors, such as vertical wind shear, relative humidity and rainfall in the main development region that are important for the tropical cyclone activity.

The model also successfully simulates the mean state and variability in the SST. The model shows warm climatological SST in the western Pacific and equatorial Atlantic except that the SST is warmer than observations. The variability in SST in the model is also similar to observations with enhanced variability on the tropical Pacific.
Considering the ability of the coupled model to simulate the observed mean state and variability of SST, tropical cyclone activity and the factors relevant to the ENSO-TC relationship, the teleconnection between ENSO and the tropical cyclone activity in the North Atlantic and the associated mechanisms are explored in the coupled model relative to observations.

Comparison of composites of SST and tropical cyclone density for both the phases of ENSO in the model suggests that the North Atlantic tropical cyclones are more likely to form during La Niña than El Niño. During El Niño, reduced tropical cyclone densities are found over the main development region, extending into the Caribbean and US coast in the model simulation. This lack of tropical cyclone activity is similar to observations. Further, consistent with observations, model simulation shows that most of the tropical cyclones are RCO, fewer are RCL and the least are SM. The model simulation of vertical wind shear during El Niño is also similar to observations, with high values, especially in the main development region. This enhanced vertical wind shear inhibits the development of tropical cyclones in the model. Similar to observations, there are anomalously low values of relative humidity over the main development region, the Caribbean and the mid-Atlantic, consistent with reduced tropical cyclone activity. With the increase in SST in the eastern Pacific, there is also an increase of precipitation in the eastern equatorial Pacific Ocean and reduced precipitation in the North Atlantic over Caribbean, suppressing tropical cyclone formation in Caribbean region.

In the model, during La Niña, enhanced tropical cyclone densities are seen over the Caribbean and the western main development region similar to observations, except that the enhanced anomaly covers the entire main
development region. Less enhanced anomalies are also found over the Gulf of Mexico, along the US Coast and in the Mid-Atlantic Ocean. Similar to observations, most of the tropical cyclones in the model are SM. However in the model, fewer tropical cyclones are RCL and the least are RCO, while in observations, fewer tropical cyclones are RCO and the least are RCL. Consistent with observations, there are low vertical wind shear values in the model during La Niña, especially in the main development region, which promotes tropical cyclone activity in the model. There are also high values of relative humidity in the main development region, the lower Caribbean and Central America, which enhance tropical cyclone development. The model simulates reduced precipitation anomalies over the eastern equatorial Pacific in the location of negative SSTs and enhanced rainfall over the main development region, the Caribbean and the Gulf of Mexico similar to observations, which also encourages tropical cyclone development.

As discussed above the model has better simulation of ENSO-tropical cyclone relationship and the associated environmental factors compared to observations. However, there are inconsistencies in the model simulation compared to observations. The model has stronger SST anomalies than observed in the equatorial Pacific for both ENSO phases. The tropical cyclone anomalies are also intensified in the model compared to observations.

During El Niño, the reduced anomaly extends over the main development region to the Caribbean and over the southern US coast in the model, where as in observations, the reduced anomaly is confined to the Mid-Atlantic region and near the Lesser Antilles. This suggests that in the model, less tropical cyclones form during El Niño than in observations. In case of simulation of environmental
factors, the vertical wind shear anomalies are stronger in the model compared to observations, creating less favorable conditions for tropical cyclone development in the model than in observations. The reduced rainfall anomalies in the model are also not as strong as observed rainfall anomalies for El Niño, which also tend to suppress tropical cyclone development in the model compared to the observations.

During La Niña, a reduced vertical wind shear anomaly does not extend to the east of the main development region as in observations, thus inhibiting tropical cyclones to develop in the entire main development region. This explains the reduced tropical cyclone anomaly in the eastern main development region. The reduced anomalies of vertical wind shear in the Southern US, Gulf of Mexico and main development region are weaker in the model than in observations, making conditions less favorable for tropical cyclone development. The model simulates weaker tropical cyclone density in these regions compared to the model.

In this study, we acknowledge the importance of the combination of environmental factors such as vertical wind shear, relative humidity and rainfall intensity to affect the tropical cyclone development in the North Atlantic during El Niño and La Niña. This study has shown that the coupled climate model is able to replicate observed the ENSO-TC relationship and the associated effects of environmental factors. The performance of the FLOR-FA exceeds that of earlier version of GFDL climate models, in producing near realistic tropical cyclone simulations in the Atlantic Ocean (Vecchi et al., 2014).
Appendix

A.1 Glossary

- **Gradient Wind Balance**\(^{14}\) – this occurs when air moves in circular trajectories (around curved isobars) around an extreme body of pressure (Fig. A.1). The inward decline of pressure forces air toward the center of circulation and balances the sum of the centripetal and Coriolis accelerations required by the curved path.
  - In a northern hemisphere low-pressure system, the wind motion is counter clockwise. For a northern hemisphere high-pressure system, the wind motion is clockwise.

- **Vorticity**\(^{15}\) – A measure of the rotation of air in a horizontal plane.

- **Convective cell**\(^{16}\) - the phenomenon that occurs when density differences exist within a body of liquid or gas. It is made up of Fluid movement via convection and a convection cell (the moving body of liquid or fluid).

- **Mesoscale convective complex (MCC)**\(^{17}\) - a unique kind of mesoscale convective system, which is defined by characteristics observed in infrared satellite imagery. They are long-lived, nocturnal in formation and usually contain heavy rainfall, wind, hail, lightning and possibly tornadoes.

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\(^{14}\) [http://www.aoml.noaa.gov/hrd/hrd_sub/gradbal.html](http://www.aoml.noaa.gov/hrd/hrd_sub/gradbal.html)

\(^{15}\) NOAA National Weather Service Glossary


• **Teleconnection**\(^{18}\) - a climate anomaly related to other climate anomalies at large distances.

• **Walker Circulation**\(^{19}\) - an east-west circulation of the atmosphere above the tropical Pacific, with air rising above warmer ocean regions, and falling over the cooler ocean areas.

• **Ensemble forecasting**\(^{20}\) - a dynamical and flow-dependent approach to quantify forecast uncertainty. It provides a basis to communicate forecast uncertainty and forecast confidence to others.

• **Climatology**\(^{21}\) - the mean state of the climate factor over a particular time period.

• **Standard deviation**\(^{22}\) - represents the mean variability of the climate factor. The higher the deviation, the more the climate variable deviates from its mean in that region. The closer the deviation is to zero, the less the climate variable deviates.

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\(^{18}\) NOAA National Weather Service Glossary


\(^{21}\) NOAA National Weather Service Glossary

\(^{22}\) NOAA National Weather Service Glossary
### A.2 Tables

<table>
<thead>
<tr>
<th>Stage of TC Development</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Depression</td>
<td>23 to 39 mph</td>
</tr>
<tr>
<td></td>
<td>(37 to 63 kilometers per hour)</td>
</tr>
<tr>
<td>Tropical Storms</td>
<td>40 to 74 mph</td>
</tr>
<tr>
<td></td>
<td>(64 to 119 kilometers per hour)</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>74 mph (119 kilometers per hour) or greater</td>
</tr>
</tbody>
</table>

Table A.1 – The stages of tropical cyclone development measured by translational speed.\(^{23}\)

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<table>
<thead>
<tr>
<th>Mode</th>
<th>Full Name</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMM</td>
<td>Atlantic Meridional Mode</td>
<td>Figure A.2</td>
</tr>
<tr>
<td>MJO</td>
<td>Madden Julian Oscillation</td>
<td>Figure A.3</td>
</tr>
<tr>
<td>NAO</td>
<td>North Atlantic Oscillation</td>
<td>Figure A.4</td>
</tr>
</tbody>
</table>

Table A.2 – Environment modes with acronym and figures
<table>
<thead>
<tr>
<th>Variable</th>
<th>Data Source</th>
<th>Spatial Resolution</th>
<th>Years</th>
<th>Cited by</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>HadISST version 1.1</td>
<td>1°x1°</td>
<td>1870-2013</td>
<td>Rayner and Coauthors, 2003</td>
</tr>
<tr>
<td>TC</td>
<td>HURDAT2/ JTWC Best Track Data</td>
<td>-</td>
<td>1979-2013</td>
<td>Knapp et al., 2010</td>
</tr>
<tr>
<td>Vertical Wind Shear</td>
<td>MERRA</td>
<td>0.5° x 0.5°</td>
<td>1979-Present</td>
<td>Rienecker and Coauthors, 2011</td>
</tr>
<tr>
<td>Precipitation</td>
<td>CPC CMAP</td>
<td>2.5° x 2.5°</td>
<td>1979-Present</td>
<td>Xie and Arkin, 1997</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>MERRA</td>
<td>0.5° x 0.5°</td>
<td>1979-Present</td>
<td>Rienecker and Coauthors, 2011</td>
</tr>
</tbody>
</table>

Table A.3 showing observation datasets
<table>
<thead>
<tr>
<th>Model</th>
<th>Function</th>
</tr>
</thead>
</table>
| FLOR       | • High-resolution coupled climate model built with the intention to create a seasonal-to-decadal forecast system for regional climate impacts.  
|            | • Has high resolution on land and atmosphere elements at 50 Km and the sea-ice and ocean components of FLOR are at lower-resolution at 1°. |
| FLOR-FA    | • Flux-adjusted version of FLOR                                          
|            | • Climatological adjustments were made to model’s momentum, enthalpy and freshwater fluxes from atmosphere to ocean                  |

Table A.4 – List of GFDL climate coupled models used in this study\(^{24}\).

A.3 Figures

Figure A.1 - The balance of forces that create a gradient wind in the Northern Hemisphere. Around a low-pressure system, the gradient wind consists of the pressure gradient force and centripetal force acting toward the center of rotation, while Coriolis force acts away from the center of the system. In a high-pressure center, the Coriolis and centripetal forces are directed toward the center of the system, while the pressure gradient force is directed outward. (PGF = pressure gradient force; CF = Coriolis force; Ce = centripetal force).25

Figure A.2 - AMM in the tropical Atlantic. Top: Regression maps of the AMM sea surface temperature (SST) normalized expansion coefficients on SST and 10-m wind vectors. Middle: Same as top, but for precipitation (mm/day). In general, shaded regions in all panels exceed the 95% confidence level. Bottom: Time series of AMM SST. From Chiang and Vimont (2004)\textsuperscript{26}

Figure A.3: Regions and impacts where MJO activity has been shown to influence weather conditions during the 1-3 week time frame\textsuperscript{27}

\begin{itemize}
  \item 1. Alternating periods of wetter/drier conditions in the tropics
  \item 2. "Pineapple express" heavy rainfall events
  \item 3. Modulation of monsoon systems
  \item 4. Influence on tropical cyclone development
  \item 5. Modulation of ENSO cycle through oceanic Kelvin waves
\end{itemize}

Figure A.4 – Different phases of the North Atlantic Oscillation\(^\text{28}\).

\[^{28}\text{http://ossfoundation.us/projects/environment/global-warming/north-atlantic-oscillation-nao}\]
References


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Delworth, T.L. et al., 2012. Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model. Journal of Climate, 25.


Sasaki, W., Doi, T., Richards, K.J. and Masumoto, Y., 2014. The influence of ENSO on the equatorial Atlantic precipitation through the Walker circulation in a CGCM.


