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Barrier Layer Impact on Rapid Intensification of Hurricanes (2000-2018) in the Atlantic Ocean

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HALMOS COLLEGE OF NATURAL SCIENCES AND OCEANOGRAPHY

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By

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Abstract

Hurricane prediction is an evolving challenge that has seen much improvement over the years. While hurricane models have improved in predicting the path of storms, forecasts of hurricane intensity are unreliable due to the complexity of environmental data, lack of understanding of how relative humidity, vertical wind shear, hurricane structure and other possible factors affect intensity. Rapid Intensification (RI), which is a wind speed increase of +30 kts over a 24-hr period, can contribute to major destruction and loss of life to coastal communities affected by hurricanes, and is especially difficult to predict. Given the continued development of coastal regions and the threat of RI occurring without warning, it is imperative to better examine all possible factors that might influence hurricane RI to better understand and predict RI. The need for more research into RI was underscored by the devastation caused by rapidly intensifying hurricanes in the Caribbean and the east and gulf coast regions of the U.S. during the 2017 and 2018 hurricane seasons, which included the first landfall of a Category 5 hurricane (Hurricane Michael, 2018) since Hurricane Andrew in 1992. Recent studies examining the barrier layer (BL) of the water column and its relationship to hurricane intensification have shown that BLs favor RI, and that barrier layer thickness (BLT) may influence the storm's intensity. To determine if BLs might improve the prediction of hurricane intensity, this study examined all hurricanes in the Atlantic Ocean, Caribbean, and Gulf of Mexico spanning the years 2000-2018. Using relevant HYCOM data, daily temperature (T), salinity (S), mixed layer thickness (mlp), isothermal layer thickness (mld), and BLT were examined to determine each factor's horizontal distribution and possible influence on RI events occurring during the 139 hurricanes. Additional analysis was conducted on 12 randomly selected hurricanes (six of which had RI events and six of which did not) to determine if these factors, specifically BLT, act as significant predictors for RI events. Although no known link has been shown in previous research, this study also sought to determine if there is a correlation between RI and the horizontal variability of BLT and other key factors near the center of a hurricane (within 1 degree lat/lon).Though BLs can exist in any ocean, they are constantly changing and not always present. In this study, however, it was observed that BLs were present during all hurricanes in the Atlantic (2000-2018), whether they experienced a period of RI or not. Using an untested horizontal statistical analysis, this study shows that barrier layer thickness (BLT) does not appear to be a significant predictor of the probability of an RI event to occur, with no clear relationship shown between BLT and the magnitude of intensification, but these results cannot be taken as definitive. Given the limitations of this study, future research on hurricane RI should incorporate all known factors that impact hurricane intensity, testing each using multiple intensity models across all ocean basins.

Keywords: Rapid intensification, barrier layer, barrier layer thickness, hurricane, intensity, prediction, Atlantic Ocean

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1. Introduction

Hurricanes are extremely dangerous natural disasters that cause death and significant damage to worldwide coastal communities (Balaguru, 2012). In particular, the Caribbean, much of the southeastern United States, the tropical Pacific, and parts of Central America regularly experience the destructive power of hurricanes. In two separate studies, global and Atlantic basin hurricane activity had been observed to decrease over a 30-year span (1986-2015 and 1970s-2000s, respectively), whereas both global and Atlantic basin data showed a trend of more frequent major hurricanes (category 4 and 5) (Balaguru, 2018). Kossin (2013) showed that, globally, hurricanes have become more intense at a rate of $+1 ms^{-1} decade^{-1}$ from 1982 to 2009. A significant rise in major hurricanes was observed during the five-year period from 1995 to 2000 (Elsner, 2000; Goldberg, 2001) and more recently, which indicates a possible trend of an increased number of major hurricanes. Therefore, improvement in understanding these catastrophic events is imperative to reduce future loss of life and property in all affected regions (Lin, 2009).

History of Hurricane Forecasting

Over the years, hurricane track prediction has been steadily improving through the development of newer, more complex models (Cangialosi, personal communication, 2018). However, hurricane intensity is extremely difficult to predict, requiring a large amount of complex data. Accordingly, intensity predictions have progressed very little in recent years (Emmanuel, 1999). Forecasting intensity one to two days out has improved somewhat, but forecasting beyond three days has still proven unreliable, with large fluctuations in yearly average intensity errors ("National Hurricane Center Forecast Verification", n.d.) (Figure 1).

Early hurricane reconnaissance started in 1944 with the United States Navy (USN) and Air Force (USAF) flying missions into tropical cyclones to help warn all those who might be affected. In the late 1940s and early 1950s, Robert H. Simpson used these missions to take measurements of hurricanes, but it was not until 1954 that US policymakers decided to start funding hurricane research. A year later, additional funding to the United States Weather Bureau allowed for the creation of the National Hurricane Research Project (NHRP) to improve scientific understanding of hurricanes and improve forecasting.

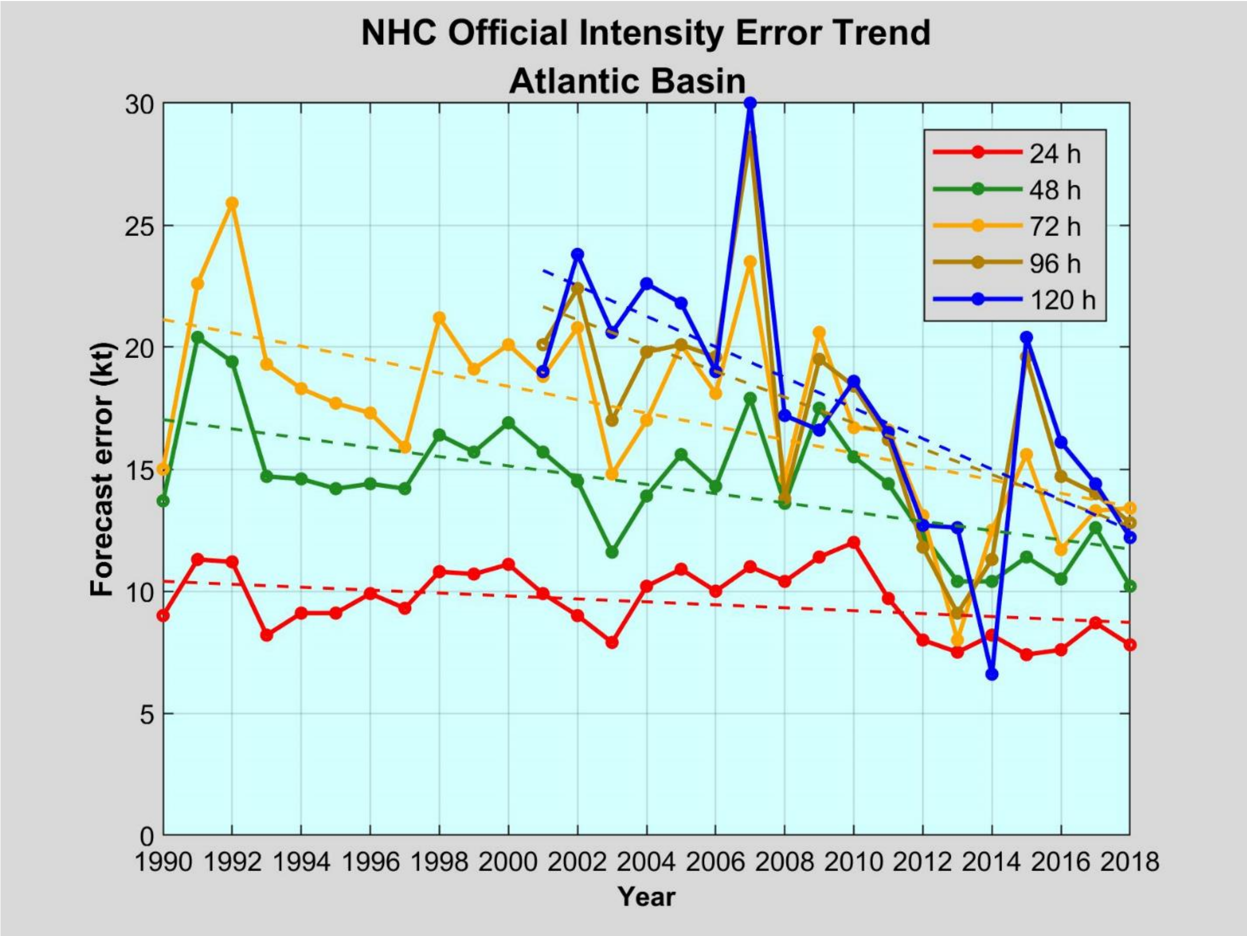

Figure 1. Yearly-average official intensity (1990-2018) forecast errors for 24-, 48-, 72-, 96- and 120-hours, Atlantic basin, excluding depressions, with least-squares trend lines added. From https://www.nhc.noaa.gov/verification/verify5.shtml

Simpson was appointed director of the Project and, in 1956, the first NHRP flight was made into Hurricane Betsy using three aircraft on loan from the USAF to measure temperature (T), humidity and pressure. The most productive year for the project was 1958, with 23 missions flown and numerous important papers published on mean atmospheric soundings, hurricane rainfall distribution, storm surge surveys, and radar descriptions of hurricanes. A year later, the Project was moved to the Miami Aviation Building, co-locating it with the Miami hurricane forecast office. These two combined organizations became known as the National Hurricane Center (NHC).

In the early 1960s, satellites became extremely important for hurricane reconnaissance and research, giving new insights into the formation of storms and allowing scientists to observe hurricanes from start to finish. Although no longer necessary to “hunt” for tropical disturbances, aircraft reconnaissance missions were still used to fly into storms to collect data.

For the next several decades, computer modeling and other significant developments in hurricane forecasting grew from multi-national, collaborative experimentation, increased government funding, consolidation of research organizations and facilities, and advances in computer, meteorological and aviation technology.

Current State of Forecasting

Current hurricane forecasting techniques continue to rely heavily on satellite data and data collected by Hurricane Hunter aircraft. Satellites allow for continuous observation of tropical cyclones (tropical storm, tropical depression, hurricanes) throughout their life cycles. Lower altitude polar-orbiting satellites fly over storms about twice daily, using microwave instruments to reveal a hurricane's structure. The US Air Force Reserve and National Oceanic and Atmospheric Administration's (NOAA) Hurricane Hunter aircraft take detailed measurements within a hurricane when there is the strong possibility it will make landfall. In addition to these techniques used to gather data and forecast tropical cyclones, NHC scientists analyze a variety of computer models to help forecast storms ("Hurricane Research Division", n.d.). Each computer model has its strengths and weaknesses, but every tropical storm is unique, and history has shown no one model to be 100 percent accurate.

Forecasting models vary greatly in their design and complexity but are separated into four types ("NHC Track and Intensity Models", 2019). Dynamical models (e.g. HWRF/HWFI – Hurricane Weather Research and Forecast system) use supercomputers to solve mathematical equations representative of the physics and motion of the atmosphere. Statistical models (e.g. SHIFOR – Statistical Hurricane Intensity Forecast Model) are based on historical relationships between storm behavior and storm-specific details such as locations and date. Statistical-dynamical models (e.g. SHIPS – Statistical Hurricane Intensity Prediction Scheme) combine the statistical and dynamical models to make forecasts based on both historical hurricane data and atmospheric variables produced by dynamic models. Ensemble models (e.g. HCCA – HFIP Corrected Consensus Approach) use multiple forecasts created by different models, different physical parameters, or varying initial conditions to generate a single ensemble forecast.

The SHIPS model is one the first models developed for hurricane intensity prediction ("NHC Track and Intensity Models", 2019) and one of the three primary models currently used for intensity prediction (DeMaria et al., 2004) by the NHC. Studies in the Atlantic and Pacific basins have identified some of the many factors that influence hurricane intensity (ocean T, wind shear, relative humidity in low to mid troposphere, hurricane structure, inner-core processes, etc.) (Bosart, 2000; Emmanuel, 2004; Wang, 2017; Holliday, 1979), but De Maria and Kaplan (2003) determined oceanic factors (sea surface temperature (SST), ocean heat content, etc.) to be the most influential predictors in the SHIPS model.

Due to our limited understanding of the mechanisms responsible for changes in hurricane intensity, current forecasting models produce large intensity errors, especially during rapid intensification (RI) events (Shu et al., 2012).

Rapid Intensification

Rapid intensification (RI) poses one of the greatest challenges to tropical weather forecasting (Shu et al., 2012). Defined in this study as an increase of 30 knots or more within a 24-hour period, RI typically occurs in regions experiencing low vertical wind shear (less than 10 knots), warmer SST, and higher relative humidity in the lower troposphere (70% or greater) (Kaplan, 2003; Cangialosi, personal communication, 2018).

RI events are extremely dangerous, especially when occurring close to land. The rapid and thus far unpredictable increase in storm intensity brought about by RI events shortens the amount of time to evacuate or prepare in advance of a hurricane. RI events played a major role in the devastation of both the hyperactive 2017 Atlantic hurricane season, the costliest on record for the US (Balaguru, 2018), and the devastating 2018 Atlantic season. This fact was particularly evident in RI events during hurricanes Maria (2017), Irma (2017) and Michael (2018).

In the 2018 Atlantic hurricane season, Hurricane Michael and Hurricane Florence underwent RI prior to making landfall in the U.S., causing devastating levels of damage. Hurricane Michael (2018) underwent RI from early October 7 to late October 10, reaching Category 5 strength just before landfall near Tyndall Air Force Base, Florida (Beven et al., 2019). Michael was the first Category 5 hurricane to make landfall in the U.S. since Hurricane Andrew in 1992. Hurricane Florence (2018) went through two RI events, reaching Category 4 intensity before weakening to a strong Category 1 and making landfall in southeastern North Carolina, resulting in major freshwater flooding (Stewart & Berg, 2019).

In all, there were 20 occurrences of RI in the 2018 Atlantic hurricane season using the definition of RI mentioned above, which is about 6% of the total 2018 Atlantic hurricane season samples. Hurricane Florence and Michael accounted for 15 of the 20 RI events. Figure 2 shows the Probability of Detection (POD) and False Alarm Rate (FAR) for the NHC OFCL model during the 2018 Atlantic hurricane season (Gopalakrishnan et al., 2018). The NHC OFCL model correctly forecasted RI events for 10-20% of the cases over a 24- to 48-hour period. For the 24-hour forecast interval, FAR is much larger than POD; RI events predicted by the models often did not occur.

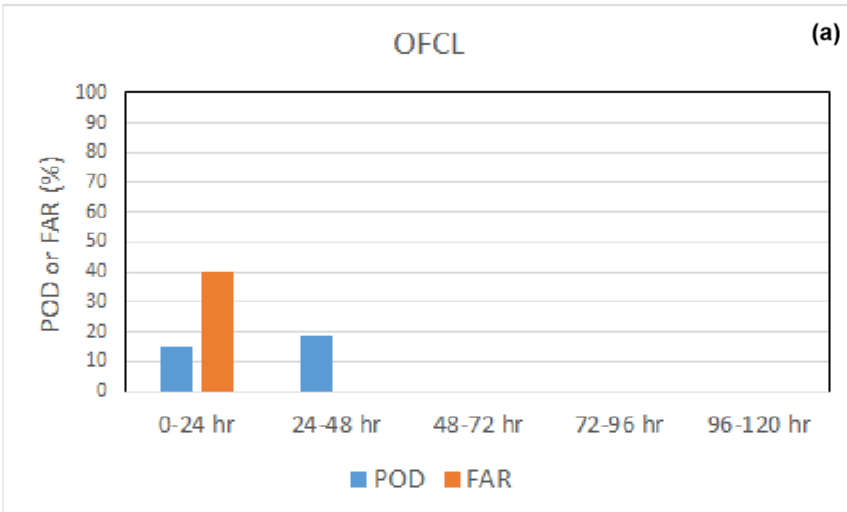

Figure 2. The Probability of Detection (POD) and False Alarm Rate (FAR) of RI forecasts from the 2018 Atlantic sample for the NHC Official (OFCL) model. From http://www.hfip.org/documents/HFIP_AnnualReport_FY2018.pdf.

In addition to the NHC, RI has been given greater attention by NOAA, which established the Hurricane Forecast Improvement Project (HFIP) in July 2007 in the wake of the particularly devastating hurricanes (e.g., Charley, 2004; Wilma, Katrina, 2005) in the first half of that decade. HFIP's 10-year (2019) goals are to (Gopalakrishnan et al., 2018):

- Reduce average intensity errors by 50% for days 1-5
- Reduce average track errors by 50% for days 1-5
- Increase the probability of detection for RI to 90% at day 1, decreasing linearly to 60% at day 5

To address these goals, NOAA developed the Hurricane Analysis and Forecasting System (HAFS), a next-generation multi-scale, multi-model numerical system and data assimilation (DA) package. The HAFS will provide an operational analysis and forecast out to seven days, with reliable and skillful guidance on tropical cyclone (TC) track and intensity (including RI), storm size, genesis, storm surge, rainfall and tornadoes associated with tropical cyclones, all within the framework of the Unified Forecast System (UFS) and its rolling three-year Strategic Implementation Plan (SIP) (Gopalakrishnan et al., 2018).

During the period examined in this study (2000-2018), there were 139 Atlantic basin hurricanes (Figure 3), 94 (67.63%) of which underwent at least one RI event (Figure 4). Of the 139 hurricanes, 63 were major (Cat 3-5) and 76 were non-major. Of the 63 major hurricanes, nearly 91 percent (90.48%) underwent at least one RI event and of the 76 non-major hurricanes, nearly half (48.68%) underwent at least one RI event. RI played a major role in what made the 2017 hurricane season so devastating, with four of the 17 hurricanes reaching Category 4 or 5 (Balaguru, 2017).

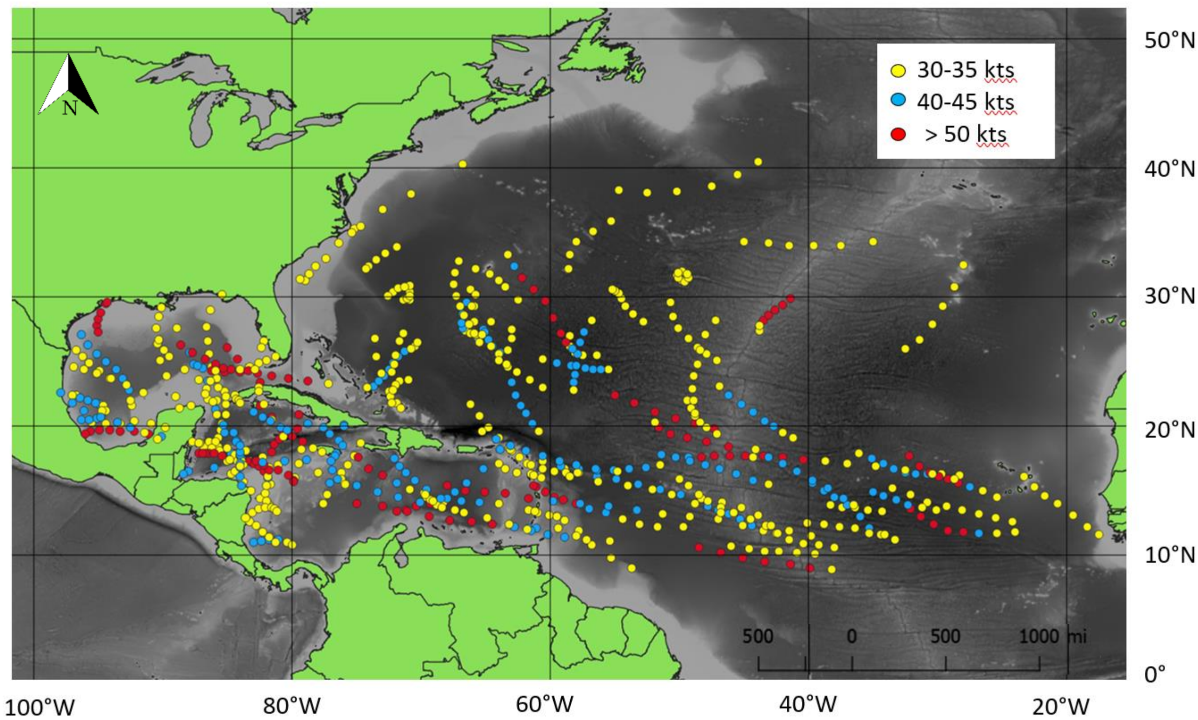

Figure 3. Hurricane track locations where rapid intensification (RI) occurred from 2000-2018. RI is defined as an increase in intensity of +30 kts over a 24-hr period. Yellow represents an increase of 30-35 kts, blue an increase of 40-45 kts, and red an increase of 50 kts or more. Latitude is spaced at 10° interval, longitude spaced at 20° interval.

According to Balaguru (2018), the magnitude of such RI events (defined in their research as an increase of 25 knots or more within a 24-hour period) has increased in the Central and Eastern Tropical Atlantic over the last 30 years. This indicates a need for research on why these events are increasing and what main factors affect RI (Kaplan, 2003), which has been designated a top forecasting priority by the NHC (Roger and Aberson, 2013).

Despite the growing attention and research into the causes of RI events, much remains unknown about the complete process.

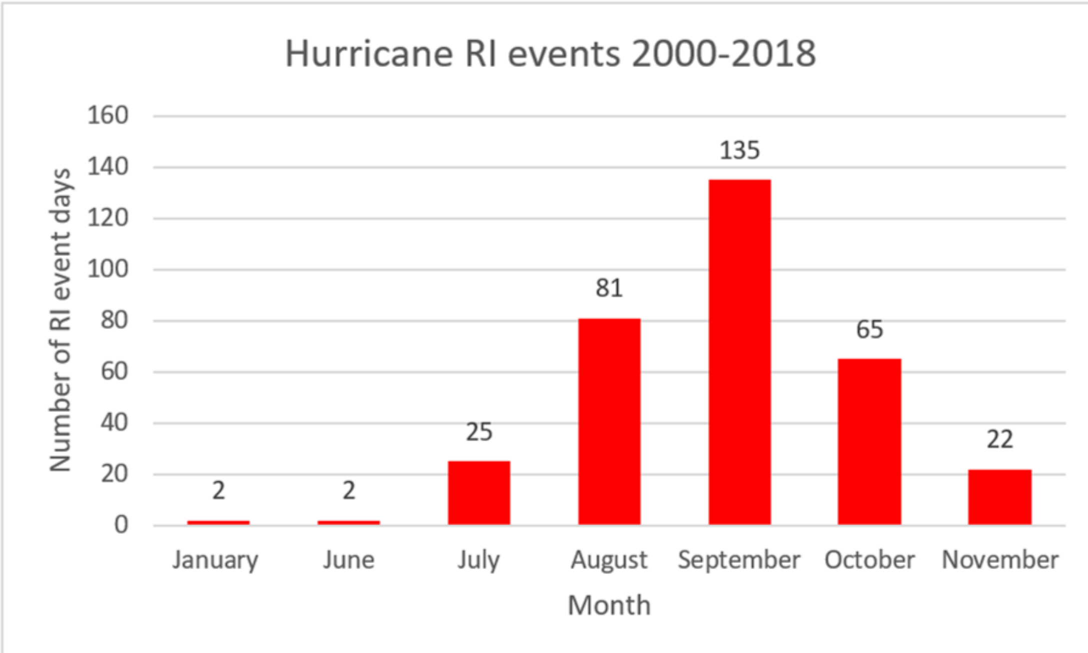

Figure 4. The graph shows the number of total days RI events occurred from 2000-2018. September has the most days where RI events occurred with 135. Early hurricane season does not experience many RI events. January was a rare occasion outside hurricane season where RI occurred.

Barrier Layers

Because hurricanes are atmospheric systems, oceanic factors are given less consideration or weight in most hurricane intensity models (Cangialosi, personal communication, 2018). As mentioned earlier by Kaplan (2003), oceanic factors are the most important intensity predictor for the SHIPS model but are not sufficient on their own to bring about intensification (DeMaria & Kaplan, 1993; Lloyd & Vecchi, 2011); atmospheric and climatological conditions must also be conducive for RI events to occur. Among oceanic factors, there has been growing interest in the impact of barrier layers (BLs) on hurricane RI.

The barrier layer is the portion of the water column separating the bottom of the mixed layer from the top of the isothermal layer (Lukas and Lindstrom, 1991; Sprintall and Tomczak, 1992) (Figure 5). Based on previous research, BLs are a global phenomenon and not unique to tropical regions (De Boyer Montégut, 2007; Kara et al., 2000). However, BLs are more prevalent in warm tropical regions (Pailler, 1999) as a result of low-salinity layers atop the mixed layer. BLs are produced either from high precipitation, evaporation, or intense freshwater discharge from rivers (De Boyer Montégut, 2007). Montégut (2007) found that tropical BLs have seasonal distribution, and the thickest BLs can be detected in the winter hemispheres.

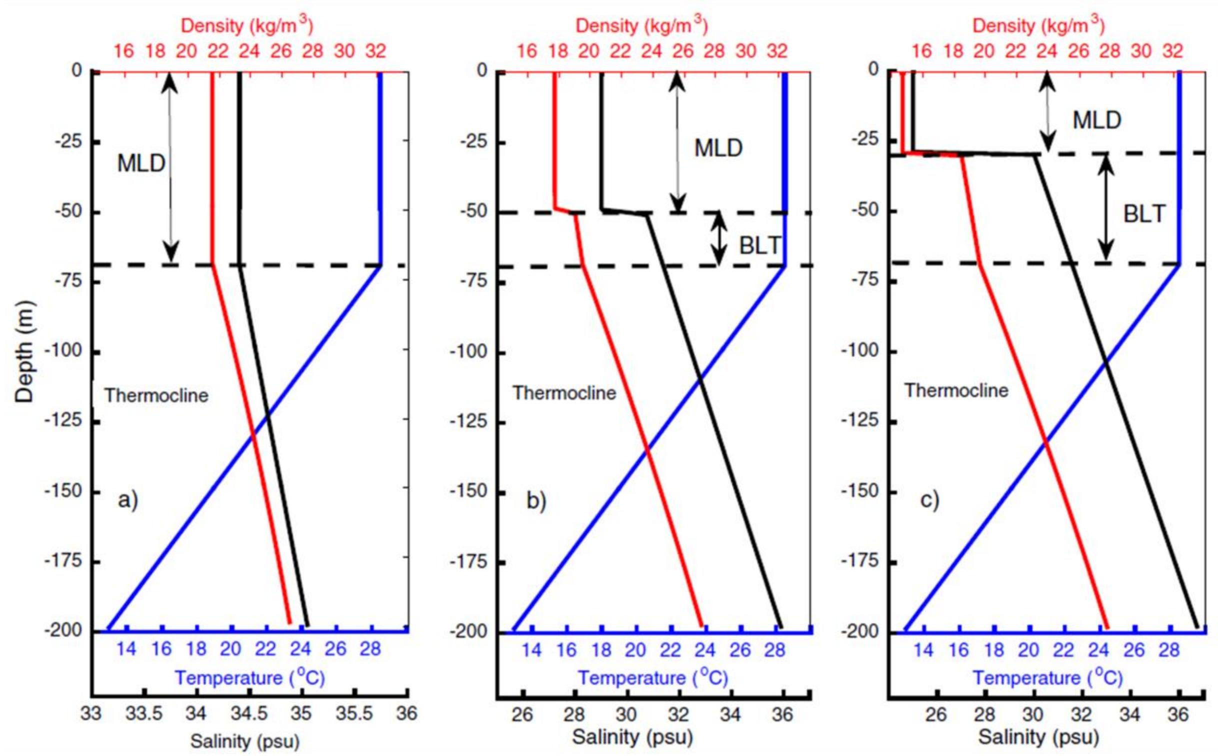

Figure 5. Simplified visualization of BLT in upper ocean. Temperature (blue), salinity (black), density (red) profiles showing mixed-layer depth (MLD) and BLT. Left to right: no BL, thin BL, thick BL. (Yan et al. 2017)

In the equatorial and western tropical Pacific and Atlantic, BLs are typically significantly present during at least 10 months per year (De Boyer Montégut, 2007). In the tropics, between 10° and 25° latitude, BLT is primarily detected in the autumn and winter seasons of each hemisphere and can last 5 to 7 months per year in the eastern Atlantic and Pacific basins and often year-round in the respective western basins (De Boyer Montégut, 2007). The lack of consistent prominent BLs in the eastern basins is due to upwelling, which causes a very shallow mixed layer and ensures a well-mixed T and S stratification. It is not clear why the thickest BLs are detected in winter or why the BL does not extend further east in the Atlantic as it does in the Pacific. It has been suggested, however, that this seasonal distribution of BLs is due to the T inversion within BLs, and where the BL is more confined to the western tropical Atlantic due to the unique bathymetry and Gulf Stream (De Boyer Montégut, 2007). The frequency of hurricanes in these same regions suggests BLs and barrier layer thickness (BLT) might have an impact on RI.

Yan et al. (2017) found that hurricanes interact with BLs in many ways, suggesting that thinner, weaker BLs are more favorable to RI than thicker BLs, which differs from past research suggesting all BLs favor RI (Grodsky et al., 2012; Balaguru et al., 2012). For example, when BLs were absent, the mixed layer and isothermal layer reacted as expected, with vertical mixing causing surface waters to cool more effectively as hurricane intensity increased. Where BLs did exist, and hurricane wind-driven currents penetrated the isothermal layer, entraining colder, deeper water also cooled surface waters. However, when hurricane wind-driven currents did not penetrate the BL, air-sea heat flux was the dominating surface cooling factor. When the BL was penetrated by hurricane wind-driven currents, the warmer water within the BL can increase the mixed layer water T before the surface layer continues to cool at a slower magnitude.

It is known that BLs suppress vertical mixing, thus preventing sea surface cooling (Sprintall and Tomczak, 1992; Balaguru, 2012; Price, 1981) from colder, deeper water moving to the surface. Hurricanes are weakened by sea surface cooling, among other factors, which is caused by two mechanisms of the passing hurricane: [1] surface heat loss due to air-sea heat flux, and [2] transport of colder water through the BL and into the mixed surface layer (Yan et al., 2017). In this way, hurricanes essentially weaken themselves, but BLs disrupt this process. In some cases, the salinity (S) stratification that controls BLs can support a T increase. This T inversion reaches a maximum T within the BL before T begins to decrease with depth (De Boyer Montégut, 2007).

For the reasons mentioned above regarding the more prominent BLs in the equatorial western tropical Atlantic, this study focuses on BLs and their possible impact as predictors for hurricane RI events. To determine what impact BLs have on RI events, this study examined data from all hurricanes in the North Atlantic Ocean, Caribbean, and Gulf of Mexico between 2000 and 2018 and the following oceanic factors – T, S, mixed layer thickness (mlp), isothermal layer thickness (mld) and barrier layer thickness (BLT) – and their impact on RI. Although no known link has been shown in previous research, this study also sought to determine if there is a correlation between RI and the horizontal variability of BLT and these four other key factors near the center of a hurricane (within 1 degree lat/lon).

Using qualitative analysis, Principal Component Analysis (PCA), and a Generalized Linear Model (GLM), tests were conducted on BLT and the four other oceanic factors to determine if they were significant predictors for the RI events. The aim of this study was to give insight into a hypothetical link between hurricane RI and horizontal mixing of BLs. Based on previous research, it was expected that BLs exist during all hurricanes and that BLT is a useful predictor of hurricane RI events. Using a previously untested method, this study sought to determine whether BLs and BLT are important to forecasting RI events and if they should be included in hurricane intensity models. By examining BLT as a predictor for RI events, this study's approach may hopefully lead to improved statistical studies into the phenomena of RI.

2. Data & Methods

2.1 Hurricane Best-Track

The hurricane best-track data from 2000-2018 in the North Atlantic basin (0°N to 40°N) were obtained from the National Hurricane Center (NHC) archive (https://www.nhc.noaa.gov/data/tcr/). Using QGIS, the data were used to map each hurricane from 2000-2018, along with intensity measurements at 6-hour intervals and RI events (Figure 3). Two hurricanes were left out of this study: Unnamed 2004, which was in the Southern Hemisphere, and Vince 2005, which occurred near Portugal. Individual NHC hurricane storm reports were obtained and used to determine accurate locations, intensity at 6-hour intervals, and when RI occurred (Figure 6).

RI events can be measured using three different intensification rates: 25, 30 or 35 kts per 24-hour period. (Sampson, 2011). In this study, hurricane RI events were defined as an increase in intensity of 30 knots or more within a 24-hour period, which is the most commonly used definition of RI (Kaplan and DeMaria, 2003; Wang et al., 2017).

2.2 Argo Float Profile Data

Argo float profile data from 2000-2018 in the tropical Atlantic was obtained from http://argo.jcommops.org/argo.kml. This data was collected and made freely available by the International Argo Program and contributing national programs (http://www.argo.ucsd.edu, http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System (http://doi.org/10.17882/42182). Argo deployments began in 2000 and continue today at a deployment rate of about 800 per year. The data collected and relayed to satellites by individual floats consists of subsurface S, T, and velocity, with sufficient coverage and resolution to allow interpretation of sea surface height variability. Argo data is used in ocean and coupled ocean-atmosphere forecast models for data assimilation and model testing ("Brief History of Argo", n.d.).

The active Argo float profile data was used to analyze T, potential density, and S vertical profiles in relationship to hurricanes in corresponding years. To analyze the Argo data for BLs, Global Marine Argo Atlas and Ocean Data View programs were used (http://www.argo.ucsd.edu/Marine_Atlas.html, Schlitzer, R., Ocean Data View, odv.awi.de, 2018). It should be noted, however, that the Global Marine Argo Atlas program was unable to produce data in the Caribbean and Gulf of Mexico. To compensate for this lack of producible data, the Ocean Data View program was utilized with active Argo float data obtained from http://argo.jcommops.org/argo.kml to examine the Caribbean and Gulf of Mexico.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
30 / 0000	16.1	26.9	1008	30	tropical depression
30 / 0600	16.2	28.3	1007	35	tropical storm
30 / 1200	16.3	29.7	1006	45	"
30 / 1800	16.3	30.8	1004	50	"
31 / 0000	16.3	31.7	999	55	"
31 / 0600	16.4	32.5	994	65	hurricane
31 / 1200	16.7	33.4	983	80	"
31 / 1800	17.1	34.2	970	95	"
01 / 0000	17.5	35.1	967	100	"
01 / 0600	17.9	36.1	967	100	"
04 / 0600	17.0	51.5	952	105	"
04 / 1200	16.8	52.6	945	110	"
04 / 1800	16.7	53.9	944	115	"
05 / 0000	16.6	55.1	943	125	"
05 / 0600	16.6	56.4	933	135	"
05 / 1200	16.7	57.8	929	150	"
05 / 1800	16.9	59.2	926	155	"
06 / 0000	17.3	60.6	915	155	"
06 / 0600	17.7	61.9	914	155	"
06 / 1115	18.1	63.1	914	155	"
06 / 1200	18.1	63.3	915	155	"
06 / 1800	18.6	64.7	916	150	"

45kt RI

40kt RI

Figure 6. Sample NHC individual storm report for Hurricane Irma showing date/time, latitude, longitude, pressure and wind speed from Aug. 30 to Sept. 12, 2017. https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf

Using these two programs, visual representations of S, T and density vertical profiles were created providing another way to examine monthly averages for each variable's distribution.

2.3 HYbrid Coordinate Ocean Model (HYCOM): Barrier Layer Thickness, Salinity, Temperature, Density

HYCOM datasets were utilized in this study because of their availability, ease of use, and vast employment as a coupled ocean-atmosphere prediction model useful for the approximation of global ocean data (Johnston & Purkis, 2015). HYCOM provides complete temporal and spatial coverage (including measurements at depth) at a high resolution compared to satellite and other measuring practices, through in situ T, S, and density measurements. HYCOM also provides real-time data, as well as data useable for hindcasts and forecasting, making this data extremely useful for global ocean prediction (Chassignet et al., 2009). From this daily HYCOM data, it was possible to calculate BLT between 2009-2018. Prior to 2009, mld and mlp were not reported in the available HYCOM data, making it impossible to measure BLT for 2000-2008.

For each day a hurricane existed, daily ocean T, S, mlp, and mld data at varying depths was obtained from HYCOM on a 1/12° Global Analysis (3.0 Analysis and 3.1 ReAnalysis). The data provided by HYCOM are snapshots of the 00Z hour, which is the beginning of each day. The HYCOM data converted to netcdf is interpolated to a uniform 0.08 degree lat/lon grid between 80.48S and 80.48N. The area sampled included the Atlantic Ocean, Caribbean, and Gulf of Mexico from 0°N to 40°N and from the westernmost coast of Africa to the eastern coast of Mexico between 2000-2018. This was initially done to ensure no important data points were excluded, although most data points would not have related to a hurricane at all and were therefore not included in the analysis. The millions of data points were downloaded as a netcdf file and converted using Matlab to a .csv filetype so that they could be plotted and analyzed in QGIS. This converted data was overlaid with hurricane best-track data and RI-only events to examine BLT, S, and T in horizontal and vertical distribution.

To calculate BLT, mixed layer thickness (mlp, 0.03 kg/m^3) and isothermal layer thickness (mld, 0.2°C) was collected from HYCOM; and in accordance with previous studies (Yan et al., 2017; Sprintall and Tomczak, 1992; Lukas and Linstrom, 1991), BLT was determined by measuring the difference between mld and mlp.

The output is publicly available at http://hycom.org.

2.4 Testing and Analysis

Initial analysis was conducted on all hurricanes between 2000 and 2018 to determine whether BLs were present. From the daily HYCOM data obtained above, BLT was calculated from 2009-2018 during the entire life of each hurricane in the tropical Atlantic. For the 2000-2008 timeframe when BLT could not be calculated, the Global Marine Argo Atlas and Ocean Data View programs were utilized to determine the existence of BLs. However, the accurate calculation of BLT was not possible in all areas. The resulting data was then overlaid with RI events in corresponding hurricanes to determine if there was any relationship between BLs and the magnitude of intensity increase. By reviewing individual storm reports provided by the NHC, each hurricane was evaluated to determine if an RI event had occurred. All identified RI events from all hurricanes were then selected and plotted into QGIS overtop corresponding daily HYCOM data to determine where the BL was in relation to each hurricane RI event. Examining the increase in intensity, each hurricane RI event (30+ knots $24hr^{-1}$) was compared to determine the relationship between BLs and the intensity increase.

Initial qualitative analysis was also conducted to examine the 24-hour intensification rates in relation to BLT to determine the relationship between BLT and the amount of intensity increase. This was done by examining the intensity increase during each RI event for hurricanes from 2009-2018 and comparing them to the calculated BLT where each RI event occurred.

As previously stated, prior to 2009, mld and mlp were not reported in the available HYCOM data, making it impossible to measure BLT for 2000-2008. Therefore, only hurricanes that underwent RI events from 2009-2018 were examined to determine any relationship between BLT and the magnitude of intensity increase. To analyze whether BLT was a significant predictor for the probability of an RI event to occur, six hurricanes from the 2009-2018 timeframe were randomly selected for further testing.

All hurricanes that underwent RI from 2009-2018 were grouped by the regions in which they occurred (Atlantic Ocean, Caribbean, Gulf of Mexico) and numbered based on chronological order of occurrence. Two hurricanes were then randomly selected from each ocean region included in this study (Figure 7): Hurricane Irma 2017 and Hurricane Danny 2015 (Atlantic Ocean), Hurricane Tomas 2010 and Hurricane Rina 2011 (Caribbean), and Hurricane Michael 2018 and Hurricane Karl 2010 (Gulf of Mexico). All 20 RI events (30+ knots $24hr^{-1}$) within the six hurricanes were included in this study.

Using a new, non-verified approach, the PCA test was used to determine which factors had the greatest influence on controlling the variances within each daily HYCOM dataset associated with an RI event for the corresponding hurricanes. The HYCOM data was also used to create PCA plots for data points associated with each RI event to give a visual representation of how the data points were grouped based on the values of the five oceanic factors. This approach sought to examine the horizontal variability of the five oceanic factors and determine whether there is any correlation between RI and the horizontal variability of BLT and other key factors near the center of a hurricane. The GLM test was chosen to determine which of the five oceanic factors studied were significant predictors for the RI event to occur. This test was also selected based on the types of variables being studied and to facilitate binomial categorization, which allowed identification of data points associates with each RI event.

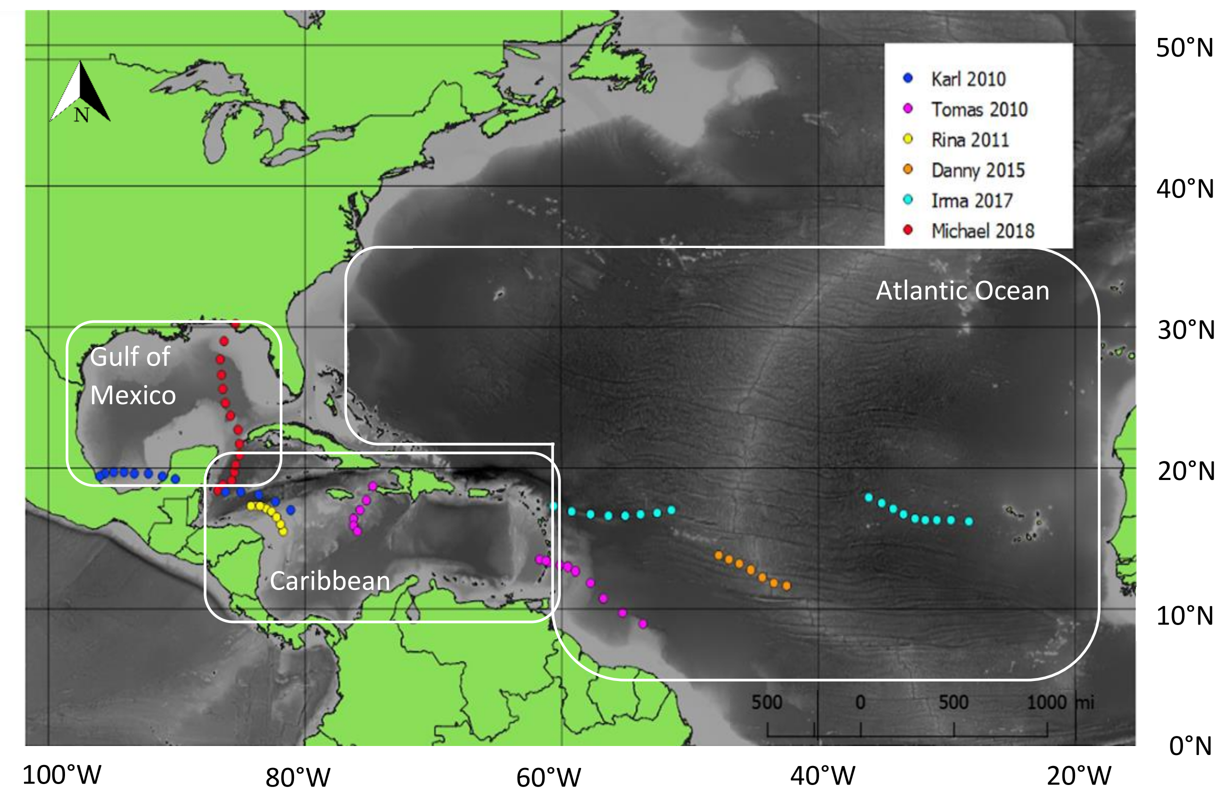

Figure 7. Hurricane RI events for Hurricane Karl (dark blue), Tomas (pink), Rina (yellow), Danny (orange), Irma (light blue), and Michael (red). The areas where these hurricanes were randomly selected are labeled above (Atlantic Ocean, Caribbean, Gulf of Mexico.)

In order to perform the PCA and GLM tests, HYCOM datasets for each hurricane had to be labeled to indicate where RI events occurred. Each data point included latitude, longitude, S, T, mld, mlp, and BLT. For a data point to be associated with an RI event, it had to fall within a one-degree direction of the hurricane best-track data points. Data points within the area were labeled with a 1 to indicate a corresponding RI event, while all other data points were labeled with a 0 to indicate no association with the RI event. To conduct PCA, it was necessary to separate the dataset, using only the data points associated with RI events (1s). For GLM, no separation was required, so that the entire dataset was included.

PCA simplifies large, complex data into fewer variables while consolidating any factors that measure the same underlying variable. PCA reduces dimensions in data and consolidates them into fewer factors called principal components (PCs). Each PC is uncorrelated, meaning a variable can be selected for only one PC and the maximum number of PCs is limited to the initial number of variables. In this study, PCA was used to test the oceanic factors on each day when RI occurred during the six hurricanes. Only PCs with eigenvalues greater than 1 were considered because they account for a larger variance in the data. Using this criterion, these PCs were then plotted against each other to create a visual representation of all data points used (Figures 9 and 10). For each PC, coefficients with the highest absolute value were then identified.

To generate a reliable PCA graph, only data points associated with the corresponding RI event were tested. Examining the six previously mentioned hurricanes, PCA was performed on

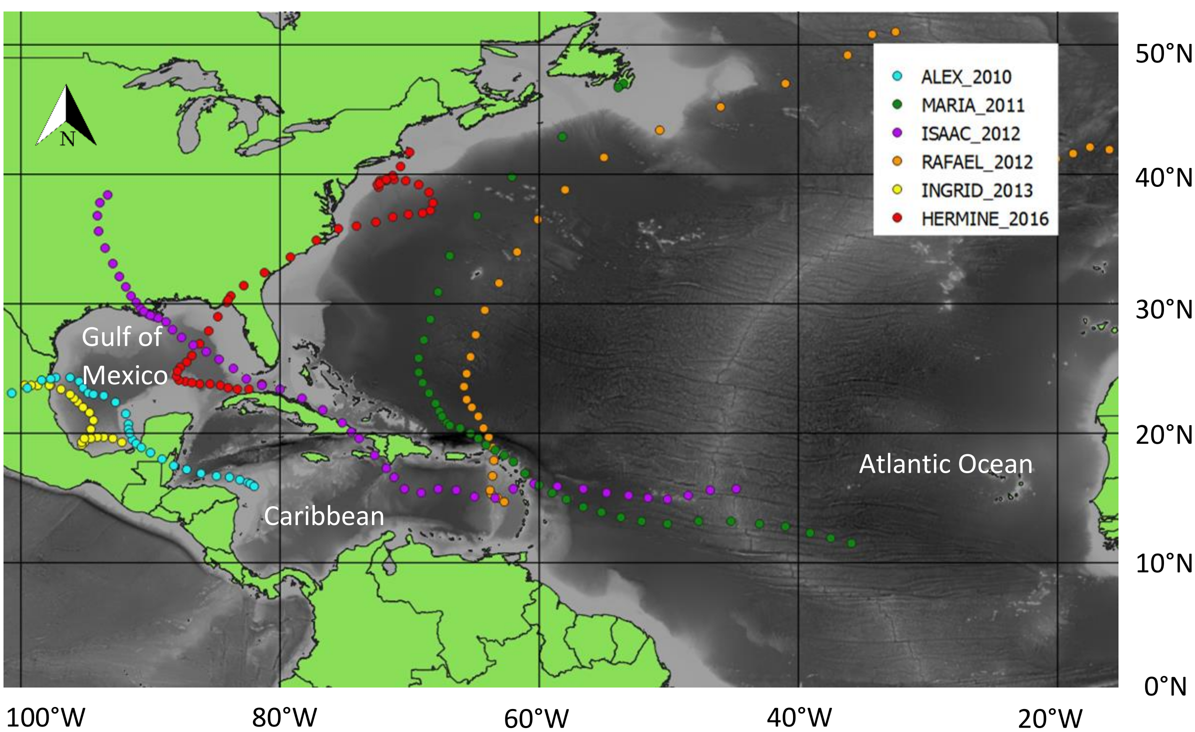

Figure 8. Full tracks for Non-RI Hurricane Alex (light blue), Isaac (purple), Ingrid (yellow), Rafael (orange), Maria (green), and Hermine (red).

all days with RI events where BLT was calculated. With each PCA performed on RI events, results showed different oceanic factors to be most influential, when controlling the variance of the dataset.

Designed for binary data, GLM tests are useful for testing multiple continuous or categorical variables that predict the probability of a single dependent variable occurring. In this study, the RI event was the dependent variable, with given values of 1 or 0. A binomial GLM test was used to determine whether each oceanic variable was a significant predictor of RI events on a given day. Data points within a one-degree direction of the hurricane best-track data points were labeled with 1s (RI event) and 0s (non-RI event). The GLM test was also performed to evaluate the statistical significance of the five variables as predictors for each RI event.

Table 1. RI hurricanes RI events paired with non-RI hurricanes 24-hour periods.

RI		**Non-RI**	
Hurricane	*Year*	*Hurricane*	*Year*
Tomas	2010	Rafael	2012
Karl	2010	Ingrid	2013
Rina	2011	Alex	2010
Danny	2015	Maria	2011
Irma	2017	Isaac	2012
Michael	2018	Hermine	2016

To determine whether the BLT measured during the 20 RI events in the six hurricanes was significantly different than during a non-RI event, six additional hurricanes were selected for comparison. To provide the best possible comparison, these six non-RI hurricanes had to occur between 2009 and 2018, not experience any RI events, and have a track that came within 100 miles of one of the 20 RI events analyzed. Each RI hurricane was matched with a non-RI hurricane from a different year (Table 1). Since an RI event is a 24-hour occurrence, a corresponding 24-hour period was selected from each of the non-RI hurricanes based on closest proximity to RI events occurring during the six RI hurricanes.

PCA was conducted on the six non-RI hurricanes to determine which factors had the greatest influence on controlling the variances within each HYCOM dataset associated with each selected 24-hour period. It was also used to create PCA plots for data points associated with each 24-hour period to give a visual representation of how the data points were grouped based on the values of the five oceanic factors.

Datasets from each RI/non-RI hurricane pair were combined and tested using GLM and paired t-test analysis. GLM analysis was conducted to show which of the five variables had the largest influence on the probability of the RI event to occur. The exponential value of estimates was calculated for each variable to determine how increasing that variable by one unit affected the probability of an RI event. The variable with the largest value produces the greatest likelihood of the RI event to occur as a predictor.

The paired t-test was conducted to show the difference of each variable between the RI hurricane and the non-RI hurricane.

It is important to note that this method is new and non-verified, and the results should be considered accordingly. This method sought to determine if the horizontal distribution and variability of the five oceanic factors relates to RI. For example, as a storm rapidly intensifies, a thicker BLT over a larger area may prevent surface cooling from both subsurface water and air-sea heat flux, thereby increasing the probability of an RI event to occur. The results of this study can be compared to previously published works on RI but cannot be used to validate or invalidate them.

3. Results

3.1 Principal Component Analysis (PCA)

The results of the PCA showed that, in some cases, BLT was the most important factor to certain PCs during an RI event. For example, during Hurricane Irma's RI event on August 31, 2017, BLT was the most important factor for PC2, with the largest absolute value of [0.83972772]. However, the coefficient value for BLT in PC2 is negative, meaning that BLT is negatively correlated with PC2; as PC2 increases, BLT decreases (Table 2). Furthermore, BLT had no correlation with mld, a slight negative correlation with T and mlp, and then slight positive correlation with S (Figure 9a and 9b). The BLT (within the green oval) was relatively thicker than at other data points during this RI event, typically around 10m. Within the area of thicker BLT, Ts were slightly warmer, and S was slightly lower than other areas during the RI event (Figure 9a and 9b), which allowed for an increase of 45 kts.

Table 2. (Top) Eigenvalues generated in RStudio for Hurricane Irma's RI event on August 31, 2017. PC1 and PC2 have values greater than 1 and were therefore included in the analysis. (Bottom) Coefficients for each variable in both PC1 and PC2. Here mld is chosen for PC1, and BLT is chosen for PC2, as they control the most variance within their respective PCs.

	PC1	PC2	PC3	PC4	PC5
Eigenvalues	2.762831156	1.22079793	0.834023585	0.180327708	0.002019621

	PC1	PC2
salinity	-0.482982	-0.28112723
temp	0.50224792	0.20850537
mlp	-0.50340215	0.41223553
mld	-0.50627693	-0.04911433
BLT	0.06888658	-0.83972772

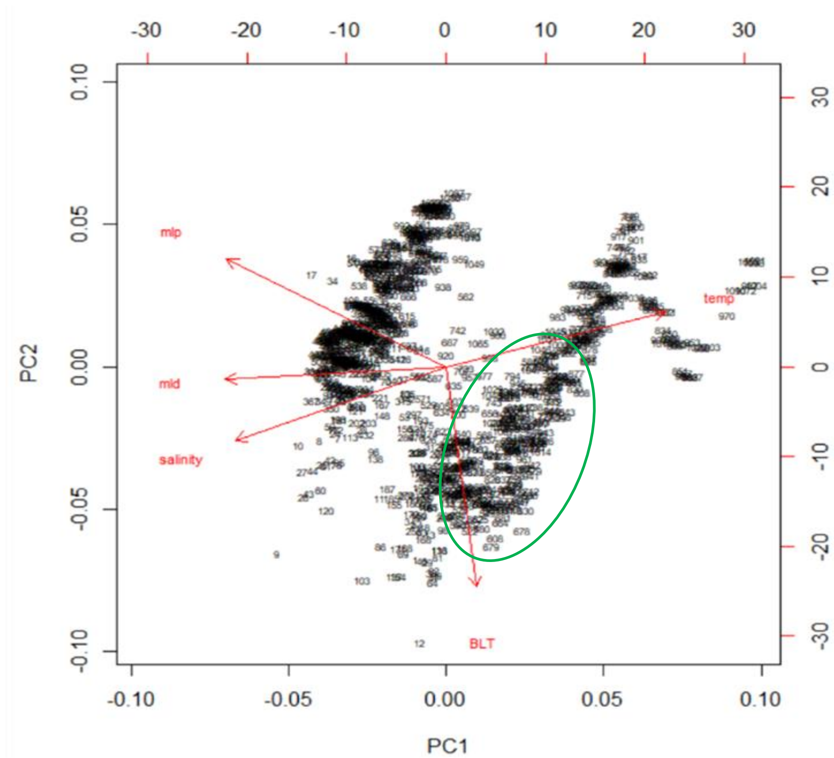

Figure 9a. Graph produced by plotting PC1 (mld) vs PC2 (BLT) for Hurricane Irma's RI event on August 31, 2017. The clustering of data points within the green oval indicates relatively warmer waters, lower salinity, and thicker BL.

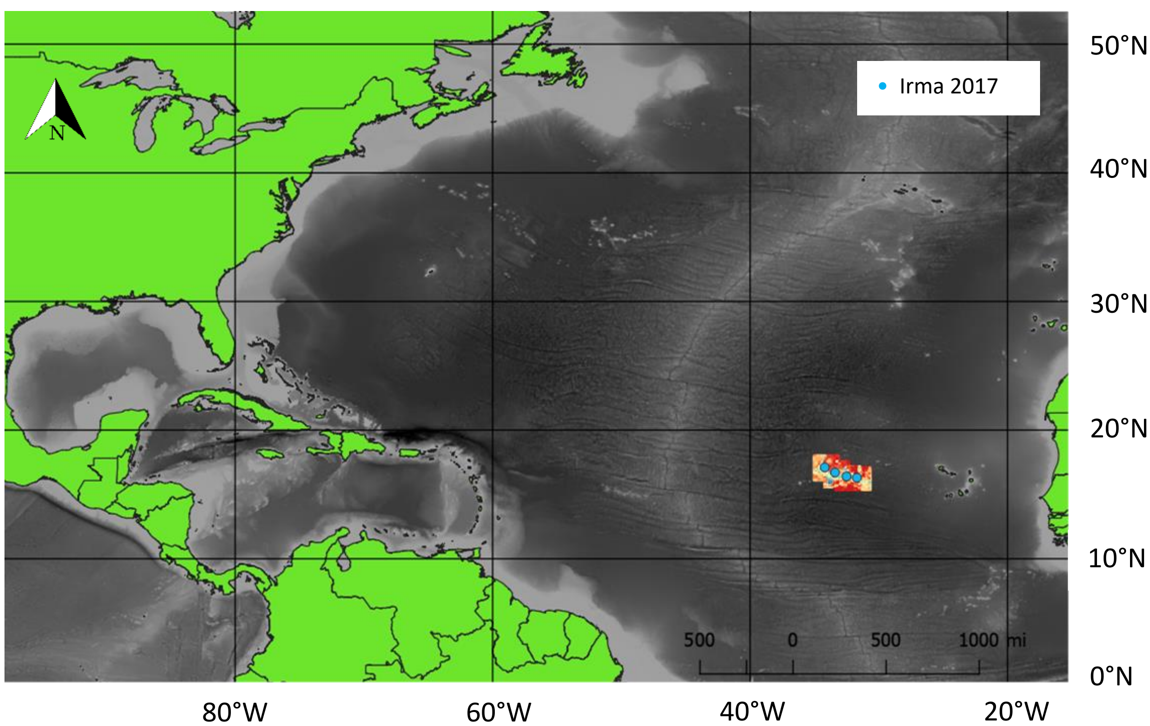

Figure 9b. Map of RI Hurricane Irma August 31, 2017 with all the data points used for the PCA. The data points shown represent the BLT with blue being the thickest and red being the thinnest.

Another example is Hurricane Michael's RI event on October 9, 2018. With the highest absolute value of [0.7507375], BLT was the most important factor for PC2. The coefficient value for BLT in PC2 was positive, meaning BLT is directly and positively correlated to PC2; as PC2 increases, BLT also increases (Table 3). Furthermore, there was a strong negative correlation between BLT and S, a slight negative correlation between BLT and mlp, and a slight positive correlation between BLT and mld and T (Figures 10a and 10b). Compared to the other data points within the RI, BLT (within the green oval) was relatively thinner, about 9m thick. This is similar to the Hurricane Irma example above, which is consistent with a previous study suggesting thinner, weaker BLs favor RI (Yan et al., 2017). Data points showed this area of the sample had lower T and higher S levels (Figures 10a and 10b) during the RI event, which allowed for an increase of 35 kts. These conditions normally counteract hurricane intensification, indicating Hurricane Michael's RI event was controlled by some other factors.

Table 3. (Top) Eigenvalues generated in RStudio for Hurricane Michael's RI event on October 9, 2018. PC1 and PC2 have values greater than 1, therefore these PCs are kept. (Bottom) Coefficients for each variable in both PC1 and PC2. Here mld is chosen for PC1, and BLT is chosen for PC2, as they control the most variance within their respective PCs.

	PC1	PC2	PC3	PC4	PC5
Eigenvalues	1.961785546	1.208085257	0.929836144	0.900090179	0.000208404

	PC1	PC2
salinity	0.07693846	-0.5504161
temp	0.25595597	0.1105665
mlp	0.63140641	-0.3345258
mld	0.69682566	0.0964512
BLT	0.21053969	0.7507375

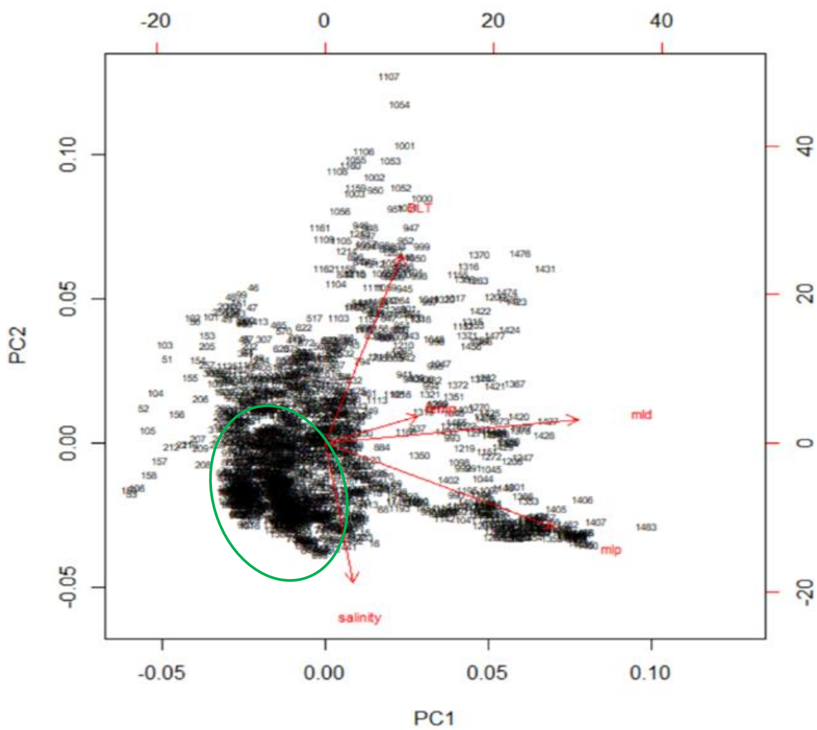

Figure 10a. Graph produced by plotting PC1 vs PC2 for Hurricane Michael's RI event on October 9, 2018. The clustering of data points within the green oval indicates relatively thinner BL, cooler waters, and higher salinity.

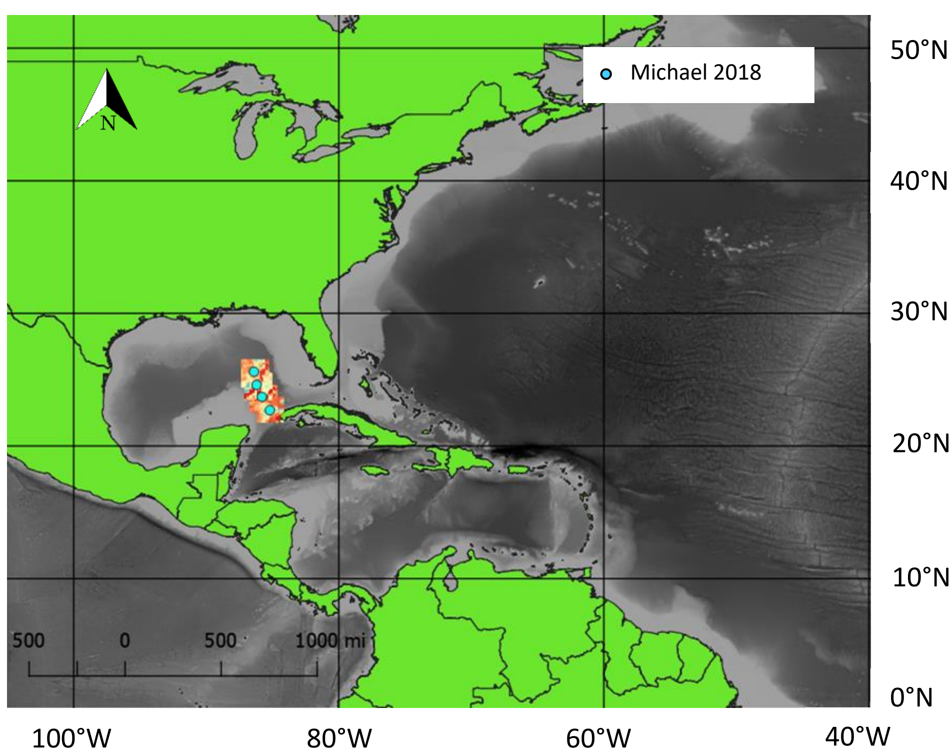

Figure 10b. Map of RI Hurricane Michael October 9, 2018 with all the data points used for the PCA. The data points shown represent the BLT with blue being the thickest and red being the thinnest.

Each 24-hour RI event the PCA was performed had one of eight combinations of S (high, low), T (warm, cool) and BLT (thin, thick): low-cool-thin, low-warm-thin, high-cool-thin, high-warm-thin, low-cool-thick, low-warm-thick, high-cool-thick, high-warm-thick. Examining each of these combinations, there seemed to be no relationship between the combination and the magnitude of storm intensification or month of occurrence.

Using PCA, BLT had the largest absolute value, making it the most important factor for PC2 in four (Maria, Hermine, Alex, Ingrid) of the six non-RI hurricanes examined. For example, examining data from non-RI Hurricane Maria (Sept. 8, 2011), the coefficient for BLT in PC2 was negative [-0.757703752], meaning BLT was negatively correlated with PC2; as PC2 increased, BLT decreased (Table 4).

Additionally, related to the other oceanic variables, BLT had no correlation with T, a slight negative correlation with mlp, and a moderate positive correlation with S and mld. The dense clustering of points away from BLT (Figures 11a and 11b) indicates the BLT was thinner during non-RI Hurricane Maria. In the same area, T was slightly cooler and S slightly lower.

PCA measures how important a variable is for a specified dimension, and therefore cannot give a definitive answer to whether BLT affects RI. The PCA plots how all variables change and relate to the RI event. In order to understand whether the variables significantly predicted the RI events, additional analysis using GLM was required.

Table 4. (Top) Eigenvalues generated in RStudio for Hurricane Maria on September 8, 2011. PC1 and PC2 have values greater than 1, therefore these PCS are kept. (Bottom) Coefficients for each variable in PC1 and PC2. Here mlp is chosen for PC1, and BLT is chosen for PC2, as they control the most variance within their respective PCs.

	PC1	PC2	PC3	PC4	PC5
Eigenvalues	2.137293511	1.49240441	0.86817496	0.501287433	0.000839686

	PC1	PC2
salinity	-0.244249	-0.413206512
temp	-0.543162	-0.007056
mlp	0.6003404	0.1645298
mld	0.529765	-0.47752
BLT	-0.0652522	-0.757703752

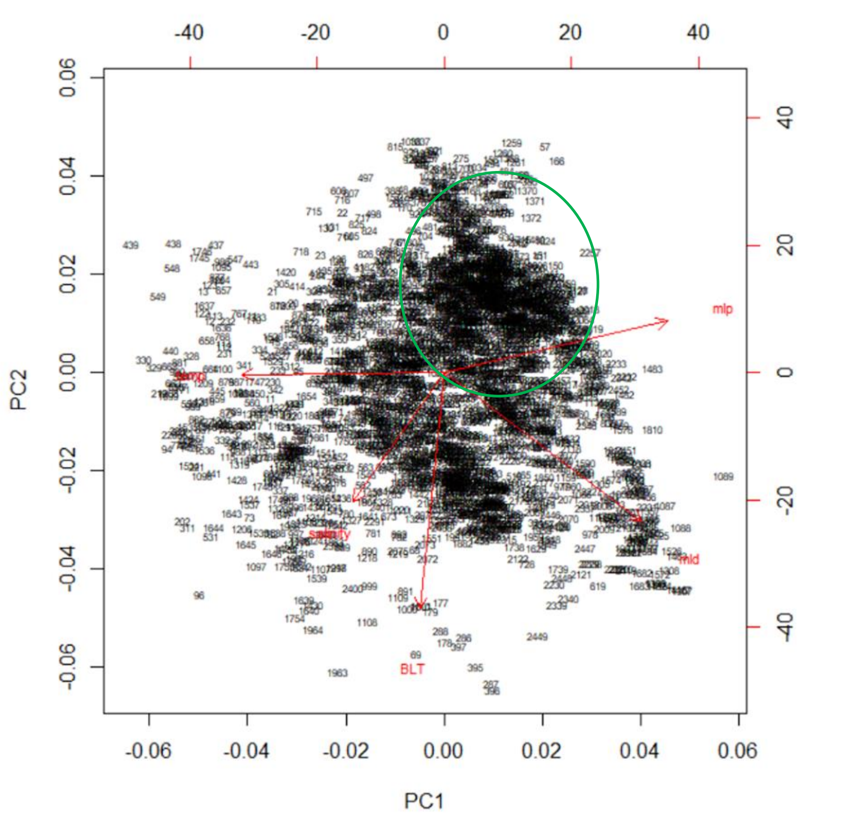

Figure 11a. Graph produced by plotting PC1 (mlp) vs PC2 (BLT) for Hurricane Maria 24-hour event on September 8, 2011. The clustering of data points within the green oval indicates slightly cooler waters, lower salinity, and thinner BL.

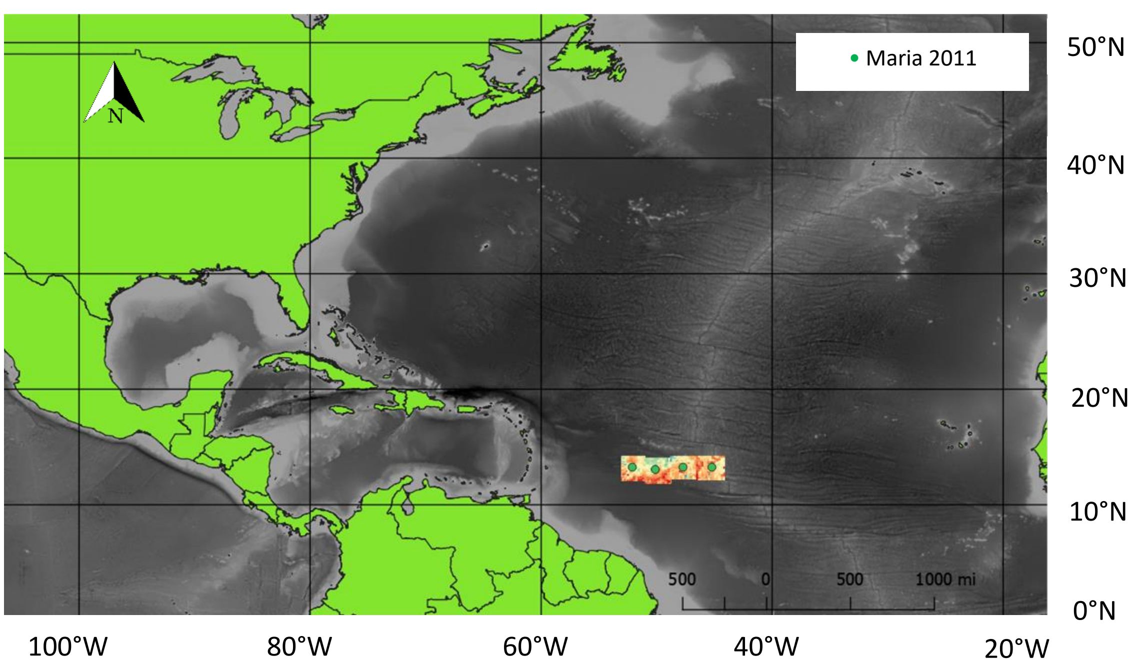

Figure 11b. Map of non-RI Hurricane Maria September 8, 2011 with all the data points used for the PCA. The data points shown represent the BLT with blue being the thickest and red being the thinnest.

3.2 Generalized Linear Model (GLM)

The results of the GLM indicated BLT might have been a significant predictor (p-value < 0.05) in two of the 20 (10%) RI events included in the analysis: August 21, 2015 (Hurricane Danny) and August 31, 2017 (Hurricane Irma).

In the Hurricane Irma example, each of the five variables appeared to be a significant predictor for the RI event (Table 5), including BLT, S and water T, which the PCA showed to be relatively thicker (~10m), lower and warmer, respectively (Figures 9a and 9b). It should be noted that the largest intensity increase (45 kts) during Hurricane Irma occurred over this same area of BLT. For this RI event, increasing BLT by one of its units (1m) increased the likelihood of the RI event to occur by 1.5x. Compared to the other variables, BLT seemed to have the largest effect on the probability of the RI event to occur.

Table 5. Binomial GLM analysis of the oceanic factors with p-values showing that each factor is a significant predictor for Hurricane Irma's RI event on August 31, 2017. Red type highlights significant p-values (<0.05).

Coefficients	Estimates	St.d Error	z value	pr(>|z|)	
Intercept	52.67695	6.99991	7.525	5.26E-14	***
salinity	-1.78157	0.17325	-10.283	< 2e-16	***
temp	0.21153	0.05542	3.817	0.000135	***
mld	-0.28108	0.10812	-2.6	0.009332	**
mlp	0.39846	0.10826	3.681	0.000233	***
BLT	0.34695	0.10804	3.211	0.001322	**
Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					

During Hurricane Michael's RI event (Oct. 9, 2018), each variable was a significant predictor, except for BLT (Table 6). Unlike the Hurricane Irma event, the PCA showed S was higher and water temperature was lower, but BLT was similar (~9m) (Figures 10a and 10b). The fact that BLT was not a significant predictor of the Hurricane Michael event is inconsistent with but does not invalidate previous research (Yan et al., 2017).

The results of the PCA and GLM tests provided additional information on which of the oceanic factors in this study may have been significant predictors for RI events. The only variables that appeared to significantly predict each of the 20 RI events were T and S. Temperature is a known key component to hurricane RI, but S was an unexpected significant factor. BLT did not appear to be a significant predictor in a majority of RI events from 2009-2018.

Table 6. Binomial GLM analysis of the oceanic factors with p-values showing which factors were significant predictors for Hurricane Michael's RI event on October 9,2018. Red type highlights significant p-values (<0.05). BLT was not a significant predictor for the RI event to occur.

Coefficients	Estimates	St.d Error	z value	pr(>|z|)	
Intercept	-47.165	5.49824	-8.578	< 2e-16	***
salinity	2.21546	0.156	14.202	< 2e-16	***
temp	-1.23416	0.03958	-31.181	< 2e-16	***
mld	-0.21089	0.10458	-2.017	0.0437	*
mlp	0.21347	0.10458	2.041	0.0412	*
BLT	0.17273	0.10449	1.653	0.0983	.
Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					

Examining the 20 RI events, increasing T by 1°C had the largest effect on the probability of the RI event to occur nine times, increasing the likelihood between 2x to 14.5x. Increasing S by one of its units (1psu) had the largest effect on the probability of an RI event to occur seven times, increasing anywhere between 1.5x to 9x more likely. Increasing BLT by one unit (1m) had the largest effect on the probability of an RI event to occur four times, but only about 1x to 1.5x more likely. In six of the 20 RI events, when BLT did not have the largest effect on probability, increasing BLT by one unit decreased the likelihood of the RI event to occur.

When examining GLM results from the combined RI and non-RI hurricane data, it was observed that between non-RI Hurricane Maria and Hurricane Danny, temperature had the largest influence on the probability of Danny's RI event to occur. However, increasing temperature by 1°C decreased the likelihood for the RI event to occur. Results from the paired t-test gave a similar indication, due to significantly lower ($p<2.2e-16$) Ts during Danny's RI events than non-RI Hurricane Maria. It should be noted that during Danny's RI events BLT was significantly thinner than non-RI Hurricane Maria.

Looking at both the GLM results of the combined RI and non-RI hurricane data and paired t-test for Hurricane Tomas and non-RI Hurricane Rafael, BLT seemed to have the largest influence on the probability of the RI event to occur. The GLM results showed that increasing BLT by 1m increased the likelihood of the RI event to occur, which was also indicated by the paired t-test showing that during Tomas's RI events (October 29, 30) BLT was significantly thicker ($p<2.2e-16$) than during non-RI Rafael.

Comparing Hurricane Irma and non-RI Hurricane Isaac, GLM results appeared to show that during Irma's Sept. 4 and Sept. 5 RI events, S and T had the largest influence on the probability of the RI event to occur, respectively. As both S and temperature increased by one of their respective units, compared to those values during Hurricane Isaac, the likelihood of the RI event to occur increased. This again is supported by the paired t-test results showing that S was significantly higher ($p<2.2e-16$) on Sept. 4 and T was significantly higher ($p<2.2e-16$) on Sept.5, compared to non-RI Isaac. It should also be noted that the BLT during these RI events was significantly thinner than during non-RI Hurricane Isaac.

Hurricane Michael's comparison to non-RI Hurricane Hermine using GLM appeared to show that S was the largest influencing factor on the probability of Michael's RI event. As S increased by 1psu, the likelihood of the RI event increased. It was also seen that S during all of Michael's RI events were significantly higher ($p<2.2e-16$) than those during non-RI Hurricane Hermine. However, it is interesting that BLT was significantly thinner in Michael's early RI events.

Comparison between Hurricane Danny and non-RI Hurricane Maria led to interesting results. When looking at the PCA results from non-RI Hurricane Maria, it appeared the BLT was thinner (~10m), which is similar to both Hurricane Irma and Michael during their RI events. However, Hurricane Maria did not go through an RI event. T-test results showed the BLT during Hurricane Danny's RI events was significantly thinner than that during non-RI Hurricane Maria.

It is important to note that although BLT did not always appear to have the largest influence on the probability of an RI event to occur, when comparing RI hurricanes to non-RI hurricanes with similar tracks, BLT was either significantly thinner or significantly thicker in exactly half of the 20 RI events compared to their respective non-RI hurricanes. Also, there were six instances where an increase in BLT led to a decrease in the likelihood of the RI event, even though BLT might not have been the most influential factor on the probability of the RI event.

3.3 Qualitative Analysis

Qualitative analysis conducted on the 139 hurricanes from 2000-2018 showed that BLs existed at some point during all hurricanes.

The average BLT and intensity increase over the lifespan of the six RI-hurricanes scrutinized in this study were plotted to determine if there was any relationship between the BLT and magnitude of intensity increase (Figure 12). The increase in intensity over a 24-hour period was measured by determining the difference between wind speed at 12 hours before midnight and 12 hours after midnight. For example, to get the change in intensity during Hurricane Irma on August 31, 2017, the difference in wind speed between August 30 at 12 p.m. and August 31 at 12 p.m. was calculated. In some cases, wind speed decreased (Figure 12), indicated by negative values. It should also be noted that this method of measurement disallowed the proper display of RI events that started at times other than 12 p.m. For instance, during Hurricane Irma (2017), one RI event occurred between 6 a.m. on Sept. 4 and 6 a.m. Sept. 5, and so was not included (Figure 12). When examining the average BLT against the intensity increase of the six randomly selected RI hurricanes, it appeared that most RI events happened between 10-15m (Figure 12). However, the lack of a significant number of hurricanes examined in this manner discounts any significant conclusions when many other factors are involved in RI.

Analysis of the distribution of RI events showed that 52% of the hurricanes from 2000-2018 that went through RI occurred in the Atlantic Ocean, Gulf of Mexico, and Caribbean between 10°N - 20°N, where BLs are more prominent (Pailler, 1999) (Figure 2). The other 48% of hurricanes from 2000-2018 that underwent RI occurred above 20°N, where BLs are not as prominent features.

The results of the t-test seem to indicate no relationship between BLT and the location of an RI event. For example, in the Gulf of Mexico, BLT was significantly thinner for some RI events and significantly thicker for others.

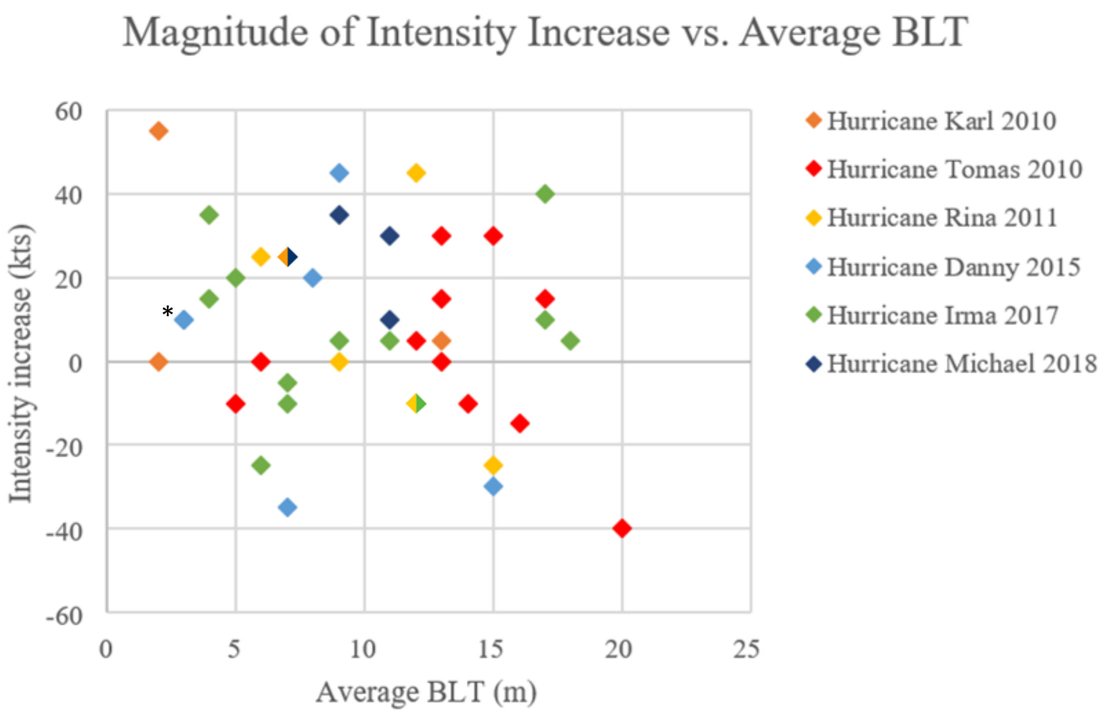

*Figure 12: The average BLT plotted against the intensity increase over the lifespan of the six RI-hurricanes scrutinized in this study: Hurricane Karl 2010 (orange), Hurricane Tomas 2010 (red), Hurricane Rina 2011 (yellow), Hurricane Danny 2015 (light blue), Hurricane Irma 2017 (green), Hurricane Michael 2018 (dark blue). Points with two colors indicate overlapping data points. * Two overlapping data points occurring during Hurricane Danny.*

4. Discussion

There are many studies giving conflicting conclusions on the subject, with some suggesting BLs favor RI (Balaguru et al., 2012; Grodsky et al., 2012; Yan et al., 2017) and others suggesting BLs have little, if any, impact on hurricane intensity (Hernandez et al., 2016). Based on the preliminary results of this study, the presence of a BL does not seem to determine the occurrence of an RI event, nor does it appear that BLs influence the magnitude of intensity increase during hurricane RI events, but these results cannot be taken as definitive. Furthermore, as one of the oceanic factors examined in this study, BLT does not appear to serve as a significant predictor for RI events, nor affect the magnitude of intensity increase during those events. However, BLT does give the impression it influences the probability of an RI event occur, as seen when comparing the RI hurricanes to non-RI hurricanes.

The comparison also shows there is a significant difference between S, T, and BLT between RI and non-RI hurricanes. As mentioned earlier, when comparing an RI hurricane with its non-RI counterpart, BLT was significantly thicker exactly half of the time. This is not consistent with the results of the Yan et al. (2017) study suggesting thinner weaker BLs favor RI.

It appears not all hurricanes are affected by S, T, and BLT equally or even in the same manner. From this study, however, it appears that these oceanic factors do influence hurricane intensity, and that S and BLT might play a role in RI. In light of other research that indicates there are multiple factors that influence hurricane RI (Emmanuel, 2004; Balaguru, 2018), and the results of this study, it is clear additional research into the complex interactions between BL and these factors is needed to better determine their individual and combined impact on hurricane RI.

Based on the limited statistics used in this study, no relationship or significant dependence of RI on BLT was found. Similarly, no clear relationship between BLT and decrease in intensity was found (Figure 12). The results and conclusions must be taken as possible correlations since there is no known link between RI and the horizontal variability of BLT and the other key factors near the center of a hurricane (within 1 degree lat/lon) and cannot be used to validate or invalidate previous works.

Barrier Layers

Examination of BLs and BLT over the Atlantic Ocean, Caribbean, and Gulf of Mexico showed that BLs can exist in any regions but are constantly shifting both vertically and horizontally. It was also observed that BLT was typically thicker (average 21m) within the Caribbean and West Atlantic near the Caribbean islands out to about 50°W; whereas BLT was much thinner (average 6m) in the Gulf of Mexico and Central and East Atlantic Ocean (east of 50°W). The reason for the thicker BLs in the Western Atlantic and Caribbean is due to high precipitation, high evaporation rates, and the North Brazil Current delivering freshwater discharge from the Amazon/Orinoco Rivers (Araujo et al., 2011; Grodsky et al., 2012).

Given the apparent even distribution of RI events between 10°N and 20°N and above 20°N (Figure 3), it cannot be concluded that one region favors RI more than the other. Every hurricane between 2009 and 2018 passed over a BL at least once during its existence, but 25% did not experience a period of RI. Simply having a BL near or in the path of a hurricane does not mean it will trigger RI, which supports studies showing multiple factors control hurricane RI, and many factors contribute to hurricane RI (Emmanuel, 2004; Balaguru, 2018).

Warm ocean Ts are known to be key factors in hurricane RI (DeMaria and Kaplan, 1993; Shapiro and Goldenberg, 1998) and was a significant predictor for all RI events in this study. According to Balaguru et al. (2018), there has been no trend of increasing RI magnitude in the western Atlantic, Caribbean, and Gulf of Mexico over the last 30 years. However, in the central and eastern tropical Atlantic, there has been an increase in RI magnitude, as well as an increase in ocean Ts by 0.25°C per decade. Balaguru et al. (2018) also showed that tropical cyclone heat potential over the same area increased 2.9 kJ/cm^2 per decade. Tropical cyclone heat potential increases with increased ocean Ts and a deepening isothermal layer. Since BLs can support T inversions, which allow for an increase in mixed layer water Ts if the BL is penetrated by hurricane wind-driven currents, BLs may have an underlying, indirect influence on the recent increase of RI events in the central and eastern tropical Atlantic.

<u>Barrier Layer Thickness</u>

The PCA and GLM analyses conducted indicate BLT was not a significant predictor for RI events occurring during the six storms scrutinized in this study.

It is interesting that BLT was a significant predictor for the Hurricane Irma RI event (August 31, 2017) east of 40°W in the Atlantic, as it is more typical to see RI events west of 40°W (Figure 7), and BLs seemed to be more prominent in the west and central Atlantic.

During all other RI events studied, except Hurricane Danny (August 21, 2015), BLT did not appear to be a significant predictor for the RI event on each given day (p-value > 0.05). During Hurricane Michael, BLT was not a significant predictor for the RI event that led to the first Category 5 hurricane to make landfall since Hurricane Andrew (Table 6). The GLM analysis appears to show that T and S were significant predictors for the RI event to occur.

Although the BLT for Hurricane Michael (October 9, 2018) was similar to that of Hurricane Irma's BLT (August 31, 2017), GLM analysis appears contradictory, showing it was not a significant predictor for Hurricane Michael's RI event. Comparing GLM results to the PCA test for the same RI event (Figures 10a, Table 6) appears that the relatively thinner BLT is not a significant predictor for the RI event. However, the increase in intensity over this 9m thick BL did allow for the largest increase (35 kts) of any RI event during Hurricane Michael.

It should be noted that, given its known interactions with T and S, which appear to significantly predict RI events, it is possible that BLT may improve prediction of those events. S, which determines both ocean density and BLT, appeared to be a significant predictor for all hurricane RI events. The relationships between T and S indicate BLT could affect hurricane RI on a level that is yet unknown.

Of the 20 RI events in the six hurricanes examined in this study, only 10% seemed to indicate BLT was a significant predictor for the event. However, given S's unexpected role as a predictor of RI events in this study, and its role in the formation of BLs, BLT should be tested in intensity models as a factor that might have an underlying influence on hurricane RI events. The possibility of better understanding and improving RI predictions, even in the slightest, justifies additional research.

In some cases when the magnitude of the intensity increase was greatest during an RI event, the BLT was typically ~10m thick. Hurricane Rina experienced an increase in intensity of 50 kts over a 10m thick BL, and Hurricane Danny increased 45 kts over a 10m thick BL. However, some of the greatest intensity increases (+65 kts) over a 24-hour period were over BLs about 15m thick. There were also instances where the largest intensity increase was over BLs thinner than 5m. Based on these observations, there appears to be no correlation between the magnitude of intensity increase and BLT. However, of the six RI hurricanes examined in this study, most of the RI events occurred over BLs between 10-15m. Large increases in intensity can occur over any variety of BLT, and the size of the intensity increase is dependent on other factors such as ocean T, relative humidity, and vertical wind shear, hurricane structure, and inner-core processes (DeMaria and Kaplan, 1993; Rogers et al., 2015).

Of the 20 RI events studied, BLT had the largest effect on RI event probability four times. Of those four, increasing BLT by 1m improved the likelihood of an RI event three times, but in one instance decreased the likelihood. For example, during Hurricane Irma's August 31 RI event, where BLT was a significant predictor, increasing BLT would increase the likelihood of the RI event by 1.5x. However, during Hurricane Michael's October 9 RI event, which was over a similar BLT but not a significant predictor, S had the largest effect on the probability of the RI event to occur. Increasing S by 1 psu would increase the likelihood of the RI event by 9x.

Role of Known Factors

Other factors more important than BLT are required for hurricanes to go through RI, such as low vertical wind shear (less than 10 kts), high relative humidity at mid-levels (>70% near 500-700mb), and warmer ocean Ts (Cangialosi, personal communication, 2018; Shapiro & Goldenberg, 1998).

Vertical wind shear is a known influential factor on hurricane intensity and is one of the factors used in predicting hurricane intensity and RI (Tao & Zhang, 2015). Large errors in vertical wind shear prediction lead to increased error in predicting RI events, and through examination of the combined interactions of moist convection and vertical wind shear it was found that small initial minute perturbations in low-levels can lead to variations in RI onset (Tao & Zhang, 2015).

During initial analysis of Hurricane Michael, it was mentioned that vertical wind shear was much too strong to allow for RI. However, during post hurricane analysis the vertical wind shear was examined at a much closer scale, which showed that prior to Hurricane Michael becoming a Category 5, it experienced a period of low vertical wind shear conducive to RI (Cangialosi, 2018).

An understanding of the relationship between relative humidity and other large-scale environmental factors, and hurricane intensity and intensification rate is important for statistical hurricane intensity forecast models (Wu et al., 2012). High mid-tropospheric relative humidity has appeared to be necessary for RI and attaining maximum intensity, where dry air intrusion has a negative effect on intensification. It has been shown that rapidly intensifying tropical cyclones are associated with higher relative humidity levels rather than weaker tropical cyclones (Wu, 2012).

The dependence of hurricane intensity on SST has been well documented (DeMaria & Kaplan, 1993). It plays a key role in the inter-annual variability of hurricane frequency and intensity as well as a direct role in providing moist enthalpy (e.g. heat flux) to help intensify hurricanes (Sun et al., 2007).

As mentioned earlier, SST and other oceanic factors are the most important predictors in the SHIPS model (Kaplan & DeMaria, 2003). However, it has been noted that SST alone cannot induce RI (DeMaria & Kaplan, 1993). In the previous study (Sun et al., 2007), it has been suggested that the spatial location of high SST anomalies with regards to the storm track may be an important factor for hurricane intensification.

Based on the results of GLM analysis of the hurricane RI events, T seemed to be the most influential factor on the probability of occurrence in nine events, therefore making it the most influential factor of all 20 events. This is consistent with the knowledge that warm ocean T is a key factor for RI events to occur. However, it is rather unexpected that S appeared to be the second most influential factor on probability of an RI event, occurring within seven of the 20 RI events. This suggests S may be an important factor affecting RI events and might be useful as a predictor for hurricane intensity. Taking the exponential function of the estimates from the GLM analysis of RI events only, as T and S increase by one unit respectively, the likelihood of the RI event increases. However, in some instances where T and S were not the most influential factors, an increase in these two variables resulted in a decreased likelihood of the RI event to occur. Therefore, without further study, it cannot be concluded that increasing T and S result in an increased probability of an RI event in hurricanes across all ocean basins.

These known factors are important for hurricane RI and more research needs to be done to better understand their impact on hurricane intensity. Errors in intensity prediction and issues related to these factors should be addressed so that hurricane intensity predictions can become more accurate and precise.

Comparing RI and non-RI Hurricanes

Although based on non-verified methods, comparison of the six RI hurricanes to the six non-RI hurricanes following a similar track to the RI events showed the difference of the oceanic factors, namely S, T, and BLT, between the corresponding storms. Results are not definitive, but in all cases, every oceanic factor appeared to be significantly different between the paired RI and non-RI hurricanes.

GLM analysis appears to show that S and T were the only significant predictors when comparing an RI event to a non-RI hurricane over a similar track. It also showed which variable had the largest effect on the probability of the RI event to occur when compared to a non-RI hurricane. In the five instances where S had the largest effect, as S increased by 1 psu, the likelihood of the RI event also increased. Likewise, in the five instances where T had the greatest influence, an increase in 1°C increased the likelihood of the RI event. However, in two instances (both when comparing Hurricane Danny to non-RI Hurricane Maria), when T increased by 1°C, the likelihood of the RI event decreased.

In the GLM analysis, it appeared that there were six instances where an increase in BLT led to a decrease in the likelihood of the RI event, even though BLT was not the most influential factor on the probability of the RI event.

The resulting paired t-test of the six sets of matched hurricanes provided interesting results. Again, all variables appeared to be significantly different between the RI hurricane and its respective non-RI hurricane. In nearly every RI to non-RI comparison (85%), the variable that had the largest influence on the probability of the RI event coincided with the paired t-test showing which variables were significantly higher or lower between RI and non-RI hurricanes. For example, comparing Hurricane Michael and non-RI Hurricane Hermine, S had the largest effect on probability in all RI events, with an increase in 1psu leading to an increase in the likelihood of the RI event, and S during Hurricane Michael was significantly higher than during Hermine. Comparing Hurricane Danny and non-RI Hurricane Maria, T had the largest influence on the probability of RI, with an increase of 1°C leading to decrease in the likelihood of the RI event, and T during Danny's RI events was significantly lower than during Hurricane Maria. These are preliminary results only, which may provide useful information for future studies and forecast models.

4.1 Limitations and Recommendations for Future Research

This study focused on hurricanes in the Atlantic Ocean basin, Caribbean, and Gulf of Mexico from 2000-2018, examining only oceanic factors (S, T, mld, mlp, and BLT); atmospheric and climatological factors known to affect RI were beyond the scope of the study. Previous studies have shown that different stages of tropical cyclones (tropical depression, tropical storm, hurricane) react differently with oceanic and atmospheric factors (Yan et al., 2017; Kaplan and DeMaria, 2003; Shu et al., 2011). Therefore, the results and conclusions of this and other studies in the Atlantic Ocean cannot be applied to tropical cyclones in the Pacific and Indian Oceans, as predictors and models differ between the basins (Shu et al., 2011).

The method used in this study is new and non-verified, and the results should be considered accordingly. There is also no known mechanism relating the PCA horizontal statistics of BLT, T, S, mld, and mlp to the hurricane RI. The results of this study can be compared to previously published works on RI but cannot be used to validate or invalidate them. The method used in this study does not incorporate any atmospheric parameters or vertical mechanism. It does, however, incorporate a previously untested horizontal mechanism, giving preliminary results that could be added to an existing forecast model. This could provide new and valuable information for future studies, but the results from this study cannot be taken as definitive.

Future studies attempting to relate BLs to hurricane RI should incorporate BLT and its interaction with ocean T, as well as its effects on relative humidity, air-sea fluxes, vertical mixing, and atmospheric conditions. To fully understand all factors that affect RI, a full study needs to unite all known factors that impact hurricane intensification, including both positive and negative forces: vertical wind shear, relative humidity, ocean T, hurricane structure, air-sea flux, vertical mixing, and other climatological factors.

These interactions should be tested using multiple intensity models throughout all ocean basins where there is high hurricane activity. The individual factors along with every possible combination of interaction should be tested to determine which should be incorporated into current hurricane intensity models to improve accuracy and lead time. This could dramatically improve our understanding of how all the influential factors interact to impact hurricane intensity.

As mentioned earlier, no current intensity model can accurately predict/forecast hurricane RI events, nor has any method examined the horizontal BLT distribution impact on hurricane RI.

Given the complexity and limited understanding of RI, even the smallest of interactions could play an important role in hurricane intensity. For example, if a future study determines that the interactions between vertical mixing, air-sea flux and relative humidity strongly contribute to hurricane intensity, a mathematical equation could be formulated and incorporated into new statistical-dynamical models (e.g. SHIPS). If it can improve our understanding or forecasting ability even in the slightest, additional research into RI should be conducted. Any additional insight into improving the prediction of RI events could prove critical for coastal communities.

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