Tropical Cyclones in the Context of Global Environmental Hazards

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1. Introduction

In recent decades, researchers have noted unique changes in tropical cyclone (TC) characteristics as global atmospheric and sea surface temperatures continue to increase (Biasutti, et al., 2011; Bacmeister, et al., 2018; Mudd, et al., 2014; Saunders, et al., 2008). The changes observed in TC magnitude and frequency can be attributed to a range of possible attributes and, most likely, result from any number of combination of factors. This includes changes in sea surface temperature (SST), salinity levels, atmospheric temperature, land use changes, rising sea levels (SLR); and not only result from rapid changes made to our climate, but generate a number of unique consequence, themselves, to modern day weather events. The effects these changes have manifested, on both local and global levels, can be observed in an increasing number of *extreme* TC events, which have taken place over the course of the last century (Biasutti, 2011). The nuanced difference should be highlighted here; between an overall increase in TC activity (which, to date, has not been found) but rather an increase in TC events which are categorized at level 4 or higher (Anderson, et al., 2014). The extent to which such changes will continue to affect the magnitude and frequency of tropical cyclone activity is a crucial aspect of understanding the nature of environmental hazards and subsequently the way which we prepare for them.

Warm SST and atmospheric temperatures both serve as fundamental agents of TC formation. As global sea and atmospheric temperatures rise, the potential for TC activity increases (Donnelly, et al., 2015). Additionally, rising temperatures also contribute to the melting of glacial reserves, causing baseline sea levels around the world continue to encroach on growing populations, even without the threat of storm surges and extensive rainfall characteristic of TC events (NHC, 2008). The following sections will provide a closer look into the inner workings of tropical cyclones, geophysical influences and characteristics, as well as measurement and tracking techniques used in the field to monitor and forecast TC movement. This paper will also examine a case study which observes lightning cluster strikes and uses remote sensing data to aggregate storm strength changes and changes in direction as a method with potential to improve storm forecasting and disaster preparedness.

2. Background

2.1. Terminology

The US National Hurricane Center defines tropical cyclones as systems of thunderstorms which are generated in predominantly tropical or subtropical latitudes (NHC, 2010). TC activity can occur at any point throughout tropical and subtropical latitudes and goes by many names throughout the world;

typhoon, hurricane, monsoon and tropical storms all refer to tropical cyclones. TCs may also go by different names even within the US depending on their scale; tropical depressions refer to a TC with sustained winds that do not exceed 63 km/h, whereas a hurricane refers to a TC with sustained winds of 119 km/h. The NHC uses a definition of 'sustained winds' to refer to the US one-minute average of wind speed (NHC, 2018). There are a number of countries who regularly experience and are effected by TC activity who use a slightly different metric; some utilizing a 3-minute or 10-minute average wind speed to calculate sustained winds used to categorize a particular storm system (Schott, 2018). This can create confusion when attempting to compare international TC data or during international relief efforts (Schott, 2018). Assuming that TC activity is limited to 'the tropics' (as well as an extent of the subtropics), this paper uses the following definition of tropics; the regions of Earth that lie between the Tropic of Cancer (23.5 degrees North) and the Tropic of Capricorn (23.5 degrees South) (Rutledge, K., et al., January 2011). The subtropics, then, refer to the regions just to the north or south of those areas, respectively. Sea surface temperature (SST) is a bit more difficult to define, as the exact measure of 'surface' varies drastically among scientists and among existing literature. Current technology, including remote sensing technologies, has allowed researchers to use infrared (IR) and microwave (MW) bands of the electromagnetic spectrum to penetrate water surfaces and obtain SST readings from extremely shallow depths between 10 micrometers (IR) and 1 millimeter (MW), while other temperature acquisition methods include on-site measurements obtained by various instruments on ships or buoys (PODAAC, 2018). Sea level rise, as defined in contemporary literature is often split into two categories; the first is global sea level rise and the second is local or relative sea level rise. It is first easiest to gain an understanding of site-specific SLR which can be influenced by a variety of factors which include but not limited to; local ocean current, land height variation, erosion, subsidence, and upstream flooding (NOAA, October 2017). Global averages, then, are obtained, most often via satellite, using height of the sea as measured along coastlines in relativity to a defined location on the mainland (NOAA, October 2017). The final piece of nomenclature crucial in climatology and in studying TC activity is ENSO, or El Niño Southern Oscillation. This complex mechanism is best described as the recurring fluctuation of SST and air pressure that moves laterally across the equatorial Pacific (NOAA, 2018).

2.2. Geophysical Influences and Characteristics

Tropical cyclones begin as thunderstorms, but once they reach the warm air sitting over an already warm ocean, they gather the fuel necessary to develop into a tropical cyclone. As hot air rises, the storm draws more energy the longer it sits over the warm ocean. Due to the enormous amount of air that rises to the top of the cyclone formation, a low-pressure zone develops on the surface of the water, below the cyclonic formation. TC storm systems are manipulated by a variety of global circulation patterns such as Trade Winds, Hadley cells, the Horse latitudes and rotate counter-clockwise in the northern hemisphere, and clockwise in the southern hemisphere, as a result of the Coriolis Effect. Vertical wind shear is another driving factor in the development of TC events. Vertical wind shear refers to the speed and direction of wind at a certain altitude above the surface of the planet and has significant effects on the development of a storm. Low vertical wind shear is preferred in the case of Atlantic TCs. If wind shear is too great, the possibility of the storm dissipating increases. This relationship is akin to blowing out a candle; if there is too much wind, the light/storm disappears. Once a storm makes landfall, the intensity usually decreases; this is a result of a loss of warm water and air, as fuel. Once a storm is hovering above land, and is no longer situated above a body of water, it's energy source runs out, and the storm begins to shrink.

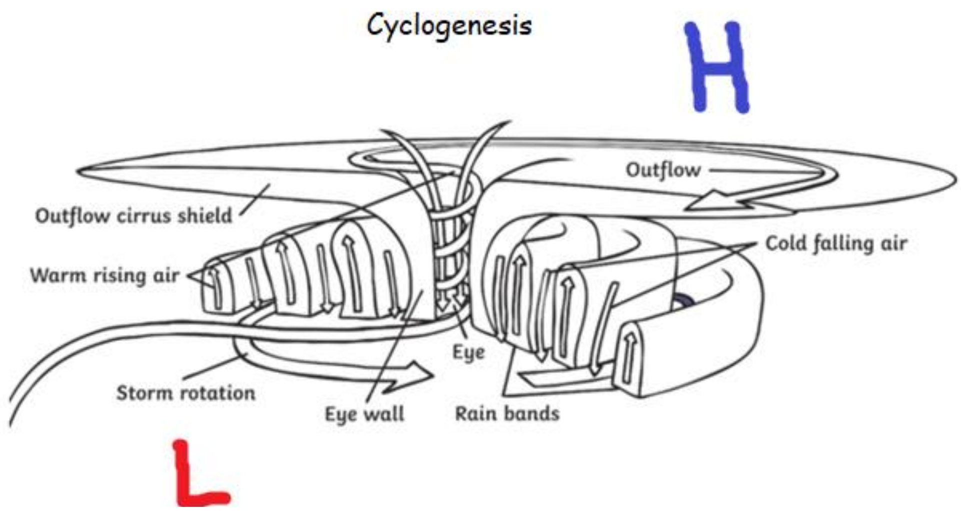


*Figure 1: Demonstrating an example of cyclogenesis. Where warmed air leaves the low-pressure (**L**) ocean surface and rises to mix with cooler air in the high-pressure (**H**) atmosphere above. Features illustrated include formation of the eye, at center, where relatively calm and clear skies occupy a smaller radius as the storm moves, the eye wall, where a large amount of energy is stored, and the outer rainbands.*

Another physical law which dictates the manner in which concentrations of high and low atmospheric pressure interact with one another; this is known as the pressure gradient force. It is comparable to spraying an aerosol and observing how the particles become dispersed from areas of high concentration to areas of low concentration in a linear fashion (NHC, 2018). Likewise, as low atmospheric pressure is generally associated with high temperatures, the spiral-like nature of a TC system draws in high atmospheric pressures from the surrounding areas, thus reinforcing the energy cycle. The mechanisms of this processes are illustrated in Figure 1. SST rise, warm moist air evaporates, creating a low-pressure area as the Coriolis effect funnels cooler, higher pressure from the surrounding areas in, warming and moisturizing it, attracting more warm air as fuel, more energy and more momentum ad nauseum. This is why TCs are sometimes also referred to by meteorologists as low-pressure systems (NHC, 2010).

Between 23 degrees north and south of the equator is the region known as the tropics, and until 35 degrees further north and south is the subtropics. Throughout tropical and subtropical latitudes, ocean temperatures typically average at around 27 degrees Celcius. Similarly, the atmospheric temperature throughout this region remains relatively constant throughout seasons; making it the perfect location for storm development (Park, et al., 2017). Moving towards the equator, very few storms have the opportunity to develop into tropical cyclones. The main reason accounting for this is a result of the Coriolis effect. The Coriolis effect is a meteorological phenomenon affecting both atmospheric currents and large bodies of water on a time-scale of about 48 hours. Within 5 degrees north and south of the equator (the equatorial region), the Coriolis effect is too weak to create the spiral-like nature which enables TC development. It is precisely due to the Coriolis effect that tropical cyclones form into storm systems; as warm water evaporates from the surface of the ocean; it rises and condenses into water vapor. The Coriolis effect ensures that this process moves in a spiral-like fashion, which then creates a draft, drawing in more warm and moist air from the ocean's surface into the cooler air above.

The subtropical and tropical regions of the planet are also subject to a number of regional atmospheric circulation patterns. Figure 2 describes a type of classification of circulation pattern known as the Hadley cell; which is characterized by trade winds moving from the northeast to the southwest (clockwise) in the northern hemisphere and from the southeast to northwest (counterclockwise) in the southern hemisphere, joining near the equator in a region known as the intertropical convergence zone (ITCZ) (PODAAC, 2018). The ITCZ previously referred to as the Intertropical Front, and by sailors as the 'doldrums,' due to the deceivingly calm nature of this highly unstable weather front, the ITCZ is a breeding ground of TC activity. As seasonal temperatures fluctuate, the extent of the ITCZ alternates between the equator and up to 45 degrees northward. Movement of the ITCZ brings with it warmer sea surface temperatures and the calm windless weather

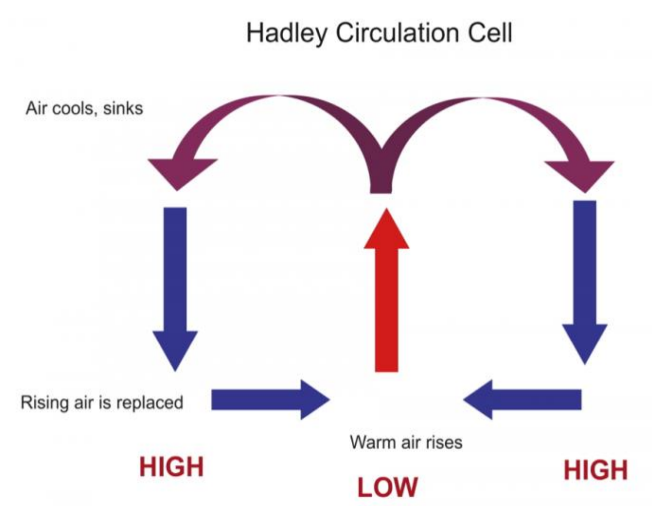


Figure 2: Hadley Cell Circulation diagram. Showing warm air rising from the low-pressure regions into cooler air, high-pressure regions before sinking and falling back towards the low-pressure regions.

allows for the previously describes trade winds to converge; following the direction of clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere. The convergence of trade wind patterns in an area with low wind shear (minimal horizontal/cross winds) over warm waters increases TC activity throughout the region it occupies. As a result of the variety in annual ITCZ location, tropical and subtropical regions of the planet to experience 'wet' and 'dry' seasons, compared to more poleward regions of the planet which are more likely to experience cold and warm seasons. The exact occurrence of ITCZ movement is correlated with the post-solar maximum of a given hemisphere's summer season (Doswell, 2015). Consequently, what many people commonly refer to as the 'hurricane season' does not occur simultaneously but rather following the warmest months, which is when ocean temperatures peak.

3. Measurement and Monitoring

3.1. Measurement Techniques

The most widely adopted measurement method in the western hemisphere is the Saffir-Simpson Hurricane Scale (SSHS), which was developed in 1971 by a structural engineer named Herbert Saffir and a meteorologist named Robert Simpson (NOAA, 2018). The method examines wind speed measurement and categorizes storms on a scale from 1-5. In order to be qualified as a category 1 hurricane, a storm much possess 1-minute sustained wind speeds of at least 119-153 km/h. Storms which exhibit wind speeds lower than this are referred to as either a tropical storm (63-118 km/h) or a tropical depression (anything up to and below 62 km/h). The scale covers wind speeds from 119-153 km/h for category 1 hurricanes, 154-177 km/h for category 2, 178-208 km/h for category 3, 209-251 km/h for category 4 and anything more than 252 km/h is considered category 5. This scale is officially used in the western hemisphere, only, but is sometimes utilized in other regions, unofficially. Other methods used for monitoring tropical cyclone activity also rely on wind speed measurement, but at different increments, such as three-minute or 10-minute sustained wind speeds. This can cause confusion across internationally, as the same 1-5 categorization may still be used, but with drastically different defined sustained wind speeds (NHC, 2018).

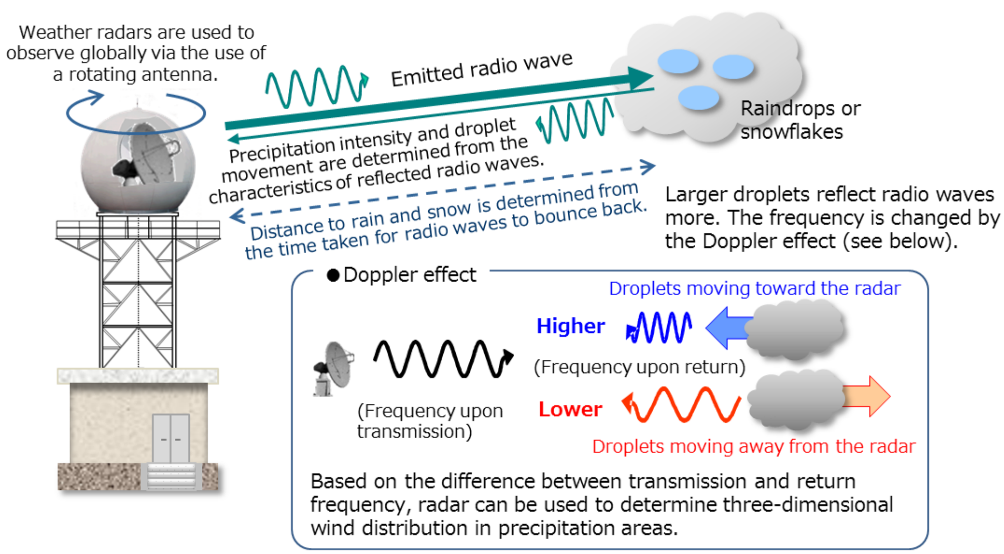
Critics of the SSHS argue that wind speed, alone, is not a sufficient measurement or predictor for potential hurricane/TC damage in that it does not consider overall storm size, rainfall or storm surge (NOAA, 2010). Others suggest that the scale should not be calculated or displayed in discrete data points, but rather along a continuous range, similar to the Richter scale used in earthquake monitoring. The scale, nevertheless has persisted as the dominant tool owing largely to the fact that proponents of the scale's use argue that another important aspect of a storm measurement is it's ability to be easily and quickly produced, as well as simple to convey to a large number of people. The more elements requiring calculation and interpretation lengthens the amount of time between data acquisition and information communication. In times of large-scale natural hazards, every hour is critical in preparing for or preventing a disaster from occurring.

3.2. Monitoring via Remote Sensing

With the advent and contemporary sophistication of satellite and unmanned aerial vehicle (UAV) technology, the ability to track and monitor the development of large- and small-scale weather events has improved significantly (Mudd, et al., 2014). It is a subject which deserves an in-depth explanation to fully appreciate all of the complexity and possibilities in meteorological applications, but a brief overview will be given here with regard to TC monitoring.

Remote sensing, whether via satellite, drone, manned aircraft or UAV can be broken down into two main categories; active and passive. Many people might be familiar with one type of active remote sensing; weather radar, where a doppler radar system emits using microwave radiometry (radio waves), towards the earth's surface. Any objects that the radar signal encounters throughout its' path, scatters the signal, eventually returning part of the refracted signal to the radar system from which it originated. An example of how this is carried out can be seen in Figure 3, below.

Figure 3: A demonstration of how doppler radar detects raindrops in the atmosphere, and is able to obtain information about the evolution of a storm system.



This measurement provides information about the presence of particles in the atmosphere, as well as their location, which is dependent upon the amount of time that it takes for a particular radio wave signal to return to the source of emission. In addition, radar systems are able to track any deviations or shifts from the signal's original form, shape and position. The mechanism at work is akin to that of the 'doppler effect' (hence the name doppler-radar) which can be observed in sound waves. As a tracked object moves closer towards the signal source, the frequency is detected as a positive phase shift, whereas objects moving away are detected as a negative phase shift (Solorzano, 2008). It is with these techniques that meteorologists are able to observe presence and changes in weather events.

In addition to doppler radar systems, many aircraft also employ the use of infrared (IR) sensors to obtain information regarding changes in temperature. This offers a significant advantage, as patterns in cloud formation can be detected and displayed; providing information on changes in size as well as shifts in the system's direction or path. This is accomplished by examining organized convection patterns associated with tropical winds and spiral formations which are characteristics of TC growth or dissipation (Schott, et al., 2019).

With respect to meteorological monitoring, passive remote sensing techniques are also used, particularly in the interest of showing real-time, high resolution multi-spectral imagery of storm systems as they develop. Passive remote sensing operates by receiving electromagnetic (EM) energy which is reflected from the earth's surface through the visible portion of the EM spectrum. These are often displayed as true color composites and may include postprocessing features indicating areas of new development and or severe danger, relative to human life. Though this provides arguably less scientific information, it does help convey messages to the general public relating to the potential severity of a storm system on infrastructure and environments. These techniques provided by remote sensing data acquisition and analysis, hazard mitigation and disaster preparedness has been provided with much more efficient and time-sensitive information to help communities around the world. It should be noted, however, that the majority of these satellites and departments equipped to handle such enormous amounts of data and data processing, this is a function largely limited to the US.

4. Case Study – Lightning

Emerging, in part, from critiques of the SSHS, recent studies have examined the possibility of alternative methods for measuring TC strength and intensity (Cecil, et al., 1999; Demetriades, et al., 2006; Squires 2006; Solorzano, et al., 2008; Wang, 2009; DeMaria, 2012; Stevenson, 2016). Owing largely to the fact that the majority of lightning monitoring stations are land based, obvious limitations with regard to tropical cyclone-related lightning activity are clear. But, as previously mentioned, with the advancement of satellite imagery analysis, the opportunities for examining the relationship between lightning and changes in tropical cyclone activity have increased (DeMaria, et al., 2012; Stevenson, et al., 2016).

Satellites such as the Tropical Measurement Mission (TRMM) or the Long-Range Lightning Detection Network (LLDN) have made the first attempts to track, quantify and analyze lightning activity in active TCs; but were ultimately unsuccessful as a result of their temporal limitations – providing data only for a few minutes each day as their paths crossed with a particular storm system (Cecil, 1999; Demetriades, 2006; Squires, 2006). More recently, however, in a study produced in cooperation with the USGS in Denver, CO – USA, Solorzano, et al., examined data collected from the World-Wide Lightning Location Network (WWLLN), "…to analyze the change in lightning activity during the evolution of tropical cyclones," (2008). Using spatial and temporal characteristics to examine eyewall and rainband region lightning activity, observations found the maximum lightning activity was present in rainbands and a second maximum in the eyewall. This activity, according to the report, was correlated to changes in the storm system's intensity; and was particularly active (increasing lightning activity) as a system approached land and made landfall.

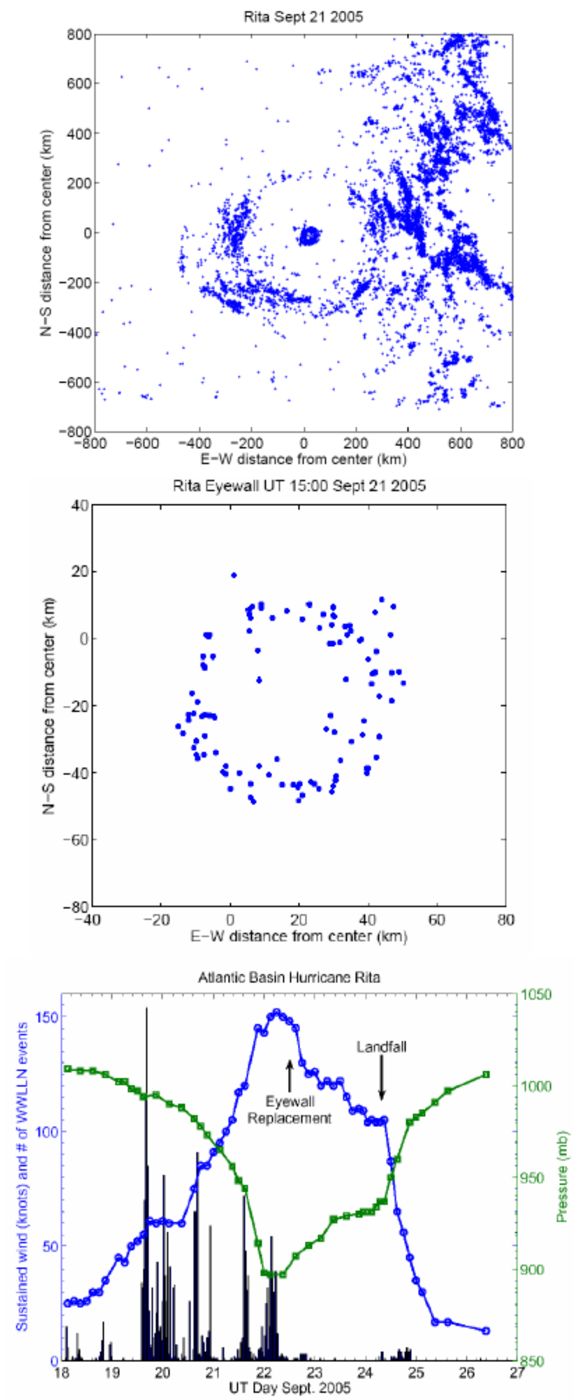


Figure 4: Lightning activity observed by WWLLN during Hurricane Rita on September 21, 2005. Top: storm system at full extent, showing lightning activity centralized in eyewall and in outer rainbands. Middle: Eyewall lightning activity distribution, Bottom: Windspeed (blue) measured in knots per hour, lightning activity (black – histogram), and atmospheric pressure (green). Image source: Solorzano, et al., 2008.

The WWLLN offers a unique and innovative approach to lightning monitoring; providing real-time data through the utilization of very low frequency (VLF) radiation discharged from lightning activity (around 3-30 kHz). In the case study produced by Solorzano, et al., (2008), WWLLN data showed patterns of interest with particular regard to the eyewall (around 20-40km from storm center) and the outer rainbands (between 200-400km from storm center. Figure 4 displays the findings of WWLLN data for Hurricane Rita on September 21, 2005; which demonstrate the increased lightning activity in areas of interest (eyewall and outer rainbands). Figure 4 (bottom) overlays another metric, the aforementioned and predominant unit for TC size, windspeed, as well as atmospheric pressure (on a descending axis) to demonstrate the synchronization of eyewall replacement, decreasing atmospheric pressure and lightning activity. These data demonstrate the applicability and efficiency of a multi-metric measurement which includes lightning activity in addition to windspeed as an indicator of TC size, and perhaps more significantly real-time changes in TC size. The benefits of which can provide meteorologists the ability to communicate critical information to the general public as a storm system develops and begins to approach landfall, should it be of concern. Adding to the plethora of tools that communities can now take advantage of in preparing for a TC and attempting to prevent a natural hazard from turning into a disaster.

5. Climate Change Discussion

Throughout the last century, changes in regional as well as global climate patterns have begun to effect individual weather events. While some researchers have concluded that the increase in SST and atmospheric temperature creates the perfect recipe for increased TC activity (Biasutti, et al., 2011; Bachmeister, et al., 2018; Donnelly, et al., 2015; Molar-Candanose, 2015; Park, et al., 2017; Risser, et al., 2017; Saunders, et al., 2008; Wehner, et al., 2017; Whitmarsh, et al., 2015; Yaukey, 2013). Others estimate with an increasing global average temperature and increasing SSTs, these patterns should accompany a respective decrease in the overall frequency of tropical cyclone (TC) frequency but an increase in TC magnitude (Saunders, et al., 2008). Current literature suggests that a correlation exists between the frequency and magnitude of recent hurricane activity and a number of contributing factors which include rising SST, changes in El Niño Southern Oscillation (ENSO) and a variety of atmospheric changes (Wallace, D., et al., June 2010). According to the Centre for Research on the Epidemiology of Disasters (Emergency Events Database - CRED-EMDAT); there is documentation of increasing overall numbers of natural disasters throughout the last 100 years (Martinez, M., et al., October 2015), but other experts suggest that it is premature to suggest that an overall increase in number of natural disasters is not necessarily correlated to an increased number in a specific type of natural disasters (e.g. hurricanes) (Park, et al., 2017; Risser, et al., 2017). It has also been hypothesized that a significant percentage of the natural disasters that have occurred throughout the last century have occurred within the last thirty years (Martinez, M., et al., October 2015). But the extent and specific scale and location of potential natural disaster events in the future is of much debate. Some research points to an increase in total number of natural disaster events around the world (Whitmarsh, et al., 2015), while other research has alluded to shifts in location, type, magnitude and frequency of natural disasters, and not necessarily an increase in frequency of all storms or natural hazards (Martinez, M., et al., October 2015, Yaukey, P., March 2014).

In understanding and estimating how TC events may change in the future, a comprehensive examination of the many characteristics of TC formation, location, seasonal atmospheric circulation patterns and pressure zones is essential. One of these factors includes a well-known secondary response of climate change – sea level rise (SLR). When a storm system moves in to make landfall, often one of the ways a storm manifests into potential threats for humans is through storm surges. A storm surge is defined as an abnormal rise in sea level due to storm activity (NOAA, October 2010). This sea level is measured by the height above the predicted astronomical tide for that particular day and can have major on-shore implications including flooding, power outages, as well as the possible destruction of property, vegetation and wildlife (NHC, 2008). A storm surge has major implications for coastal communities, even without the added threat of SLR. Coupled with even a slight rise in sea level height, storm surges have the potential to cause greater threat to communities already at risk, but also to communities that may not have been previously threatened. According to a paper published in the Climatic Change Journal in 2011, researchers have acknowledged that rising sea level is something that poses a very real threat to coastal communities and island nations, not only in and of itself, but notably when we consider the potential effects of a higher base sea level coupled with storm surges brought on by hurricanes of yet unknown sizes (Biasutti, M., et al., October 2011).

Tropical cyclones, as much a part of nature as the water and air from which they draw their energy, when closely monitored, can be prepared for and endured with a heavy reliance on remote sensing data and analysis. Within the field of meteorology, researchers have been able to develop a number of highly effective, highly accurate tools to track storm systems as they develop. Currently many of these technologies and their benefits are limited to the United States and other developed western nations. The extent to which TC activity effects communities and environments depends, to a large degree, on the ability to monitor atmospheric patterns during the event itself but also throughout the year as changes in ENSO and other circulation patterns adjust to a warming climate.

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