Extratropical Transitions in the North Atlantic with Special Reference to Hurricane Igor

By

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Abstract

There is a tendency to equate the word "hurricane" with the tropical regions of the world. Few recognize the danger and risks that occur when a tropical cyclone reaches colder subtropical waters and undergoes extratropical transition. Atlantic Canada, particularly the island of Newfoundland, is most at risk from extratropical transitions. The circumstances, location and dynamics of extratropical transitions in the North Atlantic have not been extensively studied. Consequently, forecasters continue to call approaching storms "hurricanes," when most are extratropical cyclones by the time they reach Atlantic Canada.

Extratropical transitions in the North Atlantic between 1991 and 2011 were analyzed to determine if the frequency, magnitude and intensity of potential shifts can be calculated for the purpose of more accurate forecasting and the benefit of public awareness, safety management, and preparedness. Between 1991 and 2011, 324 tropical cyclones formed, and 121 of these underwent extratropical transition, a mean of 5.76 per year. Extratropical transitions occurred more frequently in the middle of the Hurricane Season, with the peak transition month being September when 43.3% of cyclones transitioned. The largest percentage of cyclones began extratropical transition between 30 and 39.9°N, and 50.4% of cyclones completed their transition between 40 to 49.9°N. Of the 121 storms, 49.6% weakened after completing extratropical transition; 21.5% had little or no re-intensification after transition; and 29.2% re-intensified. Identifying if a cyclone will re-intensify after transition is a necessity. Cyclones have emerged from transition stronger than the tropical state, bringing widespread disaster to areas in the storms' path.

Newfoundland, in particular, has suffered devastating impacts from extratropical transition, notably Igor in 2010. Igor impacted Newfoundland as a Category 1 hybrid system which was still undergoing extratropical transition. Twenty-seven cyclones directly impacted Newfoundland between 1991 and 2011, 8% of the total for the entire North Atlantic. A third of cyclones qualified as Cape Verde Cyclones, which are cyclones that form in the deep tropics close to the Cape Verde Islands off the west coast of Africa. Cape Verde Cyclones usually have enough time to build up strength as they cross the Atlantic and frequently reach "major hurricane" status. Igor was an example of a classic Cape Verde Cyclone. Flooding was a severe problem, destroying property and roads and isolating communities. Total damages were estimated to be at least $110 million CAD with some values reaching as high as $200 million CAD. Fire and Emergency Services - Newfoundland and Labrador, the government of Canada, climatologists and meteorologists will benefit from a deeper understanding of extratropical transitions. Better forecasts could warn a given population of when and where a transition could take place and how best to prepare for the consequences.

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1. Introduction

1.1 Problem Statement

Every Hurricane Season, tropical cyclones develop in the low-latitude regions of the Atlantic Ocean. After following a dominantly northwestward track, many tropical cyclones curve northward into the higher latitudes. Leaving the warm waters of the tropics, the cyclones enter into a region of cooler waters, increased vertical wind shear, and baroclinicity. This environment weakens and eventually dissipates many cyclones. However, many tropical cyclones that enter and interact with the baroclinic environment in the midlatitude regions undergo a transformation from a tropical cyclone to an extratropical cyclone (Evans and Hart, 2003). This transformation stage is known as extratropical transition.

The topic of extratropical transition has become an increasing interest for the meteorological community (Jones et al., 2003). The University of Munich with the support of the U.S. Office of Naval Research and the World Meteorological Organization (WMO) Commission on Atmospheric Science, conducted the first International Workshop on extratropical transitions in 1999 (WMO, 1998). In 2002, the Fifth WMO International Workshop focused highly on extratropical transition as one of their main topics for discussion (WMO, 2002). Most recently, the WMO hosted the Third International Workshop on Extratropical Transition in May 2012 in Quebec (WMO, 2012).

Extratropical transition events are often not predicted and forecasted well by today's synoptic models, such as the Global Forecast System (GFS). Hart and Evans (2001) showed that extratropical transitions occur more frequently in Atlantic Canadian waters than anywhere else in the world. Therefore, a main problem faced by Canadian meteorologists and emergency measures organizations is accurately predicting these extratropical transition. The meteorological community is still struggling to understand and define an extratropical transition.

In Canada, the Canadian Hurricane Centre (CHC) is the leading forecast center responsible for recognizing extratropical transitions. CHC provides Canadians and the media with a northern latitude perspective on tropical cyclones, and works to develop an understanding on how to forecast transitions (WMO, 2010). The research in this thesis will analyze ways to better understand the complicated transformations of cyclonic storms by developing an understanding of the transition process through the retrieval and examination of data from cyclones between 1991 and 2011 that have undergone extratropical transition.

1.1.1 Research Objective

The primary goal of this research is to analyze extratropical transitions and assess if the frequency, magnitude and intensity of potential shifts can be calculated for the purpose of more accurate forecasting and the benefit of public awareness, safety management, and preparedness. A case study of the extratropical transition of Hurricane Igor (2010) will be examined in detail in Chapter 5. Igor is a classic example of a strong cyclone that underwent extratropical transition and caused devastation to Newfoundland.

Many hurricanes undergo extratropical transition in Canadian waters, and previous events have been known to cause devastating effects in Atlantic Canada. Understanding the transition process of these storms is crucial, because as these storms change from tropical to extratropical, their behavior, structure, and impacts alter. Extratropical transitions are some of the most challenging storms to predict. Forecasters cannot depend on the same prediction models used for hurricanes, but must turn to other sources to examine these storms and take appropriate steps to warn the public and emergency responders. Ongoing climate change means that concerned populations will need to know what to expect from these approaching storms, and therefore proper warning systems and more precise forecasts are necessities. Atlantic Canada will have to adapt to these changes if extratropical cyclones become more frequent, or if the Atlantic Hurricane Season becomes longer.

1.2 Background Information

Each year, starting in June, the atmosphere above the Atlantic Ocean goes through a transformation, allowing major thunderstorms to form in the tropical regions. These thunderstorms, if in a favorable area, will form into a tropical cyclone, or a hurricane as they are referred to in the North Atlantic.

Tropical cyclones are large complex thunderstorms that rotate around an area of low pressure, usually in the tropical and subtropical parts of the ocean (Keller, 2006). These massive storms are categorized according to the Saffir-Simpson Scale which measures wind speeds from a tropical depression strength, the weakest, to Category 5 strength, the strongest (Table 1.1). A

Category	Winds (mph)	Winds (km/h)	Pressure (mb)	Storm Surge (m)
Tropical Depression	< 39	< 62		
Tropical Storm	39-73	63-117		
Category 1	74-95	119-153	> 980	1.0-1.7
Category 2	96-110	154-177	965-980	1.8-2.6
Category 3	111-130	178-209	945-965	2.7-3.8
Category 4	131-155	210-249	920-945	3.9-5.6
Category 5	>155	> 250	< 920	> 5.7

Table 1.1 - The Saffir-Simpson scale which categorizes hurricanes on a scale from 1 to 5. Hurricanes strong enough to be considered "intense" begin at Category 3 (NOAA, 2012).

change takes place at the end of a tropical cyclone's life, resulting in a new weather system that incorporates elements of both tropical and extratropical cyclone characteristics. This process is called extratropical transition (Environment Canada, 2010). Extratropical transition usually occurs between 30° and 40° latitude where the upper-level troughs are strong along the prevailing westerly winds (Hart and Evans, 2001). Even after moving across the Atlantic Ocean, the initially tropical systems always retain some inherent tropical traits. A tropical cyclone, if it survives the transition phase, will emerge as an extratropical cyclone. Along the northwestern North Atlantic shoreline, several locations lie in the path of these extratropical cyclones, particularly the island of Newfoundland.

Abbreviations	Description
AIRS	Atmospheric Infrared Sounder Instrument
AMO	Atlantic Multidecadal Oscillation
CHC	Canadian Hurricane Centre
FES-NL	Fire and Emergency Services - Newfoundland and Labrador
GFS	Global Forecast System
NHC	National Hurricane Center
NLWO	Newfoundland and Labrador Weather Office
NOAA	National Oceanic and Atmospheric Administration
PDI	Atlantic Cyclonic Activity
SLP	Sea Level Pressure
SST	Sea Surface Temperature
WMO	World Meteorological Organization
WPM	Warning Preparedness Meteorologist

Table 1.2 - A list of abbreviations used for this thesis.

1.2.1 Cyclogenesis

Cyclogenesis is the initiation or strengthening of a cyclonic circulation within the atmosphere (Arctic Climatology and Meteorology, 2006). Tropical cyclogenesis refers specifically to the formation and intensification of tropical cyclones. Tropical regions are the primary source of the Earth's weather and atmospheric circulation patterns (Sharkov, 2000). Cyclones that form within 30° north or south of the equator are known as tropical cyclones. Cyclones that form between 30° and 60° are extratropical cyclones. Although all cyclones involve rotation over a large area, the two distinct types of cyclones develop and act in different ways due to many different climatic forces shaping each cyclone (Environment Canada, 2010). Towards the end of a tropical cyclone's life cycle, after it moves away from the tropics, it may undergo extratropical transition.

Tropical cyclones are storm systems containing a low-pressure center. The process that fuels a tropical cyclones involves the evaporation of water from the ocean. Heat evaporates the water and turns it into water vapor which becomes trapped in the air. The water vapor is warmer than the surrounding air and causes the water vapor particles to rise. At higher altitudes the particles experience lower temperatures and pressures and the water vapor begins to condense back into a liquid, creating clouds. As the water vapor condenses it extracts heat from the surrounding air, due to the phase transition. The latent heat of the vapor-liquid water transition is approximately 2.3×10^6 J/kg. Heat stored in the water vapor during evaporation at the ocean surface is thus released into the atmosphere at higher altitudes when water vapor condenses. As air particles become warmer than the surrounding air they begin to accelerate upward. This process draws air from below upward and the rate of rising air near the surface begins to speed up creating a positive feedback loop. Surface air rushes in to replace the air that is forced upwards creating the powerful updraft winds which are associated with tropical cyclones. The rising columns of air form large thunderstorms (Environment Canada, 2010).

There are certain conditions that are needed for tropical cyclones to form:

- Sea surface temperature need to be at least 26.5°C from the surface to a depth of more than 50 meters (Environment Canada, 2010).
- There needs to be a warm, moist tropical atmosphere which encourages the development of thunderstorms by the process of phase transition, releasing latent heat (Environment Canada, 2010).
- The Coriolis effect is necessary to generate the rotation of a disturbance and therefore, a tropical cyclone cannot develop between latitudes 5°N and 5°S (Environment Canada, 2010).
- There needs to be very little or no vertical wind shear in the atmosphere between the surface and troposphere level. Vertical wind shear disrupts the upward formation of a cyclone and interferes with the process of deep convection causing the storm to be torn apart and weaken (Environment Canada, 2010).
- There needs to be a pre-existing area of disturbance because tropical cyclones require a trigger mechanism to begin drawing surrounding air inwards towards the surface. Tropical waves are particularly important for tropical cyclones to form. These tropical waves account for 60% of Atlantic cyclones (85% of the major ones) (Environment Canada, 2010).
- An additional factor, which although not required commonly acts to facilitate formation, is an area of high pressure located in the upper troposphere above a disturbance. This can aid in the formation of a tropical cyclone by taking the rising air away from the storm's center so that it

does not gather above the storm and cause the storm to collapse. The high pressure also helps draw air up through the storm to help the air ascend and maintain low pressure near the surface (Environment Canada, 2010).

These are the primary necessities needed for a tropical cyclone to generate. However, even if all these conditions are present, cyclogenesis may not occur, sometimes creating a challenge for forecasters.

1.2.2 Tropical and Extratropical Cyclones

A tropical cyclone is a generic term for a synoptic-scale low pressure system which does not contain a front. The core of a tropical cyclone is warm and it derives its energy from latent heat released when water vapor, from the evaporation of the ocean, condenses into liquid water (Masters, 2012). The "warm core" is relatively warmer than the surrounding environment at the same pressure surface. Tropical cyclones have little or no temperature differences across the storm at the Earth's surface (Goldenberg, 2004). The size of a typical tropical cyclone can be defined as the radius of the area experiencing winds that are greater than or equal to hurricane force ($\geq$ 119 km/h). Tropical cyclones are known for being relatively symmetric in shape with the majority of the strong winds and precipitation concentrated in the thunderstorms close to the center of circulation (the eye) (WSE, 2012).

In contrast, extratropical cyclones are dominated by cold air at their core, and obtain their energy from the release of potential energy when warm and cold air masses make contact. Unlike tropical cyclones, extratropical cyclones can develop over land as well as sea. During extratropical transition, the shape begins to alter. They are distinguished by having the shape of an "inverted comma" and having a warm front and a cold front (which may combine and form an occluded front) (Fig. 1.1). The heaviest precipitation and the strongest surface winds often occur

Tropical Cyclone | **Extratropical Cyclone**

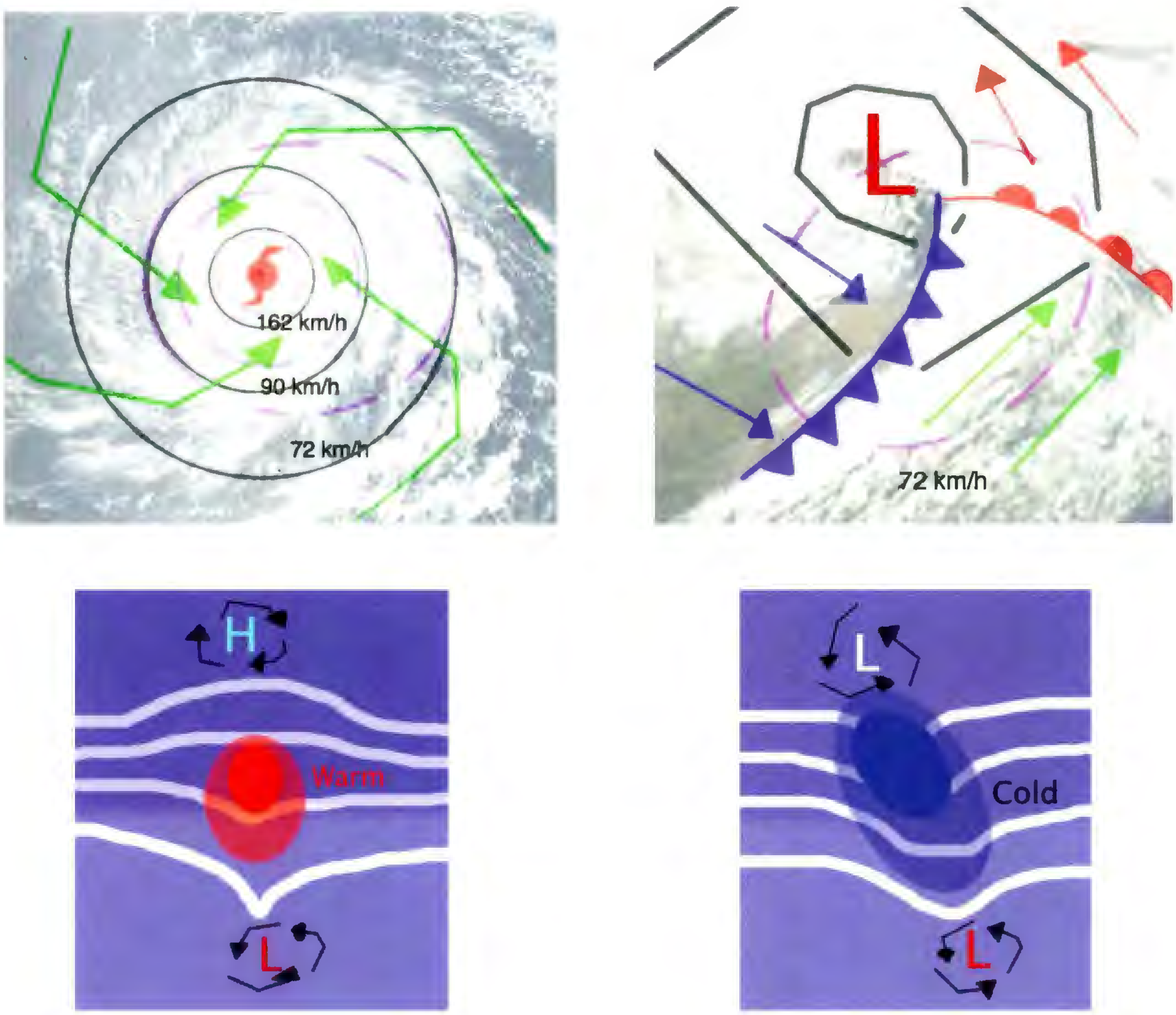


Figure 1.1 - Top schematics show horizontal maps of wind fields and pressure associated with a tropical cyclone (left; Hurricane Igor) and an extratropical cyclones (right). Dashed lines are the surface wind speeds: 72 km/h, 90 km/h, and 162 km/h. Solid lines are isobars where the atmospheric pressure is the same over a given period of time. Lower schematics show vertical maps of the temperature anomalies, pressure surfaces, and circulation at the

surface and the tropopause layer of the atmosphere (Merrill, 1993) (NOAA, 2010) (ESA, 2012).

along these frontal zones. This stands in contrast to cyclones that are purely tropical which contain no fronts because the lower tropical atmosphere is typically at a constant temperature. Extratropical cyclones grow in size during their life with some storms reaching between 200-2000 km in diameter. The belt of strongest winds is usually found to the right of the storm track and is typically 150-500 km wide (WSE, 2012).

The strongest winds in a tropical cyclone are located near the surface of the earth, compared to extratropical cyclones where the strongest winds are located near the tropopause layer of the atmosphere. These differences are related to the warm core of a tropical cyclone in the troposphere whereas an extratropical cyclone has a warm core in the stratosphere and cold core in the troposphere (Goldenberg, 2004).

Currently there is no method of scaling the intensity of extratropical storms. The Saffir-Simpson Scale is normally used to determine tropical cyclone strength. However, this scale is not suitable for determining the strength of extratropical cyclones. Due to the asymmetries in the cloud field of an extratropical storm it is more difficult to determine where the highest wind speeds, a primary defining criterion in the Saffir-Simpson Scale, are located. Another problem is introduced with a storm that re-intensifies after extratropical transition: although the minimum pressure could be lower than when it was in its tropical form. The wind speed decreases with transition. The connection between lowered barometric pressure and increase wind speed, a fundamental component of the Saffir-Simpson Scale, is not necessarily valid for an extratropical transition.

1.2.3 Extratropical Transition

Extratropical transition usually is considered to begin when satellite imagery conveys an asymmetric appearance of clouds (Fox, 2004), particularly in the shape of an inverted comma. The start of extratropical transition usually occurs when the outer bands of the tropical cyclone approach a midlatitude baroclinic zone (cold front) on the northwestern side. The transition of a tropical cyclone to an extratropical cyclone is defined as complete when both numerical weather prediction analyses and satellite imagery show that the tropical cyclone now displays characteristics of an extratropical cyclone in which the center of circulation is overcome by cold, descending air (Fox, 2004). Most tropical cyclones, when they arrive in Canadian waters, are in some stage of extratropical transition. This distinction is important, both in terms of the larger spatial scale of extratropical transitions, and the meteorological aspects.

When a tropical cyclone goes through extratropical transition the winds are usually affected. The maximum wind speed usually begins to decrease, although the decrease can be relatively minor. The strongest winds start to develop on the right side of the storm and away from the (evolving and weakening) "eye", and the area of gale-force winds (>63 km/h) expands. In a tropical cyclone, the general rule is that the difference in speed between winds on the right side (faster) and the left side is twice the mean storm track speed (Environment Canada, 2010). A tropical cyclone, for example, moving at 20 km/h will have winds that are 40 km/h stronger on the right side than on the left. However, once a tropical cyclone begins to transition, the difference in winds on the right and left side decreases. When transition is complete, the difference in speed between winds on the right and left sides is approximately equal to the storm's track speed. Hurricane Juan in 2003 was showing signs of transitioning when it made landfall with a speed of 55 km/h. The winds to the west of Juan (left side) were approximately 100 km/h, while the maximum wind speeds to the east (right side) were about 160 km/h (Environment Canada, 2010). However, compared to Juan, Hurricane Igor was towards the end of its transition when it made landfall. Igor was moving at approximately 73 km/h. The winds directly west of the track (left side) were approximately 137 km/h, while the maximum winds to the east of Igor (right side) were estimated to be around 172 km/h (NHC, 2010). The difference in wind speeds does not relate to the track speed of storms which have completed transition, thus creating difficulty in determining wind speeds in regards to track speed.

Rainfall is another factor when considering extratropical transitions. There is very little connection between the Saffir-Simpson classification of a tropical cyclone and the rainfall amounts. The designation of magnitude and stage of development of an event depends on the wind speeds and not the amount of precipitation. Extratropical cyclones can bring as much, if not more, precipitation than does a tropical cyclone. As a tropical cyclone undergoes extratropical transition, the symmetric rain bands start to encompass a larger area and the entirety of the rain falls to the left of the cyclones track. This is a good indicator in determining if a tropical cyclone is undergoing extratropical transition. Extratropical cyclones can bring rainfall totals in excess of 200 mm per 24 hours and it is not uncommon to see 20-50 mm of rain per hour (Environment Canada, 2010). The rainfall from extratropical cyclones very often is enhanced by a frontal system already in the vicinity upon the arrival of the storm. The increased amount of moisture from the tropical cyclone gets displaced into the frontal system. Eventually this moisture is released, dumping immense amounts of rain for a given area (Environment Canada, 2010). An example of the importance of rainfall in determining the intensity of extratropical cyclones is

Hurricane Hazel in 1954. Even after becoming extratropical, Hazel maintained the intensity of a Category 1 storm as it entered Ontario. Rainfall amounts exceeded 200 mm even after moving more than 1,000 km inland. Records indicate that areas west of the storm track over Toronto received significantly more rain (about 214 mm) compared to the east (about 90mm) (Bowyer, 2004), which follows the typical pattern of an extratropical cyclone structure.

Storm surge is the elevation of rising water resulting from the meteorological effects on sea-level. Storm surge can accompany both tropical and extratropical cyclones. This threat is primarily for the coastal regions, and it is the greatest tropical cyclone hazard. Storm surge is water that is pushed onto the shore and moves with the forward speed of a cyclone. The storm surge elevation is the difference between the observed water level during the storm and the level that the tide would normally rise to in the absence of storm activity (Forbes et al., 2004). Storms associated with low pressure systems, with reduced pressure of the atmosphere, pushes down on the water surface. The height of the storm surge rises with lower atmospheric pressure. A general rule with storm surge in regards to low pressure is: 1 cm of rise above predicted tidal values for each hectopascal (hPa) below the standard atmospheric pressure of 1013 hPa (Masters, 2012).

A cyclone is seen as a powerful wind machine and ocean waves are made by the frictional interaction between wind and ocean surface. The strong pressure gradient pushes water ahead of the storm, mostly on the right side of the storm. Ocean waves on the right side of the storm move with the storm and go in the same direction as the winds. On the left side of the storm, waves move in the opposite direction of the storm's movement causing minimal impact. The greatest factor is the timing of landfall in correspondence with the tidal cycle. Additional factors that contribute to storm surge are the angle at which the storm makes landfall, the storm's forward speed, and the coastal geography of the impacted area (Environment Canada, 2010).

When a tropical cyclone moves into the midlatitudes, the cyclone decreases in intensity with its central pressure increasing and its maximum surface wind speed decreasing. As the tropical cyclone undergoes its transformation into an extratropical cyclone, dry air is sometimes wrapped into the circulation and symmetry in the storm is lost. Vertical wind shear tears the storm apart and energy is cut off due to colder water temperatures. Due to these factors the transformation in most cases will weaken the storm considerably. The intensity of a tropical cyclone before it undergoes extratropical transition is crucial in determining if it will survive the transition. Tropical storms that form at higher latitudes are less likely to survive the transition to extratropical status compared to storms that form in the deep tropics (e.g. Cape Verde area). Storms forming in the deep tropics are usually stronger and can survive the transition. However, it is possible for a weak storm to reemerge stronger than when it first entered its transition process. An example of re-intensification occurs when the storm interacts with another extratropical system while undergoing extratropical transition: this could result in re-intensification as an extratropical system (Jones et al., 2003). Hurricane Iris in 1995, Hurricane Earl in 1999, and Hurricane Irene in 1999 all experienced rapid re-intensification in this manner.

Fogarty (2002) explains that tropical cyclones which undertake a northwest pattern often re-intensify if they interact with an approaching upper atmospheric short-wave trough. This information can benefit forecasters in that they need to only determine if any troughs are going to interact with the cyclone and if so advect the storm into the 500 hPa (500 mb) flow (Fogarty, 2002).

1.2.4 Active Seasons

The 2005 Atlantic Hurricane Season was the most active on record with a total of 31 systems forming in the Atlantic Ocean: 28 of those systems were named, 15 became hurricanes, and 7 were classified as major hurricanes reaching Category 3 strength and higher (Beven et al., 2008). It might be suggested that seasons with an increased amount of activity will potentially result in more extratropical transitions, but this generalization is not entirely accurate. The number of storms may not predict the percentage of transitions. Track data is a factor causing departures from "more transitions in an active year." Tropical systems that stay mainly in the tropical North Atlantic are less likely to transition than storms that curve poleward. The National Oceanic and Atmospheric Administration (NOAA) issues their yearly Atlantic Hurricane Season outlook which is an estimate of how many storms the Atlantic Basin could see in the upcoming Hurricane Season. Using climatological science and monitoring rainfall over West Africa, sea surface temperature (SST), wind shear, and El Niño/La Niña development, NOAA can produce a forecast on the number of systems that could form. However, this outlook does not inform the population of specific areas of when and where these storms will form and where they will go. This is dictated by specific weather patterns at the time of cyclone formation. Understanding the time and place of these cyclone formations is still complex as there is no way to determine the track of these storms before they form. Therefore, long-term forecasting of how many transitions will occur in an upcoming year would be highly unlikely given the knowledge and technology available today. However, scientists and forecasters could potentially forecast the probability of a transition happening once a cyclone and an estimated track have been established.

While research is still ongoing regarding the Hurricane Season of 2005, there were several contributing factors that made this season a record breaker. The first was the warmest SST's ever recorded in the Caribbean and tropical Atlantic Ocean (Fig. 1.2). The tropical regions of the

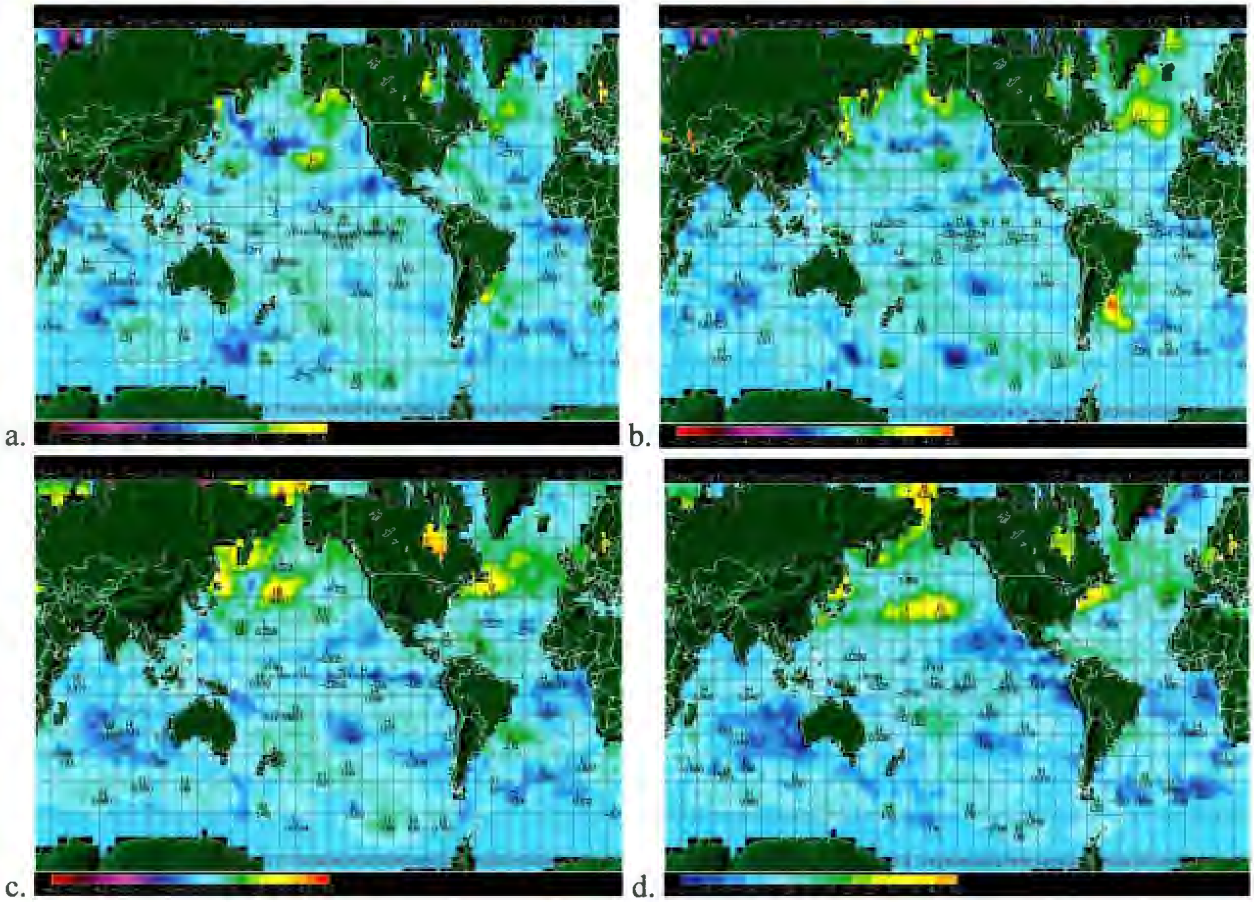


Figure 1.2 - SST anomalies taken towards the peak of Hurricane Season on a.) July 23, 2005; b.) August 13, 2005; c.) September 10, 2005; and d.) October 15, 2005 (UNISYS, 2005).

Atlantic had SST anomalies greater than 1°C (Beven et al., 2008). This extra boost of heat provided the energy for storms to form into cyclones which could last for long periods of time. Around the Canadian Maritime region SST anomalies were above normal from 0.75 C° to as high as 1.75 C° (Fig. 1.3). Water temperature is one factor that goes into the formation of cyclones and those above normal SSTs in 2005 suggest that cyclones were feeding off of

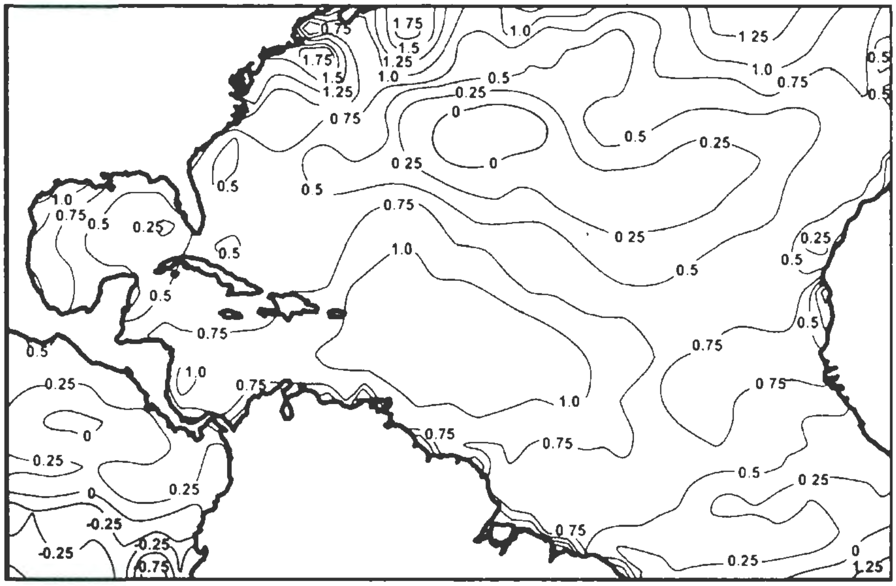


Figure 1.3 - Atlantic SST anomalies (°C) from July-October 2005. Shaded regions are cooler than normal areas (Beven et al., 2008).

the warm hydro-energy which would allow cyclones to grow, strengthen and last for longer periods of time while over the ocean. Another factor to consider during the active season was the vertical wind shear in the atmosphere. Ocean temperatures are a crucial factor for cyclones to form, but cyclones can only form in areas with low wind shear, regardless of water temperature. The Hurricane Season of 2005 saw very low wind shear over most of the Atlantic Ocean allowing for an increase in cyclogenesis. Lastly, mid-level easterly winds coming off the west coast of Africa were meteorologically favorable for storm development. These winds strengthened low pressure systems over the tropics helping them develop into cyclones (Lepore et al., 2005).

Atlantic Canada did not see an increase in cyclone activity during the active 2005 season, with only one direct hit from Hurricane Ophelia as an extratropical storm maintaining tropical storm force winds. Ophelia continued to track northeast until it dissipated in the North Sea. The above normal SSTs potentially aided Ophelia to travel such a long distance in its extratropical form which could indicate that warmer water temperatures will potentially increase the track distance in cyclones. More importantly, shear levels in the atmosphere were low in the North Atlantic throughout the 2005 Hurricane Season, allowing cyclones to continue farther.

The Hurricane Season of 2006 was particularly active regarding extratropical transitions.The Hurricane Season of 2006 was considered a significantly less active season than its predecessor, but the overall activity was considered near average. Due to a strong midlevel trough over the eastern United States during August and September, tropical activity was pushed out to sea near Bermuda and further to the east. SSTs were lower, compared to 2005, thus making it difficult for cyclogenesis to occur. There were also changes in the steering flow of winds associated with the Bermuda High (Gutro, 2007). The Bermuda High helped to steer away systems and move them northward into cooler waters and into an area favorable for extratropical transition. What scientists and forecasters can learn from the 2006 Hurricane Season is that if a similar atmospheric pattern arises, where storms are being pushed northward and back out to sea, the chance of an extratropical transition increases.

1.2.5 Less Active Years

Certain years were more active than others regarding the frequency of transitions. The 1994 Hurricane Season showed limited activity where no transitions occurred. Twelve storms formed, of which seven were named. Of those seven, three reached hurricane strength, the strongest being Hurricane Florence which reached Category 2 status. Three large-scale features confirmed this below average Hurricane Season: surface pressure patterns, SSTs, and vertical wind shear. Normally the active months for cyclone formation are September and October, but throughout this period above-normal surface pressures were dominant south of 20°N from Africa westward to the Caribbean. At the same time, below-normal pressures occurred over much of the subtropical latitudes. This pressure pattern information shows a weakening or a shift southward of the high pressure ridge (Lixion et al., 1996). This pressure shift would contribute to a decrease in tropical cyclogenesis. The low seasonal activity was attributed to an El Nino event which caused SST's to be lower in the tropical northeastern Atlantic. Temperatures were about -0.5 C° lower than normal, possibly contributing to the limited hurricane activity. Lastly, over the tropics there was strong vertical wind shear which prevented tropical cyclones from developing and strengthening (Lixion et al., 1996). Though the factors given are not the complete reason for a decreased amount of cyclone activity, the evidence does indicate that cyclogenesis activity was confined mostly to the south tropical regions in an area where transitions do not occur. Storms that wandered into the subtropical latitudes encountered unfavorable atmospheric conditions (Fig. 1.4).

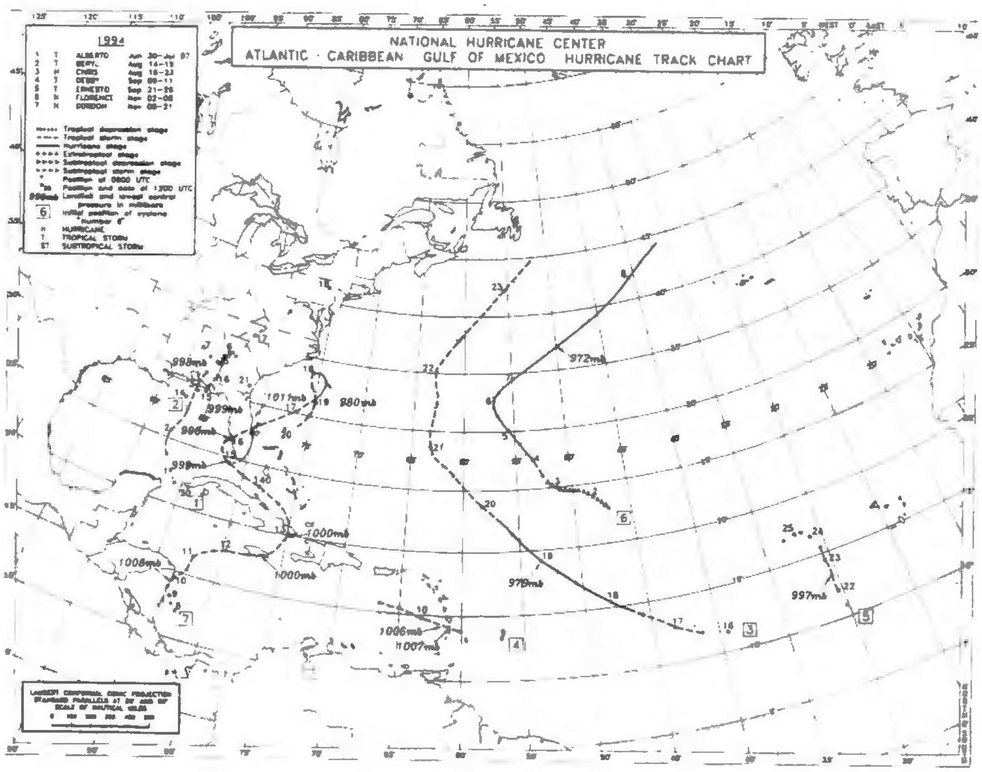


Figure 1.4 - 1994 Atlantic Hurricane Season Map (NOAA, 1994).

Data indicating warmer SSTs, conductive winds off the west coast of Africa, and low wind shear have been ongoing since 1995 and could continue for many more years which would likely increase the amount of cyclones forming. NOAA attributes the increased activity to a natural cycle known as "the tropical multi-decadal signal" which can last from 20 to 30 years or longer. NOAA believes that the recent increase in activity is due to this cycle and has been this way since 1995. Since 1995 the average number of named tropical cyclones has been 13, compared to before 1995 when the average was 8.6 (NOAA, 2005).

1.3 Effects of Cyclones

Cyclones while out at sea cause heavy rains, high winds and large waves which disrupt fisheries and international shipping and, in some cases, cause shipwrecks (Roth and Cubb, 2001).

When a cyclone makes landfall strong winds can damage and destroy infrastructure and turn loose debris into deadly flying projectiles. Storm surges and the increase of sea level from cyclones is typically viewed as the worst effect and has historically resulted in 90% of tropical cyclone deaths (Shultz et al., 2005). The degree of wind damage to structures and property depends on many factors such as the condition of the structure, the building codes, and type of ground level structure. During tropical events the wind speeds increase substantially with height because surface features produce friction that slow winds nearer to the surface. Winds may be at Category 1 strength at the surface, but may reach Category 2 strength at the top of tall structures.

The damage to vegetation depends on several factors including the type of vegetation, root system, soil conditions, and time of year (e.g., presence of leaves on deciduous trees). Falling trees and breaking limbs are the prime source for power outages during a cyclone event. Cyclones significantly interrupt lives with power outages, destruction of property, and hampers reconstruction efforts. Worldwide, over the past two centuries, cyclones have been responsible for the deaths of approximately 1.9 million people, most of these deaths caused by secondary effects of the cyclone such as disease outbreaks (Shultz et al., 2005).

1.3.1 Emergency Management

Emergency management is the process of dealing with risks. This act involves planning efforts before, during and after a disaster. Emergency management is a nonstop process in which all individuals, communities, and groups manage hazards in an effort to reduce or avoid the impact of hazards. Emergency and disaster managers have created an important tool which is used in reducing the effects of natural hazards known as the emergency management cycle. The four stages of action in this cycle are mitigation, preparedness, response, and recovery (Fig. 1.5).

Figure 1.5 - Basic image of the emergency management cycle featuring the four stages of action: mitigation, preparedness, response, and recovery (Environment Canada, 2010).

The goal for humans confronting any natural disaster is to be completely safe. However, the fact is that as long as any risk remains, each stage of the emergency management cycle is critical to make certain that the negative impacts of hazards are at least minimized.

Mitigation is to help keep hazards from turning into disasters, or at least to reduce the effects if a disaster does occur. These efforts are focused on taking long-term actions to minimize or remove the risk. In regards to cyclones, mitigation efforts help residents move inland away from the threat of storm surge along the coast, building coastal barriers to minimize storm surge, strengthening complexes and homes, and having a weather forecasting service for up-to-date information regarding an approaching cyclone. The best effort, however, is to become informed about the potential threat of storms. The CHC is part of the Canadian government's strategy for minimizing the possible impacts of cyclones in Canada. The CHC stresses to increase the awareness of cyclone hazards in eastern Canada (Environment Canada, 2010).

Preparedness entails developing plans of action to be followed when a hazard strikes. This plan focuses on what to do before a cyclone emergency occurs. Examples of preparedness include the knowledge of cyclones, securing properties, information services and developing a plan in case a cyclone approaches. The CHC continues to update their Standard Operating Procedures manual each year to better their response to the public. This manual gives information on what to do during an cyclone event and when actions will be done (Environment Canada, 2010).

Response is the act of moving the necessary emergency services and first responders to the disaster area. Examples of response efforts include issuing forecasts to the public, activating personal hurricane plans, activating emergency operations centers (EOCs) and mobilizing emergency services. In many cases the CHC forecasts trigger the response and preparedness implementation plans of the general public to the emergency managers (Environment Canada, 2010).

The final category in the emergency management cycle, recovery, attempts to aid and restore the areas affected by the hazard. This phase begins once the immediate threat to human life is over. Recovery efforts include rebuilding, providing relief and aid, and re-employment. Recovery efforts from the CHC usually involve providing ongoing weather forecast support to the recovery operations and teams (Environment Canada, 2010).

The Emergency Measures Organization for the province of Newfoundland and Labrador is the Fire and Emergency Services - Newfoundland and Labrador (FES-NL) who is tasked with the implementation of emergency management strategies designed to develop and maintain an emergency management system for the province. They collaborate with many partners and stakeholders, such as Environment Canada, to plan, prepare, respond and recover from emergencies and disasters (FES-NL, 2012).

1.4 Forecasting

Forecasters began issuing names to tropical storms and hurricanes to better communicate their watches, warnings and forecasts to the public. Before this naming process, storms were given a number and forecasters would keep track and relay information regarding the storm by latitude and longitude. Prior to 1950, hurricanes were named by the year in which they occurred, plus a letter from the alphabet. Between 1950 and 1977, hurricanes were given female names, but after 1978, the National Hurricane Center (NHC) alternated between male and female names. The NHC reports that the use of male and female names in oral and written communication is quicker, shorter and causes fewer mistakes than other hurricane identifications used to date (NOAA, 2012). By agreement, the NHC is the WMO authority for naming tropical cyclones in the Atlantic Ocean. A country that has been affected by a tropical cyclone that has made a severe impact either on the economy or cost of human lives, can request to have the name of the tropical cyclone retired by agreement of the WMO (NOAA, 2007). The following is a list used by the NHC detailing the stages of development for tropical cyclones:

Tropical Disturbance - The NHC starts to issue a formal watch when an area of disturbed weather over the tropics continues for 24 hours or more and labels the weather system a "tropical disturbance."

Tropical Depression - When rotation develops in the tropical disturbance and winds reach 37 km/h the system is upgraded to "tropical depression" and assigned a number.

Tropical Storm - If winds increase to a gale strength (63 km/h) the NHC designates the system as a "tropical storm." Each tropical storm is given a name.

Hurricane - When winds reach 119 km/h or more the weather system is classified as a "hurricane." An eye is often visible at the center of the storm during this stage.

Forecasters report surface wind from a tropical cyclone following an international standard: maximum sustained winds are averaged over 1 minute, taken at a height of 10 meters above the surface away from structures and friction of the ground (Environment Canada, 2010).

The NHC specializes in cyclones that are almost purely tropical. When a storm is transitioning into an extratropical cyclone the NHC stops issuing warnings and messages about the storm, presumably due to the geographic location of the transitions. As the NHC is the authority for naming tropical cyclones in the Atlantic Ocean, other weather agencies in the United States and other countries cannot continue to refer by name to a storm that has been designated as extratropical by the NHC. The remaining weather system is instead referred to as an "extratropical cyclone" or "the remnants" of the tropical cyclone. This rule has caused problems, especially for Canadians. Many people believe that storms designated as "extratropical cyclones" or "remnants" are less of a threat, but they can still unleash extreme or severe weather.

Most of Canada's worst cyclone disasters have come from the "remnants" of tropical cyclones that have transitioned into extratropical cyclones. The de-naming practice implies to the public that a tropical cyclone undergoing extratropical transition is less threatening, thus increasing vulnerability (Environment Canada, 2010).

Extratropical transition is generally thought to occur when a tropical cyclone encounters a synoptic disturbance in the mid-latitudes and changes from a warm core to a cold core vortex. The majority of extratropical transitions occur between 30° and 40° N. The transition causes tropical characteristics (warm core) to be lost due to the new environment the cyclone has entered. Outside of the tropics a storm may come into contact with an increase in vertical wind shear and baroclinity, meridional humidity gradients, strong SST gradients or a decrease in SST, and an increased coriolis parameter (Jones et al., 2003). Merrill (1993) stated basic criteria when determining the initiation of extratropical transition by satellite: the disappearance of the high-cloud canopy of a tropical system, a decrease in deep convection, the appearance of a "comma-shaped" tail which is a front developing (frontogenesis), and the exposure of the low-level circulation center.

A system is defined as extratropical when it has lost the warm core tropical characteristic (Fox, 2004). There are a set of problems involved in designating a tropical cyclone as extratropical. An extratropical cyclone is distinct from a tropical cyclone in that it has specific structure and geometry. Tropical cyclones that are undergoing extratropical transition, in many cases, have not fully completed their transition when they are designated extratropical cyclones. Tropical cyclones that enter mid-latitudes rarely have lost all of their tropical characteristics at landfall, making these storms hybrids. These hybrid storms keep enough moisture and circulation in the high atmosphere to energize the resulting extratropical cyclone into a storm with a higher magnitude and a greater potential impact.

Tropical cyclones that have undergone extratropical transition may re-intensify and bring heavy precipitation and strong (possibly gale force) winds to the eastern side of ocean basins (Browning et al., 1998). In addition, tropical cyclones undergoing extratropical transition often increase in speed shortly after the conclusion of the transition making accurate forecasts difficult (Jones et al., 2003). One of the best scientific resources used for this study comes from the 53rd Weather Reconnaissance Squadron, known as the Hurricane Hunters of the United States Air Force Reserve. Satellite and radar imagery and missions conducted by the Hurricane Hunters are the best forms of technology currently available to decipher if extratropical transition is occurring. The Hurricane Hunters fly out into a cyclone to collect data regarding pressure, the exact location of the storm's center, and wind speed data, which is then relayed back to forecasters. An important tool used to determine these measurements is the dropsonde. A dropsonde is a small tube which holds various instruments, such as thermometers and pressure gauges. At various places in the cyclone, the airplane will release these instruments. As the "sonde" is falling it will relay information to the plane about temperature, humidity, wind speed, barometric pressure, and wind direction using a radio transmitter. This information allows forecasters to decide if the cyclone is getting weaker or stronger (Hurricane Hunters Association, 2013).

2. Previous Research

2.1 Stages of Extratropical Transition

Researchers have tried to gain an understanding of what goes on during extratropical transition as a number of possible scenarios exist. Klein et al., (2000) conducted research in the western North Pacific on 30 tropical cyclones from June 1 through October 31 during 1994-1998. The objective of the study was to describe extratropical transition as a process of evolution that occurred over a period and involved a particular sequence of physical processes that could be described and observed by numerical weather prediction analysis and satellite imagery. The goal was to identify how many tropical cyclones would re-intensify after extratropical transition. Figure 2.1 illustrates the timeline of events during extratropical transition based on the 30 tropical cyclone cases. In this study, 4 of the 30 storms had little or no re-intensification, 15 had moderate re-intensification, and 11 experienced deep re-intensification.

Timeline of Events During Extratropical Transition in the Western North Pacific

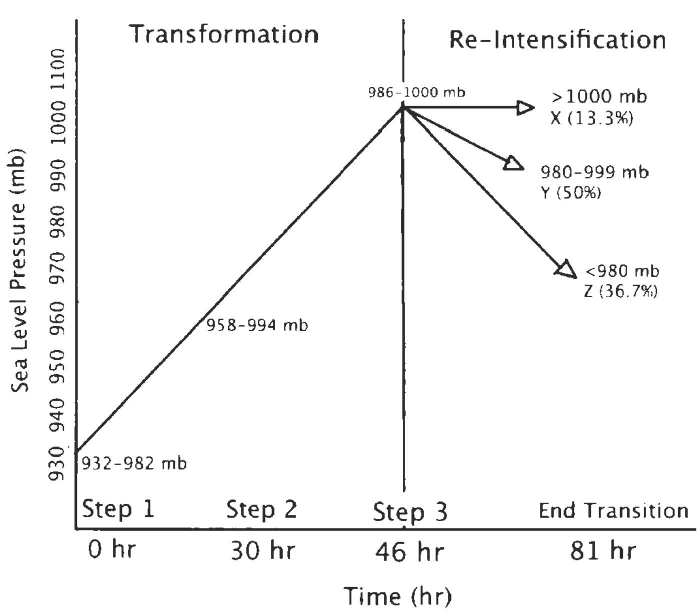


Figure 2.1 - Modified schematic of extratropical transition evolution in the western North Pacific (Klein et al., 2000). The levels of re-intensification are categorized as X: 13.3% of cyclones studied experienced little or no re-intensification (sea level pressure (SLP) >1000 mb), Y: 50% of cyclones studied experienced moderate re-intensification (SLP between 980-999 mb), and Z: 36.7% of cyclones studied experienced a deep re-intensification (SLP < 980 mb).

Klein et al., (2000) defined two stages of extratropical transition: transformation, where the tropical cyclone changes into a baroclinic storm; and re-intensification, in which the resulting transformation of the storm deepens as an extratropical cyclone. Extratropical transition, for this study, began when the transformation stage was beginning and concluded when the re-intensification stage was complete (Klein et al., 2000).

2.1.1 Transformation Stage

Step one in the transformation stage was depicted by a marked decrease of cloudiness in the western quadrant of the cyclone (Fig. 2.1). This would be represented by the distribution of clouds becoming asymmetric in appearance (the cyclone would start to lose its symmetric appearance). The southern quadrant also appears less cloudy as dry areas begin to appear within the rain bands. Step two is defined as the point where there is evidence of a reduction of deep convection in the eastern and southern quadrants of the storm. Step three occurs when the eye wall begins to decay, as deep convection erodes to the west of the center of circulation (Klein et al., 2000).

2.1.2 Re-Intensification Stage

Klein et al., (2002) proposed that when a tropical cyclone is moving poleward and interacts with a translating and strengthening midlatitude circulation, mid- and upper-tropospheric dynamic support would be provided. This interaction would affect the magnitude of the re-intensification stage. Figure 2.2 is a 3x3 matrix created to demonstrate the effects of various levels of midlatitude circulation and tropical cyclone contributions. The

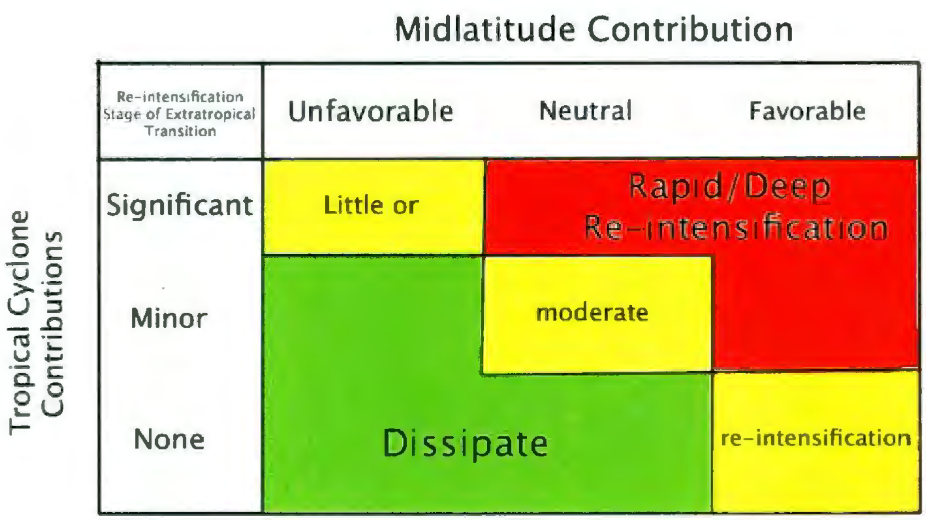


Figure 2.2 - Characterization of tropical cyclone contributions and mid-latitude circulation to the re-intensification stage of extratropical transition (Klein et al., 2002). Three outcomes can result from the combinations of these contributions: (1) rapid/deep re-intensification (depicted in red; sea level pressure < 980 mb); (2) little to moderate re-intensification (depicted in yellow; sea level pressure >980 mb); or (3) The tropical cyclone dissipates without completing extratropical transition (depicted in green).

strength and location of the tropical cyclone contributions are crucial in determining if the tropical cyclone will re-intensify or dissipate (Figure 2.2). Harr and Elsberry (2000) suggested that forecasters can anticipate both the intensity and track of an extratropical transition based on the pattern which a particular tropical cyclone is exhibiting as it completes its transformation stage. If meteorologists focused on step 2, then they should be able to anticipate the changes seen in 500 hPa isoheights. This would allow meteorological agencies to amplify intensity and track forecasts (Harr and Elsberry, 2000).

2.1.3 Study of Re-Intensification in Atlantic Transitions

Extratropical transition is known to occur in every ocean basin which experiences tropical cyclones. Extratropical transition is relatively rare in the northern Indian Ocean and the eastern North Pacific, due to the low latitude somewhat restricted of the basin and the background synoptic environment, respectively (Jones et al., 2003). Previous research regarding extratropical transition has been focused heavily in the Pacific Ocean. According to Jones et al., (2003) the largest number extratropical transition events are found in the western North Pacific, and that the largest percentage of tropical cyclones undergoing extratropical transition (about 45% from 1970 to 1999) are found in the North Atlantic.

A study from Hart and Evans (2001) focused on the Atlantic Ocean Basin regarding intensity changes. They concluded that most of the cyclones that intensified after extratropical transition (51% of storms studied that underwent transition) formed in the deep tropics, especially in the Cape Verde Region. These transitions also occurred in latitudes focused around short-wave and long-wave trough patterns and influenced by the polar jet axis. Post-transition intensifiers occurred between 37° and 47°N, with two extensions southward at 65°W and 50°W, and a northward extension at 30°W (Hart and Evans, 2001). The storms that weakened or dissipated during extratropical transition (42%) were most commonly formed outside of the deep tropics. These cyclones transitioned further northeast or over land than the cyclones that intensified. The region over eastern North America and the western Atlantic Basin produced a minimal number of transitions compared to the north-central Atlantic Ocean with many cyclones transitioning into weaker extratropical cyclones. All extratropical cyclones which weakened formed at or north of 15°N, according to Hart and Evans (2001). Having a strong baroclinic component early in a cyclones's tropical development stage appears to be crucial to its becoming an intense extratropical cyclone after extratropical transition (Hart and Evans, 2001).

2.2. Cyclone Phase Space

Instead of relying on satellite interpretation, Hart (2003) took a more quantitative path and created a cyclone phase space. The cyclone phase space is a continuum which describes the evolution of all synoptic-scale cyclones (tropical, subtropical, hybrid, and extratropical) and the transitions each one undergoes. Hart (2003) looked closely at the life cycle and evolution of the storms by identifying symmetric/nonfrontal versus asymmetrical/frontal and warm versus cold-core structure. He was convinced that the life cycle of a cyclone can be observed within this phase space and would provide insight into the structural evolution of a cyclone. Using thermal wind and thermal asymmetry, he was able to measure the structure of cyclones. From these methods, the following three parameters were identified to illustrate a cyclones's structure:

1. Lower-tropospheric thermal asymmetry (*B*). The following equation was derived to describe storm symmetry:

$$B = h(\overline{Z_{600\,\mathrm{hPa}} - Z_{900\,\mathrm{hPa}}}|_R - \overline{Z_{600\,\mathrm{hPa}} - Z_{900\,\mathrm{hPa}}}|_L),$$

(Equation 2.1)

where *h* indicates the hemisphere (1 for North and -1 for South), Z is isobaric height, R and L are the right (left) of current storm motion, and the overbar indicates the areal mean over a semicircle radius of 500km. A cyclone is seen as perfectly symmetric when $B = 0$m and $B > 10$m as the start of extratropical transition (Evans and Hart, 2003)

2. Thermal winds in the lower tropospheric region (cold vs warm core) ($-V_T^L$). The following equation was derived to show the thermal wind measure in the lower tropospheric region.

$$\left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{900\ \mathrm{hPa}}^{600\ \mathrm{hPa}} = -|V_T^L|$$

(Equation 2.2)

where $-V_T^L > 0$ is a warm core system and extratropical cyclone transition occurs when $-V_T^L$ first becomes negative (Hart, 2003).

3. Thermal winds in the upper tropospheric region (cold vs warm core) ($-V_T^U$). The following equation expresses the thermal wind measure in the upper tropospheric region.

$$\left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{600\ \mathrm{hPa}}^{300\ \mathrm{hPa}} = -|V_T^U|.$$

(Equation 2.3)

To demonstrate the difference between the upper and lower troposphere, Hart (2003) changed equation 2.2 to express the thermal wind measure in the upper troposphere (Hart, 2003).

These three parameters are crucial to synthesize model diagnostics with direct observations and conventional fields (Hart, 2003).

Hart et al., (2006) used the cyclone phase space approach and researched 34 storms that underwent extratropical transition. Synoptic composites at four stages of extratropical transition were examined: 24 hours before the beginning of transition (T_B-24), beginning of transition (T_B), conclusion of transition (T_E), and 24 hours after transition completion. A tropical cyclone is tightly constrained, with a variety of evolutions after T_E. Table 2.1 depicts nine key stages for cyclones undergoing extratropical transition. The mean evolution of cyclone structure from a

	Minimum Sea Level Pressure (mb)	Radius of gale force 925 hPa wind (km)	B	$-V_T^L$	$-V_T^U$
T_B-72 hours	1000.8 (10.6)	226.0 (183.4)	2.3 (5.6)	65.7 (67.0)	33.9 (62.2)
T_B-48 hours	997.8 (11.0)	267.9 (192.9)	1.9 (5.0)	84.9 (70.0)	44.3 (73.1)
T_B-24 hours	996.6 (10.4)	298.2 (192.5)	2.0 (3.6)	94.8 (66.8)	34.4 (70.6)
T_B	995.2 (7.8)	368.2 (151.5)	11.8 (5.1)	82.3 (62.7)	-28.2 (64.7)
T_{MID}	994.2 (9.6)	405.7 (192.4)	25.5 (13.2)	31.6 (66.3)	-87.0 (64.1)
T_E	995.0 (10.5)	440.4 (239.8)	35.0 (21.0)	-37.2 (55.0)	-134.6 (73.5)
T_E+24 hours	990.5 (12.5)	494.8 (260.2)	51.5 (28.7)	-148.1 (146.4)	-225.1 (115.5)
T_E+48 hours	985.6 (15.2)	524.8 (324.4)	30.3 (29.5)	-50.8 (119.8)	-136.2 (130.1)
T_E+72 hours	982.3 (15.9)	571.4 (352.8)	19.2 (21.5)	-38.5 (95.7)	-128.3 (88.3)

Table 2.1 - The mean and standard deviation (parentheses) for key cyclone characteristics for the nine stages identified for extratropical transition. There are three parameters that define the cyclone phase space: 900-600 mb thermal wind ($-V_T^L$), 600-300 mb thermal wind

($-V_T^U$), and 900-600 mb storm-motion-relative thickness asymmetry (*B*). All of these parameters were measured within a 500 km radius. Positive values of $-V_T^L$ and $-V_T^U$ depict a warm core structure, whereas negative values show a cold core structure. High positive values of *B* mean a system that is symmetric, and high negative values indicate asymmetric (Hart et al., 2006).

symmetric warm core, to a hybrid of warm and cold core, to an asymmetric cold core, to dissipation is shown. The average tropical cyclone that undergoes extratropical transition peaks in intensity about 24 hours before the start of its transition (T_B-24) (Hart et al., 2006). This result is consistent with the study by Hart and Evans (2001) and shows why a large number of Atlantic tropical cyclones undergo extratropical transition. Hart et al., (2006) concluded that warm-seclusion was favored when the scale of the transitioning cyclone was on the same order of the trough with which it interacted with. The conclusion from this research was important because warm-seclusion is known as the most mature stage of extratropical transition and can be associated with hurricane force winds and torrential rains.

2.3 Track Analysis of Extratropical Transitions

Hart and Evans (2001) analyzed 841 Atlantic tropical cyclones from 1899 to 1996. They concluded that 42% (355/841) were classified as undergoing some form of extratropical transition by the NHC (Hart and Evans, 2001). Comparing this conclusion with the research from Klein (1997) (focused on the western North Pacific), only 36% (213/463) of tropical cyclones underwent extratropical transition. Quantifying these transitions has resulted in agreement amongst researchers that tropical cyclones undergo extratropical transition more frequently in the Atlantic Basin compared to the Pacific and other oceanic basins.

The research undertaken by Hart and Evans (2001) determined the peak times and favorable areas for extratropical transition to occur. During the beginning of the Hurricane

Season in the Atlantic, the months of May and June showed transitions occurring at lower latitudes on average (30°-35°N). The mean latitude of transitions began to shift northward by about 5° latitude in July. Between July and September, the majority of extratropical transitions occurred between 40° and 45°N. By September and into October the transition zone shifted southward by about 4°. The patterns from this research suggested that the transition season can be categorized into three separate periods: a low-latitude quiet early season, a high-latitude active mid-season, and a midlatitude active late season (Hart and Evans, 2001). Transitions occurred at higher latitudes during the peak of the Hurricane Season compared with early and later months which resulted in lower latitude transitions.

2.3.1 Frequency of Extratropical Transitions

The probability of transitions showed a peak during the months of September and October when 50% of the 355 cyclones transitioned (October being the month in which the maximum amount of transitions occurred). Interestingly, the percent of landfalling storms at any location along eastern North America occurs early in the season and rapidly decreases as the season progresses. This is partially due to a shift in tropical cyclone development from the Caribbean and the Gulf of Mexico to further east in the open Atlantic late in Hurricane Season. However, while landfall probability does decrease further into the season, if a storm does make landfall it is more likely to undergo extratropical transition. This is due to higher baroclinicity and more troughs located over land during the peak of the season. Summarizing, while landfalling cyclones are more likely in the early season, extratropical transition is more likely to occur later in the season. October was found to have the maximum percentage of cyclones undergoing transition (Hart and Evans, 2001).

2.4 Forecasting Extratropical Transitions

Forecasters are responsible for producing the advisories and warnings during an extratropical transition event, but they are faced with the problem of accurately predicting the behavior of the changing cyclone during extratropical transition. Forecasters must not only predict the intensity and track of the system but also how strong the surface winds and precipitation will be as well as where they are located within the cyclone. Because the majority of extratropical transition events take place over the open ocean, forecasters must rely on satellite diagnostic techniques as an important forecasting tool. Jones et al., (2003) focused on the complexity of forecasting extratropical transitions and offered suggestions to improve the understanding of extratropical transition events. Currently, the prediction of extratropical transitions is a challenge for numerical weather prediction models. A transition event can substantially complicate forecasts downstream of the tropical cyclone, and thus this can have an impact on western North America and Europe. The researchers stated that a further challenge for forecasters is communicating with the local public and emergency management personnel, especially as there is minimal public awareness regarding extratropical transitions. Jones et al., (2003) discussed in detail the challenges of forecasting extratropical transition events and the impacts associated with them.

2.4.1 Track

The increase in forward speed when a tropical cyclone moves into the midlatitudes is a major challenge for forecasters. A tropical cyclone can accelerate from an initial forward speed of 5 m/s in the tropics to over 20 m/s in the midlatitudes. An increase in speed decreases the amount of warning time that can be given to the public. If the timing of increase in translation speed is incorrectly determined, track errors up to hundreds of kilometers could occur (Jones et al., 2003).

2.4.2 Intensity

When a tropical cyclones moves into the midlatitudes, it usually illustrates a decrease in intensity as the mean sea level pressure rises and there is a decrease in in the maximum surface wind speed. However, if the cyclone interacts with an extratropical system during its transition, this may result in a rapid re-intensification after the conclusion of extratropical transition. Another point is that a tropical cyclone may decay upon entering into the midlatitudes, but the remains of the system could interact with an extratropical system and increase the risk of severe weather for Atlantic Canada and western Europe. This kind of development, however, is often poorly forecast by numerical weather prediction models (Jones et al., 2003)

2.4.3 Surface Winds

Determining how the wind field will change during extratropical transition is an important challenge. The strongest winds are found close to the center of circulation when a cyclone is in its tropical form. However, this area of intense winds shift when a tropical cyclone undergoes extratropical transition and the strongest winds are found over a larger area and exhibit more significant asymmetries (Jones et al., 2003).

2.4.4 Precipitation

During the start of extratropical transition, heavy precipitation becomes trapped in the large cloud shield which extends poleward from the center of the tropical cyclone. Because the cyclone increases in size substantially, heavy precipitation can occur over land without the cyclone making landfall. Orographic effects pose a challenge to forecasters because they can increase the precipitation during extratropical transition. In the North Atlantic, cold-air damming to the east of the Appalachian Mountains has been known to enhance the precipitation of cyclones undergoing extratropical transition (Jones et al., 2003).

2.4.5 Oceanic Effects

Extratropical transition events can produce very large surface wave fields offshore. This is due to the high winds and the increase in the forward speed of the system. A slow tropical cyclone will have waves moving out ahead of the storm. However, for cyclones undergoing extratropical transition, this is not often the case. As the cyclones increases in speed during extratropical transition, the storm can arrive at the same time the waves are being generated, which offers very little warning to the public (Jones et al., 2003).

Jones et al., (2003) discusses the challenges of numerical predictions extensively, and indicates that a major contributor to errors in numerical forecast data during extratropical transitions is the uncertainty in what the initial conditions are during the time of transition. There is a lack of conventional multilevel data, and this causes problems for numerical forecasts. To provide the necessary warning time for a tropical cyclone that is about to go through extratropical transition, it is a necessity to improve the accuracy of numerical forecasts. Jones et al., (2003) believed that progress had been made as of 2003 in understanding and forecasting extratropical transition. However through enhanced collaboration between the basic research and operational forecast communities further progress will increase in a better understanding of extratropical transitions.

3. Methodology

3.1 Experimental Set-up and Data Collection

The challenge for this research involved combining a knowledge of both tropical and extratropical meteorology to gain a better understanding on extratropical transition. Tropical and extratropical cyclones are opposites in many ways, but they are part of the same coin. Different meteorological forecasting centers around the world have different criteria when assessing if a tropical cyclone is undergoing extratropical transition. For the purpose of this study the following definition was used to classify extratropical transition:

Extratropical transition involves a gradual change in the structure from a smaller warm-core symmetrical system, to a larger cold-core asymmetrical (comma-like) system (Harr and Elsberry, 2000; Hart and Evans, 2001; Klein et al., 2000).

Observations, definitions and criteria for the data presented were collected from the NHC and the CHC. Analysis from past studies on extratropical transition were identified and related back to throughout the experiment process.

Extratropical transitions can occur in any ocean where cyclones develop. This study focuses on the North Atlantic Ocean and Atlantic Canada, specifically Newfoundland. Hurricane statistics and track records were obtained from the NHC official database and transcribed into an Excel Worksheet for further examination. The following data was transcribed for each individual cyclone that underwent an extratropical transition: latitude and longitude; wind speeds (km/h); time (GMT); and directional movement speed (km/h). Stormpulse, a weather data aggregation service, was used as a reference in determining the mechanics of each hurricane and as a source comparison for the data reported by the NHC. Available data regarding extratropical transitions from United Information Systems weather (UNISYS weather) and Weather Underground were examined to compare NHC transition data. Some data sources indicated that particular cyclones underwent extratropical transition at different times and/or latitudes. These differences were reconciled by determining which meteorological agencies were in agreement with each other regarding coordinates. If more than one agency had the same coordinates the data was used. In some cases, records from all agencies showed extratropical transitions being completed at different times and latitude locations. For a case such as this, it was decided that the earliest time showing the completion of extratropical transition was recorded. The NHC updates and records cyclone activity every six hours (if a cyclone is not an immediate threat to land), in many cases a cyclone's transition would be complete before the next update was issued, therefore earlier times recorded from other meteorological agencies were used. The finalized data collection was then uploaded into ArcMap GIS 10 software. The approximate locations that the individual hurricane started to undergo extratropical transition and completed the transformation into an extratropical cyclone was then plotted.

The time frame used for this study is from 1991 to 2011. The reason for this choice is due to the availability and quality of data. The NHC has completed data for all storms from 1995 onward. Pre-1995 data obtained from the NHC had missing information on cyclone frequency and observational data. Therefore, 1991 to 1994 data was provided by Stormpulse, UNISYS Weather, Weather Underground, and partially completed data from the NHC. Missing information included the absence of forward track speed at the time of extratropical transition. However, this missing information is not important for this research, and did not affect the results. In rare cases some track data was missing from the NHC. To correct this problem track data was gathered from other agencies, particularly Stormpulse. Each cyclone suspected of undergoing extratropical transition was compared with other data from meteorological agencies. Agencies which stopped issuing advisories on cyclones before extratropical transition (or during) would not record the completion of transition. Other agencies would continue monitoring and recording the cyclone until it dissipated or merged with another system. If one meteorological agency claimed a cyclone underwent extratropical transition, this data was recorded.

Accurate pre-1991 data is more difficult to obtain, therefore this research is confined to the time period of 1991 to 2011. The problem is not accessibility of this data, but simply that the data was not collected initially in sufficient quality. Another problem is that extratropical transition is a fairly new meteorological term. Reports prior to 1991 did not use the term regularly and therefore determining which storms underwent extratropical transition before 1991 would not be reliable. Technology, collection of data, and knowledge of extratropical transition, have improved dramatically since 1991.

Each cyclone that underwent extratropical transition was tracked from the time it reached the status of tropical depression (wind speeds less than 62 km/h) to the time the storm dissipated or merged with another atmospheric system (in most cases, until the time the NHC stopped monitoring the storm). The track is important to note because it shows the general area of origin and how long the storm survived until it transitioned. Track data could be a factor in determining a potential future algorithm for where transitions occur.

Using recorded cyclone data from the NHC and satellite imagery from Stormpulse, the approximate area that a cyclone underwent extratropical transition was located and plotted in

ArcMap GIS along with available information regarding the cyclone's wind speed, movement, date and time, latitude and longitude, and pressure at the time of transition. The plotted point is the location where the cyclone became a cold core storm and completed its transition into an extratropical cyclone as determined by the NHC. Presently, the understanding of the extratropical transition process is insufficient and there is no credible data that determines the duration and physical length (km) of extratropical transition. Canadian forecasters, in recent years, have been focusing on extratropical transition and determining ways to improve the forecasting of intensity and track changes regarding these systems (Fogarty, 2002). In Canada, research and knowledge has been improving by conducting research flights into transitioning tropical cyclones, among other things (Environment Canada, 2010b).

In Canada, government policy, preparedness data and information regarding Hurricane Igor was provided by the CHC and Environment Canada. However, CHC records could not be used to augment the NHC records for this study. The NHC is the leading hurricane agency for the Atlantic Basin. The CHC does not provide data regarding track, location, intensity, or forward speed of cyclones, therefore no statistical data could be gathered from the CHC. The CHC is a government agency which aims to inform the public of approaching cyclones and how to prepare for hazardous weather, including extratropical storms. They also keep records of past storms that have caused devastation in Canada, such as Hurricane Igor. The Government of Canada and Environment Canada meteorologists summarize what meteorologists foresaw for the 2010 Atlantic Hurricane Season, what models were depicting when Igor formed, and the damage resulting from the storm. The track of Hurricane Igor as well as recorded wind speeds and wave heights are provided (Environment Canada, 2011c). Past weather statements issued from the

CHC, which describe what meteorologists were expecting from Igor were referred to for this study.

Interviews were conducted with personnel from FES-NL: David McCormack, Director of Emergency Services; Paul Peddle, Manager of Plans and Operations; and Cheryl Gullage, Public Relations Specialist. The discussions focused on Hurricane Igor, and the impact the cyclone had on Newfoundland, including the effects of preparedness, response and recovery efforts. FES-NL provided information concerning the level of preparedness prior to Igor, as well as the heightened awareness in both residents and government agencies that resulted from the storm's impact. FES-NL also discussed the actions that residents, especially those living in the prime areas of extratropical storms, can undertake to prepare for the future events that are similar to Igor.

4. Results

4.1 Frequency Statistics

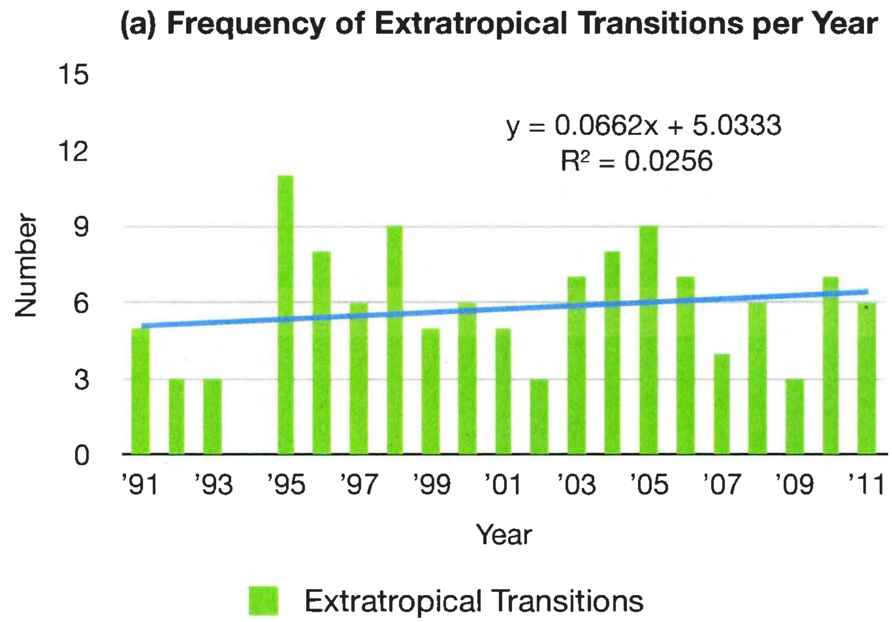
Cyclone and extratropical transition data was gathered from a variety of sources including the NHC, UNISYS Weather, Weather Underground, and StormPulse from 1991-2011 and analyzed to determine the point in which a tropical cyclone underwent extratropical transition. The cyclones that were taken into consideration were of pure tropical origin, ranging from tropical depressions to Category 5 intensity hurricanes. Table 4.1 shows the total number of tropical cyclones and how many underwent extratropical transition. The average location, pressure and wind speed of the cyclone had after completing the transition phase was determined. Out of the determined 324 tropical cyclones that formed in the Atlantic Basin, a

Total Tropical Cyclones Formed 1991-2011	Total Extratropical Transitions 1991-2011	Mean Latitude (North)	Mean Longitude (West)	Mean Pressure (mb)	Mean Wind Speed (km/h)
324	121	40 N	55.5 W	993.2	85.8

Table 4.1 - Statistics of cyclone data showing the total number of tropical cyclones that formed from 1991 to 2011. It was determined that 37.3% (121/324) of these cyclones underwent extratropical transition. The mean latitude, longitude, pressure, and wind speed was derived from the cyclones that underwent extratropical transition.

total of 121 underwent extratropical transition (37.3%). The end of a transition was determined when the NHC labeled the storm as "extratropical" based on information indicating that the storm was a cold core system, or if evidence from a variety of meteorological data bases illustrated that the cyclone had become cold-core in nature.

Fig 4.1*(a)* shows how many extratropical transitions occurred per year and the average number of transitions per year. Figure 4.1*(b)* illustrates the maximum strength each cyclone reached during its life cycle. It was concluded that the average number of transitions seen in a



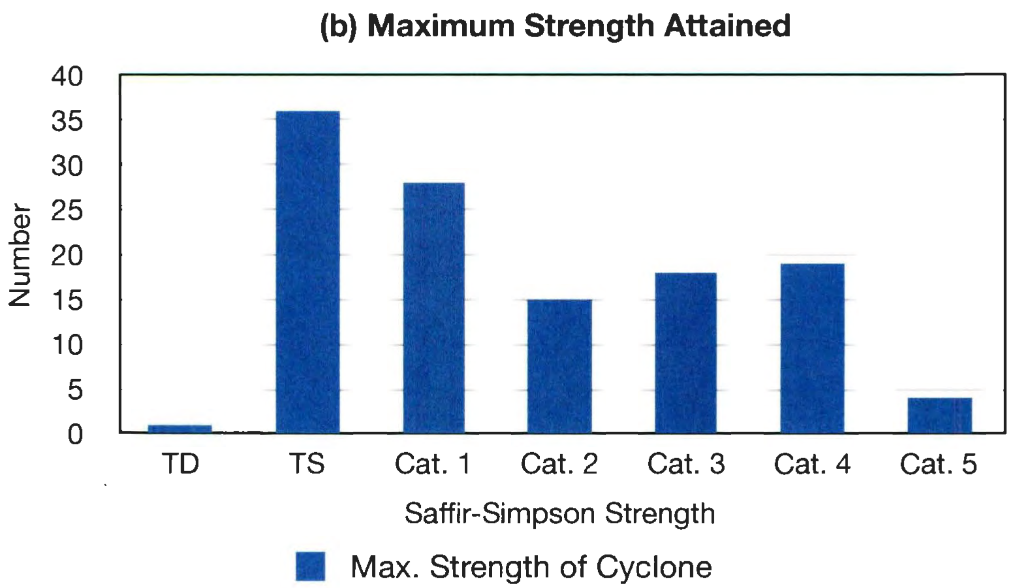


Figure 4.1 *a, b* - *(a)* The number of extratropical transitions per year (1991-2011). Linear trendline shown in blue. *(b)* The maximum strength attained by the cyclone according to the Saffir-Simpson Scale during its life cycle.

year was around 5.76. The R^2 value was determined using all of the years from this research and resulted in a slight positive upwards trend, indicating that there is a slight increase in extratropical transitions. This, however, is not statistically significant. If the timeline for this research was shorter, e.g. from 1995 to 2011, the linear trend would be negative. To improve the data, a longer timeline would be needed (about 50 years), which currently would not be possible, due to the absence of suitably detailed records.

It was determined that 29.8% (36/121) of cyclones achieved tropical storm status as their maximum strength during the course of their life span, which made up most of the cyclone data set. Excluding tropical depression strength storms, which only yielded in one storm, few storms reached Category 5 on the Saffir-Simpson Scale.

Every month in which a tropical cyclone formed was analyzed, including those that formed outside of the designated Atlantic Hurricane Season (June 1 to November 30). The greatest number of extratropical transition events occurred in September, which coincides with the peak of the Atlantic Hurricane Season (Fig. 4.2). A total of 104 tropical cyclones formed

Total Number of Tropical Cyclones and Extratropical Cyclones per Month (1991-2011)

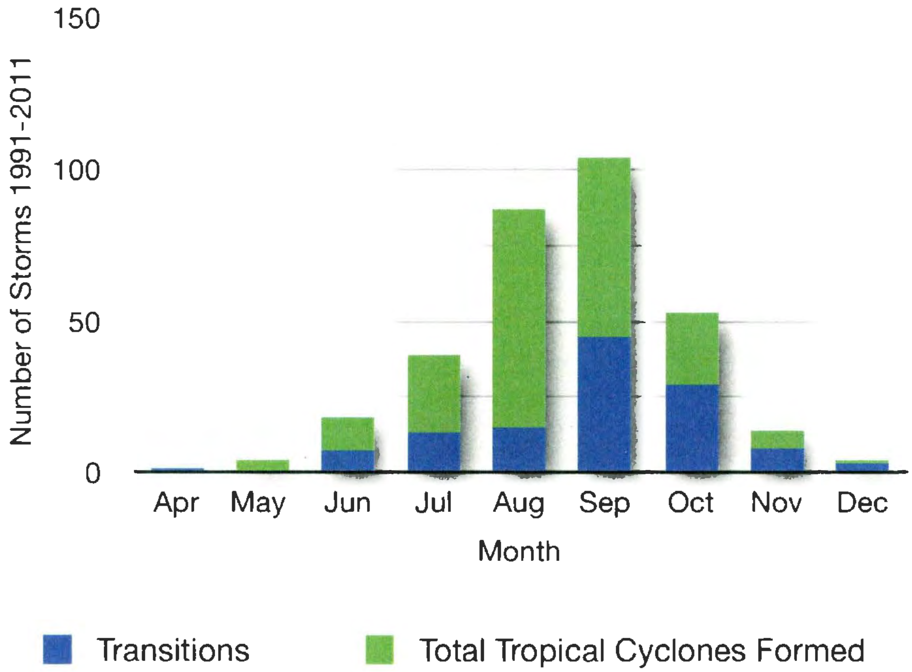


Figure 4.2 - The total number of tropical cyclones that formed in the Atlantic Basin per month from 1991 to 2011 (green) compared with the number of cyclones that underwent extratropical transition per month from 1991 to 2011 (blue).

in September, and of these 43.3% transitioned (45/104). The month which found the least amount of tropical cyclones formed was April (only one tropical cyclone underwent extratropical transition). May showed no activity in regards to extratropical transition. Mid- to late season cyclones (after mid-August) are far more likely to transition than early-season storms. The majority of tropical cyclones occur in the mid- to late Hurricane Season due to a combination of minimal vertical wind shear, warm SSTs, and increased atmospheric moisture content. An initial assumption could be that, because there is an increase in cyclone activity from August to October, the increased number of cyclones would result in a higher probability for extratropical transition to occur. However, individual years with many hurricanes, such as 2005, did not produce a proportionate number of transitions. Extratropical transition relies more on where an individual storm is going rather than the total number of cyclones seen in a season. A tropical cyclone relies on warm SST's to maintain its warm core. However when a tropical cyclone moves into cooler subtropical waters, the colder SST's will aid in the start of extratropical transition. Cyclones forming in the deep tropics and moving into the Caribbean and the Gulf of Mexico, have a reduced probability of extratropical transition.

4.2 Identifying a "Transition" Season

The start of the Hurricane Season does not yield a high percentage of extratropical transitions compared with the peak (August-October) and the end of the season (November and December). Figure 4.3*a* and *b* examines transitions that took place at the beginning (April - July), the middle (August - October) and the end (November - December) of Hurricane Season in comparison to the number of tropical cyclones during the same times of the year. The data shows

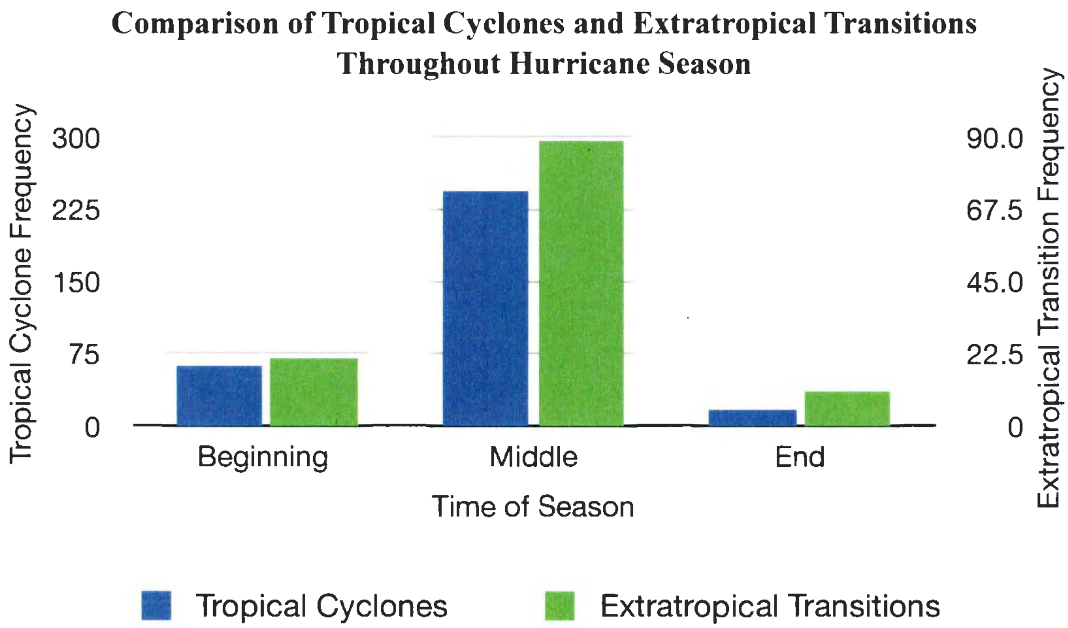


Figure 4.3 - Data comparing the beginning (April-July), middle (August-October) and the end (November-December) of Hurricane Season with respect to extratropical transition

and tropical cyclone frequency. Blue data depicting the number of total tropical cyclones throughout the season. Approximately 19.1% (62/324) of the total number of cyclones formed at the beginning of the season, 75.3% (244/324) in the middle, and 5.6% (18/324) at the end of the season. Green data showing the number of transitions occurring throughout the season. At the beginning of the season 17.4% (21/121) of transitions occurred, 73.6% (89/121) in the middle, and 9.1% (11/121) at the end.

that both tropical and extratropical transition occur more commonly in the middle of the season, followed by the beginning of the season. Differences exist in the frequency of tropical cyclone and extratropical transition occurrence, however. As the peak of Hurricane Season nears, the number of transitions tends to increase. However, early-season cyclones are less likely to transition: 21 cyclones underwent extratropical transition out of 62 total cyclones (33.9%). In comparison, the end of the season saw fewer storms forming (18 tropical), but more of these underwent transition (61.1%), almost double the percentage in the early season. The process of extratropical transition is still highly active in the late season even when tropical cyclone numbers begin to drop.

Data for August was examined to determine when the peak "transition season" for these cyclones began. Transitions that occurred between the 1st and 15th August were labeled as "early", and those from the 16th to the 31st August were designated "late" (Fig. 4.4). A total of 15 cyclones underwent

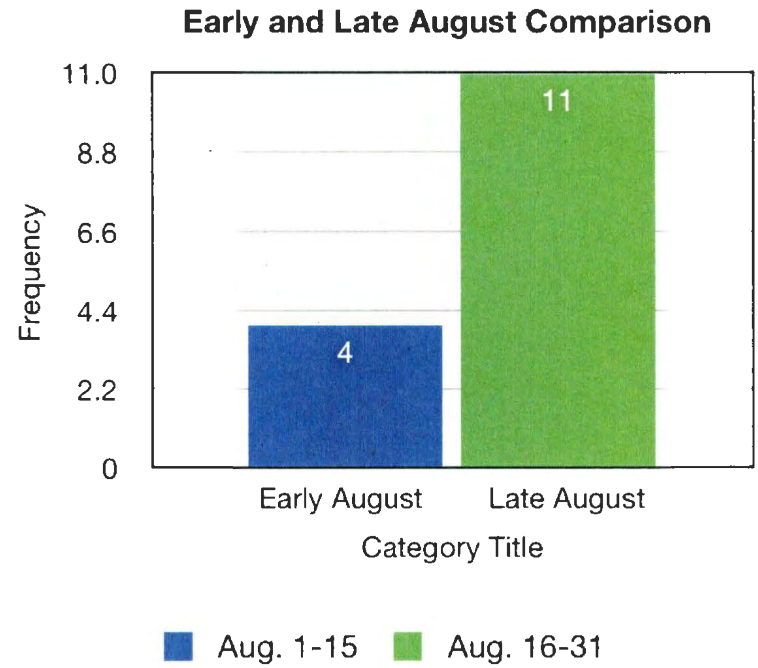
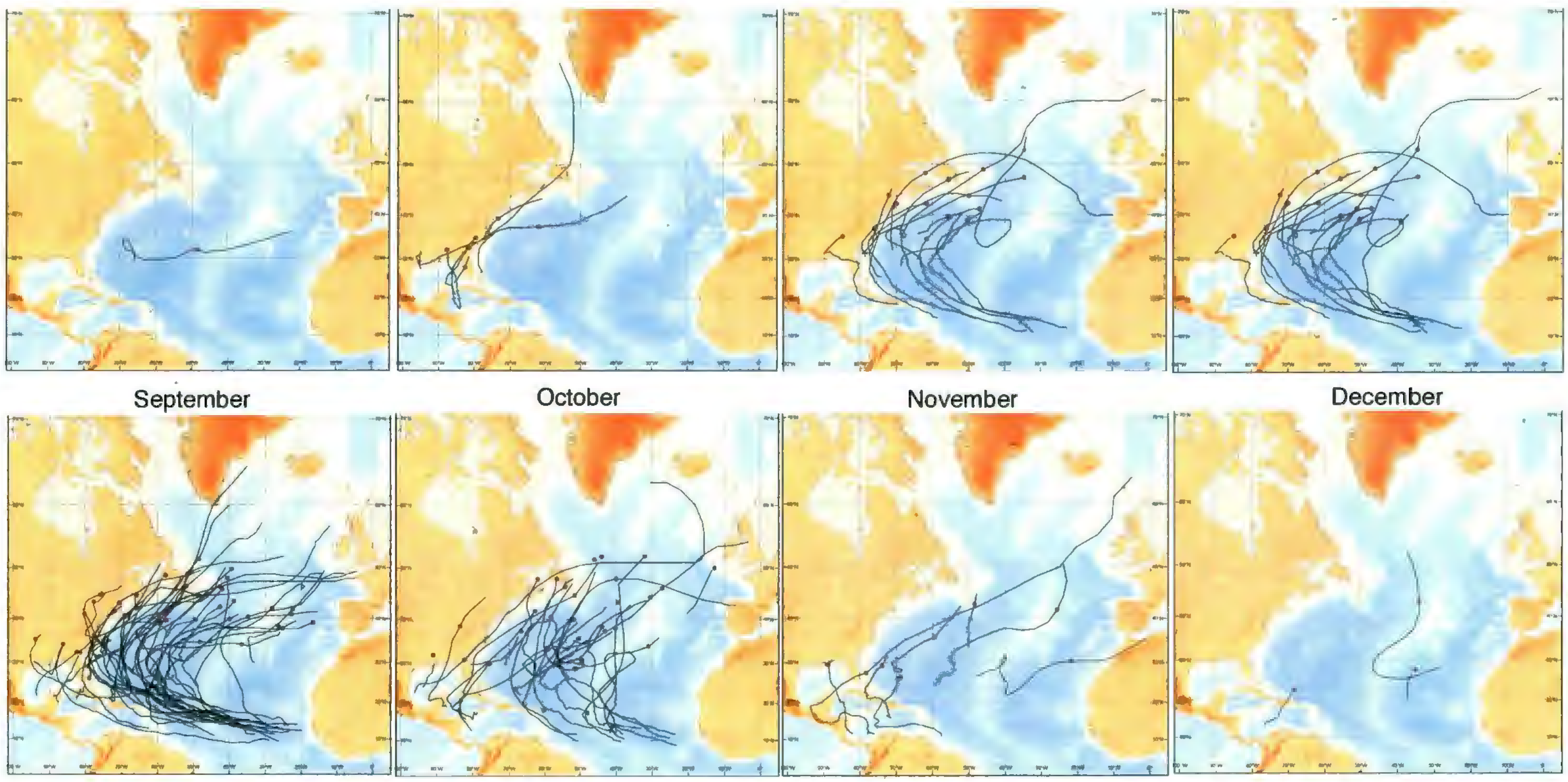


Figure 4.4 - Cyclones undergoing extratropical transition in August. Early August (blue) is from August 1-15, and late August (green) encompasses the remaining days.

extratropical transition in the month of August from 1991 to 2011. Only 26.7% (4/15) of cyclones underwent the transition process early in the month, compared to 73.3% (11/15) which underwent extratropical transition in late August. Figure 4.4 confirms that transitions begin to increase rapidly during late August and continue for the remainder of the Hurricane Season. Therefore, the start of the season for extratropical transition would be around mid-August, and the peak frequency of transitions would be in September.

4.3 Track Analysis

The monthly data was broken down further to analyze the track, transition point, and latitude/location of extratropical transitions (Fig. 4.5). Track data and the estimated point of



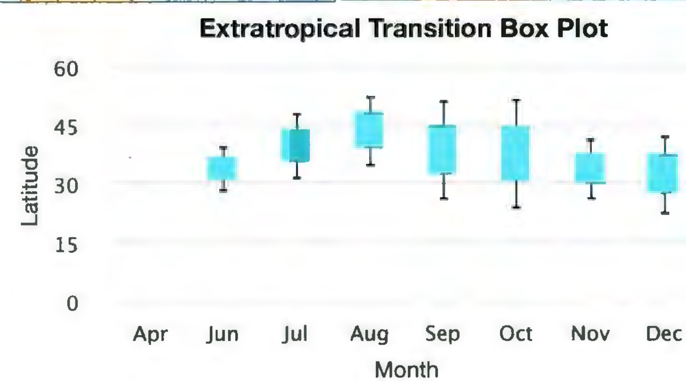


Figure 4.5 - Tracks of tropical cyclones that underwent extratropical transition by month. Red dots represent the point of transition as defined by the NHC. Bar chart represents a summary of the range of latitude over which extratropical transition occurred by month. The bars show the latitudinal range of transition (first and third quadrants). The extreme latitudes of transition are represented by the horizontal bars outside the first and third quadrants.

extratropical transition was determined from data collected by the NHC, Weather Underground, Storm Pulse and UNISYS Weather. Tropical cyclones that underwent a transition were separated into monthly categories. The month that the extratropical transition took place is plotted, which may not necessarily correspond to the date when the tropical cyclone first formed. The majority of transitions took place over the ocean (80.2%). Only 19.8% of tropical cyclones transitioned over land (24/121), most in September. The box plot shows the modal latitude in which extratropical transition took place, between 30° and 45°N.

4.4 Time Frame of Extratropical Transition

Using the data from Figure 4.5, research was focused on the start time of extratropical transition and the conclusion. Due to the lack of data, there is currently no information indicating explicitly when a cyclone began to undergo extratropical transition. Using a similar approach to Klein et al., (2000), this study defined the "beginning" of extratropical transition as 48 hours prior to the completion of the process. This is only an estimated time frame, as individual storms can take between a few hours and several days to complete extratropical transition. Figure 4.6 illustrates the locations of the storm centers 48 hours prior to the completion of extratropical transition and the conclusion of the transition. During the start of Hurricane Season (June and

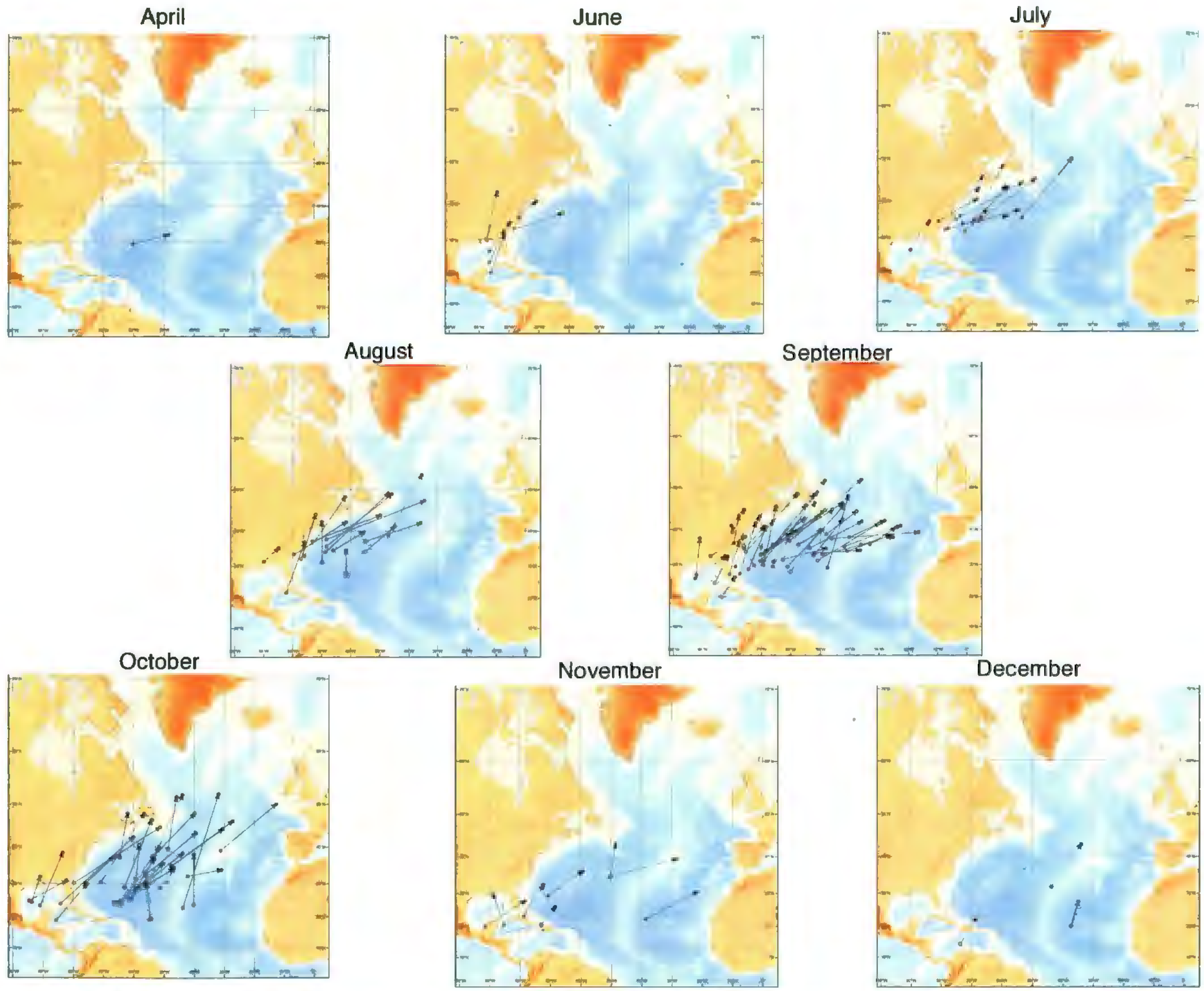


Figure 4.6: Tracks showing the beginning and conclusion of extratropical transition. Each color is unique to one storm. Arrows show the direction in which the storm moved. The beginning of extratropical transition was determined to have taken place 48 hours prior to the completion of extratropical transition.

July), transitions begin to happen closer to land, particularly in the Gulf of Mexico in June, shifting to the east coast of North America by July. The peak months of Hurricane Season (August to October) show transitions beginning mostly in the open Atlantic Ocean and following a general north-northeast pattern before the completion of extratropical transition. The end of Hurricane Season shows an increase in transitions in the Gulf of Mexico but the maximum continues to be offshore in the North Atlantic. Figure 4.7 shows where the beginning and end of extratropical transition takes place with regards to latitude. The data shows that about 62.8%

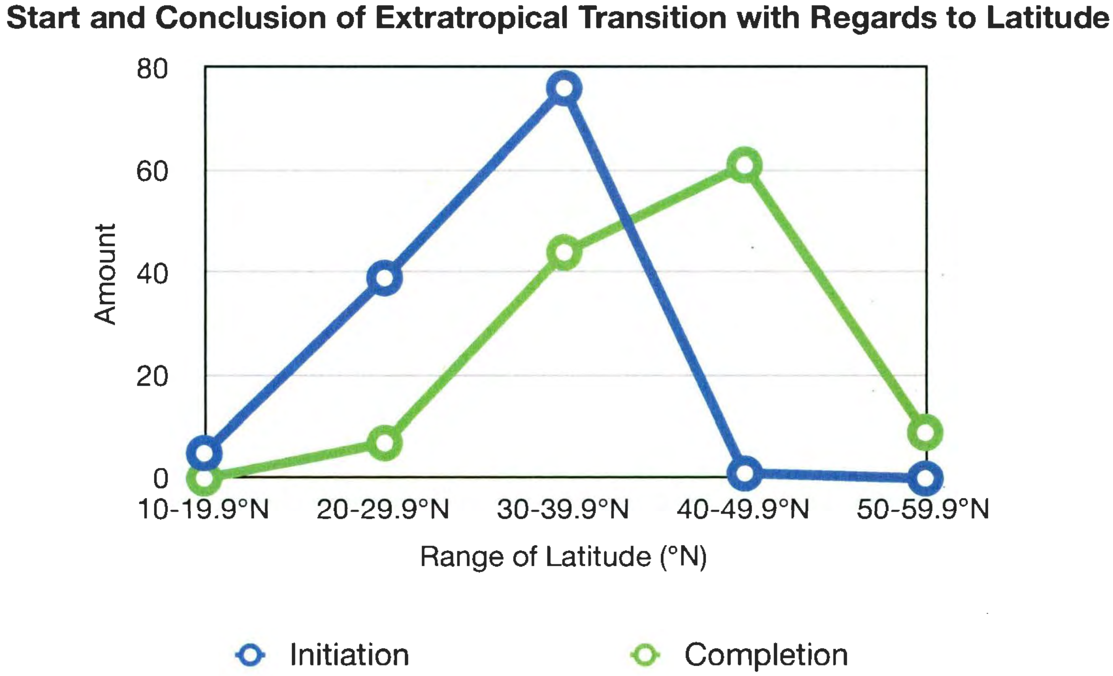


Figure 4.7 - Data showing the number of cyclones at a particular latitude that initiate extratropical transition (blue) and where tropical transition conclude (green).

(76/121) of cyclone begin to transition between the latitudes of 30 to 39.9°N and that 50.4% (61/121) complete their transition further north between 40 to 49.9°N.

With regards to the track distance between the initiation and completion of the extratropical transition, results indicate that there was an increase in the length travelled by storms undergoing transition from April to August (Table 4.2). September and October showed

Month	Average Distance (km)
April	1,309
June	1,447
July	1,994
August	2,222
September	2,034
October	2,104
November	1,577
December	1,332

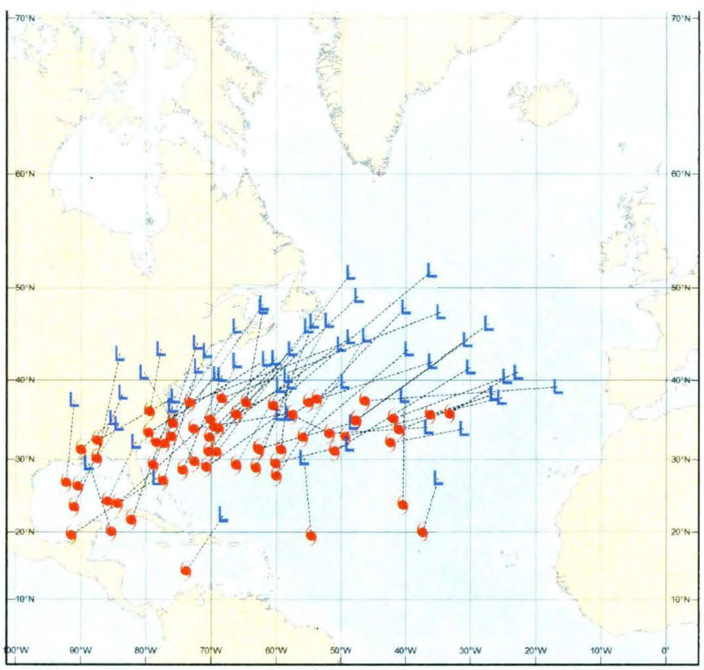
Table 4.2 - Average distance travelled by storms while undergoing extratropical transition by month.

similar transition distances, averaging about 2,069 km. There was a decrease in the transition distance from November to December. During the peak of Hurricane Season the average extratropical transition distance was around 2,120 km. This result could indicate why more tropical cyclones undergo and survive extratropical transition in the mid-season (August to October) compared to the rest of the Hurricane Season. August showed the maximum average distance for tropical cyclone completion. However, it did not produce a large percentage of extratropical transitions (17.2%). It was determined that 43.3% of tropical cyclones formed in underwent extratropical transition. This rose in October with 54.7% undergoing extratropical transition. Perhaps the long distances required for transition in August limit the number of storms that can survive the process. The somewhat shorter distances in September and October could increase the possibility of successful completion of extratropical transitions.

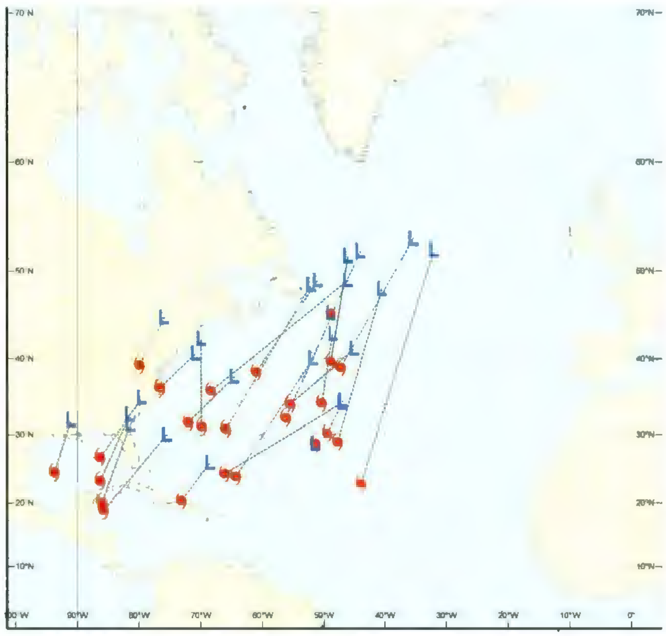
4.5 Re-intensification

Another important aspect to this study was the investigation of the possibility of re-intensification of cyclones after they transitioned. Each cyclone's barometric pressure at sea level was determined 48 hours prior to transition and compared to the barometric pressure after the completion of extratropical transition. A cyclone with pressure at completion that was higher than that 48 hours prior to transition was regarded as a "weakening system"; if the pressure was the same (±3mb) it was referred to as "little or no intensity change"; and if the pressure was lower it was labeled as a "re-intensifying system." Figure 4.8*(a-c)* illustrates the data regarding re-intensification. The greatest percentage of tropical cyclones weaken as they undergo

(a) Weakening Cyclone



(b) Cyclones that underwent Little of No Intensity Change



(c) Cyclones that Re-Intensified

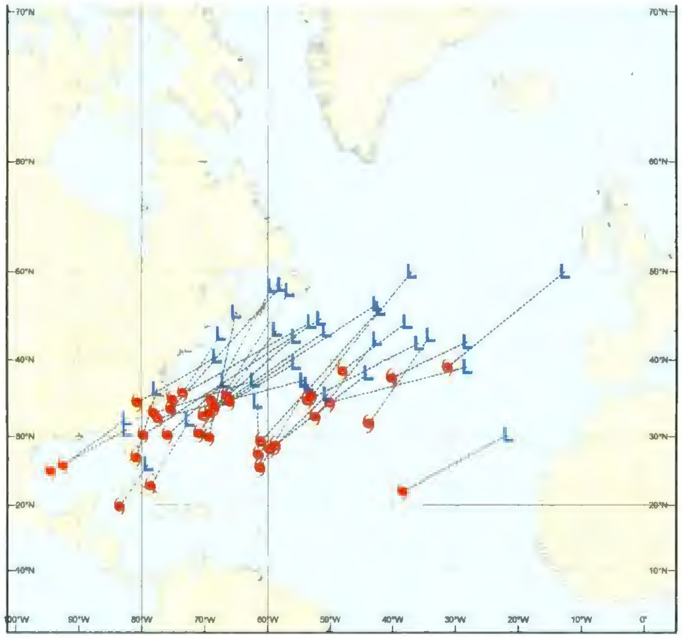
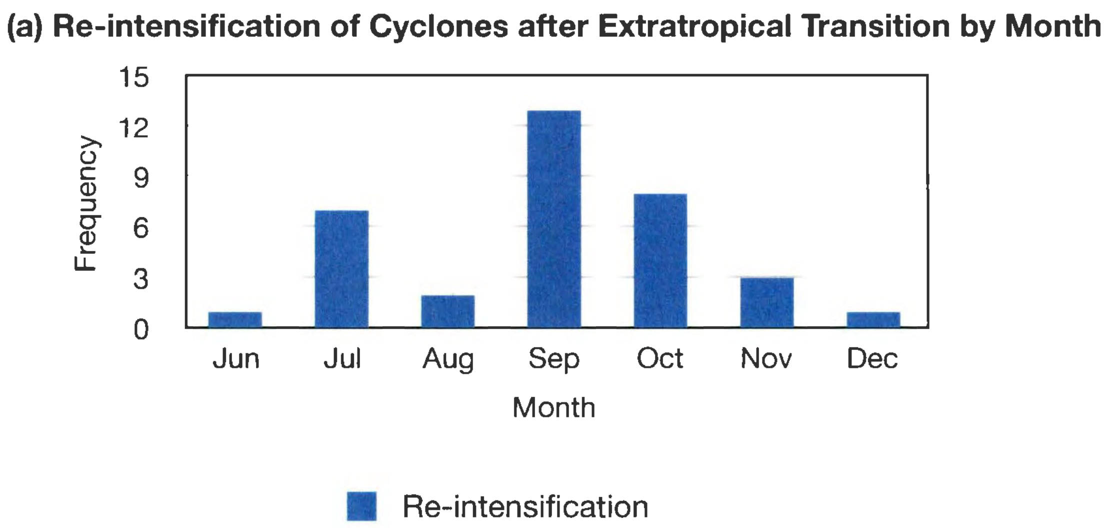


Figure 4.8 ***a, b, c - (a)*** **depicts cyclones that had weakened due to a higher sea level pressure after the completion of extratropical transition compared to 48 hours prior;** ***(b)*** **cyclones**

which had little or no change in sea level pressure and therefore no intensity change; *(c)* cyclones that developed a lower sea level pressure after extratropical transition compared to 48 hours prior. A red hurricane symbol depicts the start of transition and a blue low pressure symbol (L) is the point of transition completion, dotted black lines represent the distance between the cyclone's tropical and extratropical form.

extratropical transition and barometric pressure increases; 49.6% (60/121) of cyclones weakened. Most of those that weakened were, at one time, major cyclones with long tracks. A lesser percentage (21.5%; 26/121) of cyclones had little or no intensification change, and 29.2% (35/12) of cyclones underwent re-intensification. These cyclones had a decrease of at least 5 mb from the sea level pressure 48 hours prior to transition. Many of these cyclones had short tracks and were still in the stage of cyclogenesis when extratropical transition occurred.

Re-intensification data was broken down into monthly and seasonal plots to determine if there was a seasonal pattern (Fig. 4.9 *(a)* and *(b)*). September has the highest number of



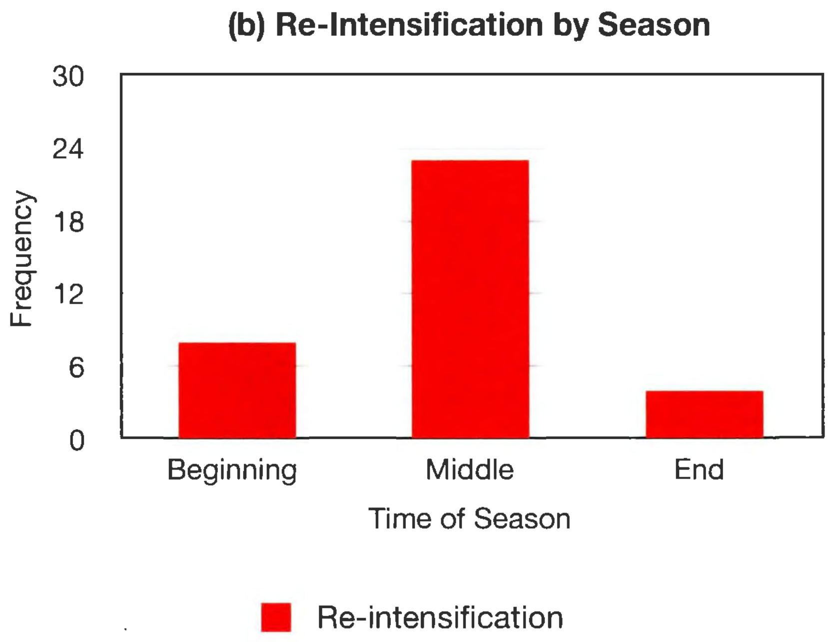


Figure 4.9 *a, b* - Data defining the likelihood of re-intensification in cyclones after extratropical transition. Total number of cyclones that re-intensified from 1991-2011 was 35. No data shown for April and May. *(a)* Re-intensification of cyclones according to month and *(b)* re-intensification according to season. Beginning (June - July), middle (August - October), and end (November - December).

transitions re-intensifying. Surprisingly, July showed an increase in re-intensification with 7 storms re-intensifying out of the total of 13 that underwent extratropical transition during the month (53.9%). August showed a dramatic decrease with respect to re-intensification with only 2 cyclones re-intensifying out of 15 (13.3%). The middle of the Hurricane Season resulted in the majority of re-intensifications at 65.7% (23/35), followed by the beginning of the season, 22.9% (8/35), and the end, 11.4% (4/35).

4.6 Impacts on Newfoundland

Newfoundland has had numerous and significant direct impacts from cyclones. The majority of these cyclones were purely extratropical or in some stage of extratropical transition when they came in contact with the island. The NHC determined that Maria (2011) was the only cyclone from the data set to be defined as purely tropical when it impacted Newfoundland (Brennan, 2012). Figure 4.10 shows the track and the point where extratropical transition took place for each of the cyclones (Maria (2011) not shown on Figure), Table 4.3 is a list of tropical and extratropical cyclones that have impacted Newfoundland.

Tracks and the Points of Extratropical Transition for Cyclones Impacting Newfoundland

Figure 4.10 - Track and points of extratropical transition of cyclones that have impacted Newfoundland (1991-2011).

List of Cyclones that have Impacted Newfoundland (1991-2011)

Storm	Year	Max. Category Reached During Lifespan	Area Impacted	Originated in Cape Verde Region
Maria (11)	2011	1	Avalon	N
Ophelia (11)	2011	4	Avalon	Y
Earl (10)	2010	4	West Coast	Y
Igor (10)	2010	4	Avalon	Y
Bill (09)	2009	4	Burin/Bonavista	Y
Hanna (08)	2008	1	Burin/Bonavista	N
Chantal (07)	2007	TS	Avalon	N
Alberto (06)	2006	TS	Burin/Bonavista	N
Beryl (06)	2006	TS	West Coast	N
Florence (06)	2006	1	Avalon	N
Isaac (06)	2006	1	Avalon	N
Ophelia (05)	2005	1	Burin/Bonavista	N
Arthur (02)	2002	TS	Avalon	N
Gustav (02)	2002	2	West Coast	N
Erin (01)	2001	3	Avalon	Y
Gabrielle (01)	2001	1	Avalon	N
Leslie (00)	2000	TS	Burin/Bonavista	N
Michael (00)	2000	2	Burin/Bonavista	N
Floyd (99)	1999	4	West Coast	Y
Gert (99)	1999	4	Avalon	Y
Earl (98)	1998	2	Avalon	N
Bertha (96)	1996	3	West Coast	Y
Josephine (96)	1996	TS	West Coast	N
Allison (95)	1995	1	Burin/Bonavista	N
Barry (95)	1995	TS	West Coast	N
Luis (95)	1995	4	Avalon	Y
Bob (91)	1991	3	West Coast	N

Table 4.3 - List of the named storms that hit the island, their year, the max Category strength attained during their lifetime, the area of Newfoundland the cyclone made landfall, and if these cyclones originated in the Cape Verde Region.

It was determines that 27 cyclones made landfall in Newfoundland over the period of 1991 to 2011. A cyclone was recorded as a "direct impact" if the center of circulation passed over land or came within 100 km of land. Figure 4.11 shows the distribution of strength and frequency of cyclones of tropical origin that have impacted Newfoundland between 1991 and

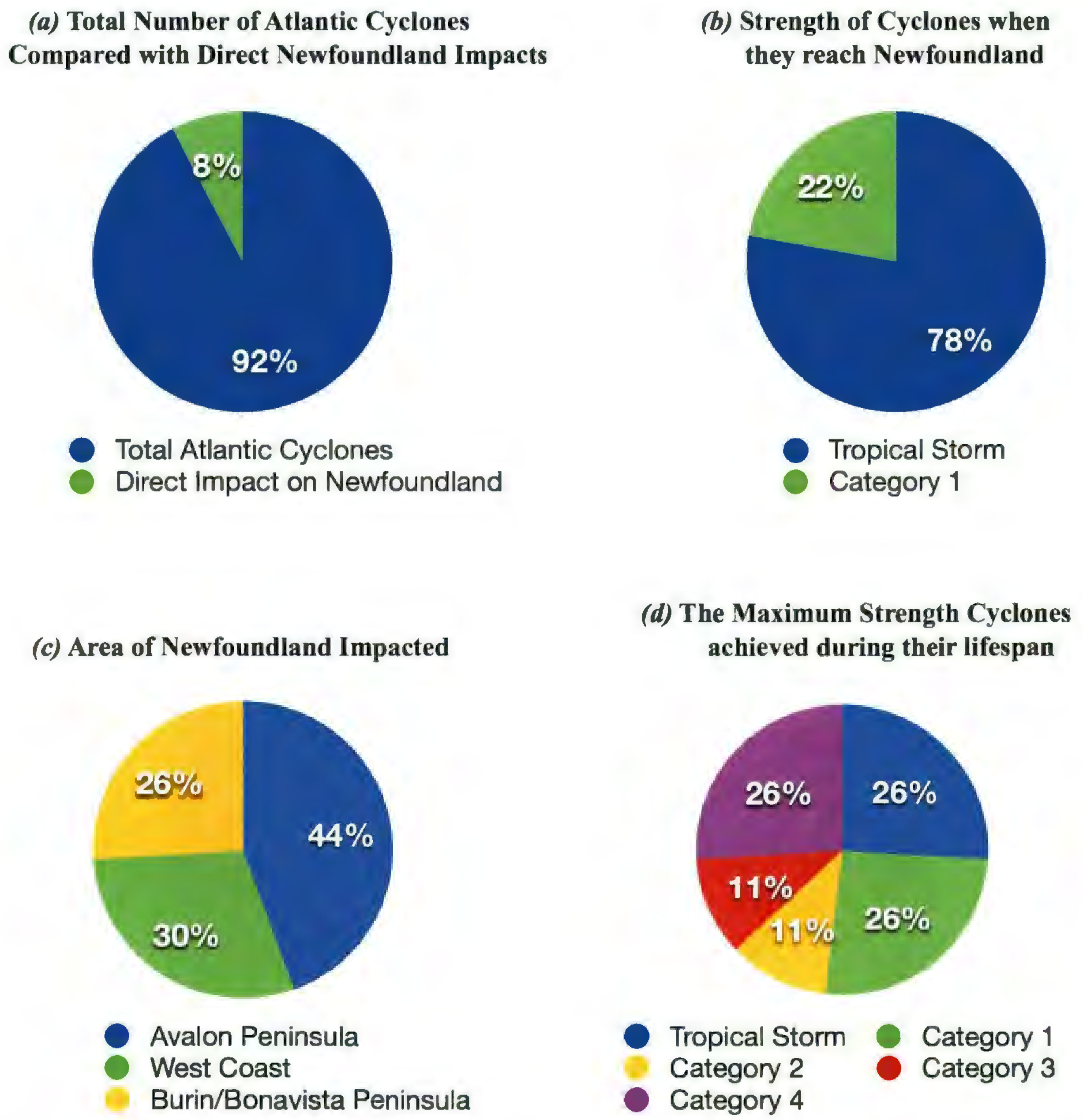


Figure 4.11 *a, b, c, d* - Tropical-origin cyclones impacting Newfoundland, 1991-2011. *(a)* The total number of cyclones that formed in the Atlantic Basin (324) and what percent impacted Newfoundland (27) over 1991-2011. *(b)* The strength of the cyclones that impacted Newfoundland (none reached Category 2). *(c)* The areas of Newfoundland that were directly impacted from the cyclones that hit. *(d)* Of the cyclones that impacted Newfoundland, the highest storm intensity each reached during the course of their lifetime.

2011. Newfoundland is directly impacted by about about 1.29 cyclones per year. The cyclones that do impact Newfoundland directly are purely extratropical, or in the process of becoming extratropical (Maria (2011) being the only exception). These cyclones have an intensity of a tropical storm or a Category 1 storm by the time they impact the island, and a large percentage of them (44%) tend to make landfall on the Avalon Peninsula. Tropical storm, Category 1, and cyclones which attain strong Category 4 strength sometime in their lifespan make up the majority of cyclones to impact Newfoundland, though they do not reach the province with that amount of strength. Newfoundland is experiencing more cyclones in recent years (Fig. 4.12). There is a

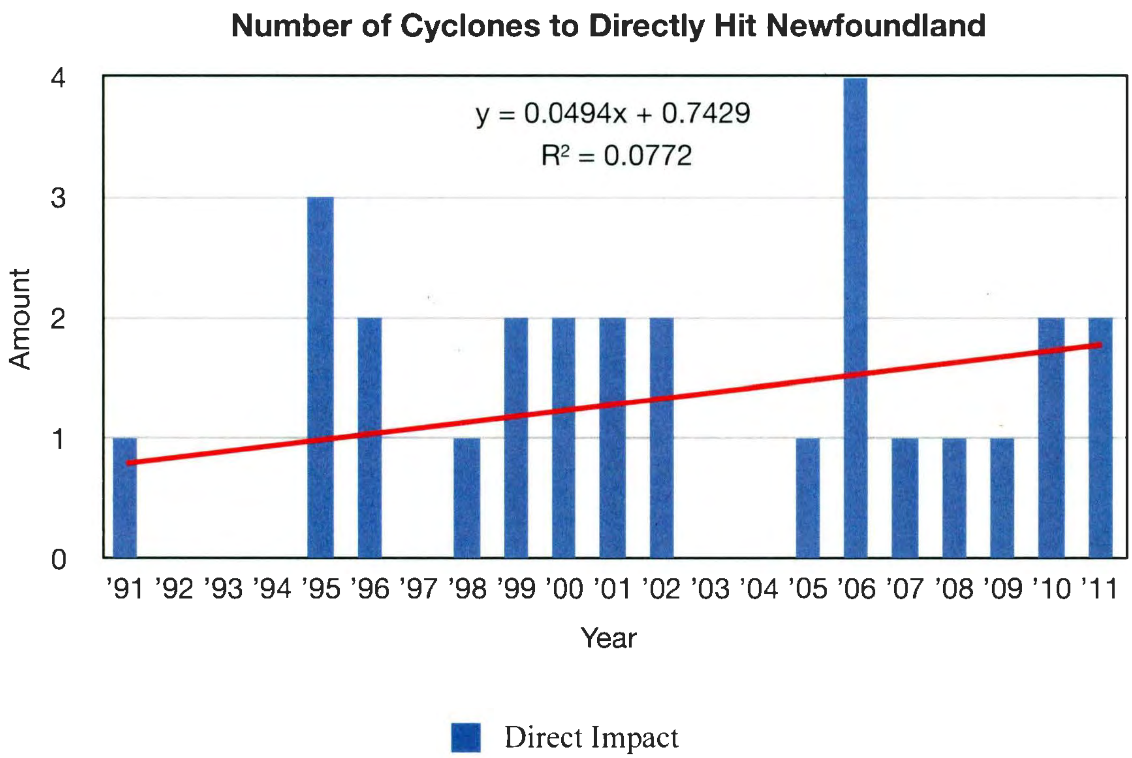


Figure 4.12 - Chart showing the number of cyclones that have directly impacted Newfoundland from 1991 to 2011. The average amount of cyclones seen is 1.29 per year for the province and there is a positive increasing upwards trend.

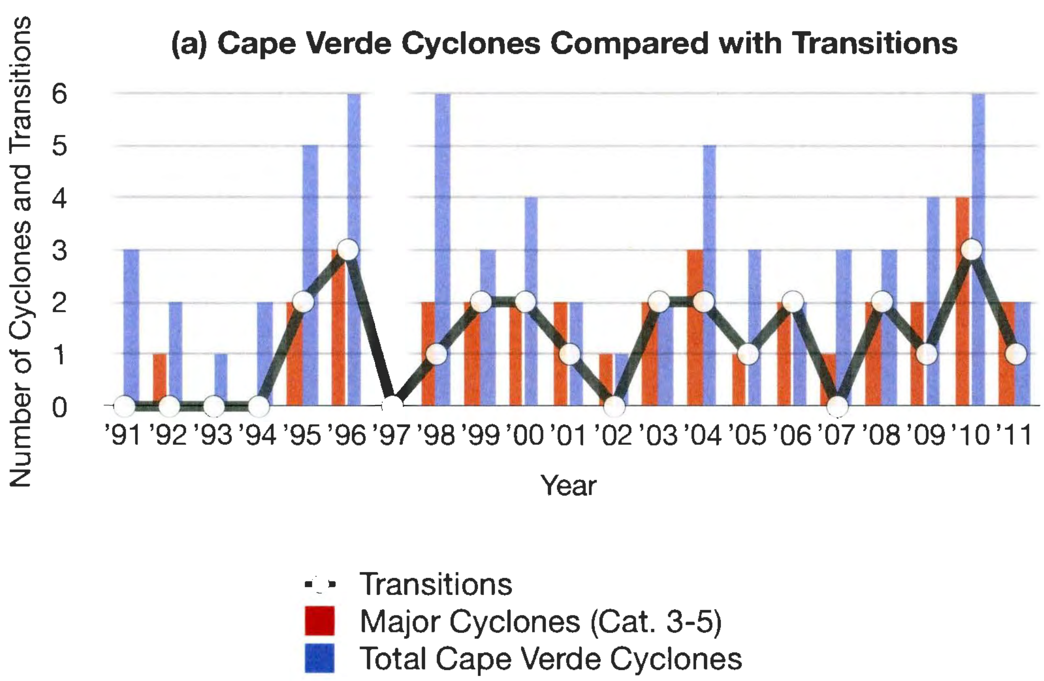
positive trend upward in the number of cyclones impacting the province. Newfoundland experiences a highly active year in 2006 with 4 cyclones making a direct hit. In the future, it is possible that Newfoundland will experience more active years such as 2006. However, this trend is only based on data from 1991-2011. The short time series means that the number of events during individual years have substantial influence on the linear trend, necessitating caution in inferring a sharp increase in storm frequency. For example, if the data analyzed had only encompassed the period 1995 to 2011, the result would be a linear trend showing a slight decrease in storm frequency, which would give the impression that cyclones that are impacting Newfoundland are on the decrease. Another example would be to disregard a single anomalously active year such as 2006, which would yield a lower R^2 value, and thus the trendline would not be as steep as the one shown in Figure 4.12. Having a longer timeline would result in a better and more reliable assessment of the linear trend. However, due to the lack of available and reliable data on extratropical transitions prior to 1991 (see Chapter 1) a longer timeline could not be used for this research.

Lastly, observations of activity of cyclones in the Atlantic Basin shows that an active year such as 2005 does not necessarily result in more direct impacts to Newfoundland. Considering consecutive years, 2005 resulted in only one direct hit to Newfoundland, compared to 2006 which was not as active overall, but resulted in more direct impacts. Thus, the total number of tropical Atlantic cyclones per year is not directly proportional to the number affecting Newfoundland.

4.7 Cape Verde Cyclones

Additional analysis involved cyclones that formed in the Cape Verde Region off the coast of West Africa. A high number of cyclones that form in the deep tropics near the Cape Verde Islands become major cyclones because they have time to form and gain strength as they cross the Atlantic Ocean. Hurricane Igor qualified as a powerful Cape Verde Cyclone, and will be discussed further in Chapter 5.

In the deep tropics, the SST's are high, and the wind shear is minimal, allowing major cyclones to form and grow for long periods. Because these cyclones have time to strengthen, there is a theoretical possibility that they could survive and undergo extratropical transition more easily than cyclones that formed further to the west. Figure 4.10a plots the total number of cyclones that formed in the Cape Verde Region Cape Verde Regionfrom 1991 to 2011. Figure 4.10b relates the data of Cape Verde Cyclones to Newfoundland, by determining what percent of cyclones



(b) Percent of Cape Verde Storms to Hit Newfoundland

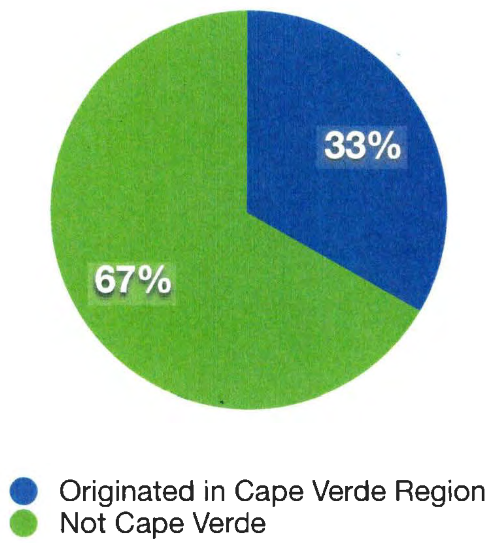


Figure 4.13 *a, b* - *(a)* Cyclones that have formed in the deep tropics (Cape Verde Region). Shows the total number Cape Verde Cyclones formed (blue) and of those how many became major tropical cyclones (Category 3-5) (red). The black linear line depicts how many of these storms underwent an extratropical transition. *(b)* Pie chart showing that of the total storms to impact Newfoundland 33% of them derived from the Cape Verde Region.

that were experienced in Newfoundland derived from the Cape Verde Region and was compared with how many of those cyclones became major cyclones and how many, in total, transitioned. Years with higher numbers of major cyclones are more likely to produce more transitions, possibly because they have the strength to survive. Years such as 1996 and 2010 which saw 3 and 4 major cyclones form, respectively, had the highest number of cyclones undergoing extratropical transitions.

The topic of Cape Verde Cyclones was researched to determine if Newfoundland is impacted by these types of cyclones more readily than others. Out of the 27 cyclones that impacted Newfoundland, nine were classified by the NHC as being Cape Verde Cyclones. As only 33.3% of the cyclones originated in the Cape Verde Region, Newfoundland does not seem to be preferentially subjected to these cyclones. However, Igor indicates that individual Cape Verde cyclones can have dramatic and unwelcome effects as discussed in Chapter 5.

4.8 Implications

An important conclusion derived from this research is that the number of extratropical transitions showed an increase from 1991 through 2011. The positive trend is very small, especially looking at the yearly number of transitions occurring in the Atlantic Ocean. The island of Newfoundland is seeing a positive trend with regards to increased amount of activity, although the time series is limited. A longer time frame is needed (at least 50 years) to develop a stronger understanding of transition increases and Newfoundland impacts. However, the available data are limited, due to the relatively recent development of knowledge concerning extratropical transitions. Another suggestion that can be taken from this research is the possibility of Newfoundland seeing more storms that are as intense as Hurricane Igor (2010) or that retain tropical characteristics, such as Hurricane Maria (2011).

5. Case Study Hurricane Igor

5.1 Site and Hurricane Description

A significant focus of this research was dedicated to observing the impacts Newfoundland received from cyclones. The decision to concentrate on Hurricane Igor for a case study was due to the widespread impacts and the strength of the cyclone as it hit Newfoundland. Although only one human life was lost, Igor caused significant disruption and destruction, and became the costliest cyclone to hit the province.

Background reports from Environment Canada and the CHC (2011) state that Hurricane Igor struck Newfoundland on September 21, 2010 with the strength of a Category 1 storm. Wind gusts of nearly 140 km/h were reported, resulting in roofs being blown off homes across the Avalon and Burin Peninsulas and numerous trees toppled. Over 200 mm of rain fell in some areas including the areas around Argentia and Whitbourne. The entire eastern part of Newfoundland experienced severe flooding, which washed away bridges and left many large chasms in major roads and highways, resulting in one fatality and weeks of road closures and construction.

Hurricane Igor was the most damaging tropical cyclone to strike Newfoundland in the modern era. Following Hurricane Igor, Environment Canada requested the WMO to have the name retired due to the devastating impacts. This is the second time that Canada requested the WMO to retire a cyclone's name, the first being Hurricane Juan in 2003 (Environment Canada, 2011).

Discussions with emergency personnel from FES-NL were conducted to gain a better understanding of what went on before, during and after Hurricane Igor impacted Newfoundland.

A focus discussion considered how FES-NL handled the crisis and to find out if Newfoundland's ability to cope has improved since Hurricane Igor.

Researching the history, formation and devastation associated with Hurricane Igor could help identify why Igor was an exceptional cyclone compared to others that have impacted Newfoundland. This chapter will look at Igor's life-cycle as it went from tropical to extratropical, the impacts the storm had on Newfoundland, and what emergency managers and the government were tasked with before and after Hurricane Igor. Igor is seen as a benchmark for future cyclones for Newfoundland and Atlantic Canada, having shown to the residents in this region that they are not immune to cyclones and could see more cyclones similar to Igor in the future.

5.2 Formation

Figure 5.1 shows the life cycle of Hurricane Igor from when it first reached tropical depression status on September 8, to when it was absorbed by a large extratropical system on September 21, 2010.

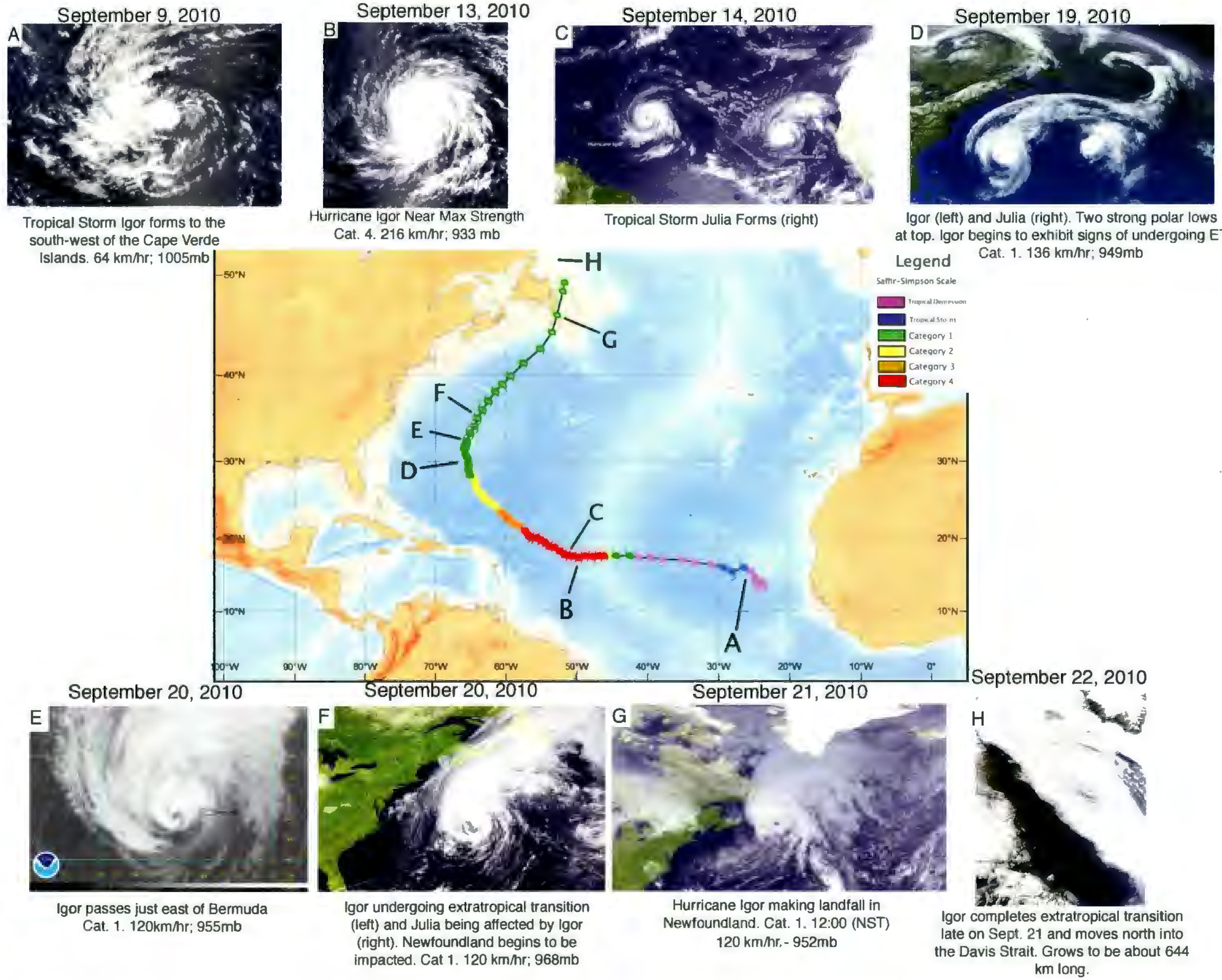


Figure 5.1 - The life-cycle of Hurricane Igor September 8 - 21, 2010 with satellite images and key notes (NASA/MODIS Rapid Response Team, 2010; Pasch and Kimberlain, 2011).

Igor qualified as a Cape Verde Hurricane and began by forming out of a tropical wave which moved off the west coast of Africa late on September 6, 2010. The system of thunderstorms moved westward, and after a few days at sea, deep convection started to become apparent near the center of the low pressure. Two days later, on September 8, about 148 km southeast of the Cape Verde Islands, at approximately 6:00 GMT, the surface circulation around the low pressure was well defined and deep convection became present allowing scientists and forecasters to designate the low pressure as a tropical depression (Pasch and Kimberlain, 2011). Thanks to the favorable tropical environment around the system and low vertical shear in the atmosphere, the depression was upgraded to tropical storm status and given the name Igor, making it the eleventh system, and ninth named storm of the 2010 Atlantic Hurricane Season.

Igor struggled to strengthen and became disorganized as it interacted with another disturbance. The deep convection around the center diminished and began to shear. Igor weakened to a tropical depression at around 12:00 GMT on September 9 and continued its track westward until it entered an area with less vertical wind shear and regained tropical storm characteristics. Igor slowly strengthened and was classified as a Category 1 hurricane at 00:00 GMT on September 11. Shortly after this upgrade Igor rapidly intensified as the central convection become symmetric and the upper-level outflow increased (Pasch and Kimberlain, 2011). Igor reached its peak wind strength as a Category 4 hurricane on the Saffir-Simpson Hurricane scale exactly two days later with the center of the storm located near 17.7 N and 50.5 W. Winds reached a maximum speed of approximately 240 km/h and a central pressure was recorded at 933 mb.

Igor's wind strength decreased to 216 km/h on the morning of September 14. However, the hurricane re-strengthened late that night and into the morning of September 15 with the lowest barometric pressure recorded at 925 mb. At this time, Igor began to decrease in speed to 14.4 km/h, strayed from its direct westward track, and started to curve to the west-northwest due to a weakening in the subtropical ridge caused by a broad deep layer trough over the northeastern United States. Igor experienced an eye wall replacement cycle late on September 15 which resulted in winds weakening to 216 km/h and a central pressure rising to 942 mb, symbolizing weakening in the storm. The final strengthening Igor underwent occurred early the next morning after the eye wall replacement cycle concluded. Maximum sustained winds rose and were documented to be 232 km/h and pressure dropped again to 929 mb. Early on September 17, the eye of Igor passed about 556 km northeast of the northernmost Leeward Island (Pasch and Kimberlain, 2011).

Igor turned north-northeast late on September 19 and increased in track speed to 22.4 km/h as it approached the Canadian Maritimes. Igor interacted with another tropical cyclone (Hurricane Julia) which had been following behind Igor since it formed on September 14. On September 16 Julia moved to the east of Hurricane Igor and the outflow from Igor began to hinder the circulation of Julia. Due to a combination of poor circulation and colder SST's Julia weakened and started to re-accelerate as it curved northward around the contiguous ridge. This almost resulted in Julia merging with Igor (Beven and Landsea, 2010). Julia, however, provided energy to Igor and allowed it to strengthen as it moved northward. Julia also served as a critical additional source of moisture, which in turn, resulted in enhanced precipitation in Igor (Catto and Batterson, 2011). On September 20, Igor began to grow in size and tropical storm force winds started to spread out to be 1,389 km wide (Pasch and Kimberlain, 2011), a significant clue that Igor was starting to undergo extratropical transition. As Igor quickly approached Newfoundland, it merged with an area of low pressure which resulted in an increase of moisture being retained in the storm, which later would result in heavy rainfall and flooding. According to the National Hurricane Center and this research, on September 21, at approximately 18:00 GMT at 48.5°N, 52.1°W, Igor completed its extratropical transition with maximum sustained wind speeds of 120 km/h and a barometric pressure of 950 mb. The circulation of Igor continued to increase as it traveled north. By 22:00 GMT on September 21, tropical storm force winds extended outward up to 836 km from its center making the system over 1,600 km wide (NASA, 2010).

On Tuesday, September 21, 2010, at approximately 15:00 GMT, the center of Igor was located 56 km south of Cape Race, Newfoundland, (46.2°N, 52.8°W) with a minimum central pressure of 952 mb and a forward speed of 74 km/h. The heavy rainfall extended far northwest from the center of Igor encompassing the whole island of Newfoundland, and hurricane force winds were measured throughout the day and into the evening hours. According to the NHC and NASA, the day before Igor's arrival a trough of low pressure passed over Newfoundland. The trough remained in the vicinity upon Igor's arrival and the two systems interacted. The moisture and energy from Igor was taken by the trough which in turn caused more heavy rainfall over the province. Hurricane strength wind speeds near 120 km/h were maintained by Igor as it continued its track north. The hurricane force winds extended out to 740 km, which made Igor's diameter a massive 1,480 km wide (NASA, 2010). Igor became fully embedded in a frontal zone and became a stronger and more vigorous extratropical cyclone immediately after leaving Newfoundland (Pasch and Kimberlain, 2011). Early on September 23, while in its extratropical form, Igor was absorbed by another large extratropical cyclone (NASA, 2010).

5.2.1 Transition of Igor

NASA's MODIS instrument, which flies aboard the Terra satellite, captured Hurricane Igor on September 18 to 20 showing Igor morphing from a symmetrical storm to a shape similar to a comma (Fig. 5.2). On September 18 and 19, Igor remained fully tropical and showed a

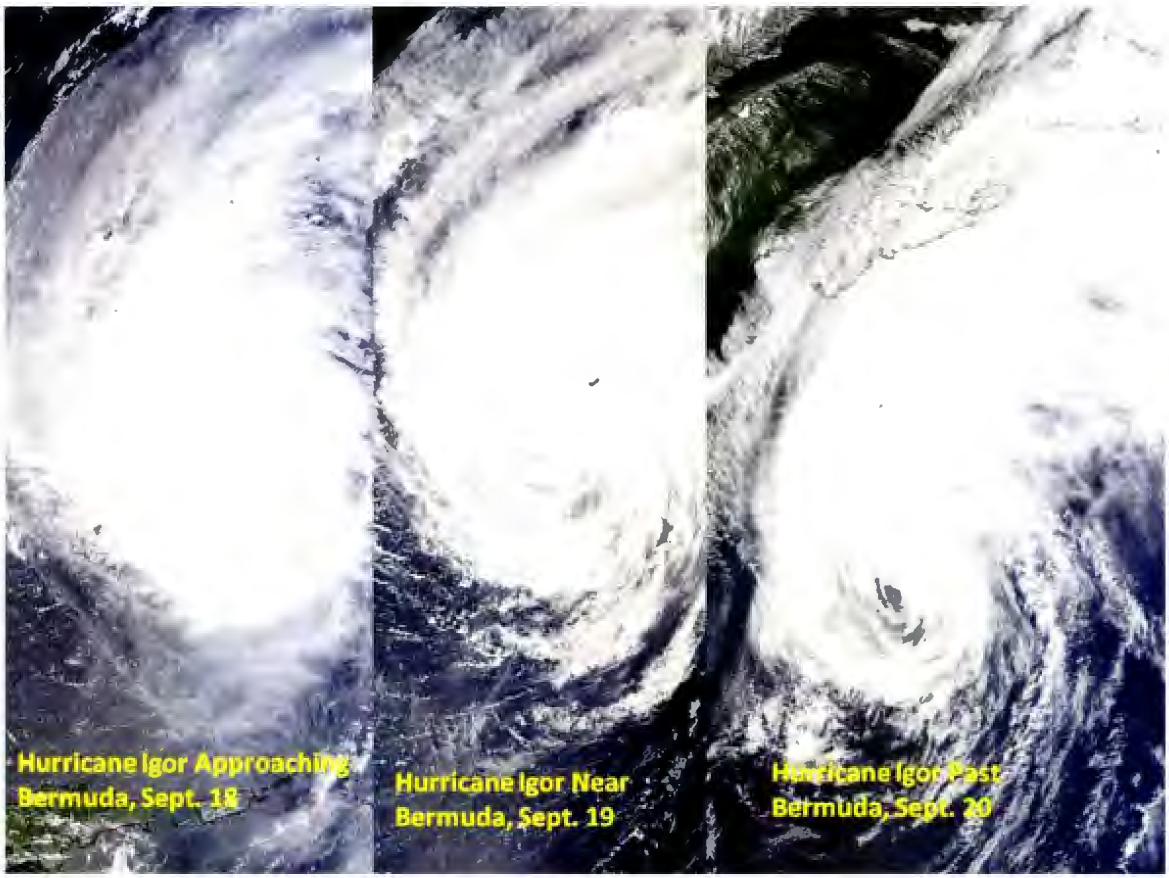


Figure 5.2 - The MODIS instrument on NASA's Terra satellite captured a visible image of Igor (Left) at 11:30 am on Sept. 18, while MODIS in the Aqua satellite captured Igor's center just southwest of Bermuda on Sept. 19 at 1:30 p.m. EDT (center). MODIS on Terra captured Igor after it passed Bermuda on Sept. 20 at 11:15 a.m. EDT (right) (NASA/ MODIS Rapid Response Team, 2010).

traditional round symmetrical shape and the eye of the hurricane was overcast. On September 20, MODIS captured Igor at 15:15 GMT after it passed Bermuda. The imagery showed that Igor became elongated from north to south and was forming an inverted comma shape, signaling a transition. The eye of the storm became visible and cloud free. The Atmospheric Infrared Sounder Instrument (AIRS) flying on the Aqua satellite captured infrared images of Igor's cloud cover and temperatures on the same days. As Hurricane Igor began to weaken on September 20, thunderstorm activity diminished and cloud tops in the thunderstorms were warming due to a decrease in altitude (Fig. 5.3). According to NASA data, on September 21, Hurricane Igor was

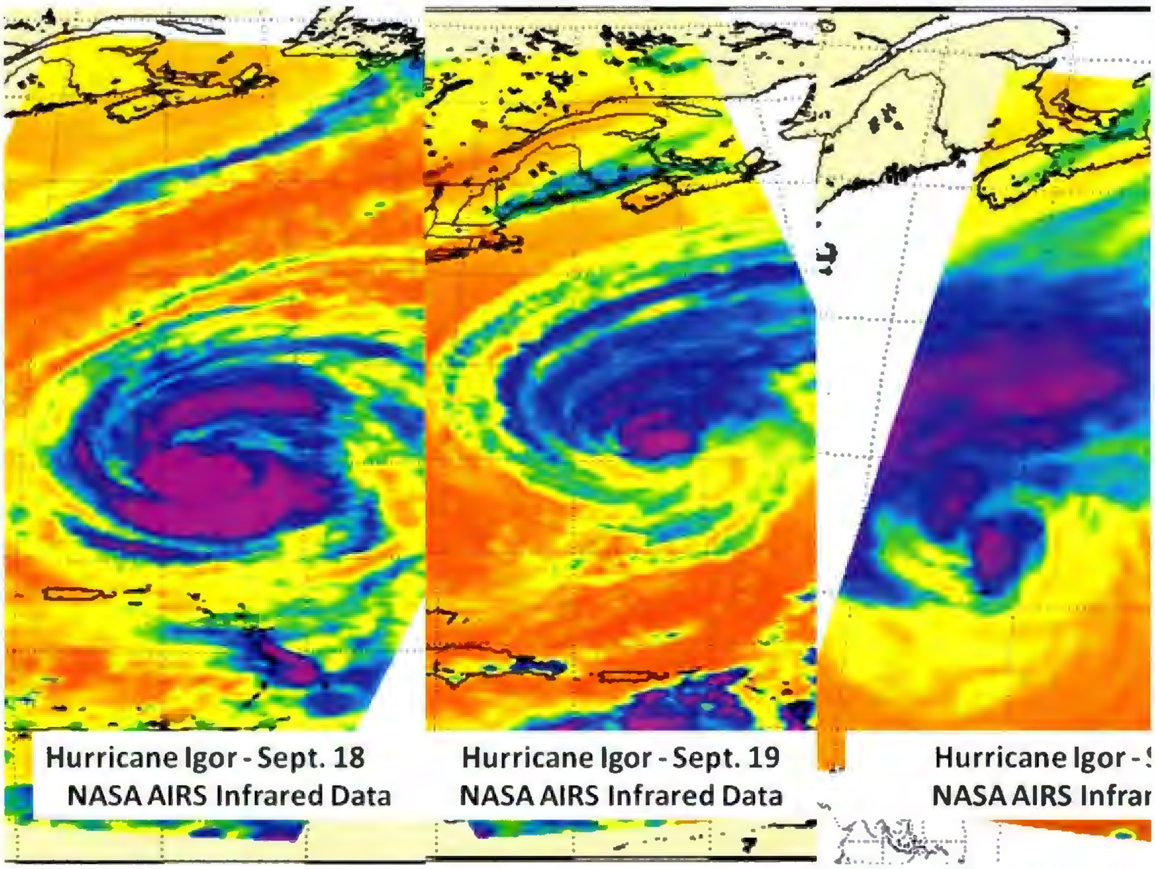


Figure 5.3 - The Atmospheric Infrared Sounder Instrument (AIRS) that flies on NASA's Aqua satellite captured infrared images of Hurricane Igor's cold cloud temperatures and cloud cover on Sept. 18 (left), Sept. 19 (center), and Sept. 20 (right). Igor lost its circular shape by Sept. 20, and there were very few high, strong thunderstorms (purple) where the cloud tops were colder than -63°F (NASA/JPL, Ed Olsen).

losing its warm energy core and beginning its transition into an extratropical cyclone. As Igor impacted Newfoundland throughout the day on September 21, NASA reported that the storm was quickly losing its warm-core, tropical characteristics and was transforming into a cold-core extratropical system (NASA, 2010). This information relayed from NASA gives the impression that Hurricane Igor was not a complete extratropical cyclone by the time the storm made landfall on Newfoundland. The thunderstorm activity was diminishing and the hurricane began to expand and develop a cold core, but there was still a remnant of warm core. This would make Igor a hybrid system which encompasses both tropical and extratropical characteristics.

Igor's center passed near Newfoundland at about 15:00 GMT (11:30 local time in Newfoundland), however, it was not considered extratropical at that time. On September 21, NASA (2010) stated that Hurricane Igor was forecasted to complete its transition and become a strong extratropical system later in the day. Finally, on September 21 at 21:00 GMT (17:30 local time in Newfoundland) Hurricane Igor was found to be a cold-core system from NASA satellite imagery and was labeled as an extratropical cyclone (NASA, 2010). This completed transition took place near 49.3°N and 51.7°W, approximately 200 km north-northeast of St. John's, Newfoundland. Pasch et al., (2010), from the NHC also recognized this area of transition and stated that the center of Igor did not make a direct landfall, straddling the east coast of the Avalon Peninsula between 15:00 to 17:00 GMT. The completed transition of Igor did not occur until four hours later, when it pushed away from Newfoundland.

5.3 Impacts

According to the NHC archives, Hurricane Igor was blamed for two deaths in the Caribbean due to high surf and rip tides.

Minimal damage occurred in Bermuda with reports of downed trees and signs. An estimated 28,000 residents of Bermuda lost power during Hurricane Igor. The main causeway which connected St. David's and St. George's Island received minor damage and one lane of traffic was closed for repairs after the passing of Igor. No loss of life was reported in Bermuda and damage cost was estimated to be less than $500,000 USD (Pasch et al., 2010).

Newfoundland received more severe impacts from Hurricane Igor. The greatest impact was the rain, with over 200 mm recorded over the Burin and Bonavista Peninsulas (Colbert, 2011) (Fig. 5.4). Over the Avalon Peninsula, rain amounts reached over 100 mm. The strongest

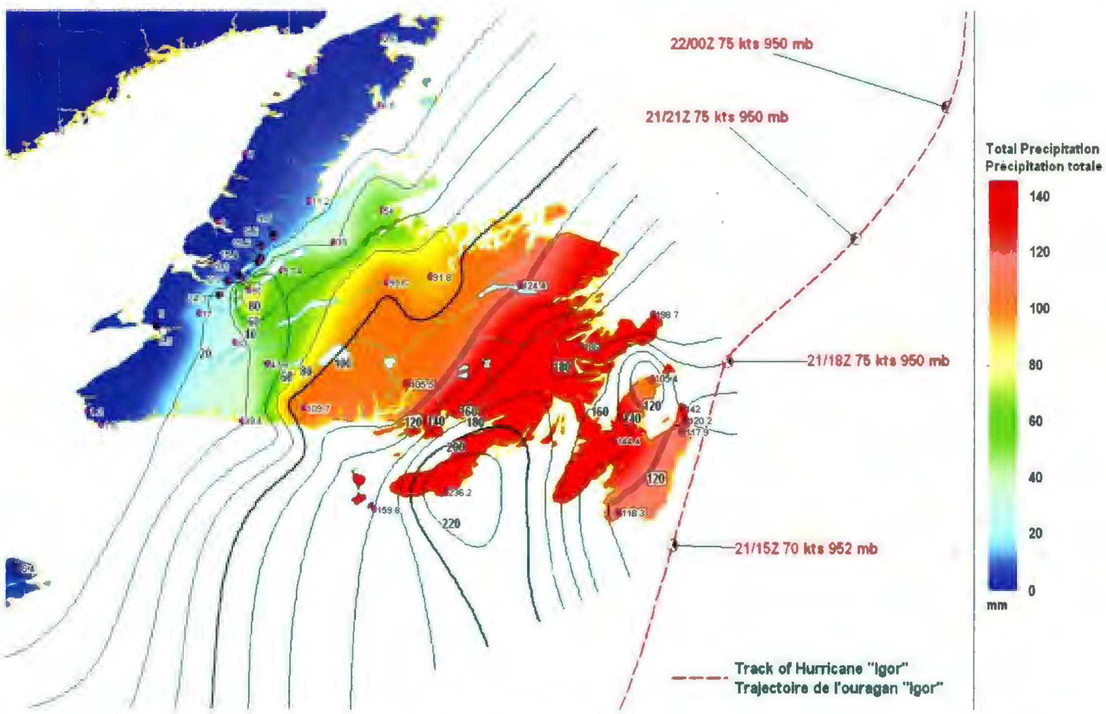


Figure 5.4 - Rainfall totals (mm) from Hurricane Igor, September 20-21, 2010. Maximum precipitation accumulation was 238 mm in St. Lawrence, Newfoundland (Colbert, 2011).

winds of Igor were located just east of the Avalon Peninsula, at sea. However, the west side of the storm which impacted Newfoundland produced particularly strong winds. Sustained hurricane force winds between 120 to 130 km/h were recorded with gusts ranging from 150 to 170 km/h, making Igor a weak Category 1 hurricane on the Saffir-Simpson Scale (Table 5.1 and Fig. 5.5). Igor's wind speeds did not break any "all-time" records at any sites in Newfoundland

Station	Wind Gusts (km/h)	Station	Rainfall (mm)
Cape Pine*	172 (122+ **)	St. Lawrence	238
Sagona Island	163 (113 **)	Bonavista	235 ***
Bonavista	155 (122 **)	Lethbridge *	194
Pouch Cove*	147	St. Pierre/Miquelon (France)	160
Pool's Island	146 (104 **)	Pouch Cove *	142
St. John's (CYYT)	137 (92 **)	St. John's (West)	134
Grates Cove	135	Gander	124
St-Pierre (France, îles)	135 (91)		
Argentia	132		

Table 5.1 - Recorded rainfall and wind gusts around Newfoundland during Hurricane Igor (Environment Canada, 2011).
*** Private or volunteer observation**
**** 10 minute sustained**
***** Rain gauge failed/overflowed around the 200 mm mark, radar-based estimate thereafter**

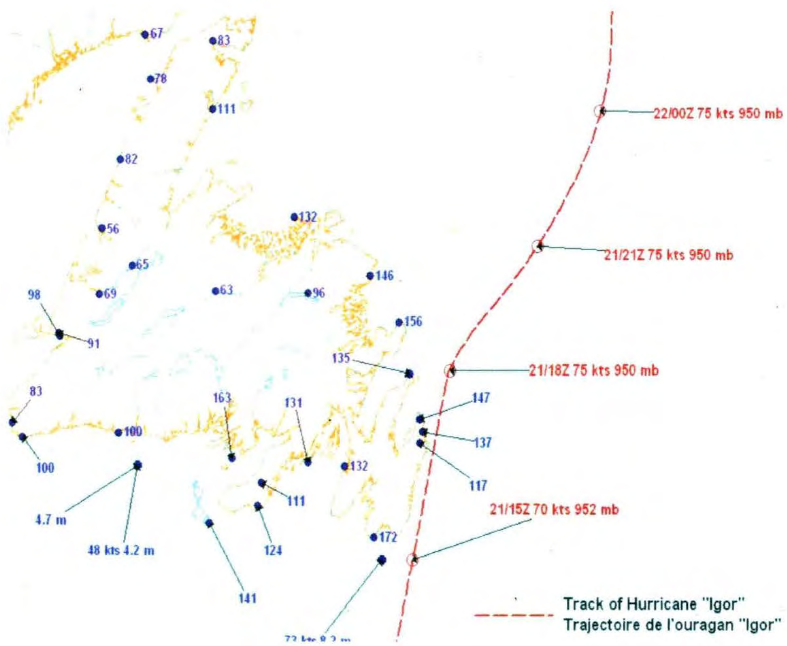
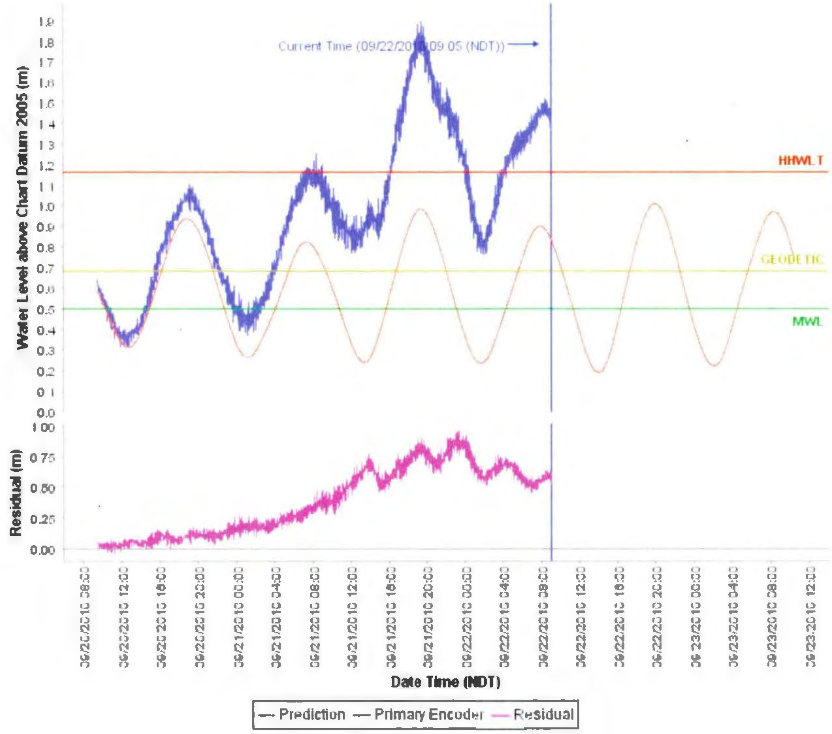


Figure 5.5 - Wind speed peaks (kts) from Hurricane Igor, September 20-21, 2010 (Colbert, 2011).

(Catto and Batterson, 2011). Wind impacts caused many trees to topple over, especially in urban areas like St. John's, and structural damage occurred to some buildings with complete roof loss and curtain wall collapse.

Wave heights measured on the east side of Igor were recorded to reach a maximum of 13 meters. The Hibernia oil platform, which was about 250 km east of Igor, measured 12 meter maximum significant wave heights. Peak wave heights of 25 meters were recorded and a storm surge of 70 to 100 cm was measured by tide gauges around eastern Newfoundland (Environment Canada, 2011). Coastal erosion in Newfoundland in this situation requires storm surges from cyclones to directly strike beaches. If the precipitation-augmented streams are relatively starved of sediment, opening of passages through barrier bars can result from accentuated runoff. In many cases, however, the quantity of natural and anthropogenic sediment eroded upstream resulted in the delivery of excess materials to the shorelines. Locally, existing stream outlets were plugged with sediment, inducing further flooding behind the obstructions. Damages from storm surge were confined largely to isolated areas on the north shore of the Bonavista Peninsula, and the geomorphic effects of storm surge activity was for the most part, very limited (Catto and Batterson, 2011) (Fig 5.6 a and b).

(a)



(b)

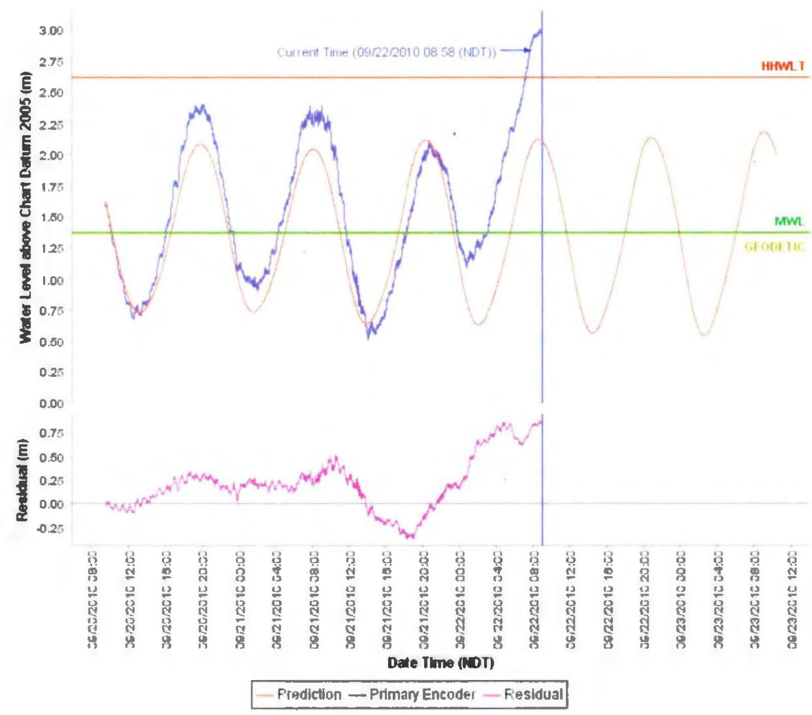


Figure 5.6 *a, b* - *(a)* Recorded storm surge for Bonavista September 20 - 23, 2010 *(b)* Recorded storm surge for Argentia September 20 - 23, 2010 (Courtesy of D. L. Forbes).

Flooding was a major contributor to the destruction seen across the island of Newfoundland. The city of St. John's received over 175 mm of rain in a 24 hour period and a record breaking 238 mm was recorded at the St. Lawrence station. Most of the damage from Igor resulted from river flooding. Peak stream flow values locally exceeded 600 m^3/s in many rivers where the mean flows were less than 10 m^3/s. All areas of Newfoundland are potentially subject to storm-induced river flooding, due to the prevalence of thin veneers of glacial sediment overlying relatively impermeable bedrock, which allows precipitation to be carried rapidly downslope. In most river systems this geological setup triggers flooding within an hour after the initiation of heavy rainfall. Due to the limited response time between precipitation and flooding, short fluvial systems are more susceptible to hurricane-related flooding (Catto and Batterson, 2011). The excessive rainfall caused rivers to crest and overflow, and numerous roads, bridges and some buildings received extensive damage. The Bonavista and Burin Peninsulas received the most serious damage. Communities of both peninsulas were cut off from the road network. The roads were so damaged that several complete bridge replacements and total rebuilding of roads were required (Environment Canada, 2010). Temporary bridges were put up to reconnect communities in St. Lawrence, Grand Bank, and Hillview so as to supply them with essential survival supplies such as fuel, water and food. In Terra Nova National Park, located in central Newfoundland, a part of the Trans-Canada Highway was washed away and required immediate attention because it had created a large ravine about 30 meters wide. Severing of the Trans-Canada Highway disconnected eastern from central and western Newfoundland (Environment Canada, 2011).

5.4 Preparedness

Thanks to the on-going advances in satellite and meteorological technology, Newfoundland had ample time in order to prepare for Hurricane Igor. The CHC in Halifax, Nova Scotia issued its first preliminary statement regarding Igor on September 17, four days before Igor made landfall along the Avalon Peninsula. This statement was intended to signal the approaching storm and to notify the public that a potential strike could be possible in the coming days. Regular bulletins began to be issued from the CHC on September 18, advising residents to prepare for the possibility of a direct hit. On September 20 forecasts indicated that Igor would pass over the central portion of the Grand Banks. However, on the morning of September 21, Igor started to track farther northwest putting it on a path straight toward Newfoundland. The track of Igor was difficult to forecast due to the upper-level trough influences. Forecasters, however, knew that Igor would maintain hurricane force winds based on the storm's persistence and track speed. A day before Igor impacted Newfoundland forecasts began to hint at a possible re-intensification during the extratropical transition stage. Tropical storm warnings and wind warnings were issued on September 20 for the eastern part of Newfoundland, giving residents about 24 hours to prepare for the coming of Igor (Environment Canada, 2011). As Igor moved north into Newfoundland on September 21, a hurricane watch was put into effect for the coast of Newfoundland from Stone Cove northward and eastward to Fogo Island. A tropical storm warning remained in effect from Burgeo northward and eastward to Triton and the islands of St-Pierre and Miquelon (Gutro, 2010).

Seventeen days earlier on September 4, the Canadian Maritimes and the CHC were busy with Hurricane Earl, which received a substantial amount of media interest. However, when Igor was approaching about two and a half weeks later, media interest in the storm was much less. According to the CHC, the lower level of media attention was most likely due to the different storm track scenarios for Igor. For Hurricane Earl, the forecasted track depicted a greater likelihood of Atlantic Canada being impacted and warnings were issued earlier (Environment Canada, 2011). Igor did not receive very much attention across Newfoundland according to Cheryl Gullage, a public relations specialist with FES-NL. The news was not highly focused on Igor and instead was focused on the whereabouts of a missing boy in the Corner Brook area who was found shortly before Igor struck. The Western Star (Corner Brook) newspaper only had a very small article about the approaching storm. The Telegram (St. John's) newspaper had more attention focused on Igor but it was not the main story, only containing articles of Environment Canada predictions (FES-NL, 2012). The seriousness of the situation was not apparent until the CHC began to issue tropical storms and wind warnings to the province, a day before the cyclone hit. Working closely with FES-NL were Environment Canada's Warning Preparedness Meteorologists (WPMs) which were responsible for alerting municipalities and other sectors of the possible threats leading up to the arrival of Hurricane Igor, during the height of the storm, and after (Environment Canada, 2011).

According to Paul Peddle (2012), the manager of plans and operations at FES-NL, the messages that were received from the Environment Canada Gander Weather Office were very good and accurate with regards to Igor's track. The models were showing that Igor was going to be serious before the storm arrived. No evacuations were ordered for any of the communities, but the severity of the approaching storm prompted the closure of schools in a timely manner and the set up of shelters by Newfoundland's Eastern Health.

The first preliminary statement on Hurricane Igor was issued on September 17 with the intention to signal the beginning of the CHC monitoring a cyclone in the Northern Atlantic and to notify the public that the storm was approaching. Even with this "heads-up" statement, there was little media interest over the weekend regarding the approaching storm. Regular bulletins being issued on September 18 and track forecasts over the weekend (Sept. 18 - 20) indicated that Igor would pass over the central area of the Grand Banks. This was changed on September 21 when it became apparent that the storm was going to move farther to the northwest, closer to the Avalon Peninsula. Interest in Hurricane Igor began to increase once the CHC and the Newfoundland and Labrador Weather Office (NLWO) began to alert the public on September 20 about high winds. On the day of Hurricane Igor's arrival interoffice communications began between the CHC and the NLWO. Throughout September 21 the CHC continued to adjust the position and track of Igor closer to the land as the details of the upper-level trough influence became stronger and more apparent. The intensity forecasts were very consistent in the days leading up to Igor making landfall, and the CHC indicated that the hurricane would undergo extratropical transition with wind speeds between 120 to 140 km/h. On September 20, meteorologists were forecasting a possible re-intensification during extratropical transition over the Grand Banks (Environment Canada, 2011).

The rainfall threat with Igor was anticipated a couple of days before the storm hit. However, the wind threat was thought to not be an issue over land, with the strongest winds remaining out at sea. Computer models a day before Igor hit indicated a greater likelihood of a strong wind jet on the cold side of the interacting front which was located north of Igor at the time. This resulted in tropical storm and wind warnings to be issued for eastern Newfoundland.

A hurricane watch was issued the morning of September 21 as Igor and the trough began to interact bringing high winds across the Avalon, Burin and Bonavista peninsulas. In total the CHC issued 22 information statements on Hurricane Igor (Environment Canada, 2011).

5.5 Government Aid and Relief

The first problems during Igor's onslaught came from the Burin Peninsula. Flooding was the main problem for the region but emergency personnel were not deployed during the height of the storm and had to wait to survey the damage after Igor had passed. Officials at FES-NL stated that once crews managed to get out to the affected areas, the community that was the most affected by Igor was Trouty (Bonavista Peninsula) followed by several on the Burin Peninsula, such as Marystown, St. Lawrence, and Burin. Houses were moved off foundations and the banks of rivers were completely eroded with road access cut off, making rescue efforts difficult (FES-NL, 2012). Figure 5.7 shows the areas of eastern Newfoundland that were significantly impacted and the track of Hurricane Igor on September 21, 2010.

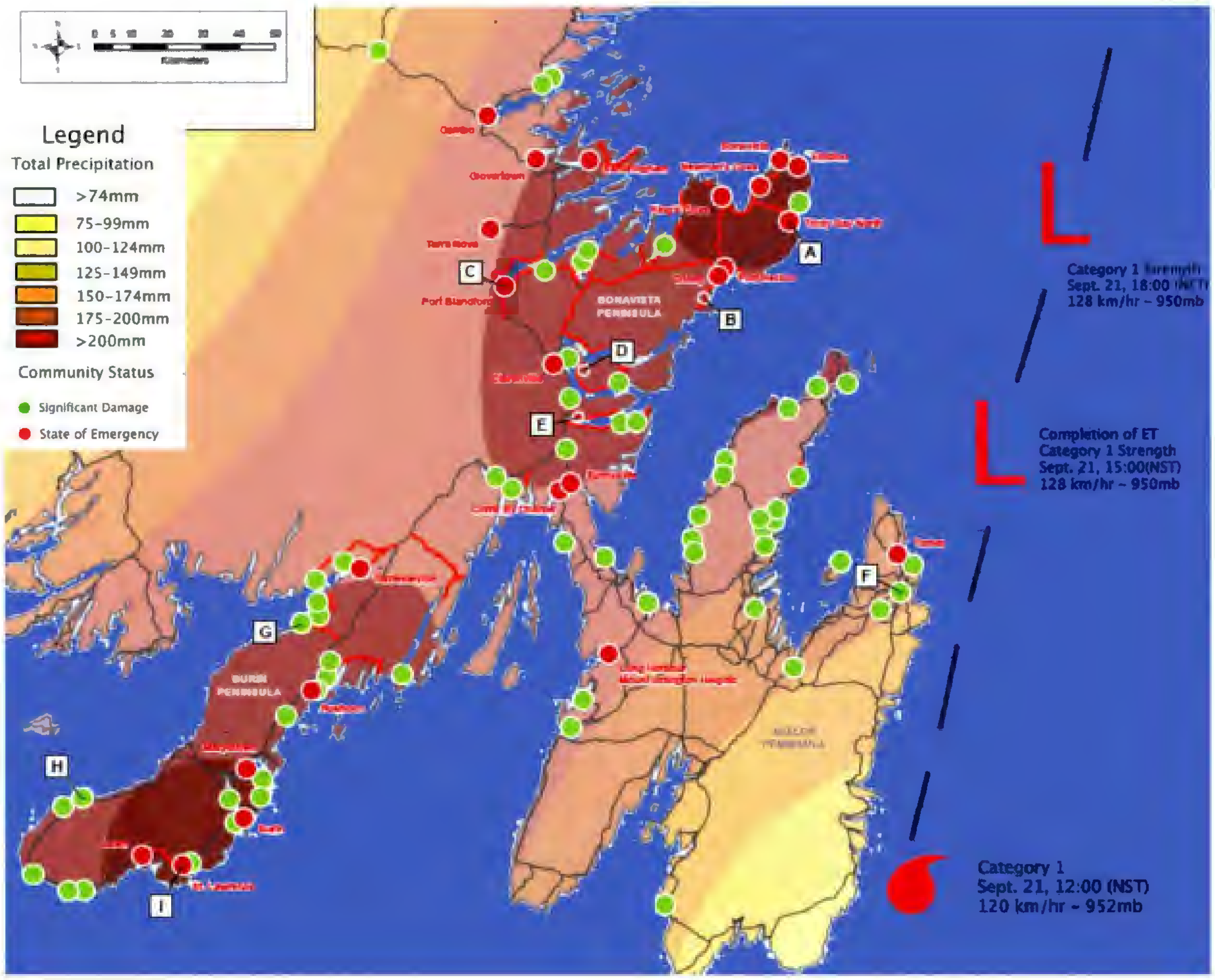


Figure 5.7 - A revised Figure showing communities that received significant damage (green) and those that issued a State of Emergency (red) after Hurricane Igor. Total rainfall amounts are given. Roads and bridges that were damaged or destroyed are shown in red. The track of Igor is shown with key notes of strength. Igor was still undergoing extratropical transition as it past to the east of Newfoundland and is depicted with the "extratropical transition" symbol created for this research (revised Figure from Department of Finance - Newfoundland and Labrador Statistics Agency).

Following the impacts from Hurricane Igor, on September 22, the Government of Canada began to implement emergency response and recovery efforts. The Canadian military was deployed to Newfoundland and federal financial aid was provided to help with recovery efforts.

The military initiated Operation Lama, which focused on rebuilding two main bridges connecting the Burin and Bonavista Peninsulas and distributing basic necessities to the people of

Newfoundland. Operation Lama is a domestic operation which focuses on support to civil authorities for hurricane recovery efforts. The Canadian Forces booked passage with the ferry service company *Marine Atlantic* to move equipment, supplies and troops from the mainland into Newfoundland. A range of vehicles including supply trucks, towing equipment, and two buses plus 123 personnel arrived in Argentia on September 25. Cheryl Gullage (personal communication, 2012) stated that the military stayed in the province for about five days where they helped re-build two bridges and assisted in repairs.

Officials with FES-NL were engaged with the Provincial Department of Municipal Affairs and Transportation and Works to review the damage across the areas affected by Igor. David McCormack (personal communication, 2012), director of emergency services with FES-NL, noted that the major problem for Newfoundland was the places that were cut off had no overland re-routing option available. Major bridges and roads that connected communities were destroyed and without them it took days to get resources in. The regional emergency management and planning officers, fire protection officers and engineers were in charge of creating temporary bridge and road access. However, these were only temporary bridges and provided little stability. Vehicles and loads over 45,000 tons could not reach communities because of this problem, and ferries had to be used instead to bring supplies to the communities in need. Along with the construction and re-building of roads, FES-NL focused on repairing water and sewer leaks and stabilizing infrastructure. The government of Newfoundland and Labrador encouraged residents after Igor's passing to document losses and damages to their properties. FES-NL implemented a disaster assistance program for home owners and small business owners that were affected by the storm (Gullage, 2010).

5.6 Aftermath

Igor was the most destructive hurricane Newfoundland had seen in 75 years. According to officials from FES-NL, the total damages in Newfoundland were initially estimated to be $110 million CAD (FES-NL, 2012), with some estimates ranging up to $200 million CAD (Feltgen, 2011). Unofficial government estimates in November 2012 said that Hurricane Igor exceeded $160 million CAD. Hurricane Igor was not a unique storm in Newfoundland in terms of meteorological statistics. The geomorphic affects from Igor were similar to those of other cyclones which have impacted Newfoundland. However, it was unprecedented in comparison to other storm events due to the areal extent of the impacted area (Catto, 2011).

Following Hurricane Igor, the geomorphic signature was marked by extensive fluvial outwash deposits along the shorelines, many small slope failures along coastal cliffs and river banks, eroded stream margins, and displaced sediment from deciduous trees that were uprooted. Storm activity in autumn 2010 and winter 2011 resulted in the mobilization of most cobbles and smaller clasts in coastal deposits. Along the beach systems on the Avalon and Burin Peninsulas, cusps that were present reflect autumn and winter storm activity. As of February 2013, the geomorphic signature of Igor has been destroyed. Excluding areas where anthropogenic debris remains, it is not possible to attribute any specific geomorphic features or accumulations of sediment to Hurricane Igor. Therefore, assessing the frequency of past storm events, particularly cyclonic events, is not possible based on sedimentologic and geomorphic records. The only way to provide an accurate indication of the effects and magnitude regarding geological records is to conduct an on-site observation directly following storm events that impact Newfoundland (Catto and Batterson, 2011).

Due to the heavy road damage associated with Igor's rain, it was not until October 2, 2010, eleven days after Igor's landfall, that road access was restored to all of the isolated communities. The final six communities to have road access restored, all on the Bonavista Peninsula, were Open Hall, Upper Amherst Cove, Middle Amherst Cove, Old Bonaventure, New Bonaventure, and Tickle Cove. The washout that isolated the community of Plate Cove East was also repaired by the Transportation and Works NL. However, many sections of road were reduced to one lane and some road connections were only temporary until permanent repair was completed much later (The Weekend Telegram, 2010).

Business owners had to wait longer for relief to come, especially along the Bonavista Peninsula. Roads that were washed out prevented customers from entering businesses and this, in turn, took away crucial sales. Nearly three weeks after Igor hit, roads leading to businesses started to be repaired. Nevertheless, business sales went down for those that were affected (The Weekend Telegram, 2010). The Port Union Fish Plant, a major employer for the Bonavista Peninsula, never reopened after Igor.

The Canadian Forces marked the completion of their thirteen day hurricane relief operation, Operation Lama, on October 6, 2010. Within hours of the Province's request for aid, the Canadian Forces were on the ground assisting the people that were most affected by Hurricane Igor. Operation Lama involved more than 1,000 reserve and regular personnel from the Army, Navy and Air Force. Approximately forty communities which were isolated by the storm damage were assisted. According to the Canadian Government, the tasks that were completed included the construction of temporary bridges and the surveys and repair of over 900 kilometers of highway; construction to communities; and the distribution of equipment, supplies, fuel, and food (Government of Canada, 2010).

As of December 2012, the effects of Hurricane Igor were still being felt across the province. David McCormack (personal communication, 2012) reported that all the important matters such as road and bridge construction were complete. He continued by saying that the 2013 construction season will finish all the damages that still need to be fixed, mostly regarding small businesses. The reason why the re-building process has required time is the limited capacity and operating season of asphalt and tar plants, necessary for road construction, as these plants close during the winter. In total, FES-NL reported that 14 houses had been purchased by the government in the Bonavista region because of intense structural damage. The greatest effect from Hurricane Igor would most likely be attributed to the psychological effects from the storm, particularly on the elderly (personal communication with David McCormack, 2012).

Despite the governmental efforts, the recovery from Hurricane Igor in the eyes of some residents, however, was very slow. Sam Synard, Mayor of Marystown, commented that the province failed to adequately repair the roads on the Burin Peninsula. He, along with other Burin Peninsula residents, complained that the roads and culverts were washed out again when Hurricane Ophelia hit the region in 2011 (CBC News, 2011).

5.7 What was Learned

Following Hurricane Igor, Newfoundland residents were on high alert for the rest of the Hurricane Season and for the 2011 and 2012 Hurricane Seasons. David McCormack referred to Igor as a "bench-mark" and commented that people were more engaged during Hurricane Maria (2011) and Hurricane Leslie (2012). Knowledge was gained regarding road stability and necessary construction in the face of rainfall and peak streamflow. Learning about the water saturation levels and the amount of rain delivered per hour during storm events allowed emergency managers to warn communities about flooding possibilities. FES-NL said that communications and recovery efforts have improved since Igor and the municipalities and Canadian government are better prepared since Hurricane Igor. The anticipated arrival of Hurricane Maria (2011) brought heightened awareness and concern, with fears of another Igor. Maria did very little damage and dissipated over the island soon after it made landfall. The latest cyclone to impact Newfoundland was Hurricane Leslie (2012), which came ashore on the Burin Peninsula on September 11, 2012. Cheryl Gullage (2012) stated that there were localized evacuations during Leslie, particularly in the community of Badger where a large water tower was considered at risk of collapse. FES-NL has no authority to require evacuations. If the people evacuate and leave their homes, FES-NL can keep them out after the storm, but they cannot be forced to evacuate. FES-NL says that by working with communities they hope that residents become more prepared for natural disaster events such as Igor. Weather cannot be controlled or mitigated but people can become more educated to deal with events, and this is the goal for FES-NL. Enduring Hurricane Igor resulted in enhanced pre-planning and preparedness due to the fact that emergency managers now have a more concrete idea of the intensity of cyclones and the destruction that they bring to Newfoundland. David McCormack (2012) believes that there is a better level of preparedness across Newfoundland since Hurricane Igor. Currently, 90% of communities across the province have an emergency management plan. Emergency managers at FES-NL try to constantly remind communities to prepare for cyclones before they strike the island.

The need for emergency services to work together across both policy and jurisdiction fields is of great concern in order to find ways to prevent or deal with emergencies. FES-NL personnel are deeply involved with preparation and future improvements for the next devastating storm. Currently, the provincial government initiatives are taking place to more fully involve municipalities in Newfoundland with regards to emergency response, planning and recovery. However, Catto and Tomblin (2013) outline a few challenges when bringing together municipal, provincial and federal officials, as well as other non-governmental organizations, to improve on emergency preparedness:

- There is a relatively weak municipal policy capacity, with many smaller municipalities lacking expertise and workers to create and implement emergency plans.
- There is a divide between urban communities (St. John's area) and smaller centers and rural communities in Newfoundland. Approximately 40% of the population lives in the northeast Avalon Peninsula, and therefore has access to greater, professional capacity and economic resources, potentially allowing improved emergency response.
- There is substantial asymmetry between the Government of Newfoundland and Labrador's approach to communities of smaller size throughout the province. Smaller communities will not receive much aid compared to larger metropolitan areas.
- There is a difference between the associated costs, the physical realties, and the public perceptions regarding the likelihood and damage done from any particular event. Depending on the strength, size and direction of an approaching cyclone, these factors will vary. Stronger

cyclones that directly impact Newfoundland will likely cause extensive damage which will result in higher damage costs compared to a weaker cyclone that directly impacts the island.

- The Government of Canada's role in emergency measures is seen as very limited. The federal government will only be involved in responding to individual events and has not committed to developing a broad, national policy formulation to help alleviate potential future disasters.

Differences in perception in part result from the lack of longer-term action which followed past events, as well as the tendency to attribute difficulties to human factors rather than meteorological conditions (Catto and Tomblin, 2013). The suggestion that Igor does represent a departure from this pattern is intriguing and important, but the longer-term effects on Emergency Measures policies at the ministerial level remain somewhat uncertain. Emergency management involves making choices about resources and priorities which may result in resources being redeveloped away from other communities perceived as less directly or severely affected. There seems to be an interest by the Government of Newfoundland and Labrador in improving policy capacity, identifying gaps in emergency preparedness and upgrading emergency measures. No events prior to Igor, however, resulted in the placement of emergency measures onto the public agenda (Catto and Tomblin, 2013). Currently, it is too early to tell if Hurricane Igor did actually heighten the political visibility and significance of preventative and anticipatory policies for Emergency Measures over the long term.

6. **Discussion**

6.1 Intensity and Re-Intensification of Cyclones

Klein et al., (2000) concluded from their study that since only one cyclone of tropical storm strength underwent extratropical transition, it was likely that cyclones which achieved hurricane strength would be able to survive the high vertical wind shear and low SSTs during the transition stage and survive it, compared to tropical storm strength cyclones. In contrast, the results from this study showed that cyclones with tropical storm intensities were more likely to undergo extratropical transition rather than tropical cyclones that achieved hurricane strength. A possible explanation for this difference is that the study from Klein et al., (2000) focused on the North Pacific which contains different atmospheric and oceanic modeling than the Atlantic Basin. The largest number of extratropical events take place in the western North Pacific compared to the North Atlantic Basin which contains the largest percentage of tropical cyclones that undergo extratropical transition. Jones et al., (2003) noted that 45% of North Atlantic tropical cyclones underwent extratropical transition. Klein et al., (2000) researched a short time series from 1994 to 1998, which could have resulted in an anomalously greater portion of tropical cyclones that underwent extratropical transition rather than tropical storms. A longer time frame could have revealed a more robust conclusion.

Using a similar approach to Klein et al. (2000) for re-intensification analysis, it was determined that 49.6% of cyclones that underwent extratropical transition weakened, with only 29.2% of cyclones re-intensifying. Re-intensification research undertaken by Klein et al. (2000) concluded that 13.3% of storms experienced no re-intensification, 50% had moderate re-intensification, and 36.7% re-intensified in the North Pacific. However, the shorter time series used by Klein et al. (2000) precludes a direct comparison with the results of the current study.

6.2 Latitude Effects

Data from Hart and Evans (2001) narrowed down the approximate areas where extratropical transition took place between May and October. They concluded that May and June showed transitions occurring modally between 30°- 35°N; transitions shifted northward by about 5° latitude in July. Between July and September, transitions occurred between 40°- 45°N; and September and October saw a shift southward by about 4°. Comparison of this data with the results from this research is shown in Table 6.1. The average latitude was 35°N for June which

Month	Average Range 1991 - 2011	Average Latitude 1991 - 2011
June	31.4° - 46.0°N	35°N
July	31.4° - 46.0°N	41.8°N
August	34.7° - 53.2°N	42.6°N
September	26.1° - 51.7°N	41.1°N
October	30.2° - 52.1°N	39.9°N

Table 6.1 - The range of latitude where extratropical transition was completed by month. April, November and December not listed.

lies within Hart and Evans' (2001) range (though this does not include May). Transitions began to shift northward by about 6.8°N in July, a 1.8°N difference northward from Hart and Evans (2001) analysis. Between July and August the average latitude of extratropical transition took place at around 41.8°N, coinciding with the range stated by Hart and Evans (2001). Lastly, between September and October the average latitude was found to be 40.5°N, only a 1.3° shift southward. The results from this research line up closely with Hart and Evans (2001). However, a significant issue in comparative analysis between these studies involves the advances in designation, recognition and understanding of extratropical transitions which occurred between the analysis of Hart and Evans (2001) and that performed in this study. Both studies indicate that transitions begin in the low latitudes between 31.4°- 46.0°N, shifting northward to a peak latitude in August, and then moving southward for the remainder of the season.

6.3 Peak of Transition Season

According to Hart and Evans (2001), there was a peak in extratropical transitions during September and October, when 50% of these cyclones transitioned. The majority of extratropical transitions in this research, however, was found to be in September with 45 storms transitioning out of the monthly total of 104. October showed a greater percentage of cyclones that underwent extratropical transition compared with September.

6.4 Cape Verde Events

Out of the total number of transitions, 25 originated in the deep tropics and were classified as Cape Verde Cyclones. Hart and Evans (2001) found from their data that the majority (51%) of cyclones that re-intensified came from the Cape Verde Region. The present study has determined that 49.6% of cyclones weakened after extratropical transition whereas only 28.9% re-intensified. Of the re-intensifications, 8 were Cape Verde Cyclones (32%).

6.5 Forecasting Extratropical Transitions

Extratropical transitions occur in most parts of the world where tropical cyclones develop. Considerable effort has been made to understand the behaviors of these transitions, and to develop forecasting methods. Currently, forecasting the onset and completion of an extratropical transition requires evaluation of synoptic and model-based indicators. Forecasters examine model-predicted extratropical transition timing in the context of synoptic conditions, identifying factors such as vertical wind shear gradients, air mass boundaries from satellite data, and SSTs (Fogarty et al., 2010). These factors and the forecasted track of a cyclone can influence when a cyclone will undergo extratropical transition.

Formulating an extratropical transition intensity forecast should first start by determining if the conditions are favorable for extratropical transition, and if the storm will re-intensify or weaken (Jones et al., 2003). This process would involve using satellite and model forecasts to look at the upper-level flow pattern in the atmosphere and see if there will be an interaction between a tropical cyclone and mid-latitude troughs (Harr et al., 2000). Considering the intensity of the vertical wind shear could determine if a cyclone will weaken significantly, or if the cyclone will re-intensify and survive its transition. Accurately analyzing from satellite imagery a cyclone's intensity, wind field, position and the stage of extratropical transition can significantly improve forecasts for determining when a cyclone will undergo extratropical transition. These analyses, however, are difficult because of the rapid changes in characteristics that occur during extratropical transition. Forecasting the track of a cyclone undergoing transition grows increasingly more difficult because the center of circulation becomes less distinct during extratropical transition. The "eye" of the storm becomes harder to identify and thus makes it difficult to track the storm. Often when vertical wind shear is high, the low level circulation center is exposed, allowing scientists and forecasters to see the center of the storm. A major problem is that meteorological agencies will continue to track an extratropical cyclone until the center of the storm is no longer visible on satellite imagery due to accelerated wind activity and shearing (Fogarty et al., 2010). This is a problem for areas that lie directly in the path of the storm. In many situations, forecasters have trouble identifying where the center of the cyclone is located, which is used to determine landfall and issuing watches and warnings. Warning and watches issued for areas may have to be adjusted many times in order to identify where the highest winds will be in comparison to the storm's center.

A more significant problem regarding forecasts is that when the center of the cyclone disappears weather services will often times stop paying attention to the storm, thinking that the storm is weakening and no longer a threat. Even though a center cannot be determined the cyclone is still active and without any warnings from meteorological agencies populations will not be informed on the intensity and risks that the storm will bring.

6.5.1 Considerations for a Future Algorithm

A potential algorithm should be developed to better determine when and where an extratropical transitions would likely take place. This would result in better forecasts and increase the potential for preparedness. This is a complicated task due to all the elements that need to be taken into consideration. A tropical cyclone and an extratropical cyclone are completely different in structure and dynamics and thus these differences need to be taken into consideration when developing a potential algorithm to help forecast a transition. The following elements should be taken into consideration:

1. The wind speed (measured in km/h) of the system undergoing extratropical transition. A weak system (tropical depression with winds beginning at 62 km/h) has a minimal chance of surviving through transition compared to a system that contains higher winds. Wind speed ranges could be used from the Saffir-Simpson Scale with a minimum of 62 km/h (tropical depression threshold) to a maximum of infinity.

2. The amount and area of precipitation (measured in millimeters) before, during and after extratropical transition. Precipitation amounts are taken from satellite data and station data. However, because cyclones spend the majority of their life out at sea, satellite data is the only precipitation indicator over much of the track length. A system will often grow to be ten times larger after transitioning which results in an increased amount of precipitation. Another observation to take into consideration is that the majority of the rain field will be displaced to the left (north-west) of the storm during extratropical transition. Calculating this shift in size and distance can also be incorporated.

3. The location of the storm (measured by latitude and longitude) is crucial. There is an increased chance for extratropical transition to take place between 30° and 40° latitude. Certain areas are more favorable for transitions depending on seasonal variation. This research has shown that transitions are completed near latitude 31.4° in the early season and shift further north to around 42.6° around the peak of the season. More data involving a longer time series would be needed to improve this conclusion on transition location.

4. The pressure (measured in millibars) helps determine the strength of a cyclone. Lower pressure implies a strong and consistent (persistent) storm. A cyclone with a deeper low pressure would probably have a better chance of surviving the harsh transition compared to a system with a high pressure (similar to the wind speed element). Future research could analyze the pressure before, during and after a transition, determining if the pressure of a system increases or decreases throughout the process.

5. The diameter of a cyclone (measured in km) grows as it undergoes extratropical transition which increases the wind and rain fields accompanied with the storm. Determining how large a cyclone will be after a transition could improve forecasts on areas that may be impacted.

6. Finding trends in extratropical transitions could provide clues on this process. Finding favorable areas where transitions occur; the direction tropical cyclones are going before they transition; and how much do the systems grow during extratropical transition can provide crucial information to future studies.

7. Identifying the center of the system after extratropical transition is complicated given that the "eye" is sometimes hidden or non-existent. Forecasters use the center of circulation to estimate where a cyclone is going. The area surrounding the center of circulation in a tropical cyclone usually contains the most powerful winds. However this area is displaced primarily to the right (south-east) of the system after transitioning into an extratropical cyclone. Finding the center of the storm possess a challenge in this respect, but determining where it is will give a more concise idea on where the majority of the rain and wind will be located and aid in determining the track of the system.

8. Time of year can help determine where these transitions and how many could occur. The majority of extratropical transitions will occur during the Hurricane Season in the North Atlantic (June-November), and the results from this study indicate that September is the most active month for extratropical transitions. This area of research can be expanded on with increased data, including a longer time frame and the confirmation that certain tropical cyclones did undergo extratropical transition.

9. There is a lack of data in regards to air temperature and moisture for storms undergoing extratropical transition. Determining the surrounding air temperature and moisture content during the time of transition could help identify why a transition occurs. A specific air temperature range could be the trigger for transitions to occur, but unfortunately data at present are very limited. The majority of transitions occur out at sea with limited amounts of temperature and moisture information being recorded. Most temperature and moisture data comes from offshore buoys and nearby ships which only gather information from a small area of the storm. Additionally, the data recorded from these sources are at the sea level surface. Temperatures and moisture in the higher levels of the atmosphere are recorded using satellite data, but they should be gathered and compiled from multiple altitudes between the sea surface and the high levels of the atmosphere for cyclones undergoing extratropical transition.

10. SST data have been a crucial component when researching and understanding tropical and extratropical cyclones. Tropical cyclones rely on warm ocean waters to develop but once they turn northward into cooler waters is when a transition occurs. Finding a trend in SSTs can identify prime temperature ranges where cyclones undergo extratropical transition.

11. Identifying how long a cyclone undergoes extratropical transition is a component that has not been studied extensively, given that the research on extratropical transitions is fairly recent. A tropical cyclone undergoing extratropical transition can take anywhere from a few hours to a couple of days to complete its transition. The problem is that scientists do not often know when a transition is starting. The key is usually to determine if the warm core is becoming cold, but this data is not available for all storms, or is not mentioned in reports issued by meteorological agencies. Knowing how to determine the amount of time a cyclone will be in its extratropical transition will help scientists to relay information to the public regarding the storm and what to expect. Communities could be able to prepare for either a hybrid storm, which would be smaller and contain less precipitation, or a fully extratropical cyclone.

These 11 elements should be taken into consideration in building an algorithm in future studies. Developing an algorithm to forecast extratropical transitions can improve forecasts, which in turn could educate and warn the public on an approaching cyclone. A community may see a cyclone that is more extratropical than tropical (a hybrid system), and if this is the case the cyclone will still be in its transition stage. In this case the strongest winds may still be located near the center of the low pressure instead of to the right (south-east) of the storm, and precipitation can be found throughout the system similar to its tropical state. However, a cyclone that is fully extratropical will be larger than a hybrid system and will contain more rain and a larger wind field (rain shifting to the left (north-west) and wind to the right (south-east)). This matters to Newfoundland in particular because, depending on the track of the storm, Newfoundland could get the worst of the rain if the cyclone impacts the east side (Avalon Peninsula); or if the cyclone hits the west side, Newfoundland will receive more wind than rain.

Knowing these difference will help emergency management crews and meteorological agencies to inform the public on what to expect and which areas will be threatened by particular cyclone parameters.

6.6 Influences of Climate Change

Climate change entails a significant long-term (30-year minimum) change. The Intergovernmental Panel on Climate Change (IPCC) reports that reinsurers have recorded an increase in disasters since the 1960's. This increase is not due to better recording, because the major disasters account for 90% of economic losses and are always recorded. This rise instead is partly due to socioeconomic factors. However, according to many insurers, the frequency of extreme events has been increasing (Watson et al. 1996). The vulnerability of coastal areas to storm surge is expected to increase with future coastal development and sea level rise (McQuaid, 2012). The topic of climate change is of vital importance because of the threats of enhanced storm surge activity and how coastal communities will deal with the threats of stronger future cyclones.

A single catastrophic event cannot be related to climate change, but multiple events over a span of time can indicate a change in climate. Global temperatures have risen about 0.5 C° the 1970s (McQuaid, 2012) and global SST's have risen approximately 1°C since 1870 (EEA, 2011). Cyclones are giant heat engines that rely on warm temperatures. If more heat is pumped into these systems by warming up the oceans and atmosphere, it can be determined that the cyclone will probably increase in strength. High SST's cause evaporation of moisture which fuels the storm. The latent heat energy is then transferred from the ocean to the atmosphere, which is what powers the storm. With each degree rise in SST, the atmosphere holds 4% more moisture.

Hurricane Sandy (2012) encountered water temperatures off the East Coast of the United States that were about 3 C° above average. This increase may have boosted the rainfall contained within Sandy by as much as 5 to 10% compared to what it may have been 40 years ago (McQuaid, 2012). The complex relationship between cyclones, climate and oceans has been wrestled with for decades.

Emanuel (1987), first suggested a link between cyclones and climate change. Observed records of cyclone activity in the Atlantic show a strong correlation, on multi-year time-scales, between the Power Dissipation Index (PDI) and the tropical Atlantic SSTs. PDI is defined by Emanuel (2007) as:

$$\mathrm{PDI} \equiv \int_0^{\tau} V_{max}^3 \, dt. \qquad \text{(Equation 6.1)}$$

where V_{max} is the maximum surface wind at any given time in a cyclone, and τ is the lifetime of the storm. PDI is a collected measure of cyclone activity in the Atlantic combining intensity, duration and frequency of cyclones in a single index. Since the 1970s, SSTs and PDI have risen sharply in the Atlantic, and some evidence shows that PDI levels are higher in recent years than in the previous active cyclone era (1950-60). According to Emanuel, past storm data shows that rising SST's and atmospheric temperatures has fueled the cumulative violence of cyclones. Model-based climate change detection have linked the increase of Atlantic SSTs to rising greenhouse gases. However, this link between greenhouse gases and PDI has been based on statistical correlations. It is suggested that there is a large anthropogenic influence on cyclones when analyzing the statistical linkage of cyclone PDI and SSTs (Fig 6.1). If the correlation

North Atlantic Power Dissipation vs. SST, 1950-2009

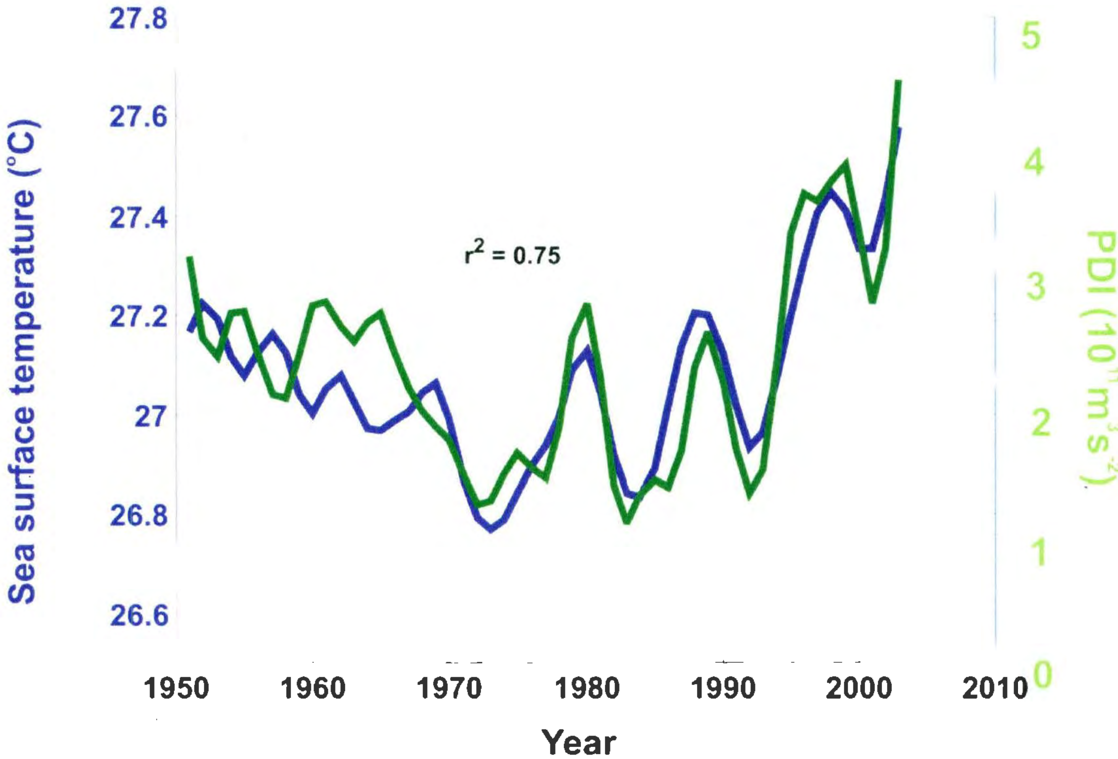


Figure 6.1 - Time series of late summer SSTs in the tropical Atlantic (blue) and the PDI (green) (Emanuel, 2007).

between SST and cyclone activity shown in Figure 6.1 is used to identify a pattern in future Atlantic cyclone frequency, the conclusion would be that if SSTs increase it can be implied that there would be a very substantial increase in cyclone destructive potential. The PDI would increase by roughly 300% by 2100 (Fig 6.2 (*a*)).

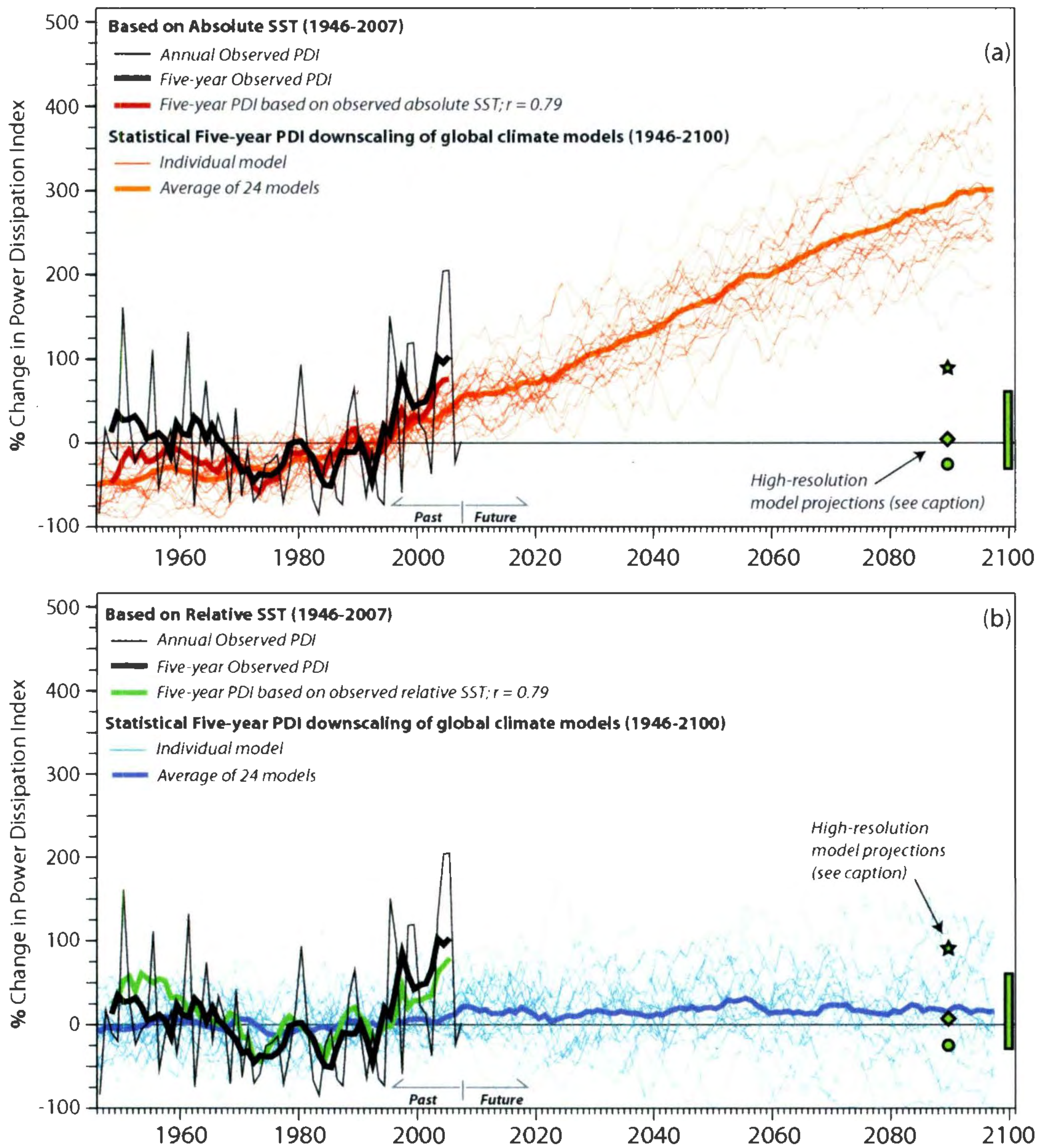


Figure 6.2 *a, b* - Two statistical models of cyclone activity in the Atlantic Ocean vs. SST. The upper data statistically models the activity of cyclones based on "local" SST. The bottom data statistically models the activity of cyclones based on SST in the tropical Atlantic relative to SST averaged over the remainder of the tropics (Vecchi et al. 2008).

Vecchi (2008) has noted that Atlantic cyclone power dissipation is well-correlated with other SST indices outside the tropical Atlantic, in particular with indices of SSTs in the Atlantic relative to mean tropical SST (Fig. 6.2*(b)*). There is a crucial distinction between the two data plots. The statistical relationship between cyclones in the Atlantic and the local Atlantic SST shown in Figure 6.2*(a)* would hint at a possible increase in Atlantic cyclone activity (PDI) due to greenhouse gas warming. In Figure 6.2*(b)*, however, there seems to be only slight changes in Atlantic cyclone activity (PDI) with increased greenhouse gases (McQuaid, 2012).

While there remains a lack of accord among various studies on how cyclone PDI will change in the Atlantic, no data shows a sensitivity of PDI to greenhouse gases as large as what was implied in Figures 6.2 *(a)* and *(b)*. Therefore there is little evidence from current data and models that climate change will lead to a large increase in cyclone frequency or PDI (300%) in the Atlantic Ocean. However, there is some indication that there will be a substantial (100%) increase in the frequency of major cyclones (Category 3 and higher) and a decrease in overall cyclone numbers (McQuaid, 2012).

Climate change could be the cause for an increase in the frequency and magnitude of cyclones, but another theory is that there is a cycle in which there is an increase in cyclone activity for a few decades. The increase in cyclone strength and frequency could be associated with the Atlantic Multidecadal Oscillation (AMO) (Landsea, 2010). The AMO is a continuing series of long-duration changes in SSTs in the North Atlantic. The AMO produces warm and cool cycles in the Atlantic with a SST range of 0.4 C°. The cycle lasts roughly about 65 to 80 years (Baum, 2011). These SST changes from warm to cool are considered to be natural and have been occurring for the last 100 years (Fig. 6.3). Records from NOAA have shown that a warm

Atlantic Multidecadal Oscillation (AMO)

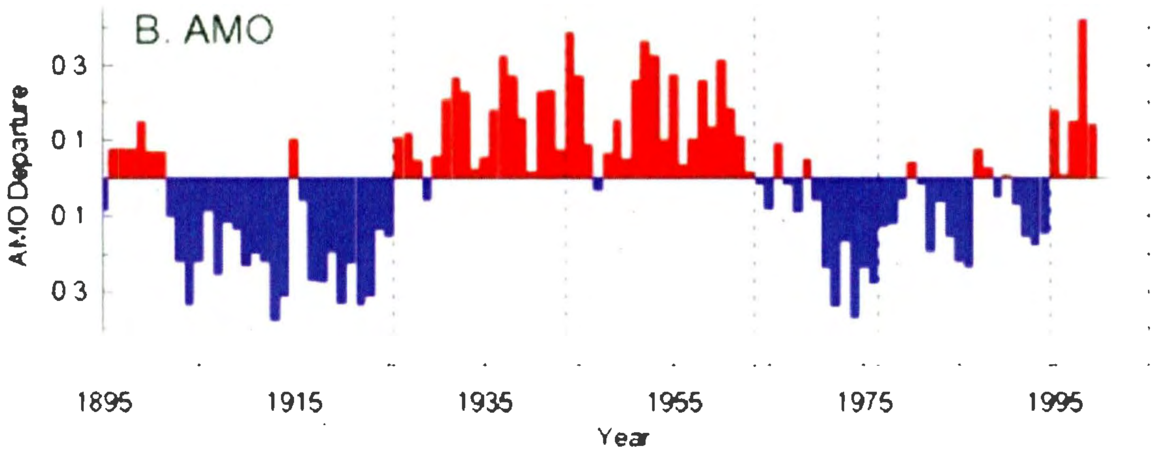


Figure 6.3 - Time series and mode of Atlantic Multidecadal Oscillation (AMO). Blue areas indicate a negative AMO period and red areas indicate a positive AMO period (Baum, 2011).

phase where SST have been warmer than usual has occurred since the 1990's. Due to this warm phase much of the Northern Hemisphere has been affected by an increase in air temperatures and precipitation. The AMO is associated with changes in the frequency of cyclonic development in the Atlantic. There is also debate on if the AMO alternately exaggerates and obscures the global increase in temperatures due to anthropogenic global warming. During a warm phase, the number of cyclones that grow into major cyclones is much greater compared to a cool phase with twice as many major cyclones developing. According to the NHC, since initiation of the warm phase around 1995, major cyclones have increased in number thus leading to a crisis in the insurance industry. Weaker cyclones are not much affected by the AMO. However, the number of weaker cyclones that mature and grow into major cyclones has noticeably increased during the warm cycle. Thus intensity is affected and the frequency of major cyclones is also affected (Landsea, 2010).

There is much debate between the existence of climate change and the theory of the AMO with an ongoing split in perspective between meteorologists and climate modelers. An important question remains among scientists and researchers: is the AMO really a natural phenomenon, or can climate change be related? Instruments have observed the AMO cycles for only the past 150 years, which is not a long enough time period to answer the question. To date, studies from ice cores and tree rings have indicated that oscillations similar to the ones that were observed instrumentally have been occurring since the last millennium, leading many scientists and researchers to believe that the AMO may indeed be a natural oscillation (NOAA, 2005).

Climate models are operated on a global scale, while weather models are more fine-grained and used to predict a cyclone's track and strength. Combining these models together to predict future climate change and how it will affect cyclones risks compounding uncertainties in the two models. Most of the current understanding of cyclones and the hard data derived from them comes from satellite observation. Reliable satellite weather data only goes back about 40 years, which is a short time span to base climate change predictions upon (McQuaid, 2012). Currently there is no way to predict when the AMO will switch from a warm to a cool phase. Computer models are at the moment far from being able to calculate this shift. It is, however, currently possible to calculate the probability that a shift from warm to cool will occur within a certain time frame. With advances in technology we are moving closer to better forecasting methods and possibly a better understanding of what our climate will be like in the future.

Relating climate change to extratropical transition is mostly speculation. Currently there is very little research which focuses on climate change and extratropical transition frequency. It can be suggested that with an increase in cyclone activity there will be a higher likelihood of seeing more transitions. This is not always true, though: as seen in 2006 which was significantly less active than 2005, there were more transitions recorded. Therefore seasons that are highly active cannot be assumed to produce more extratropical transitions. Information from McQuaid (2012) which states that there will be an increase in strong cyclones and a decrease in overall cyclone activity, would lead to the possibility of cyclones being able to survive extratropical transition which could show an increase in transition frequency. Another suggestion is that these major cyclones could re-intensify as they undergo transition and areas such as Newfoundland could experience a cyclone of a major Category (Category 3-5). This suggestion is tentative and future research related to climate change and extratropical transition should be researched in-depth.

6.7 Preparedness

Tropical cyclones and extratropical transitions will continue to happen in the Atlantic Basin and around the world. There is no way to stop the impacts and damages felt by these systems, however there are ways to mitigate them. FES-NL provided detailed accounts of what took place during Hurricane Igor's onslaught and how Newfoundland has learned and improved from this storm. There was a sense of "immunity" throughout the Newfoundland community before Igor, with people believing that powerful cyclones could not survive so far up north and cause devastating damage. Igor changed all of that and showed the residents of the Island the severity of these cyclones and the importance of taking emergency management and weather offices seriously.

Leading up to Igor's landfall residents did not take the storm seriously until the day before (September 20, 2010). Hurricane Earl which struck a couple of weeks earlier received more attention and was taken more seriously. Unfortunately, many residents under-estimated the damage potential of Igor, and preparations were not universally adequate. To some residents, the name "Igor" was considered to be somewhat comical and humorous prior to arrival, which also may have had a regrettable affect. Newfoundland has experienced many cyclones in the past but residents have never witnessed a cyclone as destructive as Igor. To many, Igor was just another typical cyclone that would soon blow over. Igor was a storm that all of Canada has learned from with communities in Newfoundland still recovering from the storm. The main goal now for Newfoundland is to improve from Igor and become better prepared for the next devastating cyclone.

6.7.1 Recommendations for FES-NL

Personnel at FES-NL have been trying to improve their warning and preparation strategies since Hurricane Igor. The goal is to try and make people aware and prepared for disaster when it arrives. The legislated rule for Newfoundland is that every municipality has to have some form of emergency preparedness, and 72 hours before a cyclone hits, it is suggested that an individual be strongly prepared and have a level of self-sufficiency (FES-NL, 2012). According to FES-NL, 90% of communities are currently supported with an Emergency Management plan, and emergency personnel are constantly updating and reminding communities to prepare for Hurricane Season. FES-NL currently works with communities in hopes that they can help people become more prepared. FES-NL is in charge of preparing and warning the public of an approaching cyclone. Afterwards, they help to survey the damage and help with the re-building process. When roads and bridges were washed away during Igor, relief efforts were at a stand still until temporary bridges were set up. In many cases, boats were used to get supplies into areas that were isolated. In some respects, partially spacial, this was the first time Newfoundland has had to deal with a disaster of this scale. Many did not know what to do to provide basic necessities to isolated communities, and because of this, the recovery went slowly. Even though Igor was destructive, it was a major lesson that identified the weak links in the preparedness chain.

Measures have been put into place since Hurricane Igor, however it is unclear yet as to whether these improvements are beneficial. According to FES-NL, Newfoundland was more prepared for Hurricane Leslie (2012) due to the improvements in awareness and warning time. However, Leslie was not a destructive storm like Igor. Newfoundland will someday face another tropical cyclone similar to Igor, and at that time the measures and improvements made by FES-NL will be put to the test. FES-NL should continue with their current plan of improving awareness and warning communities ahead of time regarding approaching cyclones, whether they be tropical or extratropical.

6.7.2 Recommendations for Meteorological Agencies

Meteorology is a complicated science and therefore forecasts can usually be wrong due to an incomplete understanding of the atmosphere. Canada relies on Environment Canada and the CHC for up-to-date news on approaching cyclones. However, due to the complicated atmosphere and jet stream patterns around Newfoundland, in particular the Greenland Block, a strong area of high pressure, forecasting techniques can be challenging. The CHC is the most experienced at forecasting and impacts of extratropical transitions. It is in Canada's best interest to continue to research and understand extratropical transition to improve forecast models. This research has demonstrated that Newfoundland does not receive purely extratropical cyclones: in many cases cyclones arrive while they are still undergoing extratropical transition. In the recent historical record, Newfoundland has started to experience pure tropical cyclones (Hurricane Maria).

The type of storms that give Newfoundland the most grief and destruction usually originate in the Cape Verde Region. Due to past cyclone experience it would be beneficial for the CHC and FES-NL to recognize that Cape Verde Cyclones do pose a threat to Newfoundland, especially in the middle of the season when cyclones tend to turn back out to sea and impact the Island. This research has shown that from 1991 to 2011, a third of cyclones that impacted Newfoundland originated from the Cape Verde Region.

It is in the people of Newfoundland's best interest to be cautious of Cape Verde Cyclones and be aware that these cyclones cause the most destruction to Newfoundland. This is not to say that the province and emergency personal should begin issuing emergency bulletins and scaring the public every time a Cape Verde Cyclone forms. Instead, the public should be alerted that a Cape Verde Cyclone has formed and that if the cyclone does head towards Newfoundland the public has about two weeks to prepare. The middle of the season (August-October) produces most of the Cape Verde Cyclones, and this is also the time when Newfoundland experiences most of their cyclone impacts. Meteorological agencies, residents and FES-NL should be on high alert and be prepared for this time of the season, especially when a Cape Verde Cyclone forms.

Obtaining more knowledge on extratropical transitions is crucial and currently there are only a limited number of ways to identify if extratropical transition is taking place. Valuable data is provided by dropsondes deployed into active cyclones by the 53rd Weather Reconnaissance squadron, US Air Force Reserve. However, the Hurricane Hunters are only deployed into tropical cyclones that pose a major threat to land, particularly the United States. According to Dr.

Gilbert Brunet (personal communication), who is head of the Meteorological Research Division at Environment Canada and the Deputy Director of Weather Science at the Met Office, if a cyclone is heading towards Atlantic Canada and not threatening the United States the Hurricane Hunters will not fly out and drop sondes. The information the sonde's receive could be crucial for forecasters by determining if a cyclone is re-intensifying during extratropical transition. Environment Canada could (should) make arrangements for the Hurricane Hunters or other designated research aircraft to drop sondes into cyclones, especially those that pose a threat to Atlantic Canada.

Technology should continue to advance in the future so that improvements in forecasts can be made. The eye wall of a cyclone contains intense thunderstorms that continue to strengthen as a cyclone moves over water. Combining this with the dynamics of SST's where a change of 1°C can make a big difference, not only at the surface, but down to 200 meters. Unfortunately, our scientific data gathering is not precise enough to pick up on these minuscule changes (Tim Deegan, meteorologist, Jacksonville FL, personal communication). Our understanding of cyclones has improved in the past 40 years, but improvements need to be made with data collection. Tim Deegan suggests that a new generation of satellites would be useful for data collection. These new satellites will not only be able to look at the top of the clouds but will be able to examine a cyclone three dimensionally. This increase in data going into computer models will lead to a better improvement in intensity forecasting, which will benefit in regards to forecasting re-intensification during extratropical transition (personal communication with Tim Deegan).

Another recommendation to meteorological agencies is the idea for a new symbol which refers to a cyclone undergoing extratropical transition. Currently when a cyclone completes extratropical transition the storm is denoted on a weather map as an "L". This tells viewers that the storm is a low pressure system and can lead residents in to thinking that the cyclone is no longer a threat or has dissipated. Residents understand a recognize a traditional hurricane symbol and know that it is a threat. A symbol that gives this same message is needed for a transitioning storm (Fig. 6.4). The tail represents the frontal region of the cyclone. The "eye" in the center

Figure 6.4 - A possible symbol to be used to represent a cyclone undergoing extratropical transition.

symbolizes a cyclone with tropical storm strength on the Saffir-Simpson Scale. This eye can be omitted if a cyclone comes out of extratropical transition as a Category 1 cyclone or stronger.

Another issue comes from the name given to a cyclone. In many cases the name is dropped once a cyclone is considered to be extratropical, so care should be taken to preserve it in public forecasts issued after the transition. Tim Deegan (personal communication) expresses that it is a disservice to the public if the name is taken off of the system once extratropical transition is completed. As long as the system has a name to it people tend to pay more attention. So even when a cyclone comes ashore and it is either an extratropical cyclone or a hybrid system, as with

Igor, the public will still care and take more action than if the system did not have a human name.

6.7.3 Recommendations for the Public

Hurricane Igor was a lesson to the residents of Newfoundland showing that they are not immune to powerful cyclones. The psychological impacts from Igor were shown when Hurricane Maria arrived a year after Igor. Many people panicked and began to prepare early fearing another Igor. However, Maria left very little damage and left the island very quickly after impact. Residents do not like to be given false information regarding cyclones. The reality, however, is that there will always be false alarms. It is the job of the resident to be prepared every Hurricane Season regardless of how many cyclones are forming and what meteorologists and emergency personnel are saying. The beginning of Hurricane Season is the best time to prepare for a cyclone, even if it does not impact an area; because nearly everything a resident can do to prepare for a cyclone will not be wasted. However, getting residents to prepare in advance before a cyclone hits can be difficult, as forecasters, emergency management officials, municipal leaders, and hazard researchers will attest. Residents should keep their housing structure up-to-date and be aware of the threats they will receive if a cyclone approaches. Houses close to shore will likely be impacted by storm surge, and houses at higher altitudes will be affected by winds. The homeowner should identify these risks and be prepared to deal with them prior to a cyclone making landfall.

A serious issue regards available insurance to the people living in cyclone prone areas in Canada. In Canada there is wind insurance and there is sewer back-up insurance, however, there is no flood insurance (FES-NL, 2012). After Igor, FES-NL surveyed the damage and had to determine if a house was flooded or if the damage was done by sewer back-up or storm surge. Houses that were determined to be flooded were not offered any insurance. Fundraising was set up by corporations such as the Red Cross and Salvation Army to give money to people who did not have insurance after Igor. Insurance companies do not offer flood insurance due to the high risk, therefore the only option for residents is to self-insure. Residents living in a cyclone prone area such as Newfoundland should be prepared and self-insure their property in case a cyclone were to devastate Newfoundland in the future.

Lastly, the people of Newfoundland should understand the term extratropical transition and what that could entail for an approaching cyclone. It has been shown from this study that Newfoundland is impacted by cyclones that are purely extratropical or are in the process of extratropical transition. Very rarely will Newfoundland be hit by a pure tropical cyclone (Hurricane Maria). While in the process of extratropical transition cyclones could be re-intensifying and could strike the island as a more powerful storm than when it was in its tropical stage. The storm can expand to be ten times larger than its previous form, thus before the cyclone arrives, Newfoundland will be feeling the effects of rain and wind, which depending on the size of the transitioning storm could last for a couple of days. It is imperative that residents understand that extratropical transition can produce an extratropical cyclone that can be stronger and contain a larger rain and wind field than when it was in its tropical from. Currently the notion is that an extratropical cyclone is weaker than its previous tropical form and that they pose little danger. This idea needs to be addressed.

7. Conclusions and Recommendations

7.1 Concluding Remarks

The primary purpose of this study was to analyze extratropical transitions and assess if the frequency, magnitude and intensity of potential shifts can be calculated for the purpose of more accurate forecasting and the benefit of public awareness, safety management, and preparedness. The analysis focused on statistical data, GIS modeling, and discussion with FES-NL officials. This researched focused closely on 121 cyclones that underwent extratropical transition from 1991 to 2011. The following conclusions were made from this research:

- Between 1991 and 2011, 324 tropical cyclones formed, and 121 of these cyclones underwent extratropical transition in the Atlantic Basin.
- The average number of extratropical transitions from 1991 to 2011 was 5.76, and a positive linear trendline was determined for this time frame.
- 32.1% of tropical cyclones formed in September, and 43.3% of these cyclones underwent extratropical transition.
- Individual years with many tropical cyclones (2005) did not produce a proportionate number of transitions.
- Tropical cyclones that formed in the deep tropics and moved into the Caribbean and the Gulf of Mexico had a reduced probability of undergoing extratropical transition.

- The start of Hurricane Season did not produce a high percentage of transitions. Extratropical transitions occurred more frequently in the middle of the season (late August).
- November and December saw fewer tropical cyclones forming but 61.1% of them transitioned.
- The majority of transitions took place over the Atlantic Ocean, 19.8% of these storms transitioned over land.
- A greater percentage (62.8%) of tropical cyclones started to undergo extratropical transition between the latitudes of 30 to 39.9°N. 50.4% of cyclones completed their transition between 40 to 49.9°N.
- 49.6% of tropical cyclones weakened after completing extratropical transition; 21.5% had little or no re-intensification after transition; and 29.2% re-intensified.
    - Out of 35 cyclones that re-intensified after extratropical transition, most took place during the middle of Hurricane Season with September producing the most, followed by October and July, respectively.
- 27 cyclones impacted Newfoundland directly between 1991 and 2011, one being purely tropical.
    - 8% of total tropical cyclones formed made landfall in Newfoundland
    - 78% were tropical storm strength; 22% were Category 1 strength

- The area of Newfoundland to be impacted the most was the Avalon Peninsula (44%).
- Most cyclones that impacted Newfoundland achieved tropical storm, Category 1 or Category 4 strength during their lifetime before impacting Newfoundland.

- Timeline data shows that Newfoundland is directly impacted by about 1.29 cyclones each year.
- Between 1991 to 2011 there is a positive trendline. Based on this time series data, Newfoundland could see an increase in cyclones.
  - 2006 was a highly active year and in the future Newfoundland could experience more active years such as this.
  - Excluding active years such as 2006 would yield a flatter trendline. Experimenting with a shorter time frame from 1995 to 2011 resulted in an apparent decrease in storm activity.
- One-third of cyclones to impact Newfoundland qualified as Cape Verde Cyclones. Hurricane Igor was classified as a Cape Verde Cyclone.
- Future research will have to be conducted on the possibility of more damaging storms to hit Newfoundland to determine if there is a possibility of an increase in cyclone frequency and intensity.
- Hurricane Igor began to undergo extratropical transition on September 18 when satellites showed Igor morphing into a "comma" like structure.

- Hurricane Earl impacted Atlantic Canada seventeen days earlier, as such Igor did not receive very much media attention across Newfoundland. The seriousness of the situation was not apparent until the CHC issued tropical storm and wind warnings.
- Before Igor arrived, FES-NL knew that Igor was going to be a serious storm, prompting the closure of schools, and set up shelters.
- The center of Igor passed to the east of the Avalon Peninsula on September 21 and later that day completed its transition around 17:30 local time.
- The CHC issued the first preliminary statement of Igor on September 17, with regular bulletins being issued September 18.
    - Tropical Storm warnings were issued on September 20 for the eastern part of Newfoundland. A hurricane watch was issued on September 21.
- Igor impacted Newfoundland as a Category 1 hurricane on the Saffir-Simpson Scale with sustained hurricane force winds between 120 to 130 km/h.
    - Over 200 mm of rain recorded over the Burin and Bonavista Peninsulas
    - Over 100 mm of rain over the Avalon Peninsula
    - Wave heights reached 13 meters on the east side of Igor and a storm surge of 0.7 to 1 meter was measured around east Newfoundland.
    - Peak stream flow values locally exceeded 600 m^3/s

- Rainfall caused rivers to crest and overflow, and numerous roads, bridges and some buildings received extensive damage.
- The geomorphic signature was marked by extensive fluvial outwash deposits along the shorelines, many slope failures along coastal cliffs and river banks, eroded stream margins, and displaced sediment from deciduous trees that were uprooted.

- The rainfall was anticipated but the wind threat was thought to not be an issue and would stay out to sea.
- Flooding was the main problem for the region with the Burin and Bonavista Peninsula's receiving the worst damage from Igor. Road access was restored to all isolated communities by October 2, 2010.
- The Canadian Armed Forces were deployed to fix roads and build temporary bridges to connect isolated communities. Federal financial aid was provided as well.
- Many businesses suffered, notably the Port Union Fish Plant, which never reopened.
- Estimates of direct damage from Igor vary from $110 to in excess of $200 million.
- The effects of Igor were still being felt as of December 2012. The 2013 construction season will repair all remaining damage.
- FES-NL says that recovery efforts and communications have improved since Igor and the municipalities and government are better prepared since Igor.

7.2 Another Igor?

An important question for emergency officials and the residents of Newfoundland is if another Igor could happen, and when will it occur. There is no way to deduce precisely when another hurricane such as Igor will hit the province. However, it can be said with confidence that it will happen. Igor was a rare and powerful storm, but it was not a "fluke": strong tropical cyclones and evolving extratropical transitions have impacted the island on many previous occasions. Newfoundland experiences many cyclones due to its proximity to their predominant northwestward track along the North American coast. Due to Newfoundland's northern latitude, the cool subtropical waters of the Northern Atlantic Basin, and increased wind shear in the atmosphere, most cyclones will weaken substantially before making landfall. However, as these cyclones start to undergo extratropical transition, they can remain as powerful storms with abundant precipitation, and in some cases intensify. Hurricane Igor was an unusual, atypical (but not unique) storm that had substantial atmospheric help to cause it to be so devastating:

- Igor maintained its intensity as it underwent extratropical transition; another cyclone (Julia 2010) provided energy to Igor allowing it to strengthen.
- Igor merged with an area of low pressure a day before landfall which increased the moisture retained in the storm
- A slow moving trough over Newfoundland interacted with Igor causing the moisture and energy from Igor to be taken by the trough and caused an increase in precipitation.

All of these factors aided Igor as it traveled north towards Newfoundland. A cyclone, in order to have disastrous consequences to Newfoundland, needs to have suitable atmospheric conditions to reach the high temperate waters of the Atlantic Basin. Another cyclone similar to Igor will happen at some undeterminable future date. Although subsequent events may be influenced by climate change, further study is required to determine the likelihood of intensifying cyclones in the North Atlantic. Given the shortness of the time series in this research, it would be difficult to address the effects of long-term climate change.

The main message to Newfoundland residents, which comes from emergency managers, is to be prepared now. Cyclones will continue to form and impact Newfoundland and the rest of Atlantic Canada. It is the resident's responsibility to be prepared when Hurricane Season arrives each year and to be aware that another Igor could be on the way at any time. FES-NL (2012) says that Newfoundlanders are now more knowledgeable and there is a better level of preparedness thanks to Hurricane Igor. This level of confidence and preparedness will be tested when another cyclone, similar to Igor, has its eye set on Newfoundland.

7.3 Future Research

Extratropical transition is an intriguing and important topic for the scientific community and the public. However, the meteorological community is still a long way from fully understanding these systems, which need to be researched in depth. The following recommendations are given to improve forecasting, emergency management, and the overall understanding of extratropical transitions:

1. Suggestions for future research include expanding the timeline of extratropical transitions from this study to include a 40-50 year time span of data. The problem is that the quality of existing data regarding extratropical transitions is not reliable. Previous data have errors in track, intensity and very little information regarding transitioning storms, thus making analysis difficult. Better records need to be taken from meteorological agencies which will allow for more reliable data in the future. A longer time span will in turn provide a better indication if cyclones, in particular extratropical transitions, are increasing in frequency. This would also have implications for the vulnerability of Newfoundland in regards to direct impacts.
2. The process of forecasting extratropical transitions should be looked at in depth. Forecasters are slowly learning the importance of extratropical transitions thanks, in part, to storms such as Igor (2010) and more recently Sandy (2012). However, problems remain to be addressed. Aircraft reconnaissance flights into cyclones often stop once the storm passes north of 40°N, or if the storm is no longer a threat to land. This results in an incomplete set of track data for tropical cyclones that have begun to undergo extratropical transition. Data consisting of storm tracks, statistical data, and intensities are halted at the point of transition or soon after. In some cases, the NHC will stop issuing advisories after a cyclone has completed extratropical transition. Due to this limitation, making post-extratropical transition pressure change diagnostics based on the NHC data sets is problematic, resulting in a bias with respect to latitude and intensity (Hart and Evans, 2001). When the NHC halts their advisories on these systems, this results in communities in more northerly latitudes having a tendency to "relax", thinking that the storm is not a threat. The reality is that extratropical transition can still pose a threat to communities in the path of the system and could re-intensify after the completion of

extratropical transition. The Japan Meteorological Association announced in 2006 that they will disseminate tropical cyclone bulletins for an intense storm after the completion of its transition (Fogarty, 2010).

The CHC is the meteorological agency that will be primarily responsible for monitoring extratropical transitions. Atlantic Canada experiences these types of storms more frequently than the United States. Tropical cyclones tend to transition more frequently close to the CHC's monitoring area. Canada will benefit from extratropical transition research because of its vulnerability to these systems. Extratropical transitions should be an ongoing concern for Canadians, because these systems are some of the most complex storms to predict. The CHC and other meteorological agencies should continue to monitor, record data, and issue advisories when appropriate until a cyclone has completely dissipated.

3. Data collection would need to be improved and continuous throughout the life of a cyclone. An increase of data going into computer models will help to improve intensity forecasting, which will benefit in regards to forecasting re-intensification during extratropical transition.
4. The possibility exists that future climate change could have an effect on extratropical transitions. Research looking into the possibility of an increase in transitions with warmer SSTs or a warmer atmosphere and if storms will have a better chance of re-intensifying after transition would be advisable.
5. Increasing awareness of extratropical transitions and education concerning their impacts will allow the public to understand the differences in risk posed by an extratropical cyclone compared to a tropical cyclone. This education could help increase the level of preparedness for future cyclones undergoing extratropical transition, particularly in Newfoundland.

6. Newfoundland's infrastructure was unable to cope with the massive amount of precipitation during Igor. Roads were washed away, and houses were flooded and lifted off their foundations. An increase in the level of preparedness by both Newfoundland residents and government agencies such as FES-NL is needed. Newfoundlanders re-learned that they are not immune from powerful storms, thanks to Hurricane Igor. Personnel from FES-NL say that Igor was a lesson that showed the Island was not prepared for such a storm and that they have learned from Igor. The effectiveness of these improvements will be demonstrated when the next devastating cyclone or transitioning cyclone arrives, but until then residents should be aware of impending storms and listen to their emergency officials when the time comes.
7. Extratropical transition should be defined universally so that forecasters and meteorological agencies around the world can research, identify and compare extratropical transitions using the same definition and terminology. The following definition was used for this research: "Extratropical transition involves a gradual change in the structure from a smaller warm-core symmetrical system, to a larger cold-core asymmetrical (comma-like) system (Harr and Elsberry, 2000; Hart and Evans, 2001; Klein et al.,data 2000)."
8. The development of an algorithm to better predict when and where these transitions are taking place and if they will re-intensify after extratropical transition. This is currently a complicated task with the amount of knowledge that is known about the atmosphere and weather patterns. If possible, a process to determine when a cyclone is beginning extratropical transition and how long it will take to complete it should be found which will aid forecasts and possibly allow for better warnings to be issued to areas in the danger zone. Emergency managers and

government officials will be able to know the type of system they are dealing with and prepare for the storm.

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