WHERE SCIENCE MEETS USERS NEEDS: STORM SURGE IN EASTERN NC

By

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Director of Dissertation: Dr. Scott Curtis

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The coast is well researched because of its intrinsic value to visitors, the lives and property of those who live at the coast, and the environmental services it provides through tourism, natural resources, and as a natural barrier to waves, wind, and water. Storm surge coupled with wave energy at the coast is partly responsible for shaping or damaging coastlines including both natural and human built environments. This dissertation work explores the storm surge hazard focused across Eastern North Carolina through three standalone but related chapters. Storm surge at longer lead times is explored through the examination of climate oscillations related to storm surge characteristics (chapter one) and the synoptic conditions responsible for storm surge (chapters one and three). Emergency support personnel's desire for different types of surge information as well as surge information at longer lead times is covered in chapter two. Statistical and synoptic climatology results indicate a significant relationship between a combination of water height and duration with climate oscillations, which show promise in enhancing the forecasting and awareness of storm surge at greater lead times to further meet storm surge users' needs.

WHERE SCIENCE MEETS USERS NEEDS: STORM SURGE IN EASTERN NC

A Dissertation

Presented To the Faculty of the Department of Coastal Resources Management East Carolina University

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Doctor of Philosophy in Coastal Resources Management

By

Robbie Munroe

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Somewhere over the rainbow, way up high
There's a land that I've heard of once in a lullaby.
Somewhere over the rainbow, skies are blue
And the dreams that you dare to dream,
Really do come true.

Someday I'll wish upon a star
And wake up where the clouds are far behind me.
Where troubles melt like lemon drops,
Way above the chimney tops,
That's where you'll find me.

Somewhere over the rainbow, blue birds fly
Birds fly over the rainbow
Why then, oh why can't I?

Somewhere over the rainbow, blue birds fly
Birds fly over the rainbow
Why then, oh why can't I?

If happy little bluebirds fly beyond the rainbow
Why, oh why can't I?

-*Yip Harburg*

Love you mom

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I am incredibly grateful to my family. This is especially true with my mom and dad who has always been incredibly supportive and would drop anything to be there for me. My siblings have also been incredibly supportive and challenged me to be a better version of myself. I am incredibly thankful for my partner in crime for traveling through this life with me, providing constant support and guidance. I would assuredly not be where I am today without her.

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LIST OF ABBREVIATIONS

NOAA	National Oceanic and Atmosphere Administration
NWS	National Weather Service
NHC	National Hurricane Center
WFO	Weather Forecast Office
CWA	County Warning Area
IWT	Integrated Warning Team
FEMA	Federal Emergency Management Agency
IPPC	Intergovernmental Panel on Climate Change
EM	Emergency manager
ESF	Emergency support function
ENSO	El Nino Southern Oscillation
PNA	Pacific North American pattern
NAO	North Atlantic Oscillation
K-S test	Kolmogorov-Smirnov test
D_S	D statistic (related to K-S test)
GEV	Generalized Extreme Value
MSLP	Mean sea level pressure
SLOSH	Sea, Lake, and Overland Surges from Hurricanes

INTRODUCTION

Storm surge or the meteorologically forced rise in sea level, above the predicted astronomical tide, is a significant hazard to coastal communities worldwide. Storm surge is often associated with tropical and extratropical cyclones, although any long (in space or time) fetch of wind such as with large high pressure systems can produce significant storm surge. Storm surge is considered a hazard at the coast as it often shapes and damages natural and human built environments at the coast. There is evidence that damaging surge events may increase in frequency and intensity through a combination of a growing at-risk coastal population and infrastructure, sea level rise, and a tendency towards more extreme weather events related to climate change (i.e. IPCC 2019). The goal of this dissertation is to help bridge the gap between storm surge users' (i.e. emergency manager) needs and the current state of the science with a focus on Eastern North Carolina. Chapter one titled, "Storm Surge Evolution and Its Relationship to Climate Oscillations at Duck, NC" explores storm surge characteristics as they relate to climate oscillations such as the El Niño Southern Oscillation. Chapter two titled, "Getting More Out of Storm Surge Forecasts: Emergency Support Personnel Needs in North Carolina" uses a social science inspired survey instrument to explore storm surge users' needs. Chapter three titled, "A Synoptic Climatology Tied to Storm Surge Power" aims to improve understanding of atmospheric patterns that produce storm surge events. While each chapter is a standalone study, each builds on each other in some way. The results from chapter one inspired many of the survey questions and related results for chapter two and the overall direction of chapter three. Exploration of different storm survey characteristics at differing lead times (chapters one and three) was likewise supported by the needs of storm surge users' (chapter two).

CHAPTER 1: STORM SURGE EVOLUTION AND ITS RELATIONSHIP TO CLIMATE OSCCILATIONS AT DUCK, NC

1. INTRODUCTION

Over half of the United States' economic activity occurs in the coastal zones (NOAA 2013) in areas of commerce such as tourism, real estate, and trade. Economic opportunity, beach amenities, and an increasing number of people with disposable income further promote economic development along the coast (Landry and Hindsley 2007), which supported a 17% increase in United States population from 1990-2008 along the Atlantic coastline (NOAA 2013). The same coastline is highly susceptible to coastal storm hazards. Flooding is the leading cause of death in the United States (NOAA 2014), with storm surge being the leading cause of death for tropical cyclones (Rappaport 2014). The storm surge hazard threatens growth along the coast through direct damages to homes and businesses, fatalities, and indirect damages which affect the broader economy such as the cost of evacuation or loss of tourism dollars (Jonkman et al. 2008). In fact, recent natural disasters, Hurricane Katrina (2005), Hurricane/Post Tropical Sandy (2012), and the extratropical cyclone dubbed "St. Jude" or "Windstorm Christian" which rocked Northern Europe (2013), have brought the storm surge hazard to the forefront in the news, planning and preparedness at the coast. Sandy alerted a large segment of the U.S. population not accustomed to high magnitude surge and wind impacts. Although tropical cyclones receive much of the attention when it comes to storm surge, massive extratropical cyclone size and slow movement up the coastline promote longer duration surge events, which can last across several tide cycles, and as a result can produce similar damage to that of its tropical counterpart (Dolan and Davis 1994). The focus of this paper is to link tropical and extratropical cyclone induced surge with climate variables for Duck, North Carolina.

Storm surge is defined as the meteorologically forced rise in sea level, above the predicted astronomical tide. Although there is a non-linear, dependent relationship between storm surge and tide (Prandle and Wolf 1978; Valle-Levinson et al. 2013), other storm surge studies have found it acceptable to focus on storm surge alone and approximate the relationship of storm surge and tide as independent variables (e.g. Walton 2000; Huang et al. 2008; Colle et al. 2010; Sweet and Zervas 2011). Coupled atmospheric-oceanic surge models have contributed significantly to short term awareness and prediction of storm surge, allowing emergency managers and the public alike to become informed of and act appropriately when faced with this dangerous hazard. In fact, the National Hurricane Center began issuing official storm surge watch/warning graphics starting with the 2016 Atlantic Hurricane season. The storm surge mapping provides useful information two to four days in advance of an impending surge event. However, emergency managers have voiced the need for accurate surge products in the 60-72 hour time frame or near the fringe of current model capability (Losego et al. 2012; ERG 2013; Hoekstra and Montz 2017b). Additionally, policy and planning measures that attempt to avoid or mitigate storm surge consequences through building codes and setbacks, beach stabilization, insurance rates, and coastal zoning value surge information on seasonal to interannual time scales. What is missing is an understanding of regional and global climate variables on storm surge characteristics from about two to four days in advance of an impending surge event to the interannual time scale.

The purpose of this paper is to enhance our climate knowledge of surge at a location on the East Coast of the U.S. The long-term goal is to contribute towards the development of climate products similar to ones currently in use for classic meteorological hazards such as precipitation and temperature, complementing existing coastal hazard predictions such as waves.

Additionally, an improved understanding of surge climate may assist operational forecasters along the fringe of model capability in the same way that weather forecasters currently blend medium to long range forecasts with climatology to account for reduced forecast reliability at longer lead times. Currently, the forecasting of surge is limited to the extent of numerical surge models (generally two to four days) and forecasters' inferences based upon forecasted tropical or extratropical cyclone characteristics (i.e. cyclone track and strength) beyond that range. Storm surge seasonality and relationships with climate oscillations developed in this study will better inform operational forecasters on the likelihood of surge magnitudes or other characteristics given the background climate conditions such as the El Nino Southern Oscillation (ENSO) phase. The additional climate information will complement numerical model output and provide additional guidance from which forecasters will be able to bias or trend their forecasts towards this climatology several days to a week or more into the forecast period as numerical model output becomes less reliable. As such, this additional climate related surge information may lead to further improvement in the understanding, communication, and preparation for the storm surge hazard.

1.1 BACKGROUND

Tropical cyclones are well known for their extensive storm surge events and associated impacts (e.g. Morrow et. al. 2015), while extratropical cyclones have historically received less attention. Dolan and Davis (1994) used coastal storm surge at Duck, NC in classifying extratropical cyclones. Higher or stronger classes of storms (measured by frequency, significant wave height, duration, and power) were positively correlated with storm surge values ranging from a maximum of 1 to 2.2 meters. Zhang et al. (2000) found a clear seasonal signal along the east coast of the U.S. using nine tide gauges from Mayport, Florida to Portland, Maine with greatest activity occurring from October to April. They also found that tropical cyclones influence the surge record from near Sandy Hook, New Jersey south to Florida through the investigation of storm surge maximum, duration, and integration (incorporates maximum and duration). DeGaetano (2008) produced skillful forecasts of east coast winter storms and surge, noting that extratropical cyclones and related surge are mainly dependent on the El Niño Southern Oscillation (ENSO - measured by the Nino 3.4 sea surface temperature anomaly), and to a lesser extent the Pacific Decadal Oscillation, although regional sea surface temperatures also played a substantial role. European surge studies (e.g. Wakelin et al. 2003; Dangendorf et al. 2012) have found a significant correlation between the North Atlantic Oscillation (NAO) and sea level or storm surge across the North Atlantic coast of Europe. In particular, Wakelin et al. (2003) found a strong positive (negative) correlation of sea level with NAO across northern (southern) Europe. Sweet and Zervas (2011) found a strong positive correlation between ENSO and cool season storm surge at four East Coast cities from Boston, MA to Charleston, SC. These results are in agreement with previous studies that ENSO controls extratropical cyclone frequency, intensity, and tracks along the East Coast of the United States (e.g. Curtis 2006). Thompson et al. (2014) examined 20 U.S. water gauges for positive or negative surge caused by extratropical cyclones. Their study found that there is increasing extratropical cyclone activity in the Gulf of Mexico and Southeast U.S. during the 20th century which the authors link to a tendency of the jet stream to meander farther south in the latter half of the 20th century. The present research targets extratropical cyclones and compares results to tropical cyclones by capitalizing on the location of Duck, NC, which is affected by both types of systems.

This paper examines a 33-year water level dataset (1981-2013) located in Duck, NC. The purpose of this work is to examine and develop relationships between climate variables and surge characteristics to supplement information available in the short term (i.e. surge models). First, we introduce the study area and present the data sets and methodology. Then water level at the hourly time step is analyzed to i) determine the return periods of annual maxima using the Generalized Extreme Value (GEV) theorem and ii) compare the overall distribution divided by different phases of interannual climate oscillations using the Kolmogorov-Smirnov (K-S) test. Finally, surge events are identified and average shape parameters are correlated with climate oscillation indices at the seasonal scale. This is followed by discussion and conclusions, with the ultimate goal of addressing the following research questions: (1) How does storm surge vary monthly, seasonally, and annually at Duck, North Carolina? (2) What climate setup triggers an increase in the frequency, intensity, and other characteristics of storm surge events?

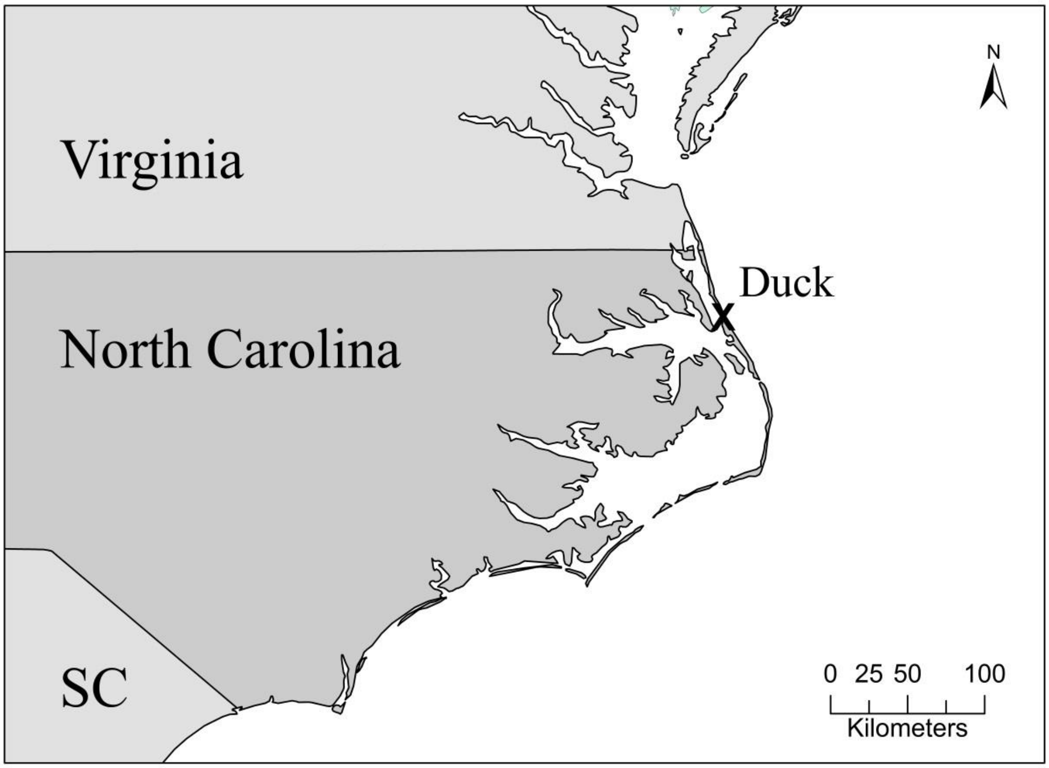


Figure 1. Duck, NC study site.

1.2 STUDY AREA

Duck, North Carolina is located on the northern periphery of the Outer Banks (Figure 1). As a barrier island system that juts out into the Atlantic Ocean between approximately 35 and 36°N, the Outer Banks are particularly vulnerable to sea level rise as well as tropical and extratropical induced storm surge. Local sea level rise is calculated to be about two mm/year above a global average of one mm/yr (Kemp et al. 2009), although other estimated global rates of sea level rise are over three mm/yr (Cazenave and Llovel 2010). The 33-year rate of sea level rise (combined local and global components) for Duck, North Carolina is calculated at 2.6 mm/yr. Common storm surge impacts in the Outer Banks include minor beach erosion and ponding in low-lying areas. During moderate to strong surge events, beach erosion and flooding are more widespread. Coastal roadways can become compromised and minor to severe damage can occur to low lying structures. The annual increase in sea level enhances individual storm surge events and their contribution to erosion and destruction along the coast (e.g. Colle et al. 2010).

Duck, NC has a semidiurnal tide cycle or approximately two high tides per day or every 12 hours and 25 minutes. The tidal range from low to hide tide is about one meter. Wave heights of two to three meters are common at the site, with wave heights in rare cases over six meters (e.g. Dolan and Davis 1994). Tides, waves, and wave run-up on top of storm surge and sea level rise further contribute to damage along the coast (Colle et al. 2010; Dolan and Davis 1994). The Outer Banks extend out onto a wide and shallow continental shelf, which favors large storm surge events (e.g. Rego and Li 2009). Significant storm surge events in the past have completely washed over sections of the barrier island system, and in some cases, such as Hurricane Irene in 2011, the overwash cut through the barrier island system, establishing new inlets.

1.3 DATA AND METHODOLOGY

The distribution of storm surge as defined by water level above mean sea level related to climate oscillations of opposing phases is described using the K-S test. Selected storm surge events are defined by measures of power, skewness, and kurtosis. Pearson's correlation is used to compare these surge characteristics with climate variables, and the GEV theorem is performed to describe frequency and return periods.

1.3.1 Surge Data

Hourly tidal data was collected from the US Army Corps of Engineers Field Research Facility in Duck, North Carolina for the period of January 1981 to December 2013 (http://www.frf.usace.army.mil/). The dataset contains tidal data minus expected tide, leaving water level dependent on meteorological conditions and currents. Sea level rise is removed using a linear regression model. Set downs (negative surge) are also removed (Figure 2). Similar beach characteristics from Oregon Inlet, North Carolina to the south of the study site northward to Corolla, North Carolina enable Duck, North Carolina to represent the surrounding region (approximately a stretch of about 70 kilometers along North Carolina's northern Outer Banks). This approach is consistent with past studies that have made generalizations about surge from one to several locations (e.g. Tancreto 1958, Dolan and Davis 1994, Zhang et al. 2000, Colle et al. 2010, and Sweet and Zervas 2011).

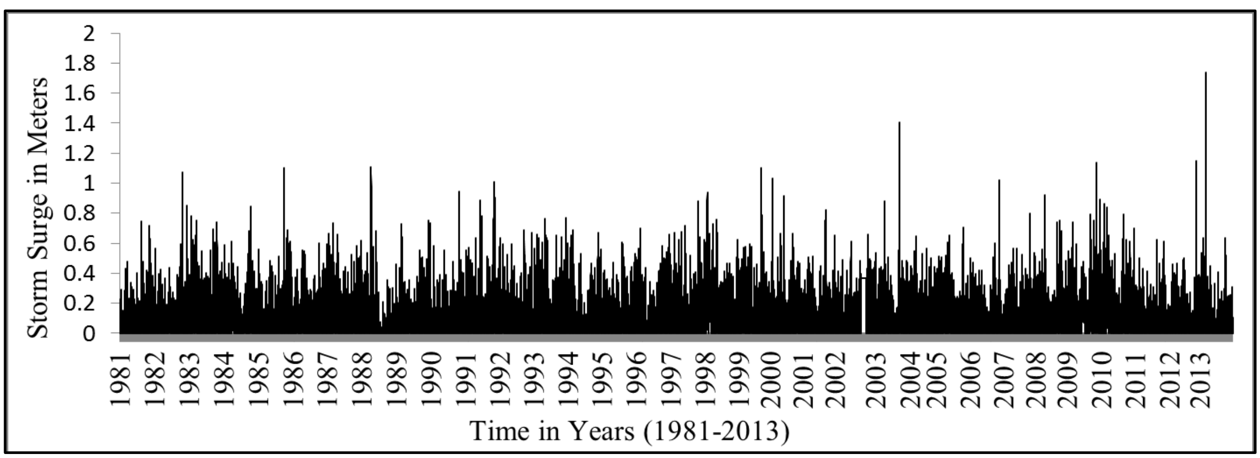


Figure 2. Hourly surge data (m) after the removal of sea level rise and set downs.

1.3.2 Missing Data

Just over one percent of the Duck, NC water level data is missing within 61 individual segments of data with a mean length of 53 hours. Fifty six percent of the missing segments were isolated hours. The longest segment of missing data is 1,895 hours or 79 days occurred starting on November 4th, 2003.

1.3.3 Generalized Extreme Value Theorem

Abnormally strong or extreme storm surge events are often the most catastrophic in terms of damage to life, property and erosion. The National Weather Service (NWS), Emergency Managers and the Federal Emergency Management Agency (FEMA) among other agencies have significant roles in preparing and reacting to powerful but rare storm surge events. To gain an understanding of how sea level rise impacts the return period of annual maximum storm surge events, storm surge extreme return periods is determined without sea level rise (e.g. Huang et al. 2008; Walton 2000; Olbert and Hartnett 2010) according to FEMA's guidelines and specifications for the Atlantic and Gulf coasts (FEMA 2007). The GEV distribution is one method commonly used to develop storm surge return periods (e.g. D'Onofrio et al. 1999; Huang et al. 2008; Olbert and Hartnett 2010) and is recommended for coastal datasets exceeding 30 years (FEMA 2007). The three-parameter GEV model combines three distribution models (Gumbel, Weibull, and Fretchet distributions) into a single model. While the performance of the leading extreme value distributions: GEV, log-logistic, Dagum, and Burr models have been found to be similar (Warner and Tissot 2012), the GEV model has been shown to have only a five to ten percent error for the towns of Wilmington, NC and Sandy Hook, NJ (Huang et al. 2008). Duck, NC falls between these two locations, shares similar environmental conditions, and possesses a long dataset (33 years). It is therefore reasonable to predict similarly reliable results within the same stretch of coastline.

1.3.4 Climate Oscillations

The ENSO is a primary driver for inter-annual climate variability globally. It is defined by anomalous sea surface temperatures and changes in local atmospheric circulations (known as the Walker circulation) in the equatorial Pacific Ocean. The Oceanic Nino Index (ONI) is calculated as the floating three month mean (centered on a given month) of the Nino 3.4 sea surface temperature anomalies (°C). According to NOAA, an ONI value greater than 0.5 °C is an El Niño or positive phase of ENSO, whereas a value less than -0.5 °C is a La Niña or negative phase of ENSO.

The NAO is a leading driver of climate over the North Atlantic (Hurrel and Deser 2009) and has been shown to affect surge from extratropical storms (Wakelin et al. 2003). The NAO is driven by alternating pressure anomalies on the weekly to monthly temporal scale, between the Icelandic Low and the Azores High. The pressure anomalies impact the upstream (to the west) configuration of the jet, which ultimately supports or suppresses the development of extratropical cyclones along the East Coast of the United States (e.g. Hurrel and Deser 2009).

The Pacific North American (PNA) pattern describes the long-wave amplitude of the jet stream across North America. It has an impact upstream over the Pacific Ocean and downstream across the North Atlantic Ocean and in some cases into Europe (Chen and Dool 2003). The positive phase is marked by an increase in amplitude of the climatological position of the jet stream. Predicted values of PNA are constrained by current numerical weather prediction capability, which is approximately one to two weeks.

Data for these three climate variables are collected from the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (CPC) for the same period as the water level data (1981-2013). These indices were standardized to produce a standard score or z-score by subtracting the mean and dividing by the standard deviation. The comparison of opposing phases of each oscillation index is achieved by segmenting the water level dataset into positive (negative) one half standard deviations and above (below) the mean of each oscillation index. For the ONI this is consistent with +/- 0.42˚ C. Increasing the standard deviation threshold to consider only strong ENSO, NAO, and PNA events reduced the sample size below acceptable levels.

1.3.5 The Kolmogorov-Smirnov Test

The K-S test locates the largest vertical difference of coupled cumulative distribution functions (D statistic is the resulting output) of storm surge data sets by month (i.e. binning hourly water level) to determine if opposing phases of ENSO, NAO, and PNA have a statistically significant impact on the distributions of storm surge, similar to what was done for daily precipitation in Munroe et al. (2014). The KS test achieves significance if the D statistic is large when compared to the sample size. The D statistic is described by the equation below, where S(x) represents each cumulative distribution function, N1 and N2 (Munroe et al. 2014).

$$D = \max(-\infty < x < \infty)|SN1(x) - SN2(x)|$$

1.3.6 Storm Selection

A 12 hour moving average smoothing technique was applied to water level data to select storm surge events that exceed 0.3 meters (smoothed data) as a singular maximum value within a 36 hour window. This was needed to avoid multiple maximum values within a single storm. Other higher surge thresholds of 0.4 m and 0.5 m were examined but the results did not change substantially. Also, as will be seen later in the KS tests, the largest differences in the surge distributions based on phases of the climate teleconnections tend to be 0.3 m or less. Next, the 0.2 m threshold was used to define the beginning and end of non-consecutive surge events. Surge events less than 12 hours total or less than five hours on either side of the time of the maximum were excluded from the final dataset. This resulted in 520 total storm surge events (e.g., in Figure 3) within the 33 year period or about 15 events per year.

storm #	max	duration	power	skew1	skew2	kurt
130	0.73	70	15.0094	0.071429	0.047435	0.004152

Table 1. Sample storm surge shape characteristics.

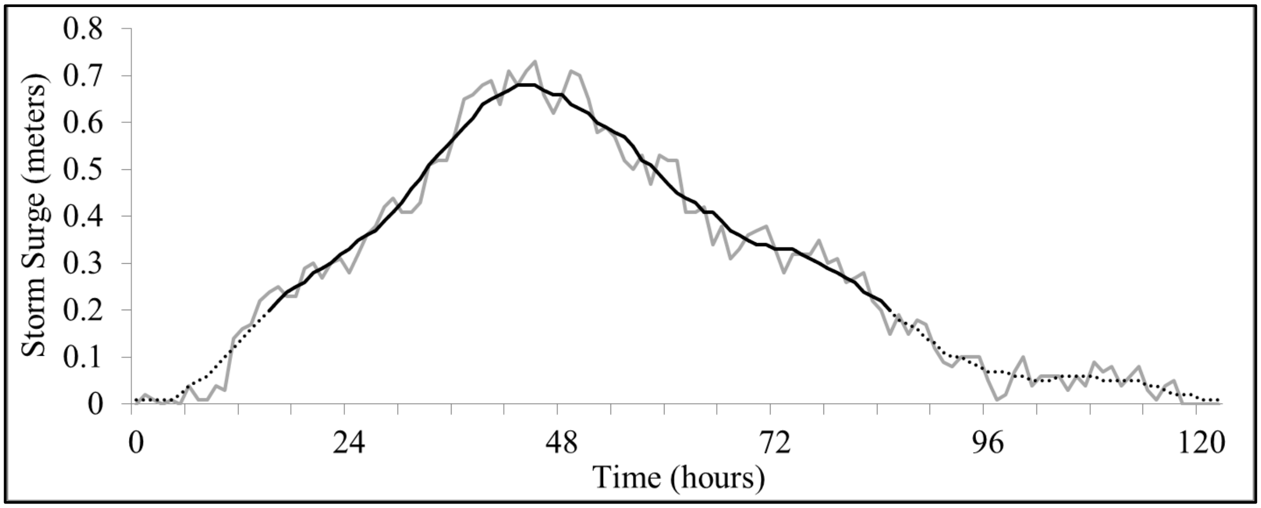


Figure 3. Sample surge event on February 24, 1989. Displayed is the original hourly water level (gray line) and 12-hour moving average (black line). Event spans the solid black line.

1.3.7 Shape Variables

For each selected surge event (Figure 3), shape characteristics were calculated (Figure 3 values are shown in Table 1) to examine how different aspects of surge events vary by time of year and due to changing climatic conditions. Characteristics include duration in hours (70 in this example), power, skewness, and kurtosis, as defined below. Table 2 provides equations for the most complex shape variables. Power is the sum of squared surge values for the duration of the selected surge event. A squared value is used to better represent impacts of storm surge, because erosion, inundation, and damage to infrastructure have been shown to be non-linearly related to the height of surge. Davis and Dolan (1993) also produced a power variable using squared values of wave heights for the Outer Banks of North Carolina and highlight the importance of higher surge carrying the destructive properties of waves further inland. Here, skewness is the measure of the speed of surge onset and decay, and is calculated in two different ways. Skewness 1 is calculated to examine the timing of maximum surge with a positive (negative) value indicating that the maximum occurs before (after) the midpoint in the surge duration (i.e. 0.071 occurs before the midpoint in Figure 3). Skewness 2 measures the mean surge height before and after the time of maximum surge, a positive (negative) value indicating that the mean surge height before (after) the time of maximum surge is higher. Lastly, the kurtosis variable measures the peakness of a particular surge event with a larger value indicating greater peakness or a more rapid change in surge height surrounding the maximum value. Skewness values relate back to how quickly storm surge advances or recedes, which can be valuable for evacuation and response purposes.

Name	Equation
Power	$\sum(x_i^2)$, from i= t_o to t_f
Skew1	0.5-[a/(a+b)]
Skew2	$(\bar{x}(a)-\bar{x}(b))/(a+b)$
Kurtosis	$(x_m-\bar{x})/(a+b)$
	where $a=t_m-t_0$ & $b=t_f-t_m$

Table 2. Equations used to calculate each storm surge shape variable. x = height in meters, x_m = maximum height in meters, t_o = 0 or start time of the surge event, t_f = finish time of the surge event in hours, a = time between t_o and the maximum surge (t_m), b = time between maximum surge (t_m) and t_f.

1.3.8 Tropical Cyclones

Tropical cyclone surge events were distinguished from those formed by extratropical cyclones. Tropical cyclones with a center of low pressure within 1,000 kilometers of Duck, NC were examined as potential surge drivers. The dates of tropical cyclones within this radius were matched up with selected surge events from the manual storm identification. In borderline cases, archived weather maps were examined to ensure storm surge was directly related to a given tropical cyclone. Subtropical and post-tropical cyclones were classified as tropical cyclones given their tropical origin. Of the 520 total storm surge events, 42 were tropical cyclones. Thus, 1.25 tropical cyclones induce storm surge at Duck, NC per year, whereas extratropical cyclones are responsible for nearly 15 surge events per year. Note that anticyclones may have played a large role or been the main driver in select cases, especially for weaker surge events.

1.4 RESULTS

1.4.1 Generalized Extreme Value Theorem

The expected 10 year return period for all cyclones (tropical and extratropical) is 1.1 meters, with a ninety-five percent confidence interval of 0.9 to 1.25 meters (Figure 4). The 100 year return period is 1.5 meters with a ninety-five percent confidence interval ranging from 0.9 to 2.2 meters. This result is supported by the findings of Huang et al. (2008) for nearby Wilmington, NC (1.574 meters). Extratropical cyclones alone exhibited considerably lower maximum values for the same return periods. The 10 year return period is estimated at 0.9 meters with a ninety-five percent confidence interval of 0.7 to 1.05 meters (Figure 4). The 100 year return period is estimated at 1.3 meters with a ninety-five percent confidence interval of 0.75 to 1.9 meters. For comparison, the actual maximum surge events over the 33 year period are 1.40 and 1.14 meters for all cyclones and extratropical cyclones respectively and further support the GEV results.

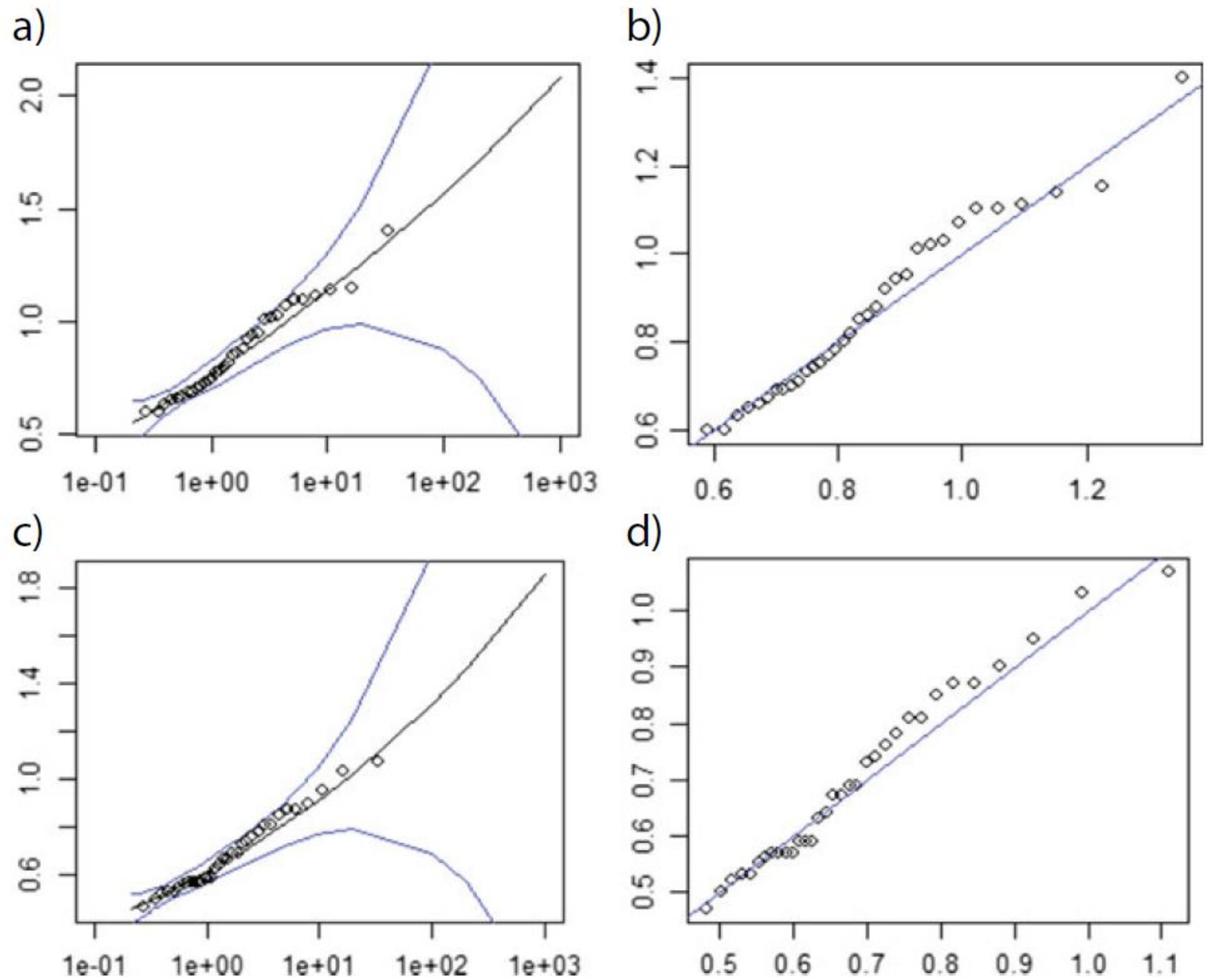


Figure 4. GEV return period plots with confidence interval lines (95th percentile) and Q-Q plots for combined extratropical and tropical cyclones (a, b) and extratropical cyclones only (c, d).

The quantile-quantile (Q-Q) plots (Figure 4b and 4d) indicate that both annual maximum surge datasets approximate a normal distribution as shown by the one to one ratio of the data points or the straight line fit. Shape parameters (Table 3) indicate that the extratropical cyclone location parameter was slightly smaller, indicating a tendency for lower annual values of storm surge. A larger shape parameter indicates a slight positive skew to the annual maximum surge distribution compared to the nearly neutral distribution of data points for tropical and extratropical cyclones. The shift towards a neutral distribution makes sense qualitatively as the inclusion of tropical cyclones leads to a greater number of years with larger storm surge values. Tropical cyclone surge itself was excluded from GEV modeling as it has several years with no surge values, bringing it well below the required 30 year recommended threshold when using the GEV theorem.

	Values		**Error**	
Parameters	All	ETC	All	ETC
Location	0.768	0.613	0.032	0.024
Scale	0.148	0.113	0.025	0.019
Shape	0.069	0.126	0.213	0.200

Table 3. GEV shape parameter values with associated errors.

1.4.2.1 El Niño Southern Oscillation

Significant negative D values (at the one percent level) occur from November to July, indicating that the distribution of water level is different between El Niño and La Niña phases, with El Niño having a greater tendency toward higher surges (Table 4). The frequency of extratropical cyclone induced surge (columns eight and nine in Table 4) indicates that El Niño also favors more frequent extratropical cyclones for seven of the eight months. A similar trend is shown by the number of hours of surge per year (columns six and seven). This result is in agreement with the consensus in the scientific community that El Niño drives an increase in the frequency and intensity of extratropical cyclones across the Southeast U.S. (e.g. Curtis 2006). The extension of the signal into June and especially July is surprising given that extratropical cyclones are generally weaker and further north and El Niño is not typically as strong of a driver during this time of year. That being said, the number of hours of surge per year (Table 4, columns six and seven) remain relatively high through August, exhibiting the persistence of surge during the summer. For the months of August through October there is a three-month reversal of sign in the D statistic indicating La Niña events are marked by more frequent strong surge events. El Niño and La Niña for the month of September are significantly different at the five percent level while the October ENSO signal is significant at the one percent level according to the K-S test. These three months match the peak of tropical cyclone induced surge (Table 4, columns ten and eleven) with the months of August and September exhibiting a greater number of hours of surge per year during La Niña. This peak in tropical cyclone activity falls in line with the peak Atlantic hurricane season (September) in agreement with scientific literature that finds that La Niña is more favorable for the development of tropical cyclones (e.g. Gray 1984).

			YRS		HRS		ETC		TC	
	D	**D_S**	**NINO**	**NINA**	**NINO**	**NINA**	**NINO**	**NINA**	**NINO**	**NINA**
JAN	**-0.083**	0.190	10	15	507	423	2.300	1.467	0.000	0.000
FEB	**-0.174**	0.150	8	13	514	355	2.875	1.077	0.000	0.000
MAR	**-0.179**	0.110	7	12	557	438	2.571	1.167	0.000	0.000
APR	**-0.142**	0.155	6	6	541	452	2.333	1.167	0.000	0.000
MAY	**-0.061**	0.280	8	7	447	520	0.875	1.571	0.000	0.000
JUN	**-0.151**	0.095	8	6	551	450	1.125	0.833	0.125	0.000
JUL	**-0.064**	0.165	7	6	494	459	0.286	0.167	0.143	0.000
AUG	0.033	0.300	8	7	467	514	0.500	1.000	0.250	0.286
SEP	0.037	0.140	11	10	339	360	1.364	0.900	0.182	0.500
OCT	**0.047**	0.170	11	10	325	275	1.545	1.100	0.455	0.300
NOV	**-0.071**	0.355	10	12	346	226	1.800	1.333	0.100	0.083
DEC	**-0.084**	0.135	10	13	325	208	1.700	1.231	0.000	0.000

Table 4. Monthly K-S test results for El Niño versus La Niña distributions. The D column shows the D statistic, where significance is indicated with italics (90^{th} percentile), underline (95^{th} percentile) and bold face (99^{th} percentile). D_S is the surge value in meters accompanying the D statistic. The sample size in years (YRS) and hours per year (HRS) is provided in columns four through seven. Columns eight through eleven indicate the number of extratropical (ETC) and tropical (TC) surge events per El Niño and La Niña years.

The location of the D statistic, labeled D_S in column two of Table 4 indicates approximately what magnitude of water level exhibits the greatest differences between the two ENSO phases. For ENSO, the months of May, August, and November have the largest D_S (surge height in meters accompanying the D statistic) indicating that the greatest change between El Niño and La Niña years occurs at higher magnitudes of surge. The tendency for significant changes at relatively high water levels during these months suggests that El Niño may be responsible for unusually strong or long lasting storm surge events during the months of May and November. The occurrence of the higher values of D_S along the fringe of the extratropical cyclone peak activity suggests that the presence of an El Niño may act to extend the period for extratropical cyclone induced surge beyond what is seen during a La Niña.

			YRS		HRS		ETC		TC	
	D	**D_S**	**PNAO**	**NNAO**	**PNAO**	**NNAO**	**PNAO**	**NNAO**	**PNAO**	**NNAO**
JAN	**0.070**	0.220	16	6	423	478	1.688	1.833	0.000	0.000
FEB	*0.028*	0.130	15	7	357	477	1.867	1.714	0.000	0.000
MAR	**0.042**	0.210	18	6	297	528	1.389	1.833	0.000	0.000
APR	**0.065**	0.095	10	9	333	554	1.000	2.111	0.000	0.000
MAY	**0.060**	0.105	10	13	480	439	1.400	1.154	0.000	0.000
JUN	**0.147**	0.175	7	14	388	356	0.857	1.071	0.000	0.000
JUL	**0.132**	0.095	10	11	368	431	0.200	0.273	0.100	0.000
AUG	**0.031**	0.230	9	9	472	451	0.556	0.556	0.222	0.111
SEP	**0.080**	0.200	8	15	460	233	1.750	0.600	0.125	0.667
OCT	0.020	0.090	4	16	571	209	1.250	1.563	0.250	0.188
NOV	**0.191**	0.145	12	8	227	396	0.667	1.750	0.167	0.250
DEC	**-0.081**	0.210	12	9	190	319	1.167	2.444	0.000	0.000

Table 5. Monthly K-S test results for positive NAO versus negative NAO distributions. The D column shows the D statistic, where significance is indicated with italics (90th percentile), underline (95th percentile) and bold face (99th percentile). D_S is the surge value in meters accompanying the D statistic. The sample size in years (YRS) and hours per year (HRS) are provided in columns four through seven. Columns eight through eleven indicate the number of extratropical (ETC) and tropical (TC) surge events per positive and negative NAO years.

1.4.2.2 North Atlantic Oscillation

A positive D value comparing phases of NAO (Table 5) is present for all months with the exception of December. All months except February and October are significant at the one percent level. However, February is significant at the ten percent level. Positive D values relate to generally more frequent strong surge events during the negative phase of the NAO. An equal or greater average surge per year (Table 5, columns eight and nine) and a greater number of surge hours per year (columns six and seven) are generally found during negative as compared to positive NAO months. These findings were expected as the negative NAO is known to relate to increased storminess along the East Coast of the U.S. during the cool season (e.g. Hurrel and Deser 2009). June and July exhibited large magnitude D values that are difficult to explain from past studies. This finding may be in part explained by the southward retreat and weakening of the Bermuda subtropical high to the east of the study region, often observed during the negative NAO (e.g. Hurrel and Deser 2009) with a tendency for the jet stream to meander further south (e.g. Hall et al. 2015), which provides a more favorable environment for extratropical cyclones.

D_S is large during the winter months (December through March) and the peak of the Atlantic Hurricane season (August and September). This suggests a negative NAO leads to relatively more frequent, stronger or longer lasting surge events during these months.

			YRS		HRS		ETC		TC	
	D	**D_S**	**PPNA**	**NPNA**	**PPNA**	**NPNA**	**PPNA**	**NPNA**	**PPNA**	**NPNA**
JAN	**-0.122**	0.125	16	4	478	433	1.938	1.500	0.000	0.000
FEB	**-0.099**	0.145	11	7	475	300	3.455	1.429	0.000	0.000
MAR	**-0.103**	0.205	15	8	443	532	2.200	1.250	0.000	0.000
APR	**-0.336**	0.155	11	11	517	306	2.909	0.273	0.000	0.000
MAY	**-0.186**	0.140	6	12	517	409	1.667	1.000	0.167	0.000
JUN	**-0.048**	0.130	6	13	517	327	1.167	0.385	0.000	0.000
JUL	**-0.168**	0.125	13	4	431	486	0.154	0.250	0.000	0.000
AUG	**0.119**	0.110	11	11	475	306	0.727	0.364	0.273	0.182
SEP	**-0.097**	0.085	10	11	516	282	1.700	0.455	0.500	0.455
OCT	0.041	0.200	7	12	471	175	2.143	1.417	0.286	0.500
NOV	**-0.089**	0.175	11	15	282	130	1.364	0.800	0.182	0.067
DEC	**-0.114**	0.165	15	8	207	217	1.800	1.000	0.000	0.000

Table 6. Monthly K-S test results for positive PNA versus negative PNA distributions. The D column shows the D statistic, where significance is indicated with italics (90th percentile), underline (95th percentile) and bold face (99th percentile). D_S is the surge value in meters accompanying the D statistic. The sample size in years (YRS) and hours per year (HRS) are provided in columns four through seven. Columns eight through eleven indicate the number of extratropical (ETC) and tropical (TC) surge events per positive and negative PNA years.

1.4.2.3 Pacific North American Pattern

The PNA exhibits a negative D value from November through July as well as September (Table 6). This relates to more frequent strong surge events during the positive phase of the PNA pattern or increased troughiness in the eastern portion of the U.S., which also relates back to generally increased storminess in this area from the fall to the spring. This is supported by a generally higher frequency of extratropical induced surge per PNA year (Table 6, columns eight and nine) and a greater number of hours of surge per PNA year (columns six and seven) during the positive phase of the PNA. From July to November there are alternating signs for the D value. However, August is the only significant month (at the one percent level) with a positive D value. Tropical cyclones often form in calm, low shear environments typical of high pressure zones. This type of environment is most common under ridge conditions or the negative phase of the PNA which may explain the positive August and October D values. However, this reasoning likely should also apply to September, the height of the Atlantic Hurricane season, which it does not. Furthermore, these months exhibit similar sample sizes (Table 6, columns four through seven).

The largest D_S values occur in March and from October through December. This suggests that a positive (negative) PNA leads to relatively stronger or longer lasting surge events during the months of March, November, and December (October).

1.4.3 Surge Event Analysis

1.4.3.1 Annual Cycle and Trends

Duck, NC exhibits bimodal peaks in both storm frequency and maximum. Firstly, the examination of storm surge frequency (Figure 5) shows these relative peaks in February and October. Extratropical cyclones induced surge peaks in February at 64 cyclones or about two per year. These numbers are lower than an extratropical storm climatology developed in relation to North Carolina (Nieto-Ferriera et al. 2013), which indicates that there may be a particular synoptic setup that would contribute to storms producing surge events as defined here (explored in Chapter 3). The secondary relative peak in October occurs due to the combination of extratropical cyclone (44) and tropical cyclone (10) induced surge. The peak in tropical cyclone surges occurs during the month of September with 17 total cyclones or about one every other year. This peak falls in line with the peak in storms during the Atlantic Basin Hurricane Season. A minimum occurs during the summer with July having merely eight storms out of the 33 years. Salmun et al. (2009) found similar patterns in monthly frequency for coastal storms (tropical and extratropical cyclones) in the New York Metropolitan area, despite the disparity in geographic location. Likewise, Zhang et al. (2000) found a similar trend in nearby Hampton Roads, Virginia.

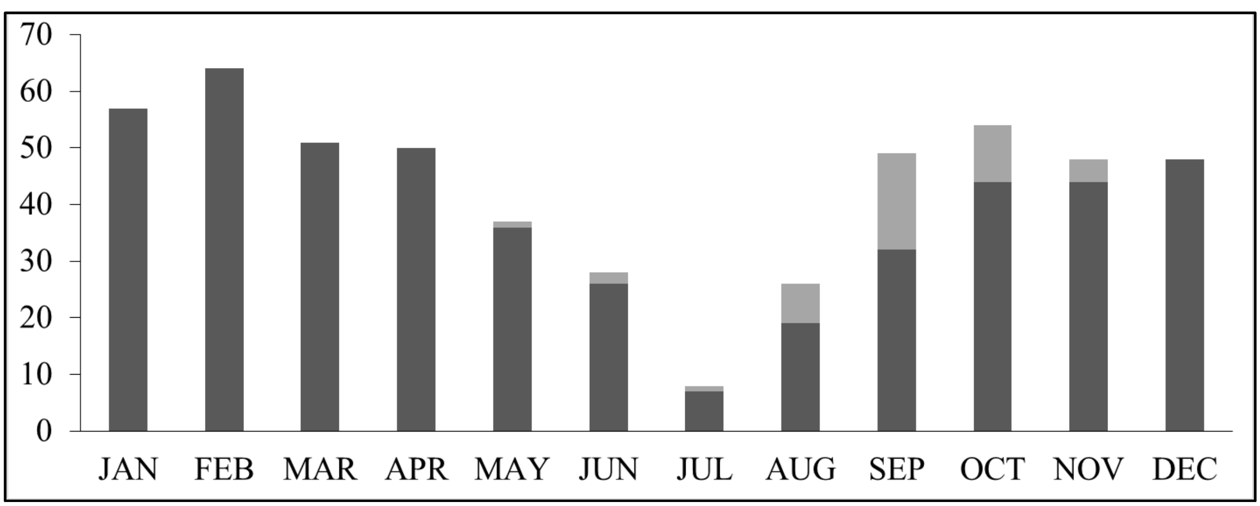


Figure 5. Total frequency of storm surge events by month for extratropical cyclones (dark gray) and tropical cyclones (light gray).

The relationship between surge maximum and duration (Figure 6) varies considerably between seasons for extratropical cyclones and by cyclone type (tropical versus extratropical).

The strongest relationship between surge maximum height and duration occurs for extratropical cyclones, with a clear trend towards the warmer months. Summer possesses the strongest positive slope and highest R^2 value, whereas winter has the smallest slope for extratropical cyclones (Figure 6) with a correlation of 0.36. Tropical cyclones exhibit the weakest relationship between surge maximum and duration with a correlation of 0.23. This is likely due to tropical cyclones' smaller size in comparison to extratropical cyclones and the inclusion of anticyclones, which favor shorter duration surge events.

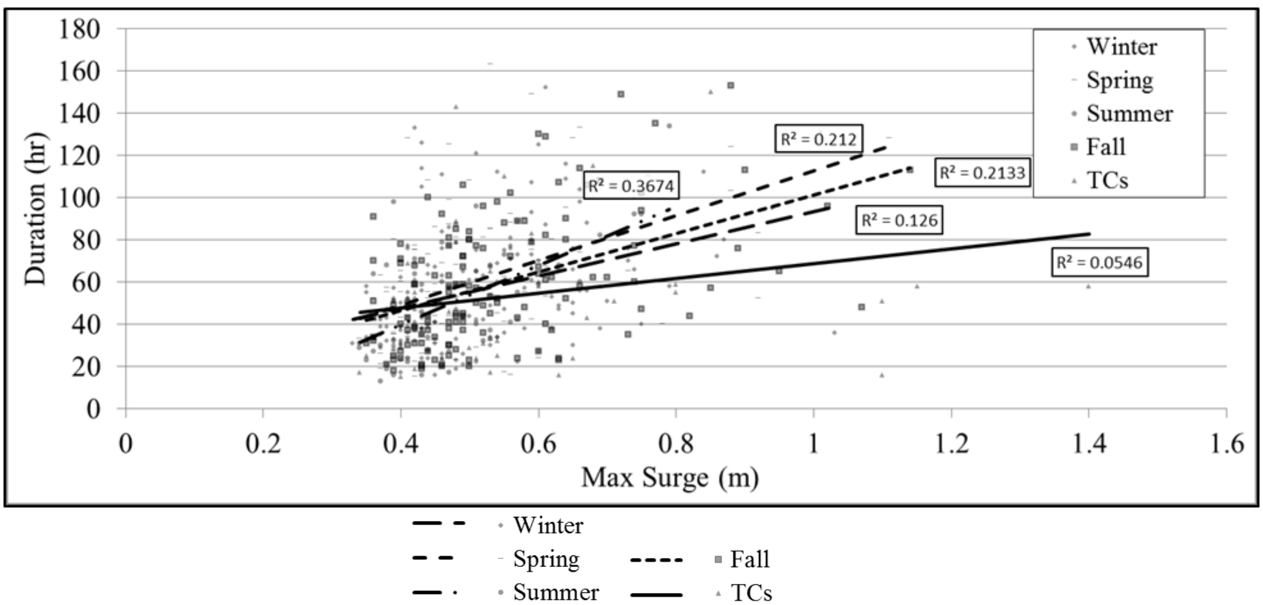


Figure 6. Scatterplot comparing surge maximum and duration for extratropical cyclone surge events in winter, spring, summer, and fall and all tropical cyclone surge events (see legend). Best fit lines and R^2 values are also plotted.

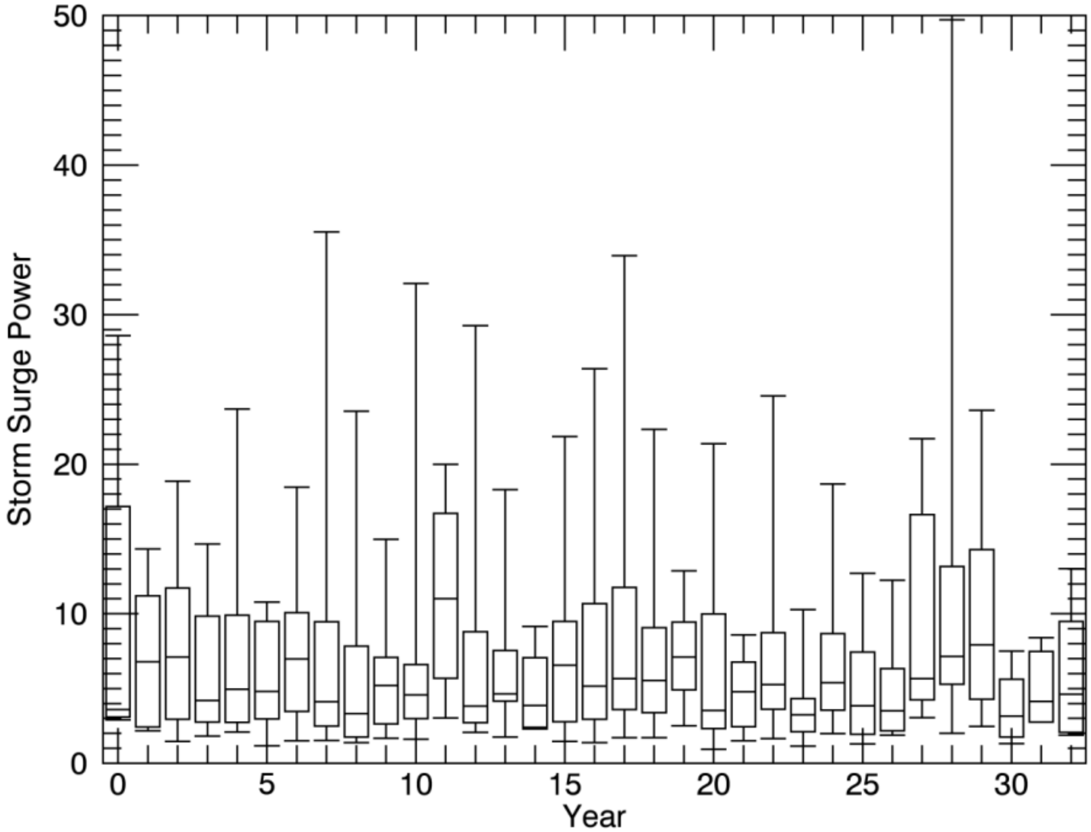
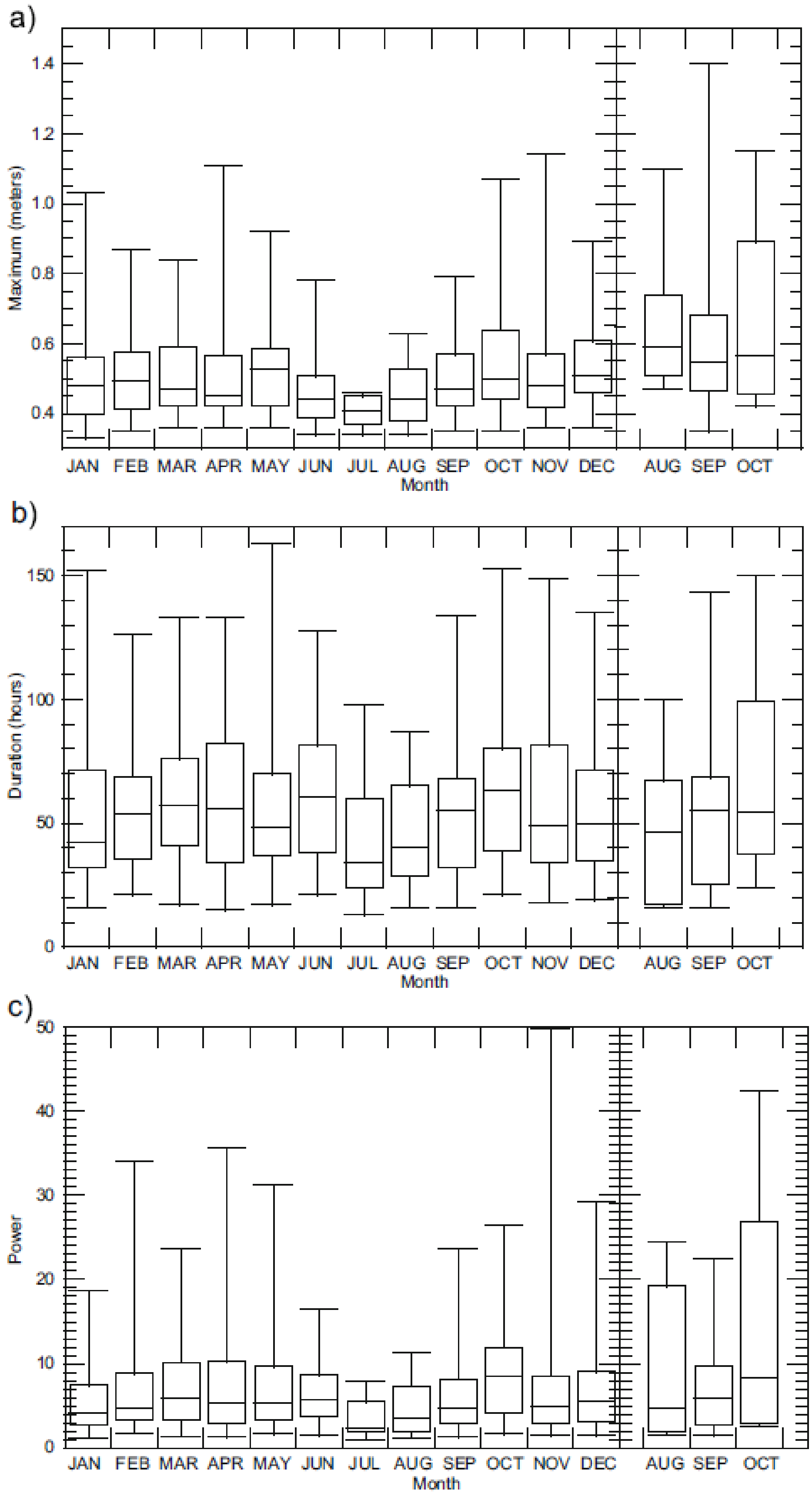


Figure 7. Boxplots of extratropical cyclone power (meters squared multiplied by hour) by year (1981(year 0)-2013(year 32)).

Extratropical cyclone power by year, or the combined effect of maximum and duration (Figure 7) show considerable year to year variability with the years 1981, 1992, 2008, 2009, and 2010 standing out in terms of median values and spread. Zhang et al. (2000) found a similar annual pattern for nearby Hampton Roads, VA when examining storm surge event integrated intensity (the integral or area under the curve of surge height) defined as being two standard deviations above normal. Boxplots at the monthly scale for extratropical cyclone surge maximum, duration and power (Figure 8) all show a similar bimodal distribution as frequency (Figure 6) with peaks in the middle of spring and early fall and with an increase in spread of values. Surprisingly, the highest maximum surge median value occurs in May, which is near the end of the peak season for extratropical cyclone activity and before the Atlantic Hurricane Season begins. October extratropical cyclone median values for the maximum surge and the duration of surge events are both high and combine to produce the highest power value compared to all other months. In fact, the median power value of October exceeds several other months' 3rd quantile values. Monthly power statistics closely correspond to Zhang et al.'s (2000) integrated intensity (described earlier) results for Hampton Roads, Virginia and to a lesser extent, Wilmington, North Carolina. They also describe the decreasing importance of tropical cyclones at higher latitudes and capture the October maximum as related to the intersection between tropical and extratropical activity (increased frequency and strength of cyclones). The boxplot for skewness 1 (not shown due to less significant results) peaks in the months of January, March, and September, with generally neutral to positively skewed surge shapes throughout the year (positive value means surge events reach a maximum within the first half of their lifetimes). Skewness 2 (not shown due to less significant results) is generally positive throughout the year and a peak in August, and the greatest variation is seen in October. The monthly boxplot for kurtosis (not shown due to less significant results) peaks in December and displays greater variability in values during the summer and winter months. These results indicate that surge events tend to rise faster than they fall (skewness 1 and 2) and have a sharp change in water level surrounding the maximum (kurtosis).



a)
1.4
1.2
1.0
0.8
0.6
0.4
Maximum (meters)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
AUG SEP OCT
Month
b)
150
100
50
0
Duration (hours)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
AUG SEP OCT
Month
c)
50
40
30
20
10
0
Power
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
AUG SEP OCT
Month

Figure 8. Boxplots of monthly surge a) maximum, b) duration, and c) power for extratropical cyclones (left) and tropical cyclones during August, September, and October (right).

Tropical cyclones exhibit similar values, during the peak of the hurricane season or months with at least five cyclones: August, September, and October (Figure 8). Both types of cyclones show an increase in the duration of storm surge events during the season (Figure 8 & Table 7). The combined effects of increasing maximum and duration value for extratropical cyclones lead to a more substantial increase in power for extratropical cyclones than tropical cyclones from August to October. In fact, extratropical cyclones have a similar median power value to tropical cyclones in October despite smaller maximum values. During the same three months, there was a strong decrease in tropical cyclone kurtosis (Table 7) or peakness while values for extratropical cyclones remained steady. Values of skewness 1 reach a maximum (minimum) for extratropical (tropical) cyclones in September, while skewness 2 shows no clear trend for either cyclone type (Table 7). The trend towards lower kurtosis for tropical cyclones is likely due to weak or longer lasting (larger or slower) storms heading into October.

	Max		Duration		Power		Skew 1[1]		Skew 2[2]		Kurtosis[2]	
Month	ETC	TC	ETC	TC	ETC	TC	ETC	TC	ETC	TC	ETC	TC
August	0.44	0.59	40	46	2.51	4.65	-0.26	1.25	0.30	0.48	0.33	0.80
September	0.47	0.55	55	55	4.81	6.03	1.41	-0.20	0.35	0.25	0.33	0.50
October	0.50	0.57	63	55	8.45	8.24	0.48	0.58	0.27	0.41	0.30	0.41

Table 7. Comparisons between extratropical and tropical cyclone median surge shape characteristics. [1] =x*10; [2] =x*10^2

1.4.3.2 Seasonal Correlation with Climate Oscillations

The surge parameters: maximum, duration, skewness, and kurtosis were averaged (power was summed up) by month to compare with the monthly indices. The climate oscillation indices have the greatest correlation with surge duration and power. An El Niño (+ENSO), negative phase of the NAO, and positive phase of the PNA pattern all support longer duration, and hence more powerful surge events in the winter and spring (Table 8). However, the PNA's correlation

a) Maximum

	Winter	Spring	Summer	Fall	TC
PNA	-0.010	-0.002	-0.078	*-0.338*	0.035
NAO	-0.054	-0.104	-0.030	-0.145	-0.263
ENSO	0.120	-0.094	*-0.329*	**0.513**	-0.130

b) Duration

	Winter	Spring	Summer	Fall	TC
PNA	<u>0.372</u>	0.154	0.137	-0.128	-0.191
NAO	-0.238	-0.093	-0.023	-0.204	-0.137
ENSO	0.240	0.105	-0.029	0.110	0.097

c) Power

	Winter	Spring	Summer	Fall	TC
PNA	**0.449**	<u>0.345</u>	0.182	0.024	-0.164
NAO	*-0.288*	-0.256	-0.100	*-0.324*	0.114
ENSO	**0.586**	-0.012	-0.030	<u>0.353</u>	-0.075

d) Skewness 1

	Winter	Spring	Summer	Fall	TC
PNA	0.022	-0.086	-0.113	*-0.323*	*0.342*
NAO	<u>-0.347</u>	0.228	<u>0.364</u>	0.081	0.084
ENSO	-0.046	0.129	0.230	0.173	-0.287

e) Skewness 2

	Winter	Spring	Summer	Fall	TC
PNA	-0.187	<u>-0.367</u>	0.067	-0.142	-0.092
NAO	0.113	0.084	-0.079	0.030	-0.190
ENSO	-0.219	0.139	-0.056	0.016	0.105

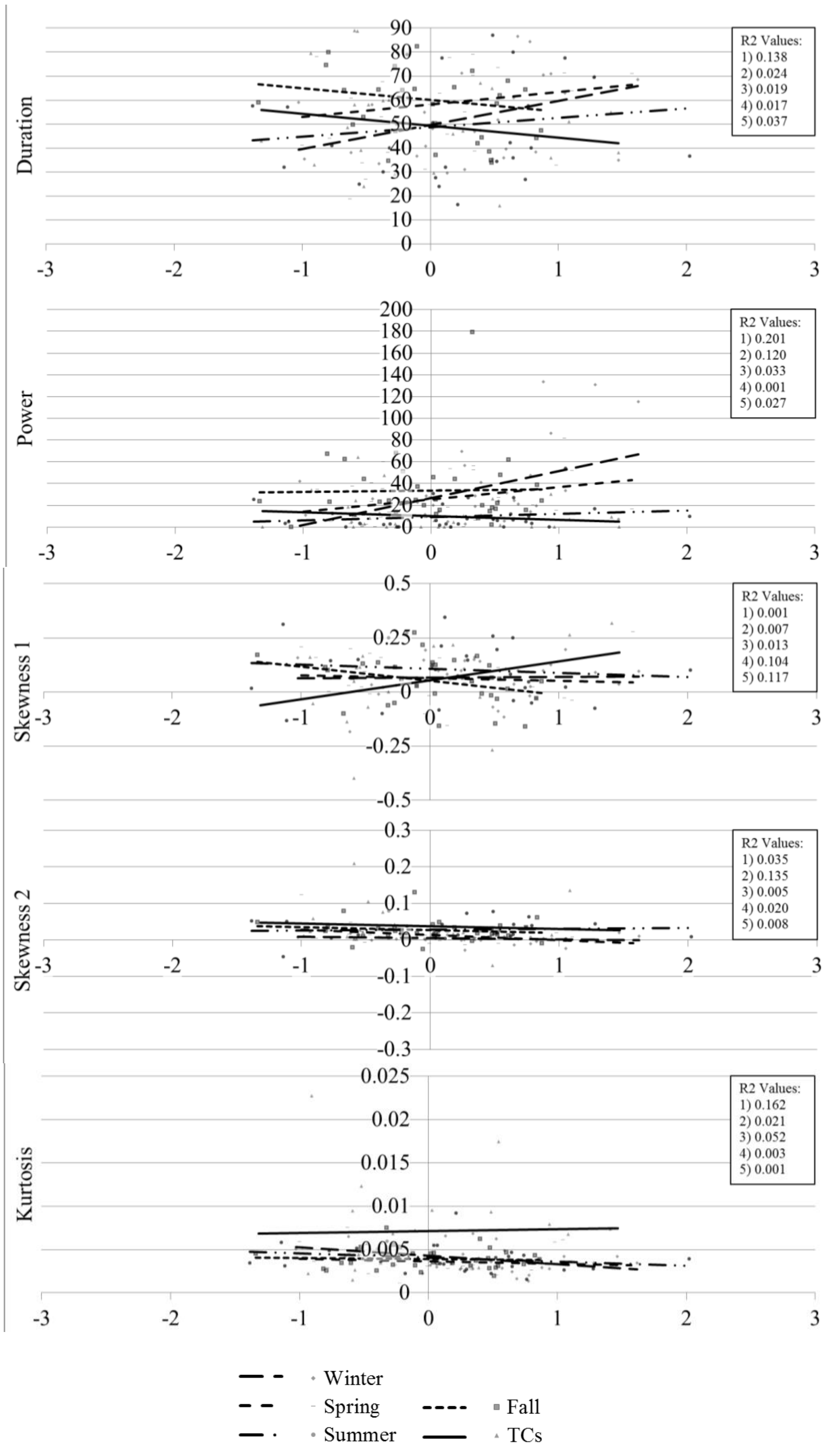
f) Kurtosis

	Winter	Spring	Summer	Fall	TC
PNA	<u>-0.402</u>	-0.146	-0.228	-0.051	0.026
NAO	0.231	0.096	-0.079	0.024	0.002
ENSO	-0.251	-0.145	-0.180	0.193	-0.117

Table 8. Correlation of a) maximum, b) duration, c) power, d) skewness1, e) skewness2, and f) kurtosis by season for extratropical cyclones and all tropical cyclones for the three climate oscillations. Significance is indicated with italics (90th percentile), underline (95th percentile) and bold face (99th percentile).

is likely, at least in part, due to the increased likelihood of a positive PNA during El Niño as shown by the strong positive correlation (0.48) between the two climate oscillations. There is also increasing evidence that ENSO also has a connection to NAO (e.g. Bell et al. 2009). The longer surge events could be caused by generally stronger cyclones, slower moving cyclones, and/or a greater involvement of large and slow moving anticyclones (high pressure systems). It seems likely that cyclone speed plays a large part, as Bernhardt and DeGaetano (2012) found that an El Niño and the negative NAO together lead to a considerable slowdown of extratropical cyclones.

PNA is negatively correlated with tropical cyclone surge power, while the NAO is positively correlated with tropical cyclone surge power (Table 8). Both oscillations are positively correlated with skewness 1 and negatively correlated with skewness 2 (Table 8). However, none of the climate oscillation correlations are statistically significant at the 5% level (Table 8). Nevertheless, the values suggest that tropical cyclones produce more powerful surge events during increased ridging across the Eastern U.S., associated with the negative phase of the PNA and the positive phase of the NAO. Under these same conditions, there is a tendency for an abnormally rapid increase in surge height (skewness 1) and for surge height to slowly fall after the maximum surge (skewness 2). Above average ridging in the Eastern U.S. is typically associated with low shear environments and generally weak steering currents that promote tropical cyclone genesis and slow movement (e.g. Gray 1984; Landsea et al. 1998). Therefore it would follow that relatively stronger and slower moving storms, all else being equal, would produce larger power surge events, such as is seen at Duck, NC in this case. The evolution of the surge itself as described by the two skewness measures is thus likely, at least in part, caused by the tendency for stronger, larger, and/or slower moving tropical cyclones.



Duration
R2 Values:
1) 0.138
2) 0.024
3) 0.019
4) 0.017
5) 0.037
Power
R2 Values:
1) 0.201
2) 0.120
3) 0.033
4) 0.001
5) 0.027
Skewness 1
R2 Values:
1) 0.001
2) 0.007
3) 0.013
4) 0.104
5) 0.117
Skewness 2
R2 Values:
1) 0.035
2) 0.135
3) 0.005
4) 0.020
5) 0.008
Kurtosis
R2 Values:
1) 0.162
2) 0.021
3) 0.052
4) 0.003
5) 0.001
Winter
Spring
Summer
Fall
TCs

Figure 9. Pacific North American pattern indices (x-axis) versus surge variables (y-axis) in winter, spring, summer, and fall and all tropical cyclone surge events (see legend). a) duration, b) power, c) skewness1, d) skewness2, e) kurtosis. Best fit lines and R^2 values are also plotted.

Figures 9-11 illustrate the general trends and variability in the relationships between storm surge evolution and climate oscillations values. Only surge evolution measures with two or more values significant at the ten percent level (Table 8) are included in Figures 9-11. The PNA pattern index (Figure 9) is positively correlated with storm surge duration during the winter (0.372, Table 8) and to a lesser extent the spring and summer. A negative, but weak relationship between surge duration and the fall as well as for tropical cyclones is found. PNA is positively correlated to accumulated storm surge power during the winter (0.449) and spring (0.345), and negatively correlated to skewness 1, with fall having the largest negative slope or correlation of -0.323. Skewness 2 for extratropical cyclones shows little correlation to the PNA index with the exception of spring (-0.367). For all extratropical cyclone seasons, kurtosis has a slight negative relationship to the PNA index with winter having the largest negative correlation (-0.402).

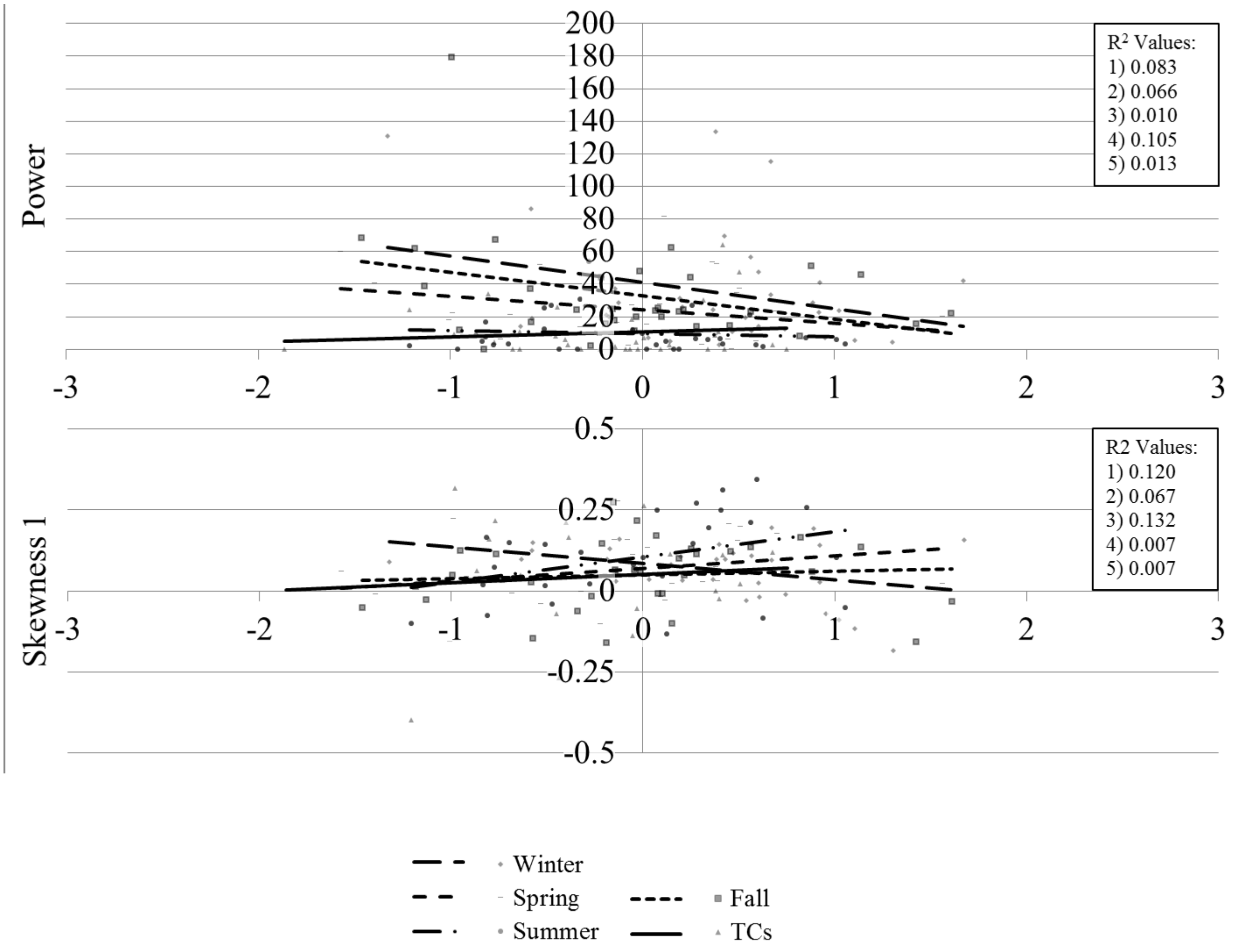


Figure 10. North Atlantic Oscillation pattern indices (x-axis) versus surge variables (y-axis) in winter, spring, summer, and fall and all tropical cyclone surge events (see legend). a) power and b) skewness1. Best fit lines and R^2 values are also plotted.

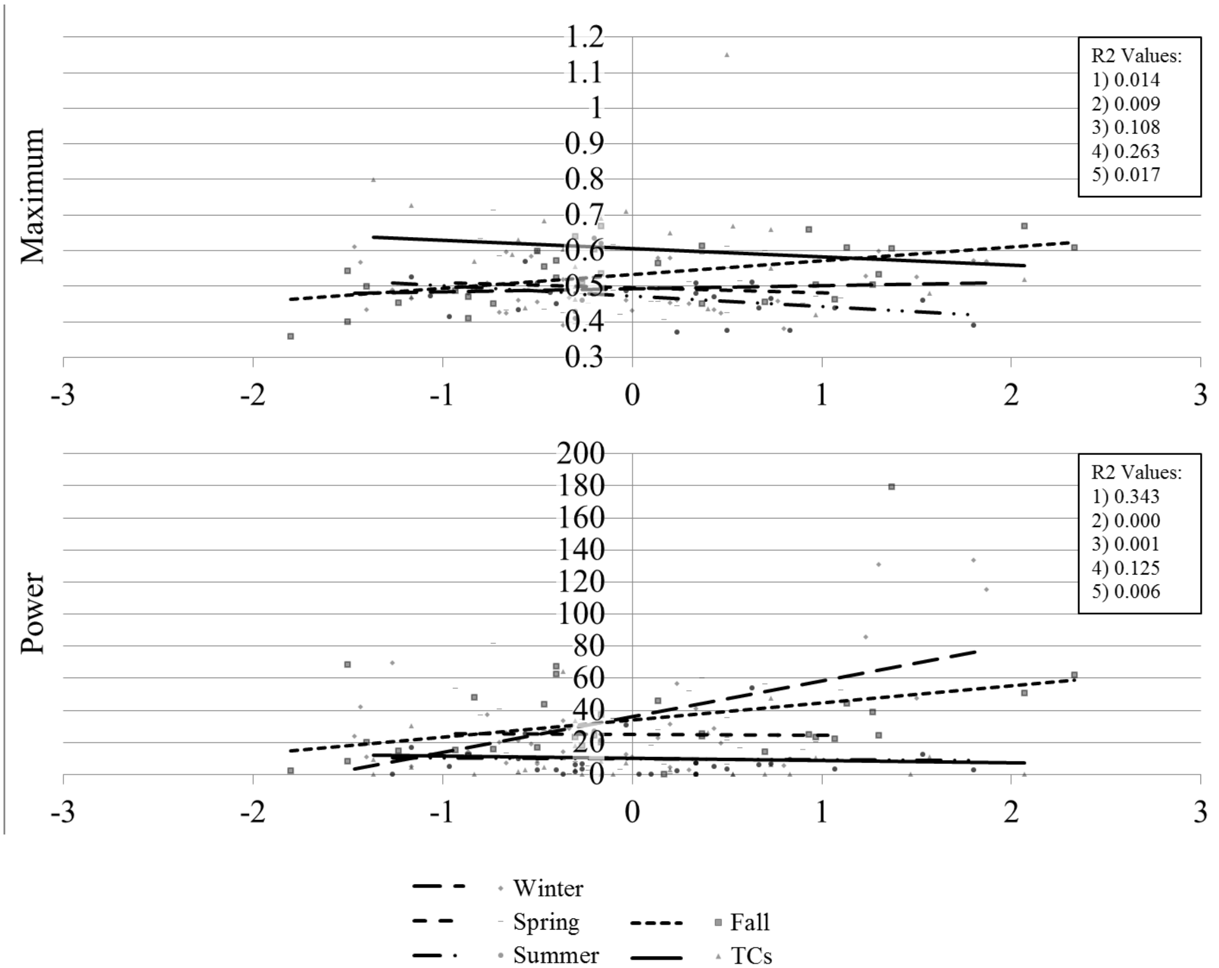


Figure 11. El Niño Southern Oscillation pattern indices (x-axis) versus surge variables (y-axis) in winter, spring, summer, and fall and all tropical cyclone surge events (see legend). a) maximum and b) power. Best fit lines and R^2 values are also plotted.

The North Atlantic Oscillation index (Figure 10) is negatively correlated with storm surge power for extratropical cyclone fall (-0.324, Table 8), winter (-0.288), and spring (-0.256) seasons, while the summer shows only small R^2 values. Skewness 1 shows a strongly positive correlation for the summer season (0.364) and slightly positive ones for the spring and fall. Conversely, the winter season of skewness 1 is strongly negatively correlated with a value of -0.347, significant at the 5% level. The El Niño Southern Oscillation index (Figure 11) exhibits a strong positive correlation to storm surge maximum and power for the fall (0.513 and 0.353

respectively, Table 8) with insignificant correlation during other seasons of the year. Similar to the PNA, ENSO is significantly correlated to surge power during the winter (0.586).

1.4.4 K-S Test and Correlations Test Comparison

The strong agreement between the K-S and correlation tests (Table 9) is a testament to the reliability of the results. This is somewhat surprising considering (1) the K-S and correlation tests use a different methodology to calculate statistical significance and (2) the format and temporal scale of the input data are different. The K-S Test incorporated all hourly surge height data (tropical and extratropical cyclones not distinguished) with each hourly surge height value treated as an independent data point, examined at the monthly scale. On the other hand, the correlation test was calculated with the power variable (incorporates surge maximum and duration) as input for the selected extratropical cyclones induced surge events (478) at the seasonal scale. Additionally, the correlation test separates tropical and extratropical cyclones unlike the K-S Test. Overall the K-S Test found a greater number of statistically significant months (Table 9) at all levels of significance (1, 5, and 10 percent). This is likely due to the substantially larger sample size of the K-S Test (Tables 4-6). There were opposing signals between the K-S and correlation tests in only eight out of a possible 36 months, five of which occurred during El Niño (Table 9). Months with opposing signals may be largely explained by the overlap of the monthly (K-S test) versus seasonal (correlations test) time scales.

	ENSO		NAO		PNA	
	KS	**CORREL**	**KS**	**CORREL**	**KS**	**CORREL**
JAN	+		-		+	
FEB	+	+	-	-	+	+
MAR	+		-		+	
APR	+		-		+	
MAY	+	-	-	-	+	+
JUN	+		-		+	
JUL	+		-		+	
AUG	-	-	-	-	-	+
SEP	-		-		+	
OCT	-		-		-	
NOV	+	+	-	-	+	+
DEC	+		+		+	

Table 9. A comparison of the KS test and correlation results relating storm surge to climate oscillation indices. A plus (minus) sign indicates a positive (negative) relationship. Statistical significance is shown by font: bold (1 percent), regular (5 percent), light gray fill (10 percent), dark gray fill (not significant).

1.5 SUMMARY AND CONCLUSIONS

Storm surge frequency takes on a bimodal distribution with peaks in the months of February and October in Duck, NC. Extratropical cyclones are substantially more common, accounting for over 90 percent of the surge events from 1981 to 2013. However, tropical cyclones contribute some of the largest maximum storm surge values. Over 80 percent of tropical cyclones occur during the months of August through October and account for over one quarter of the events seen during the tri-month period. The GEV theorem provided a 100 year return interval for surge of 1.5 meters for tropical and extratropical cyclones and a 1.3 meter surge for extratropical cyclones only.

Storm surge characteristic results indicate that storm surge frequency, duration, intensity, and power in particular are significantly impacted by ENSO, PNA, and NAO in order of greatest to least importance. From November to July the positive phases of ENSO (El Niño) and PNA along with a negative NAO related to an increase in storm surge frequency, intensity, duration and power. During the same months, El Niño provides an increased flux of moisture and heat to the mid-latitudes through a stronger subtropical jet stream, which helps to energize extratropical cyclones in the region (e.g. Ying and Ngar-Cheung 2012). The positive phase of the PNA relates to an abnormally strong or deep trough which favors extratropical cyclone development along the Southeast U.S. (e.g. Seierstad et al. 2007). The negative phase of the NAO increases the likelihood for a stronger trough upstream (to the west) across eastern portions of North America, which similar to the PNA, favors extratropical cyclone development. This set up further supports a south to north orientation of extratropical cyclone tracks, allowing for them to track nearly parallel to the coast, extending the distance and time of a given extratropical cyclone in close proximity of land and therefore increasing the probability of extratropical cyclone induced surge. For August through October, the negative phases of PNA, ENSO (La Niña), and NAO generally favor increases in extratropical storm surge frequency, intensity, duration and power.

Now focusing on tropical cyclones, the negative phases of ENSO (La Niña), PNA, and positive phase NAO correlated to increased storm surge power. These conditions (independent of each other) support a ridge of high pressure across the Eastern U.S., which during the summer months favors the expansion and strengthening of the Bermuda High (e.g. Larson et al. 2005). This large scale set up favors a low shear environment, which is conducive for tropical cyclone development and intensification (e.g. Gray 1984; Landsea et al. 1998). Depending on the

Bermuda High's exact position and strength, it may also help to direct tropical cyclones towards the Southeast U.S. (e.g. Liu and Fearn 2000).

Our results support the findings from Bernhardt and DeGaetano (2012), and indicate that changes in extratropical cyclone power are likely tied to duration of surge events, as opposed to maximum values. This finding is significant as increased duration requires one or more of the following to occur: (a) slower moving cyclones, (b) larger cyclones, and/or (c) large, slow anticyclones (high pressure systems). This not only leads to localized increases in surge power at Duck, NC, but any one of these scenarios would also result in increased impacts from storm surge across large sections of the U.S. East Coast. Additionally, increased surge duration increases the likelihood of a surge event peaking near a high tide, or during multiple high tides, further exacerbating the impacts, as seen with Hurricane/Post Tropical Sandy (2012). Increased duration may negatively impact the natural and built environments as a result of longer exposure to current and wave energy as well as the corrosive properties of salt water and therefore requires further investigation. A follow up research project will locate and describe cyclone characteristics (i.e. intensity, size, track) as they relate to storm surge at Duck, North Carolina in an effort to better understand what aspects of cyclones are important to the climatology of surge.

In summary, this study has produced a detailed surge climatology for Duck, North Carolina, which explores trends in storm surge from monthly to annual time scales, including the impacts from PNA, NAO, and ENSO. Monthly to seasonal trends correspond closely to past research in nearby regions along the East Coast of the U.S. (e.g. Dolan and Davis, 1994; Zhang et al. 2000; DeGaetano 2008; Colle et al. 2010; Sweet and Zervas 2011; Thompson et al. 2014). Extratropical cyclone surge characteristics were significantly influenced by all three climate oscillations primarily from the fall to the spring. Tropical cyclone surge characteristics were impacted primarily by the PNA pattern, with the largest impact on skewness. During the positive PNA pattern, surge takes less time to wax than to wane. One of the major findings of this paper is that duration, not maximum, seems to be the main driver in variation of surge power. Longer surge duration increases the likelihood of extensive erosion and inland inundation, among other undesirable effects of the surge hazard.

It is hoped that this climatological study of surge will assist the NWS in its mission to protect the public from physical harm and damage to property, contributing to the Weather Ready Nation initiative in improving community resiliency to climate change. Improved understanding of storm surge may also assist coastal managers, policy makers, and planners in daily to seasonal forecasting and preparedness for surge related storm impacts along the U.S. East Coast.

CHAPTER 2: GETTING MORE OUT OF STORM SURGE FORECASTS: EMERGENCY SUPPORT PERSONNEL NEEDS IN NORTH CAROLINA

2. INTRODUCTION

Storm surge has been identified as the leading cause of death from tropical cyclones (Rappaport 2014), but is relatively poorly understood compared to its counterparts (i.e. wind) in tropical and extratropical cyclones. Increased emphasis on the storm surge hazard continues within the research community and the federal government, particularly the National Hurricane Center (NHC) and the National Weather Service (NWS) as evidenced by the ongoing research and development of storm surge products and services (e.g. Morrow et al. 2015, NOAA 2017). A significant portion of this push to better understand storm surge hazards has been focused on how the public and state and local government officials, including emergency managers, currently use storm surge information and how the NHC and NWS can better cater to these user groups' needs (Losego et al. 2012; Morrow et al. 2015). Some of this research was performed to assist in implementing storm surge watch and warning products that became operational for the 2017 Atlantic Hurricane Season (NOAA 2017). These studies provided valuable feedback about how surge information is currently used and how changes in wording and graphics of the experimental surge products are likely to improve user response to this hazard. One of the major findings of this work is that surge information is poorly understood, especially for members of the public (Lazo and Morrow 2013; Meyer et al. 2014; Morrow et al. 2015; Carr et al. 2016).

Different audiences have varying needs, interpretations and uses of hazard-related information, and their decisions depend on how they understand the information that is available to them (Murphy et al. 2010). The literature is ripe with studies that address both what information people use as well as how they use (or do not use) information to make decisions when faced with an impending event (see Dillon et al. 2011, Wood et. al. 2011 and Bradford et al. 2012 for examples). While there is some concern that uncertainty in forecasts may be difficult for individuals to understand (Demeritt et al. 2010), emergency managers and other emergency support professionals address uncertainty everyday as they prepare for severe weather. Hoekstra and Montz (2017a) showed how Lindell's and Perry's (2012) Protective Action Decision Model (PADM) can be applied to emergency management decision-making because it incorporates the predecision stage that includes perceptions of the threat, protective actions, and stakeholders. Yet, all of this is dependent on the availability of information that links science to decision-making at both spatial and temporal scales that fit the context in which decisions are being made (Morss et al. 2011).

User feedback has been instrumental to implementing and advancing storm surge products and related use of storm surge information by the public (e.g. Lazo and Morrow 2013), emergency managers (EMs) and other emergency support functions (ESFs). In fact, the direct use of these studies "to empirically elicit stakeholder input as part of product development" was seen as a unique endeavor within the National Oceanic and Atmospheric Administration (NOAA) (Morrow et al. 2015, p. 44). This research takes a similar approach by eliciting user input to help inform the potential development of surge products. In contrast to previous work, this study turns its focus toward surge lead times beyond several days as well as the types of surge information beyond surge height and timing. Further, it takes advantage of an Integrated Warning Team meeting to administer the survey, thereby focusing on professionals who are 1) more comfortable with longer lead times and the uncertainties that accompany them, and 2) more likely to use the information in their decision-making.

A growing body of research has shown that simplified or less detailed storm surge information may be attainable beyond current storm surge numerical models to the weekly, monthly, and seasonal time scales, due to both improvements in weather and climate predictability as well as increasing understanding of storm surge (Dolan and Davis 1994; Zhang et al. 2000; Wakelin et al. 2003; DeGaetano 2008; Sweet and Zervas 2011; Dangendorf et al. 2012; Thompson et al. 2014; Munroe and Curtis 2017; Catalano and Broccoli 2018). In an earlier study, Munroe and Curtis (2017) defined several surge shape parameters, including height, power, duration, skewness and kurtosis, and found significant relationships between this information and climate variables (i.e. El Niño Southern Oscillation) for the Northern Outer Banks of North Carolina. While theoretically, surge information at longer lead times could be highly beneficial to those who use storm surge information in decision-making, the impact this information could have for surge related decision-making is not fully understood. There is a range of users of such information with a range of needs. For instance, EMs and ESFs may find long range surge forecasts to be helpful in their operations for, among other things, estimating potential resource needs. Thus, this follow up research aims to assist in bringing the growing body of storm surge research to operations through the following objectives: by documenting 1) what storm surge information is currently used by EMs and other ESFs; 2) what lead times are currently useful; and 3) what additional surge information, lead times, and related products could add further value for their operations. It is anticipated that the results of this research will foster understanding of how the development of additional surge products at different temporal scales might complement those at shorter lead times to benefit users of storm surge information. A recommendation of how to incorporate the findings of this study into operations through additional surge products follows at the end of the summary and conclusions section.

2.1 STUDY AREA

The region on which this study focuses is the NWS Newport/Morehead City Weather Forecast Office (WFO) County Warning Area (CWA) comprising 15 counties (Figure 12). Eight of those counties are adjacent to the Atlantic Ocean and/or Pamlico-Albemarle Sounds and are susceptible to storm surge nearly year round. One strength of the selected study area is that it frequently experiences storm surge, significant at times, from both tropical and extratropical cyclones. In fact, from a research perspective, it may be the most optimal location in all of the continental United States in terms of experiencing storm surge from both storm types. This is significant because storm surge characteristics and related impacts can differ significantly between the two storm types and also generally occur during different seasons (e.g. Munroe and Curtis 2017). As a result, EMs, ESFs, other officials, local residents and even tourists can be affected or respond differently to surge events from the two storm types. Tropical cyclone storm surge is most common during the Atlantic Basin Hurricane Season from June through November and extratropical cyclone surge is most common from October through April or May (Dolan and Davis 1994; Zhang 2000; Sweet and Zervas 2011; Thompson et al. 2014; Munroe and Curtis 2017). A second strength, but also limitation of this study, is that it is regionally specific, focused across Eastern North Carolina. For example, barrier island systems such as the Outer Banks of North Carolina, often have a limited number of evacuation routes, which typically results in longer evacuation times than other coastal areas connected more directly with the mainland. On one hand, this speaks to the importance of longer lead times for surge. On the other hand, coastal areas without significant constraints to evacuation times may have different needs in terms of storm surge lead times and preferred types of surge information. Nonetheless, the lead times that the research reported here addresses may still be of use in such areas to understand possible future events and consider needed resources. Therefore, it may be beneficial to undertake similar studies for other regions of differing coastal characteristics.

Figure 12. Study area displaying NWS Newport/Morehead City WFO CWA in Eastern North Carolina, denoted by the darkest gray shading.

2.2 METHODS

A 22 question mixed multiple choice and free response survey (Appendix D) was developed to address the research objectives. The survey was administered by the first author in June 2016 at the Beaufort Hurricane Conference and Integrated Warning Team (IWT) meeting hosted by the NWS Newport/Morehead City WFO at the NOAA Beaufort Lab in Beaufort, North Carolina. There was a general storm surge presentation given by the Science and Operations Officer at the

NWS Newport/Morehead City WFO followed by a brief presentation by the survey administrator providing information related to the survey. There was a total of 24 eligible participants at the meeting with 23 survey respondents, including 15 ESFs (ten of which self-identified as EMs), four NWS forecasters, two media representatives and two members of the public. The remaining five ESFs included two local or regional government officials, two transportation or school officials, and one public safety official. One person abstained from taking the survey because he believed he lacked the background and experience necessary to participate. The questions targeted current and potential future use of surge information from daily to seasonal time scales as well as formats and types of information that users desire. The survey was purposely vague in terms of individual characteristics such as age and job description to protect individual identity given the relatively small storm surge community in Eastern North Carolina. All but one respondent answered all questions, but fewer responded to the open ended questions at the end. The one individual seemed to have overlooked about one quarter of the survey. Where appropriate, the number of total responses per finding is included in the results section.

Multiple choice questions, including a series of questions using the Likert scale, comprised 15 of the 22 questions in the survey. Results from these questions were calculated either by a straight frequency analysis or, in the case where the order of selection was important, a linearly weighted frequency analysis, with weights decreasing by selected response (i.e. response of dabc would result in d=4, a=3, b=2, c=1). The remaining seven questions were free response. The responses to these questions were transcribed into an excel worksheet by storm surge user with their self-selected category (i.e. EM) included to allow for comparison across questions and user group. About half of the information collected in the free response portion of this survey is related to the timing of storm surge information. This information, being quantitative in nature, was portrayed in two figures to provide a visualization of the data. The remaining qualitative portion of the free response was further compiled into themes for each question by user type. Themes were identified mainly through repetition of response and by user category, where themes were weighted towards the higher frequency of similar answers. However, the analysis attempted to be as inclusive as possible while preserving desired simplicity in terms of the overall message. This portion of the analysis was revisited by the authors to assure that no important information was left out and to also to avoid the potential for bias in this stage of the research. Research bias is expected to be minimal if any at all, with any small bias likely limited to how the survey was constructed. However, ESF, EM, and to a lesser extent the NWS categories with larger sample sizes are likely more reliable than the Media and Public. As in any location, users of storm surge information in North Carolina may have biases that are regionally specific and related to local experience with the storm surge hazard characteristics (i.e. they receive surge from tropical and extratropical cyclones), influences from local geography, and related rules and policies.

2.3 RESULTS

The survey results can be divided into four areas of concern, starting first with uses of storm surge information along with required and desired lead times. Attention then turns to the needs of these groups of users with respect to the information that would be most useful and the most appropriate formats of that information.

2.3.1 Uses of Storm Surge Information

In response to a series of both multiple choice and open ended questions, ESFs, including EMs, identified that they use storm surge information to assess and communicate risk, to educate the public, to evacuate the public, or for long term resilience and recovery planning. The NWS forecasters had similar responses for surge information use and how it affects their operations, stating that this information is part of the forecast process and is used for assessing and communicating surge risk to the public and to partners. The two media respondents use surge information to communicate threats to the public. The two public citizen respondents were most interested in information about evacuation and when they can return home.

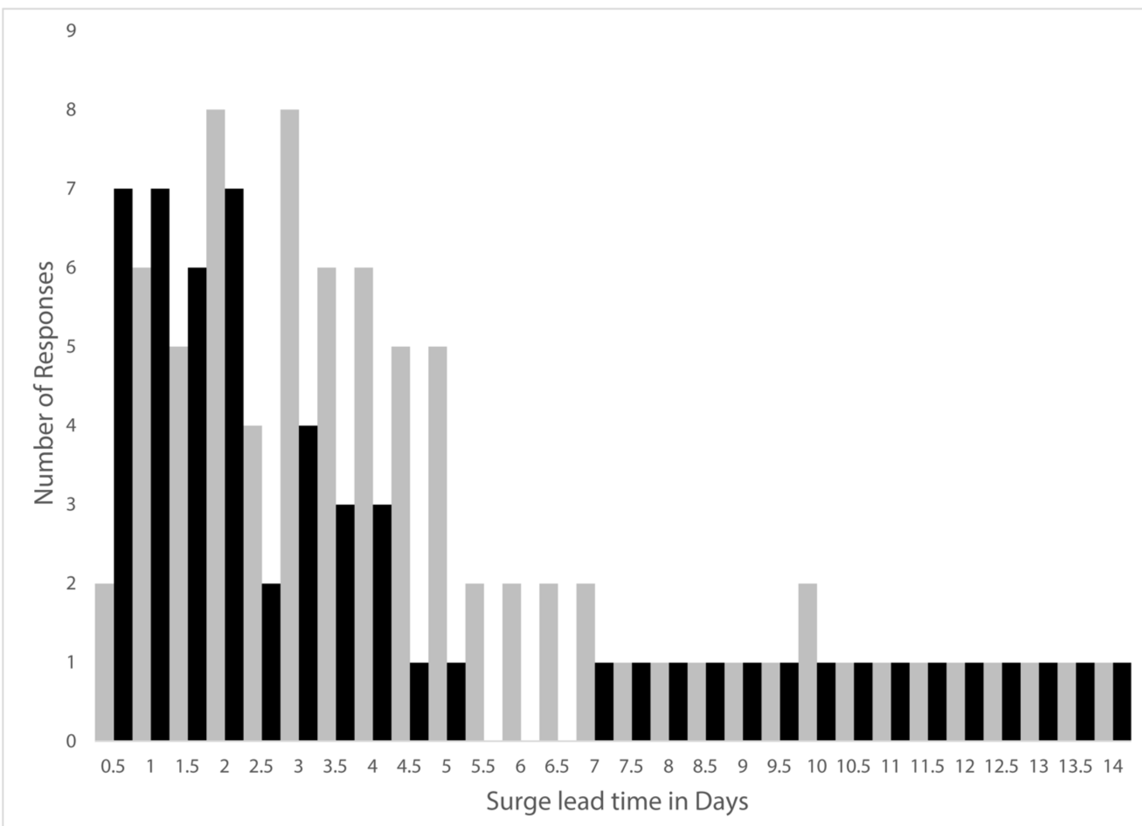


Figure 13. Frequency statistics of the lead-time each individual respondent first learned of a potential storm surge event (light gray) and the expected surge magnitude and timing (dark gray). Respondents were allowed to give a range of days.

2.3.2 Lead Times

Sixteen respondents (89%) first learned about a possible storm surge event between one and five days prior to the event with two-thirds citing between two and four days (Figure 13). Fourteen (82%) of the same respondents first learned of potential surge magnitude and timing two days or less (Figure 13). This finding suggests up to a three day margin between when respondents first learn of a potential surge event and when they become aware of the possible magnitude and timing.

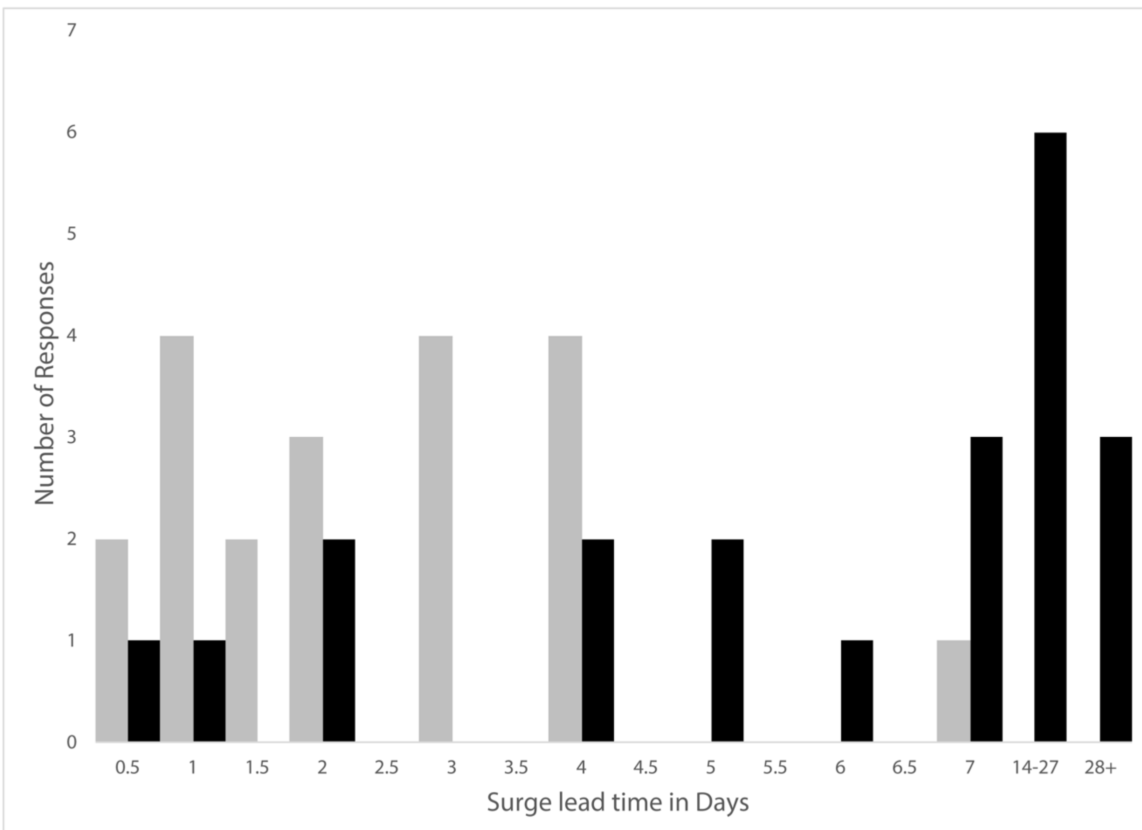


Figure 14. Frequency statistics of the shortest (light gray) and longest (dark gray) lead times that would be beneficial to respondents' operations.

Overall, storm surge event lead times of a week or less were most valued, although there was significant interest in the potential for longer lead times. Respondents were asked to provide the shortest and longest beneficial lead times of surge information, and how these lead times would facilitate related operations. The shortest lead time that would be beneficial to operations ranged from 12 hours to four days, with one response stating one week (Figure 14). According to multiple EM and ESF responses, the shortest lead times, not surprisingly, provide the most accurate information, aiding the best possible decision making with just enough time to alert the public and mobilize resources. NWS forecasters stated that short lead times were beneficial in that these forecasts have the highest accuracy and probability for warning the public as well as planning for and communicating potential impacts. There were mixed results from the media and public citizen representatives with lead times of around 48 hours preferred by one of each of the two groups and up to two weeks for the remaining media and public representatives. One member of the media showed some dependence on EMs as that individual typically first learns of a potential surge event from their local EMs.

The longest lead times that would be beneficial to operations ranged from 12 hours to a month or longer. Of those responses, over half (12 of 21 [2 respondents abstained]) stated that a week or greater lead times would be beneficial to operations, despite being made aware that forecasts become less detailed as lead times increase. In fact, ESFs involved with evacuations ahead of a potential surge event identified either 1) learning about a surge event or 2) being interested in learning about surge events about four days to two weeks in advance. The longest leads times would benefit operations by providing additional time for planning and staging, thereby allowing for quicker recovery or return to normal operations following a significant or disruptive surge event. On the other hand, one ESF stated that she may use surge information at the longer lead times only for informational purposes and that it would not likely impact decision making.

Although there is significant interest in, and in some cases a need for, longer lead times for storm surge, there are also concerns about the accuracy and meaning of this information. Several respondents were concerned about the potential for complacency given less accurate information or the potential for frequent changes. A similar response was noted from media respondents in Morrow and Lazo (2013). Another concern was that it may be confusing to some audiences. An NWS forecaster stated that "communicating threats during low probability, but high impact events seems to be most difficult." However, another NWS forecaster was more optimistic, stating that they had "no concerns, just need to educate on meaning and uses." An ESF thought that fisherman and farmers would find the longer lead times to be interesting, but that they would be unlikely to use it, similar to the El Niño Southern Oscillation predictions. This person further stated that they often hear farmers and fisherman stating "I still have to take the chance to plant/fish" in spite of an unfavorable prediction. The same respondent also recommended learning the needs and preferences of other surge user groups such as homeowners and businesses to see if a six month forecast (for example) would make them more likely to seek a home elevation or other mitigation.

2.3.3 Types of Surge Information

Overall, the impacts of storm surge were a higher priority than the type of storm (tropical or extratropical), with 19 of 23 respondents selecting that option, similar to the findings of Lazo and Morrow (2013) in their survey of the public. Survey respondents were most interested in event-specific details, including the probability of moderate/strong surge events and length of a surge event. There was limited interest for how often surge events will likely occur over a given period of time, for example if a particular season was forecast to be active or quiet. These results were investigated further through a Likert scale of 1 (disagree) to 5 (agree) in a series of six statements, related to whether surge height, duration, start time, end time, or speed of onset or frequency across a given month or season have a significant impact on decision making related to operations. Table 10 breaks down the averaged Likert response by surge user group and surge variable. All surge specific characteristics were determined to be important by nearly all respondents with 91 percent or more of the respondent selecting either "agree somewhat" or "agree" and 68 percent or more selecting "agree". At the same time, storm surge frequency over a given month or season was found to have less of an impact on decision-making, with 64 percent of respondents selecting "agree somewhat" or "agree" and the remaining 36 percent selecting "neutral". Interestingly, EMs noted that surge height (average Likert score 4.1) was less important than start time, end time, duration and speed, which all had averages of 4.7 or 4.8 (Table 10). This could be related to EMs keeping public safety in mind as they are responsible for issuing evacuation orders and initiating recovery operations, which are, in turn, related to the timeline of flooding across the region and not necessarily by the magnitude of flooding, similar to the findings of Losego et al. (2012). However, height was deemed most important for NWS and ESF respondents with average scores of 4.8 and 5.0 respectively. The NWS issues forecasts for water height above ground, and emergency responders need to know depth because they often put their safety at risk by going into flooded areas. On the other hand, the media and public representatives all selected "agree" for the usefulness of all types of storm surge information except for frequency (Table 10).

	Height	Frequency	Duration	Start	End	Speed
EM (10)	4.1	4.1	4.7	4.7	4.8	4.8
ESF (4)	4.8	4.0	4.6	4.6	4.2	4.4
NWS (4)	5.0	3.3	5.0	4.8	4.5	4.3
Media (2)	5.0	3.5	5.0	5.0	5.0	5.0
PC (2)	5.0	4.5	5.0	5.0	5.0	5.0
All (22)	4.6	3.9	4.8	4.7	4.6	4.6

Table 10. Averaged Likert response of different surge user groups when asked if each given surge variable had a significant impact on decision making related to operations. EM is Emergency Managers, ESF is other Emergency Support Functions, NWS is National Weather Service Forecasters, and PC is Public Citizens.

2.3.4 Formats of Surge Information

Question number 21 asked about preferred formats for a surge outlook, with four options: (i) climate outlooks providing simplified surge prediction similar to the Climate Prediction Center's rainfall and temperature products, (ii) probability and magnitude by day (out to two weeks), more analogous to weather forecasts, (iii) weekly briefings, and (iv) other. There was nearly equal interest in all formats for respondents as a whole, as well as for EMs and NWS forecasters, with no respondent selecting the 'other' option (Table 11). On the other hand, ESFs preferred climate outlooks and weekly briefing packets. The two private citizens preferred the probability and magnitude by day (out to two weeks), while two of the four NWS forecasters preferred all three options, with only three of the remaining 18 respondents selecting all three. Storm surge at the coast is complicated and ESFs seem to recognize the complexities, suggesting other important surge information or formats when asked to list additional information that would be useful to their operations. Examples include examining surge information using different forms of visualization such as on a Geographic Information System platform as well as incorporating inland rainfall and flooding as it relates to surge at the coast. The interest in and knowledge of surge within their area suggests they are seeking out or desire more surge information. The NWS

Newport/Morehead City WFO has helped to foster this desire for surge information as evidenced by the Hurricane Conference and IWT meeting where this survey took place.

	A	B	C
EM (9)	4.0	5.0	5.0
ESF (5)	5.0	1.0	4.0
NWS (4)	3.0	3.0	2.0
Media (2)	1.0	1.0	1.0
PC (2)	0.0	2.0	0.0
All (23)	13.0	12.0	12.0

Table 11. User group preferred formats for receiving surge information. Options included include: (A) climate outlooks, (B) surge probability and magnitude of surge by day (similar to weather forecasts), and (C) weekly briefing packets. EM is Emergency Managers, ESF is other Emergency Support Functions, NWS is National Weather Service Forecasters, and PC is Public Citizens.

2.4 SUMMARY AND CONCLUSIONS

This research has examined interests of specialized users of storm surge information regarding longer lead times of surge information as well as the type and format of surge information, including and beyond what is currently available.

The results from the survey show that surge users, mainly EMs, ESFs, and NWS forecasters, currently use surge information to assess and communicate surge risk, educate the public, order evacuations, and for long term resilience and recovery planning. Surge users as a whole were especially interested in additional types of surge information beyond surge height, including the duration, timing (including starting and ending times), and the speed of surge onset. There was less interest in the frequency of surge at monthly to seasonal scales. The results also indicate that surge users would benefit from longer lead times of storm surge information. Storm surge users generally require surge information out to four days, but for about half of the respondents, surge information at lead times of a week or greater would benefit operations, which exceeds currently available storm surge lead times. This finding aligns with previous research stating that EMs and media (broadcast meteorologists) desire greater lead times, especially when it comes to evacuations (e.g. Losego et al. 2012; Morrow and Lazo 2013a). Superstorm Sandy (2012) is a significant recent example of EMs needing accurate surge information at greater lead times as several EMs had to make critical evacuation decisions 72 hours before landfall (e.g. Hoekstra and Montz 2017b).

There were significant concerns from several of the respondents related to the level of detail and accuracy of potential surge information at longer lead times. This suggests that caution should be taken during the developmental phases of extending the lead times of available surge information. This would help to ensure a balance between the detail and type of information and the associated accuracy of surge information at longer lead times that would provide utility to end users, while gaining their trust. An iterative process of testing the new surge information at longer lead times with surge users throughout the product development process will help to ensure the usefulness of the products in the future. Additionally, the involvement of surge users within the development process will help to facilitate learning about how and when the new surge products would be used and how to educate users on the potential utility and limitations of the surge information.

Weekly to seasonal surge forecasting, however, if accurate and dependable enough, may help to heighten awareness at these time scales. Potential benefits include (1) increasing awareness of at risk populations, with educational materials aimed at providing appropriate responses before, during, and after significant surge events, (2) increasing the response rate and preparedness for individual storms during the season, and (3) initiating protective actions for individual, commercial, and government entities. Thus, while surge information at longer lead times will likely be unreliable at times (similar to extended weather forecasts and climate outlooks), stronger or better known surge relationships to weather and climate may assist in triggering important preparatory actions. Southern California offers a comparable example with the most recent, well predicted, record breaking El Niño (2015-16) as local governments and individuals took preparative actions (i.e. clearing debris from riverbeds and repairing structures such as roofs) well in advance of what was expected to be an abnormally active rainy season.

2.4.1 Study Limitations

Even though the total number of respondents was limited to 23, the strength of the survey is its regional focus on eastern North Carolina. This can also be a limitation of the study, however, as the results may not be transferrable to other coastal locations. Characteristics including geography and vulnerability to storm surge from different storm types as well as societal and policy characteristics will differ, but it would be interesting to reproduce the survey in other coastal regions to determine if the needs are universal or regionally specific.

The cross section of study participants had been invited to the meeting where the survey took place by the NWS Newport/Morehead City WFO and also included a few representatives from the WFO itself. While there was significant representation of EMs and other ESFs, the representation from the other three groups (NWS forecasters (4), media (2), and members of the public (2)) was limited due to a combination of the intent of the meeting and characteristics of the region.

2.4.2 Recommendations

The following tiered approach (closely mirroring currently available weather and climate prediction) might contribute to bringing current or near future numerical and climate prediction research to operations, thereby providing additional services to storm surge users.

(1) For days 1-5, detailed surge information with the probability of different magnitude surge events could be provided, matching the science to the needs of the customer (as recommended by Morss et al. 2011). In addition to surge height (or depth), this survey found that other surge information such as start and end times, duration, and how quickly the water advances inland has a significant impact on decision making related to operations and could be incorporated as numerical modeling limitations allow.

(2) Days 6-14 could be provided in the much desired climate format (i.e. two periods broken into days 6-9 and 10-14) with less detail, but possibly similar surge variables, as the science allows.

(3) Beyond two weeks out to several months, monthly to seasonal outlooks could provide probabilities of given magnitudes or frequencies of storm surge to assist in longer term planning and resource management.

There is increasing confidence that the science behind storm surge may be able to match the demand for user desired longer lead times (e.g. Munroe and Curtis 2017). The results from this research should encourage investment of efforts in both continued development of surge products through a combination of numerical weather and climate prediction and surveys and other means to determine how to best provide this information to surge users.

CHAPTER 3: A SYNOPTIC CLIMATOLOGY TIED TO STORM SURGE POWER

3. INTRODUCTION

The coast is often studied because of its intrinsic value to visitors, the lives and property of those who live at the coast, and the environmental services it provides through tourism, natural resources, and as a natural barrier to waves, wind, and water. Storm surge coupled with wave energy at the coast is partly responsible for shaping or damaging coastlines including both natural and human built environments. The climate system is always evolving with scientific evidence pointing towards continued sea level rise (i.e. IPCC 2019), which will likely exacerbate the impacts of storm surge on these environments. Please see chapter one for more details on the storm surge hazard and some of the impacts near the coast.

Through a survey instrument, Munroe et al. (2018) found that emergency managers, among other storm surge users mainly located in Eastern North Carolina had an unmet need for storm surge information at sub-weekly to seasonal time scales. Current surge forecasting and related products within the NWS focus on the next several days or less and mainly relate to tropical cyclones. However, there is a movement towards potentially extending products to extratropical cyclones. There is an increasing development of relationships and methods ongoing to bridge the gap between user needs and currently available surge information (i.e. Wakelin 2003, DeGaetano 2008, Sweet and Zervas 2011, Thompson et al. 2014, Munroe and Curtis 2017, Sheridan et al. 2019). The research by Sheridan et al. (2019) is particularly interesting as it has the potential to extend storm surge modeling beyond current capabilities through the use of adaptable neural networks and currently available weather models.

Results from chapter one indicate that the power variable (the summation of surge height squared over time) was found to be the statistically most significant variable at monthly to seasonal scales (others included maximum, duration, and two shape related variables). It is also the most directly related to impacts (incorporates water level and duration) and as a result it will likely highlight higher impactful storms more effectively. This study builds on Munroe and Curtis (2017) and to a lesser extent Munroe et al. (2018), focusing on the surge power variable from Duck, North Carolina in December, January, and February (DJF) with also a secondary focus in August, September, and October (ASO), to provide insight into synoptic patterns related to cool and warm season surge events, including those associated with tropical cyclones. Climate oscillations (El Niño Southern Oscillation (El Niño and La Niña), North Atlantic Oscillation (NAO, +/- phases), and Pacific North America pattern (PNA, +/- phases) with teleconnections to the region are also be explored. See chapter one for details on each oscillation and related tendencies for modulating the atmosphere in the vicinity of the Outer Banks of North Carolina.

Specific research questions include:

(1) Will the synoptic climatology developed here further support the results from chapter one, effectively tying statistical relationships of water level or storm surge to atmospheric circulations?

(2) Will the synoptic climatology provide a scientific foundation towards improved pattern recognition for weather forecasters that could serve to enhance communication and awareness of the storm surge hazard at longer lead times?

3.1 METHODOLOGY

The storm surge dataset used in this study was developed in Munroe and Curtis (2017). It was derived from water level data from Duck, NC (US ACE) and is comprised of 520 events spanning from 1981 to 2014. For details on how it was developed, please refer to the methods section of chapter one. Synoptic composites were developed using NOAA-CIRES-DOE Twentieth Century Reanalysis version three available at the ESRL website (https://www.esrl.noaa.gov/psd/data/composites/subdaily_20thc). Date and time (6-hour increments) were selected based on the time of peak storm surge for a given event. The time of the event was rounded to the nearest 6-hour synoptic time for composite creation. Dates for each composite were then selected based upon oscillation (El Niño/La Niña and +/- phase of both the NAO and PNA exceeding the 0.5 standard deviation) and between weak and strong surge events (excluding ASO oscillation composites) as determined by mean surge power (computed individually for each oscillation/phase). Mean sea level pressure (MSLP) and 500 mb geopotential height were selected as the most representative variables available within the ESRL website to show storm structure as it relates to storm surge including near surface conditions and associated atmospheric forcing at mid-levels of the atmosphere.

3.1.1 Study Limitations

The focus of the study is during the three month periods of DJF and ASO, which Munroe and Curtis (2017) found to be seasons of most significant surge impact, but does not paint a full picture for the entire year. The composites produced are based on timing of peak surge which can vary from the first day to the last day of the season. This likely led to some smoothing of the atmospheric characteristics captured in this study. Additionally, this study focuses on the conditions at peak surge with only limited information on movement and speed of these features. Finally, the relatively short water level data set led to a limited sample size for some of the composites, such as for the less than or equal to (LE) or greater than (GT) the mean surge for -

PNA during DJF (Table 12). A small sample size is concerning as it runs the risk of a couple of anomalous storms skewing the overall results.

DJF			
	Mean	Std dev	Number
ALL LE	3.95	1.65	118
ALL GT	12.49	5.28	51
NINO LE	4.32	1.68	40
NINO GT	13.40	5.68	23
NINA LE	3.99	1.79	34
NINA GT	10.44	2.49	13
nNAO LE	4.27	1.84	27
nNAO GT	12.68	4.17	17
pNAO LE	3.67	1.49	50
pNAO GT	11.63	5.40	15
nPNA LE	4.24	1.88	14
nPNA GT	13.92	5.22	7
pPNA LE	4.00	1.54	63
pPNA GT	12.76	5.89	31
ASO			
	Mean	Std dev	Number
ALL LE	3.45	1.50	72
ALL GT	13.60	7.15	57
NINO	8.43	8.37	37
NINA	7.06	6.79	37
nNAO	8.00	6.25	49
pNAO	7.18	5.51	27
nPNA	8.72	8.93	34
pPNA	7.05	5.94	49

Table 12. Storm surge power composite statistics. Column one abbreviations: less than or equal to (LE) and greater than (GT) mean surge (column two); negative (n) or positive (p).

3.2 RESULTS

3.2.1 All Surge Events

DJF composites of strong and weak surge events (Figure 15) indicate a stronger pressure gradient near the Outer Banks due primarily to a deeper surface low-pressure system. Much more prominent 500 mb geopotential height anomalies exist in the form of well below normal heights near the Southeast coastline with well above normal heights near the Hudson Bay in Canada. This configuration (vertical orientation of anomalous ridging located adjacent but north of anomalous troughing) is typical of Rex blocking and would suggest slower extratropical cyclone movement which is often associated with longer lasting and a higher maximum storm surge. Note that there is more than three times the mean power for strong compared to weak events in DJF (Table 12). There was a somewhat similar relationship between strong and weak surge ASO composites (Figure 16) near the surface and aloft. However, the tighter pressure gradient in the strong surges composite was due to a nearly equal combination of deeper low pressure centered in a favorable location just off the Outer Banks and more prominent ridging over northern New England when compared to the weak surges composite. Note that there was nearly four times greater mean power for strong versus weak events in ASO (Table 12). Despite being significantly different seasons, DJF and ASO had similar mean power values for the ALL composites with 31 percent more surge events during DJF (Table 12).

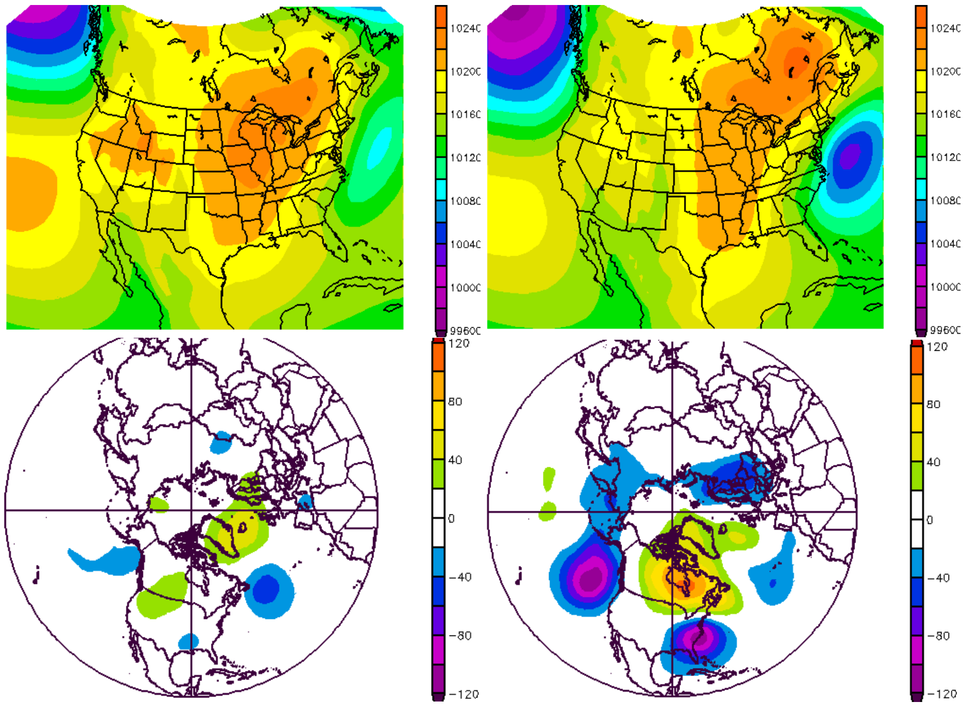


Figure 15. Weak (left) vs strong (right) surge DJF composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

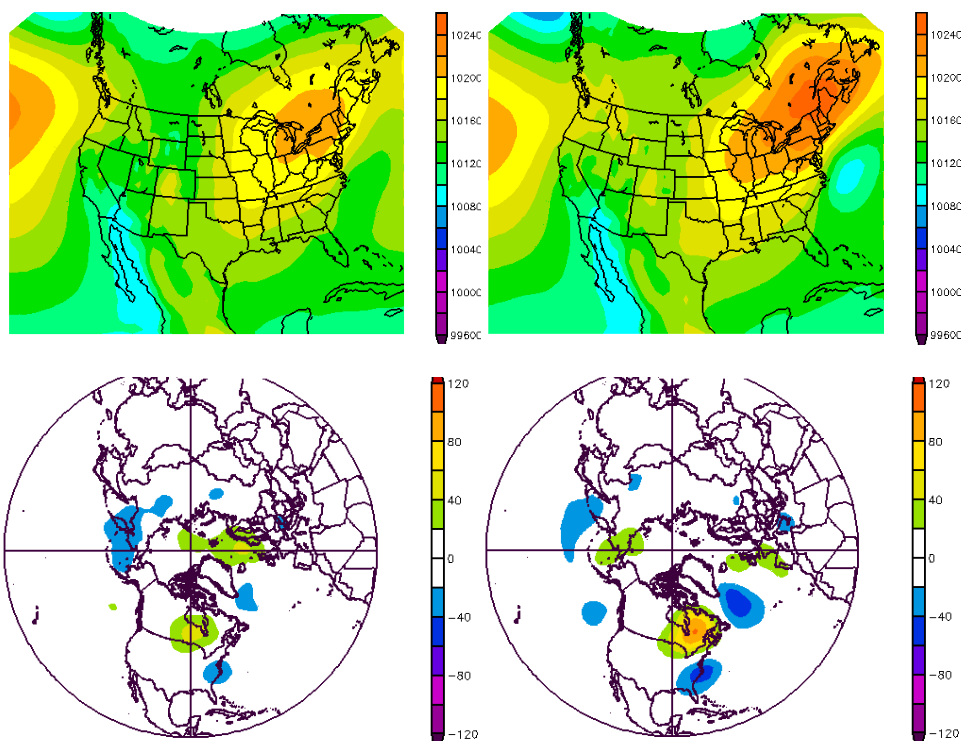


Figure 16. Weak (left) vs strong (right) surge ASO composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

3.2.2 Twenty Four Hour Evolution

Surface and upper level features of DJF evolution (Figures 15 and 17) indicate a slightly further inland track (lower MSLP pressure in the Deep South) of weak surge events. The relative minima in MSLP across the Deep South (Southeast Coast) the day prior translating to off the Mid-Atlantic coast the day of also suggest somewhat faster (slower) movement of low-pressure systems responsible for weak (strong) surge events. The more south to north orientation of the mean track over or near open water during strong surge events lends itself to a longer period of the fetch of winds over open water which, all else being equal, will increase the duration, maximum, and power of surge events. Relatively subtle differences are present in the ASO evolution as compared to DJF evolution (Figures 16 and 18). Strong surge events exhibited a slight east to west movement that was not apparent during weak events. Strong storm surge events were characterized by a modest, but small and persistent elongated anomalous ridge across eastern Canada.

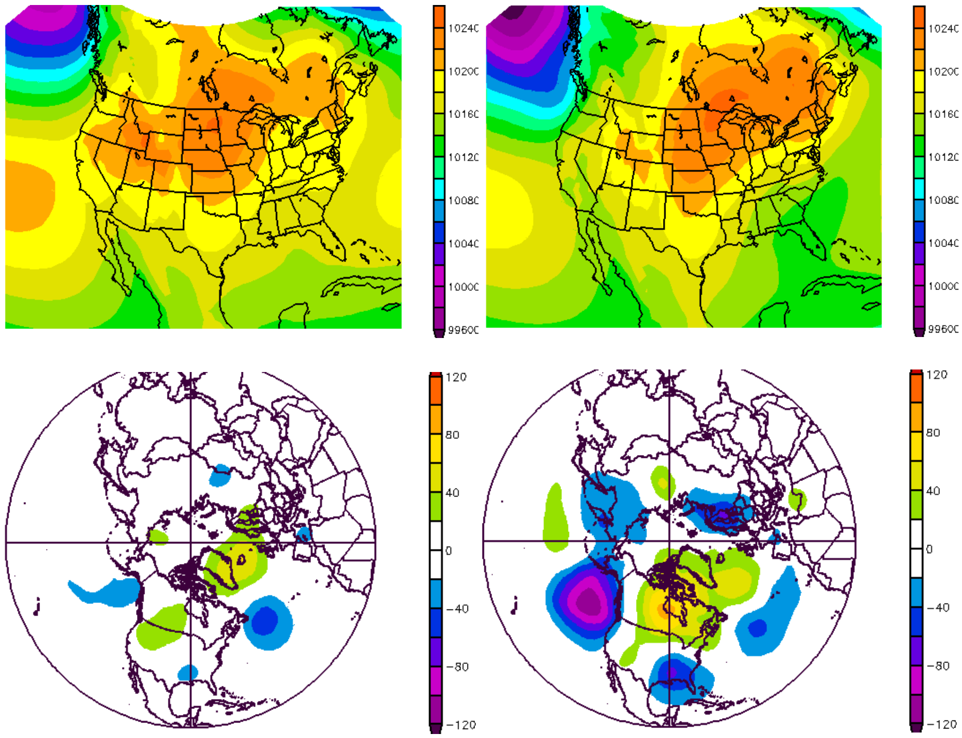


Figure 17. Weak (left) vs strong (right) surge DJF composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters. One day prior to maximum storm surge.

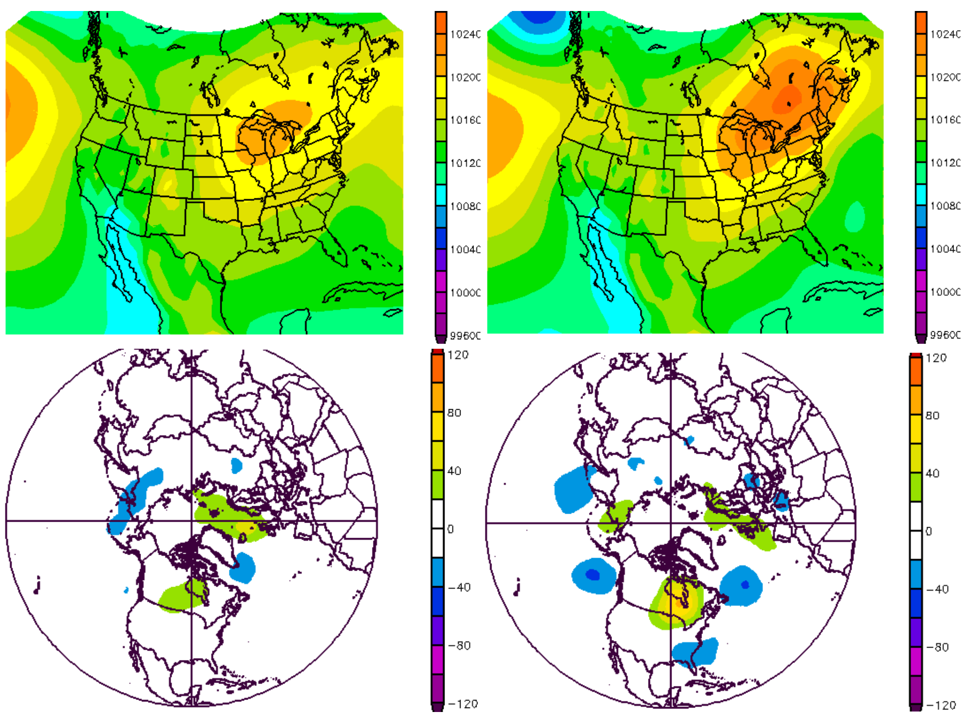


Figure 18. Weak (left) vs strong (right) surge ASO composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters. One day prior to maximum storm surge.

3.2.3 Oscillations

3.2.3.1 El Niño Southern Oscillation

For DJF ENSO composites (Figures 19 and 20), a Rex block present at 500 mb was favored during El Niño in strong surge and, to a much lesser extent, weak surge composites. The more significant anomaly couplet in strong surge events suggests stronger and/or most persistent blocking with a stronger and/or slower storm as seen strong surge event MSLP composites (Figure 19) in particular. The strong surge La Niña composite (Figure 19) did show similar position and strength of anomalous troughing near the Southeast coast as the strong surge El Niño composite, but lacks organized anomalous ridging directly poleward of this signature. Note that strong surge El Niño events were nearly twice as frequent with 28 percent greater mean power than strong surge La Niña events with no substantial difference for associated weak composites (Table 12). For ASO, El Niño and La Niña were marked by relatively similar upper level and MSLP patterns (Figure 21). El Niño tends to support a stronger surface high pressure system over northern New England while La Niña supports a slightly stronger surface low pressure system closer to the Outer Banks of North Carolina. Note that each phase had the same frequency with about a 20 percent greater mean power during El Niño (Table 12). DJF weak composites (Figure 20) shared some similarities with ASO (Figure 19), most notably the 500 mb height anomalies.

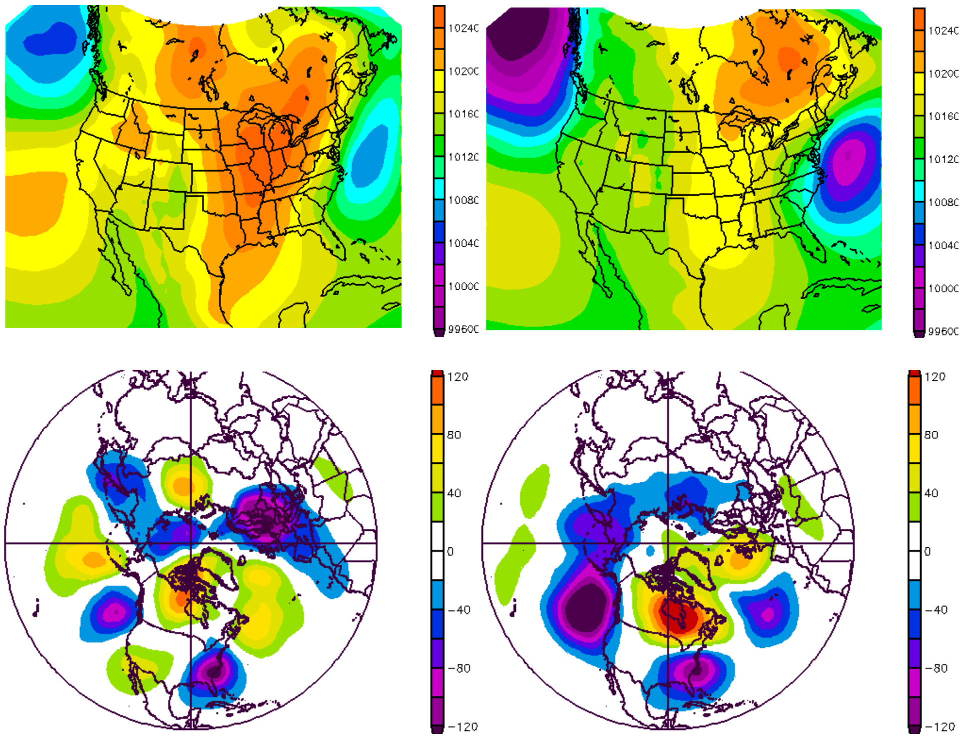


Figure 19. La Niña (left) vs El Niño (right) strong DJF surge composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

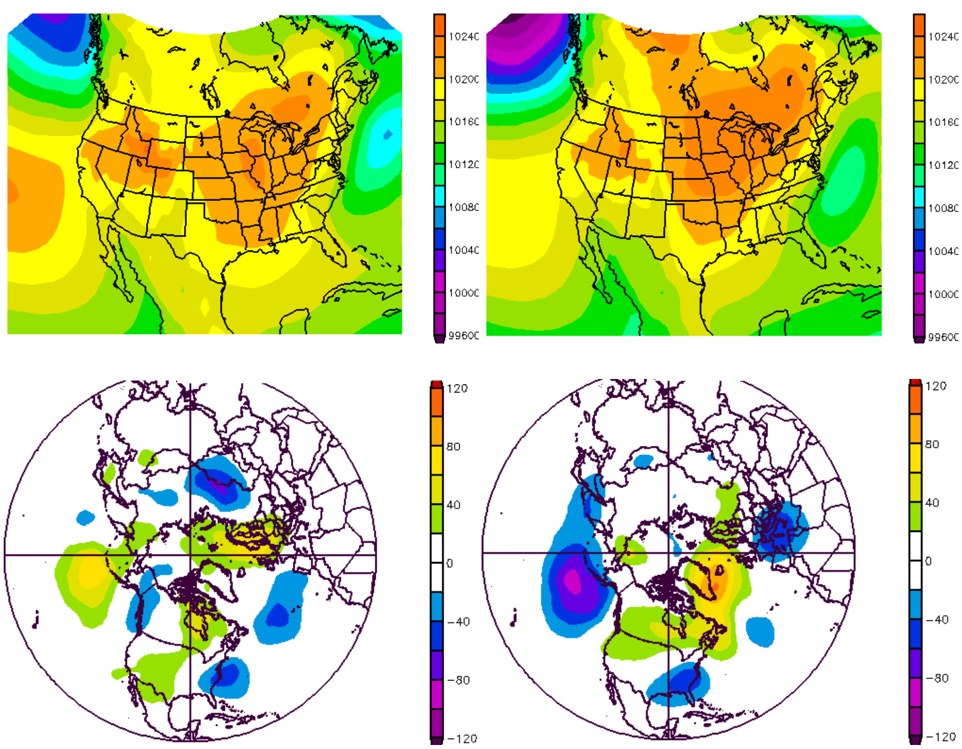


Figure 20. La Niña (left) vs El Niño (right) weak DJF surge composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

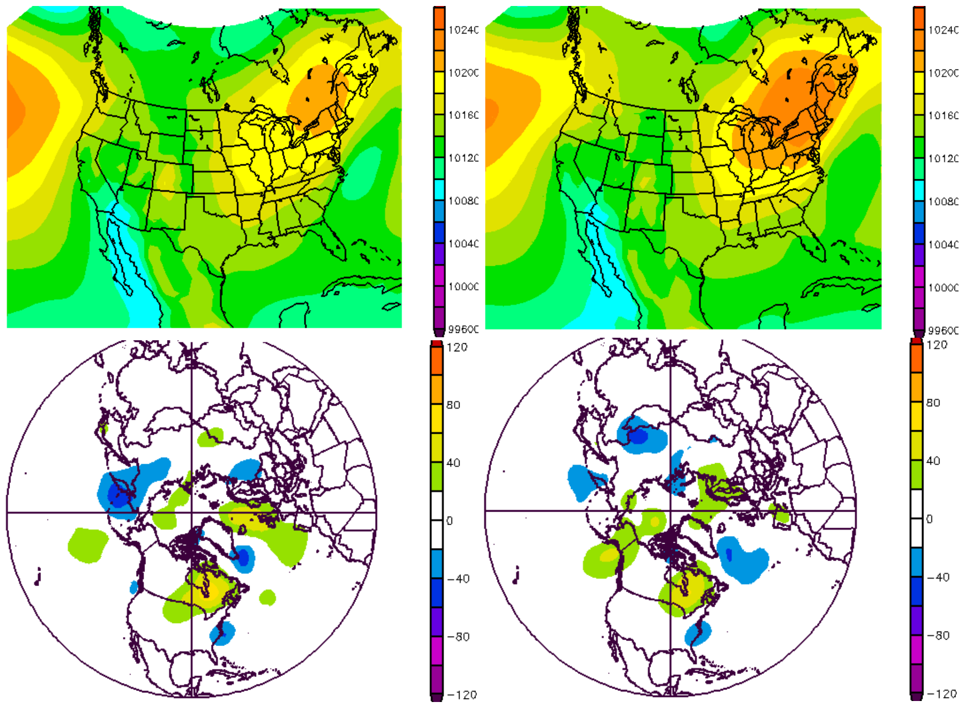


Figure 21. La Niña (left) vs El Niño (right) surge ASO composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

3.2.3.2 North Atlantic Oscillation

A Rex blocking signature was more pronounced in DJF strong-surge NAO events (especially -NAO) than in weak-surge events (Figures 22 and 23). An Omega block was most apparent in strong surge -NAO composites with a faint signature in other composites. Interestingly, -NAO surge events showed a stronger and/or a closer surface low to the Outer Banks as compared to +NAO events. -NAO surge events were on average slightly stronger with strong NAO events about three times more powerful than weak events (Table 12). For ASO, relatively weak upper level blocking was identified in both NAO cases with an upper low reflection seen in –NAO (Figure 24). The surface high seems to be the main driver during +NAO, whereas it is a more distinct combination of the high pressure system over northern New

England for -NAO, with an average surface low location just east of the Outer Banks. Note that -NAO surge events were almost twice as frequent as +NAO events, but had similar mean power values (Table 12). Interestingly, surface and upper level patterns noted in strong surge DJF NAO composites were somewhat similar albeit with a much weaker signal for ASO.

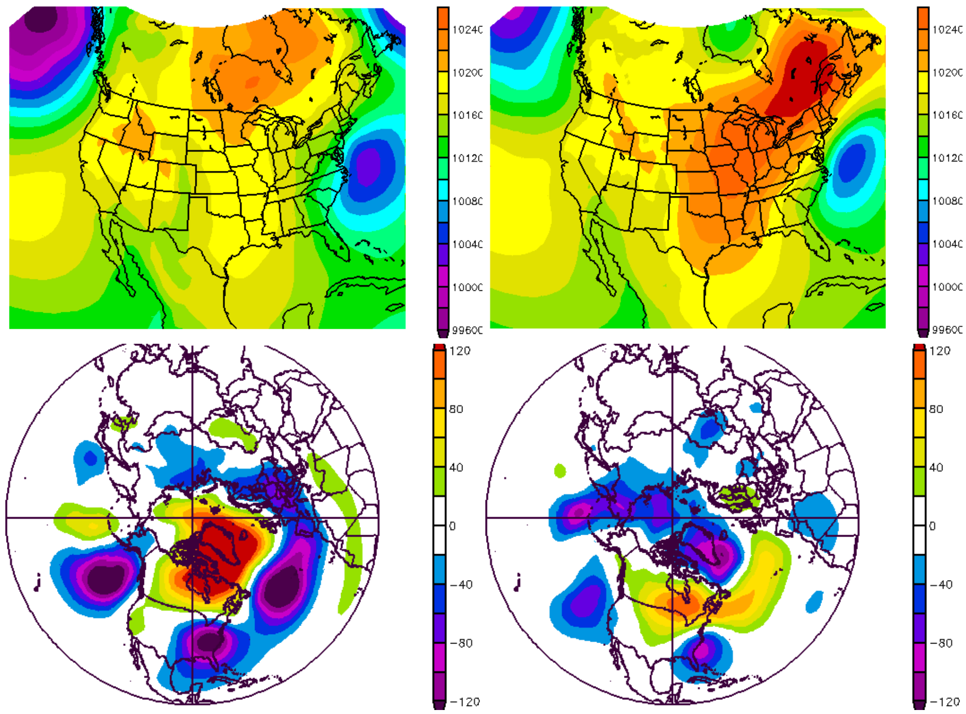


Figure 22. Negative (left) vs positive (right) NAO strong DJF surge composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

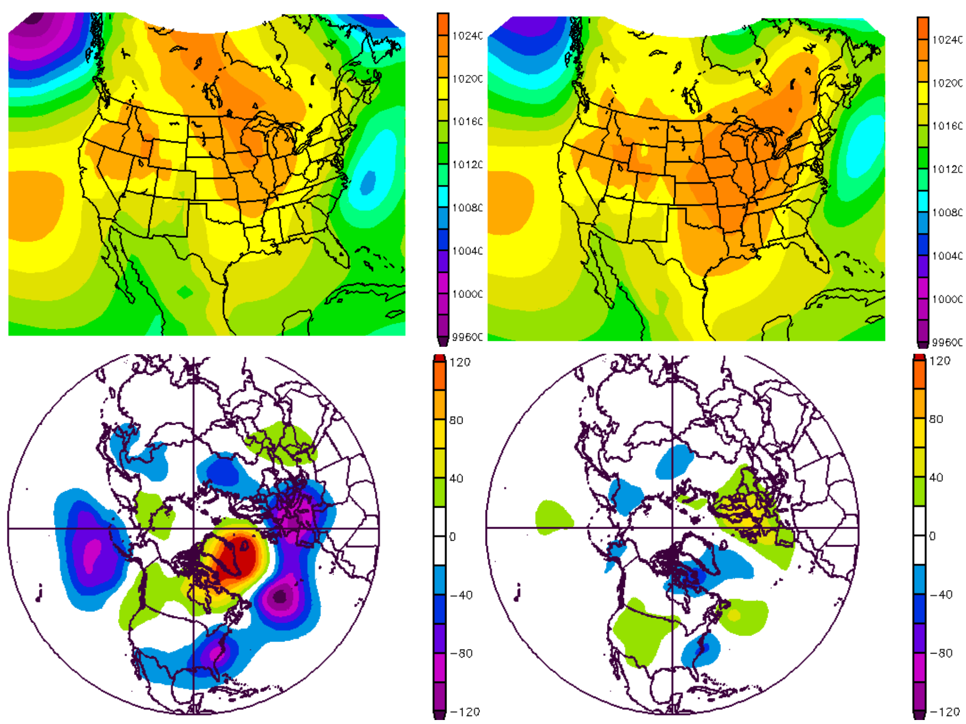


Figure 23. Negative (left) vs positive (right) NAO weak DJF surge composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

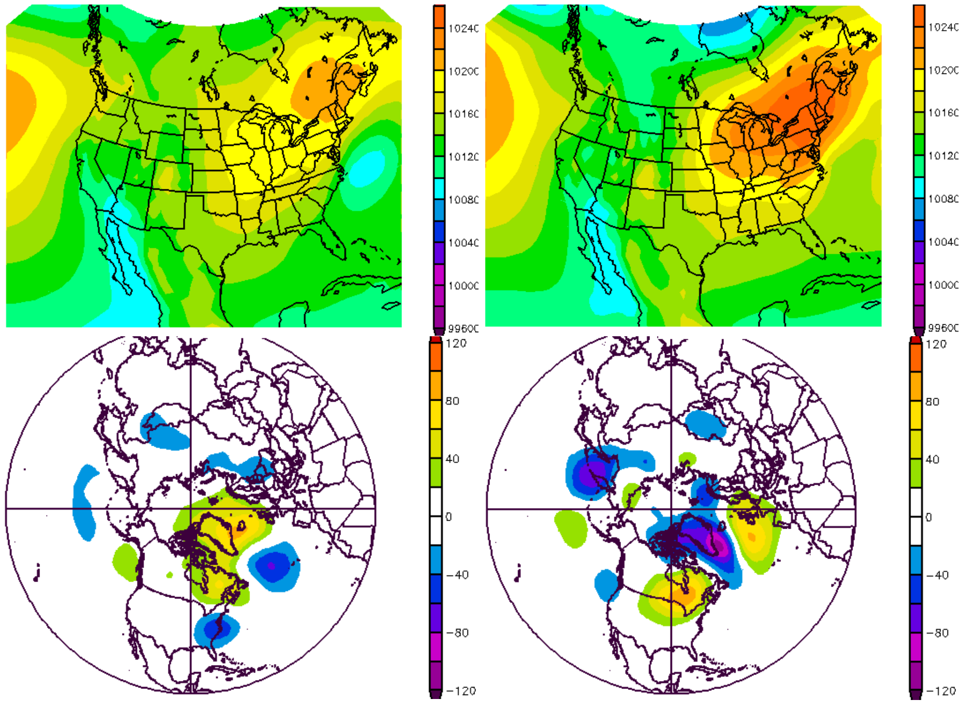


Figure 24. Negative (left) vs Positive (right) NAO surge ASO composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

3.2.3.3 Pacific North America Pattern

Somewhat similar spatial patterns were found between weak-surge and strong-surge DJF PNA events (Figures 25 and 26) with significantly more substantial anomalies in the stronger events (most notably -PNA). At least some blocking, likely supporting slower movement, was evident in the strong composites, but strong surge -PNA events indicated the most significant blocking with frequent Rex blocking likely. However, this finding is likely skewed due to a limited sample size of seven (Table 12). Note that +PNA events were more than four times more frequent with similar power values. There was little difference in surface and upper level features of both phases of PNA during ASO (Figure 27). Note that -PNA had 24 percent greater power than +PNA and was sixty percent more frequent than DJF -PNA (Table 12).

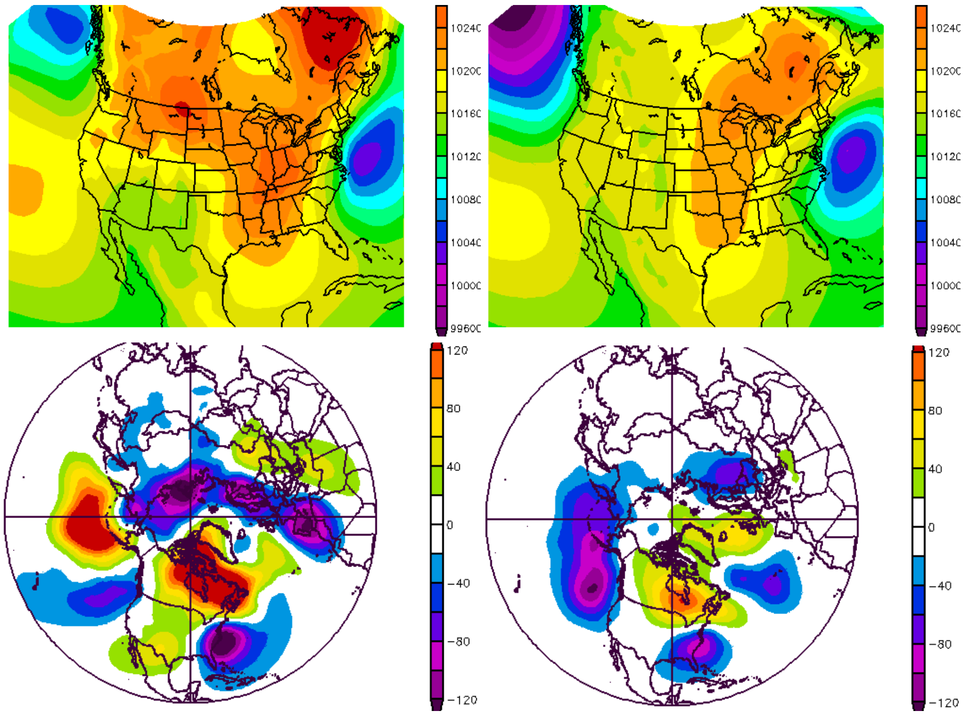


Figure 25. Negative (left) vs positive (right) PNA pattern strong surge DJF composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

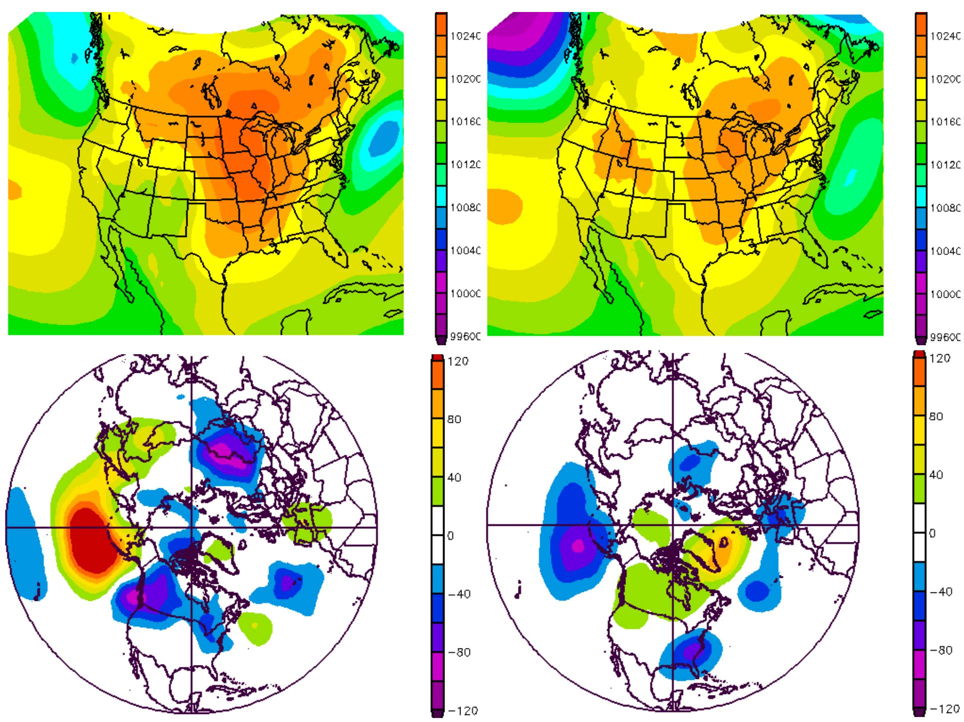


Figure 26. Negative (left) vs positive (right) PNA pattern weak surge DJF composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

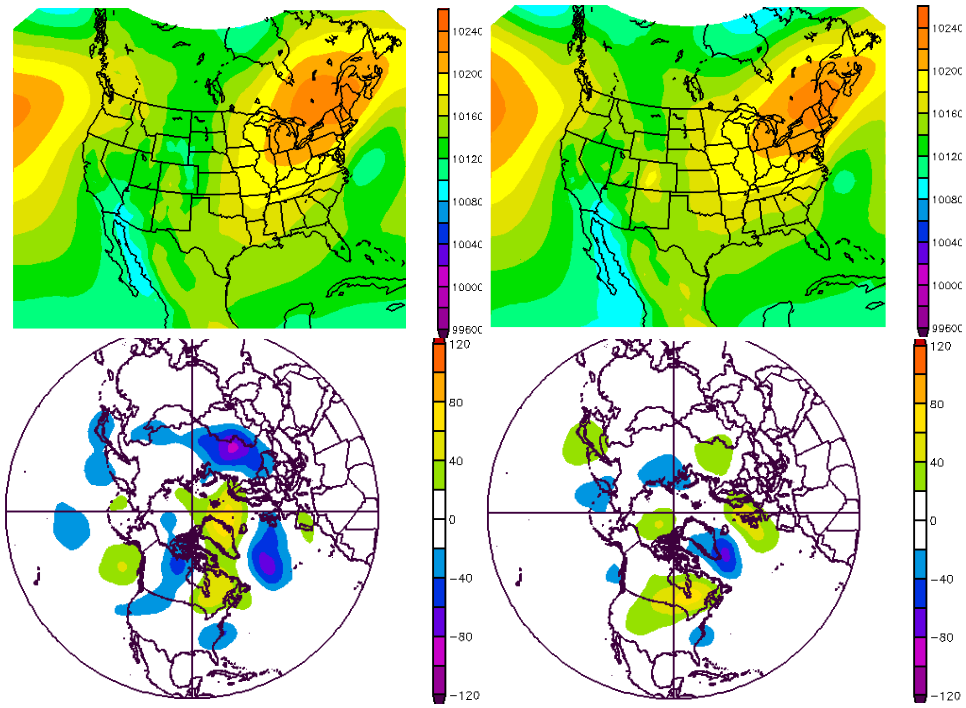


Figure 27. Negative (left) vs Positive (right) PNA pattern surge ASO composites reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

3.2.4 Extremes and Individual Events

The top (bottom) ten most (least) powerful events are driven by a strong (weak) pressure gradient generally between a surface low pressure system east of the Outer Banks and high pressure over New England into eastern Canada (Great Lakes) (Figure 28). Individual composites (Appendix E) supported by the MSLP composite (Figure 28) show that the long fetch created by high pressure is sufficient in producing low power events even in the absence of a surface low pressure system. Note that the smaller cyclone structures are likely tropical or subtropical in nature (i.e. 11/14/1981, 10/31/1991, 7/1/1981). Height anomalies at 500 mb (Figure 28) indicate the most (least) powerful events are slower (faster) as highlighted by meridional (zonal) height anomalies that often support a blocking (progressive) pattern. Through manual inspection, it appears a sample size of ten can be adequately represented by composites (i.e. Figure 28) despite strong variation between events as depicted near the surface and at 500 mb.

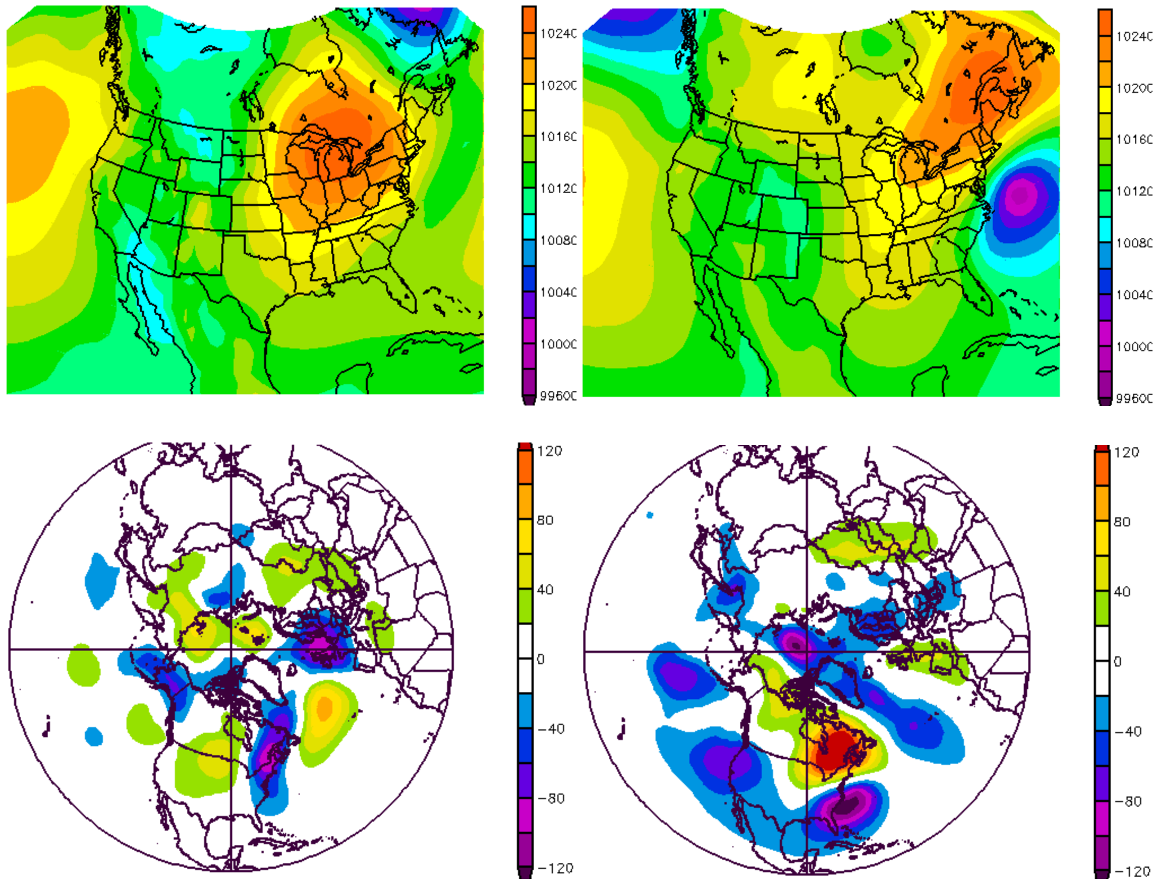


Figure 28. Bottom (left) vs top (right) 10 surge event composites ranked by power reflecting mean sea level pressure in Pascals (top) and 500 mb height anomaly in meters.

3.3 CONCLUSION

Strong surge event composites for DJF (ASO) had about three (four) times greater power than respective weak events. This matched the surface and upper level composites, which were substantially more amplified for strong surges. Anomalous ridging was observed in most composites with Rex and Omega blocking patterns also common, especially for strong surge composites. This is an important finding as blocking patterns tend to slow storm movement and can enhance onshore flow from a tightening pressure gradient between surface low pressure (often located off the Mid-Atlantic coast) and high pressure (often located across New England) systems. Slow storm movement and/or large systems increase both the duration and maximum height of an event leading to large power. The longer surge duration also increases the likelihood of a surge event peaking near a high tide, or during multiple high tides, exacerbating the impacts (i.e. Munroe and Curtis 2017).

Anomalous ridging and blocking patterns were most commonplace during DJF strong-surge event composites, especially during -NAO, +/- PNA, and El Niño. This makes sense as added energy from the equatorial Pacific Ocean during El Niño favors a more energetic and higher amplitude jet stream pattern, increasing the intensity of mid-latitude blocking patterns in particular with –NAO tied more to the frequency of mid-latitude blocking near eastern North America (i.e. Shabbar et al. 2001; Barriopedro et al. 2006). This finding is supported by Bernhardt and DeGaetano (2012), who found that the combined effects of El Nino and -NAO favors slower moving extratropical cyclones. The PNA case is more interesting as both phases produced a blocking signal. However, the +PNA case was much more frequent and/or stronger as would be expected, as anomalously strong troughing over eastern North America associated with a +PNA favors more frequent and stronger extratropical cyclones in the region. For ASO, anomalous ridging and blocking were less significant, possibly owing to the inclusion of both extratropical and tropical cyclones and the seasonal poleward retreat of the jet stream. Surface ridging or high pressure was a larger factor overall, especially for +NAO and El Niño.

Overall these results compare fairly well with the suggested mechanisms in Munroe and Curtis (2017). It seems that slower moving cyclones and large slow moving anticyclones (high-pressure systems) were the main drivers for surge events, especially stronger events. However, larger cyclones likely played a role at times similar to Sandy (2012). Interestingly, Munroe and Curtis (2017) found the ENSO to be the biggest driver for storm surge as compared with PNA and NAO (second and third respectively) during DJF cool season, and all three displayed substantial upper level atmospheric anomalies. Along those lines, +/- PNA composites indicated that this climate teleconnection can support a significant blocking pattern during DJF, as noted particularly during strong surges. Although less frequent, -PNA had a greater mean power than +PNA. However, as suggested earlier, a relatively small sample size for each may somewhat reduce the value of this finding. Interestingly, no significant anomaly was found related to the Bermuda High in any of the ASO 500 mb anomaly composites, contrary to that suggested in Munroe and Curtis (2017), indicating that this is unlikely to be a common factor for both extratropical and tropical cyclones during this time period. Synoptic and climate oscillation patterns shown to be favorable for strong versus weak surge events in different seasons in this study could be used to enhance pattern recognition capabilities of forecasters. This process may support their awareness of storm surge potential over time and confidence from daily through seasonal time scales. This increased awareness would then allow them to enhance services to partners and the public alike through earlier notification of potential impending events with additional information related to forecaster confidence.

In an effort to more closely align the science of storm surge to storm surge users' needs, it is hoped that the findings from this research can assist operational weather and climate forecasters in better determining the risk for storm surge at lead times beyond what is currently available and complement other advancements in storm surge modeling and forecasting in the near term. If useful, this study could be replicated for other parts of the country or world for both extratropical and/or tropical cyclones.

CONCLUSION

This research developed a statistical and synoptic climatology (chapters one and three) related to storm surge along the Outer Banks of North Carolina. Chapter one found statistically significant relationships between ENSO, PNA, and, NAO and a variety of storm surge characteristics with storm surge power being the most significant, especially during the winter and to a lesser extent spring. As anticipated, +ENSO, +PNA, and -NAO generally supported stronger and more frequent surge events in both winter and spring months. Relationships during the summer and fall overall were less significant with PNA being the main driver for tropical systems. These findings from chapter one helped to inform the direction of research for chapters two and three.

Chapter two explored storm surge users needs based out of Eastern North Carolina using a survey tool. Storm surge users comprised mainly of emergency support personnel found that additional storm surge information including most of the storm surge characteristics introduced in chapter one would be useful. Many users also found that storm surge information at lead times up to several weeks or even months in advance could be beneficial, even while acknowledging less detailed and accurate information at these increasing lead times.

Chapter three assessed synoptic conditions related to storm surge and focused on the power variable (summation of height squared over time). The selection of the power variable as the main descriptor of storm surge has the advantage that it incorporates information related to maximum surge height and duration. Among the available variables, storm surge power is also likely the most closely associated with impacts at the coast. Anomalous ridging and blocking patterns were commonplace during DJF and especially for composites related to strong surge events. Results from chapter three compare fairly well with the suggested mechanisms from chapter one. It seems that slower moving cyclones and large slow-moving anticyclones (high pressure systems) were the main drivers for surge events, especially stronger events. However, larger cyclones likely also played a role at times similar to Sandy (2012).

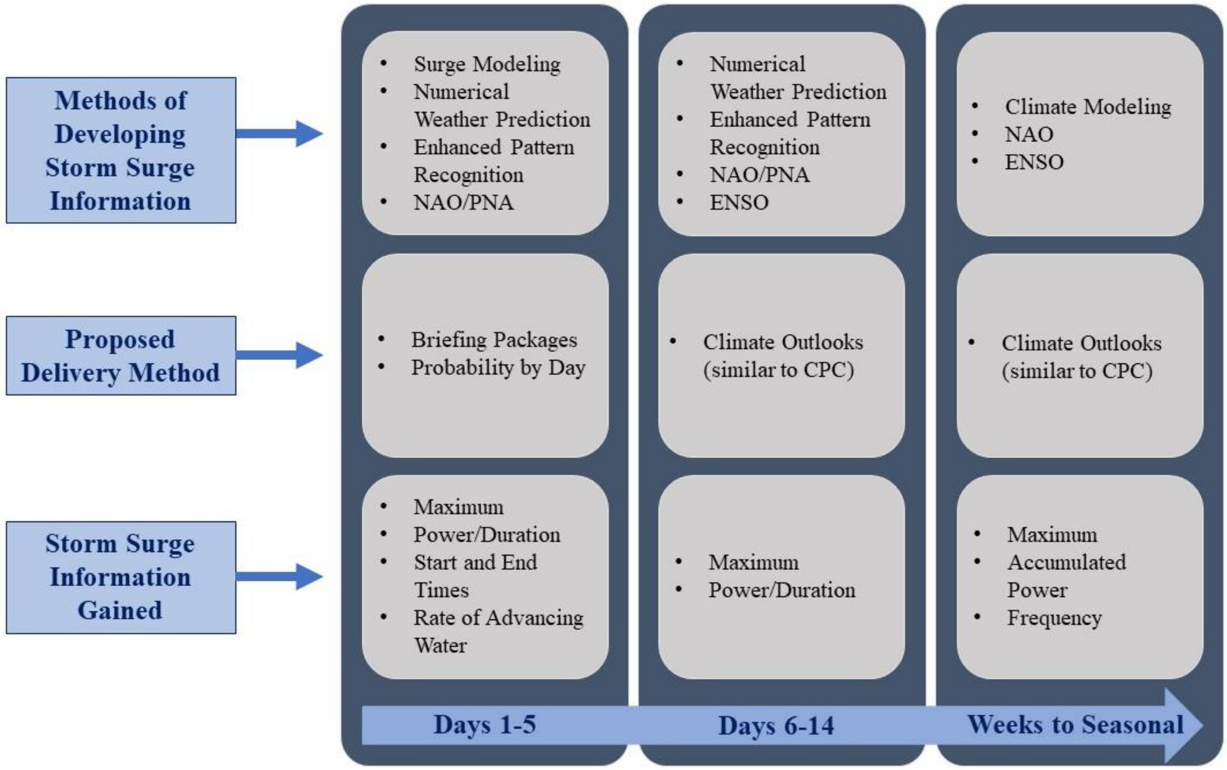


Figure 29. Tiered approach to storm surge prediction and delivery including additional types of surge information. Bulleted information within each text box is organized from more to less valuable from top to bottom. CPC is the Climate Prediction Center.

A proposed tiered approach for developing and disseminating storm surge information (Figure 29) incorporates the findings of all three chapters. Along the bottom of the graphic are three distinct time frames of interest to end users with less detailed information and greater uncertainty at the longer lead times, especially the far right column. All three time scales use similar methods for producing storm surge information (top row), including numerical and analogue modeling as well as a statistical based approach. For clarification, the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model currently used to produce storm surge forecasts from the NHC would fall under the surge modeling category. Numerical weather prediction (i.e. GFS) and climate modeling as well as climate oscillations (i.e. ENSO) go hand in hand with enhanced pattern recognition as it relates to storm surge. For example, we learned in chapter three that large and slow moving systems near a point of interest, often associated with blocking patterns, are at the greatest risk for producing higher power surge events. Thus, one would look for these type of patterns in the realm of weather or climate prediction. Relationships between climate oscillations and storm surge developed in chapter one could provide additional value especially at weekly to seasonal time scales. The proposed delivery method at each time scale (middle row) is closely tied to feedback from the chapter two survey and would be intended for the NWS (including NHC) and the CPC. The NWS already provides briefing packages or similar type products and it was a top choice for storm surge users based out of Eastern North Carolina. Climate outlooks were also a popular choice at longer lead times and could follow other CPC products (i.e. divide the second period into 6-9 and 10-14 day periods). The final row suggests additional types of storm surge information at increased lead times, which were both popular options within the surge survey (chapter two) and where atmospheric and climate relationships, uncovered in chapters one and three, would likely be capable of meeting that need. As described in greater detail in the conclusion of chapter two, the best approach to producing enhanced storm surge products and services to meet surge users' needs would be to include a subset of users in the development process. This would increase the likelihood of best matching the science to users' needs all while maintaining reasonable expectations of the enhanced products and services to come.

The main goal of this dissertation was to explore the potential to further match storm surge users' needs with the developing science. Chapters one and three among other recent work (i.e. Wakelin 2003, DeGaetano 2008, Sweet and Zervas 2011, Thompson et al. 2014, Munroe and Curtis 2017, Sheridan et al. 2019) show the great potential for additional types of information and at greater lead times desired by some surge users (chapter two) through weather and climate related modeling and enhanced pattern recognition by forecasters. It is hoped that this research will help to inspire related weather and climate surge products that will further meet surge users' needs and, in the process, reduce the impacts of storm surge at the coast.

REFERENCES

Barriopedro D, García-Herrera R, Lupo AR, Hernández, E (2006) A climatology of Northern Hemisphere blocking. J. *Clim*. **19**, 1042–1063

Bell C, Gray L, Charlton-Perez A, Joshi M, Scaife A (2009) Stratospheric communication of El Niño teleconnections to European winter. *Journal of Climate* 22:4083-4096

Bernhardt J and DeGaetano A (2012) Meteorological factors affecting the speed of movement and related impacts of extratropical cyclones along the U.S. East Coast. *Natural Hazards* 61:1463-1472

Bradford, R A, O'Sullivan J J, I M van der Craats, Krywkow J, Rotko P, Aaltonen J, Bonaiuto M, De Deominicis S, Waylen K, and Schelfaut K (2012) Risk perception – Issues for flood management in Europe. Nat. Hazards Earth Syst. Sci., 12, 2299-2309.

Carr RE, Montz B, Semmens K, Maxfield K, Hoekstra S, and Goldman E (2016) Motivating action under uncertain conditions: Enhancing emergency briefings during coastal storms. Wea. Climate Soc. 8, 421-434.

Catalano A J and Broccoli A J (2018) Synoptic characteristics of surge producing extratropical cyclones along the northeast coast of the United States. J. Appl. Meteor. Climatol. 57, 171-184.

Cazenave A and Llovel W (2010) Contemporary sea level rise. *Annual Review of Marine Science* 2:145-173

Chen W and Dool H V (2003) Sensitivity of teleconnection patterns to the sign of their primary action center. *Monthly Weather Review* 131:2885–2899

Colle B A, Rojowsky K, and Buonaito F (2010) New York City storm surges: Climatology and an analysis of the wind and cyclone evolution. *Journal of Applied Meteorology and Climatology* 49:85-100

Curtis S (2006) Developing a climatology of the South's 'other' storm season. *Southeastern Geographer* 46:231-244

Davis E and Dolan R (1993) Nor'Easters. *American Scientist* 81(5) 428-439

Dangendorf S, Wahl T, Hein H, Jensen J, Mai S, and Mudersbach C (2012) Mean sea level variability and influence of the North Atlantic Oscillation on long-term trends in the German Bight. *Water* 4:170-195

Demeritt D, Nobert S, Closea H, and Papperberger F (2010) Challenges in communicating and using ensembles in operational flood forecasting. *Meteorol, Appl.* 12:209-222

Dillon R L, Tinsley C H, and Cronin M (2011) Why near-miss events can decrease and individual's protective responses to hurricanes. *Risk Anal.* 31:440-449

Dolan R, Davis R (1994) Coastal storm hazards. *Journal of Coastal Research* 12:103-144

D'Onofrio E, Fiore M, and Romero S (1999) Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. *Continental Shelf Research* 19:1681-1693

DeGaetano A (2008) Predictability of seasonal east coast winter storm surge impacts with application to New York's Long Island. *Meteorological Applications* 15:231-242

Eastern Region Group (ERG) (2013) Storm surge marketing: Audience analysis final report. Retrieved from: http://coast.noaa.gov/digitalcoast/sites/default/files/files/1377204582/storm-surge-marketing.pdf

Gray W (1984) Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation influences. *Monthly Weather Review* 112:1649–1668

Hall R, Erdelyi R, Hanna E, Jones J, and Scaife A (2015) Drivers of North Atlantic Polar Front jet stream variability. *International Journal of Climatology* 35:1697-1720

Hirsch M, DeGaetano A, and Colucci S (2001) An East Coast winter storm climatology. *Journal of Climate* 14:882-899

Hoekstra S and Montz B (2017a) Decisions under duress: Factors influencing emergency management decision making during Superstorm Sandy. *Nat. Hazards* **88**(1):453-471

Hoekstra S and Montz, B (2017b) The inside story: Timeline of events and communication leading up to superstorm sandy from the emergency manager perspective. *Enviro Hazards* **16**(4):330-344

Huang W, Xu S, and Nnaji S (2008) Evaluation of GEV model for frequency analysis of annual maximum water levels in the coast of the United States. *Ocean Engineering* 35:1132-1147

Hurrel J and Deser C (2009) North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems* 78:28-41

Intergovernmental Panel on Climate Change (2019) The Ocean and Cryosphere in a Changing Climate. 51th Session of the IPCC, Principality of Monaco

Jonkman S N, Bočkarjova M, Kok M, and Bernardini P (2008) Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecological Economics* 66(1): 77-90

Kemp A C, Horton B P, Culver S J, Corbett D R, van de Plassche O, Gehrels W R, Douglas BC, and Parnell A C (2009) Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology* 37:1035-1038

Landry C, Hindsley P (2007) Willingness to pay for risk reduction and amenities: Applications of the Hedonic Price Method in the coastal zone. *Conference Proceedings of the 2006 Living Shoreline Summit* 105-110

Landsea C, Bell G, Gray W, and Goldenberg S (1998) The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts. *Monthly Weather Review* 126:1174-1193

Larson J, Zhou Y, and Higgins RW (2005) Characteristics of landfalling tropical cyclones in the United States and Mexico: Climatology and interannual variability. *Journal of Climate* 18:4601-4620

Lazo, J and B Morrow (2013) Survey of Coastal U.S. Public's Perspective on Extra Tropical – Tropical Cyclone Storm Surge Information. NCAR Societal Impacts Program

Lindell M K and R W Perry (2012) The protective action decision model: Theoretical modifications and additional evidence. Risk Anal. 32:616-632

Liu K and Fearn M (2000) Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from Lake Sediment records. *Quaternary Research* 54:238-245

Losego J, Galluppi K, Montz B, Smith C, and Schotz S (2012) Weather for Emergency Management: Implications for NWS tropical weather products and services. *American Meteorological Society: Seventh Symposium on Policy and Socio-Economic Research*

Meyer R, Baker J, Broad K, Czajkowski J, and Orlove B (2014) The dynamics of hurricane risk perception: Real-time evidence from the 2012 Atlantic Hurricane Season. *Bull. Amer. Meteor. Soc.* **95**(9):1389-1404

Morrow B, Lazo L, Rhome J, and Feyen J (2015) Improving storm surge risk communication: Stakeholder perspectives. *Bull. Amer. Meteor. Soc.* 96:35-48

Morrow, B, and J Lazo (2013) Broadcast media on-line survey on extratropical and tropical cyclone forecast information: NOAA Storm Surge Roadmap and hurricane forecast improvement program. NCAR Tech. Note NCAR/TN-498+STR, 83 pp., doi:10.5065/D69P2ZM1

Morss, R E, O V Wilhelmi, G A Meehl, and L Dilling (2011) Improving societal outcomes of extreme weather in a changing climate: An integrated perspective. *Annu. Rev. Env. Resour.* 36:1-25

Munroe R, Crawford T, and Curtis S (2014) Geospatial analysis of space-time patterning of ENSO forced daily precipitation distributions in the Gulf of Mexico. *Professional Geographer* 66:91-101

Munroe R and Curtis S (2017) Storm surge evolution and its relationship to climate oscillations at Duck, NC. *Theor. Appl. Climatol*. **129**(1):185-200

Munroe R, Montz B, and Curtis S (2018) Getting more out of storm surge forecasts: emergency support personnel needs in North Carolina. *WCAS* **10**:813-820. © American Meteorological Society. Used with permission.

Murphy RE, Lazo JK, and Demuth J (2010) Examining the use of weather forecasts in decision scenarios: Results from a US survey with implications for uncertainty communication. *Meteorol. Appl*. **17**:149-162

Ferreira RN, Hall L, and Rickenbach TM (2013) A climatology of the structure, evolution, and propagation of midlatitude cyclones in the southeast United States. *Journal of Climate* **26**(21): 8406-8421

NOAA Earth System Research Laboratory, Physical Sciences Division. Accessed from: https://www.esrl.noaa.gov/psd/data/composites/subdaily_20thc/

NOAA (2013) Storm surge related statistics. Retrieved from: http://www.nhc.noaa.gov/surge/

NOAA (2014) Retrieved from: http://www.noaawatch.gov/themes/coastal_inundation.php

NOAA (2017) http://www.nhc.noaa.gov/news/20170123_pa_SSWW.pdf

Olbert AI and Hartnett M (2010) Storms and surges in Irish coastal waters. *Ocean Modelling* 34 50-62

Prandle D and Wolf J (1978) The interaction of surge and tide in the North Sea and River Thames. *Geophysical Journal of the Royal Astronomical Society* 55:203–216

Rappaport E (2014) Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bulletin of the American Meteorological Society* 95:341–346

Rego JL and Li C (2009) On the importance of the forward speed of hurricanes in storm surge forecasting: A numerical study. *Geophysical Research Letters* 36:L07609

Salmun H, Molod A, Buonaiuto F, Wisniewska K, and Clarke K (2009) East Coast cool-weather storms in the New York Metropolitan Region. *Journal of Applied Meteorology and Climatology* 48:2320-2330

Seierstad I, Stephenson D, and Kvamsto N (2007) How useful are teleconnection patterns for explaining variability in extratropical cyclone storminess? *Tellus* 59A:170-181

Shabbar A, Huang J, and Higuchi K (2001) The Relationship Between the Wintertime North Atlantic Oscillation and Blocking Episodes in the North Atlantic. *Int. J. Climatol*, **21**: 355-369

Sheridan S, Lee C, Adams R, Smith E, Pirhalla D, and Ransibrahmanakul V (2019) Temporal Modeling of Anomalous Coastal Sea Level Values Using Synoptic Climatological Patterns. *JGR Oceans* 124:6531-6544

Sweet WV and Zervas C (2011) Cool-season sea level anomalies and storm surges along the U.S. East Coast: Climatology and comparison with the 2009/10 El Niño . *Monthly Weather Review* 139:2290-2299

Tancreto A (1958) A method for forecasting the maximum surge at Boston due to extratropical storms. *Monthly Weather Review* 86:197-200

Thompson P, Mitchum G, Vonesch C, and Li J (2014) Variability of winter storminess in the eastern United States during the twentieth century from tide gauges. *Journal of Climate* 26:9713-9726

US Army Corps of Engineers Field Research Facility (Duck NC). Retrieved from http://www.frf.usacearmy.mil/

Valle-Levinson A, Olabarrieta M, and Valle A (2013) Semidiurnal perturbations to the surge of Hurricane Sandy. *Geophysical Research Letters* 40: 2211-2217

Wakelin S, Woodworth PL, Flather A, Williams J A (2003) Sea-level dependence on the NAO over the NW European continental shelf. *Geophysical Research Letters* 30:1403

Walton T (2000) Distributions for storm surge extremes. *Ocean Engineering* 27:1279-1293

Warner N N and Tissot P E (2012) Storm flooding sensitivity to sea level rise for Galveston Bay, Texas. *Ocean Engineering* 44:23-32

Wood MM., Mileti DS, Kano M, Kelley MM, Regan R, and Bourque LB (2012) Communicating actionable risk for terrorism and other hazards. *Risk Analysis* 32:601–615

Ying L and Ngar-Cheung L (2012) Contributions of downstream eddy development to the teleconnection between ENSO and the atmospheric circulation over the North Atlantic. *Journal of Climate* 25:4993-5010

Zhang K, Douglas B, and Leatherman S (2000) Twentieth-Century storm activity along the U.S. East Coast. *Journal of Climate* 13:1748-1761

APPENDIX A: IRB APPROVAL

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · **www.ecu.edu/irb**

Notification of Initial Approval: Expedited

From:	Social/Behavioral IRB
To:	Robert Munroe
CC:	
	Burrell Montz Covey
Date:	6/2/2016
Re:	UMCIRB 16-000959 Survey of Storm Surge Users

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 6/2/2016 to 6/1/2017. The research study is eligible for review under expedited category # 7. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Name	Description
Munroe_Research.docx	Study Protocol or Grant Application
Munroe_Survey.docx	Surveys and Questionnaires
RecruitmentDocs.doc	Additional Items
Survey_consent_letter.docx	Consent Forms

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

APPENDIX B: COPY RIGHT PERMISSION FOR REUSE OF CHAPTER 1 ARTICLE

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Oct 21, 2019

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Licensed Content Title	Storm surge evolution and its relationship to climate oscillations at Duck, NC
Licensed Content Author	Robert Munroe, Scott Curtis
Licensed Content Date	Jan 1, 2016
Licensed Content Volume	129
Licensed Content Issue	1
Type of Use	Thesis/Dissertation
Requestor type	academic/university or research institute
Format	print and electronic
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Will you be translating?	no
Circulation/distribution	1 - 29
Author of this Springer Nature content	yes
Title	WHERE THE SCIENCE MEETS USERS NEEDS: STORM SURGE IN EASTERN NC
Institution name	East Carolina University
Expected presentation date	Oct 2019
Requestor Location	Mr. Robert Munroe 12 breckenridge court GREENVILLE, SC 29615 United States Attn: Mr. Robert Munroe
Total	**0.00 USD**

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Best,

Ms. Erin Gumbel, she/her/hers
Peer Review Support Assistant
Permissions Specialist
American Meteorological Society

APPENDIX D: STORM SURGE USER SURVEY

Storm Surge User Survey

The purpose of this survey is to better understand user needs for storm surge information. *Your contribution will be incorporated in developing potential surge related forecast products/ outlooks beyond currently available forecasts 3-5 days in advance of a surge event.*

1. What category best represents you?
Emergency Manager
National Weather Service
Private Company
Media
Private Citizen
Other: Please fill in here____

2. Briefly describe how you use storm surge information:

3. How does surge information currently benefit your operations?

4. A) How much time ahead of a potential storm surge event do you typically first learn of the possibility of the surge event? (Provide a range of values if applicable)

B) How much time before a potential surge event do you typically learn of the expected surge magnitude and timing? (Provide a range of values if applicable)

4. A) Please identify what you use storm surge information for. (Circle all that apply)
Evacuation (mandatory)
Evacuation (voluntary)
Road closures
Pre-event preparation (i.e. collecting resources/planning…protecting/moving property etc…)
Post-event response (rescue…clean up etc…)

Other:

B) What lead times are required for each selection?

Evacuation (mandatory)
Evacuation (voluntary)
Road closures
Pre-event preparation (i.e. collecting resources/planning…protecting/moving property etc…)
Post-event response (rescue…clean up etc…)
Other:

5. A) The longer the forecast or outlook the less detailed the information becomes. Which range of lead times would be beneficial to you, taking into consideration the amount of detail and type of information available, shown in parenthesis? (Circle all that apply)

a. Up to four days out. (Current surge modeling provides the most detailed storm surge information, including surge timing and expected magnitude)
b. Three days to a week out. (Detailed storm focused surge information)
c. 1-2 weeks out. (Probability of surge above a given magnitude (i.e. 20 percent chance of one foot surge over a given area) based less on individual storms and more on overall weather and climate pattern features)
d. Up to six months in advance at monthly scale. (Predict likelihood of above, near normal, or below normal surge frequency or highest surge magnitude over a given month)

B) Please list the above letters (a-d) from most to least important.

6. Storm surge prediction 4-7 days in advance of a potential storm surge event would be useful.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

7. Storm surge prediction 4 days to two weeks in advance of a potential storm surge event would be useful.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

8. Storm surge prediction for the upcoming month would be useful.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

9. A) What is the shortest lead time that would be beneficial to operations (refer to question 5 for an idea of how forecasts become less detailed further into the future)?

B) How would it be beneficial to your operations?

10. A) What is the longest lead time that would be beneficial to operations (refer to question 8 for an idea of how forecasts become less detailed further into the future)?

B) How would it be beneficial to your operations?

11. For what type of storms do you need surge information? (Choose all that apply)

a. Tropical Cyclones
b. Nor'easters (Winter Cyclones)
c. Storm type not important, only impacts of surge events
d. I don't use it

12. What type of surge information would be most beneficial? (Choose all that apply)

a. Probability of moderate or strong surge
b. Frequency of surge events
c. Length of surge (for example by number of hours or high tide cycles)
d. Other: Please describe______________________________

13. Storm surge height (i.e. above ground level) has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

14. Storm surge frequency across a given month or season has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

15. Storm surge duration (i.e. surge lasting across multiple high tide cycles) has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

16. Storm surge timing (starting time) has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

17. Storm surge timing (ending time) has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

18. Storm surge speed (how quickly water advances inland) has a significant impact on decision making related to operations.

1 (Disagree) 2 (Disagree Somewhat) 3 (Neutral) 4 (Agree Somewhat) 5 (Agree)

19. Is there additional surge information not covered above that would be helpful?

20. In what format would you like to see surge outlooks? (Choose all that apply)

a. Similar to other climate outlooks (maps by period i.e. 4-7, 7-10, 10-14 days, by month etc…)

b. Probability and possibly magnitude by day (out to two weeks similar to weather forecasts)

c. Weekly briefing packets for specified forecast period(s)

d. Other: please explain____

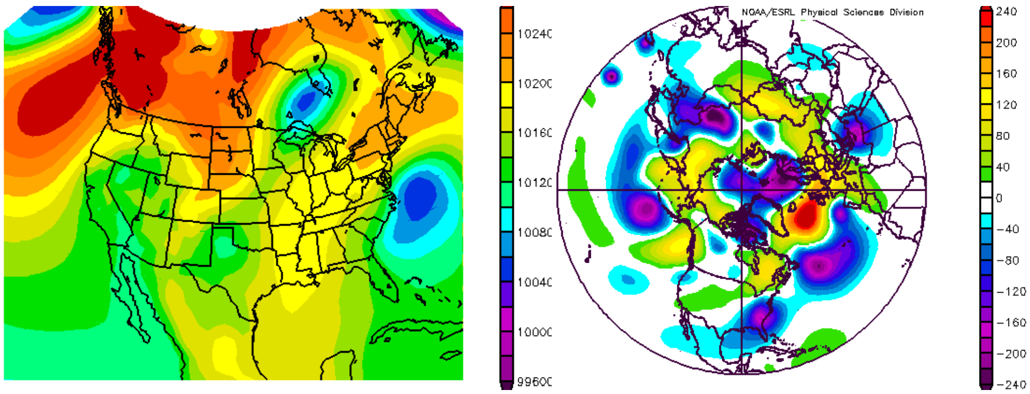
21. Please list any concerns you may have with surge outlooks at the weekly or monthly time scales.

Please add any additional thoughts/comments/concerns here:

Thank you for your time!

APPENDIX E: EXTREME EVENTS

High 10 with Increasing Power



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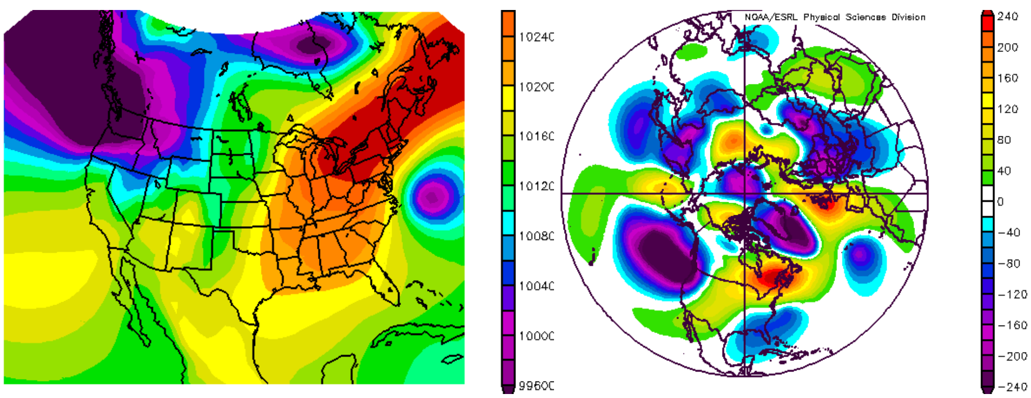

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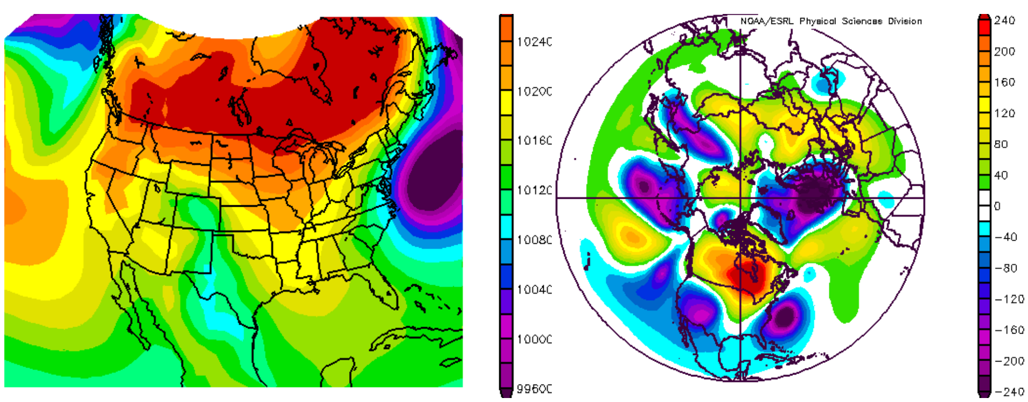

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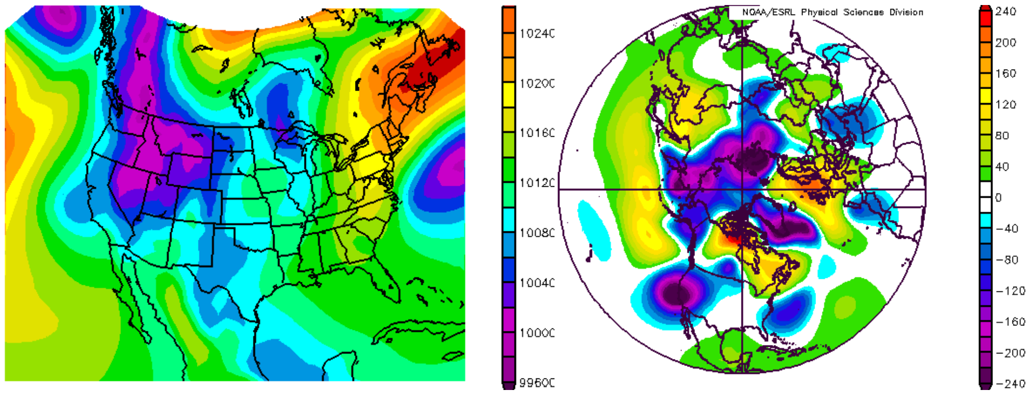

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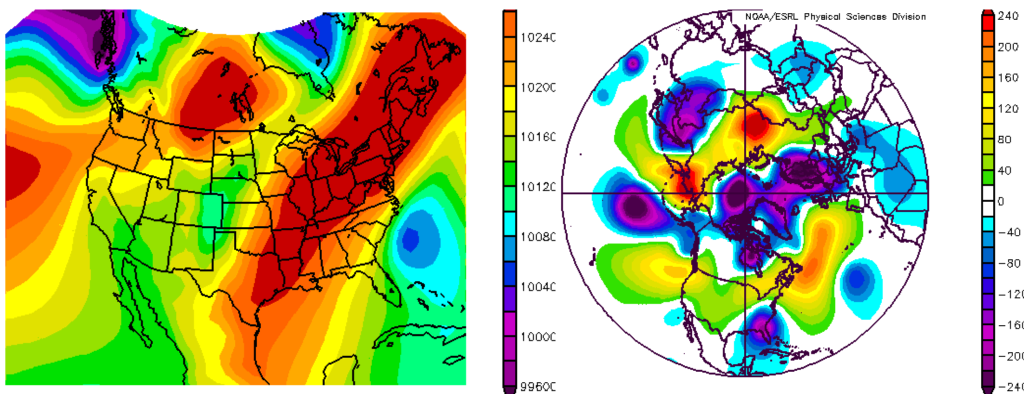

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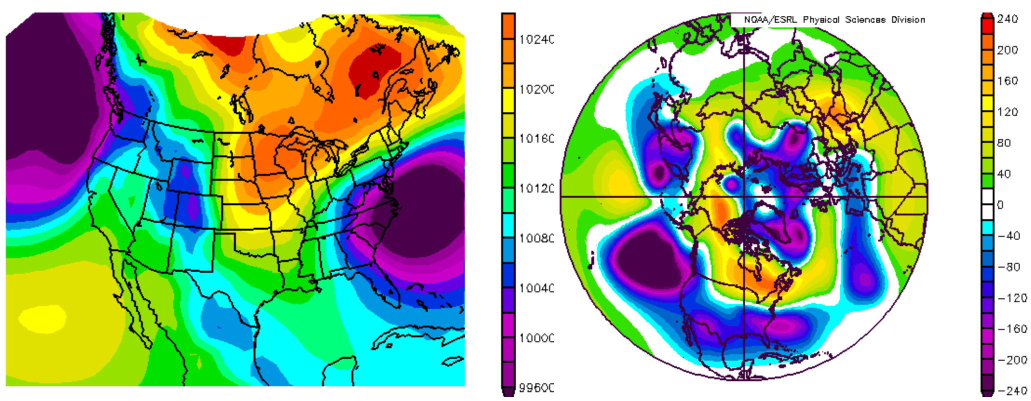

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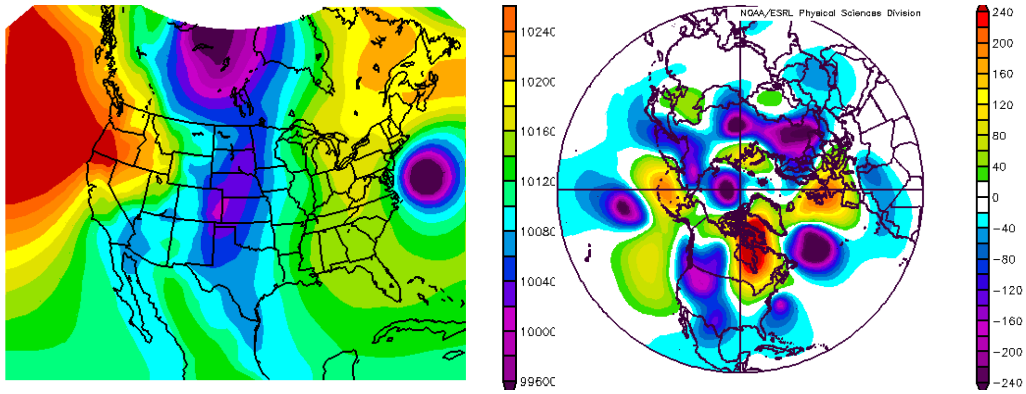

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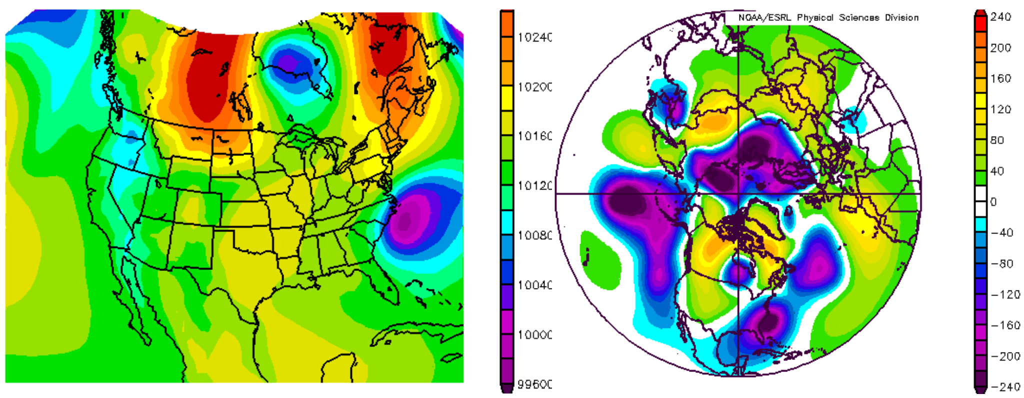

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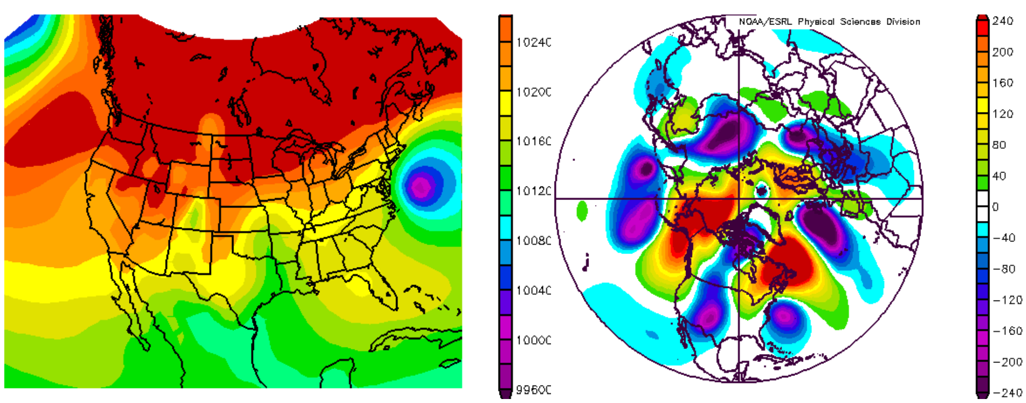

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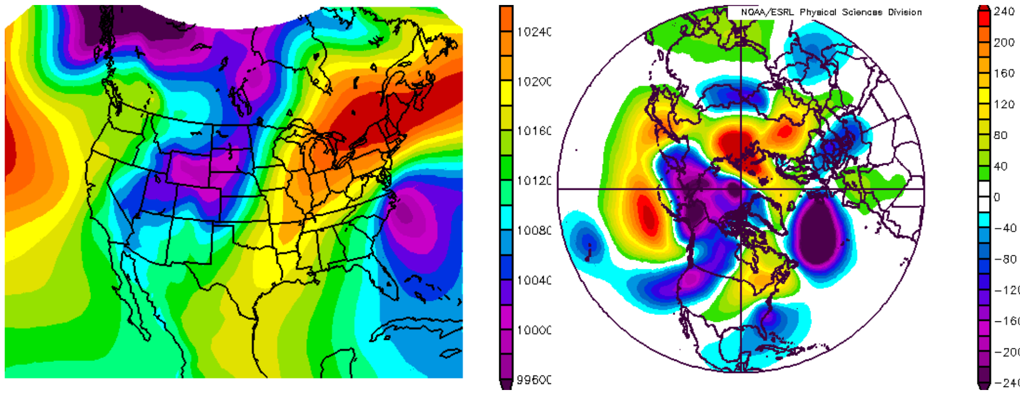

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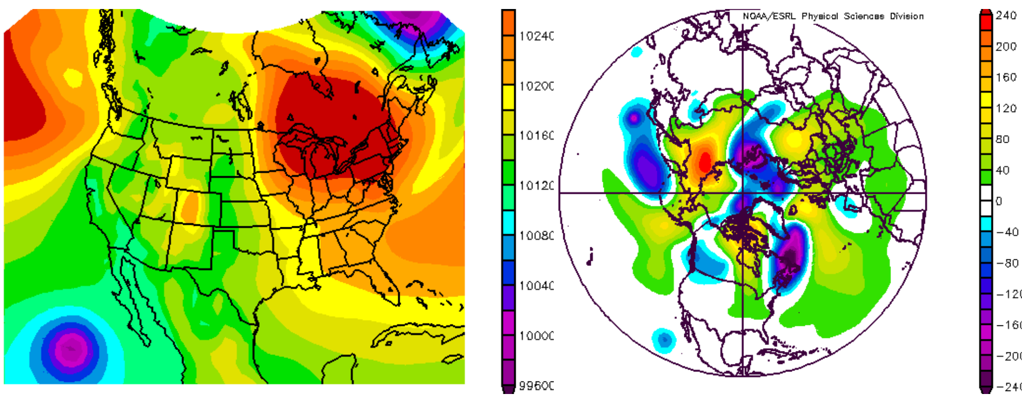
Low 10 with Increasing Power



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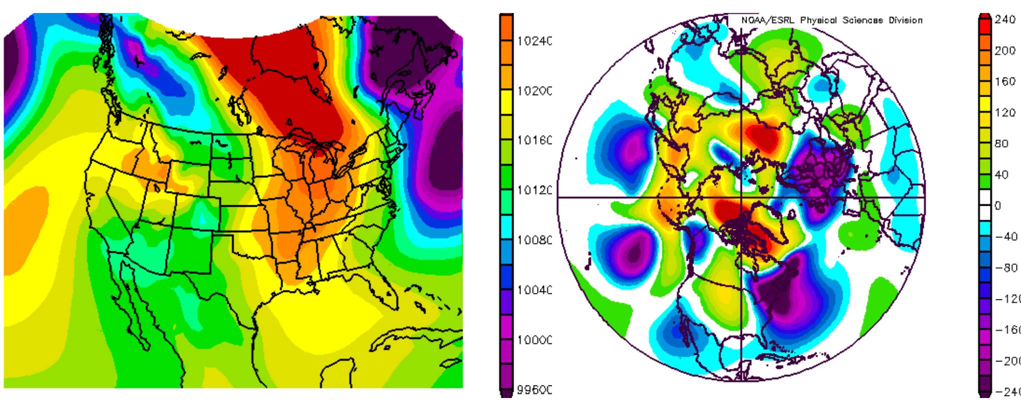

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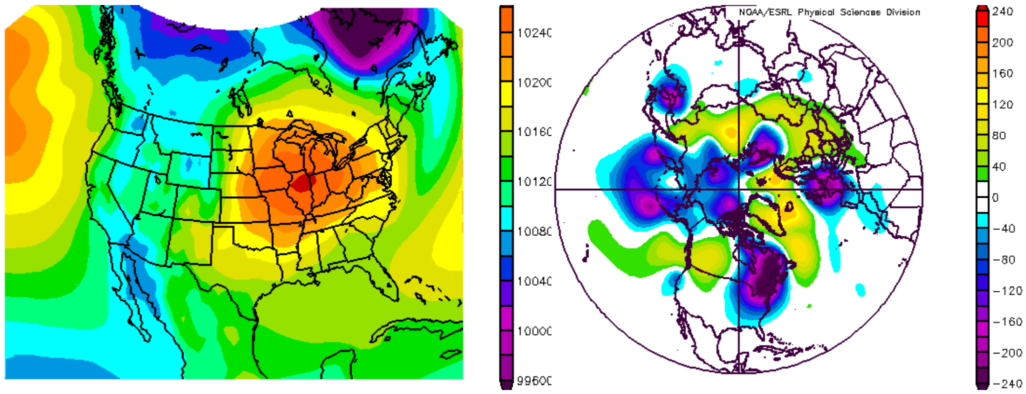

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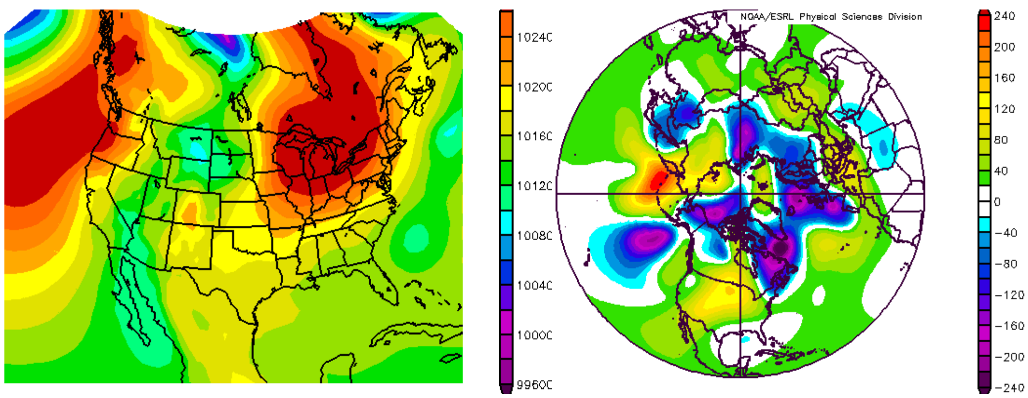

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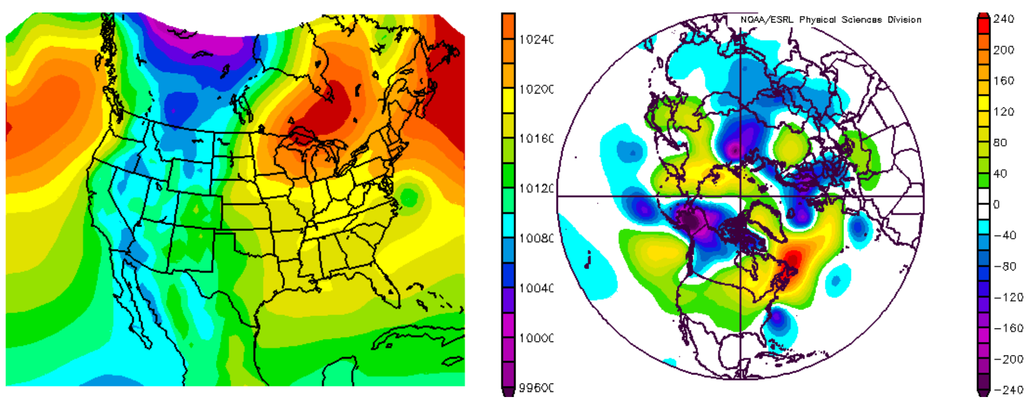

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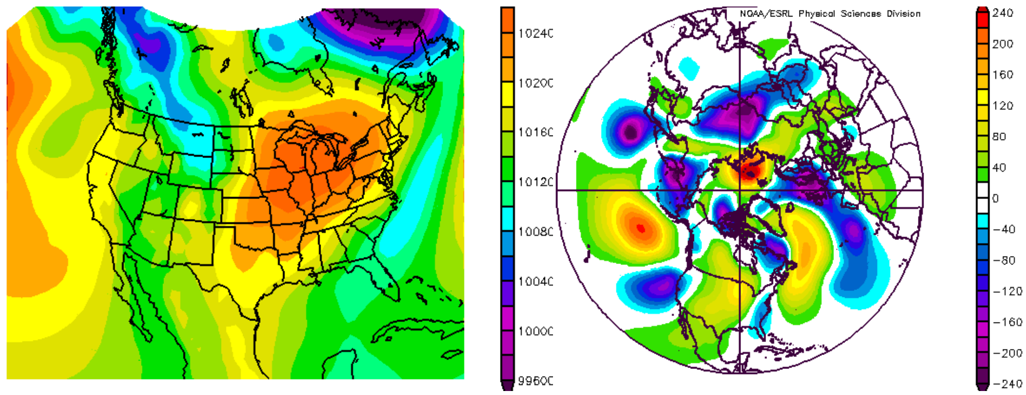

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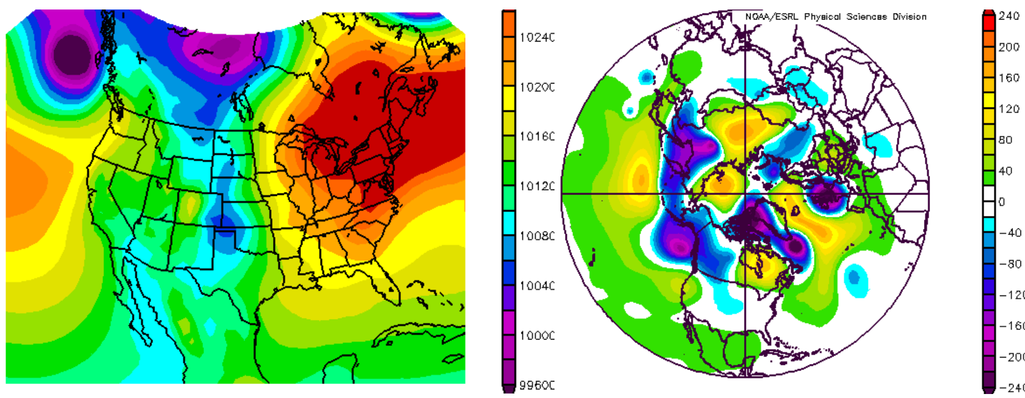

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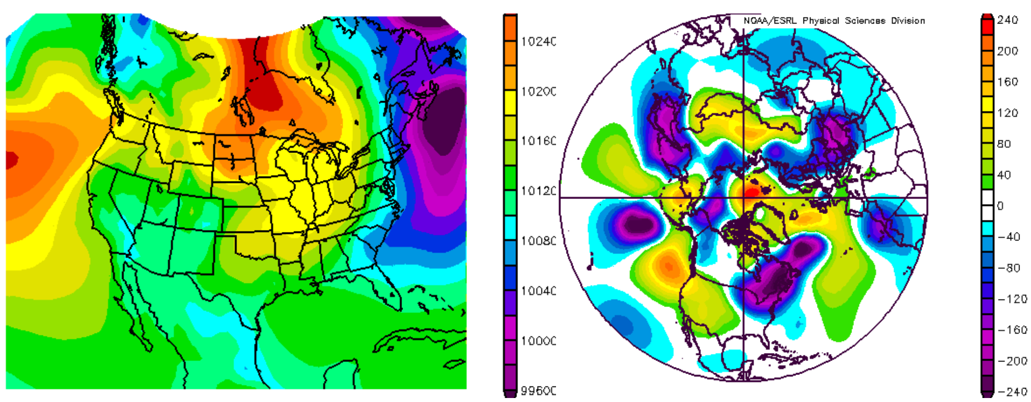

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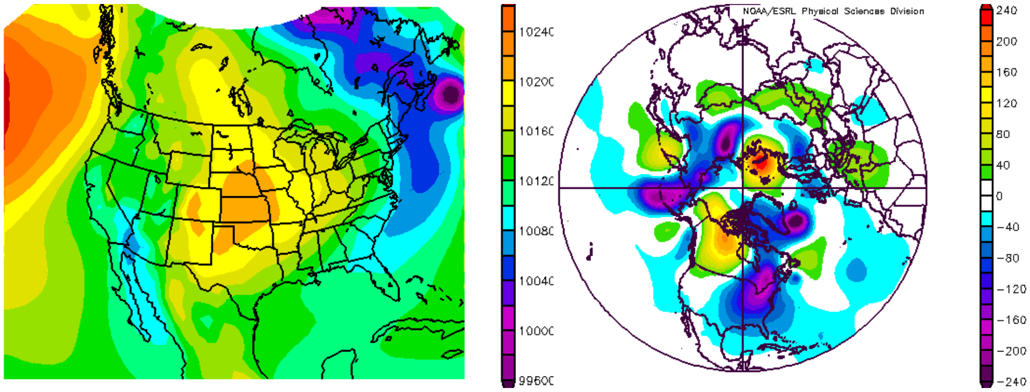

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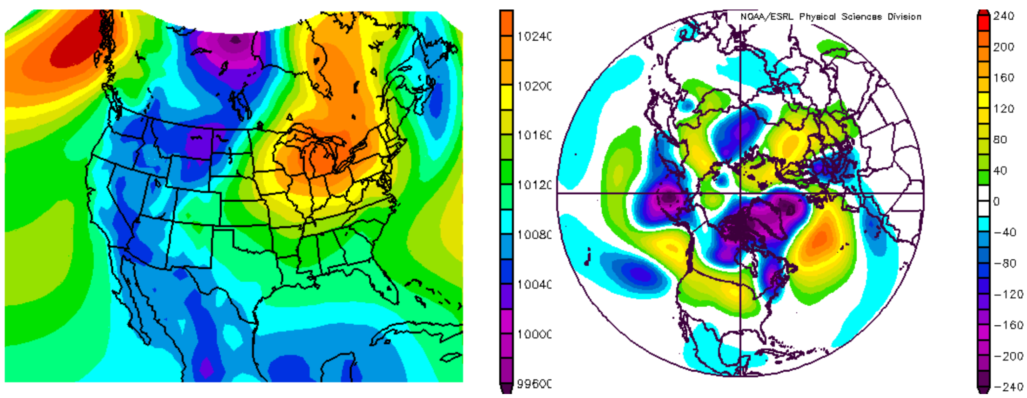

6/3/1986