KENT, TIMOTHY HARTT. Analysis of Meteorological and Oceanic Conditions During Rip Current Events Along the Outer Banks of North Carolina During the 2006 and 2007 Summer Seasons. (Under the direction of Lian Xie.)

Rip current events, as reported by lifesaving personnel along the North Carolina coast, from Duck to Nags Head, were examined during the 2006 and 2007 summer forecasting periods. Rip current events were analyzed in conjunction with various meteorological and oceanographic parameters that have been suggested to be important in the formation of rip currents elsewhere. It was found that the frequency of rip current rescues and reports increases most significantly for: 1) mean wave directions approaching shore normal 2) wind directions between 22.5 degrees and 90 degrees to shore 3) significant wave heights between 0.5 meters and 1.5 meters 4) dominant wave periods from 5-10 seconds. Surface weather maps were analyzed in an effort to assist forecasters in recognizing the weather patterns, which produce conditions that are favorable for rip current formation. The sources of ocean waves present along the NC coast during rip currents events were identified in order to determine, which types of weather systems, were most likely to produce waves that cause dangerous rips currents during the summer season. Waves generated by winds on the cold side of exiting frontal systems were found to be present on the most days with rip current reports. Storms in the South Atlantic, tropical cyclones, Atlantic high pressure systems, and prefrontal winds were responsible for generating the remainder of rip current producing waves during the summer season.

Examination of rip current events throughout the study region revealed several similarities to prior research conducted in other regions. However, some of the wave and
wind conditions, and meteorological patterns, that may create conditions favorable for
the generation of rip currents in the study region appear to be unique. Additionally,
several simulations of wave conditions, across the study region and adjacent waters,
were completed using the Simulating WAves Nearshore (SWAN) model. The simulations
depict the important roll distantly generated swells play in the forcing of rip currents
under certain conditions. A large variation in wave heights across a fairly small stretch
of coastline is also shown by the SWAN simulations. This suggests, that separate sets
of parameters and weather patterns may need to be used to predict rip currents along
adjacent coastlines.

Several changes to the current rip current forecasting scheme, utilized by the National
Weather Service Weather Forecasting Office in Morehead City, NC were made, in the
hopes of improving forecast accuracy. A directional dependency was placed on both wind
speed and wave data, so that near shore normal directions result in higher weighting. A
reduction in the overall wind factor was also placed into the forecast scheme. The swell
height/period matrix was expanded to account for short and very long period waves.
Finally, a strong offshore wind dissipation factor was added to the forecast scheme, which
reduces the overall swell weighting if offshore winds greater than 10 knots are present.
A unbiased performance evaluation of the present Morehead City rip current forecast
scheme, and the newly adjusted scheme was completed. The newly adjusted rip current
forecast scheme exhibited a significant improvement in forecast performance over the
present rip current forecast scheme, predicting more rip current rescue and report days.
Analysis of Meteorological and Oceanic Conditions During Rip Current Events Along the Outer Banks of North Carolina During the 2006 and 2007 Summer Seasons

by
Timothy Hartt Kent

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science in Marine, Earth, and Atmospheric Sciences Raleigh, North Carolina 2008

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Biography

Timothy Hartt Kent was born in Norwalk, Connecticut. He then moved to Irvine, California at the age of two. His family then relocated once more to Florence, South Carolina, where they currently reside. After attending high school at Florence Christian School, he began his undergraduate career at The College of Charleston. After receiving a Bachelor of Science in Physics, he applied to graduate schools to pursue a masters of science degree in Atmospheric Science. He chose NC State, out of several other programs, and began his graduate career in the fall of 2005.
Acknowledgements

I wish to thank Dr. Lian Xie, my advisor and chairman of the committee for his patience and direction throughout my program of study. His depth of knowledge across multiple areas enabled proper evaluation of all relevant issues.

I want to thank my committee members: Dr. Shaw and Dr. Raman. Both have been receptive to questions and have provided valuable feedback throughout the research process.

In addition, I would like to thank the members of the CFDL, specifically Xuejin Zhang and Huiqing Liu for their patience and many insightful discussions through the past few years. I would also like to extend my thanks to Dr. Hanson and Eve Devaliere from the FRF, for their help with SWAN in the early stages.

I would also like to thank my parents, family and friends for their continued support and patience.
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Chapter 1

Introduction

1.1 Problem Statement and Description of Goals

An investigation of rip current reports in concert, with wind and wave measurements, was completed to determine the relevant factors in the formation of rip currents along the northern Outer Banks of N.C. The beaches stretching from the town of Duck to Nags Head encompass the study area. The study area contains the most densely populated stretch of coastline within Dare and Currituck Counties. The region is also a popular tourist and vacation destination. In 2005 over 12 million people visited the coastal regions of N.C., many of these people undoubtedly spent time at one of our states hundreds of kilometers of beaches (Travel International 2005). Many of these people may be unfamiliar with the ocean and the hidden hazards within the surf zone. In the past 15 years, over 2,000 rip current related rescue’s, were conducted at lifeguard monitored Outer Banks beaches alone (USLA 2007). The study region beaches are characterized by long shore bar and trough morphology, which are the type of beaches most commonly associated with rip currents (Larson 2000, Wright and Short 1984). Although the average rip current does not pose a threat to most bathers, strong rip currents may generate flow
velocities that even a strong swimmer cannot overcome. Trying to fight a strong rip current by swimming against it may result in exhaustion and drowning.

In response to the ongoing coastal threat rip currents pose, the National Weather Service (NWS), along with the National Oceanic and Atmospheric Administration (NOAA) Sea Grant and the US Lifesaving Association, has developed rip current forecasts for recreational beaches (Lascody 1998, Engle 2003, Lushine 1991). These forecasts have been modified for regional variations in relevant rip current driving factors, as it has been shown that no single set of parameters can be used to forecast rip currents along different coastlines (Schrader 2004, Lascody 1998, Lushine 1991). These forecasts are primarily disseminated to the public via local Weather Forecast Offices (WFO) websites, the National Weather Radio, and lifesaving officials. Significant skill has been demonstrated by several of these rip current indices, and refinement of them continues as the research and operational community come to understand more about the dynamic factors involved in the formation of rip currents (Lascody 1998, Engle 2003, Lushine 1991). A characterization of meteorological and oceanic conditions associated with rip current events along the northern Outer Banks of NC is lacking, thus it is the goal of this study to complete such an accurate portrayal, and to use those results to improve rip current forecasting in the study area.
Chapter 2

Rip Currents

2.1 Background

A rip current is generally defined as a fairly narrow, jet like current that transports water offshore at relatively high velocities. Offshore flow velocities of rip currents average around 0.3 m/s but have been observed to exceed 2 m/s (MacMahan et al. 2004). Rip currents are most commonly associated with beaches of the long shore bar-trough paradigm, and they typically form in rip channels, which are local indentations in the long shore sandbars (Wright and Short 1984). Rip currents form in response to variations in near shore bathymetry, incident wave field, and mean water level, and they are only one part of a slightly more complex near shore circulation system seen in Figure 2.1 (Shepard and Inman 1950).

The near shore circulation system may be described in three parts. The initial longshore variation in breaking wave heights on the offshore bars causes a longshore variation in the water level or wave set up described in Figure 2.2. Water then flows from areas of high setup to areas of comparatively low setup, in a long shore current parallel to the beach. Finally, once water has converged onto these areas of low setup the resulting
increase, in pressure is relieved by a flow seaward in the path of least resistance, most commonly a rip channel (USACE 2006, Haller 2002, Bowen 1969). It is this final offshore flow or “rip current” that poses the most risk to bathers as they may be swept out to deeper water (Dean and Dalrymple 2002).

Figure 2.1: Idealized schematic of rip current cell circulation.
Figure 2.2: Schematic of wave set up along a barred beach.

2.2 Rip Current Forcing

Several factors have been shown to be important in the formation, strength, frequency and spacing of rip currents. It has been shown that rip current formation and strength increases as incident wave height increases (Shepard 1941, Bowen 1969, Haller 2002). The direction of swell energy impacting the coast has also been shown to be important. Near shore-normal waves produce a larger shoreward transport of water than obliquely incident waves (USACE 2006). In one study, angles of incident wave direction within 20 degrees of normal to shore were correlated with increased rip current rescues (Engle 2003). Waves incident at more oblique angles produce stronger longshore currents and are substantially less likely to form strong rip currents (Gutierrez 2004).
Rip current rescues have been documented to occur during fair weather under decreasing swell and wind conditions, indicating bathers may perceive that the seemingly quiescent conditions are safe when in reality dangerous rip currents may still be present (Lushine 1991, Engle 2003, Lascody 1998). Modeling studies have shown longer peak wave periods increase rip current strength and occurrence (Johnson and Pattiaratchi 2006). Studies based on rescue data have shown more rip currents occurred on days when intermediate period waves were present, than on days dominated by short period wind swell or very long period swells (Engle 2003, Lascody 1998, Lushine 1991, Schrader 2004). In South Florida wind direction and strength was correlated with rip current occurrence. More rip current rescues occurred during and after periods of sustained strong onshore winds, implying, that locally generated water rises and wind swells may also be important in the formation of rip currents at some locations (Lushine 1991). However, later research in central Florida showed no evidence to suggest, that local winds play a role in rip current formation (Engle 2003).

The beach terrain and near shore bathymetry are also important factors in the formation of rip currents, and in determining the types of breakers that will occur in the surf zone (Larson 2000, USACE 2006). Variations in the near shore bathymetry, such as, offshore canyons, ridges, and sandbars alter the incident wave field, determining which locations receive the most wave energy at the shore (Long et al 2005). As noted earlier, variations in the long shore wave field result in longshore currents, which may converge and redirect offshore as rip currents (Haller 2002, Bowen 1969). Wave-wave interaction in the surf zone may be a rip current forcing mechanism under certain conditions as well. If two wave trains of separate frequencies and incident directions approach the shore, positive super-positioning of energies may result, producing the necessary longshore variation in the incident wave field (Fowler 1990). The timing and spacing of this positive interaction is dependant on the difference in the wave group frequencies. When the waves
break, variations in the wave set up will occur throughout the surf zone, and rip currents may periodically form and slowly migrate alongshore (Dalrymple 1975, Johnson and Pattiaratchi 2006).

It is generally thought that beaches with a steep slope and narrow surf zone are less conducive for the formation of rip currents because they enable less shoreward transport of water, thereby decreasing the strength of the long shore currents and their resulting transformation into rip currents (USACE 2006, Dronen 2002, Johnson and Pattiaratchi 2006). Similarly, there is strong evidence that tidal modulation of the surf zone can effect rip current formation by changing the width and depth of the surf zone. Shallow areas in the surf zone result in shoreward transport of water, while deep regions allow transport of water offshore (Haller 2002). Rip current intensity has been observed to increase during low tide (Cooke 1970, Sonu 1972, Brander and Short 2001). Laboratory studies also confirm that rip current intensity increases with decreasing water level (Dronen et al 2002). This increase in intensity is shown to be a result of more intense wave breaking on the long shore bar, which increases the shoreward flux of water. Additionally, rip channels become more constrained at low tide, thus they become more hydrodynamically efficient pathways (MacMahan 2005). There may however be a lower limit in the relation between decreasing water depth and rip current formation. Extreme low tides may cause the long shore bar to become too shallow or even dry, thereby restricting the flow of water through the long shore bar-trough surf zone. Conversely, depth in the surf zone and over the long shore bar is increased during high tide. This fact suggests, that offshore water transport over the bar is more readily facilitated across a larger area due to greater depth and weaker wave breaking during periods of high tide (Haller 2002, MacMahan 2005).

The beaches of the outer banks are relatively straight and two-dimensional, but cuspy and rip channel features may periodically be seen along the shore (Holland 1998). These features are thought to be a result of variations in the incident wave field and the
resulting surf zone currents. Additionally, beach cusps have been documented to form during decreasing wave conditions, a characteristic which they share with rip currents (Holland 1998, Lushine 1991, Engle 2003). Once established, rip channels may serve to re-enforce rip current circulations under certain conditions, by increasing the dissipation of waves within the rip current channels, which effectively increases the strength of long shore feeder currents and therefore the rip current itself (Haller 2002). Finally, natural and man made obstacles such as headlands, jetties, and piers often force rip currents by blocking long shore currents and redirecting them offshore.

2.3 Rip Current Forecasting

Recent improvements in shallow water wave models have made it possible to propagate ocean waves into the surf zone (Ris et al 1999, Booj et al 1999). Such a shallow water wave spectrum could be used to force a surf zone current model in order to simulate the occurrence and strength of rip currents. Currently the most computationally efficient modeling techniques, that realistically produce rip currents, are based on fixed surf zone and near shore bathymetry (Yu 2001, Johnson and Pattiaratchi 2006). However, the Outer Banks is known to have a fairly dynamic near shore morphology, even though individual longshore bar and rip channel systems have been observed to be fairly steady at the Duck US Army Corp of Engineers Field Research Facility, over periods of time, on the order of several weeks, (Holland 1998, Larson 2000, MacMahan et al 2000). This dynamic near shore morphology can result in rip current circulation systems that are not fixed in time or space. Some wave-current models have been coupled with morphodynamic models to produce more realistic interactions between waves, currents, and bottom topography, but these simulations are computationally demanding (Reniers 2004, Castelle et al 2006). Thus, it is currently not practical to model the occurrence or strength of rip currents in
real time for operational forecasts.

Therefore, a statistical approach to forecasting rip currents has been adopted by NOAA’s coastal NWS WFO’s. Several of the factors that have been suggested to influence rip current formation elsewhere are represented in a forecasting worksheet (see appendix A). The NWS Morehead City (MHX) forecast sheet is essentially based on the original East Central Florida Lushine Rip Current Scale (ECFL LURCS), with some adjustments made for coastline orientation that were adopted by adjacent NWS WFO’s (Lascody 1998). The sheet accounts for: wave height, wave period, wave direction, wind speed, wind direction, and tidal amplitude. These parameters are assigned a numeric weighting based on certain ranges of values, the weightings are then totaled to reveal the rip current risk for the day. Values greater than 5.5 denote a high risk of rip currents, implying that wave and/or wind conditions are favorable for the formation of dangerous rip currents. Values between 4 and 5.5 signify moderate rip current risk, implying that wave and/or wind conditions support the formation of strong and frequent rip currents. A low risk of rip currents is triggered for values below 4, and suggests, that wave and/or wind conditions do not support the formation of strong rip currents, including a qualifying statement warning, that rips currents may still occur especially in the vicinity of hard surf zone structures (NWS MHX 2007).

2.4 Rip Current Reporting

Rip currents have proven difficult to measure consistently due to their transient existence within the ever-shifting surf zone, and until relatively recently very few in situ measurements of rip current systems have been made (MacMahan et al 2005, Smith and Largier 1995). There is currently no system in place to continuously measure rip current strength along the Outer Banks. Lushine found, that records of rescues and drownings
due to rip currents, served as an effective empirical proxy for rip current occurrence in south Florida (Lushine 1991). Similar investigations conducted along the central East coast of Florida, yielded results that improved the forecasting of rip currents in that region (Engle 2003, Lascody 1998). To expand the data set, this study utilizes visual reports, in addition to rip current rescues records, as proxies for rip current occurrence. NWS MHX staff recorded reports of rip currents and rip current rescues from Duck to Nags Head during the summer of 2006 and 2007.

Although rip current rescues and reports are thought to be a fairly reliable indicator of rip current strength and occurrence, it is reasonable to assume, that not every day with rip currents was reported. Also, it is possible, that not every day with rip currents reported had strong enough rips to cause a swimmer distress. Additionally, days when rescues do not occur do not necessarily imply, that strong rip currents were not present. That being noted, rescue reports do provide an empirical record of strong rip current occurrence that is not affected by observer subjectivity. Beach population is likely a large factor in the number of rescues that occur on any given day. Beach population and the number of bathers may fluctuate, depending on beach conditions, potentially leading to more rescues on days with high beach attendance. Engle showed that normalizing numbers of rescues by the beach population, removed the population signal from the data (Engle 2003). Unfortunately, beach population was not recorded during the study period, thus precluding normalization of the rescue data by beach population.
Chapter 3

Data

3.1 Site Description

As noted above the study area, seen in Figure 3.1 consists of the beaches that stretch from the town of Duck N.C., South to the town of Nags Head N.C. The beaches and nearshore zone within the study area can be characterized as being relatively straight with sandy beaches. The surf zone bathymetry is fairly nondescript, with longshore bars and periodic rip channels. The slope of the intertidal zone is 1:12.5 and the offshore bottom slope is approximately 1:164. The median surf zone sediment grain is 0.50 to 1 millimeter (Holland 1998). This area was chosen for several reasons. First, it is a well-exposed coastline, with a very large swell window evident in Figure 3.2. Secondly, the area is densely populated during the summer months, which requires each township to employ beach and ocean rescue personnel, ensuring that there would be rescues and rip current report records. Thirdly, the US Army Corps of Engineers operates the Field Research Facility (USACE FRF) in Duck N.C. The FRF maintains several wave and wind measuring instruments on the beach, and at multiple locations throughout the nearshore zone. A total of four wave measurement devices exists within a 3 km² area, creating the
most dense wave data measuring network in N.C. Finally, the author has a longstanding
sentimental relationship with the area, and would be hard pressed to find another area
he would rather investigate.

Figure 3.1: Satellite image of the Northern coast of NC with the study area highlighted
Figure 3.2: Great circle routes displaying the study areas large swell window (courtesy of Stormsurf)

3.2 Data Acquisition and Description

Factors contained in the NWS MHX rip current forecast sheet (Appendix A) were examined during the period, from May 27th to September 22nd, to determine their merit as predictive indicators of rip currents. As noted earlier, these factors include: wave height, wave period, wave direction, wind speed, wind direction, and tidal levels. The
exclusion of tidal data from the current analysis is based on the strong agreement, within the theoretical and observational research base, that lower water levels do indeed create stronger rip currents (Sonu 1972, MacMahan et al 2005, Shepard et al 1941, Lushine 1991, Lascody 1998, Engle 2003). Wave data was acquired from the USACE waverider buoy, located offshore of the FRF in Duck at a depth of 17.4 meters. Missing waverider data was replaced with data from the USACE FRF phased array pressure gauge wave measuring set up in 8m of water depth, or data from National Data Buoy Center (NDBC) buoy 41004 was shoaled to a depth of 17.4 meters according to linear wave theory, assuming straight and parallel contours. Meteorological data was acquired from the USACE FRF weather monitoring station on the pier at a height of 19.34 meters, and missing data was replaced by the NDBC weather station at a height of 20.4 meters on the pier at Duck. Both wind and wave data were recorded roughly every three hours for a total of eight records per day, this was done in part, to reduce the noisiness of an already robust data set, and to allow for replacements of missing data with adjacent records in time. Wave and wind direction data were adjusted to account to for coastal orientation, so that 90 degrees would correspond to shore normal. Wind measurements were not adjusted to the standard 10 meter reference level from the observation elevation on the pier. Differences in wind speed and direction would be expected if the wind data were adjusted to the 10 meter reference level. However, since one of the goals of the current study is to determine relationships between available observations and rip current reports, it is reasonable to modify observations as little as possible.

Double-bar histograms presented below, depict the normalized frequency of occurrence of different ranges of wave and wind parameters, on both days with reports of rip currents, and for the entire period of record. The data record of each variable was partitioned into ranges, thus allowing the author to discern which values most commonly occur during the period of record. In 2003, Engle showed that this was an effective method in
determining the factors that varied significantly between the days with rip currents and those without (Engle 2003). Ranges of each variable that occur more frequently on days with rip current reports than for the entire period of record are of specific interest. Any range of occurrence, that is higher than “normal” on rip current days indicates, that range of the variable corresponds to a higher risk of rip currents when present in the records. As in Engle’s 2003 study, the sum of the squared difference (SSD) is presented for each wind and wave parameter. The SSD is a measure of correlation between days with rip reports and the wave or wind variable being depicted. The SSD does not determine if a correlation is positive or negative, it only reveals that there is a correlation. The larger the SSD value the stronger the correlation.

3.3 Wave and Wind Data

Significant wave height, is defined as the average of the highest one-third of waves, and is a frequently used measurement in ocean engineering, marine meteorology, and oceanography. Figure 3.3 displays the frequency of occurrence of significant wave heights on both days with rip current reports and for the entire period of record. Significant wave heights greater than 0.5 meters and less than 1.5 meters account for 83% of days with rip current reports, yet waves in that size range only occur during 69% of the entire data record. Wave heights between 0.5 meters and 1.5 meters accounted for 87% of rip current rescues. Significant wave heights SSD value of 0.09 is the highest of any of the variables investigated. The average wave height on days with rip current reports is 1.04 meters, which is slightly larger than the Army Corps of Engineers ten-year average value of 0.8 meters for roughly the same time period (USACE FRF 2008). In contrast to Engle’s 2003 research, where he found that wave heights less than 0.45 meters accounted for nearly 25% of rip current rescues, the present study found no reports of rip currents
when wave heights were below 0.5 meters (Engle 2003). Rip rescues and reports drop off dramatically for waves larger than 1.5 meters, even though it is likely that rip currents are occurring during periods of large surf. This drop in rip current reports and rescues is likely due to the fact, that during the summer season, large waves are relatively uncommon. Additionally, when the surf is large it may be more difficult to visually identify distinct rip current circulation cells, and it is likely that fewer people enter the water during periods of rough surf. The ratio of wave heights on rip current report days to wave heights during the entire data record over each range gives a more clear indication of the relative risk of rip currents for each range of wave heights. In Figure 3.4, it is evident that with the exception of waves between 2.25 meters and 3 meters, the probability of rip currents occurring increases with increasing wave heights.

![Graph: Significant Wave Height Rip Days vs Entire Record](image)

Figure 3.3: Frequency distribution of rip current reports and the entire data record for significant wave height. May 27th through September 22nd, 2006 and 2007.
Dominant wave period is defined as the wave period associated with the peak in the wave energy spectrum. Frequency of occurrence of dominant period for days with rip current reports and for the entire record is depicted in Figure 3.5, where it is evident that 76% of rip current reports occur when dominant wave periods are between 5 seconds and 10 seconds. This result agrees reasonably well with past research, which has found that intermediate wave periods between 7.5 and 9 seconds had the strongest correlation to reported rescues (Engle 2003, Schrader 2004). Unfortunately, peak periods do not give a clear range of values that differentiate days with rip current reports from those without, as 71% of the entire data record contains waves in the same 5-10 second range. Additionally, the low SSD value of 0.004 suggests, that the relationship between peak wave periods and rip current reports is not strong. Peak wave period on days with rip current reports is on average 8.529 seconds, almost exactly the same as the Army Corps of Engineers ten-year June, July, August, and September average value of 8.525 seconds (USACE FRF 2008). This suggests that either rip currents are possible under most wave period conditions, or that short crested waves are frequently present in the data record.
even on days when longer period waves are the dominant rip current forcing mechanism. Conversely, it is possible that rip currents on days dominated by short period wind swells are strongly controlled by nearshore bathymetry, that had been formed during prior rip current events (MacMahan et al 2000, MacMahan 2007).

![Peak Wave Period Rip Days vs Entire Data Record](image)

Figure 3.5: Frequency distribution of rip current reports and the entire data record for peak wave period. May 27th through September 22nd, 2006 and 2007.

Mean wave directions on rip current report days and during the entire data record are shown in Figure 3.6. On days with rip current reports and rip current rescues there is a strong grouping of wave directions between 67.5 degrees and 135 degrees. Wave directions beyond 45 degrees of shore normal account for only 15% of rip current reports and 16% of rip rescues. It is noted that none of the wave direction ranges occur significantly more on days with rip current reports than for the entire data record. This weak correlation is specified by the low SSD value of 0.0021. This close correspondence between wave direction on days with rip current reports, and days without may be due to the waverider buoys close proximity to shore, and relatively shallow depth. According to linear wave
theory deepwater waves containing any shoreward component will shoal, and become increasingly shore normal as they approach the surf zone. Therefore, it is not surprising that we see the majority of wave directions approaching shore normal at the waverider buoy location roughly 3 Kilometers from shore.

![North Coast Wave Direction Rip Days vs Entire Data Record](image)

Figure 3.6: Frequency distribution of rip current reports and the entire data record for mean wave direction. May 27th through September 22nd, 2006 and 2007.

Wind speeds on days with rip current reports and during the entire data record are displayed in Figure 3.7. Wind speeds between 2.5 m/s and 7.5 m/s account for 65% of all days with rip current reports and 69% of days with rip current rescues. The apparent lack of variation in wind speeds between days with rip current reports and the entire data record is evidenced by the low SSD value of 0.0042. Wind speeds in the fairly low 2.5 m/s to 7.5 m/s range are unlikely to actually be increasing rip current frequency or strength, rather it is more likely that more rip current reports and rescues occur in this fairly quiescent range of wind speeds because they create good beach conditions, and likely result in higher beach attendance. As noted above, beach population data was
unfortunately not available during the present study, but Engle found similar results along the East coast of Florida using rip rescues normalized by beach population (Engle 2003). The ratio of wind speeds on rip current report days to wind speeds during the entire data record, over each range, in Figure 3.8, further illuminates the relationship between wind speed and rip current reports. It is evident in Figure 3.8, that the probability of rip currents being reported increases with increasing wind speed. Wind speeds less than 10 m/s exhibit roughly the same low probability of rip current occurrence, suggesting that under most conditions wind speed plays a small role in the formation of rip currents.

Figure 3.7: Frequency distribution of rip current reports and the entire data record for wind speed. May 27th through September 22nd, 2006 and 2007.
Figure 3.8: The probability of rip currents being reported for each range of wind speed.

Wind directions on days with rip current reports and during the entire data record are depicted in Figure 3.9. Wind directions between 22.5 degrees and 90 degrees, account for 40% of days with rip reports and 43% of days with rip rescues, while only accounting for 23% of days during the entire period. This signifies a small range of wind directions that correspond to a relatively higher risk of rip current occurrence. This is supported by the second highest SSD of all the variables investigated, 0.0023. It is important to note, that other near shore normal wind directions South of shore normal, do not correspond to a relatively higher occurrence of rip current reports or rescues. Since wind speed was discounted as an important rip current forcing mechanism, it stands to reason that wind direction would be equally impotent, but the data suggests otherwise.
Figure 3.9: Frequency distribution of rip current reports and the entire data record for wind direction. May 27th through September 22nd, 2006 and 2007.

To further illuminate the seeming contradiction between relevance of wind speed and wind direction to rip current occurrence, three hourly records of wind direction plotted against wave heights for the 2007 study period are presented in Figure 3.10. Figure 3.10 illustrates, that wind directions less that 90 degrees account for a disproportionate amount of relatively larger waves. In Figure 3.11, which depicts wave heights against mean wave direction for the 2007 time period, a cluster of relatively large wave heights corresponding to directions between roughly 45 degrees and 75 degrees, can be seen. In fact a Pearson correlation coefficient value of 0.38 between wave height and wind speed, suggests that wave heights tend to be higher when winds speeds are also high. A Pearson correlation coefficient value of -0.39 between wave height and mean wave direction suggests a moderate strength negative correlation between the two variables. That is to say, wave heights tend to be larger when mean wave direction values are smaller. Mean wave direction is plotted against peak wave period in Figure 3.12 where
it is apparent that the majority of waves from Northeast directions posses rather short peak periods. Furthermore, there is a grouping of relatively larger peak wave periods, corresponding to waves with mean directions very near and just South of shore normal. A Pearson correlation coefficient value of 0.23 suggests a slight positive correlation between mean wave direction and peak wave period. It is evident in Figures 3.10 - 3.12, that wave and wind variables are not independent of one another in the study region. This interdependence of variables precludes any possibility of multivariate analysis.

When viewed in concert, Figures 3.10-3.12 suggest, that winds directions roughly from Northeast tend to accompany fairly large short crested waves, from generally the same direction. This type of wave is evident on many days with rip current reports and rip current rescues. Furthermore, Figures 3.10-3.12 also indicate, that on the average, longer period low amplitude waves are most likely to originate from areas that are to the East or to the South of the region. These types of low amplitude long period waves are also present on many days with rip current reports and rescues. So it would be useful, from a forecasting standpoint, to understand and identify the types of synoptic weather patterns, that produce both these and other conditions identified as favorable for the formation of rip currents. Analysis of the meteorological forcing of ocean waves present on days with rip current reports will be presented in section 4.
Figure 3.10: Three hourly wind direction and wave height records for the May 27th to September 22nd 2007 period. The grouping of higher waves corresponding to approximately Northeast wind directions, indicate that wave heights and winds direction are not independent.

Figure 3.11: Three hourly mean wave direction and wave height records for the May 27th to September 22nd 2007 period. The grouping of higher waves corresponding to approximately Northeast mean wave directions, indicate that mean wave directions from the Northeast compose the majority of large waves during the period of record.
Figure 3.12: Three hourly mean wave direction and peak wave period records for the May 27th to September 22nd 2007 period. The grouping of relatively short period waves corresponding to Northeast mean wave directions, suggest that the majority of waves that originate to the Northeast of the region, will posses a fairly short peak period. The grouping of longer period waves with mean wave directions approximately equal to or greater than 90 degrees, indicates that most long period wave energy originates generally East of or South of the region.

3.4 Discussion of Results

Rip current occurrence has been shown to be affected by a number of factors in both the data above, and in research elsewhere (Engle 2003, Lascody 1998). To facilitate understanding of how the wave and wind parameters studied above influence rip current occurrence, it is helpful to view all the factors concurrently, on days with reports of rip current rescues. Figures 3.13-3.15 depict the time series of relevant wave and wind parameters recorded every three hours for the month of August 2007. Rip currents were reported on August 1st and 2nd, August 11th, August 18th and 19th, and August 22nd - August 31st. Rescues occurred only on August 22nd, August 25th - August 28th, and August 30th and 31st. For the sake of brevity only days with rescues are discussed here.
although similar conditions existed on other days when rip currents were reported.

On August 22nd a cold front passes the region, causing above average Northeast winds. Wave heights also increase, while dominant periods fall slightly from the previous days values. Rip current rescues also occurred on August 25th - August 28th. Wave heights decrease on both August 25th and August 26th, while dominant wave periods and mean wave direction remain relatively constant. Wind speeds show a decreasing trend, and wind directions are generally from the South. A cold front passed late on August 26th, causing wind directions to switch to Northeast on August 27th and 28th. Wind speeds increased behind the front, and a short period Northeast wind swell was prevalent by August 28th. Although rip currents were reported on August 29th, no rescues occurred, this is somewhat curious as wave and wind conditions on August 29th were very similar to conditions on August 28th. Wave heights and wind speeds began to decrease by August 30th, and wave directions returned towards shore normal, even though wind directions remained from the Northeast. On August 31st another cold front passed the coast, and both winds speeds and wave heights increased again. Northeast winds also appear to have shifted the mean wave direction to the North of 90 degrees, by contributing a more Northerly angled wind swell. The rescues on August 22nd, August 27th, and August 31st are somewhat exceptional because they occur within 24 hours of frontal passage, during a period of rapid local wave growth. According to Lascody and Engle’s work, rescues on storm or wave growth days were rare (Lascody 1998, Engle 2003).
Figure 3.13: Significant wave height and peak wave period for August 2007.

Figure 3.14: Mean wave direction and wind direction for August 2007.

Figure 3.15: Wind speed for August 2007
When the current analysis of rescue events during late August of 2007 is compared to the timeline of events, which Lascody hypothesized heralded high numbers of rip current rescues, some similarities and differences become apparent. In his research along the East coast of Florida, Lascody suggested, that strong onshore winds and/or high wave energy which frequently accompany frontal passages, discourage beachgoers from entering the water. Once, winds and/or waves begin to decrease, and conditions become more calm, bathers re-enter the surf. Although conditions appear calm, relatively high wave energy may still remain, and dangerous rip currents can cause high rescue totals (Lascody 1998, Schrader 2004). In contrast, the data gathered along the northern Outer Banks of N.C. suggests, that rip currents can occur anytime wave energy is high and directed relatively near shore normal. This includes the days when a rough building sea is present at the beaches, and the following days when more calm conditions return. This may indicate fundamental differences between Florida and N.C. surf zone dynamics, or perhaps differences in beachgoer attitude or perception of danger. Additionally, the Northern Outer Banks coastline has a considerably larger swell window than the Florida coast (see Figure 3.2) thus making it more likely that several different swells will impact the beaches at any one time. This further enforces the fact that rip current occurrence is not controlled by the same factors from region to region, and requires individual analysis of rip forcing mechanisms at every area where rip currents pose a threat.
In summary it has been shown that rip current reports and rescue frequency increases for:

- Above average wave heights
- Dominant wave periods between 5 to 10 seconds (most likely longer periods as well)
- Wave directions within 45 degrees of shore normal
- Wind directions from 22.5 to 90 degrees, because they frequently accompany higher waves
- Relatively light wind speeds between 2.5 m/s and 7.5 m/s
Chapter 4

Meteorological Analysis of Rip Current Producing Swell Sources

4.1 Introduction

Ocean waves are the primary rip current forcing mechanism, and are the most significant predictor of rip current occurrence (USACE 2006, Engle 2003). However, from a forecasting point of view, it is of limited use, to only be able to determine if rip currents are likely to occur once favorable wave conditions appear in the near shore buoy records. It would be of additional value to be able to identify the types of synoptic meteorological patterns that frequently generate rip current producing wave fields. Thus, archived buoy data, synoptic weather charts of mean sea level pressure, Quickscat derived wind fields, and monthly Wavewatch III v3.10 loops were analyzed to determine the meteorological source of the most dominant swells evident on days with rip current reports. Because of a gap in the reporting and forecasting of rip currents in 2006 between September 5th and the 22nd, this meteorological analysis was only completed from May 27th to September 5th for both 2006 and 2007, in order to keep the time periods equal.
The sources of swells were broken into five categories: prefrontal, postfrontal, Atlantic high pressure, tropical cyclones, or South Atlantic storms. The definition of each weather pattern designation is shown in Table. More than one dominant discrete wave train was present on many days with rip current reports, so the sources for all dominant swells evident in the buoy records were examined. It may be important to differentiate between rip currents which are forced by locally generated waves, and rip currents which are forced by distantly generated waves. Presumably these different wave conditions would result in very different surf zone circulations.

Forecasters may also benefit from knowledge about the relative frequency with which different types of weather systems produce waves that locally or distantly force rip currents. Thus, days with rip current reports were also broken up according to the type of waves present in the buoy record. Waves with relatively long periods with no evident relation to the coastal wind field were designated as distantly forced. If any of the three hourly wind speeds were greater than 5m/s, and the daily median wave direction was within 15 degrees of the daily median wind direction, the waves were designated as locally forced. Of course these are not mutually exclusive designations, so days when both distantly generated swells and local windswells were present, were analyzed as both. Overall it was determined, that distantly generated waves were present on 71% of days with rip current reports, and that locally generated waves were present on 29% of days with rip current reports. The remainder of this section will discuss in depth the types of conditions associated with each regime of weather, including several examples of each.
Table 4.1: Description of each type of meteorological swell source.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postfrontal</td>
<td>Waves generated as frontal systems exit the coast. Coastal winds behind a front typically rotate from Northwest towards Northeast. It is the Northeast winds behind a front that generate waves directed towards shore. This type of wave generation can occur both near the coast or at a great distance.</td>
</tr>
<tr>
<td>Prefrontal</td>
<td>Waves generated as frontal systems approach the coast. Coastal winds ahead of a front typically rotate from South towards Southwest. Both wind directions generate waves which are obliquely incident to the study region coast. This type of wave generation most frequently occurs very near the US East Coast.</td>
</tr>
<tr>
<td>South Atlantic Storms</td>
<td>Waves generated by strong areas of low pressure in the South Atlantic. Waves propagate through the gap between South America and Africa. Typically long period low amplitude waves due to the long travel distance.</td>
</tr>
<tr>
<td>Atlantic High Pressure</td>
<td>Waves generated by the semi-permanent summer Atlantic high pressure systems. Clockwise circulation of persistent winds around strong areas of high pressure generate swell type waves. Swells usually generated at a distance, but fetch may occasionally extend all the way to the coast.</td>
</tr>
<tr>
<td>Tropical Cyclones</td>
<td>Waves generated by a tropical cyclone of any strength. Intense wind field associated with tropical cyclones can generate very large waves. Tropical cyclones may generate waves near the coast or at a great distance.</td>
</tr>
</tbody>
</table>

4.2 Frontal Passages

Extratropical cyclones and their attending cold fronts account for the majority of swell along the East Coast of the US, and are the primary source for extreme waves in the oceans North of 35 degrees (USACE 2006). During the summer period, strong pressure gradients that force high winds are relatively absent across much of the Southeastern US coastline, but periodic areas of low pressure traverse the region and are sometimes accompanied by above average winds (Zishka and Smith 1980). It is these above average winds that are of concern to rip current forecasters, as they are the source for above average
height waves. In Florida researchers have noted elevated numbers of rip current rescues after cold fronts exit the coast (Lushine 1991, Lascody 1998). Winds often increase in strength preceding and following frontal passages. Wave heights typically increase with the strong winds, and slowly drop off in height as the frontal boundary moves away. Both Lushine and Lascody noted that rip currents frequently occurred once winds speeds and wave heights began to decrease. They theorized, that once wave heights and wind speeds peaked, a slow decline in wave height and increase in wave period provided good surf and pleasant beach conditions. These apparently quiescent surf conditions lured bathers to return to the water, even though dangerous rip currents still existed (Lascody 1998, Lushine 1991). Recognizing the apparent role that fronts may play in producing rip currents, a brief analysis of surface weather data during two frontal passages along the N.C. coast follows.

Thirty-five cold fronts passed through the study area during the analysis period of 2006 and 2007, with both years experiencing a similar number of frontal passages. On average a cold front passed the region once every 5.8 days. Yet not all of these cold fronts generated waves that were present along beaches during days with rip current reports. So, wind and pressure measurements were analyzed during frontal passages, in an effort to determine if the local observations revealed any distinguishing characteristics about the fronts that produced rip currents. Intuitively, one may think that stronger fronts would be associated with higher winds, and therefore larger wave heights, which as stated earlier is the most significant factor influencing rip current strength and occurrence. In keeping with this line of thought, the average six and twelve hour instantaneous wind speeds and peak instantaneous wind speeds were recorded before and after the approximate time of frontal passage. The time of frontal passage was designated to coincide with the lowest measured pressure near the wind shift. When comparing measurements from fronts that were associated with rip currents and fronts that were not, it quickly becomes apparent
that there is significant overlap in the “strengths” of cold fronts. No apparent threshold of pressure, six and twelve hour instantaneous winds, or six and twelve hour average sustained wind speeds exists.

Pressure and wind measurements were also analyzed both on days when rip currents were locally forced, and on days when rip currents were distantly forced. It would be reasonable to assume, that fronts with stronger winds at the coast would be more likely to locally build waves, which may then cause rip currents, and indeed that is the case. Fronts, that locally forced windswells, were on the average “stronger”, with higher six and twelve hour instantaneous and average sustained wind speeds prior to and post frontal passage. However, there is still no apparent threshold of strength required for a front to force rip currents locally or from a distance. Thus, the analysis of local surface meteorological data during frontal passages appears to give little advantage to the forecaster. Instead, the key in determining, whether or not a particular front is likely to generate rip current producing waves, may lie in the speed with which the boundary traverses the region, or the orientation of the boundary. Systems that linger off the coast produce a longer effective fetch, which can build larger waves. Frontal boundaries, that are more East to West oriented, would presumably generate waves, which are directed more normal to the shore, than fronts that are more North to South oriented. Future work may reveal possible modes of frontal progression or orientation, which favor the generation of rip current producing waves.

4.2.1 Postfrontal Wave Sources

One type of frontal source was designated as postfrontal. Waves, which were built by winds on the cold side of the frontal boundary, were categorized as postfrontally generated. The postfrontal category generated waves that were present on days with rip
current reports and rescues, more frequently than any other category, 45% and 44%, respectively. Waves with postfrontal sources dominated both the locally and distantly generated rip current days, being present on, 72% of days when locally generated waves produced rip currents, and 39% of days when distantly generated waves were the dominant rip current forcing mechanism.

One event, the June 13th to June 15th 2007 frontal passage, clearly depicts both a locally generated wind swell and distantly generated swell, both of which produced rip currents along the Outer Banks of N.C. Figures 4.1-4.2 depict the 00z Ocean Prediction Center (OPC) Western Atlantic for June 13th - June 15th, the frontal boundary passed to the South of the study region early on June 13th as a backdoor cold front, and slowly progressed to the Southeast over the next several days. Winds increase locally in response to the passage of the frontal boundary, and a Northeast wind swell quickly built in by June 14th. Meanwhile, the cold front’s parent low intensified on its trek toward the Canadian Maritimes. The frontal boundary, in combination with its parent low and high pressure to the North created an impressive swath of North and Northeast winds that stretched from off the coast of New England all the way to the N.C. coast, which is evident in the ascending June 14th Quickscat pass in Figure 4.3. Wave heights built to over 2.0 meters by late on June 14th in response to these strong winds. Note the simultaneous rise in wave height and fall in peak wave period on June 13th in Figure 4.4, while the local winds dominated the wave generation. However, on June 14th and June 15th a slow rise in peak wave period and fall in wave heights is evident. This occurred as local winds diminished, with the relaxing pressure gradient, and local wave generation ceased. Waves, that were generated hundreds of miles away, off the coast of New England were still traveling towards the regions beaches, and continued to be the primary swell until late on June 15th. This trend in wave heights and peak period agrees well with the observations made along Florida’s East coast, as rip currents were reported on June

Figure 4.1: Ocean Prediction Center Western Atlantic surface analysis for 00z on 6/13-6/14/07.
Figure 4.2: Ocean Prediction Center Western Atlantic surface analysis for 00z on 6/15/07.
Figure 4.3: Adjacent 6/14/07 ascending Quickscat swaths depict wind speed and direction.
4.2.2 Prefrontal Wave Sources

The other regime of frontal wave generation associated with rip current occurrences was prefrontal. Prefrontal wind fields only produced waves that were dominant on 2% of days with rip current reports and rip current rescues. All prefrontal events were locally generated, yet prefrontally generated swells were only present on 8% of locally generated rip current events. Both days with prefrontally generated rip currents in 2006, contained multiple swells in the buoy record, suggesting that waves generated ahead of fronts may
not be solely capable of producing rip currents along study area beaches.

The relative low frequency of occurrence of prefrontally generated swells on days with rip current reports, is likely due to several factors. As a cold front approaches the coast, barometric pressure begins to fall; this change in pressure typically results in increased wind speeds ahead of the front. Along the N.C. coast winds ahead of a front are most frequently from the South or Southwest. This results in a South or Southwest wave direction, which is far from shore normal along the Northern Outer Banks. Even though waves shoal from deep water into the shallow water zone, and become directed more towards shore normal, these types of swell events tend to produce relatively short period, high amplitude waves, which according to linear wave theory, will begin to shoal or “feel” the ocean floor in shallower water (USACE 2006). Thus the wave train has less time to refract towards shore. This type of highly angled wave field tends to produce strong longshore currents at the coast, and is less likely to produce the closed cell circulations associated with strong rip currents (Guittierrez 2004, Engle 2003, USACE 2006). Additionally, as the cold front approaches the coast, sensible weather at the beach may deteriorate, with high winds, rising surf conditions, and rain. These factors may contribute to fewer people entering the water. Furthermore, the rough confused sea state may make it difficult for beach personnel to visually identify any rip currents.

One of the few rip current events with a prefrontally generated wave field apparent in the buoy record was the June 14, 2006 frontal passage, which was associated with the remnants of Tropical Storm Alberto. The 00z OPC Western Atlantic surface analysis for June 14th in Figure 4.5, depicts a cold front already South of the study region, with strong high pressure well offshore, and Tropical Storm Alberto impacting the Florida Panhandle. Quickscat winds in Figure 4.6 from 11z on June 14th depict some Southerly fetch developing off the Southeastern coast due the circulation of dying Tropical Storm Alberto. The 12z June 14th surface analysis maps in Figure 4.5 display the Northward
progress of the remnants of Tropical Storm Alberto, which was declared extratropical by 12z on June 14th (Avila and Brown 2006). Strong Southerly winds in association with warm air advection, caused by extratropical storm Alberto, forced the old frontal boundary back to the North of the study area as a warm front by 2223z on June 14th, as seen in the hourly Hydrometeorological Prediction Center (HPC) analysis in Figure 4.7. Frontogenesis occurred along a trough to the South of extratropical storm Alberto, as the system moved offshore, evidenced in the 0126z HPC surface analysis on June 15th in Figure 4.7. The South wind swell generated by the remnants of Alberto and its attending frontal array, was not the dominant swell in the buoy records during the entire day. This fact is evidenced by the sharp drop in peak wave period and rise in wave heights, on June 14th, apparent in the June 13th - June 15th time series of wave heights and peak period in Figure 4.8. Long period waves from a storm in the South Atlantic were the dominant energy, until about midday, when the local South wind swell became large enough to overtake the long period energy in the wave energy spectrum. Rip currents were reported on June 14th, when the largest waves were present, but rip current rescues occurred on June 15th, even as waves neared prestorm levels. This further suggests, that the steep angled South wind swells associated with prefrontal rip current events may not be able to generate rip currents without underlying wave energy from another source. Additionally, this example can be considered to be somewhat of a special case, because the impetus for prefrontal wave generation was the remnants of a tropical cyclone.
Figure 4.5: OPC surface analysis for 00z and 12z on 6/14/06, depicts the Northward progression and dissipation of Tropical Storm Alberto.
Figure 4.6: Ascending Quickscat winds for 11z 6/14/06, clearly illustrate the wind field off the Southeastern coast.
Figure 4.7: Hourly HPC surface analysis maps from 1923z 6/14 to 0126z 6/15/06.

Figure 4.8: Three hourly record time series of significant wave height and peak wave period for 6/13-6/15/06.
4.3 Atlantic High pressure

High pressure over the Northern Hemisphere oceans is a dominant feature during the summer months (Zishka and Smith 1980, Davis et al 1997). In the Atlantic these strong anticyclones are called Bermuda or Azores Highs. Although these systems typically do not produce very high winds, they can create a very persistent fetch over extremely long distances. This type of scenario typically results in low amplitude waves with relatively long periods, similar to what the trade winds produce in the tropics (USACE 2006). Additionally, African Easterly Waves moving through the tropics can interact with the Southern portion of these quasi-stationary highs, producing slightly higher winds and thus larger waves. Waves generated by Atlantic highs are often directed near shore normal along the N.C. coast, due to the position of the high over the open ocean, and these waves are present, more frequently than any other wave regime during the summer season.

However, not everyday dominated by Atlantic High pressure induced waves produce rip currents. Just 15% of days with rip current reports and 20% of days with rip current rescues contained dominant waves generated by Atlantic high pressure systems. Waves from Atlantic high pressure only forced 8% of days when locally generated waves forced rip currents. Atlantic high pressure spawned waves forced 18% of days when distantly generated waves forced rip currents. Atlantic anticyclones reach their average peak intensity in July, thus we may expect that rip current events caused by Atlantic high pressure, would also have a peak frequency of occurrence in July (Davis et al 1997). Indeed, during the 2006 and 2007 study period, 78.5% of rip current report days, with Atlantic high pressure identified as the primary wave source, occurred in July. The average peak central pressure of Atlantic high pressure systems that spawned rip current producing waves during the observing period was 1030.74 millibars. Average central pressure of
the Azores high is 1023.5mb (Sahsamanoglou 1990). The average peak central pressure of Atlantic high pressure systems, that spawned rip current producing waves during the observing period, was 1030.74 millibars. This suggests that only Atlantic high pressure systems with well above average central pressures can produce winds strong enough to build waves capable of producing rip currents. However, due to the relatively small population set, setting a minimum threshold of strength necessary for high pressure systems to generate rip current producing waves would not be prudent. Future data may unveil stronger relations from which thresholds may be derived.

One Atlantic high pressure forced rip current event occurred from July 24th to July 27th, 2007. From July 25th to July 27th swell from Atlantic high pressure was the only dominant wave energy apparent in the buoy record, making this case a prime example of how even low amplitude intermediate period waves can produce rip currents. It can be seen, from the 06z July 21st - July 23rd OPC Western Atlantic surface analysis in Figure 4.9and 4.10, that a strong 1035 millibar high pressure system encompasses most of the Western Atlantic, and a cold front drapes across the Eastern seaboard. The winds behind the cold front generated rip current producing waves from July 21st to July 24th, but by July 24th the Southeast swell from the Atlantic high becomes more dominant in the buoy record.
Figure 4.9: OPC Western Atlantic surface analysis for 7/21-7/22/07.

Figure 4.10: OPC Western Atlantic surface analysis for 7/23/07.
The ascending Quickscat pass in Figure 4.11 depicts a broad area of 15 to 25 knot East and Southeast winds which are aimed at the Southeast coastline. This general pattern persisted until early on July 23rd, when weakening of the Atlantic high, apparent in Figure 4.9, led to the dissipation of East winds to below 15 knots, as evidenced in the July 23rd ascending Quickscat pass on display in Figure 4.11. The waverider buoy record for this period, seen in Figure 4.12, depicts falling wave heights, late on July 23rd and into July 24th, while wave period experiences a gradual increase. Wave directions appear to have no relation to the local wind field except early on the July 24th when they both contain a legacy Northeast component from the dissipating frontal boundary offshore. Local wind speeds, also in Figure 4.12, remain fairly light, less than 5 m/s, until late on July 27th when yet another cold front approaches the region. Rescues occurred from July 24th-July 27th, which further solidifies the claim, that distantly generated swell from the Atlantic high, which was consistently the dominant swell in the buoy record, was the primary rip current producing mechanism.
Figure 4.11: Ascending Quickscat pass on 7/21/07 and 7/23/07, with large fetch area highlighted.
4.4 Tropical Cyclones

Tropical Cyclones (TCs) are generally defined as synoptic scale warm core low-pressure systems over tropical or subtropical waters with organized convection, and are characterized by sustained wind speeds near the surface of 17m/s or greater (G.J. Holland 1993). Wave heights produced by TCs can sometimes exceed 15m (Tolman 2004).
From Cape Hatteras northward, progressive mid-latitude cyclones are the main source of large waves. In between storm systems, generally smaller waves are generated from storms moving away from the coast (USACE 2006). The N.C. coast is typically affected by much weaker mid-latitude storm systems during the summer than during the rest of the year. This results in smaller average wave heights during the months of June - August (USACE 2006). Thus, TCs, which experience their peak frequency of occurrence in the Atlantic basin during the summer months, represent a important subset of ocean wave generating storms, because they are capable of producing larger waves than would normally be seen along the East Coast during the summer season. Ten-year wave statistics from the USACE FRF in Duck, N.C. show that the top two extreme wave heights occur in the months of August and September (USACE 2006). These extreme events occur due to passing or land falling TCs. TCs are frequently responsible for producing large wave events along the East Coast of the US, thus, we may expect, that they would also be responsible for generating rip current producing wave fields. In the 2006 and 2007 study period, TCs accounted for 18% of days with rip current reports and 16% of days with rip current rescues. TCs created waves that were present on 12% of days with rip current reports, that contained dominant locally generated wave components, and 19% of rip current days with distantly generated primary wave components. These frequencies of occurrence suggest that TCs produced a relatively small portion of rip current events during the study period. However, these values should be viewed with a fair amount of caution, as the population set is so low. It is reasonable to expect, that TCs may account for slightly more or slightly fewer rip current events, depending on the level of TC activity during a given season.

When TCs are in the open ocean Wave growth is a function of wind speed, duration, and the length over which the wind blows or “fetch”. TCs can be thought of as radially symmetric systems with four quadrants of “effective fetch”— the actual distance over
which wave growth occurs (USACE 2006). These four quadrants produce wind waves in several directions as depicted in Figure 4.13. Research has shown, that for a moving storm, the effective fetches within all but the right quadrant (wave containment quadrant) are less than or equal to that within a similar stationary storm (MacAfee and Bowyer 2005). This effect results in smaller wave heights because the wind speed may be lower, relative to the surface of the ocean in the other quadrants, and because waves will not remain within the generation zone for a long period of time (MacAfee and Bowyer 2005). When the storm speed is roughly in phase with the dominant wave group velocity, waves may remain “trapped” in the growth region of the right quadrant for a longer period of time than they otherwise would. This results in much larger wave heights and wave speeds (MacAfee and Bowyer 2005). Even when TCs do not produce trapped fetch enhanced waves or are near stationary, they are frequently intense enough to build large wind waves that propagate outward from the storm as dangerous energetic swell.

![Schematic of four quadrants of fetch in a radially symetric TC.](image)

**Figure 4.13:** Idealized schematic of four quadrants of fetch in a radially symetric TC.
Ernesto was a prime example of a storm impacting the coast with local wind swell and distantly generated swells. Figure 4.14 depicts the track Ernesto took on its way towards the N.C. coast. Ernesto formed South of the Caribbean Islands and tracked generally West Northwest before striking Florida. This resulted in almost no long period swell energy being able to propagate towards the N.C. coast before Ernesto made its way off the Florida coast. This can be seen below in Figure 4.15, where the three hourly wave and wind data from the FRF 8m array wave sensor in Duck is shown prior to and post landfall of Ernesto in southern N.C. Note the rapid increase of relatively short period, high amplitude waves coinciding with a sharp rise in winds speed around the time of landfall early on September 1st. The rapid rise in wind speeds and wave heights, as well as the drop in peak wave periods, throughout the August 31st - September 1st segment of buoy data, is indicative of an actively building wind swell.
Once Ernesto moved inland and local winds turned towards a more offshore direction, wave heights were drastically reduced. The increase in wave period after Ernesto was inland and local winds had turned offshore is another important matter requiring discussion (Knabb and Mainelli 2006). This increase in peak wave period occurred, because Ernesto moved so fast to the North Northeast off the Florida coast, that it outpaced some of the South swell that was being produced by the strong winds on its right quadrant, easily seen in Figure 4.16. Thus, even after Ernesto was inland and no longer locally generating waves, distantly generated swells continued to impact the coast for several days, as they “caught up” with the center of circulation. Ernesto’s forward motion was faster than the dominant wave group speed, thus, significant enhancement of wave heights due to the trapped fetch phenomenon did not occur. Even so, rip currents were reported by emergency and life saving personnel along Outer Banks beaches, as large surf buffeted the coastline from August 31st to September 4th 2006 (NWS MHX 2006).
Figure 4.15: Time series of three hourly wave and wind data from 8/30-9/4/2006.
Figure 4.16: Descending Quickscat winds on 8/31/06, depict a large swath of South winds off the Southeast US coastline. Black wind barbs represent rain flagged data.

4.5 South Atlantic Storms

Although distantly removed from the study area the South Atlantic is a distinct source region for rip current generating waves. Strong extratropical cyclones traverse the South Atlantic during the Southern Hemisphere winter months, and if not for the orientation of the relatively small gap between South America and Africa seen in Figure 3.2, swells generated in the South Atlantic may well be more frequently apparent in the buoy records along the East Coast of the US (Hamilton 1991). The fact that extratropical cyclones track generally from West to East, causes most large swell energy produced by these
storms to be directed towards the coast of Africa. However, occasionally strong areas of low pressure move slowly to the East or even retrograde to the West, and significant energy is directed towards the equator. If a storm is located roughly East of the 10W longitude line the possibility for swell to propagate towards the Northwest over great circle routes towards the East Coast of the US exists. The time it takes for waves to propagate over any distance is dependant on the wave group speed $C_g = \frac{g}{4\pi f}$, where $g$ is acceleration due to gravity, and $f$ the wave frequency. According to wave dispersion theory, in deep water, longer period waves travel faster than shorter period waves, and thus will arrive at any given location first. (USACE 2006). Hamilton found, that waves with a dominant period of 20 seconds arrived along the East Coast approximately 7 days after they were generated roughly 10,000 kilometers away in the South Atlantic (Hamilton 1991). During the study period only four storm systems contained a strong enough fetch East of 10W, to produce waves that generated rip currents along the Northern Outer Banks of N.C.

Despite the small number of South Atlantic storms, that were identified for generating rip current producing waves, 20% of days with rip reports and 18% of days with rip rescues, contained South Atlantic storm generated waves in the buoy data. South Atlantic storms spawned waves that were present on 26% of distantly forced rip current days. These relatively high percentages are a function of the amount of time these distantly generated swells impact the coast, which is frequently several consecutive days. Additionally, several other characteristics of South Atlantic generated swells appear to make them relatively likely to force rip currents. Although, intuitively it may seem, that these swells approach the coast at very oblique angles from the South, in actuality, due to the great circle routes they travel, see Figure 3.2, they are frequently directed between 110 and 130 degrees from true North, which is relatively near shore normal. Furthermore, such long period swells begin to shoal in very deep water and by the time they are evi-
dent in nearshore buoy data, they have already begun to refract towards shore normal, and continue to do so until breaking. Also, it is possible, that surf zone bathymetry may become more conducive for the formation of rip currents, while being impacted by a similarly directed energetic wave field over the course of several days (MacMahan 2004, Castelle et al 2006, Wright and Short 1987). Once a favorable bathymetric arrangement of well defined rip channels has been created, it may be possible to form relatively strong rip currents even as wave energy declines towards the end of any particular swell event (Reniers 2004, MacMahan 2000).

Furthermore, waves generated in the South Atlantic are not related to any local sensible weather that may affect beach goer attendance, indeed they are not related to any weather in the Northern Hemisphere. This may lead the uninformed beach goer to believe that surf conditions are safe, when in reality strong rip currents may be present. Finally, waves that have traveled such long distances frequently impact the coast in seemingly sporadic groups or sets (USACE 2006). This potential wave groupiness, may lead to long spells of low waves, intermittently broken by pulses of several high waves. Rip current pulsations have been noted to occur at the infragravity wave group timescale (0.004-0.04Hz) (Shepard and Inman 1950, Sonu 1972, Brander and Short 2001, MacMahan 2004). These sporadic pulsations of relatively higher energy waves, and their resulting stronger currents may catch bathers off guard. Unfortunately, no practical measurement exists to quantify the potential groupiness of incoming wave trains in real time. Furthermore, wave groupiness cannot be forecasted, thus no investigation into wave groupiness was undertaken in this study (USCAE 2006).

One prime example of a South Atlantic storm that generated rip current producing waves along the N.C. coast occurred from August 9th - August 11th 2007. The August 9th and 10th , 00z and 12z National Center for Environmental Prediction (NCEP) Southern Hemispheric surface analysis in Figures 4.17 and 4.18, depict a well defined area of low
pressure, to the East of several areas of strong high pressure. This scenario produced a substantial fetch of South and Southeast winds aimed well up the 120 degree great circle path towards the U.S. East Coast. Both ascending and descending Quickscat passes (not shown) depict winds in excess of 45 knots across a broad area to the West of the low pressure center, on August 9th. Winds of this intensity, sustained over a 24 hour period, have been shown to produce wave heights in excess of 10 meters (Bretschneider 1970). This general area of strong South and Southeast winds remained fairly intact for several days as the storm system slowly tracked to the East between South Africa and Antarctica. The majority of the strong fetch dissipated by August 11th. Seven days after initial storm intensification wave energy with a 20 second dominant wave period appeared in the Duck waverider buoy record. As seen in Figure 4.19, long period Southern Hemisphere energy continued to dominated the wave record until early on August 20th, when swells from a distant tropical cyclone became the dominant wave energy. Rip currents were reported on August 18th and 19th, when the buoy record primarily contained peak periods of 17.4 seconds. There was also some locally generated Northeast wind swell apparent in the buoy data, as evidenced by the wind shift, modest rise in wave heights, and the two outlier short period data points on August 18th. The fact that rip currents were not reported until two independantly directed wave trains impact the coast may once again suggest, that multiple independently directed swells play a important roll in the formation of rip currents along the study regions beaches. Conversely, the fact that no rescues were reported, may reflect beach personnel’s willingness to report rip currents when the ocean looks rough, regardless of whether strong rips exist or not.
Figure 4.17: NCEP Southern Hemispheric surface analysis maps for 00z and 12z 8/9/07. North is up, and the Southern tip of Africa is apparent in the upper portion of each figure.
Figure 4.18: NCEP Southern Hemispheric surface analysis maps for 00z and 12z 8/10/07. North is up, and the Southern tip of Africa is apparent in the upper portion of each figure.
4.6 The Impact of Distantly Generated Swells

4.6.1 Description of the Problem

The Outer Banks continental shelf is varied in extent within the study region, generally tapering down in width from North to South. Additionally, that the coast is open, and exposed to a large array of wave energies. These characteristics result in a number of consequences relevant to the prediction of coastal marine conditions. One is that both local wind generated waves and distantly generated swell regularly impact coast.
other is that the inhomogeneous width and slope of the continental shelf requires high resolution bottom information to properly explain coastal processes, and nearshore wave conditions. Forecasting of rip currents requires reliable information about the likely future state of the ocean in the very nearshore zone. The majority of rip current producing waves were designated as distantly generated above. Distantly generated waves present a more subtle forecasting challenge, as these systems are often downstream and no longer producing sensible weather within a NWS WFO county warning area. It is possible, and indeed is most often the case, for weather to be very calm at the coast, while energetic waves bear down on the beaches, potentially producing dangerous conditions for days after the last weather system exited the region. Further exacerbating the problem, directional wave information is relatively scarce across the region, making it difficult to discern between several wave trains. In these situations, operational ocean wave models such as, NOAA’s Wavewatch III v3.10, can provide information on these distantly generated wave fields (Tolman 1991). Wavewatch III v3.10 generates spectral wave outputs, which allow users to discern multiple wave trains, some of which may not be obvious in the buoy data (Tolman 1991).

Global wave models such as the current installment of Wavewatch are driven primarily by regional or global weather models and are thus, subject to their entailing shortcomings (Tolman 1991, Chao et al 2005, Rogers and Wittmann 2002, Tolman 2005). Despite the shortcomings of global wave models they do fill a key role, in that they provide data in locations directional wave buoys do not exist. Global ocean models may be used in finite depth regions when a depth dependent propagation speed is introduced and Eulerian representation of refraction is used (Hasselmann et al 1973). However, it has been shown that global wave models posses several other shortcomings when applied to nearshore and coastal locations (Tolman 1991).

Global wave models do not compute all relevant physical processes for finite depth-
induced wave breaking and triad wave-wave interaction (Booij 1999). Since, these processes may be non-negligible in coastal regions, a model that incorporates them is necessary to accurately represent the sea state in shallow water. Therefore, as a general rule global wave models may only be used to effectively approximate the sea state in the offshore deep water zone at or beyond approximately 15km. Furthermore, explicit computation of all the necessary source and sink terms violates the Courant criterion for numerical computation stability, if used for smaller coastal scales of time and space (order of 10 seconds and 100 meters) (Booij 1999). To circumvent this problem an implicit numerical computational scheme is used in the simulating waves nearshore (SWAN) model (Booij 1999, Ris 1999).

4.6.2 SWAN Simulation of Distantly Generated Swells

4.6.2.1 Model Description and Set Up

The SWAN model is a third generation model capable of simulating the propagation of wind generated ocean waves from offshore to the surf zone. The model is run on a Eulerian formulation of the discrete spectral wave action balance equation. SWAN includes all the relevant shallow water physical processes discussed above. The implicit numerical scheme utilized for propagation in geographical and spectral space allows for large time steps and small space grid intervals. This feature avoids numerical instability, and allows time steps to be chosen on the basis of accuracy (Pires-Silva 2002, Booij 1999). In the current simulation the model domain was set to encompass the study domain, and to extend East to the continental shelf break. The boundaries were set beyond forty grid points away from the validation output locations, to ensure minimal boundary contamination. The x-axis of the domain was oriented West-East, over a distance of approximately 102 kilometers, and the y-axis was aligned North-South over
193 kilometers. A bathymetry file, with resolution of .0083 degrees (920 meters), provided data on the shape of the sea floor. In directional space 72 meshes were designated to span the entire 360 degrees. The frequency space spanned the range from .05 Hz to 1 Hz and was divided into 38 meshes. The entire Eastern boundary of the domain was forced with directional spectral wave data from NDBC buoy 41004 which is moored in 47.5 meters of water approximately 64 nautical miles East of Virginia Beach. The North and South boundaries of the model domain were forced with bulk swell data from NOAA’s Wavewatch III v3.10 output grids, which corresponded to the farthest East point along both boundaries. The wind source terms over the model domain were acquired from the North American Mesoscale Model (NAM) at a resolution of 13 kilometers. Finally the model was run in nonstationary mode, with all relevant shallow water processes activated. Wave data from the USACE FRF waverider buoy moored in 17.4 meters of water at 75.72W 36.3N was used to validate the model data.

4.6.2.2 Model Results and Discussion

To illustrate the important roll distantly generated waves may play in determining the nearshore sea state, and therefore in the formation of rip currents, a simple series of SWAN simulations of the wave conditions during the June 16th and 17th 2007 rip current event were completed. The June 16th and 17th event was chosen because it represents a distinct period of fading local wind swell, light winds, and relatively energetic long period swell. Model runs were completed for three different scenarios. Run A used wave forcing at the boundaries and winds over the domain. Run B contained no wind forcing over the domain. Run C contained no wave forcing along the boundary. The results are shown in Figures 4.20- 4.21, where it is evident, that in run B simulated peak wave period and significant wave height remain relatively unchanged. This data suggests that under certain situations wave conditions and therefore rip currents are almost entirely controlled
by distantly generated swells propagating into the domain. Run C simulated peak wave period and significant wave height are vastly under predicted, because there is no wave energy entering the domain from the boundaries. Run C demonstrates that under many conditions locally driven waves will not become energetic enough to dominate the wave energy spectrum and cause rip currents. Finally, simulation A, with both wave and wind forcing, not surprisingly, achieved the best results when compared to the waverider buoy data. Table 4.2 depicts the mean square error, the root mean square error and the scatter index values for significant wave height calculations from the three simulations. Table 4.3 depicts the mean square error, the root mean square error and the scatter index values for peak wave period calculations from the three simulations. It should be noted that the output location corresponding to the waverider location in the input bottom file was in 12.88 meters of water, which is 4.68 meters shallower than the actual depth of the waverider’s moored location. This difference in depth is likely a source for some of the error evident in run A, but modeled data agrees well with observational data regardless. It is readily apparent from these simulations that in the absence of strong winds at the coast, distantly generated swell can be the dominant wave energy.

Table 4.2: Verification statistics for 6/16-6/17/07 SWAN computation of significant waves heights.

<table>
<thead>
<tr>
<th></th>
<th>Swan run A</th>
<th>Swan run B</th>
<th>Swan Run C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE</td>
<td>0.021m</td>
<td>0.067m</td>
<td>0.491m</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.146m</td>
<td>0.259m</td>
<td>0.700m</td>
</tr>
<tr>
<td>SI</td>
<td>0.170</td>
<td>0.301</td>
<td>0.816</td>
</tr>
</tbody>
</table>
Table 4.3: Verification statistics for 6/16-6/17/07 SWAN computation of peak wave periods.

<table>
<thead>
<tr>
<th></th>
<th>Swan run A</th>
<th>Swan run B</th>
<th>Swan Rrun C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE</td>
<td>0.846s</td>
<td>0.846s</td>
<td>199.27s</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.919s</td>
<td>0.919s</td>
<td>14.12s</td>
</tr>
<tr>
<td>SI</td>
<td>0.057</td>
<td>0.057</td>
<td>0.878</td>
</tr>
</tbody>
</table>
SWAN simulations also show promise depicting variations in wave heights along the coast. As noted above the inhomogeneous continental shelf width and slope within the Outer Banks region can lead to a wide range in observed wave heights nearshore. To further illustrate this phenomenon, SWAN output at a location just offshore of Rodanthe N.C. in 17.21 meters of water depth is depicted in Figure 4.22. The SWAN simulation of significant wave height suggests that wave in this area, merely a few miles to the South of the waverider buoy location in Duck, would be substantially larger than, wave heights in the vicinity of the FRF. Even though there is no observational data for comparison near this location, waves in this area are known to exceed heights observed elsewhere. This detail makes the extension of information, gained from the current analysis of wave and wind conditions during rip current events, to other adjacent areas inappropriate. In fact, individual analysis of factors associated with rip current events, should be completed for every stretch of coastline, that varies in orientation or continental shelf width and slope.

![SWAN vs Waverider Significant Wave Heights](image)

Figure 4.20: SWAN and waverider buoy significant wave heights for 6/16-6/17/2007
Figure 4.21: SWAN and waverider buoy peak wave periods for 6/16-6/17/2007

Figure 4.22: SWAN and waverider buoy significant wave heights for 6/16-6/17/2007. Rodanthe SWAN output location in 17.21 meters of water, roughly 73 kilometers South of the FRF waverider.
4.7 Summary

It has been shown, that several distinct weather patterns are frequently associated with rip current events along the northern Outer Banks coastline (Schrader 2004, Lascody 1998). The frequency of rip current report days and rip current rescue days caused by each type of meteorological swell source are shown in Table 4.4 and Table 4.5, respectively. The weather pattern, which produced rip current generating waves most frequently, was the postfrontal pattern. The next most frequent generators of rip current producing waves are South Atlantic extratropical storms, tropical cyclones, Atlantic high pressure, and prefrontal sources, respectively. Days with rip current reports were designated to be either locally or distantly generated. The percentage of locally or distantly forced rip current report days caused by each wave source is apparent in Table 4.6. Similarities and differences to rip current research completed elsewhere, were noted. One similarity being, that rip currents do indeed appear to frequently occur as storm conditions subside. A primary difference, between the current work and prior research on rip current occurrence, is the propensity for rip currents to occur on stormy days, when energetic seas were still being generated. Also, a new distinct source of rip current producing swells, South Atlantic storms, was identified, that had not previously been noted in any rip current research on the East Coast of the U.S.

Table 4.4: Frequency of days with rip current reports, cause by each type of meteorological wave source.

<table>
<thead>
<tr>
<th>Source</th>
<th>Postfrontal Winds</th>
<th>South Atlantic Storms</th>
<th>Tropical Cyclones</th>
<th>Atlantic High Pressure</th>
<th>Prefrontal Winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0.45</td>
<td>0.20</td>
<td>0.18</td>
<td>0.15</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Table 4.5: Frequency of days with rip current rescues, caused by each type of meteorological wave source.

<table>
<thead>
<tr>
<th>Source</th>
<th>Postfronal Winds</th>
<th>South Atlantic Storms</th>
<th>Tropical Cyclones</th>
<th>Atlantic High Pressure</th>
<th>Prefrontal Winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0.44</td>
<td>0.18</td>
<td>0.16</td>
<td>0.20</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 4.6: Percentage of locally or distantly generated days with rip current reports, caused by each type of meteorological wave source.

<table>
<thead>
<tr>
<th>Source</th>
<th>Postfronal Winds</th>
<th>South Atlantic Storms</th>
<th>Tropical Cyclones</th>
<th>Atlantic High Pressure</th>
<th>Prefrontal Winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>72%</td>
<td>0%</td>
<td>12%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Distant</td>
<td>39%</td>
<td>26%</td>
<td>19%</td>
<td>16%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Additionally, the author has suggested, in several examples within section 4, that the study regions large swell window frequently supports the presence of several independently directed wave trains, and that the presence of multiple wave trains may play an important roll in the formation of rip currents across the region. It should be noted again, that this study was completed only for the Summer months, and that substantial variations would likely occur in all the data if the study were to encompass the rest of the year. However, because cold water temperatures may discourage bathers at other times of the year, beach attendance is highest during the summer months. Therefore, the summer time period should reveal the most crucial information on the occurrence of rip currents. Furthermore, the data set was only comprised of summer periods for two years, and long term variations in weather patterns can be expected to occur, so continued expansion of this data set would be advisable.
Chapter 5

Refinement of the Current Rip Current Forecasting Scheme

5.1 Changes to the Current Forecasting Scheme

MHX NWS has been disseminating rip current forecasts to the public for the past two summer seasons. The current forecast scheme has displayed some skill in predicting days with rip currents, and allows forecasters to adjust the forecasted rip current risk based on several “intangible” factors not displayed by wave or wind observations. The forecast scheme enables a forecaster to raise the rip current risk for weekends, holidays, and any other day that beach attendance may be high. Additionally, there is a “day after” factor, which allows for an increase in the risk factor, after rough or windy days. This factor is designed to parameterize the increase seen in rip current reports when the ocean is becoming more calm after several days of stormy or rough conditions. A forecaster may also increase the rip current risk if there are early reports of rip currents by lifeguards or other beach personnel. Finally, there is a gut feeling factor, that enables a forecaster to elevate the rip current risk if they simply feel, that there is a higher rip current risk,
than the risk computed by the worksheet.

These “intangible” factors are thought to increase the performance of the rip current forecasting process, and serve to remind forecasters that all of the factors that influence rip current occurrence and strength may not be represented in observations. However, it is desirable to improve the performance of the forecast scheme based on empirical data, and lessen the relative importance of factors that cannot be measured. Thus, several changes have been made to the current MHX NWS forecasting scheme, seen in Appendix B, based on the analysis of the relevant variables presented in section 3.3. Higher weightings were given to ranges of parameters that exhibited higher frequencies of occurrence on rip current report days, than the overall frequency of occurrence of that range. Some ranges of parameters were assigned a higher weighting even though the frequency of occurrence of that range on rip current reports days did not vary largely from that ranges overall frequency of occurrence. This was done to handicap the subjective nature of rip current reports. If risk weightings were assigned purely on probabilities of rip reports, rip current risk would actually decline, during periods of high waves, long wave periods, and high winds, even though strong rip currents would still most likely occur. This approach is consistent with the work done by Engle and Lascody in Florida (Lascody 1998, Engle 2003).

First, the swell impact matrix is expanded to include wave periods from 4-18 seconds. This will allow for even short period waves to trigger some risk, as the data suggests that rip currents do occasionally occur when short period wind swells are the dominant wave energy. Even though very long period waves (>15 seconds) are rare in the study region, they will be better represented in this swell factor matrix, because the data suggests, that nearly every time very long period waves are the dominant wave energy, rip currents are reported. The weightings of swell height and period were also increased, to compensate for the reduction of the wind factor and wave direction factor described below. Wave
directions have been partitioned into 22.5 degree bins. Wave directions closest to shore normal are given a higher weighting than more obliquely incident waves. The wave direction factor is then multiplied by the swell impact factor to reveal the direction adjusted or actual swell factor. In this way even relatively large waves may not trigger a high rip current risk if they are not directed near shore normal, because strong longshore currents are more likely to develop. The wind contribution to the overall rip current risk was also reduced. This change reflects the apparent weak relationship between wind speed and rip current rescues. Wind directions have also been partitioned into 22.5 degree bins. Wind directions closest to shore normal are given a higher weighting than more obliquely incident winds. The wind direction factor is then multiplied by the wind speed factor to reveal the direction adjusted or actual wind factor. Thus, even strong winds will yield a low wind factor if they are directed at oblique angles to the shoreline.

Finally, a strong offshore wind dissipation factor was added to the forecasting scheme. If winds are forecasted to be above 10 knots and blowing offshore, the total swell factor is reduced by 25%. Although, there has been no analysis in the current work that suggests the addition of such a factor, addition of the offshore wind dissipation factor improved forecast performance. It has been shown that the flux of momentum from wind onto the sea surface is dependant on the sea state. More momentum is transferred from the air to the sea surface when steep high frequency waves are present (Jenkins 1991, Janssen 1998). Thus, if strong winds oppose the wave direction, wave energy will be lost as waves steepen in the near shore zone. The suggested offshore wind factor is not based on any theoretical or measured dissipation factor, in fact the author is not aware of any empirical relations that describe wave-wind interactions in the nearshore and surf zones. Further discussion on wave-wind drag and momentum flux is beyond the scope of the current study, and for in depth coverage on the topic the reader is referred to the work of Janssen and Jenkins (Jenkins 1991, Janssen 1998).
5.2 Statistical Performance of Forecasting Scheme

Rip current risk values were computed, using buoy data and wind measurements, in order to assess the forecasting performance of both the old and the adjusted forecasting scheme. Wave information from the FRF waverider buoy, and anemometer data from the FRF weather station for May 27th-September 22nd, 2007 and June 1st-July 27th, 2006 were used in this test. Days with missing data, that were replaced or interpolated, were discarded. Days without report verification were also discarded. The median wind and wave direction, as well as, the average significant wave height, winds speed, and dominant period were used as representative values for eight hour periods. Forecasts were computed once daily using data from approximately 4am to 12noon. Tidal weightings were unchanged and were computed using the same tide level calendar NWS MHX utilizes (NOAA 2008). To allow for some weighting of the “intangible” factors, a maximum factor of 1 was added to the risk forecast on days following a rip current rescue or following two consecutive days of onshore winds greater than 10 knots. No risk was added to account for beach attendance, weekends, holidays, or “gut feeling”.

The following performance statistics were utilized to determine the skill of the forecast schemes. Missed events occurred when a low risk of rip currents was forecast, but moderate or high risk conditions were reported. False alarms were designated when forecasted rip current risk was moderate or high, and no rip currents were reported. Since, there were no empirical thresholds defined for categorizing severity of rip currents in the reports, and because the reports were highly subjective, no differentiation was made between moderate or high risk days. Therefore, if the rip current forecasting index computes a high risk for the day, but report records display moderate risk conditions, the forecast scheme is still awarded a hit, as opposed to a false alarm. An elevated rip current risk was initially set to be triggered for values greater than 3.5 in the adjusted forecast
scheme, to reflect some of the fundamental changes made to the scheme, optimization of the warning threshold will be covered later. Differentiation between moderate and high risk values will have to be decided upon by the NWS MHX forecasters as better reporting data becomes available in the coming years.

Several statistical measures were computed to evaluate the skill of the forecast schemes. The probability of detection (POD) is the ratio of correctly forecast events to the total number of events, or the percent of events forecasted. The false alarm rate (FAR) is the ratio of non-forecasted events to the total number of events. The critical success index (CSI) defined as the ratio of the number of correct forecasts to the number of events plus the number of false alarms, was also computed, because it denotes skill of the forecasting scheme without counting correctly forecasted nonevents as hits (Schaefer 1990). Finally, the percent of rip current rescue days, that received rip current risk forecast values of moderate or high, were computed to determine the forecast schemes skill in predicting days when rescues occurred.

The above performance statistics were calculated using two sets of criteria to define a hit. Correct forecasts or hits were first designated, when a moderate or high rip current risk was forecasted, and rip currents were reported. Hits also include days that were properly forecasted as low rip current risk days. This was done to reflect that a low rip current risk forecast does not preclude the occurrence of rip currents, it simply suggests that the risk for strong rip currents is low. Thus, rip currents of some strength may still be occurring even on days when none are reported. In that sense, a low rip current risk forecast can be considered to be a hit, even when no rip currents were reported.

The results of the performance statistics for both the old NWS MHX forecast scheme, and for the newly adjusted NWS MHX forecast scheme can be seen in Table 5.1. The adjustments made to the forecasting scheme yield improvements of 0.1, 0.016, and 0.1 in the POD, FAR and CSI, respectively. Additionally, although the majority of days with
rip current rescues are still not forecasted, the changes made to the forecast scheme result in a significant improvement in the percentage of rip current rescue days forecasted. It should be noted, that the new forecast scheme is being tested using the same data that was used to modify the scheme. Ideally, an independent data set from a different time period would be used to assess the schemes performance, but since reports of rip currents in the study region are only available for the 2006 and 2007 summer season studied such an independent data set does not yet exist.

Table 5.1: Performance statistics for the old NWS MHX forecast scheme and for the adjusted NWS MHX forecast scheme, using correctly forecasted nonevents designated as hits, in addition to correctly forecasted moderate and high risk days.

<table>
<thead>
<tr>
<th></th>
<th>Old NWS MHX Forecast Scheme</th>
<th>Newly Adjusted NWS MHX Forecast Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>POD</td>
<td>0.7195</td>
<td>0.813</td>
</tr>
<tr>
<td>FAR</td>
<td>0.0167</td>
<td>0</td>
</tr>
<tr>
<td>CSI</td>
<td>0.7108</td>
<td>0.813</td>
</tr>
<tr>
<td>% of Rescue Days</td>
<td>18.7%</td>
<td>37.5%</td>
</tr>
</tbody>
</table>

5.3 Warning Threshold Optimization

Because the adjustments made to the current NWS MHX forecast scheme did not dictate a specific value that should be used for the warning threshold, the author is conferred the freedom to adjust the warning threshold to a value that achieves peak performance. Engle determined the optimum warning threshold by maximizing the ratio of POD to FAR, but in the current study more weight was given to the CSI in determining the warning criteria (Engle 2003). Table 5.2 depicts the performance statistics of the adjusted forecasting scheme, using several different threshold values for warning, with a hit defined as in Table 5.1. It is apparent that the simple inclusion of 3.5 into the warning
range maximized the ratio of POD to FAR, while only nominally increasing the FAR, POD, and percentage of rescue days correctly forecasted. Unfortunately, the CSI was slightly reduced under this warning criteria, indicating that a disproportionate number of false alarms were triggered when 3.5 was used as the warning threshold. If warnings were issued for values $> 2.5$, more than 90% of days with rip current reports would be forecasted. Unfortunately, the FAR would be increased to 0.30 if warning were issued for values $> 2.5$, but the high number of correct forecasts generates a CSI value that is as high as for the $\geq 3.5$ warning value.

If warnings are issued for values $>2.5$, the forecast scheme would predict strong rip currents 45.8% of the time, which is not so high of an alarm ratio, as to decrease reliability of the scheme. Although false alarms are highly undesirable, it is the view of the author that the very high POD achieved by the $>2.5$ warning criteria justifies the adoption of 2.5 as the warning threshold. Since, the entire study was based almost entirely on the use of visual reports as a indicator of strong rip currents it is important to realize that the adjustments to the forecast scheme should forecast more days with reports of rip currents. As has been discussed, reports of rip currents do not necessarily imply the presence of strong rip currents. The subjectivity of visual rip current reports, the non-continuous natures of the wave and wind data, and the lack of beach population data limits the potential for any analysis to discern the exact conditions that accompany strong rip currents. However, the ability to forecast conditions that lead to reports of rip currents is an important step towards forecasting strong rip currents and rescues.
Table 5.2: Performance statistics of the newly adjusted NWS MHX forecasting scheme, using several different thresholds for warning.

<table>
<thead>
<tr>
<th>Adjusted Scheme</th>
<th>Threshold &gt; 3.5</th>
<th>Threshold ≥ 3.5</th>
<th>Threshold &gt; 3.0</th>
<th>Threshold &gt; 2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>POD</td>
<td>0.813</td>
<td>0.815</td>
<td>0.830</td>
<td>0.923</td>
</tr>
<tr>
<td>FAR</td>
<td>0</td>
<td>0.029</td>
<td>0.093</td>
<td>0.30</td>
</tr>
<tr>
<td>CSI</td>
<td>0.813</td>
<td>0.795</td>
<td>0.765</td>
<td>0.795</td>
</tr>
<tr>
<td>% of Rescue Days</td>
<td>37.5%</td>
<td>40.6%</td>
<td>43.8%</td>
<td>71.9%</td>
</tr>
<tr>
<td>POD/FAR</td>
<td>Undefined</td>
<td>27.703</td>
<td>8.939</td>
<td>6.221</td>
</tr>
</tbody>
</table>

5.4 Future Work

Although the new rip current forecast scheme shows significant improvements in forecast performance continued refinement and additions to the forecast scheme may be useful. Expansion of the data set beyond the current 2006 and 2007 summer time frame may yield further significant information pertaining to conditions favorable for rip current occurrence. Determination of moderate and high risk warning thresholds will be possible if the rescue data set is expanded. Additionally, beach population data would be useful in determining whether rip current rescues are more strongly determined by beach population than by ocean and weather conditions. Any long term surf zone current study within the study region would likely also reveal valuable information about wave and wind conditions that force rip current circulations. As noted above, it would be ideal to test the new forecast schemes performance using an independent data set. Unfortunately, such an independent test on the scheme was not possible to complete. The testing will be done during the 2008 summer forecast season as the NWS MHX WFO records forecast values and rip current reports.

Another possible source of information on conditions during rip current events is
SWAN. As noted above the USACE has developed an experimental version of SWAN which encompasses the study region. SWAN is capable producing reliable wave information all the way to the surf zone. Hindcast SWAN simulations of near shore wave conditions during rip current events may yield useful information about wave conditions that is not currently available in the observations. SWAN can produce an array of wave parameters, some of which may be useful in discerning between the conditions favorable for rip currents and those that are not. Finally, this general procedure of analysis which began along the Florida coastline may be expanded to adjacent coastal areas. Differences in coastal orientation, continental shelf width, near shore bottom slope, tidal range, and the location of strong nearshore currents such as the Gulf Stream may cause significant differences in the conditions which produce rip currents.
Chapter 6

Summary and Conclusion

Reports of rip currents and rip current rescues, by beach personnel along the Northern Outer Banks of N.C., were recorded by NWS MHX staff during the 2006 and 2007 summer months. These reports were analyzed with contemporaneous wave and wind data, in an attempt to establish a statistical relationship between rip current occurrence and wave and wind measurements. It was found that rip current occurrence increases when 1) mean wave directions approach shore normal 2) wind directions are between 22.5 and 90 degrees to shore 3) significant wave heights are between 0.5 and 1.5 meters 4) dominant wave periods are from 5-10 seconds. Also, rip currents were observed to occur frequently during periods of stormy or building wave conditions, and during more moderate wave conditions, after rough conditions subsided.

Reports of rip currents are highly subjective and the possibility for large biases in the data exists. Furthermore, beach population likely plays a large role in the number of rescues that may occur on any given day. Weather and ocean conditions that discourage bathers from entering the water also likely play an important roll in whether rescues occur. Periods of high waves may keep swimmers out of the surf negating any chance for rescues even though rip currents may be present. In spite of these shortcomings, reports
of rip currents and rescues provide the only long-term record of rip current occurrence in the study region. Correlations between rip current reports and wave and wind data provide the basis for improvements to the rip current forecasting process. Better forecasts of rip currents are important for public safety and allow rescue and emergency personnel to plan ahead.

Weather patterns, which generated rip current producing waves, were analyzed to identify the weather systems that most frequently cause rip current producing conditions during the summer season. The ability to recognize weather patterns that generate conditions conducive for rip currents in advance, may increase forecaster awareness, and give forecasters greater insight into the large scale processes that dictate rip current occurrence. Several changes were made to the current NWS MHX rip current forecasting scheme, including: the addition of a direction dependant wave and wind factor, the reduction of the relative importance of wind speeds, the expansion of the swell matrix to include both very long and fairly short period waves, and a factor which decreases the swell factor when strong offshore winds are present. These adjustments improved the NWS MHX scheme’s ability to forecast days with rescues due to rip currents, and days with reports of rip currents.
References


[cit(2008b)] , 2008b: Historical waverider buoy data from the frf duck, n.c.

[cit(2008c)] , 2008c: Historical weather station data from the frf duck, n.c.


[cit(2008e)] , 2008e: Noaa ocean prediction center: Western atlantic surface analysis.


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Appendices
Appendix A

Rip Current Forecasting Worksheet

Forecast for:

<table>
<thead>
<tr>
<th>Northern</th>
<th>Buoy Obs for Swell (Dir/Height/Pd)</th>
<th>Southern</th>
<th>Buoy Obs for Swell (Dir/Height/Pd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>44014</td>
<td>Time</td>
<td>41035</td>
</tr>
<tr>
<td></td>
<td>41025</td>
<td></td>
<td>41036</td>
</tr>
<tr>
<td>4 pm</td>
<td>+</td>
<td>4 pm</td>
<td>+</td>
</tr>
<tr>
<td>4 am</td>
<td>+</td>
<td>4 am</td>
<td>+</td>
</tr>
<tr>
<td>11 am</td>
<td>+</td>
<td>11 am</td>
<td>+</td>
</tr>
</tbody>
</table>

**Remarks**

Reasons to consider going with a higher risk category.

- **“Day After” factor:** Winds have died down or shifted offshore and the ocean looks clean after several days of brisk onshore winds.
- **“Weekend/Holiday” factor:** Nice weekends, lots of people going into the water and you are 0.5 to 1.0 point below the higher category.
- **“Scanner/Phone Call” factor:** You have heard that several rescues have occurred this morning already.
- **“Gut Feeling” factor:** Are tides a bit high? Is there a beach event? Is the ocean recovering? Are you concerned?

**Swell Impact**

Northern Beaches

- **Swell trajectory:** 340-110 deg
- **Period:** 8 sec, 9 sec, 10 sec, 12 sec, 13 sec, 14 sec
- **Height:** 1 ft - 1 1/2 ft, 2 ft - 3 1/2 ft, 3 ft - 4 ft, 4 ft - 5 ft, 5 ft - 6 ft, 6 ft - 7 ft, 7 ft - 8 ft

Southern Beaches

- **Swell trajectory:** 40-240 deg
- **Period:** 240
- **Height:** 1 ft - 1 1/2 ft, 2 ft - 3 1/2 ft, 3 ft - 4 ft, 4 ft - 5 ft, 5 ft - 6 ft, 6 ft - 7 ft, 7 ft - 8 ft

**Wind Impact**

Northern Beaches

- **Prevalent Wind:** 180-350 deg
- **Wind Speed:** < 10 kt = 0, 10 kt - 15 kt = 1, > 15 kt = 2

Southern Beaches

- **Prevalent Wind:** 100-240 deg
- **Wind Speed:** < 10 kt = 0, 10 kt - 15 kt = 1, > 15 kt = 2

**Total Tide Impact**

- **Rank:** < 4.0 = Low Risk, 4.0 to 5.5 = Moderate Risk, > 5.5 = High Risk

Figure 6.1: 2007 NWS MHX rip current forecasting sheet
Appendix B

Figure 6.2: Newly adjusted NWS MHX rip current worksheet, without embedded calculations