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Wave Analysis for Rip Current Forecasting in Southeast North Carolina

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Abstract

Rip currents are one of the deadliest weather related hazards in North Carolina and South Carolina with 101 confirmed rip current drownings in these states from 2000 to 2014. Recent rip current outbreaks highlighted the need to reevaluate the rip current forecast scheme used by the National Weather Service Weather Forecast Office in Wilmington, North Carolina. This study examines the local wave characteristics associated with rip current activity at Wrightsville Beach, North Carolina from 2009 to 2013. Wave height and direction were found to be the most significant parameters that modulate local rip current activity. An analysis of high-impact days with five or more rip current rescues revealed that the vast majority of these events were associated with significant wave heights of at least 0.7 m and wave directions within ± 10° of shore normal. By identifying the most significant parameters associated with enhanced rip current activity, the local forecast scheme can be modified to improve rip current forecasts.

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1. Introduction

Rip currents are narrow, rapid flows of water directed away from shore that commonly form at beaches with breaking waves (Bowen 1969). The United States Lifesaving Association estimates that 100 people drown annually from rip currents (USLA Rip Current Survival Guide 2015). Table 1 from the National Storm Events Database (National Climatic Data Center 2009–2013) and the Weather Forecast Office (WFO) Wilmington, NC (ILM) Rip Current Fatality Database shows the breakdown of weather related fatalities in North and South Carolina from 2009 to 2013. During this period, rip current drownings accounted for the most weather related fatalities in the Carolinas. The National Weather Service (NWS) Rip Current Program continues to face the challenges of educating a population that is often unfamiliar with the rip current hazard and providing the public with accurate rip current forecasts.

The deadliest rip current outbreak on record in the WFO ILM County Warning Area (CWA) occurred on 3–4 July 2013. During this two-day period, there were six rip current drownings – four in Brunswick County, North Carolina and two in Horry County, South Carolina. This outbreak was part of an extended period of enhanced rip current activity that spanned 2–8 July 2013. During this week, over 300 rescues were performed by beach safety services and lifeguards within the CWA. The conditions did not fit the typical local paradigm for widespread strong rip current activity since there were no long period swells associated with a tropical cyclone or storm system during this outbreak. Instead, the synoptic fetch around Bermuda high pressure offshore produced high energy wind waves that created dangerous surf conditions in the CWA. Although the rip current forecast scheme utilized by WFO ILM indicated an elevated rip current risk during this event, it became evident that enhancements were needed to better capture dangerous rip current outbreaks not associated with the classic swell events.

Present day rip current forecast schemes take into account a variety of factors including shoreline orientation, swell height and period, onshore wind direction and speed, and tides. The schemes are applied to similar beach regimes over large sections of the coast, which are likely unrepresentative for a given threat since the subtle changes of the shoreline orientation play a large role with respect to incoming waves. In absence of high-resolution modeling of the surf zone, enhancements are needed to refine the risk assessment for smaller sections of beach to provide specific information to lifeguard services and the public. Ultimately, the schemes may require additional fine-tuning from location to location based on the beach type, beach slope, recent re-nourishment projects, adjacent bathymetry, shape of the coastline (geography), water depth over the bar (tuning), and wave climatology.

Bridging rip current research to operational forecast procedures is paramount to enhance the predictability of dangerous rip current days that produce multiple rescues or fatalities. Improvements in rip current forecasting will enable forecasters to accurately predict significant rip current events. In this study, we use 5 years of wave data and lifeguard reports from Wrightsville Beach, North Carolina to evaluate the present local forecast scheme, identify critical thresholds for enhanced rip current activity, and understand the conditions that have contributed to significant past rip current outbreaks. Based on the results of recent rip current studies

(Engle et al. 2002; Dusek and Seim 2013b), we examine the influence of various wave characteristics on local rip current activity. A better understanding of the conditions commonly associated with strong rip currents and numerous rescues will help lead to improved local rip current forecasting techniques and enhance the services provided to emergency managers, lifeguards, and beach communities.

Table 1. Fatalities by hazard type in the Carolinas during the years 2009 to 2013 from the National Storm Events Database. The WFO ILM Rip Current Fatality Database was used to supplement the rip current portion of this table.

Year	Rip Current	Tropical Cyclone	Tornado	Thunder-storm Wind	Flood/Flash Flood	Cold	Heat
2009	10	0	0	1	2	0	1
2010	4	0	0	0	6	1	0
2011	5	2	29	0	2	1	0
2012	4	0	0	0	0	0	0
2013	17	1	0	0	1	0	0
Total	40	3	29	1	11	2	1

2. Background

While some coastal NWS WFOs are testing a probabilistic rip current forecast model (Dusek and Seim 2013b; Dusek et al. 2014), several continue to utilize variations of earlier schemes created by Lushine (1991) and enhanced by Lascody (1998) and Engle et al. (2002). The Lushine (1991) scheme relied heavily on local wind speed and direction given the lack of real-time wave data within the study area. Lascody (1998) subsequently identified the important role of swell height and period in rip current formation. While these early schemes showed success in identifying the likelihood of strong rip currents, they did not consider wave direction due to a lack of observational data at the time. Later, Engle et al. (2002) used directional wave data to reveal that shore normal wave incidence was strongly correlated with rip current rescues. Another important consideration within these schemes was the influence of tides. In particular, Lushine (1991) found a higher number of rip current fatalities focused a couple hours on either side of low tide, while Engle et al. (2002) recognized that low tides falling within a certain mean water level range were more often associated with dangerous rip currents.

At WFO ILM, the present rip current forecast scheme is based off the work of Lushine (1991), Lascody (1998), and Engle et al. (2002). The primary factors that are considered in this rip current forecast process include wave height and direction, prevailing wind speed and direction, percentage of wind observations directed onshore within the previous 48-hour period, tides focused around a new or full moon, and recent rip current reports from lifeguards. WFO ILM forecasters use weather and wave models (including NOAA Wavewatch III and the Simulating Waves Nearshore model) to generate an afternoon surf zone forecast which is valid on the following day, followed by an updated Day 1 forecast that is issued before sunrise the next morning. WFO ILM's Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI) (Schaefer 1990) numbers for Wrightsville Beach, North Carolina over the last 5 years (Table 2) indicate that some but not all rip current events are detected. The false alarms are likely a function of assigning an elevated rip current risk over too large of an area. Therefore, any modification to the rip current forecast scheme must do a better job identifying all significant rip current events while simultaneously reducing false alarms. The findings of recent rip current studies (Engle et al. 2002; Dusek and Seim 2013b) suggest that the current WFO ILM methodology may place too much emphasis on wind speed and direction and not enough importance on the local wave characteristics. Therefore, this study focuses on the wave components that were found to be significant predictors of rip current activity by studies including Engle et al. (2002) and Dusek and Seim (2013b). While tides also have an important influence on rip current activity (Lushine 1991; Engle et al. 2002; Dusek and Seim 2013b), due to data limitations in the study area, the focus of this work is confined to wave characteristics.

Table 2. Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI) scores for WFO ILM rip current forecasts at Wrightsville Beach from 2009 to 2013.

Year	POD	FAR	CSI
2009	0.65	0.08	0.62
2010	0.60	0.15	0.55
2011	0.71	0.23	0.59
2012	0.40	0.38	0.32
2013	0.53	0.27	0.44

3. Data and methods

Wrightsville Beach, North Carolina (Fig. 1) was chosen as the study domain based on the availability of continuous lifeguard reports and buoy data from 2009 to 2013. Wrightsville Beach is on a six-kilometer-long southeast facing island (126° ± 2°) along the Atlantic Ocean. WFO ILM staff coordinate with Wrightsville Beach Ocean Rescue twice daily during the beach season (which typically runs from April to October) via phone or 800 MHz radio for an assessment of the observed surf zone conditions. These beach reports contain valuable information including the visually observed surf height, rip current activity (classified as none, weak, moderate, or strong), and the number of rip current rescues performed by Wrightsville Beach lifeguards. Ocean Rescue personnel assess the daily rip current activity based on the strength and number of rip currents they observe from the beach and experience when they enter the water. Although there is some inherent subjectivity to classifying the rip current activity in this qualitative manner, Dusek and Seim (2013a) showed that lifeguard observations of rip current intensity can serve as a reliable estimation of rip current activity for research purposes. On days when multiple reports were received from Wrightsville Beach, the report with the most severe rip current activity or highest surf height was used to represent that day. This is the same methodology used for local verification of the surf zone forecast product. For the purposes of this study, rip current events are defined as those days with lifeguard reports of moderate or strong rip current activity. Non-events are days when weak or no rip current activity was reported.

Wave data used in this study were collected by Masonboro Inlet buoy 41110. This Waverider buoy is owned and maintained by the Coastal Ocean Research and Monitoring Program at the University of North Carolina Wilmington. The buoy is located approximately 11 kilometers southeast of Wrightsville Beach in 15.7 meters water depth (Fig. 1). Significant wave height, dominant (peak) wave period, and mean wave direction data from 41110 were used for this analysis. Each Wrightsville Beach lifeguard report was matched with the 30-minute buoy observation closest to when the lifeguard report was received. This ensures the buoy data being considered is representative of the surf conditions present when the lifeguard report was relayed to WFO ILM.

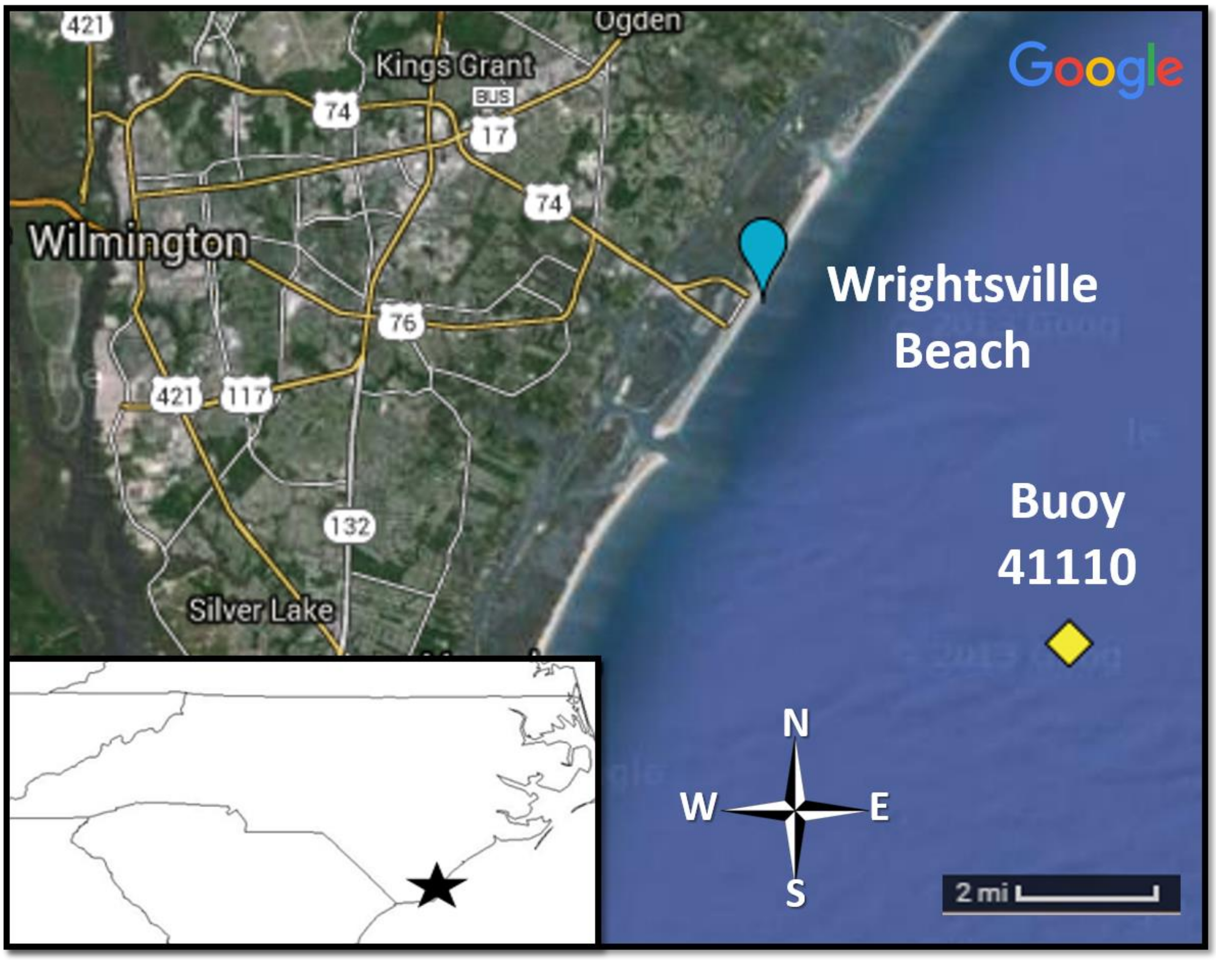

Figure 1. Wrightsville Beach is located east of Wilmington along the southeast coast of North Carolina. Masonboro Inlet buoy 41110 is moored approximately 11 km southeast of Wrightsville Beach in the Atlantic Ocean.

4. Analysis and discussion

During the 2009–2013 beach seasons, WFO ILM received at least one lifeguard report on 549 different days, or around 55% of the total number of beach days from 2009 to 2013. Figure 2 shows the breakdown of Wrightsville Beach rip current activity during the study period. Over 53% of the days were classified as non-events with weak or no rip current activity. Moderate rip current activity accounted for around 36% of the reports, while strong rip currents were reported less than 11% of the time. It should be noted that the moderate rip current activity classification includes some "low to moderate" rip current reports received from Wrightsville Beach lifeguards. Again, this is consistent with the methodology used for local forecast verification.

In the following sections, the significance of various parameters including wave height, period, and direction is evaluated to determine which factors play an important role in modulating rip current activity at Wrightsville Beach. These parameters are all included in the present WFO ILM rip current forecast scheme, and recent research (Engle et al. 2002; Dusek and Seim 2013b) has indicated these are important parameters for rip current forecasting along the Atlantic coast. Then, a detailed analysis is conducted for high-impact rip current events with five or more rip rescues to identify common characteristics associated with these dangerous days.

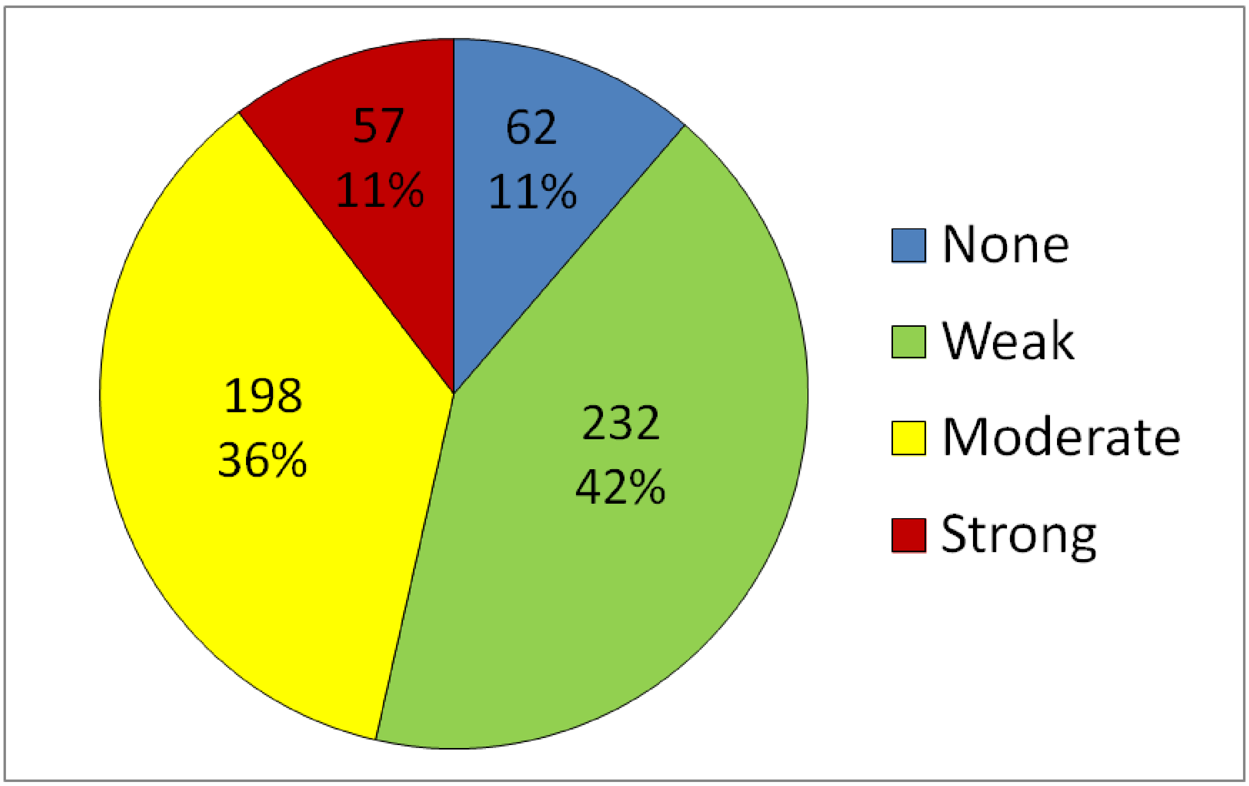

Figure 2. Distribution of rip current activity reported by Wrightsville Beach lifeguards during the beach season from 2009 to 2013. In total, there were 549 days included in the study period.

a. Wave height

Studies as early as Shepard et al. (1941) found a relationship between larger wave heights and enhanced rip current activity. Larger breaking waves in the surf zone generate an increased wave set-up (or rise above the normal water level) near the shore. When there are significant variations in the wave set-up alongshore, stronger rip current circulations can develop as excess water flows toward lower set-up areas and ultimately back out to sea through breaks or channels in the sand bar. Engle et al. (2002) found that rip current rescues at Daytona Beach, Florida increased dramatically with deep water wave heights of 0.5 to 1.0 m. In fact, 63% of their rip current rescues occurred with wave heights between 0.45 to 0.85 m. Dusek and Seim (2013a) revealed that average rip current intensity at Kill Devil Hills, North Carolina increases markedly with significant wave heights between 0.6 and 0.8 m. In their probabilistic rip current forecast model, Dusek and Seim (2013b) identified significant wave height as a key forecast parameter. Not surprisingly, the Wrightsville Beach data confirm the importance of wave height with regards to rip current activity. In Fig. 3, the average surf height visually observed by lifeguards at Wrightsville Beach and the measured wave height at buoy 41110 both increase as the rip current intensity increases from weak to strong.

Figure 4 shows the percent frequency of rip current events at Wrightsville Beach for various wave height thresholds. For instance, when wave heights of 0.6 to 0.8 m were recorded at buoy 41110, moderate to strong rip current activity was reported approximately one-third of the time. Note that once the significant wave height exceeds 0.8 m, the frequency of rip current events becomes greater than 50%. This is close to the 0.7 m threshold identified by Dusek and Seim (2013a) at which rip current intensity began to notably increase in their study domain. For waves between 1.0 to 1.2 m, rip current events occurred almost two-thirds of the time. The percent frequency levels off for wave heights greater than 1.2 m. Since the rip current reports used in this study were strictly lifeguard observations, it is possible that larger breaking waves occasionally masked rip current activity for these higher wave heights (as noted in MacMahan et al. 2005).

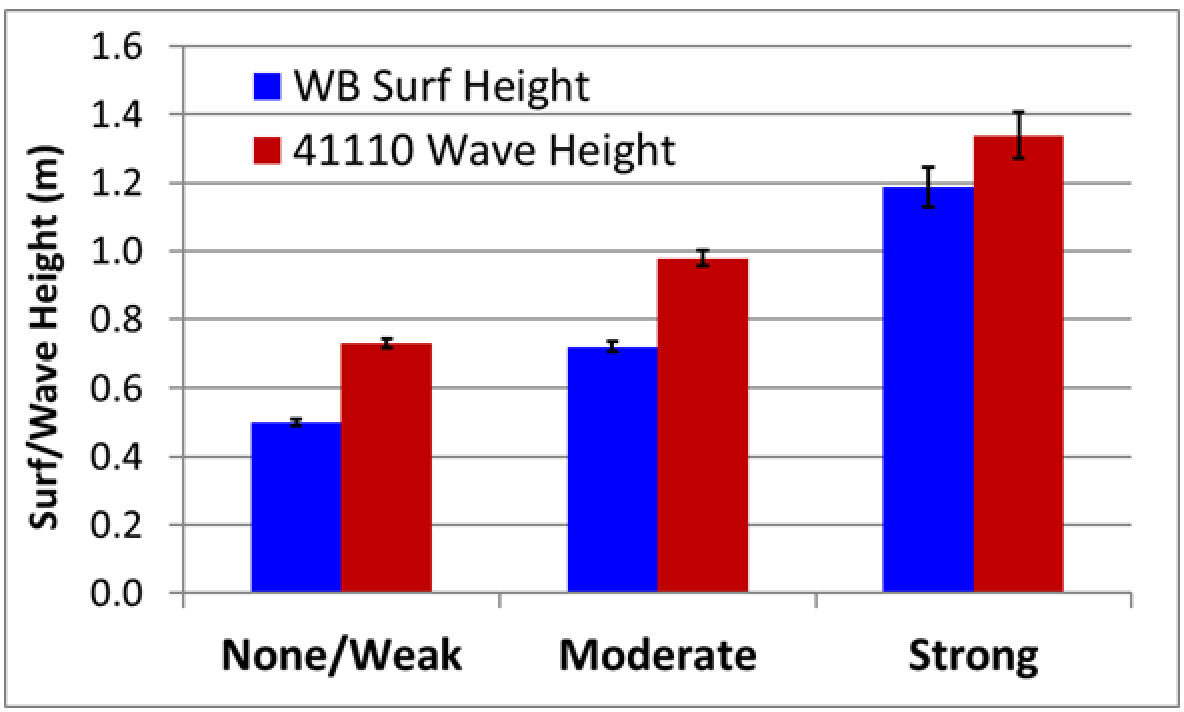

Figure 3. Average Wrightsville Beach surf heights (blue) and buoy 41110 wave heights (red) for reports of none/weak, moderate, and strong rip currents. The error bars (black) represent the standard error of the mean for each category.

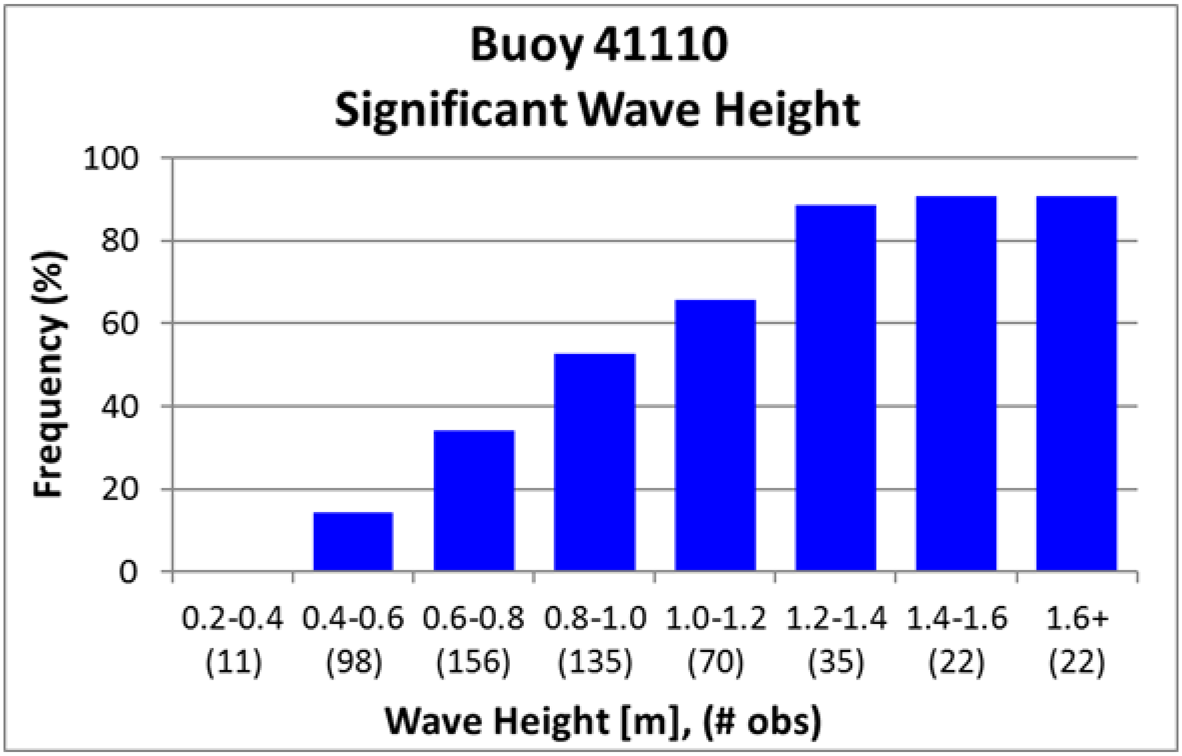

Figure 4. Percent frequency of rip current events at Wrightsville Beach from 2009 to 2013 based on significant wave height observations from buoy 41110. For reference, the number of observations in each range bin is included in parentheses below the bin label.

b. Wave period

A review of rip current literature regarding wave period for rip current forecasting purposes provides mixed results. The early work of Lushine (1991) in southeast Florida showed good correlation between rip currents and local wind speed and direction. The implication of these findings is that locally generated, shorter period wind waves were important for rip current formation. On the other hand, Lascody (1998) found that 75% of east central Florida rip current rescues occurred on days with dominant long period swell, and swell greater than 12 seconds was almost always associated with a greater number of rip current rescues. Engle et al. (2002) narrowed down the most favorable wave periods for rip currents at Daytona Beach, Florida to 8 to 10 seconds. In Engle's work, 62% of rip current rescues occurred with wave periods of 7.5 to 9.0 seconds. More recently, Dusek and Seim (2013a) found no significant relationship between rip current intensity and wave period. In fact, Dusek and Seim (2013b) noted that the inclusion of wave period in the WFO Morehead City, North Carolina forecast scheme resulted in missed events because it did not consider waves with periods less than 8 seconds. Clearly, there is no consensus regarding the forecast value of wave period.

Figure 5 shows the frequency distribution of dominant wave periods during rip current events (red bars) and non-events (blue bars) at Wrightsville Beach. A comparison of the two datasets reveals that rip current events are less likely to be associated with wave periods less than 6 seconds. Only around 10% of the rip current events occurred with wave periods of 4 to 5 seconds. But 6 seconds seems to be a significant local threshold – over 20% of the rip current events in this study had wave periods of 6 seconds. Wave periods of 6 to 9 seconds accounted for the majority (~62%) of the rip current events at Wrightsville Beach from 2009 to 2013. Longer period swells, such as from a distant tropical cyclone, obviously occur far less often at the local beaches. Still, swells of 10 seconds or greater were associated with over one-quarter of the rip current events during the study period.

In order to ensure that this local wave period threshold is not simply a byproduct of smaller waves, the scatter plot in Fig. 6 compares wave height and wave period observations for rip current events (red) and non-events (blue). Of the 549 buoy observations in this study, 112 had wave periods of less than 6 seconds. Over 64% of these observations (72/112) were associated with wave heights greater than or equal to 0.7 m. These wave heights are certainly capable of generating rip currents at Wrightsville Beach based on the wave height analysis presented above. Therefore, it doesn't appear that the lower frequency of rip currents associated with wave periods less than 6 seconds is solely a product of small waves. More conclusions will be drawn about wave period later in the results section when high-impact rescue days are examined in more detail.

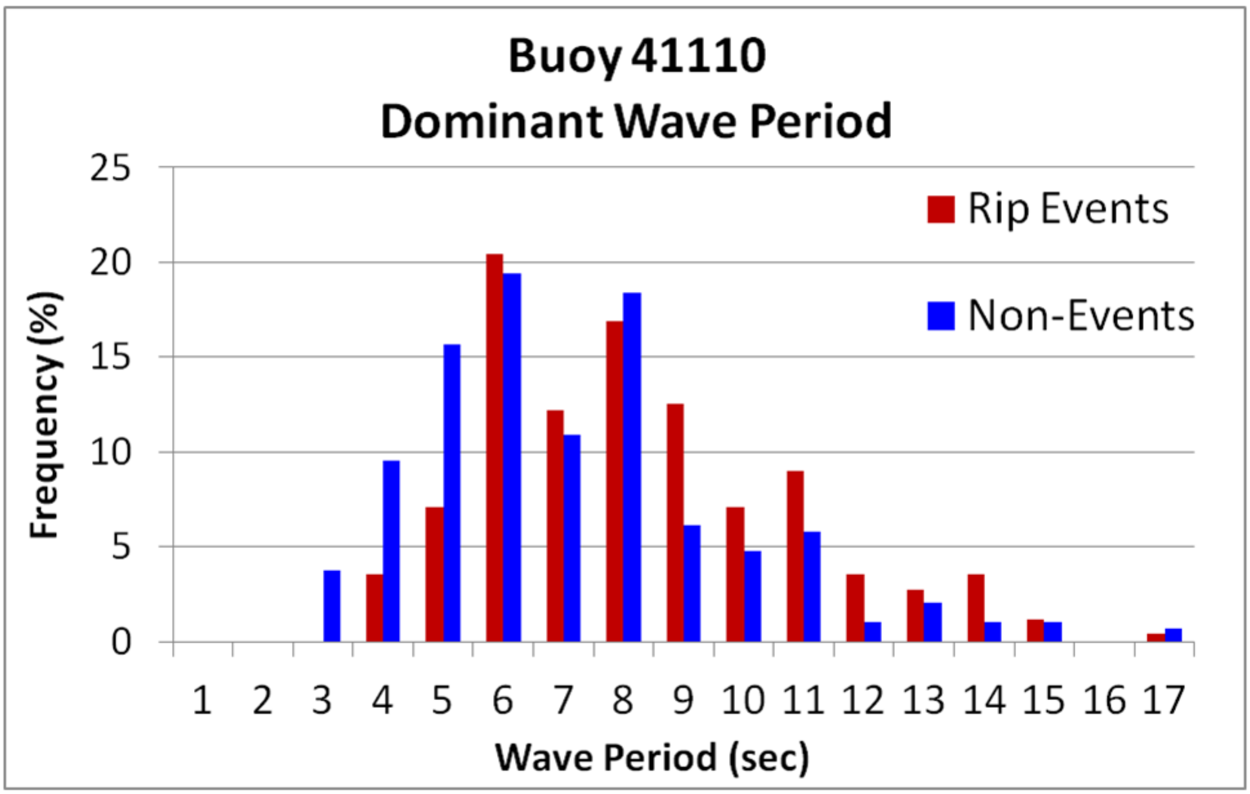

Figure 5. Dominant wave period frequency distribution for rip current events (red) and non-events (blue) at Wrightsville Beach from 2009 to 2013.

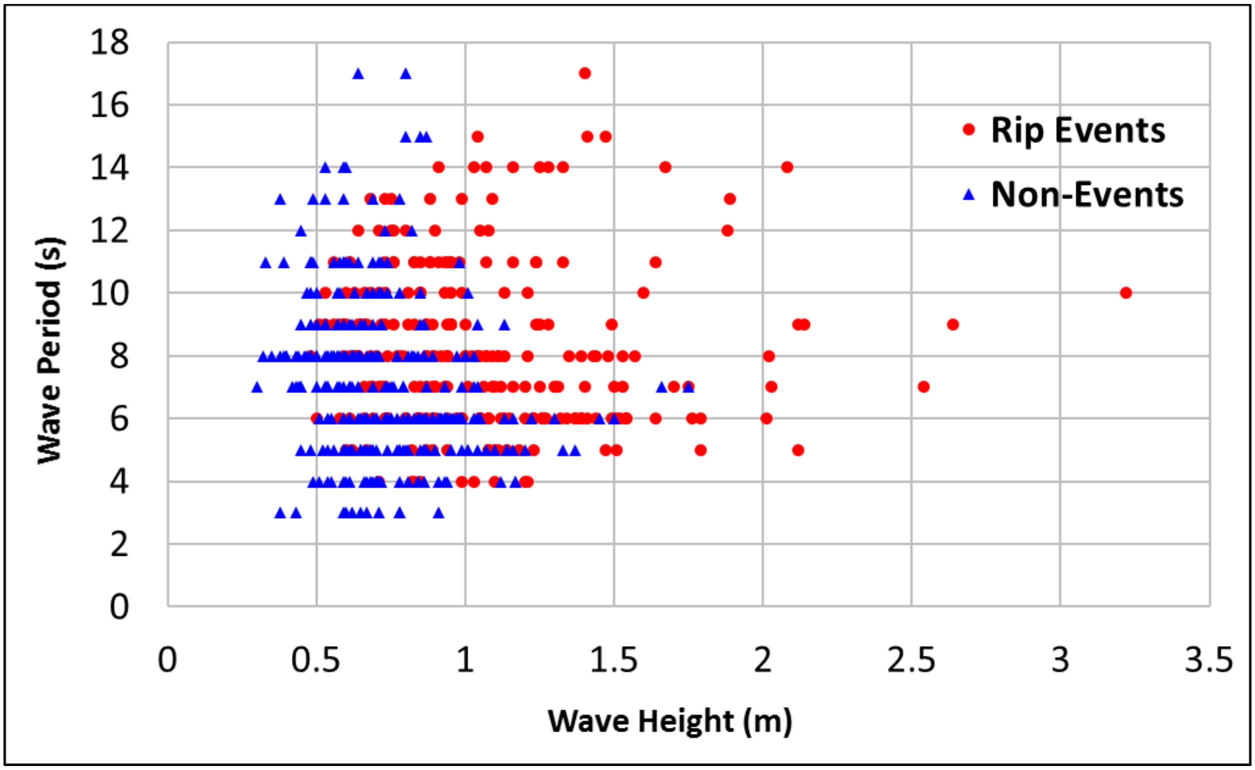

Figure 6. Scatter plot of buoy 41110 wave height and period observations for rip current events (red) and non-events (blue) from 2009 to 2013.

c. Wave direction

Another important consideration for rip current forecasting is the incoming wave direction. Early studies (Lushine 1991; Lascody 1998) linked rip currents to onshore winds, which implied that locally generated, onshore wind waves were playing a role in enhancing the rip current threat. Similarly, Engle et al. (2002) showed that shore-normal wave incidence was strongly correlated with rip current rescue activity. More recent work has affirmed the importance of wave direction as it relates to rip current activity. For instance, persistent rip current channels were noted by MacMahan et al. (2005) during an extended period of nearly shore-normal waves. Likewise, Dusek and Seim (2013a) found that rip current intensity was maximized when the mean wave direction was close to shore normal, which led to them using wave direction as a predictor in their rip current forecast model (Dusek and Seim 2013b). Directional wave data from buoy 41110 are used here to analyze the influence of wave direction on local rip current activity.

Figure 7 shows the frequency distribution of wave directions associated with rip current events (red) and non-events (blue). Mean wave directions reported to the nearest degree by buoy 41110 were binned into 16-point compass directions for this plot. Clearly, the most favorable wave directions for rip currents at Wrightsville Beach are east-southeast and southeast (between 102 and 146°). Over 61% of the rip current events occurred when the mean wave direction was within this range. As waves become increasingly shore-parallel, the rip current frequency markedly decreases. The oblique angle of approach relative to the coastline likely creates a longshore current that disrupts the rip current circulation (Sonu 1972).

Additionally, the average rip current category was calculated based on the angle of wave incidence relative to the southeast facing Wrightsville Beach coastline. A number was assigned to each rip current category (0: no rips, 1: weak, 2: moderate, and 3: strong), similar to the analysis performed in Dusek and Seim (2013a). Then, the angle of incidence was calculated for each buoy observation. Negative directions are north and positive directions are south of the line normal to the coastline. The results are shown in Fig. 8. The average rip current category is highest when the mean wave direction is within ± 20° of shore normal. When wave directions are more than 40° from shore normal in either direction, the average rip current category noticeably decreases.

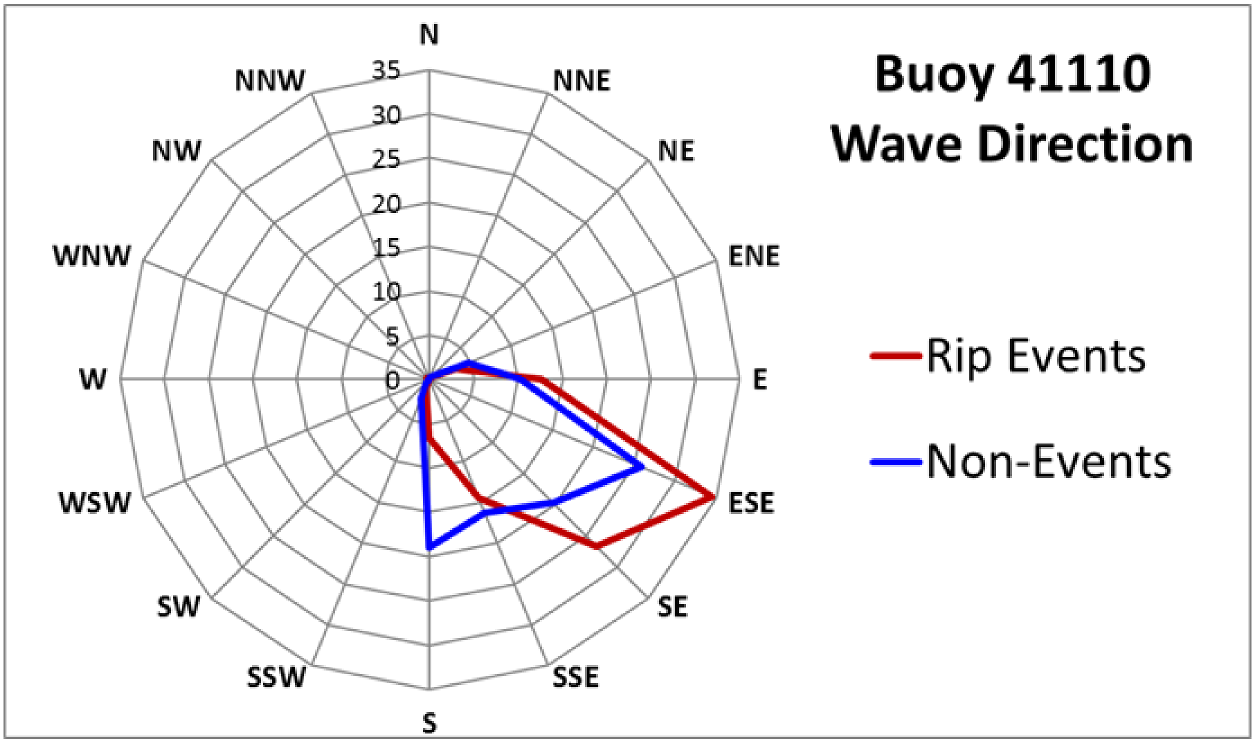

Figure 7. Buoy 41110 mean wave direction frequency plot for rip current events (red) and non-events (blue) at Wrightsville Beach. The labeled concentric circles represent increasing percent frequency of a wave direction with increased distance from the center of the plot.

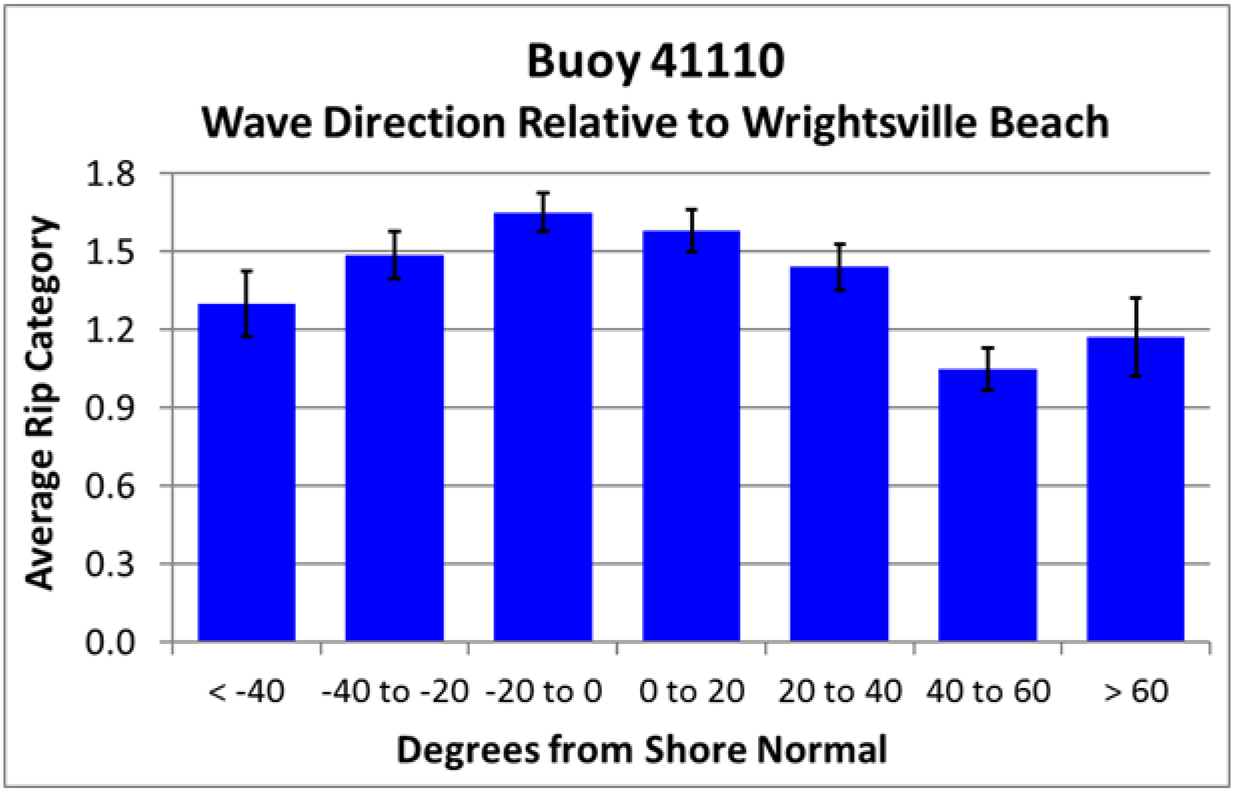

Figure 8. Average rip current category based on the mean wave direction at buoy 41110 relative to the Wrightsville Beach coastline. In order to calculate the mean, individual rip current observations were assigned numbers (0: no rips, 1: weak, 2: moderate, and 3: strong). Each observation is binned according to how many degrees the wave direction was from shore normal. Zero represents a mean wave direction that is directly onshore. The error bars (black) represent the standard error of the mean for each wave direction bin.

d. High-impact rescue days

Finally, the days with five or more rip current rescues were analyzed separately in hopes of identifying favorable wave conditions that distinguish these high-impact days. There is an inherent beach population bias when analyzing days with multiple rescues, since these days would likely be associated with a higher beach attendance. However, from a forecasting and warning perspective, it is important to understand what kind of wave conditions produce enhanced rip current activity without deterring people from entering the water. From 2009 to 2013, there were 21 days that Wrightsville Beach lifeguards reported five or more rip current rescues. Of these 21 days, 10 occurred on weekends while 11 were during the week. There were likely even more days that met this threshold but are not included in this analysis because the rescue reports were not received by WFO ILM staff. In total, over 500 rescues were performed during the 21 days considered in this section. The most notable event occurred on 7 August 2010, when 215 swimmers were rescued due to widespread rip current activity caused by swell from distant Tropical Storm Colin.

Figure 9 is a scatter plot of wave height and period observations for each of the 21 days with five or more rip current rescues. The size of each circle represents the number of rescues reported on that day by Wrightsville

Beach lifeguards. The color of the circle provides some information about the mean wave direction of the observation – blue circles indicate the waves were approaching Wrightsville Beach within 10° of shore normal, while red circles indicate the angle of incidence was greater than 10°.

Figure 9 reveals that all 21 events were associated with wave heights of 0.6 m or greater. The five reports with at least 20 rip current rescues all occurred on days with wave heights greater than 0.8 m. All 21 events analyzed here corresponded with wave periods of 6 seconds or greater. This is consistent with the earlier assertion that 6 seconds appears to be a significant local threshold for enhanced rip current activity at Wrightsville Beach. These events were distributed fairly evenly with regards to wave period; 11 events had wave periods less than 10 seconds, while 10 events occurred with wave periods greater than 10 seconds. The two most significant events with 215 and 70 rescues were linked with periods of 12 and 17 seconds, respectively. Eighty-one percent (17/21) of the events occurred when the mean wave direction was within 10° of shore normal. This figure indicates that most high-impact rip current events at Wrightsville Beach are associated with wave heights of 0.7 m or greater approaching the beach with an angle of incidence less than 10°. Although the wave periods varied greatly among these 21 events, every high-impact event in this analysis was associated with a wave period of at least 6 seconds.

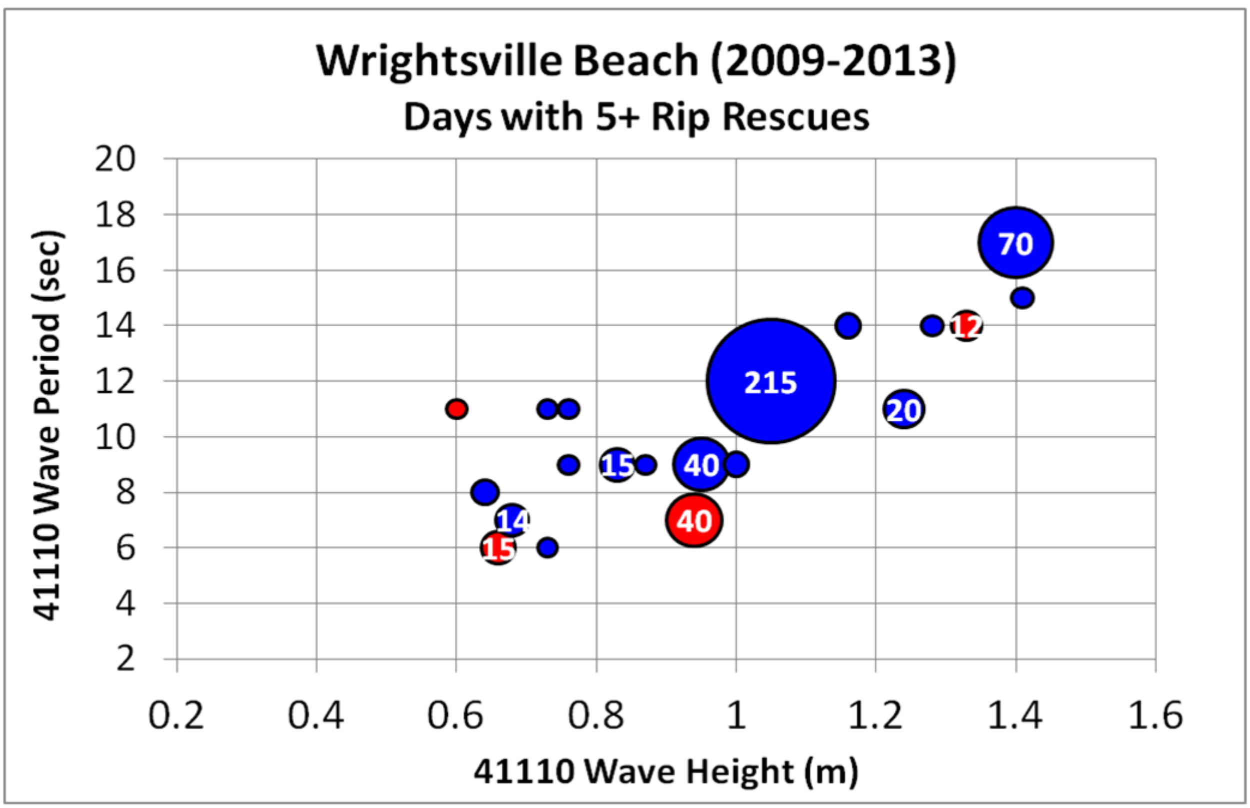

Figure 9. Scatter plot of buoy 41110 wave height and period observations for each of the 21 days with five or more rip current rescues reported by Wrightsville Beach lifeguards. The size of each circle indicates the number of rip current rescues reported on that day. Blue (red) circles denote wave observations with a mean wave direction within (greater than) 10° from shore normal.

e. Directional wave window

The results from this analysis can be used to define a "directional wave window" for dangerous rip current activity at Wrightsville Beach and other local beaches. The window simply illustrates the most favorable wave heights and directions for enhanced rip currents at a particular beach. Figure 10 is a conceptual illustration of the directional wave window for Wrightsville Beach. In Fig. 10, a greater rip current threat is represented by warmer colors (orange and red) while the cooler colors (green and yellow) denote a lesser threat. For instance, 0.9 m waves approaching from 120° (red) would pose a greater rip current danger than 0.9 m waves from 80° or 170° (green). In general, larger waves with near shore normal incidence will produce a higher risk for dangerous rip current activity, especially if the dominant wave period is 6 seconds or greater at Wrightsville Beach. As discussed earlier, Wrightsville Beach faces southeast (126° ± 2°). So, waves approaching the Wrightsville Beach coastline from directions of 106° to 146° have a much better chance of producing moderate to strong rip currents than waves outside of this window. Based on the analysis of high-impact rescue days, incoming waves focused within 10° of shore normal would further enhance the likelihood of a significant rip current event (as shown in Fig. 10). Using our findings from Wrightsville Beach, similar directional wave windows can be constructed for other local beaches to narrow down the most favorable wave conditions for rip currents and weight them appropriately in the forecast scheme.

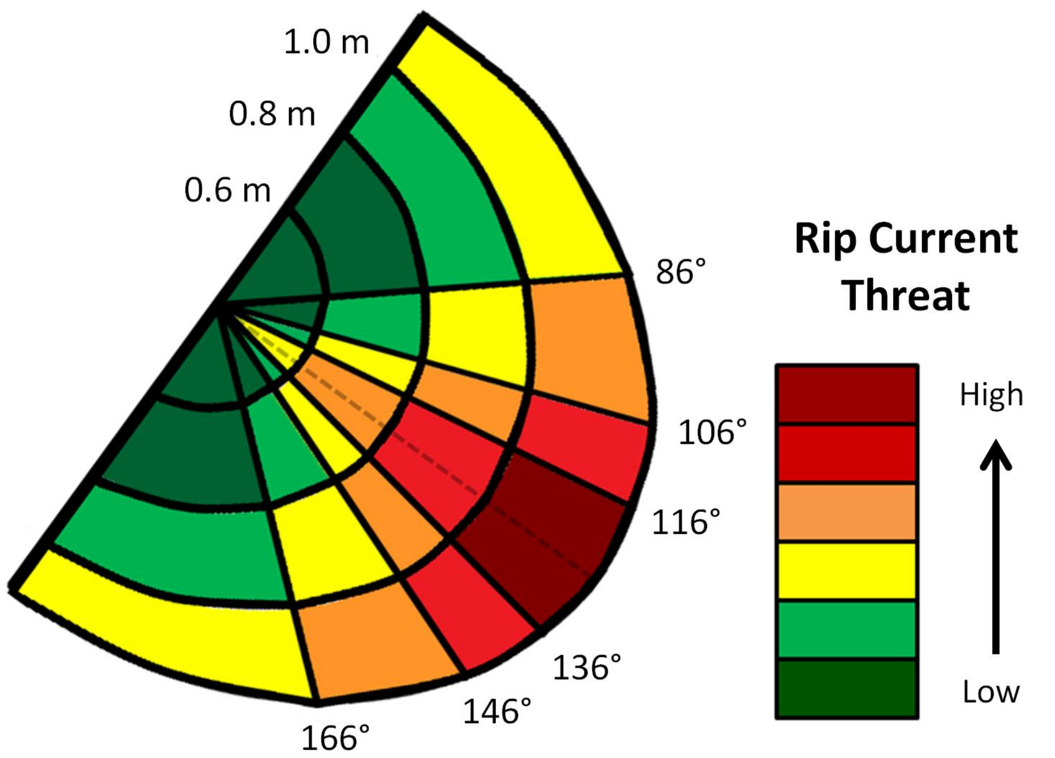

Figure 10. Conceptual illustration of a directional wave window defined for Wrightsville Beach. The labeled lines indicate significant local thresholds for incoming wave directions, while the labeled arcs represent wave height thresholds. The warmer colors denote favorable wave height/direction bins for enhanced rip current activity at Wrightsville Beach.

5. Conclusions and future work

This analysis revealed valuable information about the factors that influence rip current intensity at Wrightsville Beach, especially those wave conditions that define Wrightsville Beach's directional wave window. Wave height and direction are the most significant parameters investigated in this study that modulate the local rip current activity. The probability of rip currents at Wrightsville Beach increases greatly for significant wave heights of 0.8 m or greater. Furthermore, mean wave directions within ± 20° of shore normal (east-southeast to southeast at Wrightsville Beach) are most favorable for enhanced rip current activity. These findings are consistent with the results of previous rip current studies (Engle et al. 2002; Dusek and Seim 2013a,b) that related increased rip current activity to larger wave heights and shore normal wave incidence.

The dominant wave period did not regulate local rip current activity given the fairly uniform distribution of wave periods measured during high-impact rip current events. However, it was noted that 6 second wave periods seem to be a significant local threshold for rip currents. The data suggested that rip currents at Wrightsville Beach become increasingly unlikely for wave periods less than 6 seconds. Lastly, there were 21 days during the study period with five or more Wrightsville Beach rip current rescues reported to WFO ILM. The dominant wave periods for these events ranged from 6 to 16 seconds, with roughly half of the events each above and below 10 seconds. The majority of these high-impact events were associated with significant wave heights of at least 0.7 m and wave directions within ± 10° of shore normal.

The results presented in this study highlight some shortcomings in the present WFO ILM rip current forecast scheme. For instance, the current methodology only allows forecasters to evaluate incoming waves in terms of cardinal and intermediate directions (e.g., northeast, east, or southeast). However, our findings reveal that subtle changes in the incoming wave direction can have significant impacts on the local rip current activity. Waves approaching the beach within ± 20° of shore normal are far more likely to result in a significant rip current event than waves outside of this range. Therefore, the scheme must be modified to allow forecasters to input more specific forecast wave directions. Then, the directional wave window model can be applied to better assess the rip current risk. Ultimately, the results presented in this study can be used by WFO ILM forecasters to better identify those days that could result in dangerous surf conditions and unusual amounts of rip current rescues.

Based on these results, WFO ILM plans to modify the rip current forecast scheme for upcoming beach seasons using these localized wave height, direction, and period thresholds. The enhanced technique will be applied during an evaluation period to quantify the impacts these changes have on WFO ILM rip current forecasts. The output from the new ILM scheme could also be compared with the probabilistic rip current forecast model described in Dusek et al. (2014) if model coverage is expanded into the ILM forecast domain. Other factors that were not specifically addressed in this study should be examined in more detail. For instance, water level data could be used to examine how tides modulate local rip current activity. Also, large wave events lead to changes in the offshore sandbar structure that may require wave height thresholds to be lowered following such events. Finally, similar studies may be conducted for other beaches in the forecast area to better understand the impacts of different bathymetry and coastline orientations on local rip current activity.

Acknowledgments

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References

Bowen, A. J., 1969: Rip currents, 1. Theoretical investigations. *Journal of Geophysical Research*, **74** (23), 5467–5478.

Dusek, G., and H. Seim, 2013a: Rip current intensity estimates from lifeguard observations. *Journal of Coastal Research*, **29** (3), 505–518.

____, 2013b: A probabilistic rip current forecast model. *Journal of Coastal Research*, **29** (4), 909–925.

Dusek, G., A. J. Van der Westhuysen, A. Gibbs, D. King, S. Kennedy, R. Padilla, H. Seim, and D. Elder, 2014: Coupling a rip current forecast model to the Nearshore Wave Prediction System. *12th Symposium on the Coastal Environment*, Atlanta, GA, American Meteorological Society, 3.2. [Available online at https://ams.confex.com/ams/94Annual/webprogram/Paper238859.html].

Engle, J., J. MacMahan, R. J. Thieke, D. M. Hanes, and R. G. Dean, 2002: Formulation of a rip current predictive index using rescue data. *Proc. National Conference on Beach Preservation Technology*, Biloxi, MS, Florida Shore and Beach Preservation Association. [Available online at http://ripcurrents.noaa.gov/resources/Engle2002.pdf].

Lascody, R. L., 1998: East central Florida rip current program. *National Weather Digest*, **22** (2), 25–30.

Lushine, J. B., 1991: A study of rip current drownings and related weather factors. *National Weather Digest*, **16** (3), 13–19.

MacMahan, J. H., E. B. Thornton, T. P. Stanton, and A. J. H. M. Reniers, 2005: RIPEX: Observations of a rip current system. *Marine Geology*, **218**, 113–134.

National Climatic Data Center, 2009–2013: Storm Events Database. [Available online at http://www.ncdc.noaa.gov/stormevents/]

Schaefer, J. T., 1990: The critical success index as an indicator of warning skill. *Weather and Forecasting*, ***5*** (4), 570–575.

Shepard, F. P., K. O. Emery, and E. C. Lafond, 1941: Rip Currents: A process of geological importance. *Journal of Geology*, **49**, 338–369.

Sonu, C. J., 1972: Field observation of nearshore circulation and meandering currents. *Journal of Geophysical Research*, **77** (18), 3232–3247.

United States Lifesaving Association, 2015: USLA Rip Current Survival Guide. [Available online at http://www.usla.org/?page=RIPCURRENTS].