3.2 COUPLING A RIP CURRENT FORECAST MODEL TO THE NEARSHORE WAVE PREDICTION SYSTEM

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1. INTRODUCTION

Rip currents are the leading cause of fatalities and rescues along beaches in the United States. The United States Lifesaving Association (USLA) estimates that nearly 100 fatalities per year occur in the U.S. due to rip currents, yet rip current forecasting methods have remained relatively unchanged over the past 20 years. The present method used to generate rip current guidance from the National Weather Service (NWS) relies on an observational index based on the LURCS index created in 1991 (Lushine, 1991). Thus, it is not a true forecast and does not benefit from recent advances in wave and water level modeling.

A probabilistic rip current forecast model has been coupled with the Nearshore Wave Prediction System (NWPS, Van der Westhuysen et al., 2013) to provide guidance on the likelihood of hazardous rip currents occurring (from 0 to 1). The rip current forecast model is a statistical model developed using wave, water level, and rip current observations and an initial assessment shows improved performance over the present index based approach (Dusek and Seim, 2013a). NWPS incorporates nearshore numerical wave models and input from operational tide and surge models to provide high-resolution nearshore wave model guidance over the domains of responsibility of the NWS's coastal Weather Forecast Offices (WFOs). By coupling the rip current forecast model with NWPS, the system is able to provide a 36-hour rip current forecast at a high resolution (~500m) along the coast.

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Both NWPS and the rip current forecast have been installed operationally at the WFO in Morehead City, NC (MHX). To assess performance, a hindcast has been made for the summer of 2013 at two locations on the Outer Banks of North Carolina – Kill Devil Hills (KDH) and Emerald Isle (EMI). To determine forecast skill, the hindcast results are compared to lifeguard observations of rip currents and rip current rescues and in this paper some of the initial results are presented. First, background information on both NWPS and the rip current forecast model is presented. The next section provides methods including the hindcast set-up and how lifeguard observations were collected. This is followed by the results of the NWPS validation and a presentation of the performance of the rip current forecast model during three high rip current periods at KDH. Lastly, conclusions and future work are discussed.

2. BACKGROUND

2.1. NWPS

NWPS is presently being developed to provide on-demand, high-resolution nearshore wave guidance to the coastal forecasters of the National Weather Service. It is designed to run locally at NWS's coastal WFOs, covering their forecast domains of responsibility (e.g. Figure 1), and is driven by forecaster-developed wind grids and offshore wave boundary conditions from NCEP's operational WAVEWATCH III (Tolman et al., 2002). The nested nearshore wave model used is SWAN (Booij et al. 1999), and alternatively a nearshore version of WAVEWATCH III. Current fields are taken from NCEP's Real-Time Ocean Forecast System (RTOFS). Coastal water levels are provided by the Extratropical Surge and Tide Operational Forecast System (ESTOFS), supplemented by probabilistic output from the P-

Surge model during tropical cyclone events. NWPS produces various types of output, including fields of integral wave parameters, spectra and individual partitioned and tracked wave systems. This model guidance is subsequently ingested into NWS's Advanced Weather Interactive Processing System (AWIPS) to aid in the generation of detailed coastal marine forecasts.

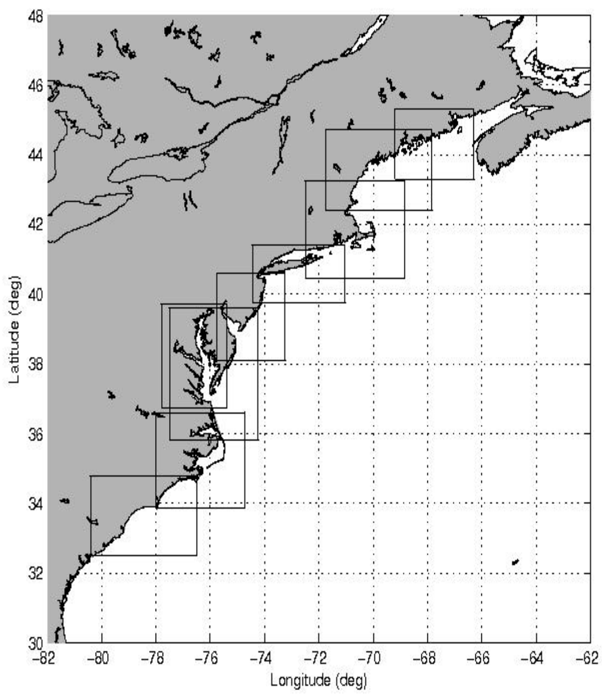

Figure 1. Example of planned coverage of the Nearshore Wave Prediction System at WFOs in NWS's Eastern Region, including the WFO Morehead City domain.

2.2. Rip current forecast model

The formulation of the rip current forecast model was created using wave field, water level and rip current observations collected at Kill Devil Hills (KDH), NC. It is a probabilistic model created through a logistic regression (Hosmer and Lemeshow, 1989), where the model inputs are significant wave height (H_s), mean wave direction (θ), water level (η) and wave event occurrence (E_p) and the output is the likelihood of hazardous rip currents occurring (from 0 to 1). The variable E_p is a binary (0 or 1) input representing if the predicted time period is within 72-hours following a moderate wave event or not (H_s exceeding 1 m). The input variables to the model were chosen based on importance to rip current dynamics and statistical significance (see Dusek and Seim, 2013a for a complete description). The forecast model showed a 67% improvement over the present NWS index based guidance approach when forecasting hazardous rip current occurrence, and significantly outperformed the index approach during extreme rescue periods (Dusek and Seim, 2013a).

2.3 Collaboration with MHX and KDH Ocean Rescue

The development of the rip current forecast model and the hindcast described here, were only possible through close collaboration with both the Morehead City Weather Forecast Office (MHX) and KDH Ocean Rescue. When developing the forecast model, MHX provided information regarding the index based guidance to enable a comparison with our forecast model (Dusek and Seim, 2013a). KDH Ocean Rescue collected a record of nearly 800 rip current rescues and provided lifeguard observations of rip currents, which were both fundamental in creating and validating the forecast model (see below and Dusek and Seim, 2013b). For hindcast validation, KDH Ocean Rescue has again provided observations of rip currents and a record of rip current rescues. MHX has implemented both NWPS and the rip current forecast model operationally and has worked with other ocean rescue groups in NC to collect additional data for validation. Close collaboration with both local WFOs and ocean rescue groups is deemed vital for successful operational implementation of this forecast model at KDH and other locations in the future.

3. METHODS

3.1. Hindcast setup

In order to provide input for the evaluation of the rip current forecast model, an NWPS wave hindcast (using the underlying SWAN model) was conducted for the WFO MHX domain over May-September 2013. The model setup included the definition of the model grids, their offshore wave boundary conditions, as well as wind and water level fields over the model domain. Figure 2 shows the grid setup over the WFO Morehead City domain, featuring an overall domain at a uniform resolution of 1 nmi, with two sets of telescopic nests over the KDH and EMI domains, going up to resolutions of 50 m (CG3) and 100 m (CG5) respectively. Results for NWPS were subsequently extracted along the 5 m contours of these nearshore domains (Figure 3).

Wave boundary conditions on the overall MHX domain were generated by means of a hindcast with NCEP's global WAVEWATCH III model, run at a ½ degree resolution and forced with forecast archives of 10 m elevation winds from NCEP Global Forecast System (GFS). For this, a short-term GFS forecast time series was created by tiling the 12 h of forecasts at the 00z and 12z daily cycles. Water levels (tide and surge) were extracted from forecast archives of NOS's ESTOFS model, and wind forcing over the MHX domain were taken from operational archives of NCEP's North American Mesoscale (NAM) model. Both of these input sources were again compiled into 12 h, short-term forecast time series.

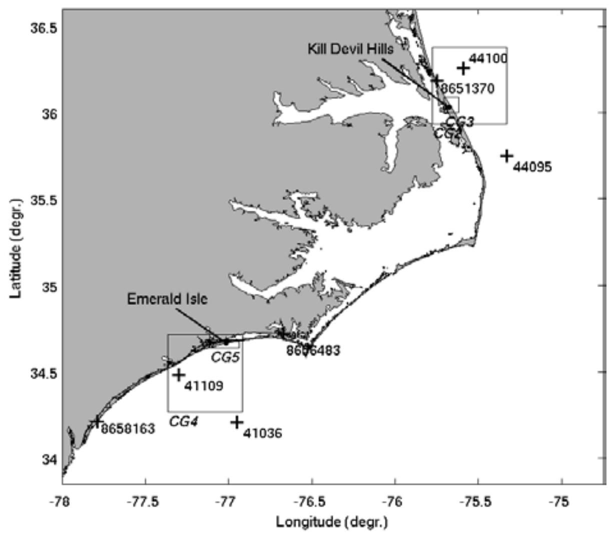

Figure 2. Definition of the nested NWPS model grid domains for WFO Morehead City, including observation stations. The overall domain is resolved at a uniform resolution of 1 nmi. Remaining resolutions are: CG2 = 500 m; CG3 = 50 m; CG4 = 500 m; CG5 = 100 m.

Over the hindcast period the rip current forecast model calculates the rip current likelihood at every three hours for each output point in the KDH and EMI domains (Figure 3). The two output points directly seaward of Bogue Inlet are not included since the forecast is representative of the open coast only. Analysis of the alongshore variability of the forecast output in each domain show very little alongshore variability – the mean standard deviation is only 0.013 at KDH and 0.019 for EMI. This is not surprising, as the NWPS inputs are also very uniform alongshore. As such, all figures and analysis shown below are for the alongshore mean rip current likelihood for each location.

3.2. Rip current observations and rescues

To assess performance of the rip current forecast model, lifeguard observations of rip current intensity were made at both KDH and EMI and a record of rip current rescues were recorded at KDH. The observations of rip current intensity were recorded from 0 to 3 depending on the likely risk to swimmers as in Dusek and Seim (2013b):

0 - No rip currents present

1 - Some low intensity rip currents present, may be hazardous to some swimmers

2 - Medium to strong rip currents present, will likely be hazardous to swimmers

3 - Very strong rip currents present, hazardous conditions

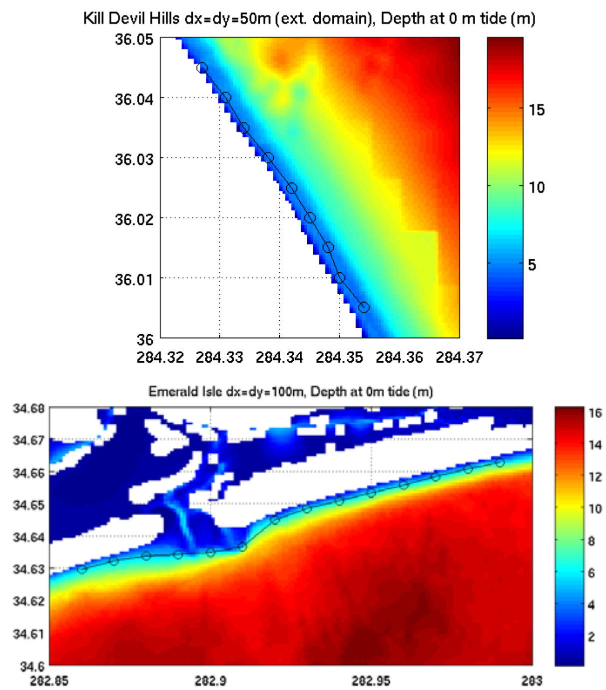

Figure 3. Nearshore domains at Kill Devil Hills (CG3 grid, top) and Emerald Isle (CG5 grid, bottom) showing the 5 m contour along which wave and water level output were extracted.

The lifeguards at KDH are trained to identify rip currents and a comparison between their observations and rip current rescues in previous field work demonstrated the validity of their observations (Dusek and Seim, 2013b). Although observations were also made at EMI – they were only made at one location and initial analysis suggests that their consistency and accuracy may be questionable. Since rip current rescues were not recorded at EMI there is no way of validating their accuracy and thus they are not considered further.

At KDH observations were made twice a day (11am and 3pm) at 19 chair locations over the domain and are the observed rip current conditions leading up to the recorded time period. In addition to observations, an hourly record of rip current rescues was collected by the lifeguards at KDH, which provides an additional data source for validation.

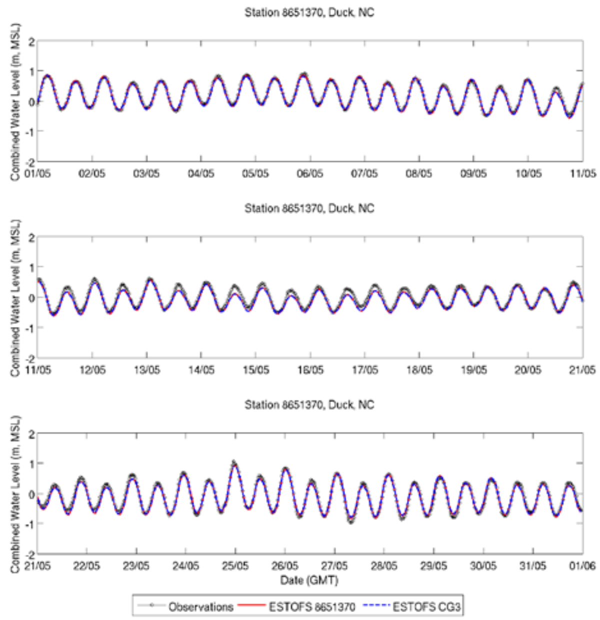

Figure 4. Validation of ESTOFS Atlantic water levels against the CO-OPS station 8851370 (Duck, NC) near the KDH field site, for the month of May 2013.

Although the hindcast period and rip current observations cover the entire summer of 2013, here we focus on three high rip intensity and rescue periods each lasting 5 days; June 20-24, August 17-21 and August 29-September 2. A complete statistical analysis and validation of the entire summer will be presented in a future paper.

4. VALIDATION AND RESULTS

4.1. NWPS and ESTOFS validation

Figure 4 shows the validation of the archived ESTOFS water level forecasts, which were used as input into NWPS and the rip current forecast model. The model results compare favorably with observations at NOAA CO-OPS station 8651370 (Duck, NC) near the KDH domain. The tidal phase is reproduced well, and likewise the tidal and surge amplitudes are mostly captured accurately. Results of similar quality are found at the EMI site to the south (not shown).

Figure 5 presents the validation of the wave model output from NWPS against observations at the NDBC station 44100, just offshore of Duck, NC, close to the KDH nested domain. Significant wave heights are reproduced well, especially within the mid-ranges of energy, which are particularly relevant to hazardous rip current occurrence. Peak wave periods also show acceptable agreement with observations, considering the well-known volatile nature of this parameter in multi-peaked (wind sea/swell) wave fields found in this region. Similar results were found at station 41109, near the EMI nested domain (not shown). Finally, mean wave directions agree generally well with observations. An exception was found for waves approaching KDH from the south, which tended to be biased to the south of shore normal, for reasons still under investigation. However, since wave direction is of secondary importance to the rip current expression considered here, this result is considered acceptable for the present purposes.

4.2. Performance of rip forecast model at three high rip intensity periods

Predicted hazardous rip current likelihood compares favorably to the lifeguard observations of rip current intensity over the three five-day periods. Plots of the lifeguard observations (averaged over all 19 chairs) and rip current likelihood are qualitatively in good agreement. For the June 20-24 example, the peak in rip current likelihood (0.92) and mean lifeguard observed rip intensity (2.6) both occur on June 21 at 11am, and then decrease slightly each day over the remaining three days (Figure 6). Of note is the fairly large tidal range during this period, which leads to significant differences in predicted likelihood over the course of the day.

For the period from August 17-21 (Figure 7), both predicted rip current likelihood and observed intensity are slightly lower than the previous June example. Again, the tidal range is fairly large in this period, and low tide is near 11am on August 18 and 19. On both of these days, the model suggests a decrease in rip likelihood in the afternoon, as the water level increases, and the observed rip intensity shows a similar trend. This period, is somewhat unique in that relatively high observed rip current intensity occurs despite fairly low significant wave height (from about 0.9 m on the 17th to about 0.6 m on the 20th and 21st).

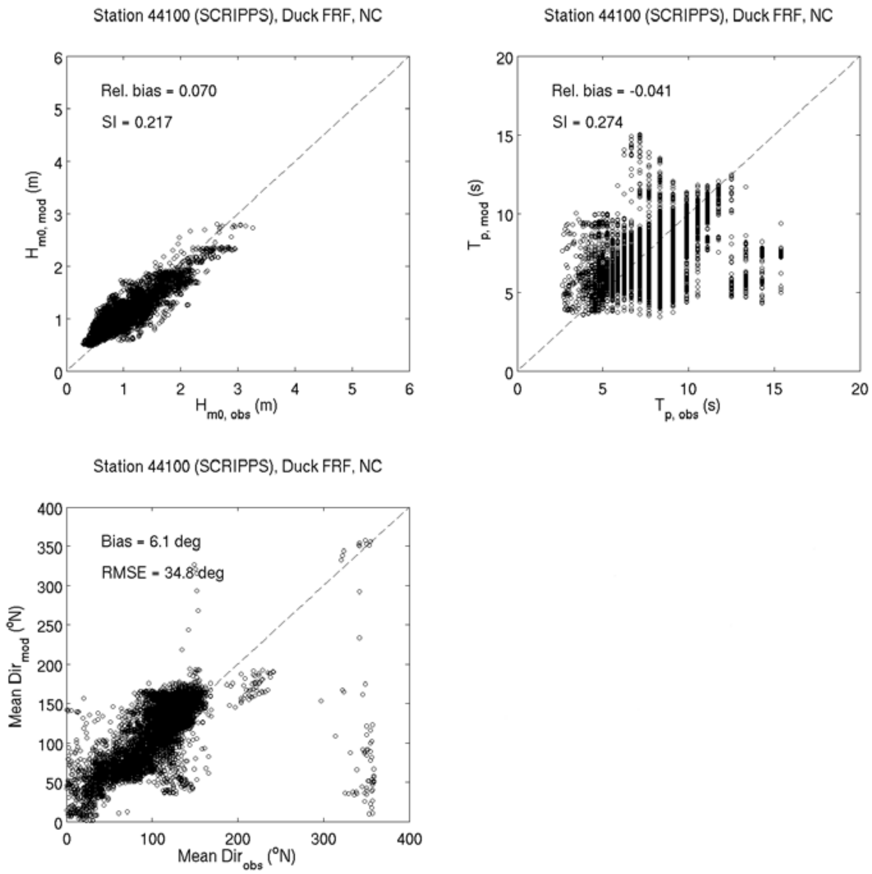

Figure 5. Validation of NWPS wave output ("mod") against observations ("obs") at NDBC 44100 (Duck Field Research Facility, NC) near the KDH field site, for the total hindcast period of May-September 2013.

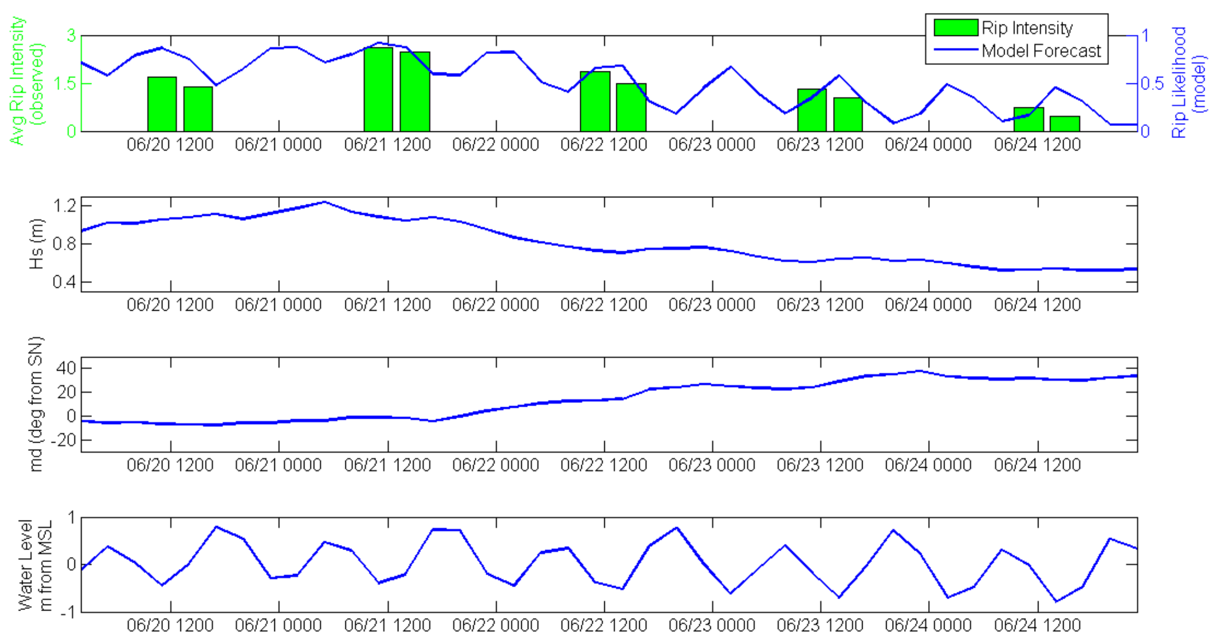

Figure 6. The hindcast output for one high rip current intensity period at KDH in June, 2013.

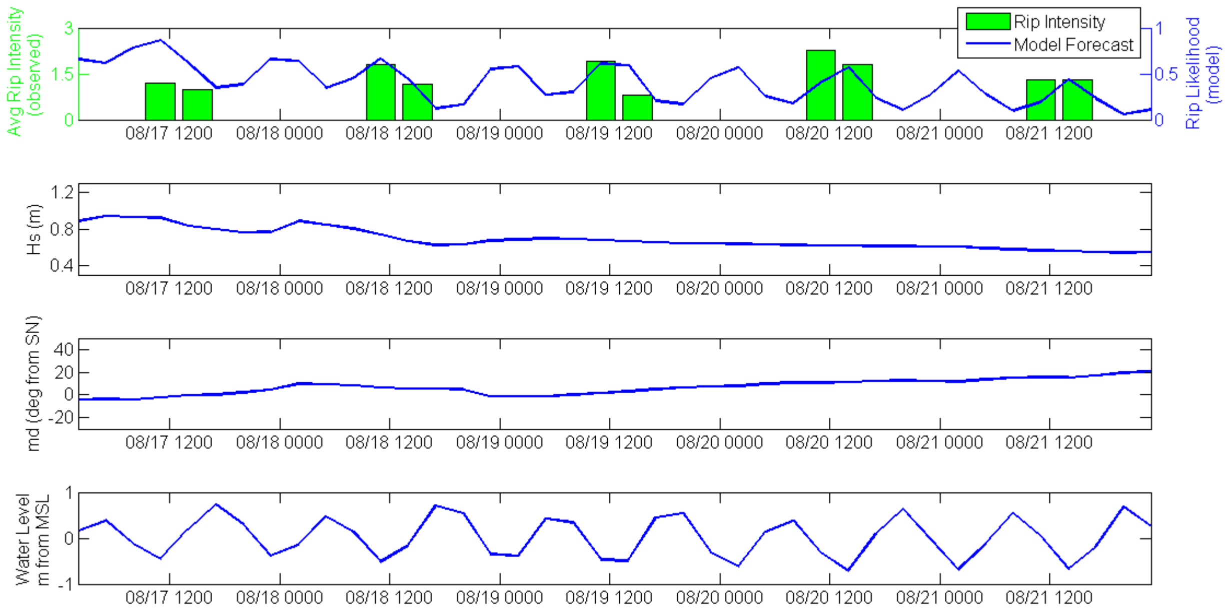

Figure 7. The hindcast output for one high rip current intensity period at KDH in August, 2013.

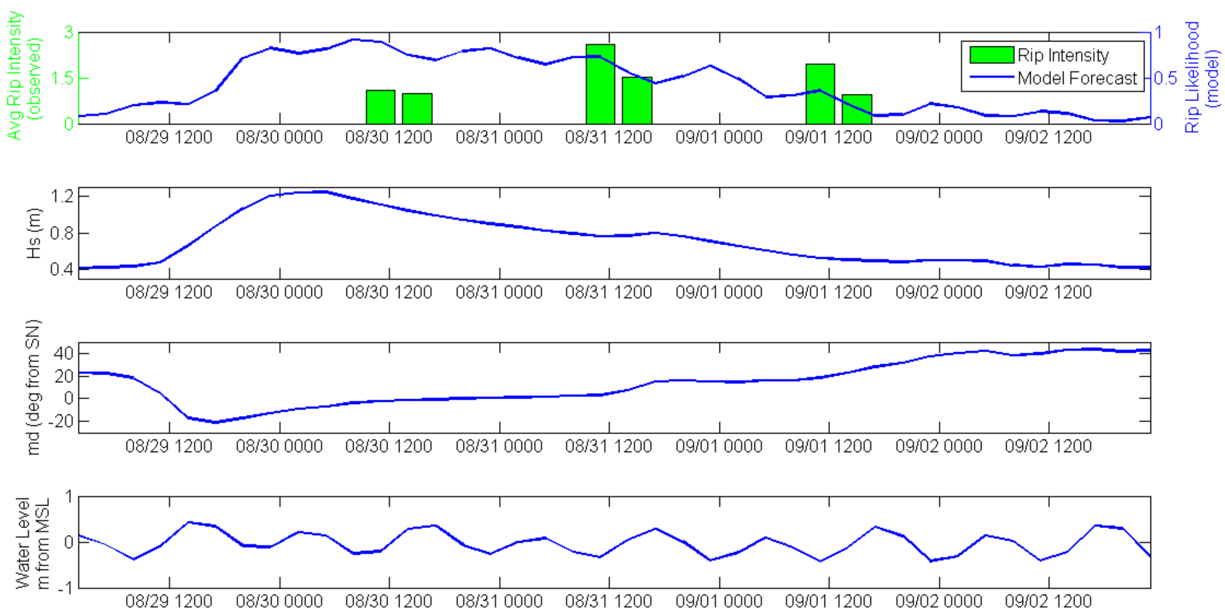

Figure 8. The hindcast output for one high rip current intensity period at KDH in August and September, 2013.

The period from August 29 to September 2 shows a quickly advancing wave event, as wave heights increase from 0.4 m to 1.2m in less than 24 hours and then drop-off quickly over only three days (Figure 8). The model predicts increased rip current likelihood corresponding closely with the wave height, and is less influenced by the tide due to the smaller tidal range in this case. The model forecast is again in fairly good agreement with the lifeguard observations, with the exception of August 30th when the model appears to overestimate likelihood. One possible explanation for this discrepancy could be changes in the surf zone morphology over this period, if a more prominent bar developed in the days following the wave event. Even with the inclusion of the wave event variable, the forecast model is obviously limited in its ability to account for morphological

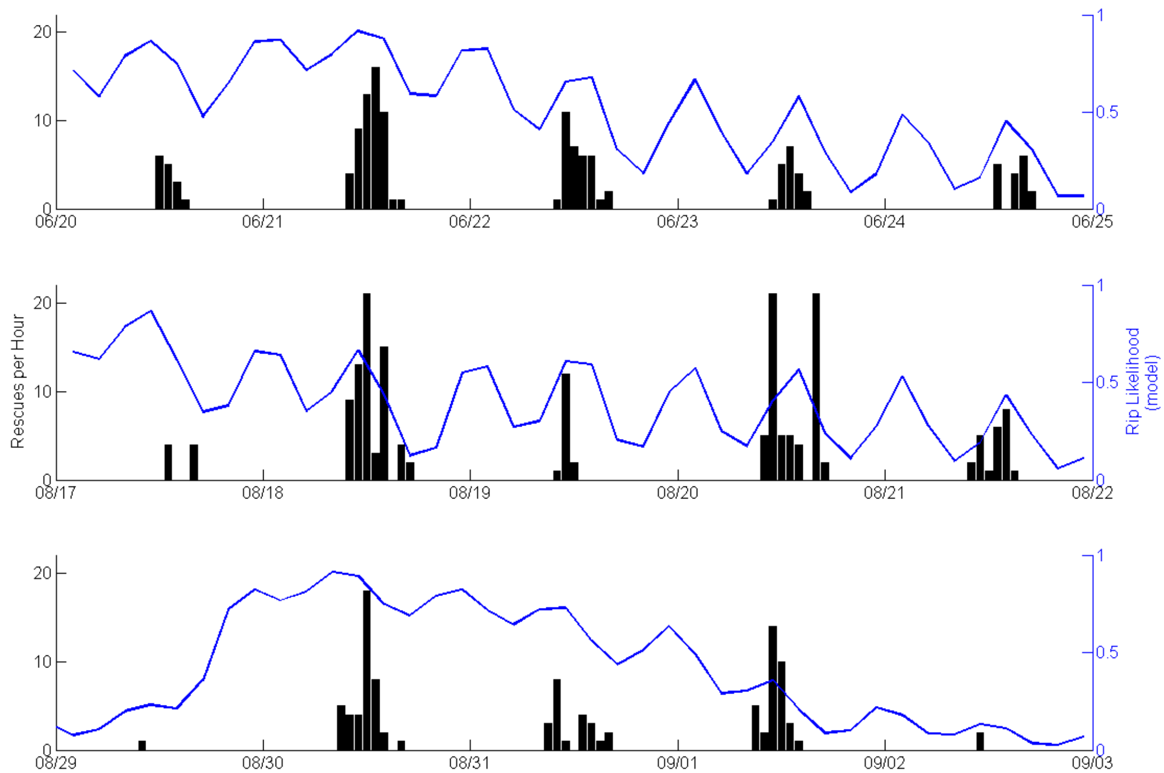

Figure 9. Hourly rip current rescues and the model hindcast for the three high rip intensity periods at KDH.

changes.

A more quantitative way to assess model performance is to use the Brier Score (essentially a measure of mean squared error) to compare predictions and observations. Where the Brier Score is:

$$\mathrm{BS} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\pi_{\mathrm{i}} - \mathrm{o}_{\mathrm{i}})^2$$

and π are the model estimates, *o* are the observations, with *i* being the index of the n observation-model pairs (Wilks, 2006). The BS will be between 0 and 1, where 0 is perfect agreement. In this case each of the 19 lifeguard observations is considered an independent measure of rip current occurrence and the observations (11am and 3pm) are compared to the model output point closest in time (11am and 2pm). Two different calculations of the Brier Score are made: where lifeguard observations of 0 indicate no hazardous rip currents (ie. *o*=0) and observations of 1,2 or 3 indicate a hazardous rip current occurs (ie. *o*=1), and where lifeguard observations of 0 and 1 indicates no hazardous rip currents (*o*=0), and observations of 2 and 3 indicate a hazardous rip current occurs (*o*=1). In both cases the BS = 0.20, which suggests good performance and compares well to a similar brier score assessment (0.15) performed during the initial forecast model validation with observed wave data (Dusek and Seim, 2013a).

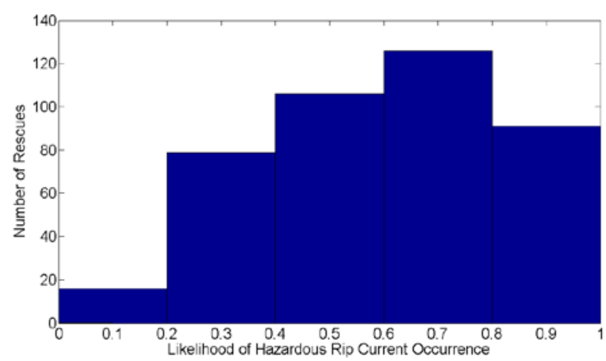

Figure 10. Histogram showing the distribution of hazardous rip current likelihood for all 418 rip current related rescues made during the three high rip periods at KDH. Rescues are binned to each 3-hour model output time (e.g. rescues occurring from 1000 to 1259 are paired with the 1100 model time).

A comparison between the modeled rip current likelihood and the hourly rip current rescues show a similarly favorable comparison (Figure 9). It is important to note that the number of rescues can't be directly compared to rip current likelihood due to their dependence on the number of bathers in the water. However, that the rip current likelihood is fairly high when at least one rescue occurs (i.e. a hazardous rip current occurs), suggests good model performance. A distribution of the rip current likelihood during each of the 418 rescues over the three five-day periods shows relatively high likelihood when rescues occur (Figure 10). In this case 77% of all rescues occurred when the rip current likelihood was at least 0.40. The mean likelihood over all 418 rescues is 0.58, which is significantly higher than the mean likelihood of 0.37 over the entire hindcast period (May to September, 2013).

5. CONCLUSIONS AND FUTURE WORK

In this paper, an operational rip current forecast model coupled to the Nearshore Wave Prediction System or NWPS is presented. The validation of NWPS suggests that it provides the appropriate modelling platform to drive a statistical rip current forecast model - as it has sufficient capacity, resolution and accuracy. An initial assessment of three high rip current intensity periods at Kill Devil Hills, NC suggests that predicted rip current likelihood compares favorably to lifeguard observations and rescues. All three high intensity periods are examples of extremely hazardous days when wave heights are relatively low, and thus accurate forecasting of rip current likelihood during these periods is extremely important to public safety.

Figure 11. An example of the rip current forecast model output shown spatially on a map for both KDH (top) and EMI (bottom).

Validation of the rip current forecast model will be performed for the entire hindcast period (May to September, 2013) in a future publication. In addition, the WFO in Miami has begun running the forecast model and collecting rip current observations, which will serve as validation of the model in a location outside of North Carolina. In addition to validation, the possibility of including confidence bounds on the rip current forecast will be investigated. It is well known that there will be a significant amount of error in even the most accurate numerical wave models. Accounting for this error will better enable the interpretation of uncertainty in the rip current forecast.

In the summer of 2014, NWPS and the rip current forecast model are to be run operationally at both the Morehead City and Miami WFOs. In addition to the test locations at KDH and EMI on the Outer Banks of North Carolina, it is anticipated that additional locations will be added along the North Carolina coast. This may occur by selecting some addition key locations for high resolution NWPS nests, or it is possible that NWPS will be run on an unstructured grid enabling a rip current forecast model to be provided along most of the North Carolina coast. At this time the precise method for expanding coverage is undetermined.

How to visualize and communicate the forecasted rip current likelihood still needs to be determined. A Google Map style interface could be used to provide a gridded color-scale output along the coast that could be easily interpreted by lifesaving agencies and the public (Figure 11). The Miami WFO is implementing a visualization of the forecast that might serve forecasters (Figure 12). However, even with adequate visualization, interpreting what rip current likelihood means will be vital to a successful product. Perhaps the presently used low, moderate and high risk scale can be applied to the probabilistic output. For instance issuing the rip current forecast as "0.75 or high risk" provides multiple interpretations of the forecast. There are undoubtedly many other methods for communicating the forecast that should also be explored.

Although not without limitations, the rip current forecast model presented here provides a significant improvement in both functionality and accuracy when compared to the present NWS index approach. This forecast can be coupled with interpretation from forecasters at NWS WFOs to provide improved guidance to both lifesaving agencies and the general public and hopefully aid in reducing both rip current related rescues and drownings.

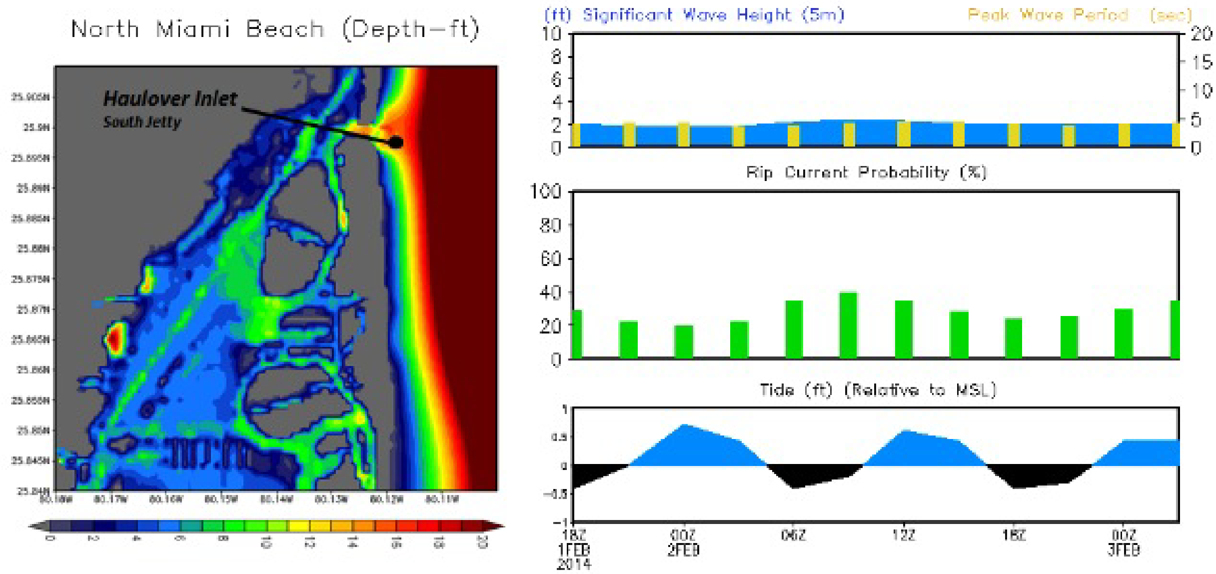

Figure 12. Example rip current forecast visualization near Haulover Inlet, Miami, FL created by the Miami WFO. The left map shows the bathymetry and the right plots show NWPS wave field output and forecasted rip current probability.

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