RIP CURRENT PREDICTIONS THROUGH MODEL-DATA ASSIMILATION ON TWO DISTINCT BEACHES

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Abstract

This paper describes the development of a physics-based rip current prediction system called CoSMoS. This system consists of a hydrodynamic prediction system which is composed of a train of surge and wave models from the global scale to the scale of a beach resort (order kilometers). For the beach resort scale model, it is of utmost importance to use a recent measured or remote-sensed estimated bathymetry in order to accurately predict morphologically-controlled rip currents. To obtain bathymetry estimates, the Beach Wizard system which makes use of Argus video data is applied to the macro-tidal coast of Perranporth UK and the meso-tidal coast of Egmond aan Zee, the Netherlands. The results for the UK site show that while the Brier Skill Scores of the estimated bathymetry are low, the resultant rip current location, strength and timing are well-predicted. For the Egmond case, the system produces good estimates of the bathymetry and of the rip current parameters. Finally, we demonstrate the potential and form of rip current warnings based on the application of the CoSMoS system for Egmond aan Zee.

Key words: rip currents, rip current predictions, numerical modeling, remote sensing, Beach Wizard, XBeach, Egmond aan Zee, Perranporth.

1. Introduction

1.1 *Rip currents on barred beaches*

On many of the world’s beaches, rip currents (narrow, offshore-directed flows) pose a serious drowning hazard to beach users. The cause of rip currents is the alongshore non-uniformity in either the wave field or the bottom topography (Bowen, 1969). Dalrymple et al, (2011) have identified morphologically-controlled rip currents as the most common form. In this case rip currents are generated as follow: as waves approach shallower water, the waves break and exert a force on the water column through so-called radiation stress gradients (Longuet-Higgins and Stewart, 1964). The momentum balance equation requires compensation by an opposing force which is a positive water level gradient (set up). Thus, intense wave breaking over a sand bar results in large radiation stress gradients which in turn generate a high set up at the coast line. Vice versa areas with less wave breaking, i.e. in an interruption in the bar, causes a lower set up at the coastline. This causes alongshore variations in set up which drive shore parallel flows, known as feeder currents. The feeder currents converge onshore of the rip channel into an offshore flow, the so-called rip neck. The location of morphologically controlled rip currents is thus tied to a rip channel that interrupts the adjacent sand bar. Outside the surf zone the rip current diffuses in the rip head, see Figure 1 for a schematic representation.

Rip current flow is dependent on wave-induced set up and thus on wave conditions and wave dissipation. Waves will break over the bar if the ratio of wave height to water depth exceeds a certain value. This implies that rip currents are not only dependent on wave height but also on water level that might be modified by the tide. The strongest rip velocities have been observed at low tide (Aagaard et al (1997), Brander and Short (2000), MacMahan et al (2005)) while during high tide, more waves propagate over the bar without breaking and the rip current is weaker or completely inactive. For the Dutch coast, Winter et al. (2013) have confirmed this mechanism of rip current occurrence as a function of water level.

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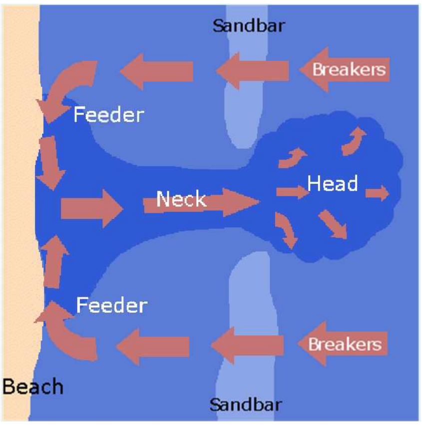

Figure 1: Rip current schematic (from Winter, 2011).

1.2 *Identification of rip currents*

Shepard et al (1941) have proposed six features that can be used to visually identify rip currents in the field.

1. Sediment laden areas outside the surf zone indicate the presence of a rip.
2. The location of the channel is marked by green water where the depth is larger.
3. The foam of the breaking waves is carried offshore beyond the breaker line by the rip current.
4. Choppy water points to locations where currents oppose the incident waves.
5. In the rip channel the waves break closer to the shore and a gap in the breaker line is observed.
6. Floating objects can be used to test if an offshore current is present.

The hostile environment of the surf zone complicates the direct measurement of rip currents in the field. Shepard et al (1941) mapped the drifter paths of floating objects. Other methods to illustrate the flow patterns were used by Brander (1999) such as the release of potassium permanganate dye in the near shore zone. Quantitative measurements with fixed instruments were performed by Dette et al (1995), Aagaard et al (1997), Brander (1999), Brander and Short (2000), Callaghan et al (2004), MacMahan et al (2005), MacMahan et al (2008) and Bruneau et al (2009). Johnson and Pattiaratchi (2004), Brander and Short (2000), MacMahan et al (2010), Austin et al (2010) and Winter et al. (2013) used GPS-equipped floaters or even human drifters.

1.3 *Rip currents and swimmer safety*

For the purpose of swimmer safety on recreational beaches, it is important to not only understand rip current dynamics but also to be able to forecast rip current conditions in terms of location, duration and strength.

Until now this has been done based on empirical relations between hydrodynamic forcing and rescue events. For example in the USA, Lushine (1991) focused on the East coast of Florida where about 21 people drown per year, which is larger than the number of deaths due to other natural hazards combined. The Lushine Rip Current Scale (LURCS) is based on statistical analysis of lifeguard logs, newspapers and medical records of rip current drownings. The empirical forecast model found the highest correlation with strong onshore winds, swell height and timing of low water. In a follow-up, Lascody (1998) showed that 75% of the rescues could be related to long period swells, and that long period swell (>12s) were always associated with a greater risk of rip currents even for low wave heights. Therefore, he adapted the LURCS model to account for the greater impact of swells. As more than 50% of drownings occur on weekends or holidays, the thresholds for issuing a warning was set lower at these days to account for the increased number of visitors. Based on the LURCS scale, the NWS used to issue rip current statements to different counties, which stated the rip current threat to be normal, greater or much greater than normal. Today, NWS forecasters use the prediction of persistent onshore wind, swells, and reports from lifeguards as the three of the main "signals" to prepare a Rip Current Outlook. For the winds and swells it makes use of the

NOAA WaveWatch III model, and other high-resolution regional wave models and the NOAA weather buoys. It is unclear whether the LURCS scale is still incorporated in the development of the NWS rip current outlook nowadays.

In the U.K, a study by Scott et al (2007) focused on the coast of Devon and Cornwall, which receives 10 million visitors per year and has 62 beaches guarded by the Royal National Lifeguarding Institute (RNLI). The region is known for a very large tidal range and ocean swell conditions. Scott et al constructed a database containing RNLI logged incidents, daily weather, sea conditions and beach population for the 2005 summer season. Analysis of the incidents shows that in 71% of the rescues, rip currents played a role. From the analysis it became clear that the type and level of hazards varied significantly with location and geology of the beach and the hydrodynamic conditions. Thus, risks were categorized per beach state (following Wright and Short's (1984) classification):

- Ultra dissipative beaches: lack of rip currents due to non-barred, dissipative wide foreshore.
- Intermediate (reflective/dissipative) beaches: highest rip current risk category (low tide bar/rip beach type). Backshore geology and intertidal rock formations have significant influence on the beach characteristics and rips.
- Reflective beaches: no significant rip current hazards

Austin et al. (2012) further investigated and quantified macro-tidal rip current dynamics and the implications of these surf zone currents for beach safety.

In the Netherlands, rip currents have received limited attention although per year a handful of people drown after being caught in a rip. There is no nationwide system available to predict rip currents. However, in a private attempt, Verbeek (2006) tried to establish a relationship between rip current threat and environmental conditions at Egmond, making use of lifeguard records, wave data and local Argus video images of the surf zone. He found a relation between rip current risk and wave height. Following up on his 2006 study, Verbeek developed a rip current forecast model based on wave set-up theory. As input for the model, he uses offshore wave and tide information along with key parameters describing the sand bar geometry (distance to shoreline of first and second bar and crest height). The model computes the difference in set-up due to breaking waves over the sand bar and in the rip channel. Based on the head difference, he then estimates the rip current velocity, which Verbeek states should be interpreted relatively and only as an indication of the rip current threat. The model has been validated throughout the summer months of 2011.

1.4 *Rip current forecasting with process-based models*

The above shows that rip currents have been recognized as serious hazards to swimmers. However, systems to forecast rip currents have until now been limited to empirical relationships between hydrodynamic forcing and swimmer safety incidents, where only in limited cases real-time physics-based process models have been used to predict the offshore hydrodynamics. A fully process-based model system to make predictions is lacking.

In this paper we will discuss the development and application of a real-time physics-based hydrodynamic model in combination with an advanced data-model integration method to derive the last, best-known near shore bathymetry. In section 2, the real-time hydrodynamic model system is described. In section 3, we describe the bathymetry estimation from video data. In Section 4, we verify the added value of the use of video-derived bathymetry estimates by application at the macro-tidal, swell-dominated site at Perranporth Beach (Cornwall, UK). In Section 5 we discuss the implementation at the meso-tidal, wind-sea dominated site at Egmond Beach (The Netherlands) into a real-time warning system for rip currents.

2. Hydrodynamic forcing system CoSMoS.

CoSMoS (Coastal Storm Modelling System) is an operational model system to simulate storm impact on coasts, but which is now applied to daily conditions as well. The system consists of a train of coupled models. This tailored model train is triggered by a task manager, which controls the data collection, preprocessing, model engines, post-processing and publication of the results on e.g. a web server. Baart et al. (2009), Van der Werff et al. (2011) and Van Ormondt et al. (2012) provide details on the ongoing development of the system. Figure 2 (left) depicts the workflow of the CoSMoS system. Two process loops are continuously executed at set intervals:

- The main loop.

This loop is executed every 6 or 12 hours when making operational forecasts. The main loop reads meta information (in xml format) of each model, and determines the start and stop times, taking into account the required spin-up times for the different models. Next, it downloads the required meteorological data from OPeNDAP servers, as well as real-time observations from the buoys and tide stations and stores these in a central database. The real-time data is only used to generate figures for model-data comparisons.

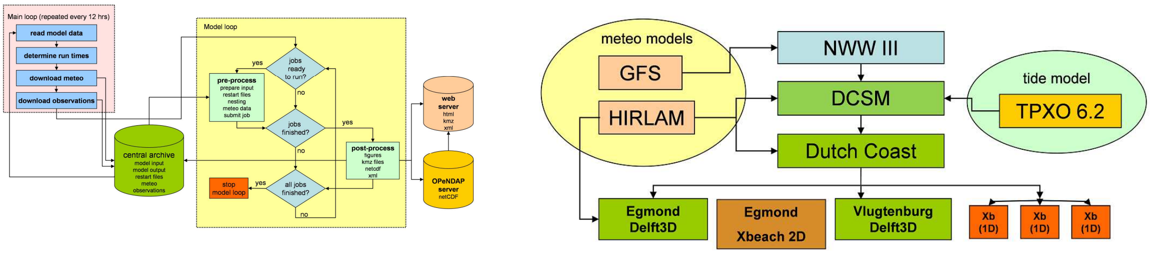

Figure 2: Left: CoSMoS workflow. Right: model linkage.

- The job loop.

This loop is executed every 10 seconds. Within the job loop, the CoSMoS system first checks whether model simulations are ready to run. The main requirement for a model to be executed is that the overall model simulation from which it gets its boundary conditions has finished and has been processed. When a model is ready to run, the system prepares its input, using the data stored in the central archive. This step includes the nesting procedure (for both water levels and 2-D wave spectra), copying of restart files and conversion of meteorological data into the proper format. Once all the model input has been prepared, the simulation is submitted to be run on a Linux cluster. In each job loop, the system checks whether any simulations have finished running. If this is the case, they go through a number of post-processing steps. The model output is first converted into the Network Common Data Form (netCDF) format and stored on an OPeNDAP server. Next, a series of figures, comparing model results and observed data, is made, and a number of KMZ files containing model output are generated. A website with a Google Earth interface displays the model results in an interactive way, highlighting locations where hazards are expected. The last step in the job loop is to check whether all simulations have finished running. If this is the case, execution of the jobs loop is stopped. Otherwise, the entire jobs loop is executed again after 10 seconds.

For the application in the Netherlands, the model system contains four main numerical model components, see Figure 2 (right) for a schematic of the model linkage and Figure 3 for the geographic extent of the models:

- a global WaveWatchIII (NWW) wave model, driven by GFS winds.
- a Delft3D/SWAN surge and wave Dutch Continental Shelf Model (DCSM) forced by Hirlam winds and Topex Poseidon tides,
- a Delft3D/SWAN Dutch Coastal Model, and
- local XBeach (transect or area) and/or local Delft3D area models.

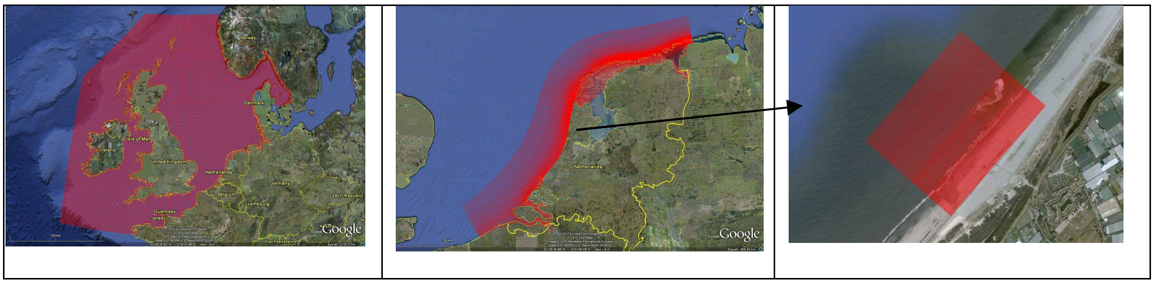

Figure 3: left: Continental Shelf Model; middle: Dutch Coastal model; right: Egmond aan Zee model. Background image courtesy of Google Maps.

The nested models have a decreasing spatial domain but an increasing spatial resolution. Except for the WaveWatchIII model which covers the entire globe, all models are nested into the previous, larger domain model. This means that the required model boundary conditions are derived from the larger domain model.

WaveWatch III (Tolman et al., 2009) solves the action density balance equation. The domain of the WaveWatch III model is the entire globe. The grid resolution is 1 x 1.25 degree (latitude, longitude), which corresponds to approximately 100 x 100 km. The Continental Shelf Model (CSM), Figure 3 (left) is a model that covers the entire North Sea area. It contains a fully coupled wave model (SWAN) and a depth-averaged, two-dimensional-horizontal (2DH) flow model (Delft3D), accounting for wave-current interaction. The wave and flow model domain are the same but the resolution of the computational grids is different. The grid resolution of the wave model is approximately 15 x 20 and of the flow model 7.5 x 10 km. The wave model boundary conditions (swell) are taken from the WaveWatch3 model. At the flow model boundaries water levels are imposed (amplitudes and phases of relevant astronomic tidal constituents). By using this type of boundary conditions, the model can be used to simulate easily any time period. The domain of the Dutch Coastal Model (DCM), Figure 3 (middle) covers the entire coastline of The Netherlands. Similar to the CSM model, it contains a fully coupled 2DH Delft3D (flow) – SWAN (wave) model. Unlike the CSM model, the computational grids of the wave and flow model are the same. The grid resolution varies between 3.5 x 3.0 km (offshore) and 0.3 x 3.0 km (near the coast). The water levels at the sea boundaries of the Delft3D flow model and the 2D wave spectra at the boundaries of the SWAN model are taken from the CSM model. The last chain of the operational modelling system is a series of 30 XBeach (Roelvink et al., 2009) transect (1D) models along the Holland Coast. For the purpose of rip current forecasts a 2D area model at Egmond Beach is set up, see Figure 3 (right).

The performance of the hydrodynamical model at deeper water has been demonstrated by Sembiring (2010) and Sembiring et al. (2013). The model performance at shallower water, and especially in the surf zone and nearshore is highly dependent on the accuracy of the bathymetry estimate. This estimate can be obtained from in situ measurements but as these measurements become outdated quickly due to morphological change, a frequent repetition of surveys would be prohibitively expensive. An alternative is to derive estimates of the bathymetry from remote-sensing as is shown in the following section.

3. Nearshore bathymetry estimation system

The model bathymetry of the local area models is estimated using the Beach Wizard (Van Dongeren et al., 2008) technique. This is a data-model assimilation method with which intertidal and nearshore subtidal bathymetry can be computed based on a data-model integration scheme of forward model predictions and video-derived (Argus video camera system) observations of wave roller dissipation and variation of the intertidal shoreline, and/or radar-derived observations of wave celerity. The procedure is as follows:

1. The system semi-automatically selects Argus 10-minute time exposure (timex) images based on preset criteria for image quality, i.e. images with sun glare, rain drops and fog are removed.
2. The images that passed are transformed into maps of wave energy dissipation, wave celerity and intertidal bathymetry using information about the tidal elevation and incoming wave conditions from the CoSMoS system or from nearby wave/tide measurements.
3. Maps of the same properties are computed using an XBeach model which is run over the last available

bathymetry and using the same hydrodynamic (wave and tidal) input data as was used to obtain the Argus-derived maps.

4. An algorithm updates the bathymetry in every grid point based on the local difference between the computed and observed properties. In its simplest form, the bed level h is updated based on the observed difference h_{obs} and the current value $h(t)$ given a weighting factor α which is based on the uncertainty in the current value and the observation.

$$h(t+\Delta t) = h(t) + \alpha\left(h_{obs} - h(t)\right) \tag{1}$$

However, in our application we do not have direct observations of the depth h_{obs}. Instead, we have remote-sensing observations f_{obs} of wave celerity and/or time-averaged image intensity, where f is a generic variable name. Thus, we must use an inverse model to relate the remotely sensed observations to the bathymetry. Using the chain rule, we obtain

$$h(t+\Delta t) = h(t) + \alpha \frac{1}{\frac{df}{dh}}\left(f_{obs} - f(t)\right) \tag{2}$$

A prerequisite is that these properties (dissipation and celerity) are differentiable to depth, i.e. the property value gives information about the depth. If f is the dissipation, this equation states that in locations where the Argus-derived observed wave dissipation f_{obs} is larger than the computed dissipation, the depth in the model is decreased, as dissipation increases with decreased water depth. More details are provided in Van Dongeren et al. (2008).

This procedure is repeated for every passed image. The bathymetric update produced by BeachWizard is input into the nearshore hydrodynamic forecast model for rip currents.

4. Improving rip current parameter prediction at Perranporth (UK).

The Beachwizard system is first applied to the beach at Perranporth (UK), with the aim of improving the capability to predict rip currents. Perranporth Beach, located in the southwest of the UK, see Figure 4 left, is known to present high incidence and severity of rip currents (Scott et al., 2007; Austin et al., 2010), which are due to a combination of its particular morphological characteristics and the incoming wave and tide conditions. Perranporth is a macro-tidal beach with a semi-diurnal tidal regime and a mean spring range of 6.3 m. It is classified as a low tide bar/rip beach (Scott et al., 2011) and thus exhibits pronounced inter-tidal bar/rip morphology around the Mean Spring Low Water (MSLW) region and a sub-tidal bar. The inter-tidal beachface landwards of MSLW is relatively flat and dissipative ($tan\beta$ = 0.015 – 0.025).

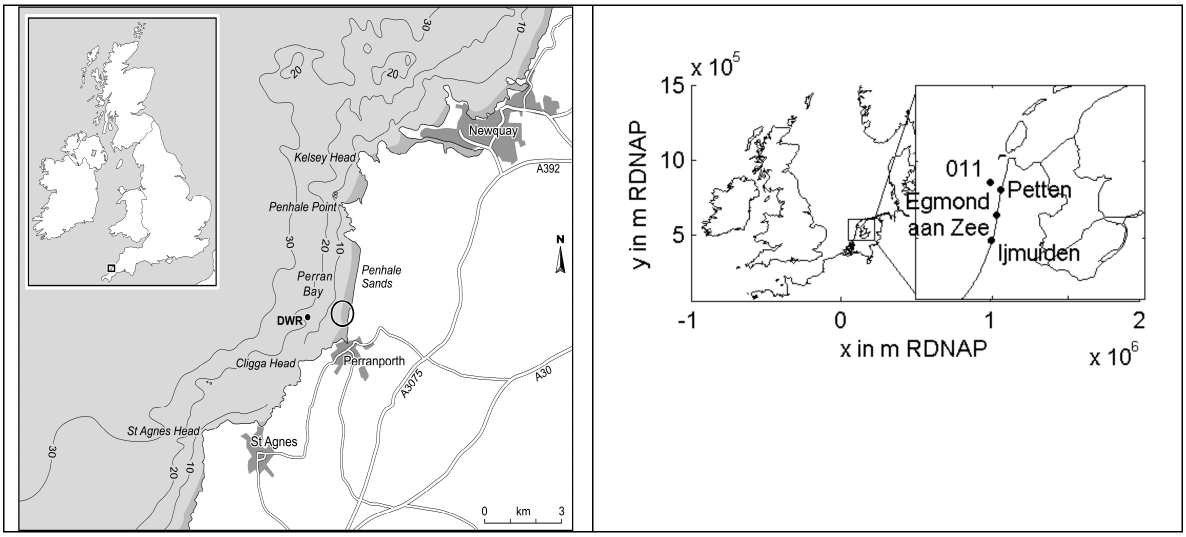

Figure 4: Left: Location of Perranporth UK from Sasso et al, (2013). Right: Location of Egmond aan Zee, The Netherlands from Winter et al., (2013)

In the framework of the DRIBS (Dynamics of Rip Currents and Implications for Beach Safety) experiments (Austin et al., 2012), which focused on the quantification of macro-tidal rip current dynamics and the implications of these surf zone currents for beach safety, in situ measurement of the nearshore bathymetry (-14 to +5 m OD) were taken at regular intervals of about one month, starting in March 2011 and ending in July 2011. Concurrent Argus time exposure images were taken using the permanent Argus station, equipped with three semi-overlapping cameras, mounted on the headland to the south of the beach and looking northwards (sideways) onto the embayed beach. As described in more detail in Sasso et al., (2013), the Beach Wizard system was initiated with the measured bathymetry of 15 March 2011 (see Figure 5, top left) and an optimal setting of BeachWizard free parameters and selection of intensity maps was sought to obtain the best Brier Skill Score (Van Rijn et al., 2003), defined as follows:

$$BSS = 1 - \frac{\overline{\left(h_m - h_{obs}\right)^2}}{\overline{\left(h_{obs} - h_i\right)^2}} \tag{3}$$

Where h_m is the modeled bathymetry at a given time instance, h_{obs} is the observed bathymetry at a given time and h_i is the initial bathymetry (at March 15). Because this formulation is based on point-by-point comparisons of modeled and measured data, it is fairly punitive for spatial shifts in predicted versus measured shoals and channels. This is reflected in the low BSS of 0.4, -0.9 and 0 for 28 April, 1 June and 13 July, respectively.

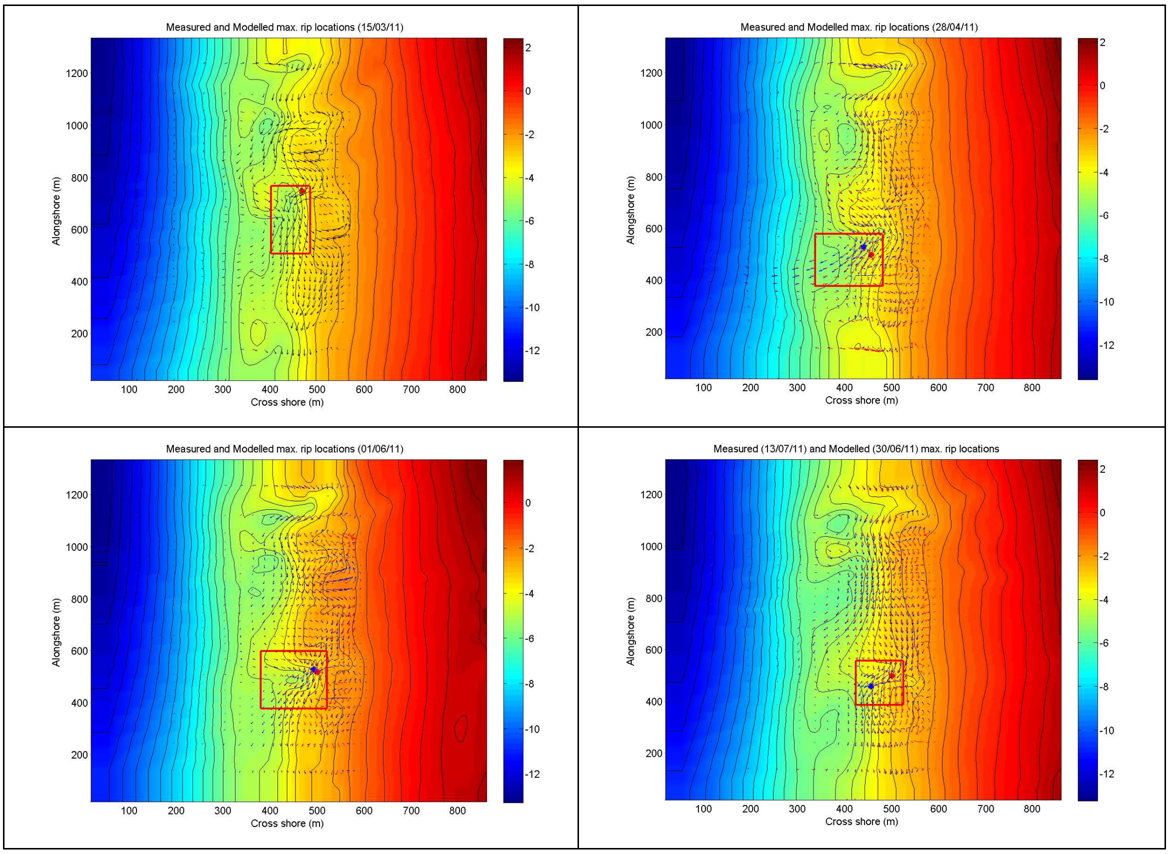

Figure 5: Right: current vectors over the BW-estimated bathymetry (red) and surveyed bathymetry (blue), indicating the close location of maximum rip strength.

However, the interest is in the skill of the prediction of the rip current location, timing (onset and cessation) and strength. For these purposes it turns out that the use of updated bathymetries has a significant added benefit. Figure 5 shows the comparison of the flow pattern using the measured bathymetry (blue) and the Beachwizard bathymetry (red), projected over the measured bathymetry and using the same offshore forcing for four instances. Since the Beach Wizard system was initiated with the measured 15 March bathymetry, the red and blue flow patterns are identical in that case (top left). For the subsequent time instances, the red and blue flow patterns are still similar but differences are recognizable due to the incurred error of the BW updated bathymetry. However, the location of the rip maximum current (indicated with the red and blue dots) is within tens of meters, which indicates the benefit of using remote-sensed bathymetry estimates. Moreover, in absence of periodic surveys and remote-sensed bathymetry estimates, a prediction system would have had to rely on most recent measurements with decreased skill. In this case, if the prediction system could only rely on the measured bathymetry of 15 March, the location of the maximum rip current would have been incorrectly predicted by more than 100 meters. We refer to Sasso et al. (2013), for a thorough description of the methodology and results for rip current timing and strength.

5. Application: swimmer safety at Egmond Beach.

The above example at Perranporth demonstrated the added value of using remote-sensed bathymetries for rip current predictions. At Egmond, the Beach Wizard prediction system is integrated into the CoSMoS hydrodynamic prediction system. Together, the hydrodynamic and bathymetry estimate elements can provide process-based predictions of rip currents, rather than empirical predictions.

The Egmond site (Figure 4, right) is situated in a meso-tidal environment with a tidal range in the order of 1.4 m and strong tidal longshore currents. The wave climate is wind-sea dominated with a modal wave height of 1 m and wave period of 5 s (Wijnberg, 2002). During summer the waves are generally low and do not vary considerably (Short, 1992). As mentioned above, rip currents have received limited attention although per year a handful of people drown after being caught in a rip.

Egmond is equipped with a permanent Argus station with five semi-overlapping cameras mounted on top of the lighthouse, providing a synoptic view of the coast. An initial (hypothetical) plane beach bathymetry was evolved using wave energy dissipation maps obtained from the Argus time exposures images from 5 August until 22 August, which resulted in the bathymetry estimate shown in Figure 6 (left). This bathymetry does compare to the in situ measured bathymetry obtained in the framework of a study conducted by Winter et al. (2013) with a BSS of 0.68 for area around the inner bar (where the rip channels are usually located). Whereas the bathymetry near the shoreline is reproduced well, the outer bar is shifted offshore. The rip channel patterns clearly appear but the trough behind the breaker bar is not reproduced well. Still, the locations of the maximum instantaneous offshore velocities are in good agreement, with alongshore offsets of 10 meters (for the black dot) and 70 meters for the red dot. The time difference between the occurrence of the offshore flow maxima over the Beach Wizard and measured bathymetry is in the order of minutes, with difference in maximum value of the rip current speed on the order of 0.10 m/s. This indicates that also for this wind-sea dominated environment a prediction system using a remote-sensed bathymetry can give useful predictions of rip current parameters.

Finally, the CoSMoS system is applied to the forecast of rip currents on Egmond Beach. For the example shown this prediction is based on the measured bathymetry of 22 August 2011. Figure 7 (left) shows a snapshot of the spatial distribution of the currents with the rip current indicated by the red arrow. This type of information may be useful to the life guards by itself, but the information can be presented in a more aggregated form as well. This is shown in Figure 7 (right), where time on the x-axis and location alongshore on the y-axis. Thus, the location and time where a rip current might be generated is shown in a color code that indicates its strength. The bottom panel shows the tidal elevation as a function of time, where the color code indicates the maximum strength in the alongshore. The figure confirms previous findings that rip currents develop most likely during low tide conditions, at locations where a discontinuity in the bathymetry is observed. This makes rip current locations and timing very predictable, with intensities depending on the meteorological conditions. These types of graphs have been presented to the local life guard organization, and will help them in allocating resources and provide warnings to the public.

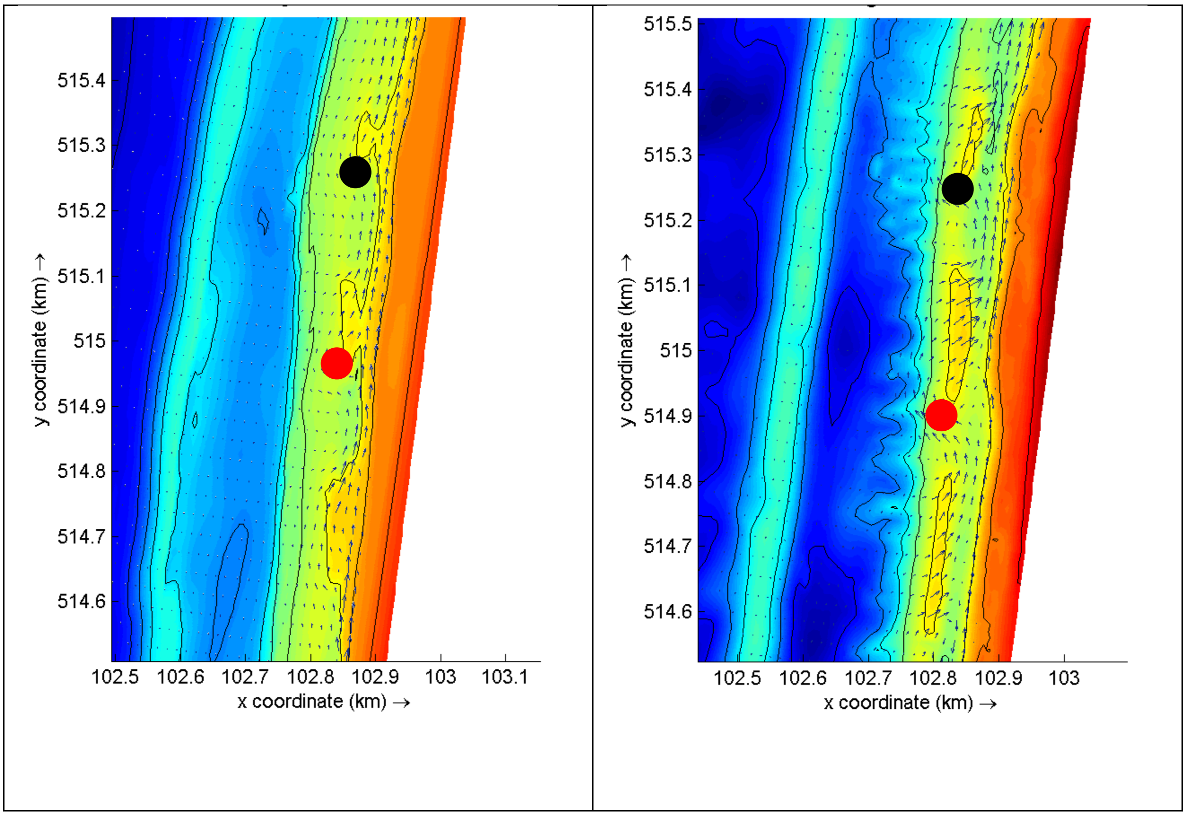

Figure 6: Left: Beachwizard predicted bathymetry for 22 August with locations of maximum offshore velocities indicated by the black and red dots. Right: In situ measured bathymetry for the same date with locations of offshore directed currents.

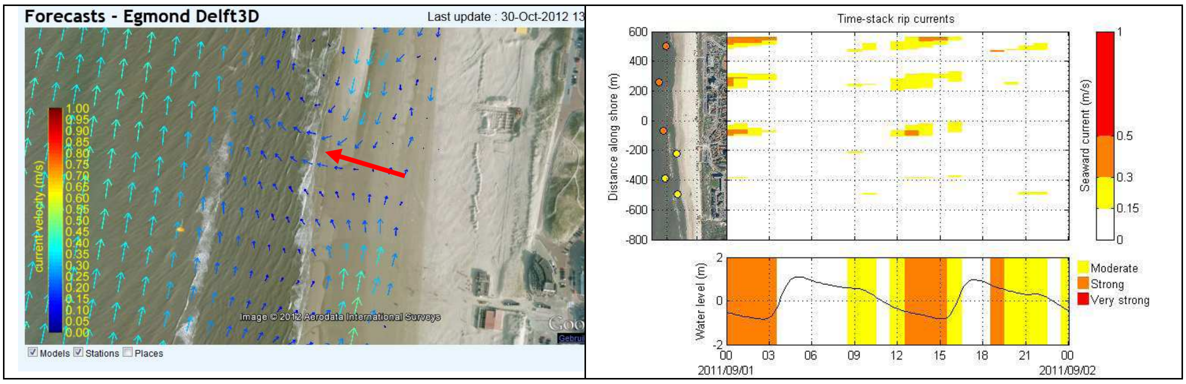

Figure 7: Left: Model prediction showing the spatial distribution of the currents . Right: Alongshore-time stack of offshore velocities (http://muienradar.nl/)

6. Conclusions

This paper describes the development of a physics-based rip current prediction system called CoSMoS. This system consists of a hydrodynamic prediction system which is composed of a train of surge and wave models from the global scale to the scale of a beach resort (order kilometers). For the beach resort scale model it is of utmost importance to use a recent measured or remote-sensed estimated bathymetry in order to accurately predict morphologically-controlled rip currents. To obtain bathymetry estimates, the Beach Wizard system which makes use of Argus video data is applied to the macro-tidal coast of Perranporth UK and the meso-tidal coast of Egmond aan Zee, the Netherlands. The results for the UK site show that while the Brier Skill Scores of the estimated bathymetry are low, the resultant rip current location, strength and timing are well-predicted. For the Egmond case, the system produces good estimates of the bathymetry and of the rip current parameters. Finally, we demonstrate the potential and form of rip current warnings based on the application of the CoSMoS system for Egmond aan Zee.

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