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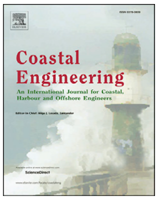

Sensitivity of rip current forecasts to errors in remotely-sensed bathymetry

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ABSTRACT

Operational nearshore current forecasts based on numerical model simulations are gaining popularity as a measure to increase the safety of swimmers. Applying remotely-sensed bathymetry in these model simulations is often proposed in order to cope with rapidly changing nearshore bathymetry. Errors in the remotely-sensed bathymetry may negatively affect performance of the hydrodynamic model. Hence, this study aims to determine the sensitivity of modelled nearshore currents (with a strong focus on rip currents) to errors in remotely-sensed bathymetries.

The errors in the remotely-sensed bathymetries (depth inversion algorithm applied to video stream) were quantified with a length scale-aware validation technique, providing useful insights in the contribution of pattern and amplitude errors to the total error throughout the analysis domain and over a range of bathymetric length scales. Subsequently, simulations with a nearshore hydrodynamic model were performed, using both in-situ and remotely-sensed bathymetries as an input. A comparison of predicted rip currents on either bathymetry yielded performance statistics for operational current forecasts on remotely-sensed bathymetries, taking the model with in-situ bathymetry as a reference. Linking these performance statistics back to the quantified errors in the remotely-sensed bathymetry finally revealed the relation between errors in flow and bathymetry.

Of all rip currents generated on an in-situ bathymetry, 55% were reproduced on the remotely-sensed bathymetry, showing that models predicting nearshore currents on remotely-sensed bathymetry have predictive value. Positive rip current predictions were promoted significantly by accurate reproduction of the pattern and amplitude of nearshore bars at length scales between 200 and 400 m. In contrast to the length-scale aware validation technique applied here, commonly used domain-wide bulk error metrics lack important information about spatial variations in the quality of remotely-sensed bathymetry.

1. Introduction

Operational prediction of nearshore currents by numerical models is an important method for mitigation of risks related to swimmer safety (Alvarez-Ellacuria et al., 2010; Voulgaris et al., 2011; Austin et al., 2012; Kim et al., 2013; Sembiring et al., 2015). The nearshore currents predicted by these models are strongly dependent on bathymetric variability, which is most clearly illustrated by field observations of rip cell circulations related to complex sand bar patterns (MacMahan et al., 2005; Austin et al., 2010; Winter et al., 2014). In turn, these sand bar patterns are affected by nearshore hydrodynamics, as waves and currents reshape the bed continuously. Consequently, sand bar patterns that cause rip cell circulations may change drastically on timescales of days to weeks (e.g. Holman et al., 2006; Price and Ruessink, 2011). In order to reliably predict nearshore hydrodynamics for swimmer safety purposes, operational numerical models should be provided with updated bed levels frequently. This is virtually impossible to achieve with labour-intensive in-situ bed level measurement techniques (e.g. a single-beam echo sounder mounted on a personal watercraft, see MacMahan, 2001). Alternatively, nearshore bathymetry can be estimated operationally using remote sensing techniques. The technical feasibility of coupling remotely-sensed bathymetry to nearshore hydrodynamic predictions was presented by Radermacher et al. (2014) and Sembiring et al. (2015), successfully demonstrating the potential of this combination. While they report the accuracy of the resulting simulated flow fields at their respective field sites, they do not address the coupling between

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errors in the remotely-sensed bathymetry and the simulated flow fields. The aim of the present research is to determine the sensitivity of simulated rip current occurrence and location to errors in remotely-sensed bathymetries. Only geometrically defined rips related to nearshore sandbar patterns are considered. Other types of rip currents (a.o. headland rips, transient rips) are excluded here.

Over the last decades, a wide range of depth inversion algorithms has been developed, which aim to fit a local water depth to remotely-sensed wave parameters based on physical relations. For instance, these algorithms may employ wave fields observed with video or radar to estimate water depth through the linear dispersion relation (a.o. Bell, 1999; Holman et al., 2013) or model-data assimilation of video-observed wave breaking patterns (a.o. Aarninkhof et al., 2005; Van Dongeren et al., 2008). Although these remote sensing techniques are capable of providing nearshore bathymetry estimates at short time intervals, it is unclear how errors in the resulting bathymetry estimates translate to errors in the resulting flow predictions and whether the bathymetric estimates are sufficiently accurate to be applied in the prediction of nearshore hydrodynamics.

In order to be a significant contribution to recreational safety, an operational hydrodynamic model should adequately predict spatio-temporally varying nearshore current patterns. Primarily, this concerns correct prediction of rip current occurrence and location. Remotely-sensed bathymetries applied in these model simulations should be of sufficient quality to support this aim. Traditionally, the accuracy of remotely-sensed bathymetry with respect to in-situ techniques is assessed from bulk error metrics, such as the root-mean-squared error (RMSE), bias and correlation, or from difference maps (Plant et al., 2007; Senet et al., 2008; Van Dongeren et al., 2008; Holman et al., 2013; Rutten et al., 2017). Previous attempts to assess the quality of hydrodynamic predictions on remotely-sensed bathymetry by Radermacher et al. (2014) and Sembiring et al. (2015) demonstrated the difficulty of linking bathymetric errors to hydrodynamic errors purely based on bulk point-wise error metrics. Nearshore currents do not just depend on the local water depth, but are influenced by bathymetric features that span a range of length scales (Wilson et al., 2013; Plant et al., 2009). Therefore, it is expected that the ability of a depth inversion algorithm to resolve spatial bathymetric patterns is strongly linked to the accuracy of nearshore current predictions on the remotely-sensed bathymetry.

Here, the performance of a video-based depth inversion algorithm is studied with a pattern-aware validation technique applied to the resulting bed topography maps (section 3.1). Subsequently, wave-driven nearshore currents are simulated with a validated numerical model on the remotely-sensed bathymetries and on traditionally obtained vessel-based bathymetries. A comparison of simulated flow patterns on both types of bathymetries, focused on rip currents, yields performance statistics of nearshore current predictions on remotely-sensed bathymetries (section 3.2). Finally, these current prediction performance statistics are linked to the bathymetric error statistics from section 3.1, which highlight the relation between bathymetric variability and nearshore flows (section 3.3). First, the methodology outlined above will be elaborated upon in section 2, along with a description of the study site.

2. Methodology

2.1. Field site and instrumental setup

In order to assess the accuracy of nearshore currents simulated on a video-derived bathymetry, data were obtained at the Sand Motor, a mega-scale beach nourishment in the Netherlands (Stive et al., 2013). The large scientific attention for this coastal engineering pilot project has yielded extensive field datasets (De Zeeuw et al., 2017), which have been employed here for comparison to video-derived bathymetry estimates and hydrodynamic model simulations. The Sand Motor was constructed in 2011 as a 17.5 Mm^3 sandy peninsula and is intended to nourish the adjacent coastline throughout the coming decades by natural alongshore sediment transport. It is situated within the Delfland coastal cell, an 18 km stretch of coastline between the harbor breakwaters of Rotterdam and The Hague. At approximately two-monthly intervals, the bathymetry was surveyed (see Fig. 1, panel A) with high accuracy using a single-beam echo sounder and RTK-DGPS mounted on a personal watercraft for the sub-aqueous part of the measurement domain and on an all-terrain vehicle for the sub-aerial part (details provided in De Schipper et al., 2016). The original bed elevation data were subsampled to a 25×25 m resolution (Plant et al., 2002) and subsequently linearly interpolated to a 20 m $\times$ 10 m grid (alongshore x cross-shore resolution). As a result, only bathymetric features at scales larger than 25 m are considered in this study. This matches conditions at the Dutch North Sea coast, where subtidal sandbar variability typically occurs at scales larger than 50 m (e.g. De Schipper et al., 2013; Winter et al., 2014; Sembiring et al., 2014). All surveys used in this study are presented in Fig. 2.

An extensive set of field observations was collected in fall 2014 during the Mega Perturbation Experiment (abbreviated to MegaPEX), comprising a.o. nearshore pressure and velocity measurements with four acoustic doppler current profilers (ADCPs) over a four-week period (Fig. 1, panel C). This type of instrument has been successfully applied before for observations of nearshore current dynamics, a.o. by Brown et al. (2015). The ADCPs were deployed on the nearshore bars and at the seaward end of an oblique rip channel. They sampled the vertical current profile in bins of 0.5 m as well as the pressure. Depth-averaged flow velocities were calculated by averaging over all sub-aqueous bins (i.e. bins that are submerged more than 99% of the time within a temporal window of 10 min). If no sub-aqueous bins were found at a particular point in time, no depth averaged flow velocity was computed for that time. In order to remove short-term fluctuations from the timeseries, the velocity timeseries were low-pass filtered with a cut-off period of 10 min. Further details of the ADCPs are provided in Table 1, where h denotes the average water depth, z_{bbc} is the vertical level of the bottom bin center and t_{av} is the internal averaging duration of the instrument. Additionally, pressure sensors were deployed at 6 m water depth just north and south of the Sand Motor.

2.2. Remotely-sensed bathymetry

A tower is located at the most elevated point of the Sand Motor, with 8 cameras covering an approximately 230° horizontal view angle (part of the Argus network, see Holman and Stanley, 2007). The depth inversion algorithm applied to the 2 Hz video stream is named *cBathy* (detailed description can be found in Holman et al., 2013). cBathy applies cross-spectral analysis to the video intensity timeseries in order to determine dominant pairs of frequency and wave number within a sliding spatial analysis window (Plant et al., 2008) and subsequently inverts the linear dispersion relation to make an estimate of the water depth. Timeseries of water depth estimates on a 20×10 m analysis grid (alongshore x cross-shore spacing) are then fed into a Kalman filter (Kalman, 1960) in order to reduce noise and make the depth estimates more robust. Applications of the cBathy algorithm to Argus imagery at various field sites and under a range of environmental conditions have demonstrated its capability to resolve nearshore bathymetry with a bulk root-mean-squared error of approximately 50 cm (Holman et al., 2013; Wengrove et al., 2013; Radermacher et al., 2014; Sembiring et al., 2015; Bergsma et al., 2016; Rutten et al., 2017). Depth estimates were obtained every four hours during daytime since installation of the camera tower in 2013, with the exception of several periods of down-time (Fig. 1, panel A). For this study, cBathy's Kalman filter was initiated on 13 June 2013 and fed with 4-hourly bathymetry estimates. In addition to the algorithm presented by Holman et al. (2013), an outlier removal routine was added here to prevent several site-specific error sources (mainly ships sailing through the camera view) from fouling the remotely-sensed bathymetry. Depth estimates falling outside a 1.5 m envelope around the nearest groundtruth survey or the previous filtered bathymetry estimate were rejected. The *process error* calibration parameter was set to a value of