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Rip currents under obliquely incident wind waves and tidal longshore currents

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ABSTRACT

A field experiment on the nature of rip currents was conducted on the Dutch coast, which differs from previous rip current study sites because it is a wind-sea dominated environment with mostly obliquely incident waves and tidally-driven longshore currents. During the experiment three distinct flow patterns, obtained with GPS tracked drifter instruments, were observed: (1) a locally governed circulation cell, (2) an offshore current that is deflected shore parallel outside the surf zone and (3) a meandering longshore current. The transition from rip currents (flow patterns 1 and 2) to meandering longshore currents (flow pattern 3) occurred gradually within the tidal cycle with longshore currents prevalent at mid to high tide. Rip currents at this site appeared at depressions in the surf zone bar and typically occurred when the water level fell below NAP (equivalent to MSL), even in the presence of obliquely incident waves and tidally driven longshore currents. Hindcast simulations of the drifter experiments were performed with the numerical model XBeach and showed good agreement with field observations. The model was subsequently used to investigate the influence of tidal water level fluctuations, longshore currents and obliquely incident waves on rip currents.

Rip currents were initiated when the water level dropped below a specific threshold with the magnitude of the rip current associated with the water level. The strength of the tidal current and its orientation with respect to the incident waves governed the offshore extent and orientation of the rip current. In contrast to other studies that suggest that rip currents solely occur under shore normal (or slightly oblique waves), in this study both observations and numerical model simulations indicate that rip currents can exist under large angles of wave incidence, when the rip channel is sufficiently wide and the wave height is small.

1. Introduction

Rip currents are narrow seaward-directed flows (Bowen, 1969) which have implications for ecology (redistribution and offshore transport of nutrients, algae, larvae, diatoms and marine species), coastal management (redistribution of sediment from the shore to deeper water) and beach safety (redistribution of pollutants and drowning hazards for swimmers).

Rip currents are typically generated by alongshore variations in either wave energy or bathymetry (Dalrymple et al., 2011). The arrival and intermittent breaking of random waves with varying wave energy alongshore can generate vertical vorticity and temporal 'transient' rip currents (Clark et al., 2012; Johnson and Pattiaratchi, 2004; MacMahan et al., 2010a). Bathymetrically controlled rip currents are generated either by wave height variations due to refraction caused by offshore features (e.g. canyons) (Long and Özkan-Haller, 2005) or by discontinuous wave breaking that results from nearshore features. Bathymetric variations in the nearshore that favour rip currents comprise bar-rip morphologies associated with intermediate beach states (Wright and Short, 1984), beach cusps or coastal boundaries (such as breakwaters and groynes) (e.g. Wind and Vreugdenhil, 1986).

This paper will focus on rip currents on a barred coast line, the most common type of rip current on the Dutch coast (Short, 1992), where the rip current is associated with a channel that intersects the shore parallel bar. In this system, waves break over the bar and exert a force on the water column through radiation stress gradients (Longuet-Higgins and Stewart, 1964). This force is balanced by a cross-shore pressure gradient, which causes a relatively high water level set-up in the trough between the beach and the bar. In the channel wave breaking is less intense or even absent (due to the deeper water) and less set-up is generated. The resultant alongshore gradient in water level initiates a flow parallel to the beach (feeder current) and towards the channel in the bar. The feeder currents from adjacent bars converge onshore of the rip channel to form an offshore flow (rip neck). This process of wave dissipation is the main source of vorticity in the mean flow on alongshore non-uniform beaches (Bruneau et al., 2011) and the generation mechanism for the type of rip current that is focused on in this paper.

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Rip currents have been measured in the field with both Eulerian and Lagrangian instruments (Dalrymple et al., 2011; MacMahan et al., 2006). Eulerian measurements have provided insight into the initiation, velocities and temporal variations of rip currents and have shown that rip current velocities generally increase with increasing wave height (MacMahan et al., 2006) and decreasing water levels (Aagaard et al., 1997; Austin et al., 2010; Brander and Short, 2000; MacMahan et al., 2005; Sonu, 1972). Austin et al. (2010) attribute the enhancement of rip currents during low tide to the large alongshore wave dissipation gradient from bar to rip channel and to restriction of the rip channel's cross-sectional flow area. Austin et al. (2014) show that in a macro-tidal environment rip currents peak just before and after low tide and weaken or cease at low tide when the bar emerges. Peak rip current velocities are stronger during ebb than during flood tide as the water drains out through the channels when the water level drops (Bruneau et al., 2014). Spatial flow patterns feature symmetric and asymmetric rip current circulation cells as well as meandering alongshore currents in the surf zone as Lagrangian measurements using GPS drifter tracking techniques have revealed (MacMahan et al., 2010b).

Typically, field experiments have been conducted on beaches with shore normal or near normal incident waves (Bruneau et al., 2009; MacMahan et al., 2005, 2010b). In contrast, the Dutch coast is characterised by wind waves that are predominantly obliquely incident (Wijnberg, 2002). Based on a numerical study, Svendsen et al. (2000) suggested that the longshore current induced by obliquely incident waves possesses too much inertia and thus hinders offshore flow in a rip current. However, Aagaard et al. (1997) reported an increase of rip current velocity for wave angles slightly deviating from shore normal (up to an incident wave angle of 10°). Whilst they attributed their observation to an enhancement of the current by wind shear stresses, Haller et al. (2002) also recorded larger rip current velocities with an angle of wave incidence of 10° in the laboratory where wind was absent. Comparable results were obtained by Kumar et al. (2011) in a numerical study. Presently, the effect of obliquely incident waves on rip current generation remains unclear, particularly for angles of wave incidence larger than 10°.

The Dutch coast is a meso-tidal environment with a strong horizontal tide of up to 0.8 m/s at the 10 m isobath flowing northward in the flood phase and southward in the ebb phase. Whilst the influence of water level fluctuations has been investigated in other field studies, the influence of tidally driven longshore currents on rip currents has not been studied in detail.

Section 2 describes the field experiment conducted on the Dutch coast where Lagrangian velocities in the surf zone were measured on a rip channelled bathymetry under the influence of obliquely incident wind-sea dominated waves and tidally driven longshore currents. In Section 3, a 2DH numerical model is used to hindcast the measured flow patterns. Section 4.1 discusses the influence of tidal water level fluctuations and longshore currents and Section 4.2 considers the influence of obliquely incident waves on rip current characteristics. In Section 4.3 the numerical results are used to clarify the field observations and to draw more general conclusions about rip current behaviour at the field site and beyond.

2. Field study

The SEAREX (Swimmer safety in Egmond aan Zee — A Rip current EXperiment) field experiment was conducted over five days in August 2011 at Egmond aan Zee, The Netherlands (Fig. 1). The aim of the experiment was to measure the rip current dynamics and flow pattern characteristics and to evaluate their dependence on the hydrodynamic conditions. Measurements were undertaken in two distinct rip channels, which had been identified by the local lifesavers as a risk to swimmer safety (Verbeek, W., 2011, pers. comm.).

2.1. Field site and methods

The study site is situated in a meso-tidal environment with a mean spring (neap) tide range of ~1.75 m (~1.25 m) and a tidal longshore current of ~0.8 m/s (~0.4 m/s) during mean spring (neap) tide at the 10 m isobath. The wave climate is wind-sea dominated with a modal significant wave height of 1.3 m and a corresponding wave period of 6.4 s (Wijnberg, 2002). During summer the waves are generally low and do not vary considerably (Short, 1992), which enables rip channels to stabilise and gradually deepen so that they are often well defined by the end of summer (when this experiment was conducted). In the year of the field experiment this natural process was disturbed by a beach and shoreface nourishment that was commenced 5 months prior to the experiment and was completed two weeks prior to the experiment. Although rip channels had developed prior to the experiment, according

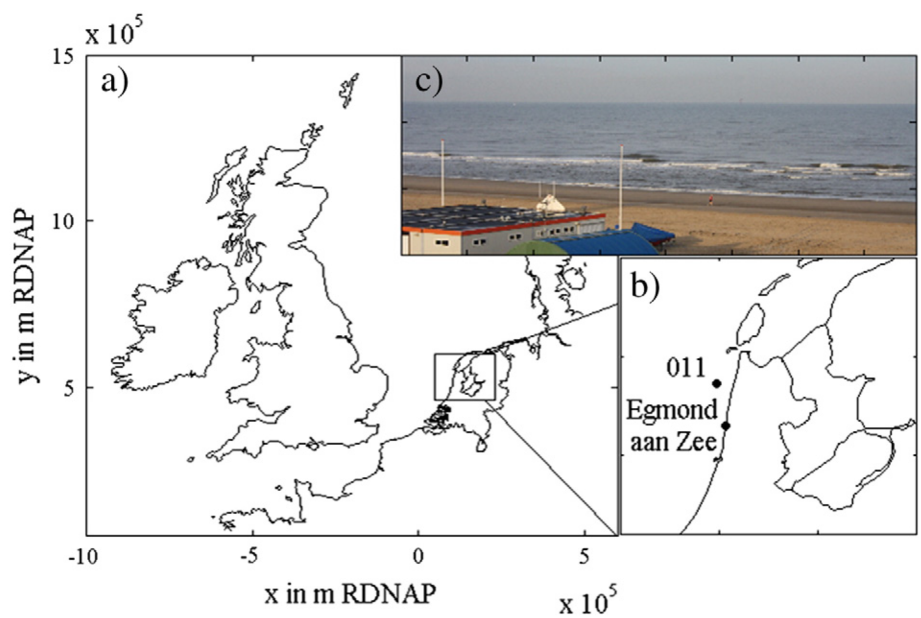

Fig. 1. a) Setting of the study environment within Europe. The coordinate system is the Dutch RD triangular system with the origin in Paris. b) Close-up of the Netherlands with the field site Egmond aan Zee and the directional WAVERIDER buoy (Instrument 011). c) Photograph of the field site taken from the Dunes (by www.muien.nl, 2011 Willem Verbeek).