ABSTRACT

Rip currents are near-shore cellular circulations that can be described as narrow, jet-like and seaward directed flows. These flows originate close to the shoreline and may be a result of alongshore variations in the surface wave field. The onshore mass transport produced by surface waves leads to a slight increase of the mean water surface level (set-up) toward the shoreline. When this set-up is spatially non-uniform alongshore (due, for example, to non-uniform wave breaking field), a pressure gradient is produced and rip currents are formed by converging alongshore flows with offshore flows concentrated in regions of low set-up and onshore flows in between. Observation of rip currents is important in coastal engineering studies because they can cause a seaward transport of beach sand and thus change beach morphology. Since rip currents are an efficient mechanism for exchange of near-shore and offshore water, they are important for across shore mixing of heat, nutrients, pollutants and biological species. So far however, studies of rip currents have mainly relied on numerical modelling and video camera observations. We show an ENVISAT ASAR observation in Precision Image mode of bright near-shore cell-like signatures on a dark background that are interpreted as surface signatures of rip currents. These signatures are typical of very low wind conditions, and were observed off the Portuguese West coast. A mechanism is proposed to explain the feature high contrast. It is suggested that, at such low wind speed conditions, wind direction relative to the beach may play a dominant role on the observability mechanism, enhancing the effective Bragg wave wind generation threshold within the rip cells. Because new SAR missions (such as Terrasar-X) are equipped with finer resolution modes, SAR observations could significantly improve our capabilities to observe rip currents from satellite. The work was carried out in the frame of ESA project AOPT-2423, and Portuguese FCT project “Amazing – A Multi-sensor Analysis and Interpretation System for the Coastal Zone Remote Sensing”.

1 INTRODUCTION

Near-shore water regions have been successfully studied with Synthetic Aperture Radar (SAR) systems, which provide breaking wave signatures indicative of the location of the surf zone, identify bathymetry changes and detect current fronts [1]. Upcoming enhanced spatial resolution SAR systems, such as Radarsat-2 and TerraSAR-X, are thus specially suited for near-shore research, such as to study smaller scale currents. An example of such small scale (of the order of hundreds of meters) processes are rip currents.

Rip currents are near-shore cell circulations usually consisting of two converging longshore feeder currents which meet and turn seaward into a narrow, jet-like and fast-flowing rip-neck that extends through the surf zone, decelerating and expanding into a rip-head past the line of breakers (Fig.1). Rip currents are ephemeral and have been observed to persist for periods of 2 days to several months [11].

Rip flows are often, but not always, contained within distinct topographic channels typically aligned perpendicularly to longshore bars. The bars, which are generally formed by sediment eroded from the foreshore and transported offshore, can extend alongshore for kilometres except for breaks located at the topographic channels (see Fig.1). Rips are relatively easy to observe visually due to increased turbulence generated by wave-current interaction, gaps in the breaker line, streaks of darker water due to increased water depths, sediment plumes and/or foam or bubble patches seaward of the breakers [2].

Rip currents exist as a response to an excess of water built up on shore by breaking waves, so called set up, and often display a periodic longshore spacing. They increase in intensity and decrease in number as wave height increases, and can vary in location and intensity over time. Typical rip velocities are between 0.3 - 1 m/s and can easily exceed 1 m/s during high energy conditions and short periods of time (of the order of 10 min), due to its non-stationary character [3], [11]. The flow associated to rip currents is maximum in the rip neck between bars, and flows faster at low tide, having also a considerable vertical shear near the surface [11]. A review paper on rip current formation mechanisms, the rip currents hydrodynamics and associated morphology, as well as on observations and measurements is given in [11].
Observation of rip currents is important in coastal engineering studies because they can cause a seaward transport of beach sand and thus change beach morphology. Since rip currents are an efficient mechanism for exchange of near-shore and offshore water, they are important for across shore mixing of heat, nutrients, pollutants and biological species. Rip currents are particularly dangerous for beachgoers, as swimmers may be caught in the strong offshore-directed currents and flushed out to sea [4]. Over 100 drownings due to rip currents occur every year in the United States alone, and statistics show that more than 80% of water rescues on surf beaches are due to rip currents [5].

So far, studies of rip currents have mainly relied on numerical modelling and video camera observations [6]. High resolution SAR observations would significantly improve our capabilities to observe and study rip currents, providing periodic observations of rip current morphology and distribution, monitoring the occurrence/migration of the most threatening rip current occurrences and under which circumstances rip currents are most prominent.

Fig. 1 Diagram showing rip current morphology relative to near-shore bathymetry.

2 STUDY REGION: BATHYMETRY AND WAVE FIELD

This study covers an area in the West coast of Portugal, between “Praia da Vieira” and “Praia Velha”, south of Figueira da Foz and to the North of Lisbon (see Fig. 2). The bathymetry south of Figueira da Foz down to Nazaré is characterized by a quasi-continuous under-water ondulatory near-shore bar some 500 m offshore, with a variable height of 2-6 meters [7], characteristic of rip-channel systems. The bar is particularly well defined to the South of river Liz (Praia da Vieira), and as it can be seen in Fig. 3, it is continuous and quasi-linear. The bottom is mostly sandy for the stretch considered here.

The wave field is available at the Leixões buoy, which represents well the wave field in the study area [8]. The offshore wave conditions on the 27th August 2003, and 30th August 2004, are summarised in Table 1, where H_s is the significant wave height, T_p the peak wave period and α the wave angle relative to the normal to the coast. Further, information for the 30th August 2004 reveals that the wave directional spreading is low and that the wave conditions had been approximately constant for 2 days. Breaking wave angle estimates for the 1st and 2nd dates are 4º and 12º, respectively. It is thus estimated that on the 27-08-2003 the surf zone waves are nearly normal to the coast, whereas for the 30-08-2004 the wave angle is rather large and is able to form non-negligible longshore currents flowing southwards.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>H_s (m)</th>
<th>T_p (s)</th>
<th>Wave direction α (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27-AUG-2003</td>
<td>12:00 UTC</td>
<td>2.03</td>
<td>9.0</td>
<td>281 (from W)</td>
</tr>
<tr>
<td>30-AUG-2004</td>
<td>12:00 UTC</td>
<td>1.13</td>
<td>6.2</td>
<td>321 (from NW)</td>
</tr>
</tbody>
</table>
3 SATELLITE OBSERVATIONS

Rip cell features were identified in two radar images of the West coast of Portugal (near Figueira da Foz). Fig.4a is an ERS-2 SAR PRI image dated 27 of August 2003 acquired at 11:20 UTC and Fig.4b is an Envisat asar image in precision mode IMP VV polarization dated 30 of August 2004 acquired at 10:54 UTC. Their acquisition times both correspond to low tide situations: low tide was at 9:35 and 9:55 for the ERS and Envisat overpasses, respectively. This favours rip observations because rip current flow fastest at low tide, suggesting that the radar observability mechanism is linked to some sort of interaction involving currents, wind and waves. Fig.4a is a low wind speed image, where several slicks can be seen near-shore. A remarkable feature of Fig.4a is the non-uniform wave breaking field (owing to higher wave heights as relative to the wave field of Fig.4b) that can be observed close to shore, near the surf zone (wave breaking events appear as bright bands on a dark background). This gives a "jig-saw tooth" appearance to the surf zone, and it can be seen that near-shore slicks seem to periodically alternate with the structure of the wave breaking field. In Fig.4b a similar "jig-saw tooth" structure is intensified, and rip currents are observed as bright features with the form of rip-cells with enhanced backscatter. Note how remarkably (see white arrows) the rip cells observed in the envisat image (Fig.4b) correlate with the slick-like features observed in the ERS image (Fig.4a). The near-shore slicks in Fig.4a are believed to be correlated with bathymetry channels, where wave breaking would occur closer to shore, because admittedly the bottom is deeper. On the contrary, in between slicks, wave breaking occurs further offshore admitted due to the presence of shallower bar formations. We also note that the features interpreted here as rip-cells in the Envisat asar image (Fig. 4b) are periodically observed for some 60km alongshore, and 34 of these features have been identified along the coast in one single sar frame, with characteristic length (perpendicular to coast) and width (parallel to coast) of some 650m and 200m, respectively. The challenge now is to explain why rips appear as enhanced backscatter features in Fig.4b, and why these correspond to locations where slick-like signatures are observed in Fig.4a.

![Map of Portugal with Study Region](image)

**Fig. 2.** Study region: dashed rectangle indicates the location of the Envisat asar image obtained 30 August 2004, where rip currents were observed, and the solid line rectangle corresponds to the area between “Praia da Vieira” and “Praia Velha”, where intense rip current features were identified in the asar image (see Fig. 4) and the detailed bathymetry is presented in Fig. 3.
4 RIP SAR SIGNATURE INTERPRETATION: A SIMPLE MODEL.

Both SAR images presented in Fig.4a and 4b correspond to low wind speed conditions. Wind records at Figueira da Foz meteorological station show low wind conditions at satellite acquisition times (see Table 2).

Examination of Fig.4b reveals that in fact the enviSAT ASAR image represents a situation where the near-shore background backscatter level is near the noise level (noise floor). This usually occurs when the wind speed is below some threshold of wind wave excitation (which for C-Band Bragg waves is $V<1.5\text{m/s}$). In the region where rip features are observed, we thus assume that wind speed is below this threshold ($V<1.5\text{ m/s}$), but according to the average direction registered at Figueira da Foz Meteorological station (see Table 2).

A wind contrast model based on a simple first-order Bragg scattering theory can be used to explain the enhanced backscatter signatures of the near-shore rip cells in Fig. 4b. It takes into account the modulation of short-scale surface waves by the effect of relative variations of wind velocity and the surface rip currents.

The wind contrast $K_w$ is given by

$$K_w = \frac{\beta - \beta_0}{\beta_0}$$

with $\beta_0 = 0.04(U_0^* k^2/\omega)$ where $\beta$ and $\beta_0$ are the wind wave growth rates affected and unaffected by the rip currents, respectively; $k$ is the wavenumber of surface waves, $\omega$ is the intrinsic frequency of surface waves that is given by

$$\omega = \sqrt{gk + k^3 \sigma / \rho}$$

($g$ is the acceleration of gravity, $\rho$ the water density and $\sigma$ the surface tension, and $U_0^*$, the friction velocity unperturbed by the currents. We note that the expression for $\beta_0$ assumes isotropy for wind wave generation. The relation between wind speed $V_w$ at the standard height of 10m and $U^*$ can be obtained by the empirical formula $U^* = 0.034 V_w$ for $V_w < 7 \text{ m/s}$ (see e.g. [10]).

The effective wind velocity relative to the water surface, $V_e$, moving with characteristic offshore current velocity $U$, is given by

$$V_e = V_w - U$$

where
\[ |V_e| = \sqrt{V_w^2 - 2V_w U \cos \theta_v + U^2} \quad (4) \]

and where \( \theta_v \) is the angle between \( V_w \) and \( U \).

For the Envisat image dated 30 August 2004 (Fig. 4b), taking \( V_w = 1.5 \text{m/s} \) as background wind speed and \( U = 1 \text{m/s} \) (typical of rip currents), this would give \( V_e = 2.7 \text{m/s} \) within rip currents, well above the threshold for Bragg wave generation. This would explain why the rip features appear as enhanced backscatter signatures on a dark image background. The wind contrast \( K_w \) near threshold wind conditions would be large, producing strong positive contrast signatures.

### Table 2

<table>
<thead>
<tr>
<th>Acquisition date</th>
<th>Acquisition time</th>
<th>Wind speed</th>
<th>Wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS SAR 27-AUG-2003</td>
<td>11:20 UTC</td>
<td>1.5m/s</td>
<td>200 deg. (from SSW)</td>
</tr>
<tr>
<td>Envisat 30-AUG-2004</td>
<td>10:54 UTC</td>
<td>2.7m/s</td>
<td>270 deg. (from W)</td>
</tr>
</tbody>
</table>

We noted in section 3 that the ERS SAR image presented in Fig. 4a exhibits a non-uniform wave breaking field near-shore. And we also further noticed that the locations of the rip-cell features observed in Fig. 4b are correlated with slick-like features in Fig. 4a, which were presumed to occur where the bottom is deeper (topographic channels). If we now compute the effective wind speed over the channels, assuming a rip current of 1m/s (as in the previous case), we get \( 1.5 < V_e < 1.9 \text{ m/s} \) for \( 70^\circ < \theta_v < 80^\circ \). Such an effective wind speed is still low and near the threshold for Bragg wave generation, so that in these conditions it is not surprising we may observe rip-currents as slick signatures.

Fig. 4. a) ERS-2 SAR image dated 27 August 2003 and b) Envisat asar image dated 30 August 2004 of the region corresponding to the solid line rectangle between “Praia da Vieira” and “Praia Velha” shown in Fig. 2. Arrows indicate correspondence between rip current features at different wind direction conditions. Wind velocity vectors are indicated in the top right corner of figures.

The “jig-saw tooth” appearance of the ERS-2 SAR image shown in Fig. 4a results from the inhomogeneous wave breaking field, which on average produces higher backscatter than on areas where breaking does not occur. The slicks admittedly correspond to areas of deeper water (topographic channels) where waves would be less steep and non-breaking (or breaking closer to shore). Since in the near-shore region, very low wind conditions prevail and the wind is mainly under the threshold for Bragg wave generation, we believe the slicks result from the fact that the wind is so small that the background backscatter is lower or equal to the radar noise level (Normalized Equivalent \( \sigma_0 \)).
5 SUMMARY

We have been able to identify signatures of rip currents in two SAR images. We believe this is the first time such signatures have been identified in civilian spaceborne SAR data. The images correspond to low wind speed conditions, and according to the wind direction and rip strength, the rip signatures may display different type of image contrasts. When the rip currents flow in the opposite direction to the wind, they are imaged as positive contrast signatures on a dark clutter background. If however wave breaking is clearly visible in the near-shore, rip currents may be revealed by slicks, if the wind flows parallel or nearly perpendicular to the rip flow. The SAR rip signatures presented here are consistent with rip current morphology, and we have been able to explain them with a wind contrast model based on a simple first-order Bragg scattering theory.

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REFERENCES