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Storm waves focusing and steepening in the Agulhas current: Satellite observations and modeling

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ABSTRACT

Strong ocean currents can modify the height and shape of ocean waves, possibly causing extreme sea states in particular conditions. The risk of extreme waves is a known hazard in the shipping routes crossing some of the main current systems. Modeling surface current interactions in standard wave numerical models is an active area of research that benefits from the increased availability and accuracy of satellite observations. We report a typical case of a swell system propagating in the Agulhas current, using wind and sea state measurements from several satellites, jointly with state of the art analytical and numerical modeling of wave-current interactions. In particular, Synthetic Aperture Radar and altimeter measurements are used to show the evolution of the swell train and resulting local extreme waves. A ray tracing analysis shows that the significant wave height variability at scales < ~100 km is well associated with the current vorticity patterns. Predictions of the WAVEWATCH III numerical model in a version that accounts for wave-current interactions are consistent with observations, although their effects are still under-predicted in the present configuration. From altimeter measurements, very large significant wave height gradients are shown to be well captured, and also associated with the current vorticity patterns at global scale.

1. Introduction

Severe sea states are encountered in the vicinity of storm tracks with extreme values of significant wave height (Hs) driven by the stormy winds and associated fetch length and duration (e. g. Hanafin et al., 2012). Extreme sea states not necessarily generated by local winds can also occasionally be found in some regions. Indeed, interactions between waves and currents induce change in the wave direction (Kenyon, 1971; Smith, 1976; Dysthe, 2001; Gallet and Young, 2014) and energy (Ardhuin et al., 2017; Kudryavtsev et al., 2017). For reference, the refraction of waves over random currents leading to the formation of rogue waves has been discussed in White and Fornberg (1998). Spatial wave height variations at scales < ~100 km are then very often associated with current variability at the same scales.

Rogue or freak waves have been particularly recorded in the Agulhas current system (Mallory, 1974; Lavrenov, 1998). Although numerical wave models are capable to represent such effects (Holthuijsen and Tolman, 1991), the use of ocean currents in operational wave forecasting has been mostly applied to tidal currents (e.g. Ardhuin et al., 2012). Indeed, a key limitation of wave-current forecasting in the global ocean is the apparent inadequate combination of surface currents that are probably too coarse or not well positioned in space or time. When using resolutions of the order of 2 km for both current forcing and wave model implementation, the variability of modeled waves becomes indeed more consistent with observations in the range where these are available (Ardhuin et al., 2017).

From a satellite perspective, altimeters can provide robust measurements of the local significant wave height, sea surface roughness, and sea surface height, currently used to validate ocean numerical models for wave heights, mean sea level and eddy kinetic energy (Quilfen et al., 2000; Feng et al., 2006; Stopa et al., 2016). Continuous improvements in sensor technology and processing help to reduce measurements noise and open perspectives to analyze mesoscale variability (20 km < L < 80 km). Altimeter sea state measurements are further complemented by Synthetic Aperture Radar (SAR) with estimates of swell wave spectra and to help more precisely monitor swell propagation (e.g. Chapron et al., 2001; Collard et al., 2005; Ardhuin et al., 2009; Collard et al., 2009).

This potential gives the motivation for the present study to efficiently merge SAR directional measurements and swell propagation

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characteristics with altimeter sea state information. A case is analyzed using satellite altimeter and SAR measurements with numerical modeling, to highlight the main role of currents in focusing storm waves generated in the South Atlantic Ocean and propagating into the Agulhas current system. The analyzed case study is particularly well sampled by SAR and altimeter measurements, which are, for our case, very well synchronized in time to enable precise space-time tracking of the impinging swell system in the Agulhas current region. This region is known for frequent occurrence of extreme waves and is a challenging one for wave forecasting. The Agulhas Current is a strong western boundary current flowing poleward along the east coast of Africa from 27°S to 40°S. The sources of the Agulhas Current are the East Madagascar Current, the Mozambique Current and a re-circulated part of the south-west Indian sub-gyre south of Madagascar. Large-scale cyclonic meanders are formed as the Agulhas Current reaches the continental shelf on the South African east-coast. In the south-east Atlantic Ocean the current turns back on itself in the Agulhas Retroflection and becomes the Agulhas Return Current meandering and flowing eastward to rejoin the Indian Ocean Gyre. Many eddies populate the Agulhas current area. A view of the Agulhas stream is shown on Fig. 4 at our case study time, and the interested reader may refer to Lutjeharms (2006) for a thorough description of this major current system. Unlike other western boundary currents (Brazil Current, Gulf Stream, and Kuroshio) it is exposed to strong westerly surface waves in the retroflection region.

Section 2 describes the storm case study, Section 4 describes the WAVEWATCH III numerical model experiment and the satellite data used, Section 5 presents the methods applied for altimeter data processing and swell rays calculation, Section 6 presents results in four main sub-sections: 1) the description and modeling of the incident swell trajectories after refraction and advection by the surface currents, 2) the analysis of wave energy transformation along the swell path using altimeter measurements and modeling results, 3) a discussion on potential errors likely to affect the proposed analysis, 4) a global statistical analysis that shows a ubiquitous relationship between large sea state gradients and surface current vorticity, probably associated with more frequent extreme waves (both in height and shape). Section 6 contains a summary of the results and discussion.

2. Case study: Storm description

A low pressure system developed off the Argentina coast near 60°W/40°S on 24 February 2016. Then it propagated eastward and merged with the circumpolar jet stream while strengthening. It reached its maximum intensity at about 30 m/s on the 26th, with a translation velocity near 16 m/s. The storm intensity decreased slightly on the 27th while it crossed the zero meridian, then south of the Cape of Good Hope early on the 28th, and dissipated a few days later. Fig. 1 shows the wind field at times near the maximum intensity, obtained by the European Center for Medium range Weather Forecasting (ECMWF) numerical model (0.125° resolution) and by the Advanced Microwave Scanning Radiometer 2 (AMSR-2). Different radiometers (Soil Moisture Active Passive, Windsat, AMSR-2) give estimates consistently higher than the ECMWF ones. The Meteorological Operational (Metop) Advanced SCATterometer (ASCAT) -A and -B gave values in line with the ECMWF winds, as expected since scatterometer winds are assimilated into the numerical model. Differences with radiometer measurements are consistent with previous results (Reul et al., 2017; Zabolotskikh et al., 2016). It can be explained 1) by the inherent smoothing performed by the numerical model, although its grid resolution is quite fine, 2) because sensitivity of actual scatterometers dramatically decrease for winds getting close to 30 m/s and beyond (e.g. Quilfen et al., 2010; Mouche et al., 2017), and measurements can be biased with wave age (Quilfen et al., 2004), 3) and finally because both ECMWF model and scatterometer wind sources are strongly correlated (Pineau-Guillou et al., 2018). Radiometer winds are not assimilated into the ECMWF model, but their sensitivity to high winds, beyond 30 m/s, has often been reported (Quilfen et al., 2007; Reul et al., 2012). Yet, accurate calibration of the satellite data should be performed using a recognized reference source, which is still a matter of debate. In the frame of the present study, we make the hypothesis that the ECMWF maximum winds are underestimated, to possibly impact the WAVEWATCH III model results.

Size of the storm also matters as it determines the fetch conditions, together with the wind intensity and the translation speed. Size and translation speed are at least as important as maximum winds to constrain the wave field and its main characteristics: significant wave height and peak wavelength (Hanafin et al., 2012; Kudryavtsev et al., 2015). Storm size estimates from satellite sensors and ECMWF numerical model, often referenced as the 17 m/s wind radius, are certainly defined with better accuracy than maximum winds. For our case study, ECMWF and satellite storm size estimates are indeed in very good agreement up to 20 m/s radius, with above gale-force (17 m/s) winds covering an area of about 4.10^5 km^2.

3. Model and observations

3.1. WAVEWATCH III model runs

The numerical model hindcasts were obtained on a quasi-global grid, with a resolution of 1/6° in latitude (48°S to 47°N) and longitude (28°W to 57°E). The general numerical model framework is described by the WAVEWATCH III development group (2016). The particular settings used here follow from Rascle and Ardhuin (2013), with the addition of a 1/6° two-way nested zoom around southern Africa, with a southern boundary at 48°S. These model nests use third-order schemes with garden-sprinkler correction, and sub-grid island and iceberg blocking. The parameterizations combine the Discrete Interaction Approximation (Hasselmann et al., 1985), a wind-wave generation term adapted from Janssen (1991), [see Ardhuin et al., 2010 for the adjustment details], and dissipation parameterizations (Ardhuin et al., 2010). The model uses 24 directions and 32 frequencies (0.037–0.72 Hz). In the case presented here, the hindcast was run from 25 February 2016 until 29 February 2016, with an output grid every 3 h. Forcing was provided by ECMWF analysis winds and by the Globcurrent daily geostrophic current components (http://www.globcurrent.org). These surface current fields are estimated on a 1/4° resolution grid from sea surface height (SSH) measurements performed by several operational altimeters and using an optimal interpolation method (Ducet et al., 2000).

3.2. Observations sources

Ocean Surface Topography Mission (OSTM)/Jason-2 is a follow-on altimetric mission to the TOPEX/Poseidon and Jason-1 missions. The Jason-2 altimeter operates at two frequencies (13.6 GHz in the Ku band, 5.3 GHz in the C band) to determine ionospheric electron content, which affects the radar signal path delay. The altimeter performs measurements at nadir at about 6 km ground sampling along the satellite track. The Geophysical Data Records (GDR) used in this study are processed at Aviso center in Toulouse under the responsibility of the Centre National d'Etudes Spatiales (CNES) and the National Aeronautics and Space Administration (NASA).

The European Space Agency Sentinel-1 (S1) mission carries a SAR operating at C-band, which offers medium and high resolution imaging capabilities in all weather conditions. SAR Wave mode acquires data in 20 km by 20 km vignettes, at 5 m by 5 m spatial resolution, every 100 km along the orbit, acquired alternately on two different incidence angles. Vignettes on the same incidence angle are separated by 200 km. Swaths alternate incidence angles between near range and far range (23° and 36.5° incidence angle, respectively).

The Advanced Microwave Sounding Radiometer 2 (AMSR-2) is a