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Assessing mobility and redistribution patterns of sand and oil agglomerates in the surf zone

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ABSTRACT

Heavier-than-water sand and oil agglomerates that formed in the surf zone following the Deepwater Horizon oil spill continued to cause beach re-oiling 3 years after initial stranding. To understand this phenomena and inform operational response now and for future spills, a numerical method to assess the mobility and alongshore movement of these “surface residual balls” (SRBs) was developed and applied to the Alabama and western Florida coasts. Alongshore flow and SRB mobility and potential flux were used to identify likely patterns of transport and deposition. Results indicate that under typical calm conditions, cm-size SRBs are unlikely to move alongshore, whereas mobility and transport is likely during storms. The greater mobility of sand compared to SRBs makes burial and exhumation of SRBs likely, and inlets were identified as probable SRB traps. Analysis of field data supports these model results.

1. Introduction

As a result of the Deepwater Horizon oil spill, several million barrels of gas and oil flowed into the Gulf of Mexico between April and July of 2010 from the Macondo well’s location southeast of coastal Louisiana (Fig. 1A; McNutt et al., 2011; Reddy et al., 2012). Some oil that was not collected or dispersed was transported via surface currents to the coast along the northern Gulf of Mexico. In the surf zone, oil mixed with suspended sediment to form heavier-than-water sand and oil agglomerates that sank to the seafloor (Operational Science Advisory Team, 2011). Stranded oil that mixed with sand to form deposits on the beach face could also be subsequently eroded and introduced into the surf zone (Michel et al., 2013). Agglomerates range in size from small millimeter (mm) to centimeter (cm) sized pieces to large submerged oil mats (also called SOMs) that extend up to a few meters in the cross shore and 10–100’s of meters (m) in the alongshore, with thickness up to 20 cm. Under energetic wave conditions, mats may break up to form smaller, more mobile pieces referred to as surface residual balls (SRBs). These SRB’s, typically consisting of between 70% and 95% sand by weight with the remainder a mix of oil and water (Operational Science Advisory Team, 2011), can be transported onshore of their formation location or elsewhere along the beach to cause re-oiling. Because the sand that comprises the seafloor is highly mobile within the surf zone, mats and SRBs may be buried up to meters in depth when features such as ripples and sand bars migrate over them. If formed at the shoreline and the shoreline accretes, mats and SRBs can be buried there as well. Subsequently, the beach profile may change again, exposing the mats or SRBs and resulting in re-oiling.

As part of the response and mitigation efforts, mats are identified by clean-up teams who perform regular patrols and respond to alerts of re-oiling. When mats are discovered, they are generally removed unless this is not acceptable due to constraints posed by sensitive wildlife. SRBs are also removed from the beach by clean-up teams. Key questions for response and mitigation operations are when and where SRBs are mobilized, whether they move alongshore, and in what direction. Answers to these questions determine if a newly observed deposition at a previously cleaned site is indicative of a local source requiring mitigation and determine what areas are most likely to have continued re-oiling through transport from other locations.

Little is known about the processes of mat formation or fragmentation, or about SRB dynamics. Prior studies have focused on lower density residual oil lumps or “tarballs” that typically float, and only become neutrally buoyant or sink through accumulation of sand or shell hash on the outer surface (Antia, 1993; Balkas et al., 1982; Del Sontro et al., 2007; Gabche et al., 1998; Georges and Oostdam, 1983; Goli, 1982; Iliffe and Knap, 1979; Owens et al., 2002; Tsouk et al., 1985). To address this knowledge gap, a numerical methodology was developed to: (1) identify spatial patterns in alongshore currents that drive SRB transport within the surf zone; (2) determine when SRBs are mobilized; (3) identify probable patterns of SRB redistribution; and (4) determine the effects of inlets on SRB mobility, transport, and deposition. In addition, observational data based on collection of SRB and mat material by clean-up teams were analyzed to assess the numerical model results. The methodology was applied to the Alabama (AL) and western Florida (FL) coasts where oiling and SRB generation occurred

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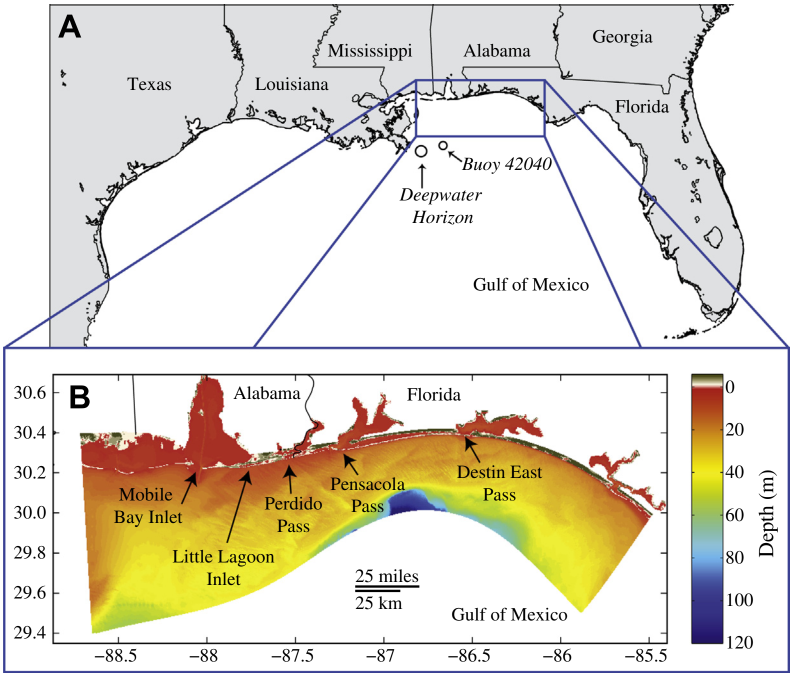

Fig. 1. (A) Location of the study area within the northern Gulf of Mexico and (B) the numerical model bathymetry.

following the Deepwater Horizon blowout. In the next section, the methods used to evaluate 1–4 are described. The results section contains predictions of alongshore current patterns, SRB/sand mobility and transport, and analysis of observational data. The discussion section focuses on the correlations between predicted and observed SRB mobility patterns, and implications for future applications are discussed. The primary findings are summarized in the conclusion section.

2. Methodology

Because surf zone alongshore currents are driven, in part, by waves approaching the shore at an angle to the coast, the range of hydrodynamic variability was determined by numerically modeling waves and alongshore currents for 80 characteristic wave scenarios. A set of six mobility and transport metrics were calculated for each scenario to determine SRB response. Two additional metrics identified probable long-term distribution patterns by combining the results of all scenarios. A ninth metric characterized the effects of tidal currents near inlets for a tidally-variant case. The modeling approach and the suite of metrics are described below.

2.1. Hydrodynamic modeling

A scenario-based modeling approach was established to reduce computational expense and facilitate application to future time periods. Wave conditions from April 2010 to May 2012 were taken from the National Oceanic and Atmospheric Administration (NOAA) WAVEWATCH-III 4′ operational forecast (WW3; http://polar.ncep.noaa.gov/waves/; Tolman, 2008) at the location of National Data Buoy Center (NDBC) buoy 42040 (Fig. 1A). WW3 model results, which are archived every three hours, were used instead of buoy observations which contain gaps in the time-series. Each WW3 time step was classified into 1 of 80 wave scenarios based on 5 wave heights and 16 wave directions. A representative WW3 prediction at a specific time was chosen to represent each scenario, based on multivariate comparison to the conditional mean values of wave height, wave direction, wave period, wind speed, and wind direction for all time steps matched to that scenario (Plant et al., 2013).

Waves and alongshore currents were modeled for each scenario using a 2D application of the Delft3D (D3D) version 4.00.01 (Delft, 2007) coupled wave-flow model (Fig. 1B). The curvilinear model grid had a resolution of approximately 250 m in the alongshore and varying resolution in the cross shore, with a maximum resolution of approximately 3 m. Bathymetry was interpolated to the model domain from the 30 m resolution NOAA National Geophysical Data Center Northern Gulf Coast digital elevation map (DEM). Although this resolution resolved sand bars, large mega cusps, and other relevant features, there was no evolution of model bathymetry with time, and ripples, narrow rip channels, and other spatial features that likely have relevance to local SRB transport were not resolved. The higher resolution of the model grid relative to the resolution of the underlying bathymetry is necessary to resolve wave-breaking processes and resulting currents. The depth-averaged model does not resolve vertical velocity distribution, such as undertow.

A 36-h time-series was also run for a single set of wave conditions (corresponding to the scenario of 1.5–2 m waves from the SE) and varying water levels to determine the effect of the tides on SRB transport, particularly around inlets. For this simulation, time-varying water levels at the model boundary were obtained from the TPXO7.2 global tide model (http://volkov.oce.orst.edu/tides/global.html). The bathymetry around Little Lagoon, AL, a 10-m wide inlet of interest in the model domain, was further refined by inclusion of higher resolution bathymetry data from the U.S. Army Corps of Engineers (USACE) (downloaded via NOAA's Coastal Services Center Digital Coast Viewer) that were collected in January–March 2010. Additional information on the numerical model configuration and scenario-based wave reconstruction may be found in Plant et al. (2013) and Long et al. (in preparation).

2.2. SRB and sand movement

Soulsby (1997) parameterized four theoretical methods of wave-current shear stress calculation shown to provide a good