Continental Shelf Research 163 (2018) 1–11

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

# Coastal protection by a small scale river plume against oil spills in the Northern Gulf of Mexico

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ARTICLE INFO

*Keywords:*
River plume
Surface material transport
Inner shelf
Coastal barriers
Oil spill

ABSTRACT

The Deepwater Horizon oil spill damaged some beaches along the Northern Gulf of Mexico (NGoMex) coast more than others, possibly related to the presence of natural protection mechanisms. In order to optimize future mitigation efforts to protect the coast, these mechanisms should be understood. The NGoMex coast is characterized by relatively long stretches of sandy beach interrupted by tidal inlets creating ebb-tidal river plumes featuring frontal zones that may act as transport barriers. This research investigates to what extent these plumes are capable of protecting the adjacent coast. This is done by means of a combination of a 3D Eulerian flow model and a Lagrangian particle model to track oil pathways and visualize Lagrangian Coherent Structures located at the plume front. The models are verified with measurements from a field experiment adjacent to Destin Inlet, Florida. The effects of wind, tidal range and river discharge on the oil fate are discussed. It was found that wind is the dominant parameter. Offshore wind prevents oil from beaching. During onshore winds, oil is pushed to shore, but near the inlet the plume is effective in reducing the amount of oil washing ashore during the ebbing tide. In general, the plume redistributes the oil but is not capable of preventing oil from beaching. For strong winds, the influence of the plume is reduced.

## 1. Introduction

The Deepwater Horizon oil spill caused severe damage to many coastal ecosystems in the Northern Gulf of Mexico (NGoMex) (Upton, 2011). Despite much effort being made in cleaning up the oil before it washed ashore, it was impossible to protect all coastal systems because of the sheer quantity of spilled oil in comparison to the means of cleaning (Graham et al., 2011; Smithsonian, 2016). Moreover, the spreading and mixing of surface material is not well modeled at the submesoscale (1–10 km) by circulation models (Poje et al., 2014; Gildor et al., 2009) resulting in uncertainties on where and when oil will wash ashore (Roth et al., 2017).

In order to reduce the damage of oil spills, first responders should be pointed to those patches of oil that are most harmful to coastal ecosystems and have greatest socio-economic impact, that is, the patches of oil that wash ashore (Smith et al., 2010; Morris et al., 2013; Huguenard et al., 2016). Understanding where these patches of oil come from requires a thorough understanding of the circulation on the inner shelf, which is the zone where the turbulent surface and bottom boundary layer overlap (Lentz and Fewings, 2012) and reaches from the surfzone to approximately 30 m water depth (Kennish, 2000), which is >20 km offshore for the biggest portion of the coast in the NGoMex. The most important forcing mechanisms on the inner shelf are wave-, wind- and tidal forcing in general, however the influence of rivers forming brackish buoyant plumes can be important as well (Lentz and Fewings, 2012; Horner-Devine et al., 2015; Xia et al., 2011). In a study on the effects of the Mississippi river plume, Kourafalou and Androulidakis (2013) found that onshore transport was restrained due to circulations related such a plume. Roth et al. (2017) has shown that the wind driven plume of the Choctawhatchee bay is an effective barrier for surface drifters and is therefore expected to prevent offshore surface pollution from washing ashore. His findings were derived from data from the Surfzone and Coastal Oil Pathways Experiment (SCOPE), a two week field experiment near Destin, Florida in December 2013. During SCOPE, an ADCP and a CTD array were deployed at location A in Fig. 1 to measure flow velocity and salinity. The array was positioned perpendicular to the coast, consisted of six stations and ranged from the beach to 500 m offshore where the water depth is 10 m. The locations and bottom levels of the stations in the array are also shown in Fig. 1. Besides that, surface drifters were deployed and their paths were tracked. As SCOPE lasted two weeks, there was only a limited set of forcing conditions.

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https://doi.org/10.1016/j.csr.2018.05.002
Received 11 June 2017; Received in revised form 30 April 2018; Accepted 9 May 2018
Available online 12 May 2018

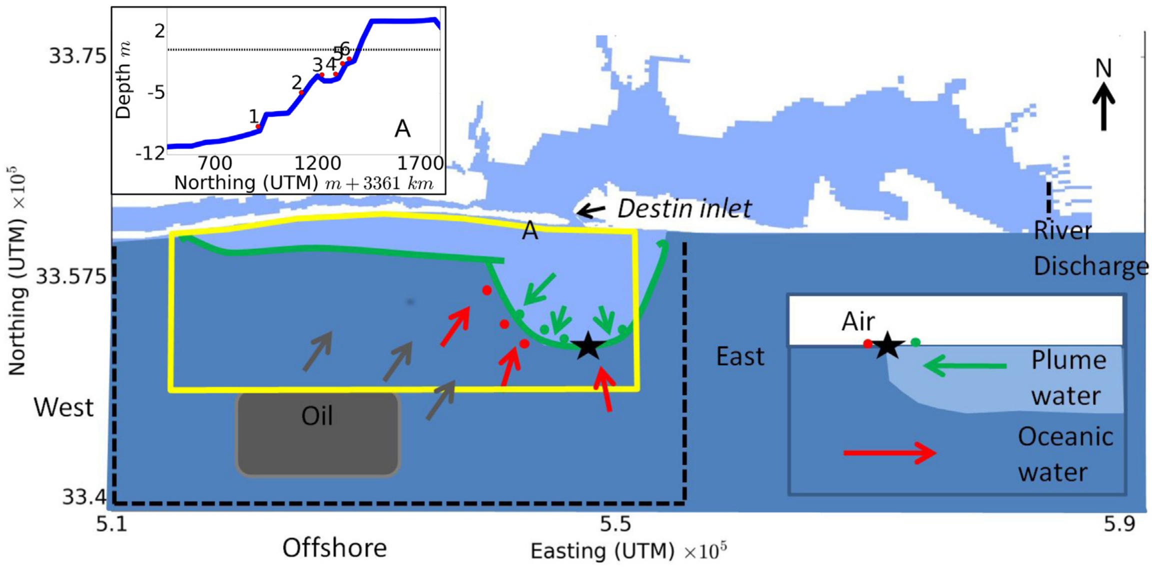


**Fig. 1.** Overview of the research domain and the buoyant plume. The light blue water denotes brackish water from the bay, whereas the darker blue denotes oceanic saline water. Green and red arrows and dots refer to the movement of particles within the plume and oceanic waters respectively. The green line highlights the edge of the plume waters, where surface flotsam is expected to gather. The boundaries of the Eulerian flow model are shown as the black dashed line and are named West, Offshore, East and River Discharge. The yellow shape shows the initial position of Lagrangian tracers and is therefore the area within which LCS can be calculated. The inset in the left upper corner shows the sea bed level of the measurement stations in the cross-shore measurement array during SCOPE at location A. Figure adjusted from Roth et al. (2017) and Huguenard et al. (2016).

This work makes use of the findings of SCOPE and goes one step further by creating a broader understanding on the plume related coastal protection against offshore oil for various wind forcings, tidal ranges and river discharges. An Eulerian flow model (Delft3D) is used to calculate pathways of Lagrangian tracers, allowing for the calculation of Lagrangian Coherent Structures (LCS). In a theoretical work, Shadden (2006) found that the flux through LCS is negligible when they are properly defined. In accordance with the findings of Roth et al. (2017), plume fronts may form barriers through which no transport occurs, hence they should show up as LCS. This method has been used to visualize the location and evolution of transport barriers in systems on the scale of rip currents $O(100\ m)$ (Reniers et al., 2010), driven by waves and with time scales on the order of 10 min. Also, the method has been used on the scale of a bay $O(1\ km)$ (Fiorentino et al., 2012), with the dominant forcing being a semidiurnal tide. Lastly, the method has been shown to be useful up to the oceanic mesoscales on the order of $O(100\ km)$ (Olascoaga et al., 2013) driven by various types of oceanic forcings on the order of weeks, showing that the method is useful over a wide range of forcing types and time scales. In this work, the LCS are used to visualize flow features rather than finding barriers through which no transport at all occurs.

Lagrangian tracers serve to understand where oil beaches and where it comes from. Consequently, the positions of the plumes together with data on where oil beaches is used to get a better idea on the actual coastal protection due to the plume for various forcing sets. This can then be used as a guide for first responders on how to use their resources most effectively in reducing damage to the coastal ecosystem.

In the following, the domain of research - the NGoMex and the Choctawhatchee bay - are discussed, followed by the protection mechanism of the plume. The numerical models are discussed to a greater extent and they are verified with data from SCOPE. Lastly it is discussed how the Choctawhatchee plume protects the coast and how first responders can make use of these findings.

## 2. The buoyant plume of the Choctawhatchee bay as a coastal protection mechanism

The Choctawhatchee river plume is a small-scale river plume (Huguenard et al., 2016). River plumes are driven by density gradients which are a result of fresh river water. The fate of such plumes is influenced by many factors such as tides, ambient currents, Coriolis, wind, river discharge, the bathymetry and the angle between the coastline and the inlet feeding into it (Horner-Devine et al., 2009; Bianchi et al., 2013).

Horner-Devine et al. (2015) describe the spatial evolution of a river plume in terms of four different dynamically defined zones. The first zone is the source zone in the estuary, where the dynamics are determined by estuarine processes. The second zone is the near-field where the flow is steered by inertia, both barotropic- and baroclinic pressure gradients and deceleration through turbulent stress with the ambient water. In this zone the flow is supercritical, that is, the Froude number is greater than one, $Fr = U/c_i > 1$, with $U$ the flow velocity and $c_i$ the internal wave speed. Therefore the near-field often features a sharp frontal boundary with strong surface convergence (Garvine, 1984; Garvine and Monk, 1974; O'Donnell et al., 1998). At the point where the Froude number drops below one, the near-field ends (Hetland, 2005) and the mid-field starts. In this field the dynamics are dominated by the Earth's rotation and wind steering and the inflow momentum is lost. In the mid-field, the plume often forms a shore parellel coastal current as a result of Coriolis (Garvine, 1987) or ambient alongshore currents (Fong and Geyer, 2002). The last zone is the far-field. In this field there is no remembrance of the inflow momentum and the plume is steered by the Earth's rotation, buoyancy and wind (Horner-Devine et al., 2015). Turbulent mixing of the plume with ambient water due to wind can be substantial in all zones. The strength of mixing at the plume front in the near field is often orders of magnitude greater than due to wind, however as the wind affects the entire plume and hence a large spatial area wind effects remain important (Horner-Devine et al., 2015).

The Choctawhatchee bay is located in the NGoMex, it is approximately 43 km long, on average 5 km wide and it is relatively shallow with an average depth of 4 m (Valle-Levinson et al., 2015; Schaeffer, 2010). The Destin inlet is the connection between the gulf and the bay and is ~ 450 m wide and 7 m deep. The Choctawhatchee river feeds into the bay on the Eastern end, as shown in Fig. 1. An analysis of volumetric river flux data from 2007 to 2016 from USGS station 02365500