Continental Shelf Research 137 (2017) 142–153

Contents lists available at ScienceDirect

Continental Shelf Research

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

Observations of inner shelf cross-shore surface material transport adjacent to a coastal inlet in the northern Gulf of Mexico

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ARTICLE INFO

Keywords:
River Plume
Dispersion
Surface material transport
Nearshore
Coastal barriers
Surface drifters

ABSTRACT

Motivated by the Deepwater Horizon oil spill, the Surfzone and Coastal Oil Pathways Experiment obtained Acoustic Doppler Current Profiler (ADCP) Eulerian and GPS-drifter based Lagrangian "surface" (< 1 m) flow observations in the northern Gulf of Mexico to describe the influence of small-scale river plumes on surface material transport pathways in the nearshore. Lagrangian paths are qualitatively similar to surface pathlines derived from non-traditional, near-surface ADCP velocities, but both differ significantly from depth-averaged subsurface pathlines. Near-surface currents are linearly correlated with wind velocities ($r = 0.76$ in the alongshore and $r = 0.85$ in the cross-shore) at the 95% confidence level, and are 4–7 times larger than theoretical estimates of wind and wave-driven surface flow in an un-stratified water column. Differences in near-surface flow are attributed to the presence of a buoyant river plume forced by winds from passing extratropical storms. Plume boundary fronts induce a horizontal velocity gradient where drifters deployed outside of the plume in oceanic water routinely converge, slow, and are re-directed. When the plume flows west parallel to the beach, the seaward plume boundary front acts as a coastal barrier that prevents 100% of oceanic drifters from beaching within 27 km of the inlet. As a result, small-scale, wind-driven river plumes in the northern Gulf of Mexico act as coastal barriers that prevent offshore surface pollution from washing ashore west of river inlets.

1. Introduction

The Deepwater Horizon (DwH) oil spill (Aigner et al., 2010) demonstrated a need to further understand the physical processes that are important for the transport of oil at the surface of the nearshore region of the ocean (Dzwonkowski et al., 2014). The nearshore is the "last mile" for oil to transit to the beach and includes the surf zone, where waves break, and the inner shelf, defined by Lentz and Fewings (2012) as the region seaward of the surf zone, where the surface and bottom boundary layers overlap. As oil approached the Florida Panhandle in early June of 2010, nearshore surface oil forecasts available from the National Oceanic and Atmospheric Administration's (NOAA) Office of Response and Restoration relied upon satellite imagery and ocean circulation models that produced large "uncertainty boundaries" for where the oil would wash ashore (NOAA, 2010; Mariano et al., 2011). Oil location estimates were also inconsistent between forecasts (Mariano et al., 2011). Additionally, the spreading and mixing of surface material, defined as dispersion, is not predicted well by circulation models, particularly at the submesoscale (1–10 km) (Poje et al., 2014; Gildor et al., 2009). This challenge stems from anisotropic conditions near coastal boundaries where physical processes are non-homogeneous owing to dominant forcing mechanisms and response(s) that can change quickly with concomitant changes in water depth, inhibiting accurate parameterization of a bulk eddy diffusivity term (Swenson and Niller, 1996; LaCasce and Ohlmann, 2003; Haza et al., 2008; Romero et al., 2013). Field observations are necessary to increase knowledge of small-scale, anisotropic, nearshore transport processes and further develop oil forecasting capabilities.

Inner shelf circulation studies find that waves and winds are the principal forcing mechanisms for cross-shelf surface transport in the absence of stratification, as described in an inner shelf review article by Lentz and Fewings (2012) and briefly summarized here. When winds are absent, the Stokes drift velocities and wave-driven undertow balance each other at depth resulting in no net transport (Lentz et al., 2008). When the winds and waves are onshore, flow is onshore

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http://dx.doi.org/10.1016/j.csr.2016.12.017
Received 18 May 2016; Received in revised form 12 December 2016; Accepted 22 December 2016

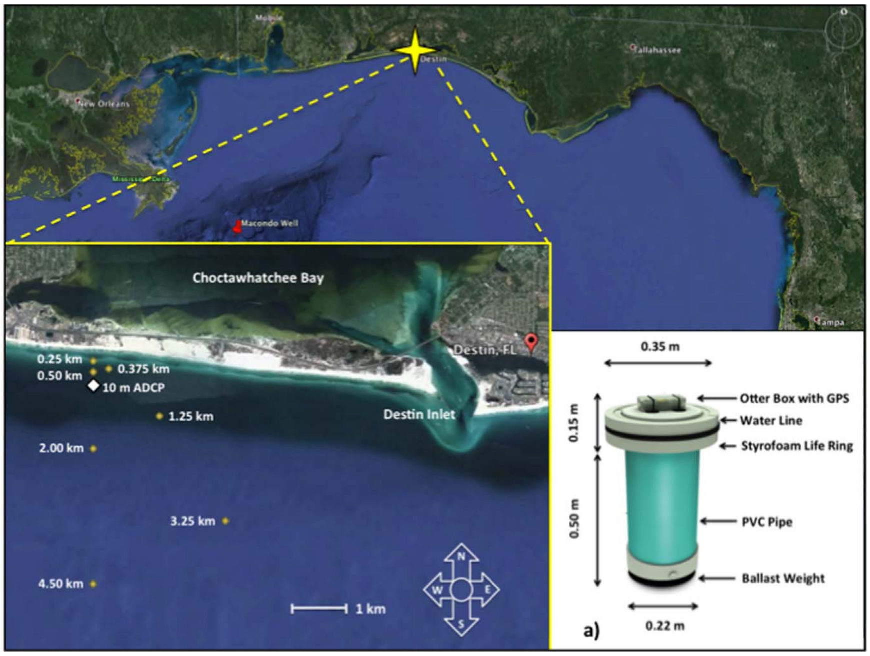

Fig. 1. Google Maps image of the northern Gulf of Mexico with SCOPE site indicated with a yellow star and the Macondo Well with a red marker to the southwest. Inner shelf drifter deployment locations are depicted by gold dots on zoom in of Destin Inlet and adjoining beach. 10 m ADCP is annotated with a white diamond and offset farther south for clarity. Inset a) SCOPE drifter with SPOT hand-held GPS affixed on top, inside an Otter Box.

near the surface and offshore at depth (Fewings et al., 2008; Hendrickson and MacMahan, 2009). Offshore winds and onshore waves result in strong offshore flow near the surface with decreasing offshore flow (Fewings et al., 2008) or onshore flow (Lentz and Fewings, 2012) at depth. As opposed to the mid- and outer continental shelves where cross-shore flow is driven by alongshore winds, cross-shore winds are more effective at driving cross-shore transport in the vertically well mixed inner shelf (Fewings, 2008; Lentz and Fewings, 2012; Dzwonkowski et al., 2011).

There have been fewer studies of cross-shore transport in stratified inner shelves, but for the stratified inner shelf in the northern Gulf of Mexico alongshore winds are more important for cross-shore transport than cross-shore winds (Dzwonkowski, 2011). Wind direction is also important for setting the orientation of river plumes as they emerge into the inner shelf of the northern Gulf of Mexico (Xia et al., 2011). Brackish, buoyant river plumes that emerge from coastal inlets are a source of stratification in the inner shelf and frequently add to coastal anisotropic conditions by propagating alongshore as a coastal current (Horner-Devine et al., 2015). When this occurs, the plume is typically a shallow surface feature (Chapman and Lentz, 1994) that deepens with downwelling winds (Haus et al., 2003) and extends stratification for tens of kilometers, or more, before mixing with the ambient oceanic water (Garvine, 1987; Yankovsky et al., 2000). Density fronts form as boundaries between the brackish riverine water and oceanic water (Garvine, 1987) and become submesoscale mechanisms for dispersion (Schroeder et al., 2012), where surface material converges and slows (Garvine, 1974; Garvine and Monk, 1974). Based on these studies it is expected that buoyant plumes within the inner shelf will alter the cross-shore transport of surface materials. However, to be useful in future oil spill prediction tools, the effect of the plume on cross-shore transport pathways needs to be further explored and quantified.

This study describes the Surfzone and Coastal Oil Pathways Experiment (SCOPE), performed in the inner shelf adjacent to Destin Inlet, Florida to explain the cross-shore surface transport of oil in the nearshore region during the Deepwater Horizon oil spill. As is common in inner shelf studies, water column velocity observations were collected using bottom-mounted Acoustic Doppler Current Profilers (ADCP). However, the common practice of removing observations from near-surface ADCP bins to avoid side lobe effects was not followed. This practice leads to a substantial loss of data in shallow waters (Dzwonkowski et al., 2014), and for the study of oil transport eliminates the critical layer of the water column where oil floated in the aftermath of the DwH spill (Kourafalou and Androulidakis, 2013). Instead, near-surface velocity observations below the wave trough level are retained while minimizing side lobe errors, as described in Section 2.3. To further overcome the deficiencies of the ADCP near-surface observations, GPS-drifters designed to float only in the top meter of the water column are employed to describe the Lagrangian surface behavior (Schmidt et al., 2003; MacMahan et al., 2009; Poulain, 1999), and are detailed in Section 2.2. Drifters have been successfully deployed to observe the variability of circulation patterns (Ohlmann and Niiler, 2005) and surface material dispersion in both the surf zone (Brown et al., 2009; MacMahan et al., 2010; Spydell et al., 2007) and inner shelf (Ohlmann et al., 2012). In addition to using drifters to observe circulation and dispersion, a unique comparison between drifter pathways and near-surface ADCP derived pathlines is employed to quantify the role of small-scale river plumes in cross-shore surface transport (Section 3). These findings highlight the formation of an important submesoscale, cross-shore transport barrier, it's frequency, persistence, and alongshore extent westward away from the inlet, which are then applied to the wind conditions that occurred during the DwH oil spill.

2. Materials and methods

2.1. Description of the field experiment

SCOPE was conducted in December 2013 at John Beasley Park (JBP) in Destin, FL along an open, nearly east-west oriented stretch of the NGoMex on a barrier island that was impacted by the Deepwater Horizon oil spill from the Macondo Well (Fig. 1). A cross-shore array of 4 RBR bottom Conductivity, Temperature, and Depth (CTD) sensors were deployed at 50 m, 100 m, 200 m, and 500 m from the beach in 1.5 m, 2.0 m, 3.0 m, and 10.0 m water depths. At the end of the array, collocated with the 10 m CTD, a bottom-mounted, upward-looking ADCP was deployed to collect pressure and along- (u) and cross-shore