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Shelf break exchange events near the De Soto Canyon

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Observations of currents, temperature, sea-surface height, sea-surface temperature and ocean color, derived from moorings, surface and deep drifters, hydrographic surveys, and satellites, are used to characterize shelf-slope exchange events near the apex of the De Soto Canyon in the northeast Gulf of Mexico. During the winter of 2012–2013, shelf-break time series showed a number of events where cold shelf water extruded over the slope. These events were largely consistent with slope eddies of both signs influencing shelf break currents. Larger-scale circulations, derived from the Loop Current and a separating Loop Current eddy, strongly influenced circulation over the De Soto slope during summer 2012, with flow patterns consistent with potential vorticity conservation over shoaling topography. Statistical investigation into shelf-slope exchange using large numbers of surface drifters indicated that export from the shelf is larger than vice-versa, and is more uniformly distributed along the shelf break. Import onto the shelf appears to favor a region just east of the Mississippi Delta, which is also consistent with the observed onshore transport of surface oil from the *Deepwater Horizon* disaster.

1. Introduction

The interactions between shelf and slope waters are generally complex, involving deep-water processes such as eddies, and shallow shelf dynamics generally dominated by wind forcing and coastal-trapped waves. Elucidating mechanisms that determine the export of nutrients and pollution from the shelf to the generally less productive slope waters, as well as larval transport on to and off the shelf, are important as a basis for understanding ecological dynamics and ecosystem health. In the northeast Gulf of Mexico, large freshwater flows, dominated by the eastward discharge of the Mississippi River near the shelf break (defined as the 75 m isobath), extend along the coasts of Mississippi, Alabama, and northern Florida (Fig. 1). The shelf varies in width from the Mississippi Delta to the apex of the slope; i.e., the closest approach of the shelf break to the coast. This point, where the alongshore direction of the shelf break and slope changes through 90° from northeast to southeast, is commonly referred to as the head of the De Soto Canyon (e.g., Wang et al., 2003), even though a narrow canyon is not present there (Fig. 1). Slope topography is also complex, with the northern side having rough bathymetry, and the eastern side having a broad smooth slope down to 1000 m (known as the Florida Terrace) and thence a very steep escarpment down to abyssal depths. The S-shaped vestigial canyon (Fig. 1) is found between the 500 and 1000 m isobaths, where it is narrow with the bottom at a maximum of ~100–200 m below the rim, and serves to separate these two slope topographic regimes (Harbison, 1968). In this study, "De Soto Canyon" generally refers to the upper slope in this northeast corner of the Gulf rather than the narrow Canyon per se.

The massive *Deepwater Horizon* (*DWH)* oil spill in April 2010 from a platform ~80 km southeast of the Mississippi Delta (Fig. 1) resulted in transport of surface oil from the slope to the shore (Liu et al., 2011; Walker et al., 2011). The majority of shoreward surface transport took place near the delta and then spread eastward along the Mississippi – Alabama coast. There is not a strong shelf-break front along this shelf, as is seen along the US east coast in the Middle Atlantic Bight (Houghton et al., 1994), that would act as a barrier to shelf-slope exchanges, thus the question arises why there was limited onshore transport of oil over most of the shelf-break between the delta and the canyon head during the *DWH* oil spill.

Previous observations of currents and hydrography on the shelf break and slope consist of a two-year moored array and hydrographic surveys over the slope between the delta and the west

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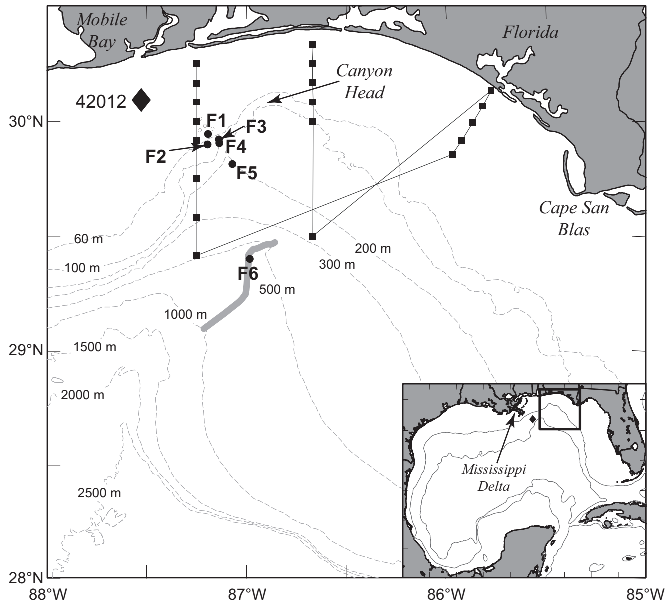

Fig. 1. Map of the De Soto Canyon region in the NE Gulf of Mexico (see inset, where the Deepwater Horizon wellhead is shown about 80 km SE of the Mississippi Delta; inset isobaths: 200 and 2000 m) showing locations (round dots) of Deep-C moorings F1–F6, and a representative Deep-C water quality cruise over the shelf and slope where CTD stations are given by squares. Location of the De Soto Canyon is given by the thick gray line through F6, and NDBC buoy 42012 is given by the diamond.

Florida shelf (Hamilton and Lee, 2005), and a closely spaced array of 14 ADCP's over the shelf break and upper slope, between the 60 and 500 m isobaths south of Mobile Bay (Carnes et al., 2008). The former established the importance of cyclonic and anticyclonic eddies with relatively long persistence times of weeks to months, as well as southwestward subsurface jets at ~200–400 m adjacent to the slope that were opposite to the surface flows. The latter established differing time scales between the shelf (few days to a week) and upper slope (1–2 weeks), and established relations between the integrated wind stress curl over the west Florida shelf and along-shelf flow fluctuations at the array. Hallock et al. (2009) established that the longer period (specifically 21.5 and 16.1 days) along-slope velocity fluctuations were a form of coastal-trapped waves. Forcing for these waves was uncertain, but possibilities include small scale eddies over the northeast slope, and the Loop Current interacting with the west Florida shelf and slope as discussed by Hetland et al. (1999). Nguyen et al. (2015) show that in their model, large-scale slope isopycnal fields move up and down on seasonal time scales due to forcing by Loop Current interactions with the West Florida Shelf, suggesting that such a link operates on longer time scales.

Northeast slope eddy statistics were explored further by Hamilton (2007), using surface drifters deployed by the Surface Current and Lagrangian-drift Program, *SCULP-II* (Ohlmann and Niiler, 2005; Ohlmann et al., 2001) that were exported from the northeast shelf over a one-year interval. Cyclones and anticyclones were present in approximately equal numbers, with median diameters and periods of 50–60 km and 12–15 days, respectively, as determined from drifter orbits. At any one time, an average of about 6 eddies would be present over the slope. It is noted that because of their relatively small size, and weak circulations (maximum velocities ~60 cm s^{-1}), these type of slope eddies are not resolved by standard altimeter maps of sea surface height (SSH) anomalies (Leben, 2005). It also noted that slope eddies are only indirectly related to the Loop Current (LC) and separated LC anticyclonic eddies that dominate the eastern Gulf basin (Schmitz et al., 2005). LC and LC eddy induced flows that interact with slope topography through potential vorticity conservation (Hamilton and Lee, 2005) seem to be important eddy generation mechanisms. On rare occasions, the LC can extend far enough north to intrude over the upper slope and outer shelf (Huh et al., 1981; Wiseman and Dinnel, 1988).

The relationship between the extension of the LC and the separation of LC eddies and slope circulation was explored by Wang et al. (2003) using the near-surface current observations from Hamilton and Lee (2005), and numerical model simulations that assimilated SSH and sea-surface temperature (SST) data (Oey, 1996). A coupled analysis of observed and simulated currents show two dominant modes for slope eddies: mode 1 in which fluctuations are concentrated on the lower slope and appear to be associated with frontal cyclones traveling around an extended LC, and mode 2 in which a pair of counter rotating eddies occupy the head and the foot of the canyon. The latter is associated with an intrusion of a LC meander crest and trough over the west Florida shelf.

The purpose of this paper is to explore some new observations of shelf break circulation in the De Soto Canyon, particularly in regard to shelf-slope exchange. Since *DWH,* the Gulf of Mexico Research Initiative (*GoMRI*) has funded comprehensive ecosystem and oil fate related studies through university-based consortia. The *Deep-C* consortium funded shelf-slope studies in the De Soto Canyon and adjacent shelves where six moorings were deployed for one year in a transect (Fig. 1). The moorings were designed to measure velocity and temperature throughout the water column with good vertical resolution. This differs from Carnes et al. (2008) ADCP study that was restricted to currents, and the earlier Hamilton and Lee (2005) study where the moorings were all seaward of the shelf break, and except for currents above 100 m, vertical resolution was limited. However, because the moorings were deployed as a transect, primarily to support ecosystem and water quality studies, information is lacking on horizontal spatial variability. This is made up for by a *Deep-C* subsurface RAFOS float study, a Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (*CARTHE*) study that deployed a very large number of surface drifters in the summer of 2012 on the northeastern slope, various consortia hydrographic surveys of the shelf and slope, and the usual satellite altimeter, SST and ocean color products. *CARTHE* and older *SCULP-II* drifter results are also used to statistically characterize shelf-slope exchange. All these data sources and analysis methods are described in the next section.

2. Data sources

Characterizing shelf-slope exchange events is complex because of the range of spatial and time scales, associated with wind-forced flow on the shelf (Mitchum and Clarke, 1986), and eddies on the slope (Carnes et al., 2008; Hamilton, 2007; Hamilton and Lee, 2005). Of the data available, no one type (moorings, hydrographic surveys, satellite imagery and altimetry, and drifters) is able to adequately sample the events over the required range of scales necessary for a complete description. Therefore, a multivariate approach has been taken to use all these resources in an attempt to place events shown by the moored data in context of the larger scale slope and eastern Gulf circulation processes.

2.1. Moorings

Six moorings were deployed by *Deep-C* across the outer shelf and upper slope on the northern side of the De Soto Canyon in depths ranging from 50 to 700 m (Fig. 1). Placing of instruments was designed to measure both temperature and velocity through