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Key Points:

- A multidecadal model is used to study cross-slope flow in the NE Gulf of Mexico
- Loop Current impingement on the shelf can remotely modulate cross-slope flow
- The remote connection is a consequence of a SSH anomaly along the slope

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Nonlocal impacts of the Loop Current on cross-slope near-bottom flow in the northeastern Gulf of Mexico

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Abstract Cross-slope near-bottom motions near De Soto Canyon in the northeastern Gulf of Mexico are analyzed from a multidecadal ocean model simulation to characterize upwelling and downwelling, important mechanisms for exchange between the deep ocean and shelf in the vicinity of the 2010 BP Macondo well oil spill. Across the continental slope, large-scale depression and offshore movement of isopycnals (downwelling) occur more frequently when the Loop Current impinges upon the West Florida Shelf slope farther south. Upwelling and onshore movement of isopycnals occurs with roughly the same likelihood regardless of Loop Current impingement on the slope. The remote influence of Loop Current on the De Soto Canyon region downwelling is a consequence of a high-pressure anomaly that extends along the continental slope emanating from the location of Loop Current impact.

1. Introduction

The De Soto Canyon of the northeastern Gulf of Mexico is an important area for oil and gas exploration, commercial and recreational fisheries, and maritime services. The British Petroleum Deepwater Horizon Macondo well oil spill in 2010 posed serious threats to industry and ecosystems in this region. The De Soto Canyon and surrounding area is characterized by complex bathymetry, including a constriction between two wide continental shelves (the West Florida Shelf and the Mississippi-Alabama Shelf), steep escarpments along the outer shelf slope, and numerous small-scale (roughly 10 km) salt domes and minibasins along the western slope of the canyon [e.g., *Murray*, 1966; *Madof et al*., 2009]. The proximity of deep water to the coast at De Soto Canyon suggests that the bathymetry here may be favorable for deep ocean to shelf exchange. Because an unknown amount of the approximately 780,000 m^3 of oil released from the Macondo well may have been deposited on the seafloor [*Ramseur*, 2010], characterizing cross-slope benthic flow and associated upwelling and downwelling in this region is important for understanding and predicting the potential dispersal of hydrocarbons, dispersants, and other materials between the deep ocean and shelf. These processes are also of critical importance for governing the shelf water properties that can dramatically impact local marine ecosystems; an example was the anomalous 1998 upwelling event described by *Muller-Karger* [2000].

A ubiquitous feature of the Gulf of Mexico is the Loop Current, a branch of the subtropical North Atlantic's western boundary current system that enters the Gulf through the Yucatan Channel, circulates anticyclonically, and exits through the Straits of Florida. At irregular intervals (described in many papers including *Sturges and Leben* [2000], *Leben* [2005], and *Dukhovskoy et al*. [2015]), the Loop Current penetrates deeply northwestward into the Gulf and sheds anticyclonic eddies that migrate generally westward but may also temporarily drift northward or southward or even remerge with the Loop Current. Following a shedding event with no reattachment, the Loop Current subsequently retreats to the south.

Though wind and riverine input primarily govern hydrographic properties and dynamics on the relatively broad shelves bracketing De Soto Canyon [*Dzwonkowski and Park*, 2010; *Morey et al*., 2003, 2005], deeper waters of canyon can be influenced by eddies associated with the Loop Current that occasionally extends near the area. These eddies may impinge upon the deeper shelf slope, but potential vorticity conservation limits their influence over shallower isobaths due to their depth signatures of several hundreds to 1000 m [*Oey et al*., 2005].

There is evidence that dynamics over the outer shelf and slope along the West Florida Shelf extending through De Soto Canyon may be influenced by the Loop Current in the southeastern Gulf of Mexico [*Hetland et al*., 1999; *Weisberg and He*, 2003; *Wang et al*., 2003]. At times, the Loop Current contacts the

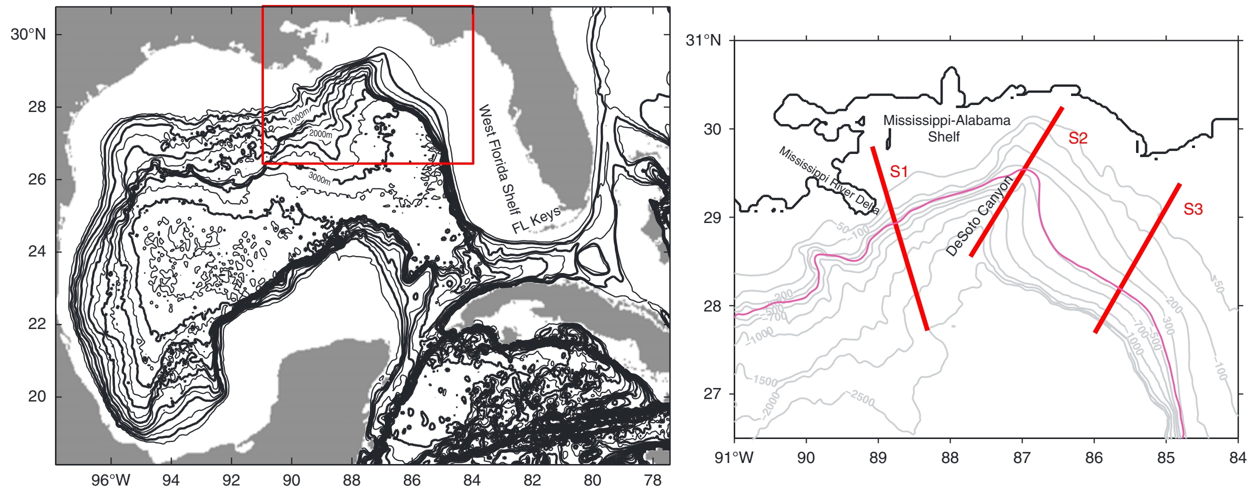

Figure 1. Map of the Gulf of Mexico HYCOM domain and bathymetry with inset showing the De Soto Canyon region and location of the cross slope transects S1–S3. The location of intersection of layer interface 15 with the seafloor for one specific time is shown by the magenta contour.

West Florida Shelf slope, which is more common during a retracted Loop Current configuration, but can also occur when frontal cyclones along the Loop Current periphery form meanders which can contact the shelf slope. When the Loop Current contacts the slope, a high sea surface height (SSH) anomaly frequently extends northward from the contact point along the continental slope in the topographic wave propagation direction toward the Mississippi River Delta. Evidence of this high SSH anomaly can be seen in satellite altimeter observations and numerical model results, such as those presented in *Hetland et al.* [1999], *Weisberg and He* [2003], and *Zavala-Hidalgo et al.* [2006]. This present study shows remote impacts of these Loop Current/slope interactions on the De Soto Canyon region.

Data from a multidecadal numerical simulation of the Gulf of Mexico are used to identify and characterize cross-slope near-bottom flows and associated upwelling and downwelling in the De Soto Canyon region. This paper shows that large-scale downwelling events along the shelf slope of the De Soto Canyon region are more common during times of impingement of the Loop Current on the southern West Florida Shelf. This is due to the high SSH anomaly and associated depression of isopycnals extending along the slope during Loop Current impingements on the West Florida Shelf slope farther to the south. Upwelling of isopycnals, which can be attributed to local mesoscale features migrating over the slope, can occur with or without such Loop Current impingements.

2. Methods

Cross-slope flows in the northeastern Gulf of Mexico are studied using a multidecadal HYbrid Coordinate Ocean Model (HYCOM) simulation of the Gulf of Mexico. The model domain spans from 18.9°N to 31.96°N and from 98°W to 76.4°W with horizontal resolution of 1/25° longitude by (cos(latitude)/25)°, or approximately 3.8–4.2 km grid spacing. The simulation has 20 vertical layers using the HYCOM hybrid vertical coordinate, which consists of isopycnal layers in the open ocean below the mixed layer, transitioning to pressure coordinates in the mixed layer and terrain-following coordinates in shallow water. Open boundary conditions are prescribed as a bimonthly climatology derived from a 1/12° resolution North Atlantic HYCOM simulation. Following a spin-up period, surface forcing for the simulation is computed from hourly 10 m wind speed, vector wind stress, 2 m humidity, short-wave and long-wave radiation and precipitation from the Climate Forecast System Analysis [*Saha et al.*, 2006] for the period 1992 to 2009. This forcing field is repeated three times to generate a 54 year simulation. *Dukhovskoy et al.* [2015] show that this model realistically represents the stochastic Loop Current cycle and eddy propagation pathways, and *Nedbor-Gross et al.* [2014] show that the simulation represents Loop Current variability in a manner consistent with past theoretical and observational studies [*Maul*, 1977; *Bunge et al.*, 2002]. Further details of this simulation can also be found in these two papers.

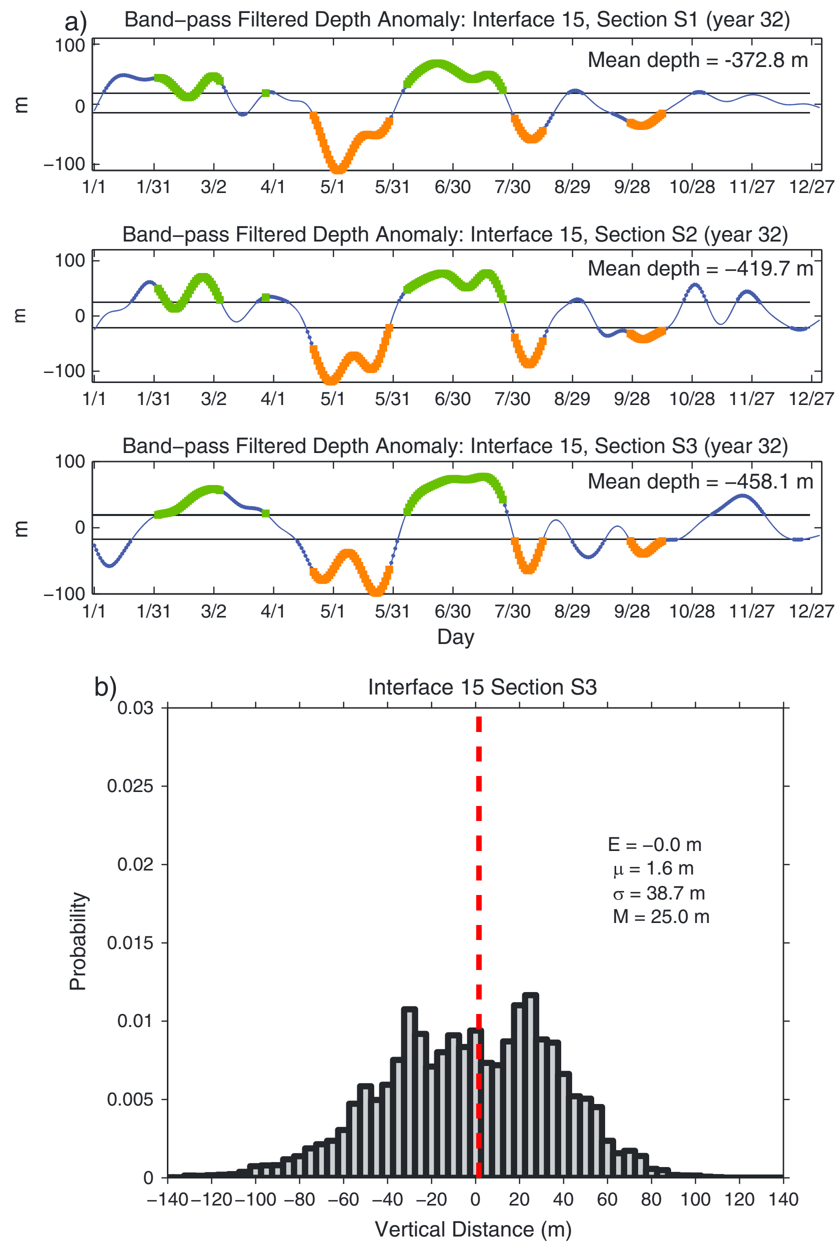

Figure 2. (a) One year subset of the 54 year long band pass-filtered time series of depth anomaly of intersection between layer interface 15 and the seafloor across sections S1–S3 (depicted in Figure 1). The mean depths of the interface/seafloor intersection are indicated on the plots. The 25th and 75th percentile depths are indicated, and large-scale upwelling and downwelling time periods are colored with green and orange, respectively. (b) Normalized histogram (bin size of 5 m) for the entire 54 year record of the time series shown in Figure 2a at S3. The mean (*E*), median (μ), standard deviation (σ), and mode (*M*) are indicated.

The movement of the intersection of the interfaces between model isopycnal layers and the seafloor across the continental slope is tracked along three transect lines, crossing the western and eastern slopes of De Soto Canyon and roughly along the axis of the canyon (Figure 1). The displacement of the interface/seafloor intersection depth from its mean depth is tied to vertical motion associated with cross-slope flows and upwelling or downwelling. These time series are constructed for several model layer interfaces representing isopycnals having mean depths at their intersection points with the De Soto Canyon slope between approximately 270 m and 1000 m. The anomalies of these time series are analyzed at daily intervals from 54 years of the HYCOM simulation.

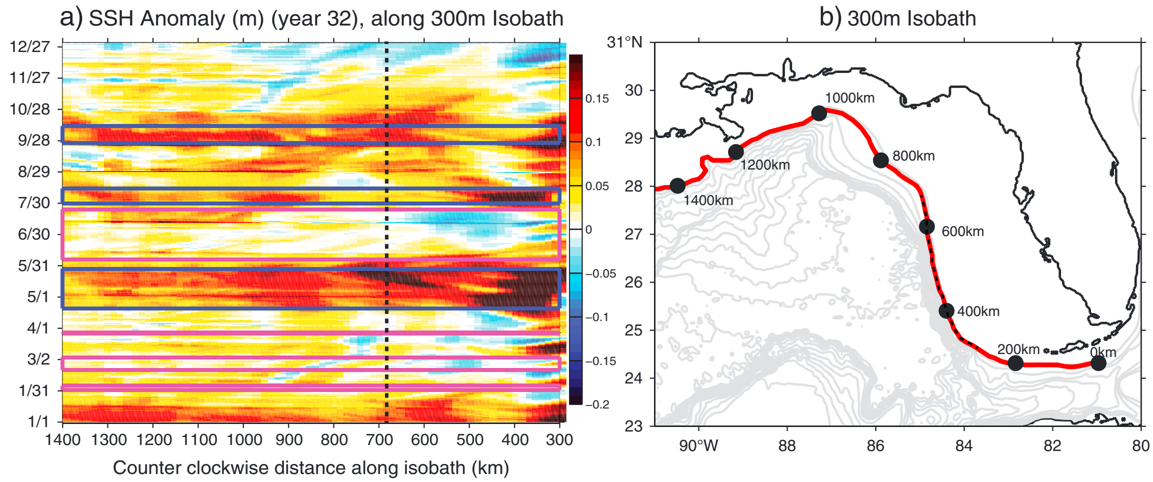

Figure 3. (a) Hovmöller plot of SSH anomaly along the 300 m isobath for the single model year shown by the time series in Figure 2a. Blue and magenta boxes enclose time periods identified as large-scale De Soto Canyon downwelling and upwelling events, respectively. (b) The along-isobath distance is indicated in the map. The length segment of the isobaths over which the SSH anomalies are averaged for analysis is shown by the dashed line over the 300 m isobaths in Figure 3b, and the time-distance limits for the SSH averaging are the regions within the blue and magenta rectangles in Figure 3a, to the right of the vertical dashed line.

Spectral analysis of these time series reveals two dominant frequencies equivalent to 4–6 month and 12 month periodicities. The 4–6 month period is close to the mode of the Loop Current eddy separation (6 months as determined both from altimeter data and from the HYCOM simulation) and consequently a Loop Current growth and retreat cycle [*Dukhovskoy et al*., 2015], and the latter is obviously the annual cycle. In order to extract the role, the Loop Current and its associated mesoscale features play in cross-slope flow variability, and to limit the influence of the annual cycle, the time series of layer interface depth are band pass filtered with cutoff periods of 20 and 180 days.

Inspection of the time series of interface depth shows that shallow or deep anomalies can often be seen concurrently at all three sections (labeled S1–S3 in Figure 1), indicating a large-scale upwelling or downwelling event. These large-scale upwelling and downwelling events are identified throughout the 54 year time series using the following protocol. The 25th and 75th percentiles are determined for each transect's interface depth time series (in the convention used here, depth is negative downward, so the 25th percentile depth is deeper than the median and the 75th percentile depth is shallower than the median). An upwelling (downwelling) event is identified when the depth of the layer interface intersection with the seafloor lies above (below) the 75th (25th) percentile depth. If a gap in time between consecutive upwelling or downwelling events is less than 14 days, and the layer interface does not cross the median depth during this gap, then the consecutive events are considered as a single event. Time periods corresponding to "large-scale" upwelling or downwelling events are defined by the intersection of upwelling or downwelling time periods from all three sections.

The Loop Current is a geostrophically balanced flow along a sea surface height (SSH) gradient surrounding a high-pressure anomaly. Following the Loop Current tracking method of *Leben* [2005], *Dukhovskoy et al*. [2015] defines daily Loop Current positions from the 54 year Gulf of Mexico HYCOM simulation by the 17 cm sea surface height (SSH) contour (following removal of the instantaneous spatial mean of SSH over deep water in the Gulf of Mexico) that connects the Yucatan Channel to the Straits of Florida. Impingement of the Loop Current on the West Florida Shelf slope is identified when the Loop Current 17 cm contour contacts an isobath along the continental slope (several isobaths are considered from 200 m to 800 m depth) between latitudes 24.5°N and 27.7°N. Time periods of Loop Current contact with these isobaths are identified for joint analysis with the large-scale De Soto Canyon upwelling and downwelling time periods described above.

To identify connectivity of cross-slope isopycnal movement in the De Soto Canyon region with the SSH along the southern West Florida Shelf slope, daily SSH anomalies are extracted along several isobaths from near the Florida Keys to the Mississippi River Delta. These SSH anomalies are analyzed as functions of time versus along-isobath distance and can be displayed as Hovmöller plots.

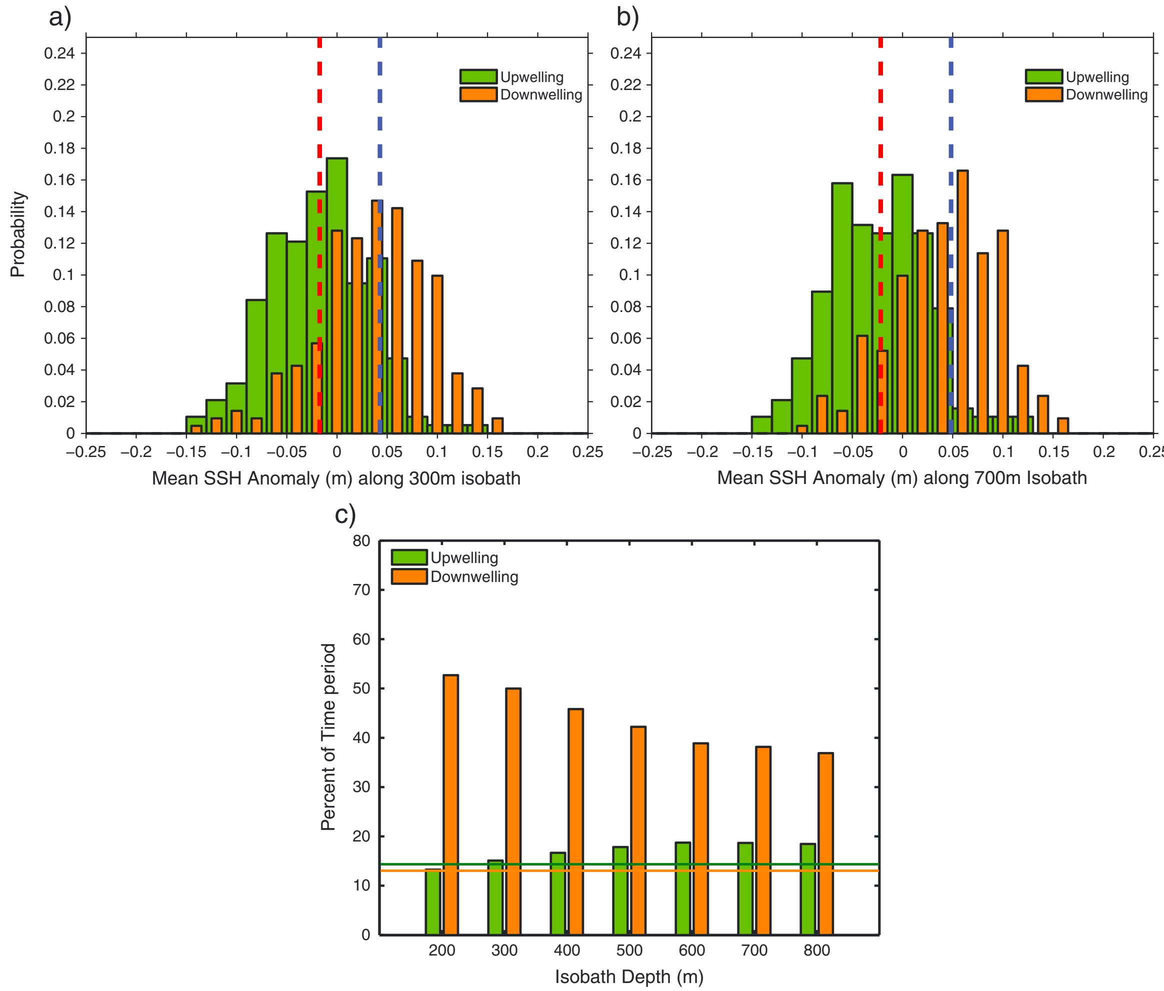

Figure 4. Normalized histograms of SSH anomaly along the (a) 300 m and (b) 700 m isobaths between latitudes 24.5°N and 27.7°N during time periods of large-scale De Soto Canyon upwelling (green) and downwelling (orange) (average SSH computed over time-space limits such as those outlined by the magenta and blue boxes and black dashed line in Figure 3a). The median SSH anomalies along these isobaths segments during upwelling and downwelling events are shown with the red and blue lines, respectively. (c) Percent of time period of Loop Current contact with isobaths (indicated along the abscissa) along the West Florida Shelf slope south 27.7°N during which large-scale De Soto Canyon upwelling (green) and downwelling (orange) events occur. Green and orange horizontal lines indicate the percent of the total 54 year model time period during which upwelling and downwelling occur.

3. Results

Upwelling and downwelling in the De Soto Canyon region is clearly shown in the movement of the model layer interfaces across the slope. Analysis of the band pass-filtered time series of the depth of intersection of model layer interface 15 with the seafloor along S1–S3 (the interface 15 mean depth is 372.8 m, 419.7 m, and 458.1 m along the sections, respectively) reveals time periods of upwelling and downwelling with vertical excursions that can exceed 100 m (Figure 2). Using the criteria presented in section 2, 190 large-scale upwelling events and 211 downwelling events are identified for the De Soto Canyon region from the 54 year simulation. These events range in duration from 1 to 60 days with a median of 10 days for upwelling events and from 1 to 51 days with a median of 12 days for downwelling events. These upwelling events occur during 13% of the 54 year model time period, and downwelling events occur 15% of the time.

A Hovmöller (time versus distance) plot of SSH anomalies (Figure 3) along the continental slope spanning from the Dry Tortugas to the Mississippi River shows bands of positive SSH anomalies extending along the slope (illustrated here by the 300 m isobath but also along other isobaths between 100 m and 500 m) during times of large-scale downwelling in De Soto Canyon. Time periods corresponding to the large-scale downwelling

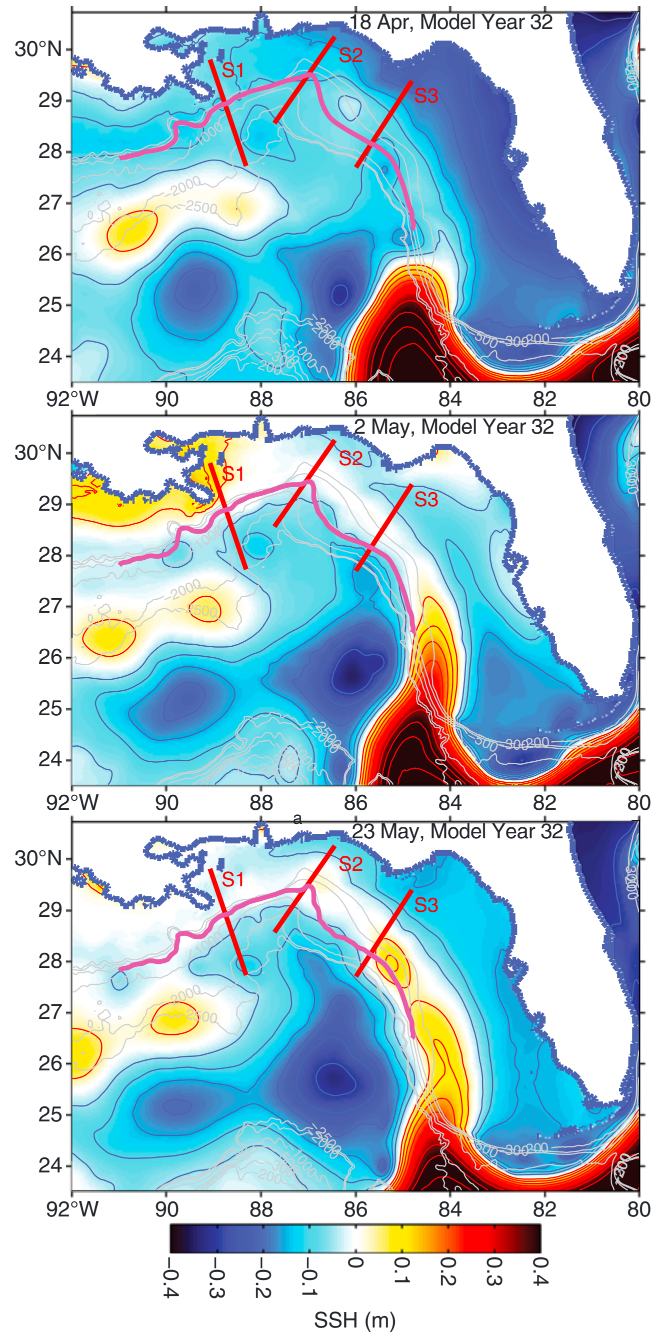

Figure 5. Synoptic maps of SSH from the HYCOM simulation showing the evolution of Loop Current contact with the southern West Florida Shelf slope during a De Soto Canyon downwelling event highlighted in Figure 2 (April through May). The location of intersection of layer interface 15 with the seafloor is shown by the magenta contour.

or upwelling events identified from the band pass-filtered interface/slope intersection depth time series for the De Soto Canyon sections are used to conditionally sample the along-isobath SSH (outlined by blue and magenta rectangles on the Hovmöller plot of Figure 3). For each discrete event, the mean SSH for that time period is computed along the isobaths between latitudes 24.5°N and 27.7°N, an area to the southeast of the De Soto Canyon region (shown by the dashed line segment on the 300 m isobath in Figure 3b).

The distributions of the mean along-isobath SSH values for the 190 upwelling events and 211 downwelling events are distinctly shifted for all isobaths from 100 m to 1500 m (Figure 4). Positive SSH anomalies along the southern West Florida Shelf slope are more likely during downwelling events in the De Soto Canyon region, and negative SSH anomalies occur more frequently during upwelling events. Thus, there appears to be a link between upwelling and downwelling across the slope of De Soto Canyon and SSH along the continental slope over a region several hundreds of kilometers away, where the Loop Current may occasionally contact the West Florida Shelf slope inducing along-slope positive SSH anomalies.

Tracking Loop Current impingements on the West Florida Shelf slope from the 54 year HYCOM simulation reveals a clear relation between the probability of these impingements and downwelling events over the De Soto Canyon region (Figure 4c). During times of Loop Current impingement over the slope south of 27.7°N, large-scale downwelling events are two to three times more likely to occur than at any given time during the 54 year simulation. These Loop Current impingements are relatively rare; the Loop Current extends over the 800 m isobaths 25% of the time, but over the 200 m isobath along the southern West Florida Shelf slope only 6% of the time. However, these extreme Loop Current impingements over the shallower slope depths are associated with the most dramatic increase in probability of large-scale downwelling events in De Soto Canyon. There appears to be little impact of Loop Current impingements on the likelihood of upwelling across the De Soto Canyon slope. Inspection of model SSH during times of large-scale upwelling shows that local mesoscale features (cyclones over the slope) are largely responsible for downwelling of isopycnals.

4. Discussion and Conclusions

A clear association between Loop Current contact with the southern West Florida Shelf slope, SSH along the shelf slope, and likelihood of downwelling along the continental slope of the De Soto Canyon region has been shown by analysis of a multidecadal HYCOM simulation of the Gulf of Mexico. The vertical structure of mesoscale features away from the shallow shelf is dominated by the first baroclinic mode [*Cole and DiMarco*, 2010]. That is, anomalously high SSH is compensated by depression of isopycnals below. Analysis of model results shows that, similarly, the SSH anomaly over the shelf slope (at depths of roughly 300–1000 m) is compensated by isopycnal movement, with downwelling of isopycnals across the shelf slope coincident with high SSH anomalies.

Loop Current contact with the West Florida Shelf slope forms a high SSH anomaly that extends along the slope from the point of Loop Current contact, in a topographic wave propagation sense, to the Mississippi River mouth (where there is almost no shelf at all). This forms the mechanism by which Loop Current contact with West Florida Shelf slope, SSH anomalies along the slope, and cross-slope motion in the De Soto Canyon region are remotely connected. When the Loop Current contacts the West Florida Shelf slope, the high SSH anomaly extends along the slope over the De Soto Canyon region, depressing isopycnals, and thus causing downwelling. Indeed, a high SSH anomaly is frequently observed in the model snaking along the shelf slope from the point of Loop Current contact to the De Soto Canyon region during time periods when the model layer interfaces retreat down the slope (Figure 5). Local mesoscale features or low-pressure anomalies caused by cyclones migrating over the shelf slope may induce upwelling regardless of whether the Loop Current is in contact with the slope or not.

Analysis of the model results not presented here yields the expected result that the upwelling and downwelling motions shoreward of the shelf break differ from the movement of isopycnals over the deeper slope in that they are dominantly driven by wind forcing with higher frequency fluctuations and have little relationship to the Loop Current. However, *Weisberg and He* [2003] demonstrated that when the Loop Current impinges over the slope at the far southwestern corner of the West Florida Shelf, a narrow part of the shelf where the isobaths are compressed, the Loop Current can influence the density structure at the shelf break such that deeper waters of the Gulf can be upwelled onto the shelf by wind forcing. These impingements on the southwestern corner are sporadic, and the more frequently occurring Loop Current impingements farther to the north do not affect the shelf because only the deep isobaths are influenced. Yet even the upwelling and downwelling across the deeper isobaths of the slope, modulated by Loop Current impingements, can be important for certain reef fish such as red snapper (*Lutjanus campechanus*) that are thought to migrate offshore of the relatively shallow shelf break (approximately 130 m) for spawning [*Gallaway et al*., 2009].

This analysis of a new multidecadal realistic simulation of the Gulf of Mexico circulation has shown that there is substantial cross-slope movement of water masses in the De Soto Canyon region linked with the Loop Current interaction with the southern West Florida Shelf. This work shows that in this area material surfaces can move up and down the slope with a range of over 200 m, with downwelling events more likely during times of Loop Current impingement on the West Florida Shelf slope to the south. These results have implications for predicting and understanding the possible impacts of pollutants released in the deep ocean in this region of oil and gas extraction activities on the ecologically sensitive shelf and slope.

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