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Key Points:
- Loop Current intrusions occur without west Florida shelf contact
- Loop Current direct entry and exit pathways occur with west Florida shelf contact
- We hypothesize that the west Florida shelf anchors the Loop Current to its direct pathway

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On the Loop Current Penetration into the Gulf of Mexico

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Abstract The Gulf of Mexico Loop Current generally intrudes some distance into the Gulf of Mexico before shedding an anticyclonic eddy and retreating back to its more direct entry to exit pathway. The control of this aperiodic process remains only partially known. Here we describe the evolution of the Loop Current throughout the era of satellite altimetry, and offer a mechanistic hypothesis on Loop Current intrusion. As a complement to the known effects of Loop Current forcing on the west Florida shelf circulation, we argue that the west Florida shelf, in turn, impacts the Loop Current evolution. A Self-Organizing Map analysis shows that anomalous northward penetrations of the Loop Current into the Gulf of Mexico occur when the eastern side of Loop Current is positioned west from the southwest corner of the west Florida shelf, whereas the more direct inflow to outflow route occurs when the eastern side of the Loop Current comes in contact with the southwest corner of the west Florida shelf. In essence, we argue that the west Florida shelf anchors the Loop Current in its direct path configuration and that farther northward penetration into the Gulf of Mexico occurs when such anchoring is released. To test of this hypothesis heuristically, we estimate that the dissipation and buoyancy work due to known Loop Current forcing of the west Florida shelf circulation (when in contact with the southwest corner) may exceed the pressure work required for the Loop Current to advance against the ambient Gulf of Mexico fluid.

Plain Language Summary The Gulf of Mexico Loop Current may intrude far into the Gulf of Mexico or take a more direct entry to exit pathway. Such Loop Current behaviors are described using remote observations by satellites, and a heuristic hypothesis on the control of Loop Current intrusion is presented. We argue that energy dissipation and buoyancy work by the west Florida shelf circulation, when the Loop Current contacts the southwest corner of the west Florida shelf, may exceed the work against the ambient fluid that is required to move the Loop Current farther into the Gulf of Mexico. When this occurs the Loop Current may become anchored to the west Florida shelf.

1. Introduction

Forming in the western Caribbean Sea between the Nicaraguan Rise and the Mexican coast, the Gulf of Mexico Loop Current is both the dominant oceanographic feature of the Gulf of Mexico and the precursor of the Gulf Stream. Upon entering the Gulf of Mexico through the Yucatan Strait and exiting through the Straits of Florida, the Loop Current may take either a direct pathway between these entry and exit portals or a more circuitous route, which at times may take it as far north as the Mississippi River Delta and as far west as Texas. Large intrusion lengths are generally followed by the shedding of an anticyclonic eddy as the Loop Current retreats back to its more direct pathway. Sturges and Lugo-Fernández (2005) review such Loop Current and associated eddy behavior studies prior to 2005, and a compendium of recent studies is introduced by Lugo-Fernández and Hamilton (2016). The control mechanisms for both the intrusion of the Loop Current into the Gulf of Mexico and the eddy shedding, while the subject of numerous theoretical investigations (e.g., Hurlburt & Thompson, 1980; Kuehl & Sheremet, 2014; Nof, 2005; Reid, 1972; Sheremet, 2001) remain to be more fully explored.

The present paper describes the Loop Current variability using satellite altimetry-derived sea surface height data (e.g., Alvera-Azcárate et al., 2009; Leben, 2005; Liu et al., 2014). A neural network, Self-Organizing Map (SOM) analysis (e.g., Kohonen, 2001) defines characteristic patterns of Loop Current behavior and their time evolution. It is found that certain patterns are conducive to Loop Current intrusion far into the Gulf of Mexico, whereas others are not. From this we offer a heuristic hypothesis on what may be a controlling mechanism.

The paper is organized as follows. Section 2 shows the evolution of the Gulf of Mexico Loop Current as evident in sea surface height measured by satellite altimetry and the associated surface geostrophic currents. Section 3 describes the SOM analysis. Section 4 presents the SOM analysis results. Section 5 then summarizes the findings, offers a hypothesis in explanation, and suggests a pathway forward for testing this hypothesis.

2. The Observations

Similar to our previous Gulf of Mexico Loop Current analyses (Liu et al., 2011, 2016a, 2016b), we use the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO+) multimission gridded sea level anomaly data set produced by the *Ssalto/Duacs* with support from the *Cnes* (http://www.aviso.altimetry.fr/duacs/), and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS, http://www.marine.copernicus.eu). The AVISO+ gridded product is global with horizontal resolution of 1/4°, and temporal resolution of 1 day. These delayed-time data are used for the period 1 January 1993 through 6 May 2016, and appended to these are the near real-time version for the more recent period (7 May 2016 to 9 May 2017). Added to the anomaly fields is the mean dynamic topography (MDT_CNES-CLS13, Rio et al., 2014) produced by CLS Space Oceanography Division and distributed by *Aviso*, with support from *Cnes*. The mean dynamic height field, plus the surface geostrophic velocity vectors calculated from the dynamic height gradient are shown in Figure 1. The Loop Current on average is seen to penetrate into the Gulf of Mexico at a northwest tending angle and reaching latitudes between 26°N and 27°N.

Sea surface height in the Gulf of Mexico has a steric contribution due primarily to seasonal heating and cooling (Liu & Weisberg, 2012). Unlike the dynamic contribution, the steric part, when averaged across the Gulf of Mexico, does not contribute to the spatial variation of the circulation. Thus to reduce the effects of the steric contribution on our analyses to follow, we remove an area-averaged value from each of the individual daily SLA maps following a procedure described in Dukhovskoy et al. (2015) and Hall and Leben (2016). The resulting SLA data are then combined with the long-term mean dynamic topography. Additionally, the *Aviso* data used are limited to the Gulf of Mexico region, within latitude and longitude ranges of [22°, 31°] north and [98°, 81°] west, respectively, and with the omission of coastal ocean regions with water depth $<$ 100 m where conventional altimetry data are not as reliable as in the open oceans due to a number of factors explained by Vignudelli et al. (2011).

A time series of the deep Gulf of Mexico averaged steric contribution to sea surface height is shown in Figure 2. Note the secular trend of about 0.06 m from 1993 through 2016 consistent with global findings (e.g.,

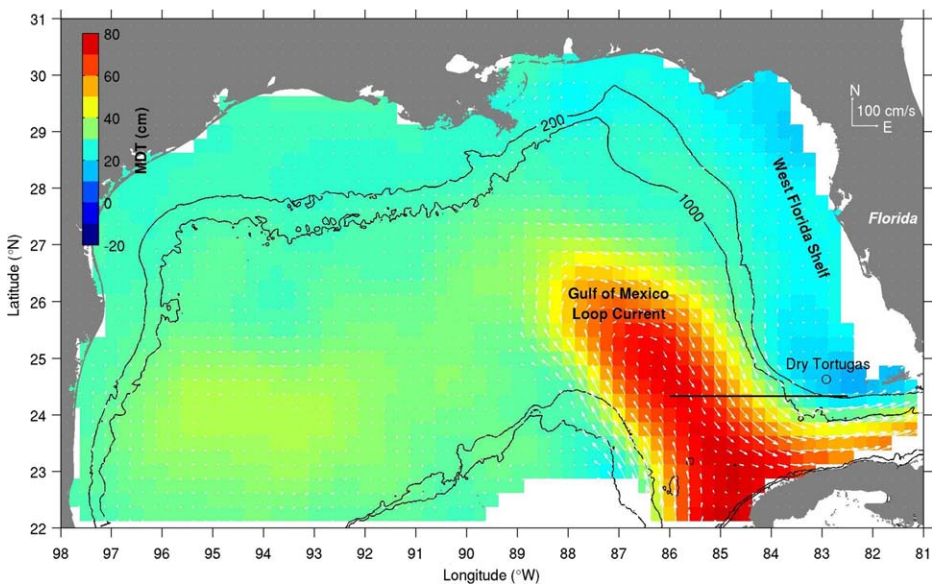

Figure 1. Mean dynamic topography (MDT) of MDT_CNES-CLS2013 and calculated surface geostrophic velocity vectors for the Gulf of Mexico. The deep Gulf of Mexico is distinguished from the coastal ocean by the 200 and 1,000 m bathymetric contours, and a zonally oriented line is drawn at 24° 20′ N for later purposes. The Dry Tortugas is shown as an open circle.

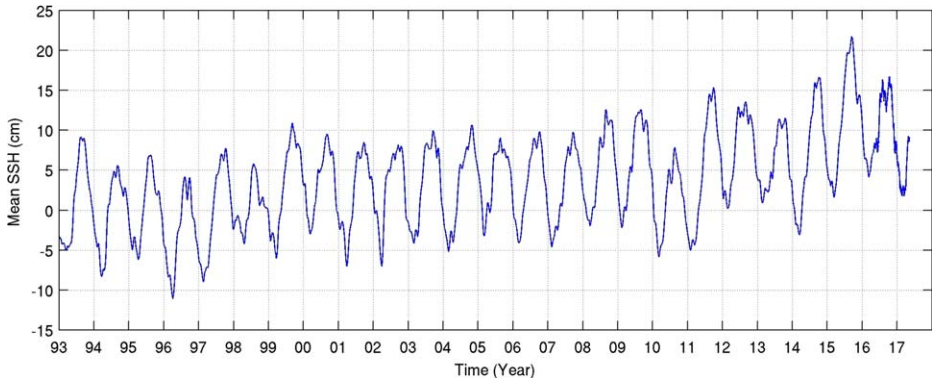

Figure 2. The Gulf of Mexico spatially averaged steric contribution to the sea surface height anomaly. Note the seasonal cycle, due primarily to seasonal heating and cooling, the interannual variations, and the secular trend.

Watson et al., 2015) and the seasonal cycle of about 0.15 m (Liu & Weisberg, 2012). Along with the trend and the season cycle, there are also interannual variations, e.g., note the relatively steady values from about 2002–2008 when compared with the time periods both prior to and subsequent to these years.

Examples of when the Loop Current extends far into the Gulf of Mexico, versus when it takes a more direct route between entry and exit portals are provided in Figures 3 and 4, respectively. The first of these, for successive 3 day intervals in February 2002, shows penetration as far north as the Mississippi River Delta and then west to the longitude of Texas, and the second of these, only 2 months later, shows the change after the Loop Current abruptly shed two eddies and retreated back to the vicinity of its entry and exit portals.

3. Methods

The present study employs the unsupervised learning, neural network, SOM technique to organize Loop Current behaviors into an enumerated set of spatial patterns, whose evolution over time may be described.

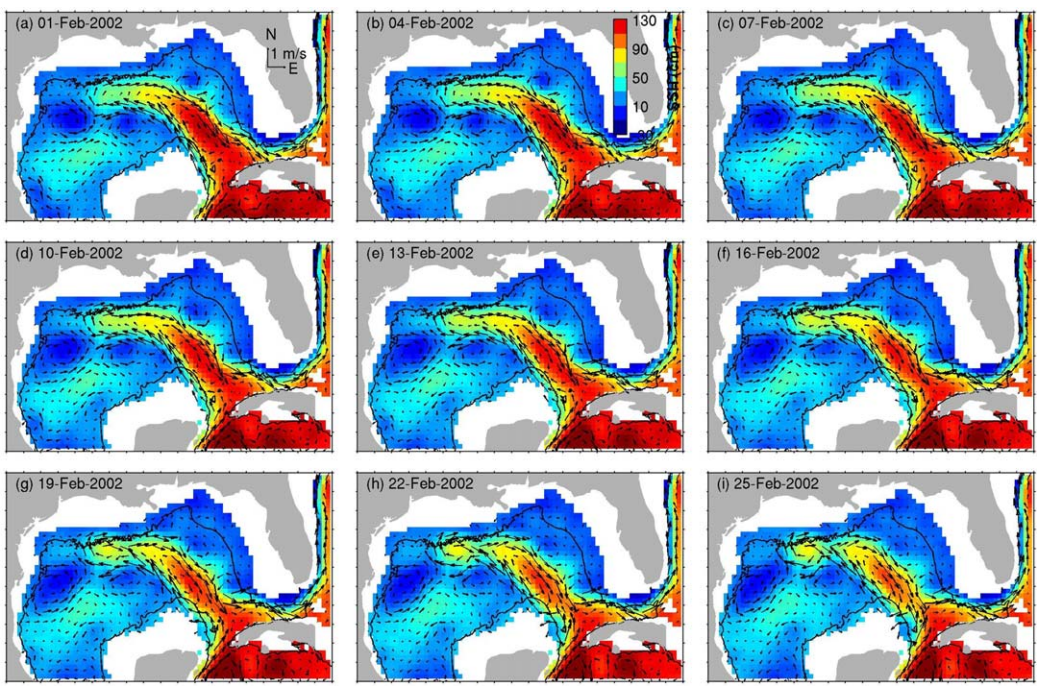

Figure 3. A succession of daily snapshots of sea surface height after removal of the thermosteric contribution at successive 3 day intervals for the month of February 2002.

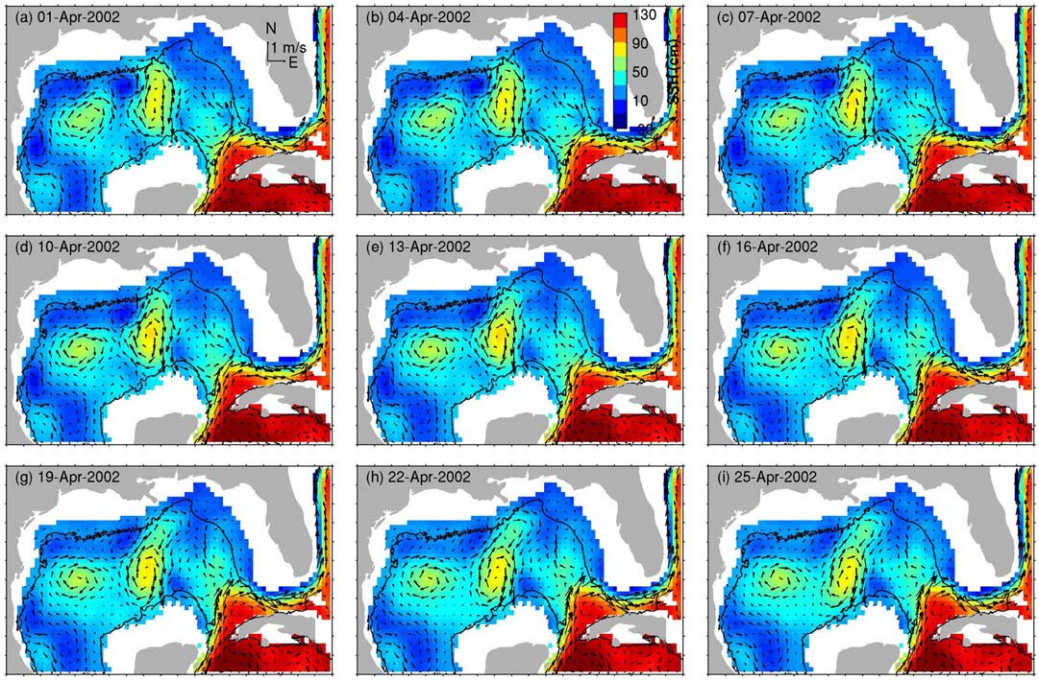

Figure 4. A succession of daily snapshots of sea surface height after removal of the thermosteric contribution at successive 3 day intervals for the month of April 2002.

The SOM, developed by the computer science community (e.g., Kohonen, 2001; Vesanto & Alhoniemi, 2000), was introduced to the climate science community as a method for clustering and pattern recognition (e.g., Ambroise et al., 2000; Hewitson & Crane, 1994). This was followed by applications to oceanography (e.g., Liu & Weisberg, 2005; Richardson et al., 2003), and such initial SOM applications to meteorology and oceanography are reviewed in Liu and Weisberg (2011). Some of the more recent oceanography applications of SOM are provided by Dunić et al. (2016), Hisaki et al. (2016), and Huang et al. (2017).

SOM applications to satellite altimetry data have increased in recent years. Subsequent to its first application for extracting surface geostrophic currents in the South China Sea (Liu et al., 2008), the SOM was similarly employed to study the intrusions of the Kuroshio into both the East China Sea (Tsui & Wu, 2012; Yin et al., 2014) and the South China Sea (Sun et al., 2016). Recent Gulf of Mexico Loop Current specific applications include Zeng et al. (2015) and Liu et al. (2016b), the latter of which was a dual SOM application in which both the characteristic spatial patterns of the Loop Current system were identified along with regions of differing contributions to sea level variability. Here the work of Liu et al. (2016b) is extended to include the entire Gulf of Mexico for the purpose of contrasting instances when the Loop Current extends far into the Gulf, versus those when the Loop Current penetration is limited to the vicinity of the entry and exit points.

We use the MATLAB Toolbox of the SOM (Vesanto et al., 2000) provided by the Laboratory of Information and Computer Science in the Helsinki University of Technology (http://www.cis.hut.fi/somtoolbox/). The SOM tunable parameters are selected following the suggestions of Liu et al. (2006).

As with other SOM applications, choosing the number of neurons upon which to project the input data is arbitrary. Here we opted for a large set of 40 patterns to provide adequate separation between the two extreme behaviors that we are interested in describing. This is in contrast with Zeng et al. (2015) who used three patterns to define three specifically different behaviors.

4. Results

The analysis interval, spanning the period 1 January 1993 through 9 May 2017, resulted in the projection of 8,831 daily patterns onto 40 neurons. These neurons (labeled P1 through P40) are shown in Figures 5 and 6

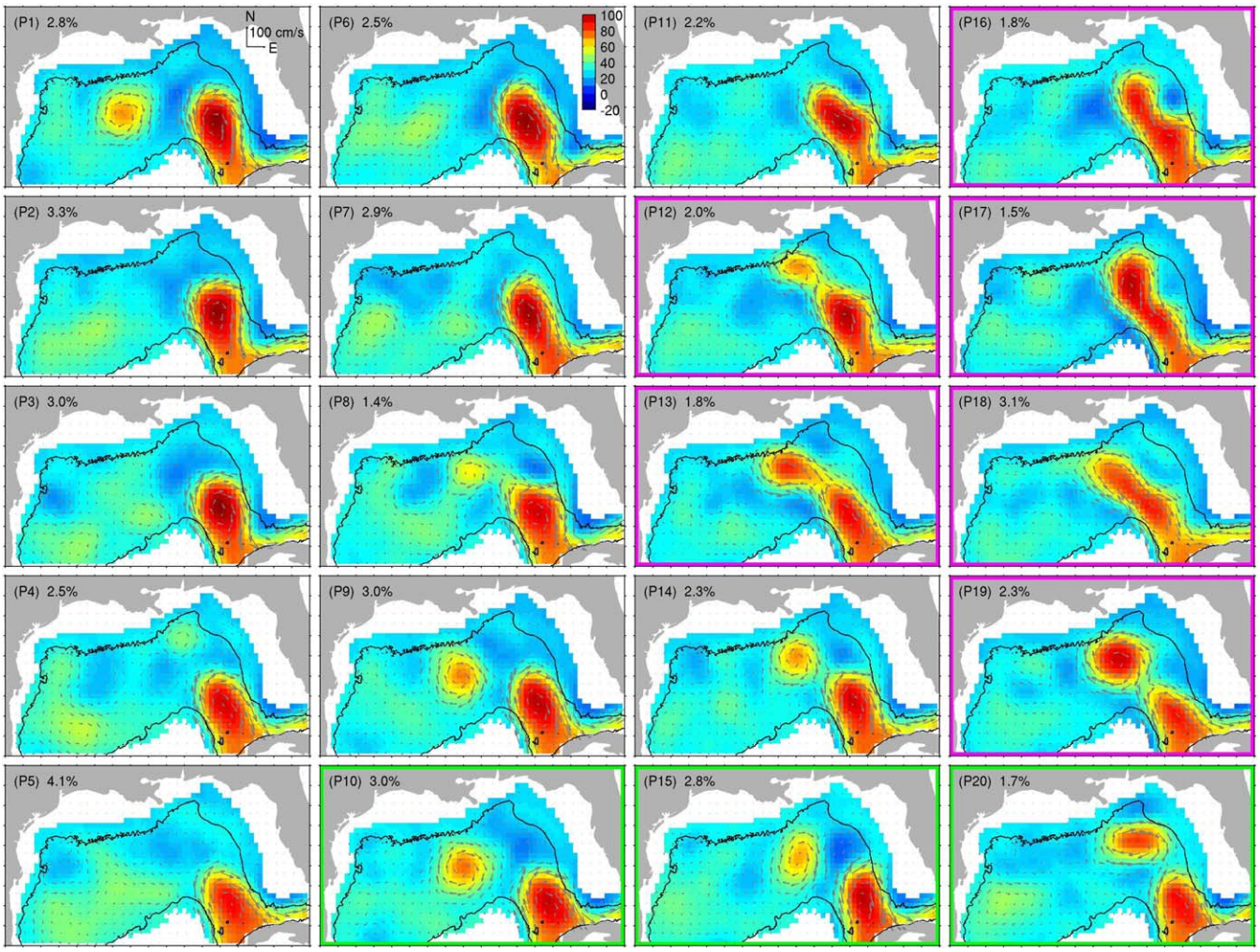

Figure 5. Characteristic patterns of the Loop Current behaviors in the Gulf of Mexico extracted by a 5 × 8 Self-Organizing Map (the first 20 patterns). Shown are the sea surface height and surface geostrophic velocity vectors for each pattern, with the pattern number and its frequency of occurrence given in the upper right of each plot. The black line is the 1,000 m isobath. Patterns with Loop Current intruding far into the Gulf of Mexico are highlighted in magenta, and those with the Loop Current contacting the southwest corner of the WFS slope are highlighted in green.

(20 in each), and their best matching unit (BMU) time series are shown in Figures 7 and 8 for the years 1993 through 2004 and 2005 through 2017, respectively. The neurons self-organize such that those most resembling the mean state (Figure 1) occupy the first 11 patterns, those with the Loop Current penetrating farther into the Gulf of Mexico occupy the middle numbered patterns and those for which the Loop Current follows the most direct path between the entry and exit portals occupy the highest numbered patterns. Highlighted by a magenta border are those patterns that tend to be positioned westward from the west Florida continental shelf slope (indicated by the 1,000 m isobath), particularly away from the southwest corner of the west Florida continental shelf (WFS). In contrast with the magenta highlighted patterns, those patterns that tend to show contact between the Loop Current and the WFS slope near the southwest corner are highlighted by a green border.

The significance of the WFS, and in particular the southwest corner, is discussed in several previous papers. For a geophysical (rotating and stratified) fluid influenced by varying topography, three principles are applicable to these discussions (e.g., Gill, 1982): (1) topographic Rossby waves propagate along-isobath with shallow water to the right (in the northern hemisphere), (2) large-scale flows tend to orient along-isobath, and (3) pressure perturbation adjustment occurs over a length scale equal to a baroclinic Rossby radius of deformation. Given that a Loop Current impingement on the WFS slope may be thought of as a pressure perturbation, by (1), (2), and (3) above, such a perturbation occurring to the north of the southwest corner will set

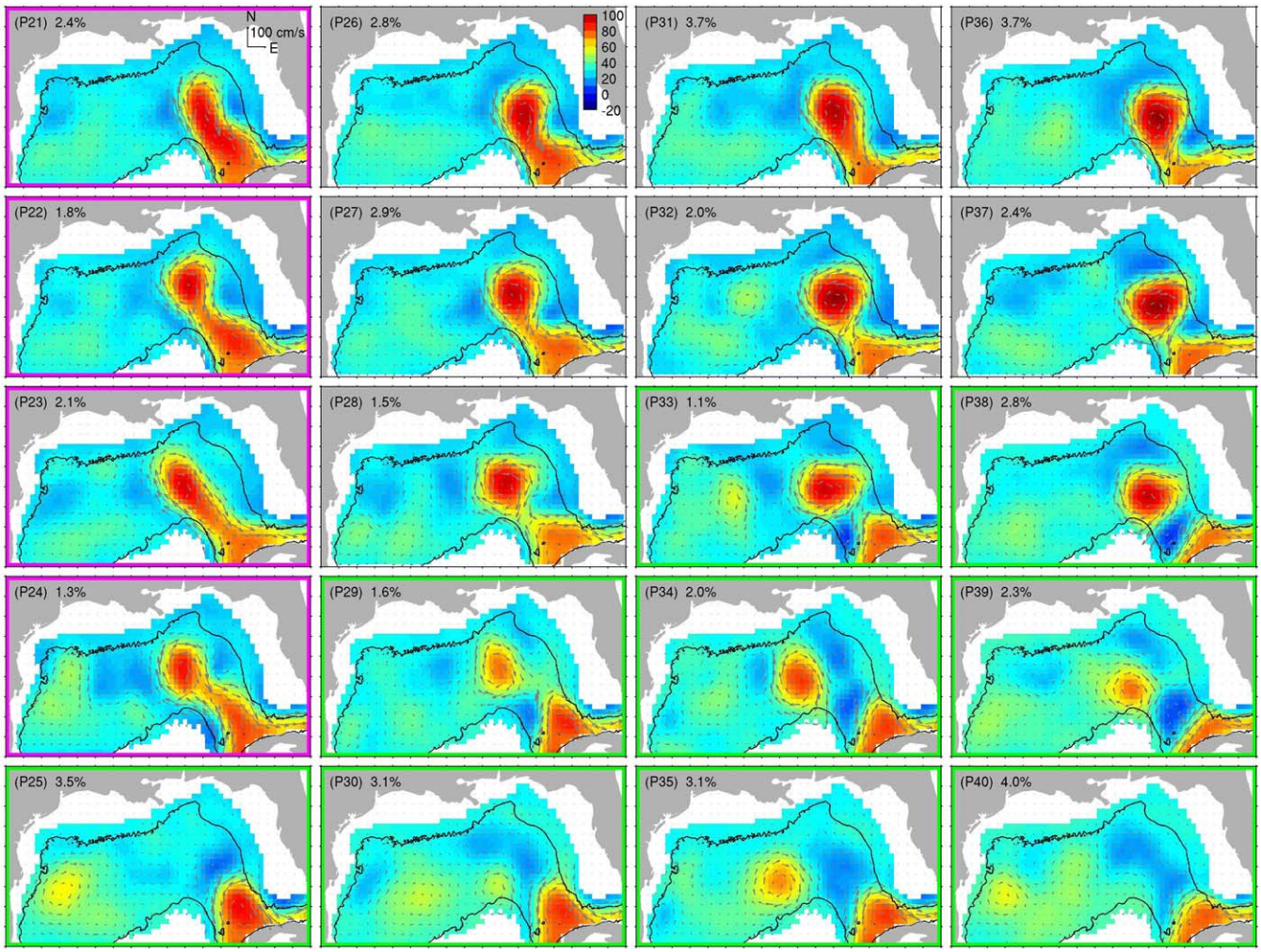

Figure 6. Characteristic patterns of the Loop Current behaviors in the Gulf of Mexico extracted by a 5 × 8 Self-Organizing Map (the second 20 patterns). Shown are the sea surface height and surface geostrophic velocity vectors for each pattern, with the pattern number and its frequency of occurrence given in the upper right of each plot. The black line is the 1,000 m isobath. Patterns with Loop Current intruding far into the Gulf of Mexico are highlighted in magenta, and those with the Loop Current contacting the southwest corner of the WFS slope are highlighted in green.

the shelf slope region into geostrophic motion, but this current will only extend inshore from the shelf break by a Rossby radius of deformation. Brink (1998) reviews the theory for this limitation, and a WFS demonstration of this is given by He and Weisberg (2003), where the Rossby radius of deformation is estimated to be about 30 km. Hetland et al. (1999) drew attention to the fact that, by virtue of the Dry Tortugas being the westernmost extremity of the Florida Keys chain of islets, all shallow water isobaths must wrap around the Dry Tortugas. Hence a Loop Current contact in that vicinity can excite currents over the entire WFS by coming into contact with shallow isobaths. This theory was confirmed by Weisberg and He (2003) in their analysis of the anomalous conditions observed and modeled for the WFS in 1998, when the Loop Current was in contact with the southwest corner of the WFS for a protracted time interval. Such southwest corner contacts (termed pressure point contacts by Liu et al., 2016a) were subsequently shown to be controlling of advection of new water of deeper ocean origin onto the WFS, the movement of gag grouper larvae from spawning to settlement, the transport to the nearshore of *K. brevis* red tide, and the movement of Deepwater Horizon Oil (Liu et al., 2016a; Weisberg et al., 2014a, 2014b, 2015, 2016a, 2016b, 2017).

Before examining the BMU time series (and hence the evolution of the Figures 5 and 6 patterns), it is helpful to consider the eastward extent of the Loop Current along a line (drawn in Figure 1) that intercepts the Dry Tortugas. A Hovmöller plot of the north component of velocity along that line from 86°W to 82.5°W is provided in Figure 7, where the -0.5 m s^{-1} contour is highlighted as a solid black line (separating the deep

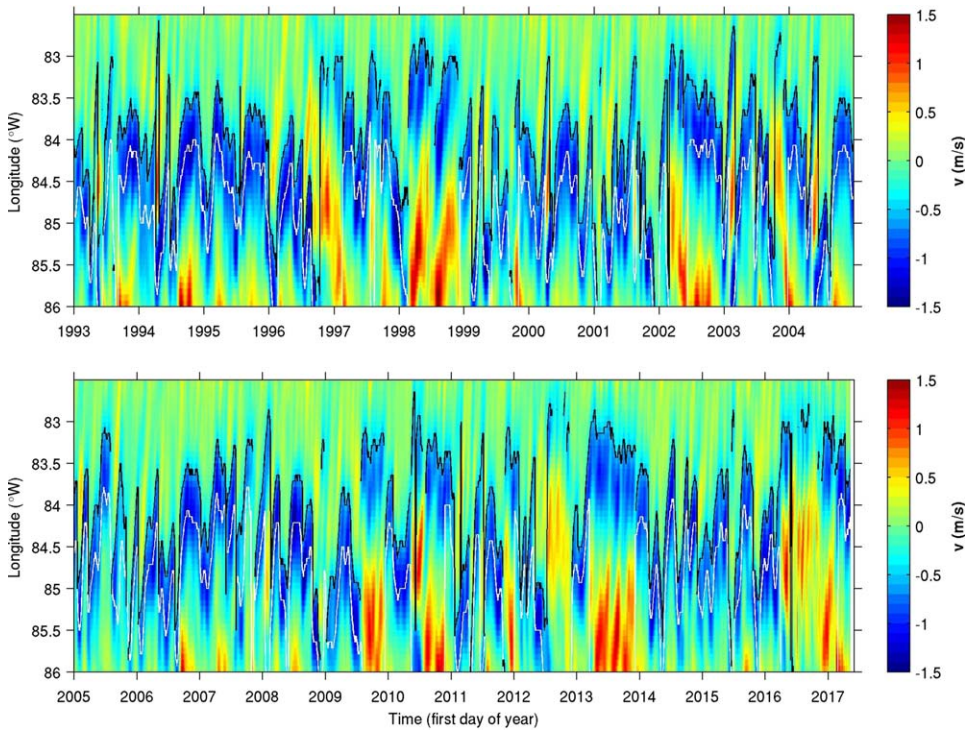

Figure 7. Hovmöller plots of north component of the surface geostrophic velocity along a zonally oriented line at 24° 35′ N. The black line denotes the -0.5 m s^{-1} contour. The white line indicates the location of the 17 cm adjusted sea surface height.

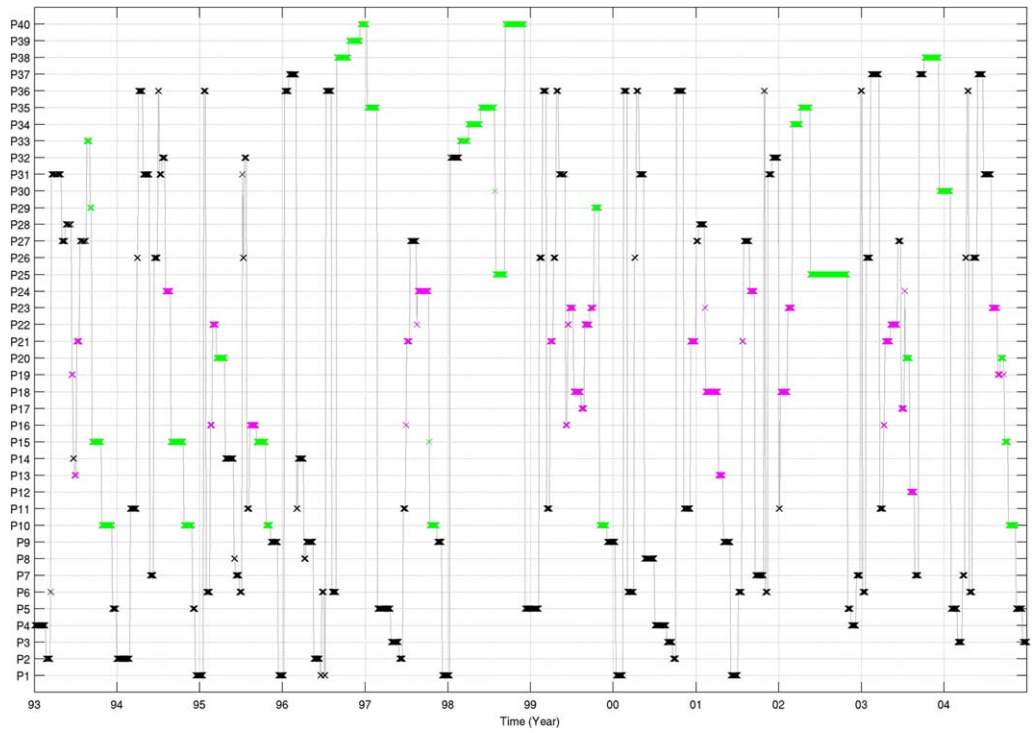

Figure 8. Time evolution of the patterns as defined by the Best Matching Units for the period of 1993–2004.

blue from the lighter colors above). When this contour is positioned to the east of 83.5°W, the Loop Current is in contact with the shelf slope near the Dry Tortugas. Certain particular years stand out for which either protracted contacts (e.g., 1998, 2010, 2016), or lack of such contacts (e.g., 2005, 2014, 2015), are evident.

The BMU time series of Figure 8 (1993–2004) and Figure 9 (2005–2017) show the temporal evolution of the P1–P40 patterns, with emphases given to the patterns highlighted in either magenta or green. Much has already been described regarding how Loop Current impingement on the shelf slope near the Dry Tortugas results in phenomenological variability on the WFS, and these occurrences are expressed in Figures 8 and 9. For instance, 1998 was a year of anomalously strong and protracted upwelling onto the WFS (Weisberg & He, 2003) consistent with the protracted contact seen in Figure 8 (the succession of green highlighted patterns). A successful gag grouper recruitment event was observed and attributed to an upwelling event that lasted from the end of March to the middle of May of 2007 (Weisberg et al., 2014a), and this is also evident in Figure 9 (after the Loop Current shed an eddy and retracted from patterns 21 and 22 to pattern 20). An explanation of why no *K. brevis* red tide was observed on the WFS in 2010 was provided (Weisberg et al., 2014b) on the basis of a protracted upwelling event lasting from mid-May until the end of that year, as also seen in the succession of the green highlighted patterns in Figure 9. In other words, how the Loop Current interacts with the WFS is of great ecological importance, and the SOM provides a useful description of these interaction patterns.

Now consider the contrasting occurrences, when there is little interaction between the Loop Current and the WFS (the magenta highlighted patterns). The rapid transition from February 2002 (Figure 3) to April 2002 (Figure 4) when the Loop Current behavior changed from one of large intrusion to nominal intrusion is apparent in the SOM with magenta corresponding to large intrusion; green with nominal intrusion and then staying green for the remainder of 2002. Similarly, but for longer durations, consider the extended periods of magenta highlighted patterns throughout most of 2005 and into 2006, and then again throughout most of 2014 and 2015. We further note that these magenta highlighted times were ones for which the WFS had pronounced *K. brevis* red tide blooms (e.g., see Walsh et al., 2009; Weisberg et al., 2009 for discussions of the 2005 and 2006 blooms).

Whereas the durations of individual patterns show no remarkable repetition, there are times when the Loop Current behaviors do seem to lock onto certain patterns for extended intervals. With only brief

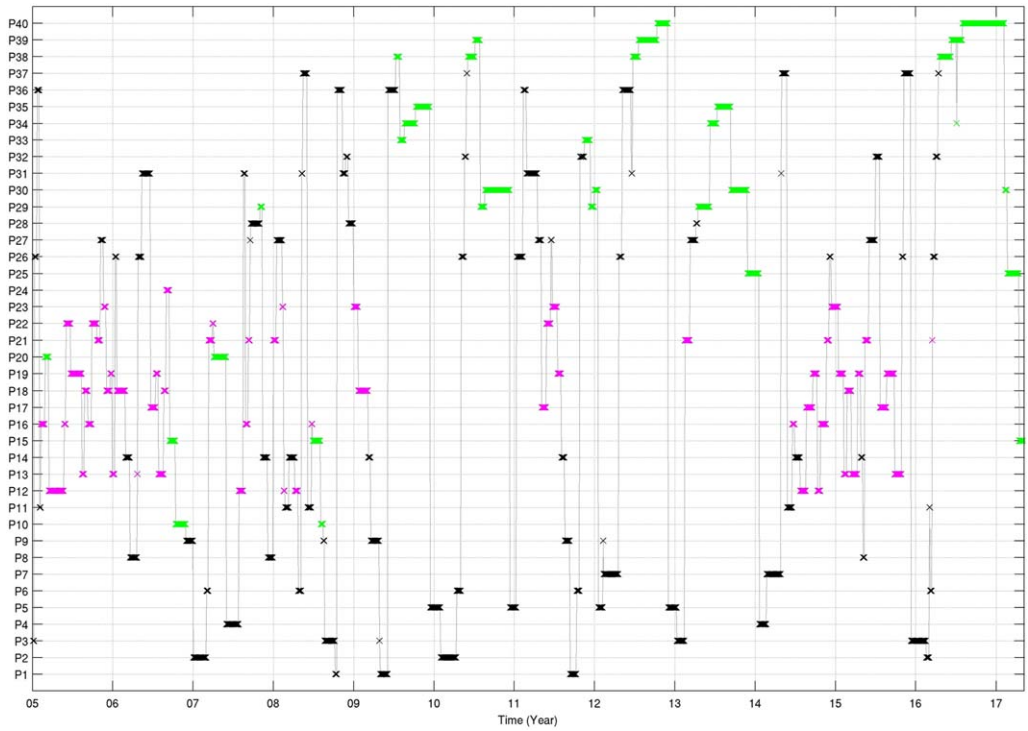

Figure 9. Time evolution of the patterns as defined by the Best Matching Units for the period of 2005–2017.

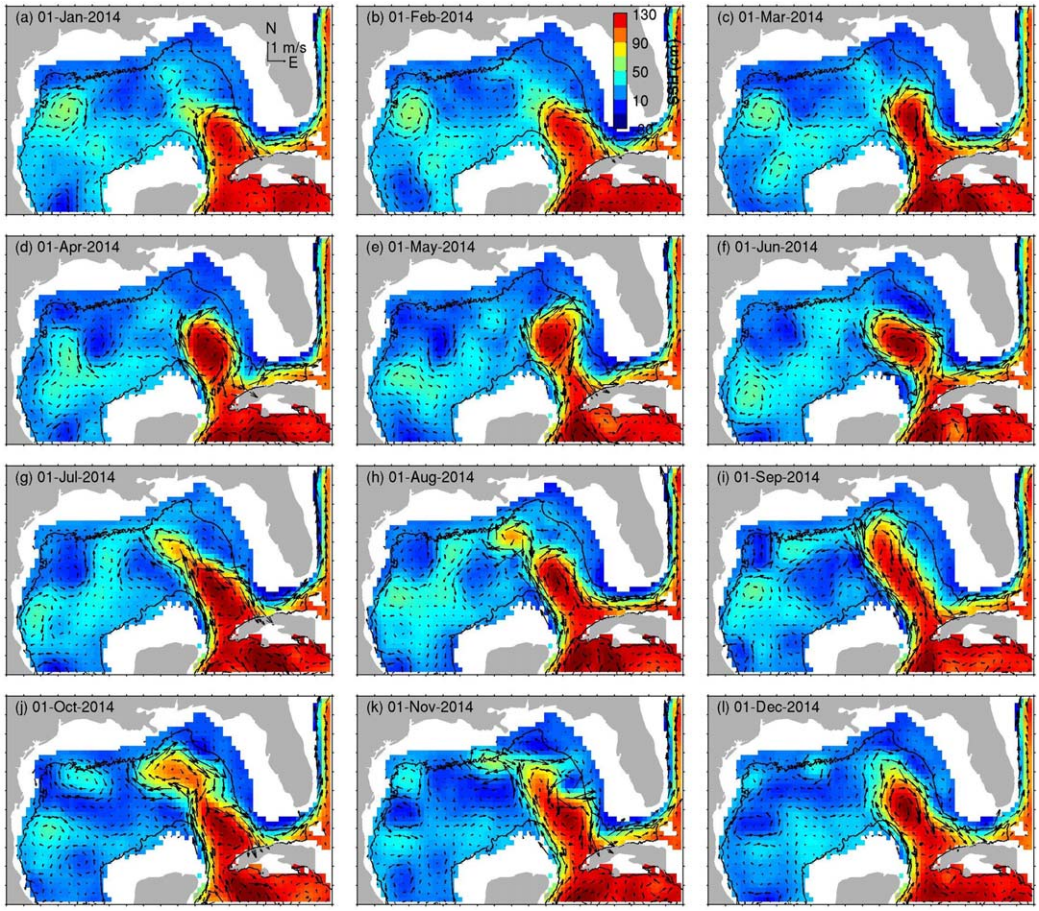

Figure 10. Snapshots of the sea surface height and surface geostrophic velocity vectors in the Gulf of Mexico on the first day of each month for 2014. The black line is the 1,000 m isobath.

deviations, the period 2009–2017 shows largely green highlighted patterns giving way to magenta highlighted patterns and then back to green again. The Figure 7 Hovmöller plot and the Figure 9 BMU time series both show these transitions from the Loop Current contacting the southwest corner of the WFS slope (green) to no such contact (magenta) and then back again. Inescapable in these pattern evolutions is the fact that elongated penetration of the Loop Current into the Gulf of Mexico is associated with little or no contact between the Loop Current and the WFS slope near the Dry Tortugas.

The 2014–2015 period was particularly disruptive to oil and gas operations offshore because of the Loop Current's persistent elongated penetration to the far north of the Gulf of Mexico. What began to set up in spring of 2014 (from April onward in the sea surface height and surface geostrophic currents shown in Figure 10) and then persisted throughout 2015 (Figure 11) is associated with the magenta highlighted SOM patterns (Figure 9) of little to no contact between the Loop Current and the WFS slope near the Dry Tortugas. Note in both Figures 10 and 11 that, as the Loop Current penetrated farther northward, it was also distant from the southwest corner of the WFS, and it remained that way until the Loop Current eventually retreated back to the vicinity of the entry and exit portals, upon which it again made contact with the WFS slope near the Dry Tortugas in the early part of 2016 (Figure 12) and then remained in that retracted state for the duration of the analysis period.

5. Discussion

Along with the SOM analysis results, section 4 addressed why the region of the Dry Tortugas is an essential one for the ecology of the WFS. Protracted Loop Current contacts, there result in the upwelling of nutrient replete water of upper slope origin (Weisberg et al., 2016b) that resets WFS water properties. Here we

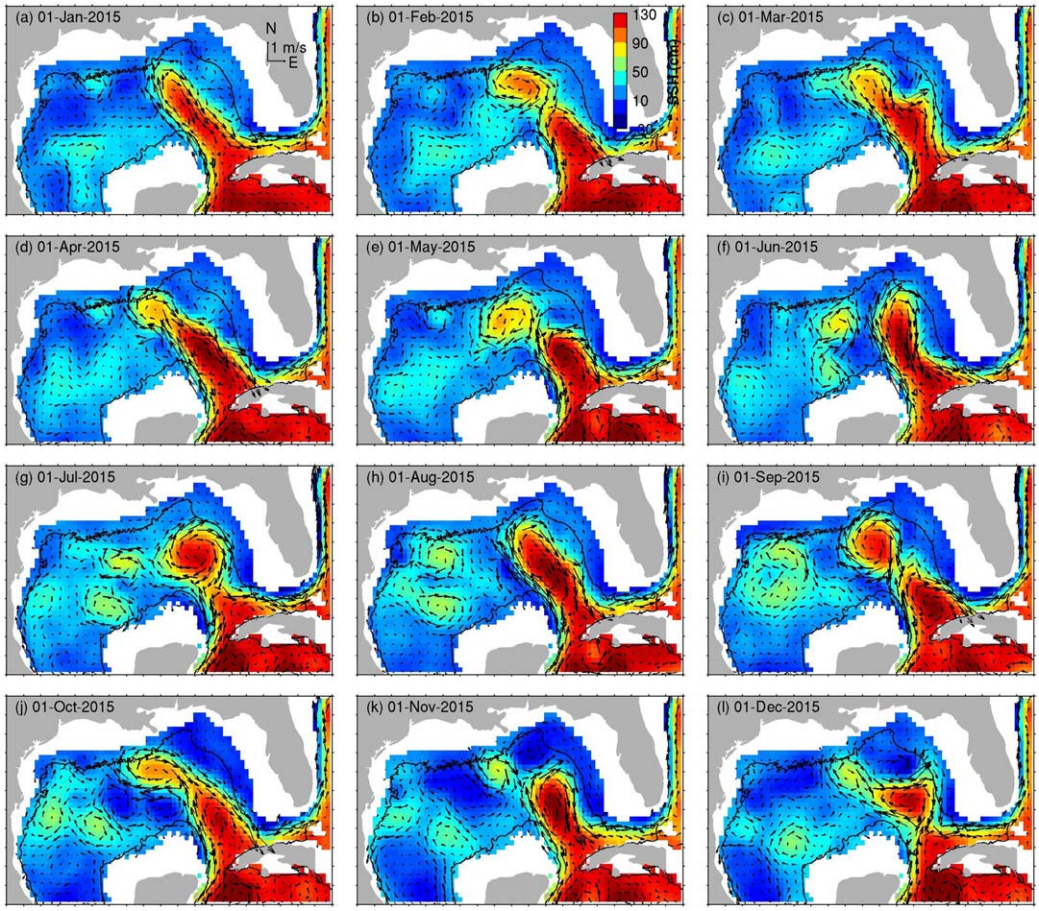

Figure 11. Snapshots of the sea surface height and surface geostrophic velocity vectors in the Gulf of Mexico on the first day of each month for 2015. The black line is the 1,000 m isobath.

hypothesize, that this "pressure point" region (Liu et al., 2016b) is also a critical one for controlling the behavior of the Loop Current penetration within the Gulf of Mexico. While the testing of our hypothesis, that the Dry Tortugas, pressure point controls Loop Current intrusion into the Gulf of Mexico, is beyond the scope of the present paper, this hypothesis has its origin in geophysical fluid dynamics fundamentals in two ways. First, waves are nature's way of transporting energy away from a region of excitation. For large-scale geophysical waves, the intrinsic property of the medium through which these may propagate are the gradients in vorticity due to the planetary β effect (Rossby waves), the ambient vorticity gradient of the currents (e.g., eddies encircling the Loop Current jet), and the sloping bottom (topographic Rossby waves). Second, for the Loop Current to intrude into the Gulf of Mexico, the Loop Current must do work against the fluid already there. Thus, from an energetics perspective, the difference between the fluxes of mechanical energy into and out of the Gulf of Mexico through the Yucatan Strait and the Straits of Florida, respectively, minus what may be radiated away by large-scale geophysical waves must be sufficient to move the Loop Current against the ambient Gulf of Mexico fluid. The generation of eddies through instability is nature's way of ridding a system of excess energy so eddy shedding is a consequence of Loop Current excess as it penetrates, versus a cause of Loop Current penetration. In other words, eddy shedding occurs after the fact, not before, so we can neglect the process of eddy shedding in the discussion of what controls Loop Current penetration. That leaves us with topographic Rossby waves.

Discussions on the role of topography in controlling the Loop Current date back to Reid (1972) who argued that the rapid transition from the relatively shallow depths of the Yucatan Strait to the much deeper depths of the interior Gulf of Mexico, in essence, decouples the flow field from the topography through a nearly complete baroclinic adjustment of the upper ocean waters to the north of the Campeche Bank. With the

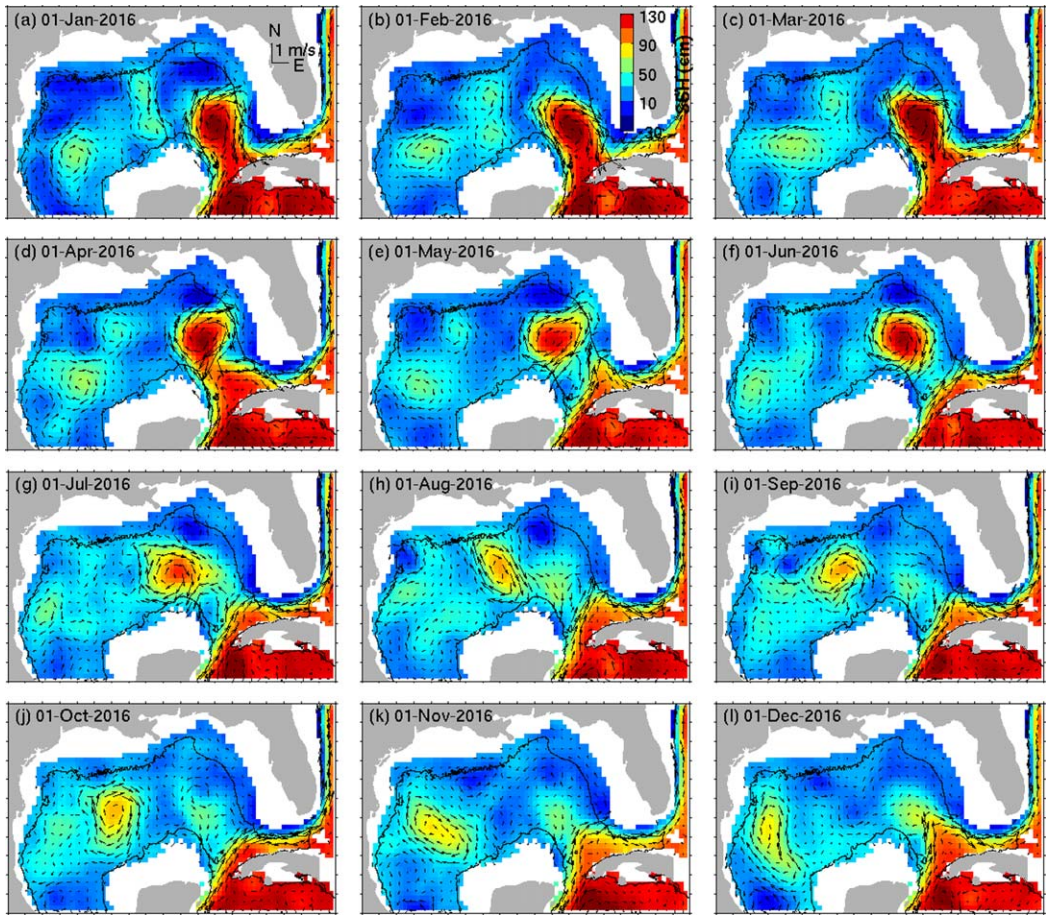

Figure 12. Snapshots of the sea surface height and surface geostrophic velocity vectors in the Gulf of Mexico on the first day of each month for 2016. The black line is the 1,000 m isobath.

Loop Current unconstrained by topography, the planetary β-effect then determines the latitude to which the Loop Current may penetrate. This idea was followed up on by Hurlburt and Thompson (1980) who through a series of barotropic, two-layered, and reduced-gravity numerical model simulations, showed that planetary β is necessary for the Loop Current to penetrate and shed an eddy, that the process of eddy shedding may be altered by dissipation and that topographic control is also important. They particularly highlighted the WFS as follows: "In terms of vorticity dynamics, the northward penetration of the Loop Current is halted when the interaction between the topography of the Florida Shelf and the pressure field results in a near balance between the pressure torques and the nonlinear terms in the mass transport vorticity equation." Independent of the Loop Current, a similar vorticity dynamics finding was provided by Weisberg et al. (2001) as a way of distinguishing the responses of the inner and outer portions of the WFS to wind forcing. The inner shelf is where bottom pressure torque is balanced by bottom stress torque, whereas the outer shelf is where bottom pressure torque is balanced by a material rate of change of relative vorticity. For clarity, what is meant by pressure torques in either Hurlburt and Thompson (1980) or Weisberg et al. (2001) is the stretching of planetary vorticity filaments by across-isobath flow. This excites topographic Rossby waves when not compensated by bottom friction torque.

Analytical solutions to topographic Rossby waves exist for many different shelf slope geometries and for an idealized WFS itself (e.g., Clarke & Brink, 1985; Clarke & Van Gorder, 1986; Hetland et al., 1999; Mitchum & Clarke, 1986a, 1986b). However, the broad, shallow nature of the WFS gives friction an added importance that is not easily accounted for in analytical solutions. From the works previously cited, we know that excitation at the pressure point propagates not only along the shelf slope, but also along the entire shallow region of the WFS that results in both: (1) a bottom Ekman layer response that extends northward to the

northern Gulf coastline and (2) an upwelling and advection of water from the deeper Gulf of Mexico across the entire WFS, independent of any wind forced shelf waves. Here we hypothesize that the work by friction within the bottom Ekman layer, plus the work against buoyancy to upwell deeper ocean waters onto the WFS, when summed over such a large area (and which is in addition to the radiation of energy along the shelf slope by topographic Rossby waves) is sufficient to anchor of the Loop Current to the Dry Tortugas pressure point, inhibiting farther intrusion into the Gulf of Mexico until such anchoring is loosened.

Short of a complete control volume energetics analysis, as done, for example, by Weisberg and Zheng (2003) in a discussion of estuarine circulation transition from partially mixed to well mixed, we provide a heuristic argument in support for our Loop Current intrusion hypothesis by showing that the mechanical energy utilization of the WFS by Loop Current impingement against the pressure point is as large as the requirement for the Loop Current to penetrate into the Gulf of Mexico. We do this by contrasting 2010, a year when the Loop Current was anchored to the pressure point, with 2014/2015 when the Loop Current was not anchored and instead penetrated and remained far into the Gulf of Mexico.

Three calculations are involved for this heuristic argument: (1) dissipation of mechanical energy across the WFS through the work by the bottom stress (W_τ), (2) utilization of energy to lift heavier, deeper ocean water from the upper shelf slope to and across the WFS (W_B), and (3) the pressure work required to move the Loop Current from its entry/exit location to points farther into the Gulf (W_{LC}). The hypothesis requires that the combined work of $W_\tau + W_B$ is comparable to, or exceeds that of W_{LC}.

Rough estimates of these terms follow from observations. Consider dissipation over the WFS. Under the protracted Loop Current induced (versus wind-driven) upwelling of 2010, the observed velocity using moored Acoustic Doppler Current Profilers had speeds of order 0.25 m s^{-1} at the 25 m isobath, this being somewhat smaller inshore and larger offshore of that location. For the purpose of argument, we choose 0.20 m s^{-1} as a characteristic geostrophic current speed to be dissipated by friction across the bottom Ekman layer. The work by bottom stress, W_τ, may be estimated from:

$$W_\tau = \iint \tau \cdot V dA, \tag{1}$$

where the magnitude of $\tau = \rho C_d V^2$. Using a $C_d = 2.5 \times 10^{-3}$, $V = 0.20$ m s^{-1}, and a WFS area of approximately 5.5° × 1.5°, or about 10^{11} m^2, results in an estimated dissipation rate of about 2.0 GW.

A similarly crude estimate of the rate of work against buoyancy, W_B, for upwelling deeper ocean fluid onto the WFS follows from:

$$W_B = \left[\iiint \Delta\rho g z dz dx dy\right] \Big/ \Delta t, \tag{2}$$

where $\Delta\rho$ is the density difference between WFS water prior to and after the exchange by a protracted upwelling event, and Δt is the time that it takes to effect such a change in density. Observations from either 1998 or 2010 show that colder (by about 4°C) and saltier by about (0.5 psu) water pervades the WFS under protracted upwelling events resulting in a $\Delta\rho$ of about 2.0 kg m^{-3}. From particle trajectory estimates for 2010 (Weisberg et al., 2016b), the time to transit most of the shelf from the upwelling origin is about 1 month. With the upwelling origin on the upper slope at about 100 m depth, an intermediate shelf depth of 35 m to which this heavier water is lifted to and the same shelf area as before, the estimated rate of work against buoyancy is about 1.6 GW.

Estimating the rate of work to advance the Loop Current into the Gulf of Mexico follows from:

$$W_{LC} = \iiint Va \cdot \nabla P \partial x \partial y \partial z, \tag{3}$$

where Va is the rate of advance of the Loop Current into the Gulf of Mexico, which for 2014 was about 100 km in 3 months, consistent with estimates by Lugo-Fernández et al. (2016). Estimating the horizontal pressure gradient, ∇P, from the sea surface height difference across the Loop Current (~0.5 m), assuming a baroclinic adjustment across the upper 600 m (e.g., Hamilton et al., 2016; Sheinbaum et al., 2002) and taking

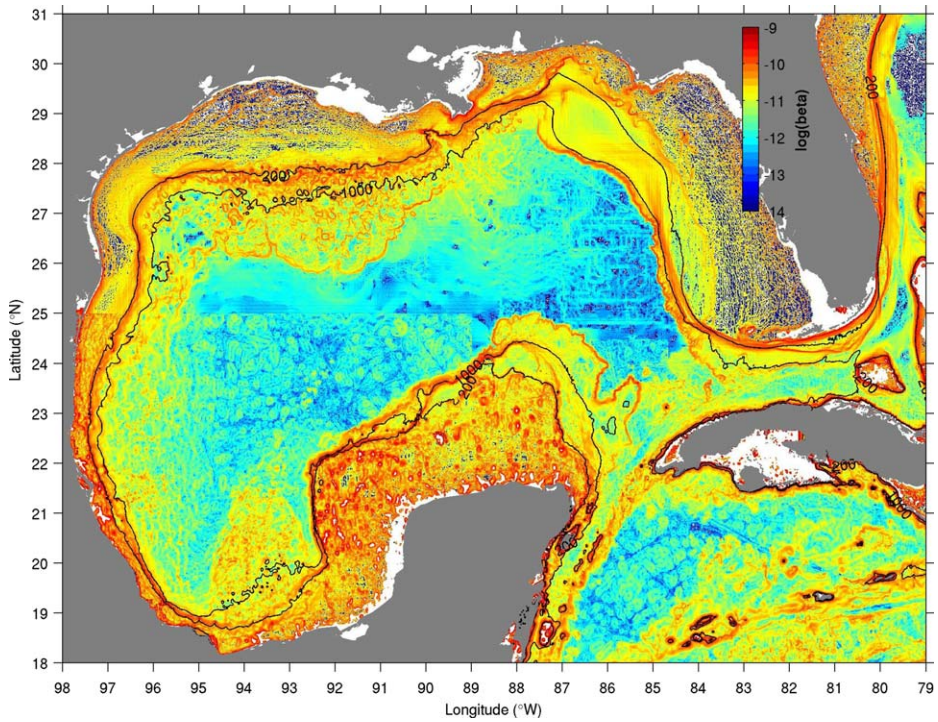

Figure 13. Contours of the topographic β parameter, $\beta_H = \frac{f}{H}\nabla H$, where f is the Coriolis parameter and H is the water depth. Topographic β values exceed the planetary β (equal to about 2×10^{-11} m^{-1} s^{-1} by 1 order of magnitude for shelf slope regions.

the width of the Loop Current as it advances to be 150 km (Figures 10 and 11), the estimated rate of work against the ambient Gulf of Mexico fluid is about 2.9 GW.

A comparison of these crude, heuristically determined estimates provide support for the hypothesis that the WFS can anchor the Loop Current to the vicinity of the entry and exit portals when the Loop Current is in proximity to the Dry Tortugas pressure point. A cursory look at the (Figure 13) contours of the topographic β parameter, $\beta_H = \frac{f}{H}\nabla H$, f being the Coriolis parameter and H the water depth, shows that the topographic β_H exceeds the planetary β (equal to about 2×10^{-11} m^{-1} s^{-1}) by an order of magnitude along the shelf slope region. This, plus the areal extent of the WFS relative to the scale of the Loop Current when it is in its retracted state near the entry and exit portals offer a further conceptional appreciation for why topography in general and WFS processes in particular may be of importance.

Our hypothesis on the anchoring potential of the WFS is also consistent with the work of Kuehl and Sheremet (2014), which extends the theory of Sheremet (2001) on the relative importance of inertia and planetary β in controlling the penetration of a western boundary current though a gap. With large enough inertia the boundary current leaps past the gap, whereas with less inertia the boundary current penetrates the gap and may form eddies that separate. The Kuehl and Sheremet (2014) work included two layers and hence dissipation within a bottom Ekman layer, which, when large enough inhibits penetration and favors gap leaping. Here we argue that such dissipation may be associated with the WFS, as contrasted with that of the ocean bottom beneath the Loop Current itself.

6. Summary and Recommendations

The mechanisms that control the penetration of the Loop Current into the Gulf of Mexico remain important topics of research. Here we hypothesize that the west Florida continental shelf (WFS) plays an important role. We begin by describing Loop Current behaviors, using a neural network, Self-Organizing Map analysis to reduce 24+ years of daily satellite altimetry and surface geostrophic current maps (a total of 8,831 daily

maps) into an enumerated set of 40 patterns, the temporal evolution of which is objectively assessed via the SOM best matching unit time series. This analysis reveals that when the Loop Current penetrates far into the Gulf of Mexico, the eastern side of the Loop Current tends to be displaced westward from the southwest (Dry Tortugas) corner of the WFS. Conversely, when the Loop Current remains in the vicinity of its entry (Yucatan Strait) and exit (Straits of Florida) portals, it tends to be in close proximity to this Dry Tortugas pressure point.

The significance of the Loop Current being in prolonged contact with the pressure point in both driving the WFS circulation and affecting the WFS ecology is well established. That this contact also feeds back upon the Loop Current itself is new. The heuristic argument is energetics based. For the Loop Current to penetrate into the Gulf of Mexico, it must do work against the ambient fluid. This requires a certain excess of energy between the influx and efflux of the two portals. Our argument is that if this excess is consumed by excitation of flow on the WFS (as is known to happen when the Loop Current stays in proximity to the pressure point) then there will be insufficient energy flux differential between influx and efflux to enable further penetration by the Loop Current into the Gulf of Mexico. Under this scenario the WFS, in essence, acts as an anchor for the Loop Current. Releasing this anchor allows the Loop Current to penetrate and for any excess in energy flux to then induce eddy shedding by instability (e.g., Chang & Oey, 2013; Donohue et al., 2016; Hurlburt & Thompson, 1980; Oey et al., 2005; Xu et al., 2013). Interestingly, while Loop Current eddy shedding has received much attention, the process of instability is one of ridding a system of excess energy. Hence it is a consequence of Loop Current penetration, versus a cause for such. The most vexing Loop Current behavior question remains the constraint on Loop Current penetration for which we contend that topography (through wave radiation) and both frictional dissipation and buoyancy work on the west Florida continental shelf itself are important factors consistent with previous work.

Our heuristic argument may be further tested by employing a more complete control volume analysis on the energetics of Loop Current penetration. Of fundamental importance is the propagation of pressure perturbations imposed on the pressure point. Not only will these excite topographic Rossby waves in the traditional sense along the shelf slope (e.g., Hamilton, 19901990, 2009; Oey & Lee, 2002); they will also set the entire WFS in motion (Fan et al., 2004; Hetland et al., 1999; Weisberg & He, 2003), resulting in dissipation over the entire WFS as well as work against buoyancy in upwelling new water of upper slope origin onto the WFS (Weisberg et al., 2016b). Such frictional response with protracted upwelling is not readily modeled analytically; hence, there is a need for analyses of numerical model simulations supported by observations. Of particular importance are time series observations just inshore of the shelf break to the north of the Dry Tortugas with similar observations along the upper shelf slope and across the WFS farther north. These will enable a better quantification of energy radiating northward along the shelf slope and of the excitation of a shelf response.

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