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Key Points:

- Loop Current interactions at a critical shelf slope location induces anomalous upwelling
- Such occurrences are identified by the self-organizing map using altimetry data
- An altimetry-derived index is useful for the seasonal forecast of major *K. brevis* blooms

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Offshore forcing on the “pressure point” of the West Florida Shelf: Anomalous upwelling and its influence on harmful algal blooms

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Abstract Gulf of Mexico Loop Current (LC) interactions with the West Florida Shelf (WFS) slope play an important role in shelf ecology through the upwelling of new inorganic nutrients across the shelf break. This is particularly the case when the LC impinges upon the shelf slope in the southwest portion of the WFS near the Dry Tortugas. By contacting shallow water isobaths at this “pressure point” the LC forcing sets the entire shelf into motion. Characteristic patterns of LC interactions with the WFS and their occurrences are identified using unsupervised neural network, self-organizing map, from 23 years (1993–2015) of altimetry data. The duration of the occurrences of such LC patterns is used as an indicator of offshore forcing of anomalous upwelling. Consistency is found between the altimetry-derived offshore forcing and the occurrence and severity of WFS coastal blooms of the toxic dinoflagellate, *Karenia brevis*: years without major blooms tend to have prolonged LC contact at the “pressure point,” whereas years with major blooms tend not to have prolonged offshore forcing. Resetting the nutrient state of the shelf by the coastal ocean circulation in response to deep-ocean forcing demonstrates the importance of physical oceanography in shelf ecology. A satellite altimetry-derived seasonal predictor for major *K. brevis* blooms is also proposed.

1. Introduction

Harmful algal blooms (HABs) regularly occur in Gulf of Mexico (GoM) coastal waters. The development and transport of such blooms are impacted by physical interactions along the West Florida Shelf (WFS) slope that control the transport of nutrients supplied from offshore and the subsequent evolution of planktonic organisms [e.g., Weisberg and He, 2003; Walsh et al., 2003]. Blooms of the toxic dinoflagellate *Karenia brevis* [Steidinger, 1975] occur almost annually on the central West Florida Shelf (WFS) posing threats to public health and local economies throughout Florida. Numerous efforts have been made to better understand the variability in *K. brevis* bloom initiation and severity [e.g., Heil and Steidinger, 2009].

Since the WFS is generally an oligotrophic marine environment, the nutrient sources available for *K. brevis* prior to and during blooms have been the topic of many studies [e.g., Weisberg and He, 2003; Walsh et al., 2003, 2006; Stumpf et al., 2008; Lenes and Heil, 2010; McCulloch et al., 2013; Heil et al., 2014; Weisberg et al., 2014a]. According to the literature review by Vargo [2009], more than 20 proposed theories relating to nutrient sources and *K. brevis* have been investigated. Recent studies reexamined the nutrients released from fish kills due to toxins produced by *K. brevis* [Killberg-Thoreson et al., 2014; Mulholland et al., 2014] and from the benthic layer [Sinclair et al., 2006; Dixon et al., 2014]. Although nutrient composition and concentration is clearly important for *K. brevis* physiology, no single hypothesis can account for the ecologically complex blooms on the WFS.

Blooms of *K. brevis* are generally thought to originate in midshelf waters at depth [e.g., Steidinger, 1975; Steidinger and Haddad, 1981] and to arrive near shore via the bottom Ekman layer under upwelling conditions [e.g., Weisberg et al., 2009a]. Mature blooms nearshore often occur in the fall months [e.g., Tester and Steidinger, 1997; Walsh et al., 2006], and this coincides with the seasonal transition to predominantly upwelling circulation conditions on the WFS [Weisberg et al., 2005, 2009a, 2009b; Liu and Weisberg, 2012]. Coastal upwelling on the inner WFS is mainly driven by local winds on synoptic weather to interannual time scales [Weisberg et al., 2000, 2001, 2005; Liu and Weisberg, 2005, 2007, 2012]. Upwelling across the shelf break,

resulting in the advection of deeper ocean nutrient-rich onto the WFS, may be induced by the interactions of the GoM Loop Current (LC) system with the WFS slope [Weisberg and He, 2003], with subsequent phytoplankton responses observed and modeled [e.g., Walsh *et al.*, 2003]. From these precedent works, it was generally accepted that the upwelling of midshelf water was a necessary condition for a *K. brevis* bloom to manifest near shore. However, in 2010 when anomalously protracted upwelling conditions were induced by offshore forcing, no WFS red tide was observed [Weisberg *et al.*, 2014a]. This result led to a new hypothesis relating offshore forcing to *K. brevis* blooms—while upwelling is necessary for a *K. brevis* bloom to manifest at the coast, too much upwelling may suppress bloom formation. Thus, both the physics of the coastal ocean circulation and the organism biology each provide necessary conditions for bloom development, but neither alone is a sufficient condition [Weisberg *et al.*, 2014a]. Recent case studies for the years 2012 (with a major bloom) and 2013 (without a major bloom) further support this hypothesis [Weisberg *et al.*, 2016b].

The present paper further investigates the relationship between offshore forcing and *K. brevis* blooms by extending the analysis to include all 23 years of available satellite altimetry data. Questions to be examined are (1) Is LC forcing a determinant of the location and intensity of *K. brevis* blooms on the WFS, and if so, how? (2) Can altimetry data be used as an offshore index for the seasonal forecast of a *K. brevis* bloom?

2. Hypothesis on Offshore Forcing

2.1. The “Pressure Point” of the West Florida Shelf

The LC system dominates the ocean circulation of the eastern GoM [e.g., Sturges and Lugo-Fernández, 2005]. The LC generally penetrates northwestward into the GoM (as seen in the long-term mean LC pattern of Figure 1) before shedding an anticyclonic eddy and then retreating back to the south. The LC system generally varies in a complicated manner over multiple temporal and spatial scales [e.g., Schmitz *et al.*, 2005; Oey *et al.*, 2005; Alvera-Azcárate *et al.*, 2009; Lugo-Fernández and Leben, 2010] and is known to influence the shelf circulation and water properties [Molinari *et al.*, 1977; Palusziewicz *et al.*, 1983; He and Weisberg, 2003; Barth *et al.*, 2008].

Of particular importance is the Dry Tortugas located in the southwest portion of the WFS. Using a general ocean circulation model, Hetland *et al.* [1999] ascribed a southward jet along the shelf edge to the pressure perturbation imposed by the LC, and when this pressure perturbation was applied near the Dry Tortugas their simulations further showed southward currents extending across the shelf. Also using a numerical ocean circulation model applied to the eastern GoM, both with and without the imposition of LC forcing and supported with in situ observations, Weisberg and He [2003] described the relative importance of local and deep-ocean forcing in driving the WFS to account for the anomalous circulation and water property conditions that were observed in 1998, and to confirm the hypothesis advanced by Hetland *et al.* [1999]. Recent glider observations of anomalous upwelling on the WFS were subsequently linked to persistent LC forcing near the Dry Tortugas, and this was further shown to affect *K. brevis*, juvenile fish recruitment, and subsurface transport of hazardous materials [Weisberg *et al.*, 2014a, 2014b, 2016b]. These cumulative investigations led to the realization that the Dry Tortugas region serves as a “pressure point” for the WFS (Figure 2). LC interactions with the shelf slope in this vicinity can set the entire WFS in motion by contacting shallow isobaths that wrap around the Dry Tortugas. Hence, pressure perturbations contacting the slope there will project across the entire shelf resulting in an across shelf pressure gradient propagating to the north (with shallow isobaths to the right), consistent with shelf wave dynamics [e.g., Gill, 1982; Brink, 1991]. With an across shelf pressure gradient thus established, there will be a southward directed geostrophic current response whose left-hand turning across the bottom Ekman layer results in an upwelling circulation. Protracted LC contact causes protracted upwelling across the shelf break and subsequent advection toward the nearshore [e.g., Weisberg and He, 2003; Weisberg *et al.*, 2016c].

Such protracted upwelling also carries with elevated concentrations of inorganic nutrients from below the euphotic zone. Historical hydrographic data show very highly correlated temperature—salinity and temperature—nutrient relationships on the shelf slope for temperatures less than about 19°C, below which nutrients increase monotonically with decreasing temperature [e.g., Weisberg and He, 2003]. The upwelling of such water from depths below the shelf break is what ventilates the shelf with new inorganic nutrients, as demonstrated for a protracted period of upwelling in 1998 by Weisberg and He [2003] and Walsh *et al.* [2003]. For the more recent anomalous upwelling year of 2010, we further considered the origins and

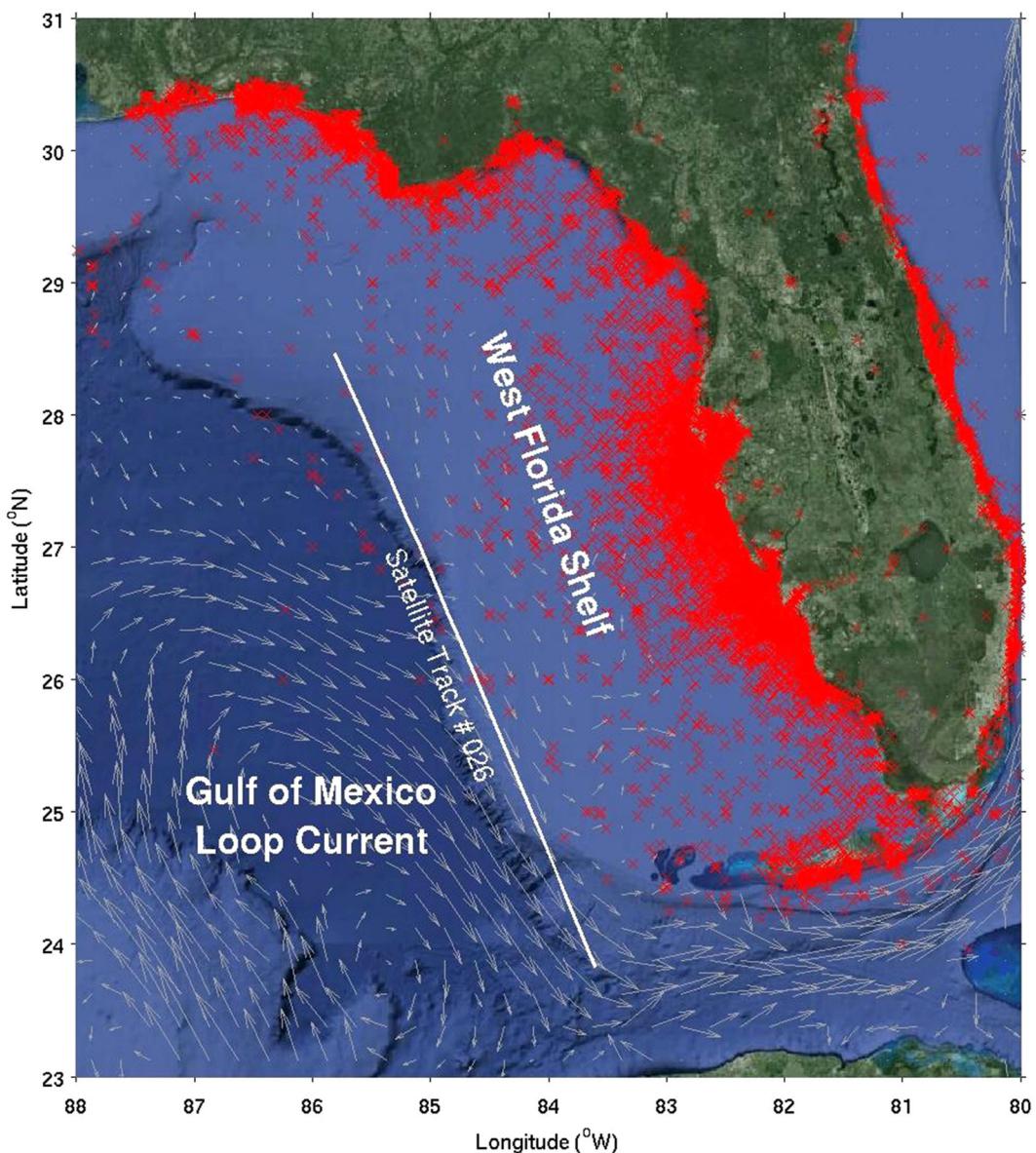


Figure 1. Locations of in situ observations of *Karenia brevis* cell counts (red crosses) in the Florida coastal region during 1953–2015. The long-term mean Gulf of Mexico Loop Current is shown as mean surface geostrophic velocity vectors derived from the mean dynamic topography. Also shown is a part of the ground track of satellite altimeters (Topex/Poseidon, Jason 1 and Jason 2) along the West Florida Shelf slope (solid white line).

pathways of such nutrient rich water onto and across the WFS. The origins are the upper continental slope, primarily down to about 150 m depth, and the pathway from the shelf break to the nearshore is the bottom Ekman layer [Weisberg *et al.*, 2016a].

Note that LC or LC eddy interactions with the shelf farther north from the Dry Tortugas area may also induce a pressure gradient force, but one that only extends inshore from the shelf break by an internal Rossby radius of deformation [e.g., He and Weisberg, 2003; Liu *et al.*, 2011b], consistent with the findings of Chapman and Brink [1987] and Hetland *et al.* [1999].

2.2. Adverse Effects on *K. brevis* Blooms

A present working hypothesis on *K. brevis* bloom development under oligotrophic conditions relies on a complex biological sequence of events [Walsh *et al.*, 2006]. Accordingly, blooms initiate at depth in offshore waters [e.g., Steidinger, 1975], gaining nutrient support through, and receiving shading from, colocated

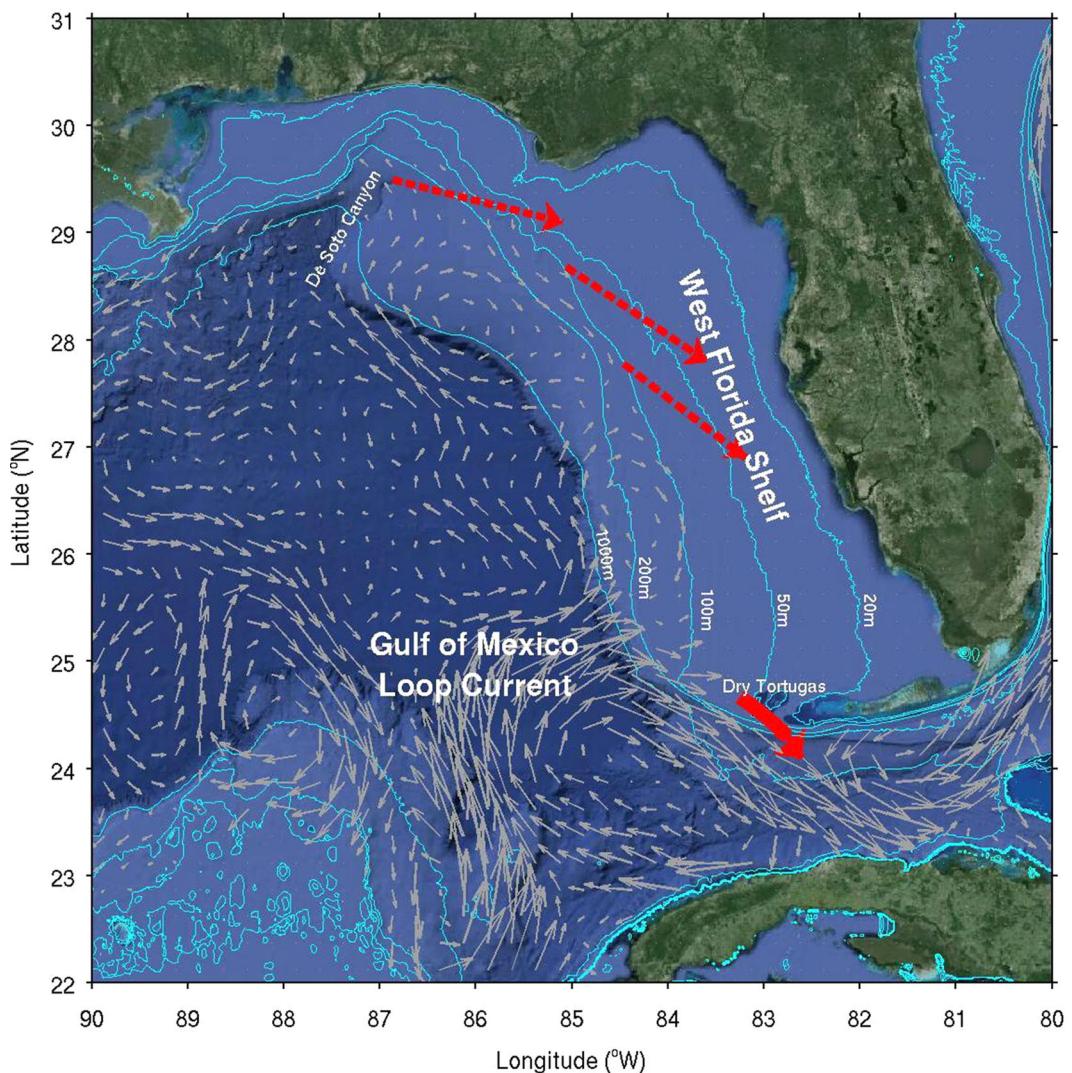


Figure 2. A schematic map showing Gulf of Mexico Loop Current (LC) system impinging on the southwest part of the West Florida Shelf slope area and inducing anomalous upwelling on the shelf. A snapshot of altimetry-derived surface geostrophic currents (gray arrows) on 1 October 2010 is given as an example. By contacting the shallow isobaths near the Dry Tortugas area, pressure perturbations of the LC system (red fat arrow) can project across the entire shelf and induce upwelling of the nutrient-rich deep water onto the shelf (red arrows with long dashed shafts). Also shown are isobaths of 20, 50, 100, 200, and 1000 m (contours).

populations of the nitrogen-fixing cyanobacterium *Trichodesmium* facilitated in part by iron enrichment via Saharan dust [Lenes et al., 2001; Walsh et al., 2006]. The *K. brevis* cells are then transported to the nearshore via the bottom Ekman layer by an upwelling circulation [Weisberg et al., 2009a], whence nearshore shading is provided by colored dissolved organic matter (CDOM) [Lenes et al., 2008; Walsh et al., 2009]. Further support for nearshore advection within the bottom Ekman layer comes from Janowitz and Kamykowski [2006], Janowitz et al. [2008], and Kamykowski et al. [2013] although the necessity of shading remains in question due to laboratory studies showing that *K. brevis* can photo-adapt to grow under full surface light intensities [e.g., Schaeffer et al., 2007; McCulloch et al., 2013], as well as field studies that highlight spatiotemporal variability in factors likely to cause shading [e.g., Lenes et al., 2001; Conmy et al., 2009]. Numerous lab and field studies show that *K. brevis* can utilize a diversity of available nutrient sources. Once at cell concentrations high enough to dominate the phytoplankton community, the toxins produced by *K. brevis*, known as brevetoxins, can cause fish kills, which can contribute to novel nutrient pools [Walsh et al., 2009]. Given this complex sequence of events, its initiation under oligotrophic conditions and the slow *K. brevis* growth rates, it should not be surprising that abundant new inorganic nutrients under anomalous upwelling conditions might suppress *K. brevis* bloom development by favoring more rapidly growing phytoplankton species

(diatoms). This assertion finds support in the suppression of *K. brevis* blooms in 1998 [Walsh *et al.*, 2003] and in 2010 and 2013 [Weisberg *et al.*, 2014a, 2016b], all under anomalously protracted and strong upwelling conditions. Upwelling also has the added impact of advecting near surface cells offshore, which further suppresses bloom evolution if new cells are not advected to the nearshore from below. The 2007 *K. brevis* bloom season provides an example of when a WFS initiated bloom was exported from the GoM to the southeast coast of the US [Walsh *et al.*, 2009].

3. Data Sets

Altimetry data provide a means for studying LC system pattern evolution in the eastern GoM [e.g., Liu *et al.*, 2016]. We use the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) gridded data [e.g., Ducet *et al.*, 2000; Le Traon *et al.*, 2003; Pascual *et al.*, 2006], a global product with horizontal resolution of 1/3° and daily time stamps. The delayed-time data are used for the period between 1 January 1993 through 23 April 2015, and the near real-time version are used for the remainder of 2015. The AVISO gridded SLA data are combined with a mean dynamic topography (CNES-CLS09 MDT) [e.g., Rio and Hernandez, 2004; Rio *et al.*, 2011], the mean sea surface above the geoid, to get absolute SSH. Similarly processed SSH data were used by members of our group in studies of the Caribbean and GoM region [Alvera-Azcárate *et al.*, 2009; Liu *et al.*, 2014, 2016].

The *K. brevis* cell abundance data from 1993 through 2015 are provided by the Florida Fish and Wildlife Conservation Commission's Harmful Algal Bloom Program [e.g., Heil and Steidinger, 2009]. Seawater samples, collected in response to suspected or ongoing blooms, are preserved using Lugol's solution and enumerated via light microscopy. Because sampling was event driven, its temporal and spatial coverage varied from year to year [Brand and Compton, 2007; Walsh *et al.*, 2009; Lenes and Heil, 2010]. Nonetheless, the composite of samples from 1953 to 2015 show that *K. brevis* blooms most commonly occur in central WFS coastal waters from Tampa Bay to Marco Island (Figure 1).

4. Methods

Satellite altimetry has been used in previous WFS-LC interaction studies beginning with Hetland *et al.* [1999]. Law [2003] used weekly snapshots of satellite altimetry fields to describe these. Weisberg and He [2003] used positive sea level height anomalies (SLA) along the (former) TOPEX/Poseidon ground track #026 to infer WFS forcing when these SLA anomalies were positioned near the Dry Tortugas. With the importance of such forcing established, Weisberg *et al.* [2014a] used monthly snapshots to describe the evolution of the LC in 2010 along with numerical model simulations to explain why there was no red tide observed on the WFS in 2010 and Weisberg *et al.* [2016c] used a similar approach to describe the WFS circulation throughout the duration of the *Deepwater Horizon* oil spill and the potential for subsurface transport of dissolved hydrocarbons to the WFS. Other recent applications using SLA at selected locations along the WFS slope for similar purpose are by Dukhovskoy *et al.* [2015] and Maze *et al.* [2015].

Harkening back to the Hetland *et al.* [1999] and Weisberg and He [2003] arguments of Dry Tortugas contact importance, Figure 3 shows a Hovmöller plot of SLA sampled along the TOPEX/Poseidon (and then Jason 1 and Jason 2) ground track #026 from 1993 through 2015. The events of LC contact with the WFS may be identified by examining the positive SLA clusters. However, a high indicated along this track does not necessarily translate to a LC impact near the Dry Tortugas, because a distance of about 100 km separates the line and Dry Tortugas (Figure 1). Although these weekly and monthly snapshots have provided critical insight into WFS dynamics, a better approach for pattern recognition is needed to examine the temporal evolution over the past 23 years (or approximately 8400 daily SSH maps).

The Self-Organizing Map (SOM) is an unsupervised learning neural network technique useful for pattern recognition in large data sets [e.g., Kohonen, 2001]. The SOM, developed by the computer science community [e.g., Vesanto and Alhoniemi, 2000], was introduced to the climate science community as a clustering and pattern recognition method [e.g., Hewitson and Crane, 1994; Ambroise *et al.*, 2000], followed by applications to oceanography [e.g., Richardson *et al.*, 2003; Liu and Weisberg, 2005]. Early SOM applications in meteorology and oceanography are reviewed in Liu and Weisberg [2011]. More recent oceanography applications of SOM are provided by Hisaki [2013], Falcieri *et al.* [2014], and Vilibić *et al.* [2016].

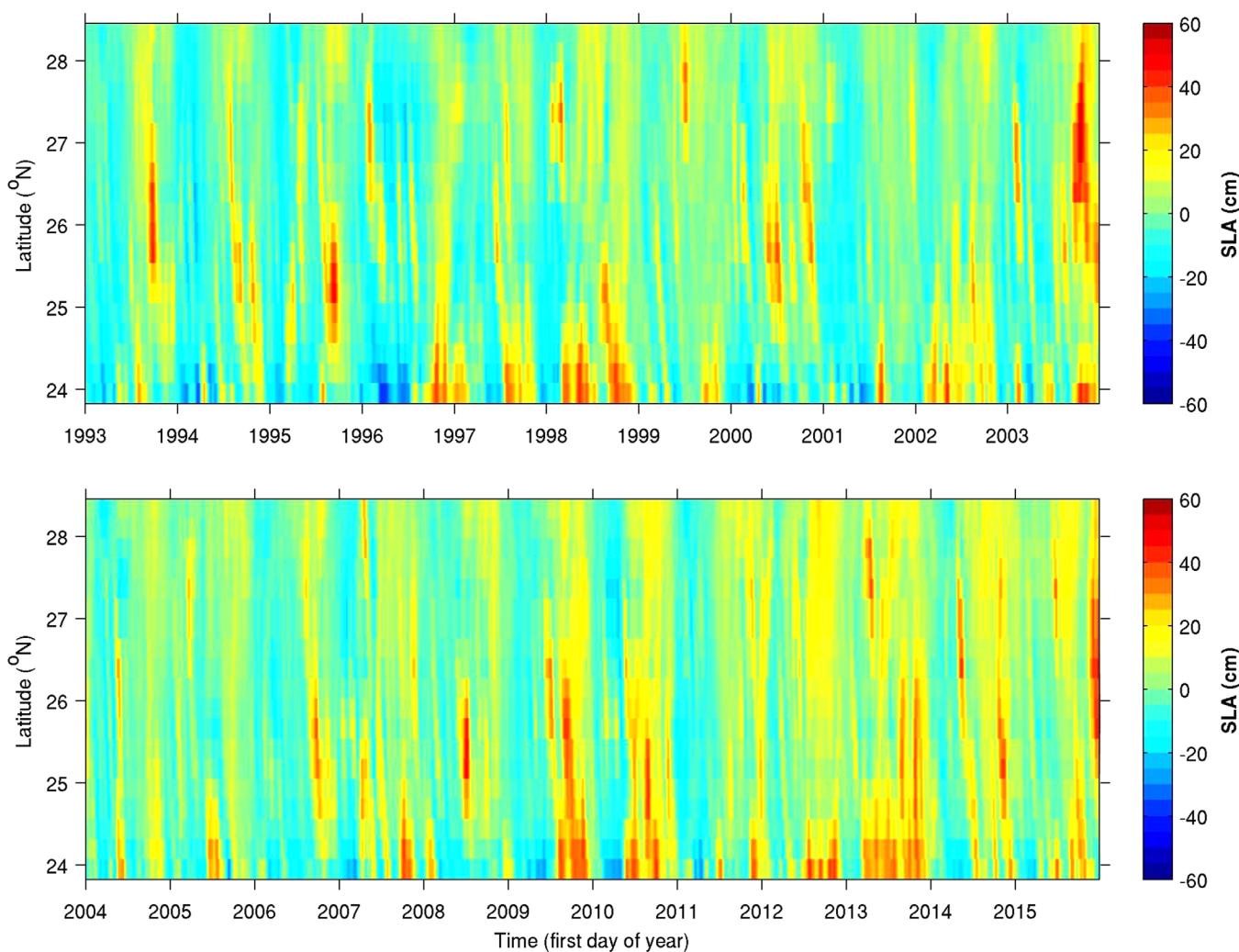


Figure 3. Hovmöller plots of the sea level anomaly (SLA) along the altimetry satellite (T/P) ground track #026 from 1993 to 2003 (top) and from 2004 to 2015 (bottom), respectively. The x-axis tick marks correspond to the first day of each year.

SOM applications to satellite altimetry data have increased in recent years. Since its first application in extracting surface geostrophic currents in the South China Sea [Liu *et al.*, 2008], SOM has been similarly employed to study the Kuroshio intrusions into the East China Sea [Tsui and Wu, 2012; Yin *et al.*, 2014] and the South China Sea [Sun *et al.*, 2016], and to extract characteristic patterns of the GoM LC [Zeng *et al.*, 2015; Liu *et al.*, 2016]. Recently, a dual SOM application for altimetry data analysis was demonstrated using the GoM LC as an example, in which both the characteristic spatial patterns of the LC system were extracted and the regions of different sea level variability were also identified [Liu *et al.*, 2016].

In the present study, the SOM is used to extract patterns of LC interactions with the WFS using daily satellite altimetry data, and to specifically examine the LC system interactions with the Dry Tortugas area of the WFS. Thus, a smaller data domain than that of Liu *et al.* [2016] is used here to study and focus on the central to southern WFS slope region (Figure 4). Note that conventional altimetry data are designed mainly for open ocean applications, and for the coastal regions they are not as reliable as in open oceans due to a number of factors [e.g., Vignudelli *et al.*, 2011]. To reduce the effects of the uncertainties of the altimetry data quality in the coastal band, the SSH data in shallow water regions (water depth <100 m) are removed. We use the MATLAB Toolbox of the SOM [Vesanto *et al.*, 2000], which is 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].

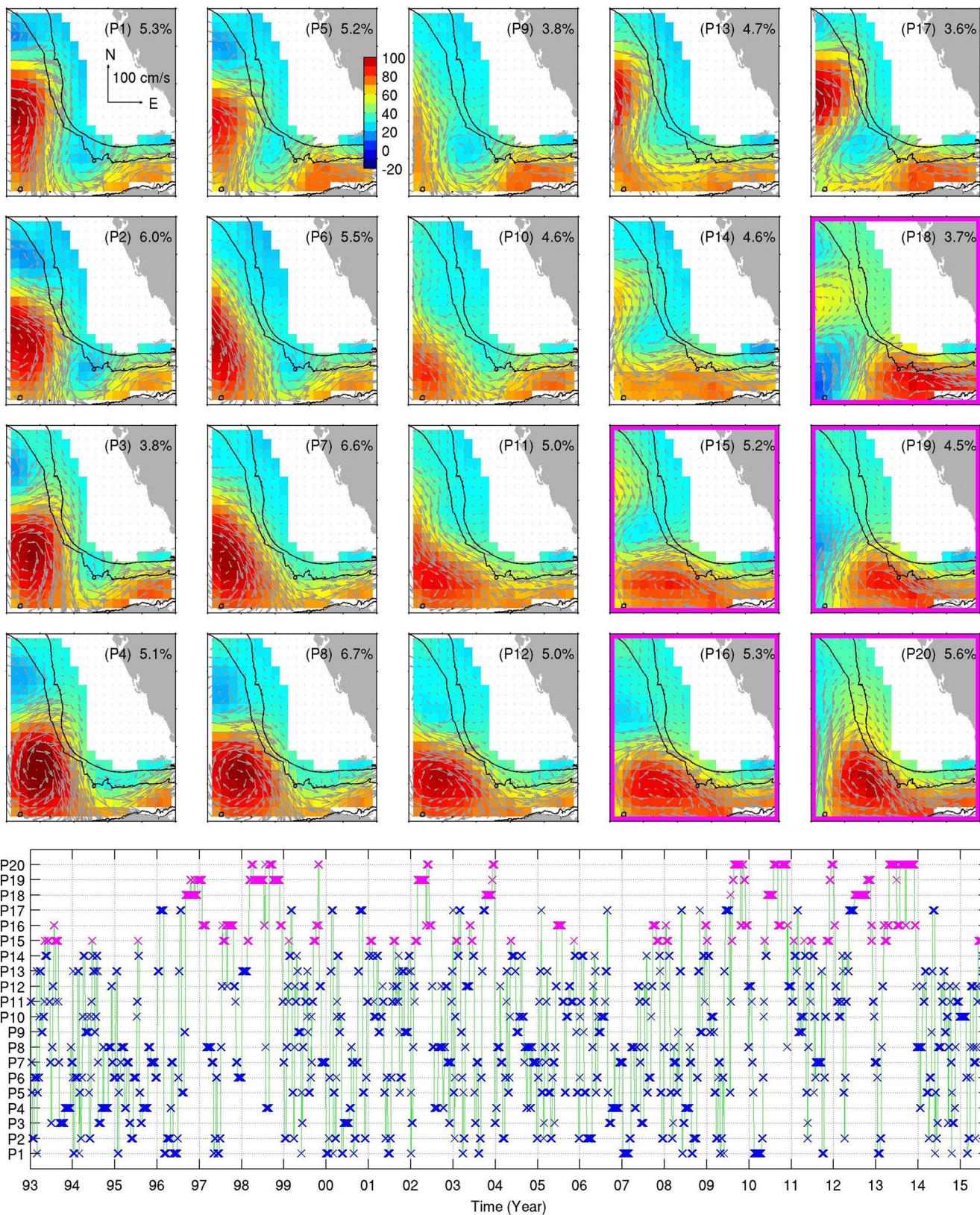


Figure 4. Characteristic patterns of the Loop Current systems southwest off the West Florida Shelf (top 20 figures) and their occurrence during 1993–2015 (bottom, green line) as revealed by a 4 × 5 self-organizing map. The frequency of occurrence is given as a percentage for each pattern. Sea surface heights and surface geostrophic velocities are shown in the maps. The black lines designate the 200 and 1000 m isobaths, respectively. The patterns showing Loop Current forcing on the southwest part of the West Florida Shelf are indicated in magenta boxes (P15, P16, P18, P19, and P20), and their occurrences in time are also shown as magenta in the bottom panel.

The occurrence of specific LC patterns is then compared with the occurrence of *K. brevis* based on available cell count data, collected in the study domain during the 23 year satellite altimetry record. The examination of interactions between WFS upwelling, LC structure, and bloom dynamics across varied time scales will provide an improved framework for evaluating hypotheses relating upwelling and bloom intensity.

5. Results

5.1. Characteristic Patterns of the LC Interactions With the WFS

Using the 8400 daily snapshots of SSH and related surface geostrophic velocity as inputs, the 4×5 SOM extracts 20 patterns of the LC system, showing different relative positions of the LC system with respect to the WFS (Figure 4, top 20 figures). Note that only a part of the LC system (the LC and its eddies) is shown, the main body of the LC is indicated as the reddish area in the southern part of the maps. The patterns on the lower right corner of the SOM show a retracted LC impinging on the southwestern part of the WFS (P18, P19, P20, P15, and P16). The patterns on the lower left corner of the SOM indicate a LC extending farther to the northwest and contacting the WFS break at a more northern location (P12, P8, P4, and P3). The patterns on the upper left corner of the SOM (P3, P2, P1, P5, and P9) exhibit the development of a cyclonic eddy on the northern edge of the Florida Current, varying from the Dry Tortugas eddy [Vukovich and Maul, 1985; Fratantoni *et al.*, 1998] to the West Florida LC cold front eddy [Schmitz, 2005]. As these mesoscale cyclones strengthen, they contribute to the separation of the LC anticyclonic eddy (LCE) from the LC [Chérubin *et al.*, 2010]. The patterns on the upper right corner show that the LCE is pinched-off and separated from the main body of the LC (P13, P17, P14, and P18). The patterns on the center of the SOM show that the LC stays off the WFS (P6, P7, P9, P10, and P11). Note that such categorization into pattern groups is not strict and that some of the transitional patterns (e.g., P15 and P18) may belong to two or more groups due to the way the SOM orders its units (similar patterns are located in neighboring units). These transitional patterns may contribute to uncertainties in the analysis interpretations but nevertheless provide information about the location and transition of the LC.

By comparing the 20 SOM patterns with the input data maps, a best matching unit (BMU) can be found for each of the daily input data maps. The BMU is defined as the “winner” unit on the SOM that has the smallest Euclidian distance from the presented data map, and it is the SOM unit that is most “similar” to the presented data map [Kohonen, 2001; Liu *et al.*, 2006]. Thus, the BMU time series indicates the evolution and stability of the patterns over time and/or when those patterns occur (Figure 4, bottom). Frequency of occurrence of each pattern can be obtained by dividing the number of a given BMU by the total record length. The frequency of occurrence of each unit is shown in the upper right corner of each pattern. The BMUs corresponding to the SOM patterns showing the LC impinging at the southwestern part of the WFS (P15, P16, P18, P19, and P20) are also plotted in magenta (Figure 4, bottom). Thus, the SOM provides a concise and informative way to describe the pattern evolution of the LC interactions with the WFS.

Examining the BMU time series at finer temporal resolution provides information on pattern evolution. In 2010, for example, the time of the *Deepwater Horizon* oil spill [e.g., Liu *et al.*, 2011a] coincided with anomalous upwelling on the WFS [Weisberg *et al.*, 2014a, 2016c]. The BMU time series and the associated spatial patterns (highlighted in colors) observed for 2010 are shown in Figure 5. From January through April 2010, the LC grew in size and extended northward into the GoM, and the patterns changed in sequence: P8 → P12 → P11 → P7 → P5 → P1 (Figure 5). The LC intruded onto the central WFS for several days between the end of April and early May 2010 (P5) [e.g., Liu *et al.*, 2011b]. Starting in mid-May 2010, the LC retracted southeastward (P14 and P15), and the LC started impinging on the southwest portion of the WFS (P15). From June through early December 2010, the dominant BMU patterns were all in the lower right corner of the SOM (P18 → P20 → P16 → P20 → P16), indicating that offshore forcing of the LC on the southwest part of the WFS occurred for >6 months. The persistent LC forcing resulted in anomalous upwelling on the WFS that was confirmed with glider observations [Weisberg *et al.*, 2014a, 2016c].

The total frequency of occurrence of the patterns that show the LC in contact with the southwestern part of the WFS is roughly 25% over the 23 years. It is expected that during the time period of their occurrences, the WFS may have anomalous upwelling if the offshore forcing persists long enough. To examine when and for how long each pattern persisted, the number of daily occurrences within each month is computed from

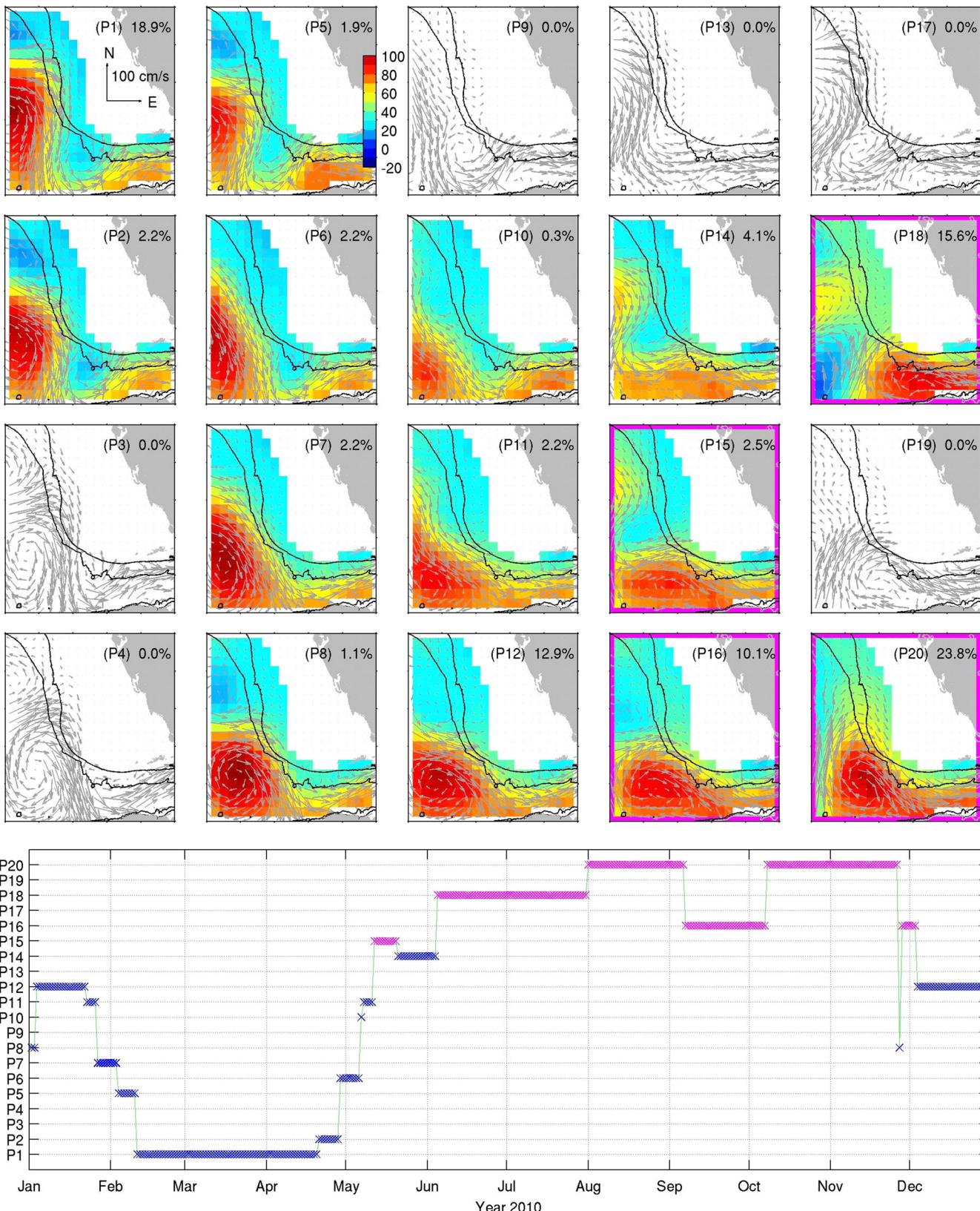


Figure 5. Similar to Figure 4 but for year 2010. Only the patterns appeared in 2010 are shown in colors. The frequency of occurrence is calculated based on the 1-year data.

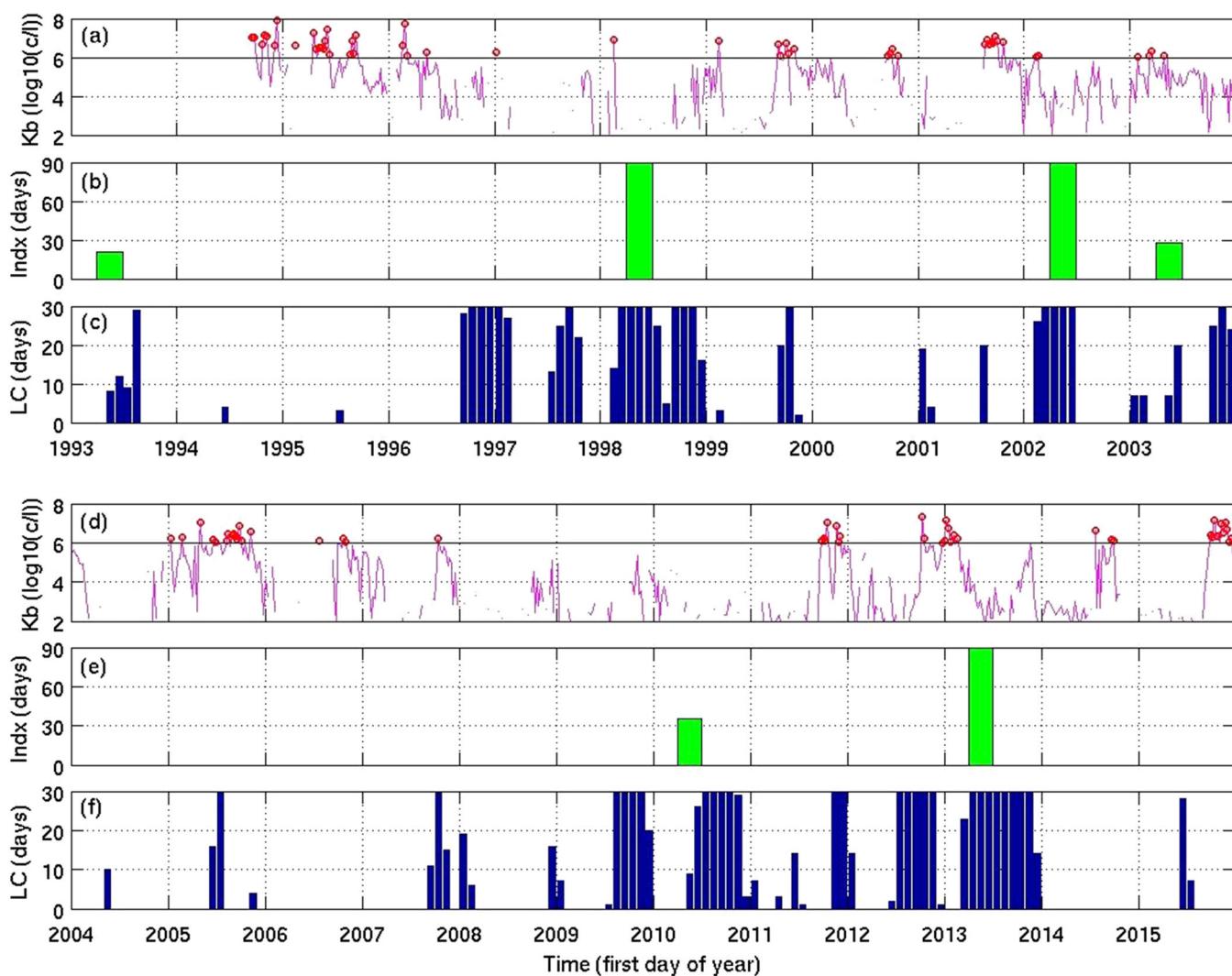


Figure 6. Occurrences of the red tide events on the West Florida Shelf and the offshore forcing at the “pressure point.” (a, d) Weekly average of top five *Karenia brevis* cell counts (magenta lines) on the West Florida Shelf. The black thick line indicates the threshold of a major red tide bloom (1 million cells per liter sea water), and the cell counts exceeding this threshold are indicated as red circles. (b, e) The offshore forcing index (green bars) of Loop Current impinging on the southwest part of the shelf, defined as the cumulative number of days that SOM pattern 15, 16, 18, 19, or 20 occurred during early summer (1 April through 30 June) for at least 2 months with at least 7 days in each of the months. (d, f) The number of the days that SOM patterns 15, 16, 18, 19, and 20 occurred in each month (blue bars).

the BMU time series. This monthly time series indicates the offshore forcing of the LC near the Dry Tortugas over the 23 years (Figures 6c and 6f).

5.2. Relationship Between Altimetry Patterns and *K. brevis* Blooms

Similar to approaches used by Walsh *et al.* [2006] and Lenes and Heil [2010], the five highest *K. brevis* cell concentrations observed within a week are averaged and the weekly mean values for the three regions are shown in Figure 6a. Since *K. brevis* concentrations (cells per liter of seawater) occur across a broad range from hundreds to tens of millions [Heil and Steidinger, 2009], a logarithmic scale is used in the figure. A bloom is considered major when *K. brevis* concentration exceeds a million cells per liter. The cell counts associated with the major *K. brevis* blooms are indicated as red circles in Figure 6a.

A close relationship is seen between the cell concentration and the LC forcing at the WFS “pressure point.” During major bloom years, e.g., 1994, 1995 (and early 1996), 1999, 2001, 2005, and 2011, offshore forcing by the LC at Dry Tortugas was weak and/or intermittent. However, during the years with prolonged LC forcing at the Dry Tortugas (lasting several months), e.g., 1996–1997, 1998, 2002, 2009, 2010, and 2013, either no

Table 1. Summary of the Occurrences of the *Karenia brevis* Blooms and Offshore Forcing Events

Year	Persistent Offshore Forcing During Spring and Early Summer (✓)	Major Blooms (✗)	No Major Blooms in Fall (✗) or Occurred in Early of the Year but the Intensity is Reduced in Fall (✗*)
1993	✓		✓
1994		✗	
1995		✗	
1996		✗	
1997			
1998	✓		✗*
1999		✗	✗*
2000		✗	
2001		✗	
2002	✓		✓
2003	✓		✓
2004		✗	✓
2005		✗	
2006		✗	
2007		✗	
2008			✓
2009			✓
2010	✓		✓
2011		✗	
2012		✗	
2013	✓		✗*
2014		✗	
2015		✗	

bloom was observed, or a reduction in bloom intensity occurred (Figure 6). Whereas LC forcing at the Dry Tortugas lasting several months may help minimize a bloom, LC forcing of only 1–2 months seems to increase the chance of a major bloom event (e.g., 1999, 2005, and 2011). Thus, the offshore forcing induced anomalous upwelling circulation is suspected to have diverse and varied impacts on *K. brevis* blooms on the WFS.

Year 2012 was special as explained in Weisberg *et al.* [2016b]. There was prolonged offshore forcing but it did not start until the end of June 2012. A major bloom occurred from fall through winter. Note that the *K. brevis* bloom is hypothesized to initiates offshore and develops in early summer (May–June). Across-shelf movement associated with upwelling circulation can transport cells and nutrients inshore via the bottom boundary layer and by the time that upwelling started in 2012, a bloom may have already formed. To effectively suppress major bloom formation, anomalous upwelling needs to be in place during the formative spring through early summer months like years 2010 and 2013 [Weisberg *et al.*, 2016b].

Even if the LC forcing occurred in early summer, e.g., as in 2005, if the forcing lasts only a short period (<2 months), this may not be sufficient to effectively suppress a major bloom. In this case, the upwelling could favor major bloom development, as it is possible that new inorganic nutrients could be upwelled from the shelf slope into nearshore waters where they have the potential to be used by *K. brevis*.

Based on our hypothesis and the above considerations, we define an offshore forcing index by LC interaction with the southwest portion of the WFS as the cumulative number of days for SOM patterns 15, 16, 18, 19, or 20 during the formative spring and early summer period (1 April through 30 June), with the added modifier that these patterns must extend over at least two of these months and for at least 7 days in each of the months. This offshore forcing index is shown as green bars in Figures 6b and 6e and the binary relationship between the index and the occurrence (or lack of occurrence) of a major red tide bloom is summarized in Table 1. During the 23 year altimetry observation period, such persistent offshore forcing occurred in six of these years (i.e., 1993, 1998, 2002, 2003, 2010, and 2013). Interestingly, during each of these 6 years either no major *K. brevis* bloom was observed or a major bloom occurred in the early

months of the year, but the intensity was greatly reduced during the late summer and fall (Table 1). On the other hand, during the 17 years without the presence of the “green bars,” major blooms were seen in 13 of these years (15 years if years 1997 and 2004 with delayed blooms, i.e., the bloom occurred in January or February of the next year, are counted). Thus, the offshore forcing index (as defined above) appears to serve as a seasonal predictor of major *K. brevis* red tide blooms on the WFS. As a binary random variable (a major bloom occurrence or not), the forecast success rate for “no major bloom” is 100% (6 out of 6 years), and for a “major bloom” is either 88% (15 out of 17 years) or 76% (13 out of 17) for a more conservative forecast.

6. Summary

The underlying premise of this work is that the ocean circulation physics and the organism biology each provide necessary conditions for *K. brevis* red tide blooms on the WFS, whereas neither alone provides a sufficient condition [Weisberg *et al.*, 2014a]. Given the complexity of the biology [e.g., Walsh *et al.*, 2006], we sought a simpler means through the circulation physics to serve as a seasonal predictor of a major bloom. In other words, is there a physical state of the coastal ocean that might suppress major bloom occurrence? Previous studies show that Loop Current interactions with the southwest corner of the WFS near the Dry Tortugas can set the entire shelf in an upwelling favorable circulation [Hetland *et al.*, 1999; Weisberg and He, 2003] and that this could result in *K. brevis* bloom suppression by changing the nutrient state of the shelf [Walsh *et al.*, 2003].

Thus, we applied the neural network (SOM) technique to extract characteristic patterns of LC interactions with the WFS from 23 years of satellite altimetry data to identify LC patterns indicative of anomalous WFS upwelling by prolonged contacts with what we term the “pressure point” of the WFS, and we related these patterns to 23 years of *K. brevis* abundance data. Considering the occurrence, or lack of occurrence, of a major bloom to be a binary random variable, the index defined by SOM pattern extraction for the incipient period of bloom evolution (spring through early summer) appears to have worked successfully for all but four of the 23 years of concomitant (SSH and *K. brevis*) data. During the years with strong upwelling due to prolonged LC forcing, there were no major red tide blooms, whereas during the major red tide bloom years, there was not a persistent upwelling due to prolonged “pressure point” contact.

Resetting the nutrient state of the shelf by the coastal ocean circulation in response to deep-ocean forcing demonstrates the importance of the coastal ocean circulation in shelf ecology [e.g., Weisberg *et al.*, 2015]. Ecological impacts of the “pressure point” are not limited to HABs or primary producers. Similar arguments by Weisberg *et al.* [2014b, 2016c] highlight offshore to nearshore transport mechanisms important for spawning and settlement in gag grouper juveniles and relate modeled distributions of subsurface hydrocarbons with lesions found in fish on the WFS subsequent to the *Deepwater Horizon* oil spill. It may be argued that nothing of an ecological nature on the WFS goes unaffected by the “pressure point,” because this is what determines the deep-ocean flux of nutrients to the WFS and hence whether or not the WFS is in an oligotrophic state.

Further advancements in WFS ecology will benefit from the systematic sampling of a multidisciplinary set of relevant variables and the integration of primary higher trophic level phenomena within circulation models to better predict, monitor, and manage living marine resources [Liu *et al.*, 2015]. It is the coastal ocean circulation that sets the water properties in which organisms reside. In the same way that *K. brevis* appears to respond to oligotrophic, versus nutrient replete conditions so will many other ecological phenomena. Improved concomitant data sets are required to better understand the complex physical-biological interactions occurring across a multiple of time scales that together comprise coastal ocean ecology. Satellite altimetry, as shown herein, is an important component of such a data set, and the increased spatial resolution anticipated with the future Surface Water and Ocean Topography (SWOT) mission [e.g., Fu *et al.*, 2012] may lead to better definition of the patterns of LC interaction discussed. Further integration with other remote sensing data streams, including ocean color satellite products [e.g., Hu *et al.*, 2005; Blondeau-Patissier *et al.*, 2014; Kudela *et al.*, 2015] will also contribute to building a more robust framework for harmful algal bloom monitoring and prediction in the GoM.

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