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Persistent transport barrier on the West Florida Shelf

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[1] Analysis of drifter trajectories in the Gulf of Mexico has revealed the existence of a region on the southern portion of the West Florida Shelf (WFS) that is not visited by drifters that are released outside of the region. This so-called "forbidden zone" (FZ) suggests the existence of a persistent cross-shelf transport barrier on the southern portion of the WFS. In this letter a year-long record of surface currents produced by a Hybrid-Coordinate Ocean Model simulation of the WFS is used to compute Lagrangian coherent structures (LCSs), which reveal the presence of a persistent cross-shelf transport barrier in approximately the same location as the boundary of the FZ. The location of the cross-shelf transport barrier undergoes a seasonal oscillation, being closer to the coast in the summer than in the winter. A month-long record of surface currents inferred from high-frequency (HF) radar measurements in a roughly 60 km × 80 km region on the WFS off Tampa Bay is also used to compute LCSs, and these also reveal the presence of transient transport barriers. While the HF-radar-derived transport barriers cannot be unambiguously linked to the boundary of the FZ, this analysis does demonstrate the feasibility of monitoring transport barriers on the WFS using a HF-radar-based measurement system. The implications of a persistent cross-shelf transport barrier on the WFS for the development of harmful algal blooms on the shoreward side of the barrier are considered.
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1. Introduction

[2] *Yang et al.* [1999] present the results of the analysis of trajectories of satellite-tracked drifters released during the period February 1996 through February 1997 on the continental shelf in the northeastern portion of the Gulf of Mexico (GoM). Inspection of the drifter trajectories depicted in Figure 2 of that paper reveals the presence of a trajectory-free triangular-shaped region on the southern portion of the West Florida Shelf (WFS), which has been referred to by those authors as a "forbidden zone" (FZ). The FZ is identified using cross-hatching in the top left plot of Figure 1 in this paper. Although little can be inferred about the spatio-temporal variability of the FZ from Figure 2 of *Yang et al.* [1999], the FZ almost certainly wobbles with a complicated spatio-temporal structure. This expectation finds some support in the seasonal analysis of drifter trajectories presented by *Morey et al.* [2003], which also included trajectories of drifters released on the continental shelf in the northwestern portion of the GoM.

[3] The presence of the FZ suggests the existence of a persistent barrier on the WFS that inhibits transport across the shelf. This cross-shelf transport barrier not only can have implications for pollutant dispersal, but may also be consequential for harmful algal blooms on the shoreward side of the barrier.

[4] In this letter we employ methods from dynamical systems theory with two goals in mind. First, we seek to demonstrate that when suitably analyzed, the output of a fairly realistic numerical model of the GoM predicts the presence of a persistent cross-shelf transport barrier in approximately the location of the boundary of the FZ. Second, we seek to demonstrate the feasibility of monitoring transport barriers on the WFS using high-frequency (HF) radar measurements.

2. Lagrangian Coherent Structures (LCSs)

[5] Theoretical work on dynamical systems [e.g., *Haller*, 2000; *Haller and Yuan*, 2000; *Haller*, 2001a, 2001b, 2002; *Shadden et al.*, 2005] has characterized transport barriers in unsteady two-dimensional incompressible flows as Lagrangian coherent structures (LCSs). The theory behind LCSs will not be discussed in this letter. We note, however, that the LCSs of interest correspond to the stable and/or unstable invariant manifolds of generally nonstationary hyperbolic points.

[6] An invariant manifold can be understood as a material curve of fluid, i.e., composed always of the same fluid particles. Associated with a hyperbolic point in a steady flow there are two invariant manifolds, one stable and another one unstable. Along the stable (unstable) manifold, a fluid particle asymptotically approaches the hyperbolic point in forward (backward) time. Initially nearby fluid particle trajectories flanking a stable (unstable) manifold repel (attract) from each other at an exponential rate. These manifolds therefore constitute separatrices that divide the space into regions with dynamically distinct characteristics. Furthermore, being material curves these separatrices cannot be traversed by fluid particles, i.e., they constitute true transport barriers. In an unsteady flow there are also hyperbolic points with associated stable and unstable manifolds. Unlike the steady case, these hyperbolic points are not fixed in space but rather undergo motion, which is typically aperiodic in predominantly turbulent ocean flows. As in the steady case, the associated manifolds also constitute separatrices, and hence transport barriers, albeit in a spatially

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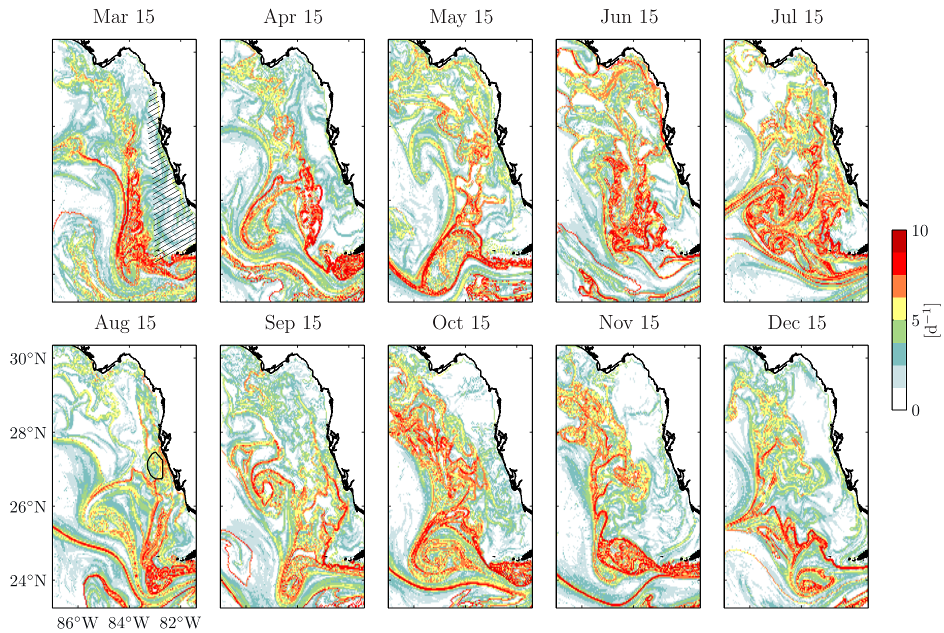

Figure 1. Sequence of snapshots of FTLE field (1) computed backward in time using surface currents generated by a HYCOM simulation of the WFS for year 2004. Ridges of FTLE field define attracting LCSs. Note the presence of a triangular-shaped area on the southern portion of the WFS with small FTLEs bounded by the western Florida coast on the east, the lower Florida keys on the south, and large ridges of FTLE field on the west. The latter constitute a barrier for cross-shelf transport, which is seen to undergo a seasonal oscillation near the western boundary of the FZ. The FZ, as identified by *Yang et al.* [1999], corresponds to the cross-hatched domain in the top left plot. The HF-radar measurement domain that was used to produce Figure 2 is identified in the bottom left plot.

local sense and for sufficiently short time. Generically there is chaotic motion in the vicinity of the points where the stable and unstable manifolds intersect one another after successively stretching and folding. These intersections lead to the formation of regions with a highly intricate tangle-like structure. In these regions trajectories of initially nearby fluid particles rapidly diverge and fluid particles from other regions are injected in between, which constitutes a very effective mechanism for mixing.

[7] Identification of LCSs, which is generally not possible from naked-eye inspection of snapshots of simulated or measured velocity fields and is very difficult from the inspection of individual fluid particle trajectories, is critically important for understanding transport and mixing of tracers in the ocean. The computation of finite-time Lyapunov exponents (FTLEs) provides a practical means of identifying repelling and attracting LCSs that approximate stable and unstable manifolds, respectively. The FTLE is the finite-time average of the maximum expansion or contraction rate for pairs of passively advected fluid particles. More specifically, the FTLE is defined as

$$\sigma_t^\tau(\mathbf{x}) := \frac{1}{|\tau|} \ln\left\|\partial_\mathbf{x}\varphi_t^{t+\tau}(\mathbf{x})\right\|, \tag{1}$$

where $\| \ \|$ denotes the L_2 norm and $\varphi_t^{t+\tau}$: $\mathbf{x}(t) \mapsto \mathbf{x}(t+\tau)$ is the flow map that takes fluid particles from their initial location at time t to their location at time $t + \tau$. The flow map $\varphi_t^{t+\tau}$ is obtained by solving the fluid particle motion regarded as a dynamical system obeying

$$\dot{\mathbf{x}} = \mathbf{u}(\mathbf{x}, t), \tag{2}$$

where the overdot stands for time differentiation and $\mathbf{u}(\mathbf{x}, t)$ is a prescribed velocity field. Repelling and attracting LCSs are then defined [*Haller*, 2002; *Shadden et al.*, 2005] as maximizing ridges of FTLE field computed forward ($\tau > 0$) and backward ($\tau < 0$) in time, respectively. Some caveats are noted in these references. This calculation method is particularly well suited for the identification of stable and unstable manifolds near hyperbolic regions [*Molcard et al.*, 2006].

[8] We remark that while LCSs are fundamentally a Lagrangian concept, the algorithm used to identify such structures requires a high resolution Eulerian description of the flow. Recently, *Lekien et al.* [2005] has successfully applied this theory to identify transport barriers using HF-radar-derived surface velocity on the east Florida shelf.

3. LCSs Derived From Simulated Currents

[9] Numerical model output provides a flow description $\mathbf{u}(\mathbf{x}, t)$ that is suitable for use to identify LCSs. Also, it has the advantage of allowing for a spatio-temporal coverage that is impossible to attain with existing observational systems. Here we consider a year-long record of surface currents produced by a Hybrid-Coordinate Ocean Model (HYCOM) simulation along the WFS for the year 2004.

[10] The year-long record of simulated currents consists of daily surface velocity fields extracted in the WFS domain from a 0.04°-resolution, free-running HYCOM simulation

of the GoM, itself nested within a 0.08°-resolution Atlantic basin data assimilative nowcast, which was generated at the Naval Research Laboratory as part of a National Oceanographic Partnership Program in support of the Global Ocean Data Assimilation Experiment [*Chassignet et al.*, 2006a, 2006b]. The Atlantic nowcast was forced with realistic high-frequency forcing obtained from the U. S. Navy NOGAPS operational atmospheric model. It assimilated sea surface temperature and anomalous sea surface height from satellite altimetry with downward projection of anomalous temperature and salinity profiles. The nested GoM model was free-running and driven by the same high-frequency atmospheric forcing. The topography used in both models was derived from the ETOPO5 dataset, with the coastline in the GoM model following the 2 m isobath. Both models included river runoff.

[11] Figure 1 shows snapshots of FTLE field, which were computed using the software package MANGEN, a dynamical systems toolkit designed by F. Lekien that is available at http://www.lekien.com/~francois/software/mangen. At each time t the algorithm coded in MANGEN performs the following tasks. First, system (2) is integrated using a fourth-order Runge–Kutta–Fehlberg method for a grid of particles at time t to get their positions at time $t + \tau$, which are the values of the flow map at each point. This requires a smooth velocity field, which is attained by using a cubic interpolation method. Second, the spatial gradient of the flow map is obtained at each point in the initial grid by central differencing with neighboring grid points. Third, the FTLE is computed at each point in the initial grid by evaluating (1). The previous three steps are repeated for a range of t values to produce a time series of FTLE field. Here we have set $\tau = -60$ d so that the ridges of the FTLE fields shown in Figure 1 correspond to attracting LCSs. The choice $\tau = -60$ d was chosen because 60 d is approximately the time it takes a typical fluid particle to leave the WFS domain. Clearly, some particles will exit the domain before 60 d of integration. In this case, MANGEN evaluates expression (1) using the position of each such particles prior exiting the domain. Note that due to the choice $\tau = -60$ d, the time series of computed FTLE fields based on our year-long record of simulated currents can only have a 10-month maximum duration.

[12] The regions of most intense red tones in each plot of Figure 1 roughly indicate maximizing ridges of FTLE field. These regions are seen to form smooth, albeit structured, curves that constitute the desired LCSs or transport barriers. Of particular interest is the triangular-shaped area on the southern portion of the WFS with small FTLEs bounded by the western Florida coast on the east, the lower Florida keys on the south, and large maximizing ridges of FTLE field on the west. The latter constitute a cross-shelf transport barrier that approximately coincides in position with the western boundary of the FZ identified by *Yang et al.* [1999]. This is most clearly visible during the period May through September. The sequence of snapshots of FTLE field in Figure 1 also reveals a seasonal movement of the cross-shelf transport barrier, being farthest offshore during the winter and closest to the coast during the summer, which is in agreement with drifter observations [*Morey et al.*, 2003].

[13] We have also computed FTLEs forward in time to produce repelling LCS fields (not shown). The combination of attracting and repelling LCS fields allows one to approximately identify the hyperbolic region where the aforementioned cross-shelf transport barrier originates. The hyperbolic region identified in this manner coincides approximately with that identified by *Toner et al.* [2003] where the computational domains overlap. In the *Toner et al.* [2003] work, stable and unstable manifolds were calculated using the straddling technique of *Miller et al.* [1997] based on velocity fields produced by a Princeton Ocean Model (POM) simulation of the GoM.

4. LCSs Derived From Measured Currents

[14] Figure 2 shows a sequence of snapshots of FTLE field computed using surface velocity inferred from HF radar measurements taken during September 2003 in an approximately 60 km × 80 km domain on the WFS off Tampa Bay (Figure 1, bottom left plot).

[15] The HF radar measurements were made with the Wellen radar system, which mapped coastal ocean surface currents over the above domain with 30-minute interval during one month [*Shay et al.*, 2006]. The computation of FTLEs was performed backward in time ($\tau = -60$ h) so that the maximizing ridges of FTLE field in Figure 2 indicate attracting LCSs, which approximate the unstable manifolds of the strongest hyperbolic structures in the area. The numerical computation of the FTLEs was not carried out using the MANGEN software package. Instead, we developed our own MATLAB codes, which, employing a methodology similar to that outlined in the previous section, allowed us to more easily handling FTLE computation based on velocity data defined on an irregular and completely open domain.

[16] The transport barrier character of the attracting LCSs identified in the FTLE fields depicted in Figure 2 is illustrated by numerically simulating the evolution of three clusters of fluid particles. One of the clusters (black spot in Figure 2) is initially chosen to lie on top of one LCS, while the other two clusters (dark-blue and magenta spots in Figure 2) are initially located on opposite sides of the LCS. The temporal evolution of the clusters reveals that the black cluster remains on top of the LCS and stretches along it as time progresses. The dark-blue and magenta clusters remain on opposite sides, indicating the absence of transport across the LCS.

[17] We remark that LCSs are identifiable in the region covered by the HF radar system through the whole month of September 2003. However, because of the limited domain of the radar footprint and the short deployment time window, we cannot say with certainty that any of the observed structures corresponds to the boundary of the FZ. In spite of this uncertainty, our analysis of the HF radar measurements is highly encouraging inasmuch as it demonstrates the feasibility of tracking the evolution of the boundary of the FZ in near real time.

5. Biological Implications

[18] In addition to being an interesting physical feature whose underlying dynamics deserves further study, the cross-shelf transport barrier on the WFS also has potentially important biological implications.

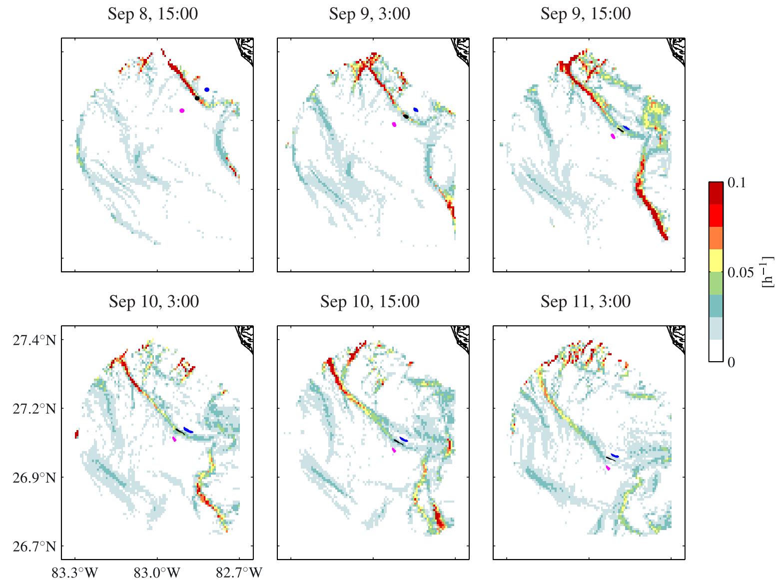

Figure 2. As in Figure 1 but using HF-radar-derived surface currents in a roughly 60 km ×80 km domain on the WFS off Tampa Bay (Figure 1, bottom left plot). The black, dark-blue, and magenta spots in each plot indicate clusters of passively advected fluid particles tracked from their initial location in the top left plot. Note how the black spot stretches along one of the identified LCSs and the dark-blue and magenta spots flanking this LCS are attracted to the LCS but do not cross it.

[19] The toxic dinoflagellate *Karenia brevis* has a rather restricted spatial distribution, primarily the GoM [*Kusek et al.*, 1999]. While *K. brevis* exists in low concentrations in vast areas of the GoM, it occasionally forms blooms along the northern and eastern coasts of the GoM [*Wilson and Ray*, 1956; *Geesey and Tester*, 1993; *Tester and Steidinger*, 1997; *Dortch et al.*, 1998; *Kusek et al.*, 1999; *Magana et al.*, 2003]. The largest and most frequent blooms, however, occur along the southern portion of the WFS [*Steidinger and Haddad*, 1981; *Kusek et al.*, 1999]. Where these occur, there can be widespread death of fish, manatees, dolphins, turtles, and seabirds as a result of the brevetoxins produced by *K. brevis* [*Bossart et al.*, 1998; *Landsberg and Steidinger*, 1998; *Landsberg*, 2002; *Shumway et al.*, 2003; *Flewelling et al.*, 2005]. The brevetoxins also end up in an aerosol, which affects human respiration [*Backer et al.*, 2003; *Kirkpatrick et al.*, 2004]. Being slow growing while fast swimming algae [*Chan*, 1978; *Brand and Guillard*, 1981], dinoflagellates have the highest potential for achieving high population densities as a consequence of biophysical accumulation rather than actual growth. As a result of expatriate losses, *K. brevis* (and other dinoflagellates) would be expected to develop large blooms only in regions where stirring by currents is weak. Indeed, many dinoflagellate blooms tend to occur in enclosed basins such as estuaries and lagoons, where expatriate losses are reduced. However, as mentioned above, *K. brevis* often forms large blooms along the open coastline of the southern portion of the WFS, typically inside the FZ.

[20] We hypothesize that the cross-shelf transport barrier associated with the FZ provides a mechanism that reduces *K. brevis* expatriation. A corollary of this hypothesis is that this barrier allows the nutrients from land runoff to accumulate near the coastline rather than being swept away by currents. While we cannot explain why *K. brevis* often dominates over other species of dinoflagellates in the FZ, we can predict that slow growing dinoflagellates will be more prevalent within the FZ than outside.

6. Summary

[21] In this letter we have shown that, when analyzed using dynamical systems methods, a year-long record of surface currents produced using a regional version of HYCOM reveals the presence of a cross-shelf transport barrier on the southern portion of the WFS, which is in approximately the same location as the boundary of the FZ identified earlier by *Yang et al.* [1999] using satellite-tracked drifter trajectories. The simulated cross-shelf transport barrier is persistent, being present in all seasons, while undergoing a seasonal oscillation. The simulated cross-shelf transport barrier is closer to shore in the summer months than in the winter months, in agreement with observations [*Morey et al.*, 2003]. HF radar measurements were analyzed in a similar fashion and this analysis demonstrated the feasibility of experimentally monitoring transport barriers on the WFS using a system that can be operated in near real time. Finally, we have argued that a cross shelf transport barrier on the WFS has potentially important biological implications.

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