1.3.6 Nonlinear Dynamics Can Shed Light on the Understanding of Transport Processes in the Southwestern Gulf of Mexico

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1.3.6.1 Abstract

The purpose of these notes is to acquaint GOM researchers with recent results that improve our knowledge of transport processes in the GOM using nontraditional tools, describe how much has been achieved, and identify what aspects remain to be understood especially in the southwestern GOM and the mechanisms for achieving the needed understanding. The exposition is largely biased toward the personal interests of the authors, some of whom have been actively involved in developing these new analysis tools.

1.3.6.2 Background—Transport Processes

The emergence of organized patterns such as filaments or eddies of different sizes and shapes in the distribution of tracers on the surface of the ocean (like temperature, salinity, pollutants or plankton) suggests the existence of an underlying material or Lagrangian (i.e., composed at all times by the same fluid elements) skeletal structure responsible for shaping lateral mixing into such patterns. The building blocks of the hidden Lagrangian skeleton of the surface ocean circulation are given by unique material lines, called "Lagrangian coherent structures" or LCS (Peacock and Haller 2013; Samelson 2013; Haller 2015).

Recent developments have occurred in an area that lies at the interface between nonlinear dynamical systems and fluid mechanics (Haller and Beron-Vera 2012; Farazmand and Haller 2013; Beron-Vera et al. 2013; Farazmand et al. 2014; Haller and Beron-Vera 2013, 2014; Haller et al. 2016; Serra and Haller 2016; Hadjighasem et al. 2016, 2017). These developments have enabled the construction of specialized deterministic techniques for the extraction of LCS from velocity fields that depend aperiodically on time (as is the case of the ocean flow) and are defined over finite time intervals (as is the case for numerical simulations, experiments or observations).

Understanding these structures is important because it helps explain the existence of a particular tracer pattern based on a firm theoretical basis (Beron-Vera 2015). But this exceeds a mere theoretical interest. Indeed, identifying LCS has very practical consequences. For instance, it allows one to carry out precise calculations of transport (of mass, heat, or salt) by eddies (Beron-Vera et al. 2013; Wang et al. 2015, 2016), including Loop Current rings (Andrade-Canto et al. 2013; Romero et al. 2016; Olascoaga et al. 2018; Beron-Vera et al. 2018). Also, these structures can be used for tracking the initial distribution of a current tracer distribution, such as for locating the nutrient source of a Florida red tide (Olascoaga et al. 2008). They are useful, too, in making predictions of how the shape of a certain tracer distribution (e.g., oil from a spill such as that produced by the explosion of the Deepwater Horizon) will change over time (Olascoaga and Haller 2012; Olascoaga et al. 2013). LCS can furthermore help identify flow regions difficult to reach by pollutants originated from sources outside of the regions, but at the same time can be heavily impacted by pollutants released within the region and provide the required isolation to favor the development of toxic blooms such as in the West Florida Shelf, the Louisiana-Texas (LaTex) Shelf, or the Yucatan Shelf (Olascoaga et al. 2006; Olascoaga 2010). LCS can, in addition, unveil persistent transport patterns from long-term circulation model simulations which are not obvious in mean flow streamlines, such as those produced by state-of-the-art models of the GOM (Duran et al. 2018; Gough et al. 2018). Moreover, patterns formed by floating objects such as marine debris or unanchored buoys are organized around LCS underlying the flows induced by these objects (Beron-Vera et al. 2016), as has been shown for buoys deployed from airplanes in the GOM (Beron-Vera et al. 2015).

Additional developments led to probabilistic approaches to LCS which expanded the reach of the above deterministic approaches. An especially interesting aspect of these approaches is that they cover the possibility of a statistical description of the long-term evolution of a passive tracer. This includes the opportunity of identifying regions of the flow where trajectories converge in forward time, as well as the regions where those trajectories originate from (i.e., their backward-time basins of attraction), thereby determining the connectivity between separated locations in the flow domain (Dellnitz and Junge 1999; Froyland 2005). Attracting regions may be small and trap tracer for long periods of time before eventually exiting and forming what are known as almost-invariant regions. If their basins of attraction are large, they can exert great influence on the global Lagrangian dynamics. Decomposition of the surface-ocean flow into almost-invariant sets is the foundation of a dynamical geography of an ocean region, where the boundaries between basins are determined by the Lagrangian circulation itself rather than by an arbitrary geographical division. Offshore oil exploration, oil spill contingency planning, and fish larval connectivity assessments are among the many activities than can benefit from the dynamical information contained in such a geography.

Recently, Miron et al. (2017a) computed for the first time a dynamical geography for the GOM using the largest collection to date of satellite-tracked drifter trajectories. The dynamical geography revealed a basic partition of the GOM into two halves by a line running from the Mississippi Delta to the tip of the Yucatan Peninsula. In particular, the western province forms the basin of attraction for trajectories accumulating temporarily along a region of the US-Mexico maritime border. Interestingly, this region turns out to lie within Atlantic bluefin tuna preferred breeding grounds (Teo et al. 2007). On the other hand, this region includes the Perdido Foldbelt, a geological formation that is known to have great ultra-deepwater oil exploration potential. Refined partitions of the GOM dynamical geography highlighted the LaTex, West Florida, and Yucatan shelves as regions weakly communicated with the rest of the GOM.

The above techniques critically rely on the availability of flow realizations (the deterministic approaches) or fluid trajectories (the probabilistic approaches). Fluid trajectories are in many cases well approximated by satellite-tracked drifter trajectories, but these may not be available with the required spatiotemporal coverage. Also, drifter datasets are not uniform in design, so variations in water-following characteristics can be expected (Beron-Vera et al. 2016). Likewise, flow realizations may not be available with the required spatiotemporal coverage, either directly or indirectly, from observations. Direct flow observations such as those obtained from current meters are highly localized in space. A widely-used, indirect source of velocity data is given by satellite altimetry. But this can only resolve the mesoscale range of the kinetic energy spectrum, which may have substantial levels of energy in the submesoscale range (Corrado et al. 2017). High-frequency radar technology can access the submesoscale range, but it is restricted to near-coastal areas. Thus, to this date, flow realizations with the required spatiotemporal coverage can only be provided by ocean general circulation models.

A subject of intensive debate is "What is the smallest horizontal scale a model should resolve to produce reliable flow realizations for meaningful Lagrangian transport calculations?" To answer this question, knowledge of the actual shape of the kinetic energy wavenumber spectrum, E(k), is critical (Bennett 2006; LaCasce 2008). If $E(k) \sim k^{-5/3}$, the dispersion of pairs of particles (or "relative dispersion") is local, meaning separations between pairs of particles are dominated by eddies of comparable scales. If $E(k) \sim k^{-3}$ or steeper, the dispersion is nonlocal and governed by the largest eddies in the k^{-3} range. Thus, when dispersion is local, deterministic transport calculations are essentially hopeless because a model would have to resolve the velocity field all the way into the submesoscale range. In that range, state-of-the-art, primitive-equation (i.e., hydrostatic) ocean general circulation models are not valid, and the reliability of simulations based on such models is uncertain (McWilliams 2008). But if, on the other hand, the interest is in describing transport statistically, then the situation is less pessimistic: a coarse representation of the velocity field with the addition of diffusion may be sufficient. By contrast, if dispersion is nonlocal, low-resolution model simulations can be enough for producing meaningful deterministic transport calculations.

Local dispersion produces small scale "billowing," as with smoke from a stack, while nonlocal dispersion results in filaments. Particle dispersion can thus be used to infer aspects of the energy spectrum. This has been attempted in the GOM using satellite-tracked drifters, mainly deployed in the northern part of the GOM. LaCasce and Ohlmann (2003) examined "chance pairs" of drifters (i.e., drifter pairs, which while not deployed together, approached one another after deployment) from the Surface-Current and Lagrangian drifter Program (SCULP) (Ohlmann and Niiler 2005) and found nonlocal dispersion below the deformation radius, which is approximately 45 km in the GOM (Chelton et al. 1998). Supporting evidence, using pair separation probability distribution functions (PDFs), was obtained by LaCasce (2010). However, using different measures (the second order longitudinal velocity structure function and the separation averaged relative diffusivity) with original drifter pairs from the Grand LAgrangian Deployment (GLAD) in the vicinity of the DWH oil spill site (Olascoaga et al. 2013), Poje et al. (2014) concluded the dispersion was local, from a few hundred meters to several hundred kilometers, implying a shallower kinetic energy spectrum. Analyzing the same drifter dataset using various measures of dispersion, Beron-Vera and LaCasce (2016) obtained ambiguous results, some indicating local dispersion (in which pair separations exhibit power-law growth) and others suggesting nonlocal dispersion. The reason for the discrepancies across the measures was attributed in part to inertial oscillations, which affected the energy levels at small scales without greatly altering pair dispersion, and also to the fact that the GLAD drifters were launched over a limited geographical area, producing few independent realizations and hence low statistical significance.

Relative dispersion was also investigated in the southwestern GOM, but only using chance pairs (Zavala-Sansón et al. 2017). The set of drifters used was part of a long-term program of oceanographic observations funded by PEMEX and conducted by CICESE. Zavala-Sansón et al. (2017) found nonlocal dispersion from the analysis of time-dependent measures (separation PDFs and second and fourth moments) versus local dispersion from the analysis of distance-dependent measures (e.g., separation-averaged relative diffusivity). In this case, the reason for the discrepancies might be attributed to limited geographic sampling and, consequently, lack of statistical independence. But these discrepancies may well reflect differences in how quickly chance pairs lose their "memory" of their initial condition, which depends on the correlation between their initial separation and velocity (Babiano et al. 1990).

1.3.6.3 Transport Processes in the Southern GOM

The above studies have shed some light on the nature of relative dispersion, and consequently the shape of the kinetic energy wavenumber spectrum in the GOM. Further research is still needed to constrain it better, especially in the southwestern GOM, where the uncertainty is larger due to poorer sampling compared to that in the northern and northwestern GOM. But why study transport processes in the southwestern GOM? There are a number of important reasons.

The southwestern GOM constitutes a large subsystem of the much larger GOM marine ecosystem, a mixture of ecological characteristics of temperate and tropical environments (Kumpf et al. 1999). It receives discharges of nutrients and dissolved organic material from many natural river systems and a network of coastal lagoons and estuaries, which favor the development of environmentally- and biologically-diverse coastal systems. Coral reefs with variable morphology and development are found on the East Mexico Shelf, which narrows from a width of about 90 km to 6 km from north to south and then widens to~150 km or more as it encounters the Yucatan Shelf. The variable morphology of the reef system is mainly attributed to the sedimentary gradient on the shelf, ranging from terrigenous to biogenic materials (Lara et al. 1992; Ortiz-Lozano et al. 2013). The physiographic complexity of the region is important in modifying flows generated by different components of the circulation, supporting retention and survival of the reefs (Salas-Pérez and Granados-Barba 2008).

The mesoscale circulation of the southwestern GOM is influenced by Loop Current rings. Loop Current rings are anticyclonic eddies of 150–300 km in diameter that pinch off from the Loop Current and travel westward across the GOM nearly reaching the western margin (Vukovich 2007). These eddies do not seem to penetrate south of 22º N into the Bay of Campeche, where a semipermanent mesoscale cyclonic circulation known as the Campeche Gyre tends to develop (Monreal-Gómez and Salas de Leon 1997). Based on oceanographic data, Vázquez de la Cerda et al. (2005) documented the Campeche Gyre and argued that it is seasonally forced by the wind, but the actual drivers of the gyre are still largely unknown (Cordero-Quiros 2015). Using surface drifters and moorings, Pérez-Brunius et al. (2013) found that the Campeche Gyre tends to reside on the western side of the Bay of Campeche, possibly topographically constrained by the continental shelf break. An additional important characteristic of the southwestern GOM is the presence of intense currents along its western margin that can flow in either direction. On the continental shelf, the direction of the flow depends on the along-coast winds or the presence of eddies interacting with the shelf (Zavala-Hidalgo et al. 2003; Dubranna et al. 2011). Along the continental shelf break, a western boundary current flowing northward is present throughout the year, driven by the wind stress curl over the northern GOM (Sturges 1993; DiMarco et al. 2005). Its intensity varies with the seasonal variability of the wind curl and by the presence of mesoscale eddies on synoptic scales (Dubranna et al. 2011). In addition to along-shelf transport, transport tends to develop across the narrower portions of the continental shelf, where the East Mexican Shelf meets the Yucatan Shelf and the southern LaTex Shelf, and varies during the year depending on the wind forcing (Zavala-Hidalgo et al. 2014).

Due to its high biodiversity and living resources as well as urban and industrial expansion and energy resources, the southwestern GOM has been considered strategic in national plans for the social and economic development of Mexico. The discovery of fossil fuel reserves in the seabed of the Bay of Campeche in the 1970s promoted the rapid expansion of the Mexican oil industry in offshore waters. Large regions over the Yucatan Shelf are currently home to numerous offshore rigs and oil platforms, exposing the southwestern GOM ecosystem to potentially negative environmental impacts.

Indeed, tropical marine systems maintain a delicate ecological balance among their different components that can easily be disrupted by anthropogenic disturbances. Major oil spills are prone to cause severe and long-term ecological effects (Soto et al. 2014). An example of an accidental oil spill in the region is the one produced by the explosion of Ixtoc I, an exploratory oil well drilled by a semisubmersible drilling rig in waters nearly 50 m deep. In June 1979, the well suffered a blow-out resulting in the world's first massive oil spill occurring in offshore waters of a tropical environment. More than 3.4 million barrels of crude oil were released into the southwestern GOM over nearly 9 months (PC-EESC 1980). Growing concern has been building ever since this ghastly oil spill because of the harmful environmental effects on a marine ecosystem that was once known for its pristine characteristics before the rapid expansion of oil exploration and the extraction of fossil fuels in the area.

The regions of oil exploration have extended in recent years further away from the Yucatan Shelf and into the southern LaTex Shelf, expanding the areas exposed to potential anthropogenic stress beyond Mexican waters. Indeed, the Mexican national oil company made a major discovery in the Perdido Foldbelt in 2012. The Perdido Foldbelt is a geological formation that encompasses an area of nearly 40,000 km^2 across the maritime border between the United States and Mexico, which is a rich discovery of crude oil and natural gas that lies in water that is close to 2,500 m deep. On the US side of this rich oil-gas reservoir, international oil companies are already producing large amounts of oil and planning expansions.

Hence, it is of utmost interest for the environment and the Mexican and US economies to study the short- and long-term fate of pollutants released in the southwestern GOM. Specifically, it is quite relevant to determine under what circumstances a tracer will remain in the south or otherwise will spread and move northward, identifying scenarios in which either or both situations could take place. The nonlinear dynamics tools discussed above have been designed to specifically address these kinds of problems.

For instance, they can be used to identify in an observer-independent fashion Loop Current rings with coherent material boundaries at the time of generation and track them across the GOM until their demise. Because of the potential of these mesoscale rings in shaping the circulation in the southwestern GOM, it is of interest to determine with precision their fate as they reach the continental margin. Do they migrate northward or southward upon encountering this margin? Are there offspring byproducts of these encounters? What is their precise fate? These and many other pertinent questions may be answered by applying deterministic LCS detection designed to reveal coherent Lagrangian eddy motion (Haller and Beron-Vera 2013; Haller et al. 2016).

Deterministic LCS detection can also be utilized to unveil cores along LCS with uninterrupted attraction (Olascoaga and Haller 2012; Olascoaga et al. 2013). When applied in backward time, this so-called LCS-core detection can be used to make predictive assessments of the evolution of a tracer patch. More specifically, it can be used to predict sudden changes in the shape of an oil slick from a spill with a few days of anticipation using velocity information up to the moment of the assessment without the need of predicted ocean velocities beyond that moment.

The connectivity problem can be tackled using the probabilistic LCS methods (Froyland et al. 2014; Miron et al. 2017b). Determining ecological reserves can benefit from the information contained in the dynamical geographies determined by the Lagrangian circulation that these techniques can help construct. A question that the probabilistic techniques can elucidate is the extent to which the southwestern GOM reefs are connected with the LaTex shelfbreak reefs. Likewise, regions that may be more susceptible to ecological damage for being isolated can be detected using the probabilistic LCS methods. Where does pollution tend to accumulate? Where are the sources of pollution located? These are important questions since there is a growing consensus that chronic oil pollution caused by inshore and offshore routine operations is eventually as harmful to the environment or more harmful than accidental oil spills.

In all cases, as noted earlier, reliable flow realizations or sufficiently dense Lagrangian observations (buoy trajectories) are critical. The latter can be used directly to feed the probabilistic LCS methods and reveal 2-D aspects of the upper-ocean Lagrangian circulation (if surface drifters are considered) or 3-D aspects of the deep-ocean Lagrangian motion (if submerged float trajectories are analyzed). These data in large amounts are fundamental to elucidate the essential features of oceanic turbulence, and thus validate ocean general circulation models that assimilate available observations including altimetry data. That the latter may or may not be a reliable source of velocity data in the southern GOM, given the presence of the wide Yucatan Shelf, needs to be thoroughly assessed. All this demands a comprehensive observational program.

Beron-Vera and LaCasce (2016) have provided guidance for making surface drifter deployments in such a way that they produce statistically-independent pairs of trajectories which are meaningful for relative dispersion studies. The deployments must be planned to account for the fact that the spatial decorrelation scale tends to be on the order of the Rossby radius of deformation, about 45 km in the GOM. This indicates that well-spread drifter pair deployments should be preferred over localized deployments. If this is not feasible in practice, then a similar effect may be achieved by repeated pair deployments at intervals longer than the temporal decorrelation scale, which is of one day or so at the surface (LaCasce 2008). Numerical experimentation suggests that a very large number of independent pairs of trajectories is not needed to produce robust separation statistics. Indeed, on the order of 100 pairs may be enough to achieve the goals. Existing oil rigs might perhaps be used as platforms for coordinated, repeated drifter pair deployments.

Longer spatial and temporal decorrelation scales can be expected deeper in the water column. The Lagrangian circulation in the deep ocean is by far much less understood than the surface ocean Lagrangian circulation. Some understanding has been recently gained from the analysis of submerged floats. Pérez-Brunius et al. (2017) describe an abyssal cyclonic circulation in the western basin, and Miron et al. (2018) construct a Markov-chain model that reveals a partition into various weakly communicating deep-flow regions. Deployment and analysis of additional submerged floats is required to shed further light on the picture, including the tendency of floats deployed inside the deep GOM domain to remain within the domain (Pérez-Brunius et al. 2017; Miron et al. 2018) in connection with ventilation of the abyssal layer (Rivas et al 2005).

Dense mooring arrays across the continental shelf recording velocity using ADCPs and hydrographic variables over long periods of time in a sustained manner would ideally complement the drifting buoy dispersion analyses and together would help determine the structure of the kinetic energy spectrum in the region. The information gathered would provide metrics for model performance and eventually could be used in model development.

The near-coastal Lagrangian transport may be monitored by high-frequency radars. While plans exist to establish a network of radars along the southwestern GOM, validation of the velocity fields inferred from the radar measurements is critical. This can be achieved by satellite-tracked drifter deployments and possibly dye releases in the coastal environment.

In summary, the southwestern GOM offers a number of opportunities for using nonlinear dynamics techniques to advance knowledge in transport processes. The knowledge gained would be very helpful for guiding activities such as those dealing with preventing and/or ameliorating the effects of accidental as well as chronic oil spills or blooms of toxic algae, or for supporting stock assessment efforts and management decisions for fishing regulations. These are all matters of concern for both the Mexican and US societies, so collaboration between the two countries should be encouraged for their mutual benefit.

1.3.6.4 References

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