Lagrangian characterization of surface transport from the Equatorial Atlantic to the Caribbean Sea using climatological Lagrangian Coherent Structures and Self-Organizing Maps

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Key Points:

- Current transport routes and barriers are characterized from the Equatorial Atlantic to the Caribbean Sea.
- Wind forcing is a significant factor in transporting suspended material by surface ocean currents.
- Different areas in the Caribbean Sea require distinct wind conditions for floating material to arrive.
- Transport routes and barriers over large regions can be characterized using tools from dynamical systems and unsupervised neural networks.

Abstract

This study presents an assessment of the transport of suspended material by surface ocean currents, which have a critical role in determining the connectivity and distribution of living and non-living material. Lagrangian experiments reveal pathways from the Equatorial Atlantic to ten strategic regions within the Caribbean Sea, determined by considering the space-time variability of climatological Lagrangian Coherent Structures, which act as recurrent attracting pathways and transport barriers. Due to windage or Stokes drift, wind forcing is a significant factor in determining the spatial locations where particles cluster and the time needed to reach the Caribbean from the Equatorial Atlantic. Pathways shift westward within the Caribbean and take less time to arrive with increasing wind influence. Depending on the wind effect, the particles show higher confluence in different areas of the Caribbean. A case study is presented for the Mexican Caribbean nearshore area, isolated from ocean-current trajectories. Here, wind weakens the transport barrier responsible for this isolation and causes particle confluence towards that region. Spatial patterns of the Eulerian velocity identified through Self-Organizing Maps, with time dependence given by their best matching units, can reproduce the characteristic Lagrangian patterns of surface current climate variability. Our study demonstrates the application of tools from dynamical systems and unsupervised neural networks to understand Lagrangian patterns and identify the processes that drive them. These findings improve our understanding of transport mechanisms of suspended material by surface ocean currents in the Western Atlantic and the Caribbean Sea, which is essential for managing and conserving marine ecosystems.

Plain Language Summary

Ocean currents' movement of suspended material is important for ecosystems as it affects the connection of marine populations and the distribution of suspended material such as plastics and sargassum. This research studies the transport routes from the Equatorial Atlantic to the Yucatan Peninsula by identifying the distribution of particles in different Caribbean Sea areas. We used different analysis methods to determine the transport pathways and natural barriers. When barriers are present, particles cannot reach certain areas without the influence of wind. We found that particles released during the autumn-winter months with a 1% windage reached the Yucatan Peninsula in the following year's spring, while particles released in the spring months with a 2% windage reached the area in the summer months of the same year. Understanding the effect of wind forcing over suspended particles moving over surface ocean currents allows for better managing and conserving marine ecosystems.

1 Introduction

Ocean currents are a major factor in the movement of suspended material over large distances along ocean basins. The conveyance of suspended material by currents as a main transport mechanism is critical for ecosystems as they determine the connectivity of some marine populations inhabiting the benthic or pelagic environments (e.g., Bryan-Brown et al., 2017; Sanvicente-Añorve et al., 2014, 2018). Ocean currents also transport contaminant materials derived from anthropogenic activities (Dow, 1999; Pohl et al., 2020; Zaborska et al., 2017), eventually reaching the coast, accumulating in remote places, or sinking to the ocean bottom. Considering the importance of currents in transporting living and non-living suspended material, it is crucial to understand their kinematics. For the Tropical Atlantic, different authors have described the surface currents (Johns et al., 2014; Lumpkin & Garzoli, 2005; Müller-Karger et al., 1989), while others have characterized the climatological surface currents from the western tropical Atlantic to the Gulf of Mexico (GoM) (Andrade & Barton, 2000; Gordon, 1967; Johns et al., 2002; Muller-Karger et al., 1988, 1995; Romanou et al., 2004; Zavala-Hidalgo et al., 2014). Recently, studies have focused on understanding the sargassum transport routes from the Equatorial Atlantic through the Caribbean Sea (CS) and into the GoM (Athié et al., 2020; Beron-Vera et al., 2022; Orfila et al., 2021; Ortiz-Royero et al., 2013; Otero et al., 2016; Putman et al., 2018, 2020). This is due to the emergence of a new sargassum generation area in the tropical Atlantic (Gower et al., 2013; Wang & Hu, 2017), resulting in substantial environmental, social, and economic effects across the Caribbean region. Besides sargassum, understanding the currents system from Equatorial Atlantic to the GoM is relevant for plastics (Law et al., 2010), nutrients (Williams & Follows, 2003), and organisms (Sanvicente-Añorve et al., 2019), as the results indicate the fundamental role of the North Brazil and Guyana currents (Johns et al., 2014), establishing the connectivity between the western Atlantic and the Caribbean (Andrade-Canto & Beron-Vera, 2022; Muller-Karger et al., 1988, 1995).

The Equatorial Atlantic to the GoM currents system has a clear seasonal variability. During the summer and fall, a significant part of the North Brazil Current (NBC) retroflects and merges into the eastward-flowing North Equatorial Countercurrent (NEC), which then intensifies. In spring, the NEC weakens and superficially reverses. In some cases, the NBC and the western boundary current to the north intensify simultaneously, forming part of the North Atlantic large-scale gyre moving northwestward to the CS (Garzoli et al., 2003; Johns et al., 2003). The current dynamics in the CS are dominated by a primary jet that forms the Caribbean Current (CC) as water is transported through the southern region of the Lesser Antilles by a boundary current along the South American coasts (Rhein et al., 2005), continuing to flow northwestward through the Yucatan Channel. The southern CS has small recirculation gyres off Panama and south of the Yucatan Channel interacting with the bathymetry, while the slower northern jet is dominated by mesoscale anticyclones (Chérubin & Richardson, 2007). In addition to ocean currents, atmospheric forcing influences

surface transport, partly determining the trajectory of near-surface material (Johns et al., 2020; Müller-Karger et al., 1989; Putman et al., 2018). The atmospheric variability in the region is dominated mainly by the easterly winds, which in turn are modulated by the Intertropical Convergence Zone (ITCZ) migration, cold fronts' arrival, and the Caribbean Low-Level Jet (CLLJ) variability. This atmospheric dynamic results in two climatic seasons, a windier and drier season from December to March and the wet season from August to November, regulated by the location of the ITCZ. May-June and September-October are considered a transition period between seasons since easterlies tend to weaken, coinciding with the intensification and bi-modal variability of the CLLJ (García-Martínez & Bollasina, 2020; Hidalgo et al., 2015; Orfila et al., 2021).

While the mentioned studies characterize the ocean currents system or the atmospheric variability in the region, the interaction of wind, waves, and surface currents dictate transport routes of floating matter in the ocean's surface layer. As such, this study aims to characterize sea-surface current patterns and assess the effect of surface currents and wind interaction on the displacement of floating particles. We utilized Self-Organizing Maps (SOMs) and climatological Lagrangian Coherent Structures (cLCS) to identify the primary transport routes and transport barriers in the region stretching from the western tropical Atlantic to the Central Subtropical Atlantic, including the entrance to the GoM and the Yucatan Peninsula (YP). We used synthetic surface drifters to compute the probability of arrival at select locations within the CS with an emphasis on the eastern coast of the YP, where we also included the effect of wind over the drifters. The results show how the windage plays a key role in advecting particles to some areas along the CS but also provide insight into using SOMs to represent climatological conditions for particle dispersal. This paper is organized as follows: section two describes the data and methods; section three presents the results, describing preferential routes for different combinations of wind and currents, persistent attraction zones and transport barriers by the wind. We summarize our main findings in section four.

2 Data and Methods

Our study uses daily sea-surface velocity data from a 25-year climatology (1994-2018) based on the HYbrid Coordinate Ocean Model (HYCOM) reanalysis, encompassing from the Equatorial Atlantic Ocean to the coast of North Carolina, USA, including the Gulf of Mexico, as delimited by coordinates -100°W to -20°W and -7°S to 35°N (Figure 1 and Figure S1 in Supplementary Information). To gain a deeper understanding of the primary current pathways and transport barriers, we computed climatological Lagrangian Coherent Structures (cLCS) and identified the main current patterns using Self-Organized Maps (SOMs). The cLCS provided insights into the transport barriers and primary current pathways, while the SOMs allowed us to efficiently characterize the system by synthesizing spatial and temporal variability into limited current patterns. To further identify transport routes, the effect of wind, and the probability of particle arrival in the CS region, we conducted Lagrangian experiments under three different scenarios: (i) currents without additional wind, (ii) currents with an additional 1% of wind, and (iii) currents with an additional 2% of wind. For each scenario, we integrated trajectories using time-dependent velocities from a HYCOM climatology, wind climatology, and SOMs patterns. We further illustrate the implications of our findings by analyzing a case study for the YP. Our approach allowed us to understand the region's ocean currents system, characteristics. and response to varying wind conditions in Lagrangian terms. Following is a description of the data and methods employed in the study.



Figure 1. Study area denoting the region for the Caribbean Sea particle analysis (red box). Surface currents time-averaged from the HYCOM climatology; the colors indicate the current's magnitude, the arrows' current direction, and the red asterisks the location from which the particles were released. The acronyms shown are referred to in the text and correspond to the following: Gulf of Mexico (GoM), Yucatan Peninsula (YP), Florida Current (FC), Gulf Stream (GC), Loop Current (LC), Caribbean Current (CC), Guyana Current (GC), North Brazil Current (NBC), North Equatorial Atlantic (NEA), North Equatorial Current (NEC), North Equatorial Recirculation Region (NERR).

2.1 Data

2.1.1 Currents

To characterize ocean currents, we used the horizontal surface velocity components from HYCOM (CDAM, 2015). HYCOM is a primitive equation ocean general circulation model that remains isopycnic in the open stratified ocean, smoothly reverting to a terrain-following coordinate near the bottom and z-level coordinates in the mixed layer and/or unstratified seas (Bleck, 2002). HYCOM provides different vertical mixing schemes for the surface mixed layer and the interior diapycnal mixing, parameterizing the contribution of background internal wave breaking, shear instability mixing, and double diffusion. Processes are parameterized in the surface boundary layer, including wind-driven mixing, surface buoyancy fluxes, and convective instability (Chassignet et al., 2003; Halliwell, 2004; Large et al., 1997). HYCOM simulations include the Navy Coupled Ocean Data Assimilation data (NCODA) (Cummings, 2006; Cummings & Smedstad, 2013). We used the eastward (u -component) and northward (v -component) surface current velocity from the HYCOM + NCODA GOFS 3.1 reanalysis from 1994 to 2015, and analysis GLBv0.08 experiment from 2016 to 2018, which has a temporal resolution of 3 hours and a spatial resolution of $1/12^{\circ}$. In the rest of the article, we refer to this velocity time series as HYCOM. HYCOM is forced by the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR), described in the next section. We calculated daily means for the current data to create the 25-year climatology. A critically important aspect to this study which is based on climatological currents: Duran et al. (2018) showed that climatological ocean currents preserve the ensemble-mean Lagrangian transport patterns of the instantaneous velocity, thus using a climatological velocity to study instantaneous Lagrangian patterns produces meaningful results; more details are presented in section 2.2.1.

2.1.2 Wind

The wind used for this study is a climatology computed from the CFSR, the same wind used to force the HyCOM simulations described in 2.1.1. This reanalysis is a fully coupled model representing the interaction between the atmosphere, oceans, land, and sea ice, described by Saha et al. (2010). The CFSR assimilates in situ and satellite observations using sigma-pressure hybrid vertical coordinates, a simplified Arakawa-Schubert convection scheme with momentum mixing (Hong & Pan, 1996, 1998; Pan & Wu, 1995), and orographic gravity wave drag (Alpert et al., 1988, 1996; Young-Joon Kim & Arakawa, 1995). The land surface model is based on the two-layer OSU land model (H. L. Pan & Mahrt, 1987), the SW radiation is parameterized following the NASA approach (Chou et al., 1998; Hou et al., 2002), and the LW radiation following the GFDL approach (Fels & Schwarzkopf, 1975; Schwarzkopf & Fels, 1991), based on the RRTM developed at AER (Taubman et al., 1997). CFSR is coupled to a four-layer Noah land surface model (Ek et al., 2003) and a two-layer sea ice model (Wu et al., 2005). The temporal data resolution is 1 hour, with a spatial resolution of 0.5° . We used the zonal (*u* -component) and meridional (*v* -component) wind 10 m above the surface from the CFSRv1 and CFSRv2 reanalysis data. To ensure consistency, we also calculated daily means for the wind data and interpolated them onto the current data grid to create the 25-year climatology. For interpolation, we employed the Modified Akima cubic Hermite interpolation method. This approach utilizes a piecewise function of polynomials, with a maximum degree of three, to interpolate the values of neighboring grid points in each dimension. Specifically, the method employs local data information to generate a continuous curve that passes through the given data points while minimizing the curvature in the resulting interpolated function.

2.1.3 Drifters

To validate particle model parameterizations and particle displacement in the Lagrangian experiments, we used the Global Drifter Program (GDP) data (*National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory*, 2019). The GDP is a branch of NOAA's Global Ocean Observing System and a scientific project of the Data Buoy Cooperation Panel (*Data Buoy Cooperation Panel*, 1885). The GDP maintains a global 5° x 5° gridded array of ~1,300 satellite-tracked surface drifters to meet the need for an accurate and globally dense set of *in situ*observations of mixed layer currents, sea surface temperature, atmospheric pressure, winds, waves, and salinity (Lumpkin & Pazos, 2009). Elipot et al. (2016) describe the interpolation methods for drifter trajectories. We used surface drifter trajectory data from 2017 and 2018 with an hourly resolution.

2.2 Analysis

2.2.1 Climatological Lagrangian Coherent Structures

In recent decades, the theory of nonlinear dynamics has been applied to vector fields with arbitrary time dependence, such as geophysical datasets. Thorough reviews can be found in Samelson (2013) and Haller (2015). The result of this research—often termed Lagrangian Coherent Structures (LCS)—has been shown in many studies to accurately identify, and even predict, ocean kinematics (e.g., Beron-Vera et al., 2008, 2019; Duran et al., 2021; Filippi et al., 2021; Olascoaga et al., 2006, 2008, 2013; Olascoaga & Haller, 2012). LCS have proven an ideal tool to search for persistent and recurrent pathways in the ocean, enabling the detection of low-frequency structures that tend to modulate parcel's movements, and that cannot be reliably found using Eulerian methods (Duran et al., 2018). Termed climatological LCS (cLCS), these structures provide a generic yet accurate and detailed Lagrangian climatology without the need to know trajectories' initial location, initial time, or when the trajectory ends. Of particular interest to our study, cLCS have been shown to be effective in identifying transport barriers and dominant pathways. Comparisons with a variety of observed and synthetic drifter data have shown that strongly attracting cLCS can act as efficient transport barriers, considerably reducing cross-cLCS transport, other strongly attracting cLCS indicate recurrent pathways, including possibly when cLCS are deformed as chevrons (Duran et al., 2018; Gough et al., 2019: Gouveia et al., 2021). In regions where currents are less energetic, cLCS are less attracting and are more often deformed as chevrons, thus indicating recurrent pathways as well (Kurczyn et al., 2021). These Lagrangian transport patterns can be efficiently and accurately extracted from large time series of Eulerian velocity data with the proper tools from nonlinear dynamics (Duran et al., 2018), but cannot be identified

with commonly used Eulerian methods, such as streamlines of a time-averaged velocity (e.g., supplemental information of Duran et al., 2018). While cLCS have proven very efficient in identifying predominant and recurrent Lagrangian patterns, we note that they cannot always explain instantaneous patterns, similar to how the climate is useful but cannot always explain the weather. Additional evidence of the adequacy of the climatological velocity for our study is provided in Text S1, where we show that the climatological currents have very similar patterns to the instantaneous 1994–2018 time series using Self-Organizing Maps.

cLCS are based on the concept of hyperbolic LCS, material lines that maximize the normal attraction of nearby trajectories; thus, LCS delineate and shape Lagrangian transport. cLCS differ from LCS in two crucial ways. Firstly, cLCS are computed from a climatological velocity instead of an instantaneous one. Secondly, the Cauchy-Green tensor, needed to solve the normal-attraction maximization problem, is averaged over different initial times while LCS are computed from the Cauchy-Green tensor of one initial time. In Duran et al. (2018), these two averaging steps are shown to efficiently preserve and extract the main Lagrangian transport patterns from large time series of instantaneous velocities. Because of the latter averaging step, cLCS are not material lines but rather result in an Eulerian field representing recurring or persistent trajectory patterns. Interested readers can refer to Duran et al. (2018) for further details and mathematical explanation, while detailed information regarding the numerical implementation is found in Duran et al. (2019).

We obtained cLCS from the daily HYCOM climatology described above, which allows us to characterize the Lagrangian kinematics of the currents in the study area, identifying transport routes and barriers. The code to compute cLCS is freely available (Duran et al., 2019).

2.2.2 Self-Organizing Maps

SOMs are a non-linear technique of artificial neural networks based on an unsupervised training process that allows multivariate analysis. The results obtained using SOMs retain the original data's topology while projecting into a two-dimensional scheme for simplification. This allows for visualizing, classifying, grouping, and detecting complex patterns of any set of variables used in training simultaneously (Liu et al., 2006). SOMs have been used for long-term currents characterization and to study the possible hydrodynamic conditions in specific regions, such as in Liu & Weisberg (2005, 2007), who obtained the current patterns on the west Florida platform and established a relationship between local winds and coastal up/downwelling processes, or as in Vilibić et al. (2016), who used the SOMs method for forecasting system of surface currents. More recently, Orfila et al. (2021) used SOMs to establish the patterns and seasonal dynamics of the southern CS. These examples show the versatility and capacity of the method as a useful and robust technique for pattern recognition and feature extraction in variables where non-linearity is important, as may be the case in oceanographic processes. Further details of the SOMs method are in Liu & Weisberg (2011).

In this study, we determined the current patterns by applying SOMs over the HYCOM 25-year climatology. The method uses a neighborhood function, a unit search radius, and a linear initialization process. The training algorithm employed a group series approach, carefully analyzing parameters to ensure the lowest quantization and topological errors, following best practices outlined by Meza-Padilla et al. (2019) and Liu et al. (2006). Before the training process, each variable was spatially and temporally normalized to prevent any single component from dominating the map organization in cases where its magnitude is disproportionately higher than that of the other components. This normalization ensured that all variables contributed equally to the SOMs, leading to a more balanced and accurate data representation. After the training process, the components were denormalized and further analyzed under the terms of each variable. The determination of each map size (cluster) is a subjective and empirical process that depends on the desired detail for the analysis (Liu, Weisberg, Lenes, et al., 2016; Liu, Weisberg, Vignudelli, et al., 2016; Meza-Padilla et al., 2019; Weisberg & Liu, 2017; Zeng et al., 2015). After a series of sensitivity tests, we choose the map sizes to obtain the minimum number without losing essential pattern variation. The sensitivity tests were based on the quantization error (QE), measuring how much detail is being learned by the SOMs, and on the topological error (TE), measuring the properties of the preserved space and the variation percentage of each pattern. This empirical procedure depends intrinsically on the study (Polzbauer, 2004). We determined the optimal number of patterns by quantifying the associated QE and TE errors through various tests using different cluster arrangements, including 2x2, 2x3, 3x3, 3x4, and 4x4. The results showed that the QE decreases using the 3x3 cluster, and although the TE increases when increasing the number of patterns, it remains an acceptable and small value in terms of space preservation. As a result, the spatial characterization was done for a cluster of nine patterns (3x3 cluster). An additional recommendation when using SOMs to integrate trajectories is to maximize the number of spatial patterns so that the temporal variability given by BMUs, will correctly approximate the data temporal variability. At some point, the method will detect that further spatial patterns do not provide any additional information, e.g., in our case with the 3x3 cluster, there is one pattern with 0% frequency; this means that eight spatial patterns are enough to extract the dominant patterns and therefore additional patterns will not improve the spatial or temporal representation of the data. We use the SOMs MATLAB Toolbox developed by Vesanto & Alhoniemi (2000) from the Laboratory of Computer and Information at the Helsinki University of Technology (Laboratory of Computer and Information Science, Adaptative and Informatics Research Center , 2015).

2.2.3 Lagrangian experiments

To identify transport routes and confluence zones in the study region, we conducted several numerical experiments using a particle advection model developed by the Ocean-Atmosphere Interaction working group at the Institute of Atmospheric Sciences and Climate Change of UNAM. This model has already been used to successfully model connectivity between coral reefs in the southern GoM (Sanvicente-Añorve et al., 2018, 2019). The Lagrangian model is implemented in MATLAB and operates offline with archived ocean velocity data from HYCOM, integrating with a second-order Runge-Kutta method. To simulate horizontal diffusion, we applied a random walk scheme (Fabbroni, 2009; Lynch et al., 2015; Majda & Kramer, 1999; Okubo & Levin, 2001), determining a diffusion coefficient of 13, by doing sensitivity tests with values in the range of 0 to 14 m²s⁻¹ (Döös et al., 2011; Döös & Jönsson, 2013; LaCasce & Ohlmann, 2003; Lara-Hernández et al., 2019). To calibrate the model, we used 21 GDP surface drifters released between 2017 and 2018 and optimized the diffusion coefficient to minimize the daily distance between the drifters and the corresponding numerical particles' positions after a 45-day advection. After 45 days, we calculated the daily distance between the drifter and the synthetic drifter positions. The optimal value of the diffusion coefficient resulted from finding the minimum distance between the numerical particles and the drifters in more than 50% of the particles. After calibrating the model, we conducted Lagrangian experiments by releasing 1,866,600 numerical particles (100 particles for each initial trajectory position) during a climatological year, every third day, starting January 1st. The release polygon covered the Central West Atlantic, between -45°W and -29°W longitude and 0° and 8°N latitude, and consisted of a 17 x 9 node grid with a spatial resolution of 1°. The Lagrangian model was integrated forward in time during a climatological year comprised of 365 days, starting when the particles were released. To complete a year of Lagrangian simulations, the field of climatological velocities was repeated consecutively. We used the HYCOM climatological daily data and the spatial patterns obtained from the SOMs analysis to drive the particle model with currents. The SOMs patterns were chronologically ordered according to the Best Match Units (BMUs), thus identifying the corresponding pattern for each day of the year. With this approach, we will demonstrate that the patterns obtained from SOMs are comparable, in Lagrangian terms, to the HYCOM data climatology. Besides forcing the Lagrangian experiments with currents from the HyCOM climatology and the SOMs patterns, we also forced them with these currents plus 1% or 2% of wind from the CFSR climatological daily data. To analyze the relationship between particle advection and the cLCS, we conducted a case study on the east coast of the YP. For this area, we delimited an irregular polygon to identify particles approaching the coastal region and calculated the yearly and monthly accumulated sum of particles.

3 Results and discussion

3.1 Hydrodynamic characterization

The hydrodynamic characterization from the Equatorial Atlantic to the GoM was done by characterizing the transport routes and barriers using the cLCS and identifying the main current patterns using the SOMs. As the cLCS denotes areas of maximum attraction (warm colors in Figure 2, where red indicates the highest attraction strength of nearby water parcels), they can be used to identify the likely displacement of the released particles in the Lagrangian experiments, presented in section 3.2. From the cLCS results, we identified four regions of persistent trajectories in the study area: (i) near the coast of Brazil, Suriname, and the French Guiana coasts (associated with the Guiana Current (GC) and the North Brazil Current (NBC), (ii) the Lesser Antilles, (iii) the channel between Honduras and Jamaica, and (iv) the region from the Yucatan Channel to the Florida Peninsula (associated with the Loop Current (LC), the Florida Current (FC), and the Gulf Stream (GS)). Besides being related to the intensification of currents, these regions constitute paths that maximize the normal attraction of nearby trajectories. This implies that any floating, suspended material or, as in this case, numerical particles, are attracted by the cLCS and can flow along them without crossing strongly-attracting cLCS, thus acting as transport barriers (Duran et al., 2018; Gough et al., 2019; Gouveia et al., 2021). These persistent trajectories organize and characterize Lagrangian transport, where the cLCS are critical to interpreting the Lagrangian expression of surface currents driving the transport of drifting material.



Figure 2. Annual climatological Lagrangian Coherent Structures. The colors indicate the strength of attraction, where red is the strongest, and white indicates low persistent stirring and isolated regions behind a transport barrier.

While cLCS allow us to characterize transport routes and barriers, SOMs enable identifying main patterns of surface velocity and their temporal occurrence. Using SOMs, we identified eight dominating patterns in a 3x3 array (Figure 3). Patterns 8 and 9 are slightly more frequent than the others. They occur from August-December when the North Equatorial Recirculation Region (NERR) and the NBC are well-defined and reach their maximum intensity. The cLCS showed the most extensive spatial coverage during these months in the NERR area. From January to April, patterns 7 and 4 show a significant decrease in the intensity of the NERR and the NBC, while there is an increase in the CC and LC magnitude. These four surface current patterns (8, 9, 7, and 4) occur 54.79% of the time, showing that the most intense surface currents in the study area are present about half the time. Of the four remaining patterns, pattern 3 stands out, as it shows an intensification of the currents from the Equatorial Atlantic to Florida (NERR, NBC, GC, CC, LC, FC), while pattern 2 shows the most well-defined LC, followed by pattern 4. Also, pattern 6 is relevant, as it thickens the NERR before reaching its maximum intensity. BMUs give the temporal evolution of the patterns: the NBC intensifies in the summer months to give rise to the formation and separation of the NERR, reaching its maximum latitudinal extension in September, between 10°N and -5°S. In this same period, the currents within the CS intensify, mainly in July and August, while the LC weakens in late August.

Between January and March, the NERR weakens, the CS current intensifies, and the LC is re-established. Each pattern's occurrence percentage was larger than 10% in all cases. Thus the SOM analysis provides a clear overview of the current variability observed in the HYCOM climatology and its evolution over a year.



Figure 3. The maps denote the identified spatial patterns by the Self-Organized Maps (a), while the time series (b) show the Best Match Units (BMUs), indicating the dates each pattern dominates. Each map, placed according to its occurrence, indicates a pattern (according to the number in parenthesis) and its respective percentage of spatial variability. The colors indicate the current magnitude, and the arrows the current direction. The BMUs are a key output of the SOMs analysis. These units provide information on the temporal evolution of each pattern the analysis identifies. Specifically, the BMUs indicate the duration or periodicity with which each pattern occurs. The red line indicates each pattern's period throughout the year.

3.2 Lagrangian experiments

3.2.1 North Equatorial Atlantic without wind

To understand the surface currents' Lagrangian transport, we used surface current velocity data to integrate the trajectories of particles released each third day and looked at the annual accumulated density of particles (Figure 4). When released between June and November, the distribution of particles shows that they tend to remain outside the CS and move towards the northeast. Notably, during this period, particles released in June and July remain in the NERR, and there is no significant increase in particle density in the North Equatorial Atlantic (NEA) areas. For particles released in September to November, the particles that can enter the CS leave to the North Atlantic by the northern arc of the Lesser Antilles. In contrast, particles released between December and May enter the CS, and while some leave to the North Atlantic, those remaining lead to the maximum particle density within the CS. This maximum density is located in the Lesser Antilles and the southern region of the Great Antilles.

The displacement and distribution of particles are associated with the ocean currents' seasonality (Athié et al., 2020; De Souza & Robinson, 2004; Holt & Proctor, 2008) and, therefore, with the cLCS location (Figure 2). Analyzing the particle distribution, we found that particles take approximately 8 to 10 months to reach

Florida from the Equatorial Atlantic. We also found that particles reach the Yucatan Peninsula (YP) and the GoM in about 6-7 months when released between October and January (Figure 4). Between May and August, the particles are spatially limited about 150 km offshore from Brazil to the YP, corresponding with the months the cLCS intensifies (Figures S2 in Supplementary Information and 4). Considering that cLCS have been shown to identify critical oceanic kinematics aptly, the cross-cLCS transport is often limited, and particle attraction causes flow along cLCS (Duran et al., 2018), our findings confirm that the cLCS act as transport routes and hydrodynamic barriers, limiting the movement of particles towards the coast. This highlights the influence of the continental shelf on ocean dynamics, where the transport is constrained not only by bathymetry but also by the Earth's rotation, leading currents to move along isobaths and inhibiting flow from crossing isobaths (vorticity conservation) (Brink, 2016).



Figure 4. Lagrangian experiments results. The maps show the annual accumulated particle density using the HYCOM climatology, without wind, and according to the release month. The annual accumulated particle density refers to the number of steps the particles take during a year. The black line is the coastline, and the gray line is the 200 m isobath.

The Lagrangian experiments were also performed using the spatial patterns identified by the SOMs analysis with the temporal evolution given by the BMUs (Figure 3) as the surface current velocity. The results (Figure 5) show that the SOMs' pathways and distribution of particles are similar to those from the HyCOM climatology. A difference between both datasets is that the velocity from the spatial SOMs remains stationary according to the BMUs time series (Figure 3). However, the differences in the distribution of particles are not significant, as we will describe in section 3.2.3. The SOMs Lagrangian results show that when particles are released between May and September, their accumulation in the CS is minimal (<300 particles). Starting in June, the NERR intensifies, the NBC moves eastward (Condie, 1991), and the cLCS intensifies at the coasts of Brazil, Suriname, the French Guiana, and the Lesser Antilles region.

On the other hand, the particles released in October-December show the effect of the NERR intensification and of the cLCS as transport barriers, which cause the particles to drift northward along the NEC toward the Sargasso Sea, and promote a large accumulation of particles from the Equatorial Atlantic to the north of the Dominican Republic. This could be associated with NBC rings that stall and decay east of the Lesser Antilles (between 14°N and 18°N) during these months, as described by Chérubin & Richardson (2007), and which could displace the particles to the northern part of the eastern CS and merging with inflow from the NEC. Between January and April, the NEA, the eastern CS, the Greater Antilles, and the Bahamas show the largest accumulation of particles. It should be noted that during this period, the cLCS in the Lesser Antilles and the Yucatan Channel are intensified, acting as transport channels that carry particles into the CS and the GoM, respectively.

Regardless of using the HYCOM climatology or the SOMs-derived velocities used in the Lagrangian expe-

riments, the particle trajectories show paths following the strongest currents and the spatial distribution of cLCS. Those paths create specific accumulation regions, particularly the NEA and the Lesser and Greater Antilles. However, these results do not consider wind as an additional forcing (e.g., windage), despite being one of the most critical factors determining the dynamics at the ocean surface, as we will analyze in the following experiments.



Figure 5. Lagrangian experiments results. The maps show the annual accumulated particle density using SOMs, without wind, and according to the release pattern. The color indicates the accumulated particle density, and the gray line is the 200 m isobath.

3.2.2 North Equatorial Atlantic with wind

Previous studies have shown the importance of wind over surface currents (Allshouse et al., 2017; Clarke & Van Gorder, 2018) related to the transport of particles (Johns et al., 2020; Kwon et al., 2019; Laxague et al., 2018; Lodise et al., 2019), we proceeded to include wind in the Lagrangian experiments. Lumpkin & Pazos (2007) found that near-surface drifters have a windage factor effect of ~1% in the wind direction, while drifters at 15 m depth have a windage effect factor one order of magnitude smaller. Later, Lumpkin et al. (2013) showed that this difference could be attributed to the combination of the surface wind drag, the vertical shear of wind-driven currents above 15 m depth, and the wave-induced Stokes drift, which was shown to be important by Clarke & Van Gorder (2018). Here we included the direct wind momentum transfer to floating material as windage (Putman et al., 2020) by adding 1% of the wind. To incorporate the effect of Stokes drift, as Clarke & Van Gorder (2018) suggested from analyzing large times series of observations, we included an additional 1% of the wind to the current velocity. As such, we study wind's influence at the surface by adding 1% of the wind and, in other experiments, by adding 2% of the wind. The latter may represent the effect of strong windage or the joint effect of windage and Stokes drift. Similar approximations have been applied by Putman et al. (2020), Johns et al. (2020), and Kwon et al. (2019).

Our results show that 1% windage is enough for the particles to remain in the CC and reach the GoM independently of the particle release month (Figure 6a). The 1% windage allows the particles to either approach the strong cLCS or to cross them so that they are advected towards the CS and follow their path into the GoM. The largest accumulation of particles near the northern CS and YP coast occurs for particles released between October and March, when the particles also reach the Florida coast, including the US Atlantic coast. The results suggest that the wind is a key factor for accumulating particles in coastal regions and that cLCS act as transport paths that cause particles to travel greater distances. Important to notice is that the particles released from September to January start entering the region of Central America, particularly the coastal zone of Costa Rica, Panama, and Colombia.



Figure 6. Lagrangian experiments results. According to the release month, the maps show the annual accumulated particle density using the HYCOM climatology, (a) with 1% and (b) 2% windage. The color indicates the accumulated particle density, and the gray line is the 200 m isobath.

We included a 2% windage to the Lagrangian experiments to approximate either strong windage or a combination of windage and Stokes drift (Clarke & Van Gorder, 2018). The results are shown in Figure 6b. We found that particles remain near the coastal zone from Brazil to the Lesser Antilles, covering the CS and reaching the GoM regardless of the release month. Under 1% windage, a high concentration of particles follows the LC between October to April. Still, under 2% windage, this stops occurring as the particles are advected further south before entering the LC. Nevertheless, a large concentration of particles reaches the northern coast of Mexico and Texas during March and April. Particles released between June and August with 2% windage remain in the NERR and leave the domain eastward, while those released from September to November enter the CS through the Lesser Antilles southern area, reaching the coasts of Nicaragua and the coasts of Central America. The particle's distribution and trajectories are associated with seasonal atmospheric variability. The periods of maximum particle accumulation coincide with the latitudinal displacement of the ITCZ (Aliaga Nestares et al., 2022; Haffke et al., 2016; Henke et al., 2012; Skliris et al., 2022), which gives rise to significant wind variability in the study area. When the ITCZ is in its southernmost location $(^{3})^{\circ}$ N) from February to March, the wind intensifies in the Caribbean area, causing the particles to move towards the southern region of the Caribbean basin and on the NBC between October and January. This period corresponds to a weakening of the cCLS in the Caribbean (Figure S2 in Supplementary Information). On the other hand, during the summer months (June to September), the windage intensity decreases in the Caribbean due to a northern displacement of the ITCZ ($^{11\circ}$ N), allowing the particles to advect towards the center and north of the Caribbean basin. This particle's distribution is expected due to the change of direction of the trade winds (Orfila et al., 2021). During these months, the cLCS intensified in the Yucatan Channel, Honduras, Panama, Colombia, and Venezuela, as well as in the Lesser Antilles region (Figure S2 in Supplementary Information). It should be noted that with 2% wind, in addition to the particles that enter the Caribbean, the highest particle density is found in the NERR region.

When adding 1% or 2% windage in the Lagrangian experiments, we obtained similar results whether the currents were from the HYCOM climatology (Figure 6) or the SOMs patterns (Figure 7). These results indicate that using the current patterns obtained with the SOMs are an adequate approximation to the currents' climatology, thus validating their use to calculate particle displacement, as suggested in Meza-Padilla et al. (2021). Comparing the results using 1% and 2% wind, we found that particles move from the Equatorial Atlantic to the CS. Some particles enter the GoM and exit through the Straits of Florida. It is observed that with 1% windage, the easterly winds displace the particles further south so that more particles enter the CS, covering the CS basin with the largest accumulation of particles near the Greater Antilles coast (Caribbean northern region). The 1% windage also allows particles to reach areas with intense cLCS, such as the Yucatan Current, where particles follow the LC and exit through the Florida Strait. When including 2% windage, particles are distributed further into the southern Caribbean region, where the cLCS lead to previously unreached areas, such as the Central America region. Also, including 2% windage results in stranded particles are stranded before entering the Yucatan Current and into the LC, and those entering the LC are displaced into the western GoM.



Figure 7. Lagrangian experiments results. The maps show the annual accumulated particle density using SOMs patterns, with (a) 1% and (b) 2% windage added to the Lagrangian experiments. The color indicates the accumulated particle density, and the gray line denotes the 200 m isobath.

3.2.3 Particle confluence in the Caribbean Sea

To quantify particle density within the CS, we strategically defined ten irregular polygons, hereafter called zones (Figure 8). We found that the spatial distribution of particle density over one year within these polygons is similar when using the HYCOM climatology or SOMs patterns (Table 1; Figure 8). We also found that the areas can be grouped according to the wind effect on particle clustering, dividing the Caribbean into three regions:

- Region I: Comprises zone 7 (Dominican Republic-Puerto Rico Channel) and zone 8 (Northern Lesser Antilles). This region has the most significant particle density in the absence of wind.
- Region II: Comprises zone 1 (Yucatan Channel), zone 4 (Honduras-Jamaica Central Channel), zone 5

(Honduras-Jamaica East Channel), and zone 6 (Jamaica-Haiti Channel). This region has the largest confluence when including 1% windage.

• Region III: Comprises zone 2 (Quintana Roo, Mexico), zone 3 (Honduras-Jamaica West Channel), zone 9 (Southern Lesser Antilles), and zone 10 (Central America). This region has the largest particle confluence with a 2% windage.

Table 1 shows a breakdown of the results by zone. We identified three main routes for particles to enter the CS: (i) along the edge of the continental shelf by the GC, (ii) through the NBC separation and intensification, and (iii) through the NERR and NEC dynamic interaction. Those same inflow areas were reported by Johns et al. (2014), Goni & Johns (2001), and Condie (1991). The resulting percentages suggest that less than 10% of the total particles moving from the Equatorial Atlantic to the CS reach the Caribbean coastal regions, even with 2% windage (Table 1). The results suggest that particles enter the Caribbean basin regardless of the windage; however, the density of particles increases or decreases in different regions according to the windage. We find that the effect of wind is crucial for particles to cross transport barriers to reach the coastal zone in the western Caribbean (zones 10, 3, and 2). Further discussion focusing on the Mexican Caribbean (zone 2) can be found in section 3.2.3.



Figure 8. Zones comprising different regions according to the effect of wind on particle clustering. Red indicates zones with the largest particle confluence without the influence of wind (Region I). Similarly, green denotes the zones with the largest confluence with 1% wind (Region II) and blue with 2% wind (Region III). Time series represent particle density (number of particles per unit area) of the three Lagrangian experiments derived from HYCOM and SOM patterns as a function of release month (lower abscissa, HYCOM) and SOM pattern (upper abscissa, SOMs). The left ordinate axis is particle density for HYCOM, and the right is particle density for SOMs. The variation in the y-axes is attributed to the difference in the temporal occurrence velocity fields used in the Lagrangian experiments. The current velocity fields obtained from HYCOM climatology have a daily occurrence, whereas the velocity fields generated by SOMs are semi-stationary, with a pattern's duration determined by the BMUs. The annual accumulated particle density, regarding the released month or pattern, refers to the number of steps taken by the particles within each area during a year. Acronyms indicate (Z) zone identifier number, (*) HYCOM climatology, and (o) SOMs Patterns.

Table 1. Lagrangian experiment results for each zone within the Caribbean basin. Colors indicate the area according to the wind effect (Figure 8); % is the particle percentage that arrives at each zone based on the total number of particles released, **H** YCOM climatology, and SOMs **P** atterns. Percentage values in**bold** indicate the zones with the largest confluence according to windage.

Zone	Location	Only currents	Only currents	$egin{array}{c} { m Currents}\ +\ 1\%\ { m windage} \end{array}$	$egin{array}{c} { m Currents}\ +\ 1\%\ { m windage} \end{array}$	$egin{array}{c} { m Currents}\ +\ 2\%\ { m windage} \end{array}$	$egin{array}{c} { m Currents}\ +\ 2\%\ { m windage} \end{array}$
		% H	% P	% H	% P	% H	% P
2	Quintana Roo	0.00	0.00	0.42	0.39	1.23	1.66
3	H-J West Channel	0.00	0.00	0.08	0.12	0.37	0.93
4	H-J Central Channel	0.09	0.09	0.42	0.67	0.35	0.49
5	H-J East Channel	0.24	0.21	0.54	0.55	0.07	0.04
6	J-Haiti Channel	0.35	0.36	0.57	0.50	0.02	0.01
7	DR-PR Channel	0.24	0.28	0.04	0.03	0.00	0.00
8	N Lesser Antilles	1.81	1.75	0.71	0.58	0.12	0.11
9	S Lesser Antilles	0.63	0.30	3.64	2.14	5.36	4.56
10	Panama	0.00	0.00	0.11	0.02	1.87	0.80

Delving into the analysis for each zone, we observed certain characteristics in the particles' spatial distribution associated with the forcings and main currents as defined by cLCS (Table 1; Figure S2 in Supplementary Information and 10):

- Zone 1: The largest particle density is found with 1% windage. These particles follow the cLCS formed by LC to enter the GoM.
- Zone 2: The particle's density increases by three orders of magnitude with 1% windage compared to the particle density by only considering currents. However, maximum particle confluence occurs with 2% windage.
- Zone 3: The maximum particle density occurs with 2% windage as the particles are advected to this area, crossing barriers imposed by the cCLS from the currents.
- Zone 4: The maximum particle confluence occurs with 1% windage, although the particle density is in the same order of magnitude without windage. In comparison, with 2% windage, the particles cluster west of the cLCS (zone 3) and follow their northward trajectory over the continental platform (Sheng & Tang, 2004), as currents follow the orientation of the isobaths over the continental shelf (Brink, 2016; Lago et al., 2019)
- Zone 5: The maximum particle density occurs with 1% windage, as particles are displaced south in the eastern CS, leading the particles in this area and zone 4. With increased windage (2%), the particles are advected further south, increasing the particle's density in zone 3.
- Zone 6: The density of particles is larger with 1% windage, followed by the case without windage. When considering 2% windage, the particle density diminished considerably, as the particles coming from the east are advected further south.
- Zones 7 and 8: The highest density of particles occurs in the absence of windage, showing these areas as being located in the main transport route by currents and without winds. This result denotes the wind's relevance for advecting the particles into the CS.

- Zone 9: For particles to arrive into this area, windage is essential as it advects particles to the south, creating a transport route towards the coast of Venezuela.
- Zone 10: The particles only reach this area when considering a 2% windage, as a strong windage allows crossing into an isolated region delimited by the cyclonic gyre located off the coast of Central America (Andrade & Barton, 2000).

The most important result of these experiments is the particles' geographical distribution according to the effect of wind. Zones 1, 4, 5, and 6 are dominated by windage (1% windage), while zones 2, 3, 10, and 9 are dominated by windage and Stokes drift (2% of wind). The distribution of particles can be explained by the persistent presence of the cLCS identifying transport barriers that prevent particles from reaching the coast (Figure 2 and Figure 9). For the particles to cross these barriers, it is necessary for the winds to weaken the cLCS.

The dynamics of surface transport are partially controlled by the inflow into the CS, which according to Johns et al. (2002), can be divided into three main groups of passages: the Greater Antilles (zones 6 and 7), the Leeward Islands (zone 8), and the Windward Islands passages (zone 9), which coincide with the main transport routes identified by the cLCS. The seasonal cycle of the mean currents inflow distribution in the passages connecting the Atlantic Ocean with the CS has an annual and semiannual variability with a maximum in late spring and summer and a minimum in fall, continuing to the Yucatan Channel (Johns et al., 2002). Nevertheless, the NBC is the single largest inflow source (40%) to the Caribbean (Chérubin et al., 2005), which displays a strong mesoscale variability in inter-island passage transports. Chérubin et al. (2005) also found that the current's maximum velocity position is in phase with the transport variations and independently of its extension. The Lagrangian experiments show that identifying transport pathways and barriers can explain particle displacement distribution, where the wind is a crucial parameter explaining particle intrusion into the Caribbean. Once in the CS, the three westward jets described by Chérubin & Richardson (2007) flow with their speeds decreasing with increasing latitude. These jets and their relation to our results are described below.

- 1. The southern and fastest jet is located at ~11.5°N, coinciding with the passage of particles at zone 9 with 2% windage. This southern jet is characterized by southern cyclones, which move northwestward as the anticyclonic CC circulation intensifies.
- 2. The center and second fastest jet, at ~14°N, coincides with the particle's passage through zone 8 without wind or with 1% windage. This center jet flows faster between August and December and is seasonally intensified by the NBC; this coincides with the larger particle density found in the zone during this period when considering low wind influence (1% windage or less). It is important to note that the intensification of the center jet is due to an increase in the mean kinetic energy (negative potential vorticity anomaly) that increases the number of cyclones during the fall. This is observed in the particle's trajectory once they enter the CS.
- 3. The northern and slowest jet is found at ~16.8°N, corresponding to zones 6 and 7. These zones show confluence only without windage (zone 7) and 1% windage (zone 6). This area is dominated by mesoscale anticyclones, sustaining westward currents south of Puerto Rico and Hispañola (Baums et al., 2006), so particles remain in this area with low wind conditions and are displaced further south only with 2% windage. Therefore, the wind effect in this region is decisive in the particle's trajectory.

Besides the water inflow and current jets, the Caribbean basin is influenced by atmospheric phenomena such as the easterly waves, anticyclonic cold fronts (also known as Central American Cold Surges), Caribbean Low-Level Jet (CLLJ), the trade winds, and the ITCZ. The easterly waves are wave-type disturbances in the tropical easterly current. These waves are associated with the hurricane season (summer), characterized by a cyclonic circulation that deforms the pressure field, causing the wind direction to change from northeast to the east (Caviedes, 1991). As such, easterly waves could promote particle displacement from the Equatorial Atlantic towards the CS by the windage effect. The arrival of anticyclonic cold fronts typically occurs between September and April and can extend as far south as 10°N latitude (DiMego et al., 1976). These cold fronts are associated with a significant increase in wind intensity, cloud cover, atmospheric pressure, wave height, and a decrease in temperature (Appendini et al., 2014, 2018; Cao et al., 2020; Ortiz-Royero et al., 2013). Considering the strong northerly wind component during cold fronts, they could influence the particle transport by displacing them towards the south, impending them to reach areas such as the Yucatan Peninsula. The Caribbean Low-Level Jet (CLLJ) is a near-surface branch of the easterlies that intensifies seasonally and has a nearly east-west direction (García-Martínez & Bollasina, 2020; Hidalgo et al., 2015). The Caribbean Counter Current (CCC) is controlled by the CLLJ, which during relatively mild wind conditions, promotes the intensification of the Panama-Colombia Gyre (Orfila et al., 2021). While the CLLJ can promote windage displacing particles towards the west, during its relaxation phase, the particle displacement into the CCC and the Panama-Colombia Gyre could be expected. Finally, the trade winds' seasonality and the ITCZ's consequent latitudinal displacement (Aliaga Nestares et al., 2022; Haffke et al., 2016; Henke et al., 2012; Skliris et al., 2022) likely influence the currents and particularly the windage effect on particle transport.

3.2.4 Case study: particle confluence near the Yucatan Peninsula

This section analyzes connectivity with the nearshore area in the Mexican Caribbean defined by zone 2. Before reaching zone 2, the released particles are strongly influenced by the persistent cLCS in zone 4, off the coast of Honduras and Nicaragua (Figure 9). These prominent cLCS tend to attract trajectories as seen by most particle density maxima within the CS interior, yet effectively block onshore transport keeping zone 3 isolated as seen through persistent particle density minima (Figures 5 and 6). An exception occurs with 2% windage when particles are released in March and September (Figure 6b). SOMs with 1% and 2% windage have more trajectories reaching the coast but also have several instances where the cLCS redirect transport northeastward (Figure 7). Thus, the cLCS in zone 4 effectively attracts particles and redirects them northward. Further north, next to the coast of Mexico (north of about 18.5N), the Yucatan Current creates a strong transport barrier that persists year-round along the Mexican coast between ~18°N to 21°N (Figure 9). However, the maximum attraction has variations in intensity and spatial coverage. During May and December, the barrier may be less protective than in other months, and September is the only month in which the cLCS from zone 2 connect with the cLCS from zone 4, suggesting a direct path towards the GoM.



Figure 9. Climatological Lagrangian Coherent Structures (cLCS) at the western Caribbean Sea. Colors indicate the strength of attraction, with red indicating the strongest attraction of nearby parcels; white indicates isolated regions or low stirring activity. Panel (a) are the annual and (b) the monthly cLCS for the Caribbean basin and the Yucatan Peninsula region, respectively.

The persistence of strong cLCS throughout the year efficiently prevents particles from reaching zone 2 without the influence of wind (Figure 8). However, the isolation of region 2 changes with the wind: some particles enter zone 2 with 1% windage, and considerably more enter zone 2 with 2% windage (Figure 8).

The persistent Yucatan Current transport barrier is debilitated when cLCS are computed with currents plus 1% windage, and it is completely erased when cLCS are computed with currents plus 2% windage (Figure 10). Also notable is that with 2% windage, the zone 4 cLCS tend to converge while directing towards the Mexican coast from about 84°W to 86°W in the vicinity of 18°N, a feature absent in the cLCS computed from only currents (Figure 10, cf. left and right panels). Independent experiments using an instantaneous velocity from HYCOM by Lara-Hernández et al. (2023) show that with 2% windage, trajectories reaching the Mexican Caribbean coast move along these strongly attracting cLCS while approaching the coast and then spread along the coastline (Text S2 and figure S6). This constitutes an additional independent confirmation that cLCS identifies and extracts the predominant transport patterns from the instantaneous velocity.



Figure 10. cLCS for July with only currents (left panel), currents plus 1% windage (middle panel), and currents plus 2% windage (right panel).

To characterize particle distribution in zone 2, we considered the seasonal variability of both surface currents and cLCS. Therefore, we divided the results according to the different wind-forcing conditions.

With 1% windage, particles will reach zone 2 using the transport route defined by the cCLS in zone 4, which can be considered the CC continuance ending on the YP eastern coast. The cLCS continues towards the Yucatan Channel, giving rise to the LC. This suggests that the cLCS at zone 4 are a pathway for offshore particles (further from the continental shelf) to move towards the Yucatan Channel. Considering the cLCS seasonal variability, the particles are transported over the regions of maximum attraction located in zones 4 and 5 and up to zone 1. Regardless of the release month, it takes approximately 5 to 8 months for particles to reach zone 2 (Figure 11). The highest particle density for zone 2 occurs when particles are released between September and December, reaching the YP the following year and starting to cluster in April.

With 2% windage, particles are directed towards zone 2 by the cLCS in zone 4, moving over the continental shelf and into the coastal regions of Honduras and Belize before clustering in zone 2. Regardless of the release month, the particle's arrival to zone 2 is between 4 and 8 months (Figure 11). In this case, there is considerable clustering independent of the release month. Nevertheless, when particles are released between March and June, there are a high number of months (> 5) with a very high confluence in zone 2. Particles released between these months arrive at the YP as soon as July, showing the highest density starting in September.

Notably, the arrival and distribution of particles in zone 2, observed in both HYCOM climatology and SOMs patterns (Figure 11), and the temporal variability of particle density are closely linked to seasonal changes in surface currents. Coastal geostrophic currents act as transport barriers, hindering transport perpendicular to the coast; therefore, the impact of wind is significant. When the wind blows perpendicular to the coast, it adds a cross-shelf component in the upper centimeters of the ocean due to windage or Stokes drift, in contrast with geostrophic currents that flow along isobaths (Brink, 2016). Thus wind allows particles to move perpendicular to the coast and cross the transport barriers caused by along-slope currents. Perhaps more accurately, the cross-shelf component due to wind erases the transport barriers imposed by the coastal Yucatan Current while forcing trajectories towards the coast (Figure 10).



Figure 11. Accumulated particle density, according to the release month (HYCOM) or pattern (SOMs) (yaxis; Equatorial Atlantic) and the arrival month (HYCOM) or pattern (SOMs) in zone 2 (x-axis; east coast of the Yucatan Peninsula). The two panels on the left side are the monthly accumulated particle density with the HYCOM climatology, and the two panels on the right side are the accumulated particle density obtained from the SOMs patterns. The listed months in the SOMs panels correspond to the months given by the BMUs corresponding to the release pattern. For each dataset, the first panel is the experiment with 1% windage, followed by 2% windage. The color of the bullets indicates the density of particles accumulated in zone 2.

As shown, the confluence of particles in zone 2 depends on currents and the effect of wind. As the wind conditions depend on atmospheric phenomena with a well-defined seasonal variability in the region, we expect an influence on particle transport by the passage of easterly waves, cold fronts, and the ITCZ latitudinal migration, as described previously. In general, this zone's regional atmospheric dynamics dominate zonal westward winds, with maximum intensities during February and July due to the strengthening of the North Atlantic easterlies, intensifying the CLLJ, and weakening during May and October.

5 Conclusions

This work identified the transport routes from the Equatorial Atlantic to the YP using Lagrangian experiments correlated to the cLCS. We used climatological currents from HYCOM and the most recurrent surface current patterns obtained from the climatological SOMs analysis for those experiments. The cLCS were calculated for the entire domain, and the transport barriers were determined, emphasizing the CS to interpret the distribution of particles in that area. We delimited ten strategic areas based on transport barriers, for which the area adjacent to the YP east coast was studied in detail.

We found that the SOMs reproduce the characteristic patterns of surface currents climate variability while the cLCS identified recurrent trajectories and persistent transport barriers, as confirmed with Lagrangian particle release experiments. The cLCS show a yearly persistence indicating mesoscale patterns in surface transport and a surface transport barrier isolating the continental shelf from circulation beyond the shelf break. Integrating these results with the Lagrangian experiments, we found that the cLCS determine particle trajectories since they function as transport pathways and transport barriers. When the cLCS act as transport barriers, particles are restrained from reaching specific areas unless there is windage to debilitate or completely erase the cLCS transport barriers due to currents.

Our results show that wind is a needed condition for particle confluence within different regions of the CS, either representative of the effect of windage or Stokes drift. For the regions of the Yucatan Channel, Honduras-Jamaica Central Channel, Honduras-Jamaica East Channel, and Jamaica-Haiti Channel, the 1% windage is necessary, while the 2% windage is needed for the particles to reach Quintana Roo, Mexico, Honduras-Jamaica West Channel, Southern Lesser Antilles, and Central America. From the Equatorial Atlantic region, the particles will take approximately four to eight months to reach the YP and will be influenced by the atmosphere phenomena and the space-time cLCS variability, being the Honduras-Jamaica West Channel, the main passage of particles transported towards the peninsula. The particles released during the autumn-winter months with a 1% windage are those that reach Quintana Roo, Mexico coasts in the spring of the following year, while the particles released in the spring months with a 2% windage are those that reach this zone in the summer months of the same year. The higher arrival of sargassum to the Mexican Caribbean in the summer months reaffirms the importance of the 2% windage for particles to arrive in this area.

This spatio-temporal particle distribution is similar whether using the HYCOM climatological data or the current patterns obtained with the SOMs. In addition to the hydrodynamics that determines the trajectory of particulate matter in the ocean, another important result is the representation of ocean climate by SOMs. The seasonality in the surface circulation is clearly illustrated by the BMUs distribution. From a numerical model perspective, the SOMs approach, together with the cLCS and its interaction with the large-scale dynamical atmospheric circulation features, can be applied to study and improve the representation of physical processes and approximate particulate matter transport and distribution on the sea surface. Atmospheric phenomena such as the easterly waves, anticyclonic cold fronts, Caribbean Low-Level Jet, the trade winds, and the ITCZ influence particle distribution, confluence, and aggregation. A more detailed study is required to determine the influence on windage of each of these phenomena.

Forecasting particle matter trajectories on the ocean still requires further studies to reproduce the transport accurately, incorporating other processes, such as degradation, growth, mortality, etc.. Nevertheless, this study is an advance in implementing different analysis methods of the interaction between different processes that determine ocean surface dynamics and their effect on particle transport.

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Open Research

Data from HyCOM and CFSR were used for this study (CDAM, 2015) and are publicly available at https://www.hycom.org/dataserver/gofs-3pt1/analysis, https://www.hycom.org/dataserver/gofs-3pt1/reanalysis, and https://www.hycom.org/dataserver/ncep-cfsr. cLCS computation code (Duran et el. 2019) is freely available at https://bitbucket.org/rodu/clcss/src. The code to compute SOMs (Vatanen et al. 2015) is freely available at http://research.ics.aalto.fi/software/somtoolbox/.

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Supporting Information for

Lagrangian characterization of surface transport from the Equatorial Atlantic to the Caribbean Sea using climatological Lagrangian Coherent Structures and Self-Organizing Maps

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Captions for Table S1

Table S1. Correspondence between the HYCOM climatology (HC) SOMs spatial patterns and the HYCOM instantaneous (HI) SOMs spatial patterns based on the highest correlation between the directions (angle) of each spatial pattern with another (see Figure S4).

Introduction

The text, figures, and table in this file complement the information in the manuscript by presenting additional figures and providing information on the HYCOM climatology, in particular the match between climatology and instantaneous SOM patterns (Text S1), and the correspondence of cLCS with trajectories from an instantaneous velocity near the Yucatan Peninsula (Text S2).



Figure S1. Surface currents monthly average from the HYCOM climatology. The colors indicate the current's magnitude, and the arrows' indicate the current direction.



Figure S2. Monthly climatological Lagrangian Coherent Structures. The colors indicate the strength of attraction, where red is the strongest, and white indicates low persistent stirring and isolated regions behind a transport barrier.

Text S1.

The spatial SOMs of the 1994–2018 time series of sea-surface velocity (SSV) were computed from the HYCOM + NCODA GOFS 3.1 reanalysis and analysis (described in the main document). The resulting spatial patterns from this HYCOM instantaneous (HI) SSV time series were compared to the spatial patterns from the HYCOM 1994–2018 climatology (HC) by correlating both the SSV angle and the SSV magnitude at each grid cell. The magnitude correlation was always above 0.7 (Figure S3); thus, the angle correlation between SSV vectors was used to identify the spatial pattern of the climatology that corresponded most closely to the instantaneous time series SOMs (Figure S4). The climatological pattern number 5 has a null frequency, i.e., it rarely happens; thus, it was ignored. Except for HC 5, each climatological spatial pattern has one clear maximum correlation with one of the instantaneous spatial patterns. The correspondence between HC and HI patterns according to the highest angle correlation is shown in Table S1. Using the correspondence in Table S1 to rename the HI spatial patterns so that the names of the two patterns that correlate the highest match, we can compare the temporal evolution of matching spatial patterns according to BMUs (Figure S5). Each year between 1994 and 2018, the period over which we have a temporal evolution of instantaneous spatial patterns, the HI BMUs are similar to the temporal evolution of the climatological spatial patterns, i.e., the HC BMUs. Starting in 2016, and especially in 2017, HI and HC BMUs differ more than in most previous years. It is unclear if the ocean dynamics were different these years, or if the different model setup may be partly responsible; data from 1994 to 2015 is from the HYCOM GOFS 3.1 reanalysis, while the velocity starting in 2016 comes from HYCOM GOFS 3.1 analysis.



Figure S3. Correlation matrix of the magnitude between each of the 8 SOMs spatial patterns from the HYCOM climatology (HC) and the 8 SOMs spatial patterns from the HYCOM instantaneous time series (HI). Only significant correlations are shown as different from zero.



Figure S4. Correlation matrix of the vector angle from each of the 8 SOMs spatial patterns from the HYCOM climatology (HC) and the 8 SOMs spatial patterns from the HYCOM instantaneous time series (HI). Only significant correlations are shown as different from zero.



Figure S5. Top panel is the BMUs for the climatological velocity (red line), repeated each year of the time series for comparison, and the BMUs for the instantaneous velocity (blue line) over 1994–2018. The middle panel is a histogram of the difference between the two BMUs in the top panel. The bottom panel is each year's sum of differences other than zero, the sum of the histogram in the second panel; the green line is the

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Table S1. Correspondence between the HYCOM climatology (HC) SOMs spatial patterns and the HYCOM instantaneous (HI) SOMs spatial patterns based on the highest correlation between the directions (angle) of each spatial pattern with another (see Figure S4).

	SOMs Patterns	SOMs Pa					
HC	1	2	3	4	6	7	8
HI	5	2	1	6	4	9	8

Text S2.

The ocean currents plus 2% windage cLCS pointing towards the coast discussed in section 3.2.3, are shown here to direct pathways of particles toward the Mexican coast in August 2018 (Figure S6). As trajectories get closer to the coast, another strong cLCS parallel to the coast redirects trajectories along the coast toward the north. Trajectory data was produced by Lara-Hernández et al. (2023) using instantaneous velocity (not the same velocity as the cLCS) plus 2% windage. Similar results hold for other months (not shown).



Figure S6. The color contours are the density of trajectories points initiated along the Mexican Caribbean coastline and integrated back in time to find their provenance using HYCOM Global instantaneous velocity of August 2018. Only the most attracting August cLCS (black lines) are plotted (i.e. when their attraction strength is above 1.2).