Three-dimensional connectivity in the Gulf of California based on a numerical model

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Abstract

Quantifying connectivity is useful for understanding the exchange and trapping of some tracers, such as fish larvae and nutrients. In the Gulf of California, connectivity studies have been limited to certain periods and regions. The current study investigated the connectivity among 17 areas, defined by the presence of eddies and weak or strong flows as obtained from a three-dimensional non-linear baroclinic model. The particles were released into the water column and advected for 28 days using an advection–diffusion scheme. The results revealed a seasonal connectivity pattern. In the northern region, particle trapping was greater during the cyclonic circulation period (June to September) compared with the anticyclonic period (November to March). This high retention was due to both the presence of a cyclonic eddy in the central portion of the region and the intense northwestward flow off the coast of Sonora. Retentions were low for the large island region due to the intense exchange between the northern and southern regions. East of Ángel de La Guarda Island the transport occurred predominantly towards the northwest due to the nearly permanent deep flow in that direction and to a branching of the surface flow among the large islands during the anticyclonic period and the northwestward low during the cyclonic period. In the peninsular and central areas of the southern region, retentions were high due to weak flows and the presence of eddies, respectively. The greatest retention and low dispersion of particles in practically all of the provinces were recorded during the transition periods of the circulation.

1. Introduction

The Gulf of California (GC) is a long, semi-closed sea located to the northeast of Mexico (Fig. 1). The northern region of the GC has an average depth of ~200 m and two basins: Delfín and Wagner. These basins are separated from the rest of the Gulf by Ángel de la Guarda Island (AG), the Tiburón Island, and a series of sills that are connected to the southern region, upon which a series of basins is situated: San Pedro Mártir, Guaymas, Carmen, Farallón, and Pescadero. These basins connect with the Pacific Ocean.

Circulation in the GC is strongly seasonal due to the characteristics of the principal forcings: the Pacific Ocean (Ripa, 1990, 1997), the wind regime (Badan-Dangon et al., 1991), and heat flows (Castro et al., 1994: Berón-Vera and Ripa, 2000). These conditions impose certain characteristics that are particular to the Gulf such as the circulation in the northern region, which is anticyclonic from November to March and cyclonic from June to September, as well as transition periods that occur from April to May and in October (Palacios Hernández et al., 2002; Carrillo et al., 2002). In contrast, the flows are intense in the large island region due to the exchange of water between the northern and southern regions (Beier, 1997; Mateos et al., 2006). This region is distinguished by intense tidal mixing (Argote et al., 1995) that is modulated by semi-diurnal, diurnal, and fortnightly frequencies (Lavín and Marinone, 2003) as well as a branching of deep flow that typically moves north. One branch flows toward the Ballenas–Salsipuedes Channel (BC) through the San Lorenzo sill, and the other flows through the San Esteban sill. The latter surrounds Ángel de la Guarda Island and converges with the other branch in the Ballenas–Salsipuedes Channel, thus producing a persistent upwelling in the channel (López et al., 2006, 2008; Marinone et al., 2008).

In the southern region, a train of eddies along the Gulf has been reported in both models and observations (Marinone, 2003; Figueyroa et al., 2003; Zamudio et al., 2008; Lavín et al., 2013). Marinone (2003) identified a series of anticyclonic (April to May and October to November) and cyclonic (June to August) eddies in the southern region as well as a quasi-permanent eddy on San Pedro Martir Basin. The generation of eddies was studied by Zamudio et al. (2008) using a three-dimensional model with local and/or remote forcing. They concluded that the remote forcing is essential for the generation of eddies and that the mechanism of formation occurs by the interaction of the near-coastal poleward eastern boundary currents.
with coastline and topographic irregularities. They also showed the distribution of three anticyclonic eddies in the August monthly average, and for August of 1999 and 2004, they showed an alternating sense of rotation.

The tendency of an alternating sense of rotation of eddies along the Gulf was documented by Figueroa et al. (2003) with geostrophic calculations of historical hydrographic data. They further found the presence of eddies throughout the year with hydrographic information. Recently, Lavín et al. (2013), using hydrographic data, drifters and a lowered acoustic Doppler profiler of an oceanographic survey (August, 2004), showed the presence of a train of eddies with an alternating sense of rotation that had a radius between 32 and 35 km, a depth of 400 and 700 m, an average speed of 0.3 m s\(^{-1}\), and a maximum speed of 0.5 m s\(^{-1}\) with similar scales to those reported by Figueroa et al. (2003).

The dynamic and circulation characteristics in the GC imply various degrees of connection (i.e., connectivity) among the different regions. Quantifying the connectivity or material flow among the Gulf provinces is useful for understanding, for example, the transport of fish larvae between continental and peninsular coasts, as has been documented (Contreras-Catala et al., 2012; Sánchez-Velasco et al., 2013) due to the presence of eddies and dispersal patterns of some marine protected areas (UG and BC).

Connectivity has been investigated in the GC with regard to specific regions and periods; however, exploration of the southern region has been scant. An essential portion of studying connectivity is delimiting the areas upon which to focus. For the Gulf, these areas have been defined in a variety of ways. Marinone et al. (2008), upon defining 21 areas between isobaths of 0 and 60 m in the northern region of the Gulf, studied the connectivity of these areas during the cyclonic period. The results indicated that the low-frequency (seasonal currents) circulation dominates the spatial connectivity. Peguero-Icaza et al. (2011) delimitated provinces in the large island and northern regions of the Gulf based on the distribution of fish larva groups (i.e., larval fish assemblages; LFAs) obtained from four oceanographic samples. These authors reported that the retention in each LFA is more effective (>55%) compared with anticyclonic circulation conditions (<35%). Recently, Marinone (2012) defined 12 provinces based on the dynamical and circulation characteristics of the Gulf. The exploration of surface connectivity over monthly periods indicated that retention is more effective (>30%) in the northern region of the Gulf.

Lagrangian studies in the GC have also revealed connectivity patterns. In the northern region, particle retention occurs over periods longer than 30 days, whereas particle transport on the continental shelf occurs many hundreds of kilometers toward the northern region in the summer and the southern region in the winter (Velasco Fuentes and Marinone, 1999; Gutiérrez et al., 2004; Marinone et al., 2011). Low particle retention occurs in the large island region due to the presence of intense flows; however, the Ballenas–Salsipuedes Channel retains particles due to weak residual flows (Marinone et al., 2011). Similarly, particle trapping occurs with small 100 km displacements over 30 days on the peninsular coast of the southern region (Marinone et al., 2011). In addition, the low frequency currents dominate the particle trajectories on monthly scales, and advection is more important than diffusion (Marinone et al., 2008, 2011). However, Lagrangian studies have not quantified spatial connectivity.

As a general connectivity knowledge does not exist in the GC, the current work explores the three-dimensional connectivity among the regions of the Gulf. Areas within the different regions were defined by the presence of certain structures (e.g., eddies or intense/weak flows) that tend to trap or disperse particles in the water column. The structures were identified using the critical value of the Okubo-Weiss parameter and the flow geometry of the monthly averaged velocity fields obtained from the results of a three-dimensional and non-linear baroclinic model.

2. Data and methodology

2.1. Euler model

The trajectory of a particle was calculated with hourly velocity for a climatological year obtained from the Hamburg Shelf Ocean Model (HAMSOM, Backhaus, 1985), a three-dimensional and non-linear baroclinic model adapted to the GC by Marinone (2003, 2008). This model was forced for the climatological field of the hydrography and the tides at the mouth of the Gulf as well
as at the ocean–atmosphere interface by the climatology of the wind, heat flows, and freshwater. The HAMSOM has a horizontal spatial resolution of 1.3 × 1.5 km and 12 vertical layers defined by the following lower limits (in m): 10, 20, 30, 60, 100, 150, 200, 250, 350, 600, 1000, and 4000. The thickness of the first layer was defined as that between the free surface and 10 m, and the last layer depended on the local depth. This model reproduces the seasonal circulation characteristics of the northern region (Lavín et al., 1997; Carrillo et al., 2002; Palacios Hernández et al., 2002), the seasonal evolution of the surface temperature of the sea (Soto Mardones et al., 1999), the heat balance (Castro et al., 1994), the height and currents of the tides (Marinone and Lavín, 2005), the deep circulation in the Ballenas–Salsipuedes Channel and around the Ángel de la Guarda Island (López et al., 2006, 2008), the presence of the mesoscale eddies in the basins of the southern region, and the intense flows over the continental shelf (Figueroa et al., 2003; Zamudio et al., 2008).

2.2. Areas of connectivity

Connectivity in the GC was studied in 17 areas, and the delineation was based on the identification of trapping or material transit zones using the Okubo Weiss parameter (Q) and flow geometry. The Q parameter (Okubo, 1970; Weiss, 1991) is defined as

\[ Q = s_x^2 + s_y^2 - \alpha^2, \]

where \( s_x = u_x - u_y, \ s_y = u_y + u_x \) are the deformation components and \( \alpha = v_x - v_y \) is the vertical component of vorticity. The \( Q(x, y, t) \) parameter defines regions dominated by deformation (\( Q > 0 \)) or rotation (\( Q < 0 \)) in a stationary and bidimensional velocity field. The identification of eddies using sea-level altimetry data and numerical models is based on vorticity properties, and the critical value of \( Q \) (defined as \( Q_c = -0.2\sigma Q \), where \( \sigma \) is the standard deviation of the \( Q \) field) is identified via convection (Isern-Fontanet et al., 2003; Nencioli et al., 2010). Although this eddy-detection method has some limitations (Nencioli et al., 2010), it provides a way to define the properties of the fluid and identify vortiginous structures.

Flow geometry can be defined as a set of fixed points (i.e., stagnation points; \( \mathbf{u} = 0 \)) and their associated streamlines. Together, these elements determine particle advection (Velasco Fuentes and Marinone, 1999). The presence of a stagnation point in the velocity field imparts a structure around this point and is defined by the Jacobian matrix

\[
J = \begin{bmatrix}
u_x & u_y \\ u_x & \nu_y
\end{bmatrix},
\]

which is evaluated by the centered finite difference approximation. The eigenvalues of this matrix are the roots of the characteristic polynomial

\[ \lambda^2 - (u_x + v_y)\lambda + u_x v_y - u_y v_x = 0. \]

The points of interest in this document are elliptical and hyperbolic. An elliptical point is defined by the imaginary eigenvalues such that the fluid rotates around a fixed point and corresponds to a particle-retention zone. In contrast, a hyperbolic point is defined by real eigenvalues of the opposite sign whereby these particles approach the point of the compressive direction and move away in the stretching direction of the fluid. Moreover, both of these points are associated with transit zones.

The fixed points were located using four-point bilinear interpolation. These points, and the critical value \( Q_c \), were calculated on the monthly average of the horizontal velocity fields (\( \frac{1}{2} \times 10^5 \)) for each model layer, and the barotropic fields, as well as on the spatial structure of empirical orthogonal functions (EOFs). The EOFs were constructed for each model layer, from the twelve monthly averages of the velocity fields.

Fig. 2 shows the contours of \( Q_c \) and the fixed points of the velocity field of the surface layer in January. Small eddies were found in the northeastern region, as were the anticyclonic eddy that dominates the northern region and an intense flow on the continental shelf. The contours of \( Q_c \) identified the anticyclonic eddy and the zones with strong horizontal shear in velocity (meanders) but not the peninsular eddies associated with the method limitations (Nencioli et al., 2010). The elliptical points, however, were more sensitive in the identification of the structures that define particle advection.

The results show a considerable temporal and spatial variability in the distribution of contour \( Q_c \) and the fixed points due to the complex three-dimensional circulation pattern of the GC throughout the year. For example, the surface circulation between Ángel de la Guarda and Tiburón Islands is southward and northward in the bottom during the anticyclonic period, and vice versa in the cyclonic period, while in the transition periods, the flows are weaker and there is the presence of some eddies. However, some zones present patterns that are well defined as the central portion of the NGC, where the seasonal eddy dominates the circulation. These features complicate the objective definition of the areas. Accord-

![Fig. 2. Fixed points: elliptical (dots), hyperbolic (crosses) and the critical Okubo Weiss parameter (Qc) contour for the monthly averaged surface velocity field (cm s⁻¹) for January. Only one in every four vectors is shown.](image-url)
ingly, to simplify this, a limitation of the province EOF analysis of monthly velocity fields was performed for each model layer. Fig. 3 shows the velocity fields for the first EOF analysis mode for model layers that represent >49% of the variance in the monthly fields. The analysis captures the structures observed in the different layers analyzed. The identification of trapping and dispersion zones defines 17 areas (Table 1), thus resulting in connectivity areas smaller than those in previous research (i.e., Peguero-Icaza et al., 2011; Marinone, 2012). Furthermore, the analysis and identification of the zones provides better information on transport between provinces and identifies areas with well-defined Lagrangian properties. For example, the intense flow on the mainland coast of the northern region (TI and SO) produces high dispersion compared to that of the central part (SE) and the peninsular regions (UG, BZ and PE), where the seasonal eddy dominates the particle advection, except for a portion of the Delfín Basin (DB), which apparently corresponds to an area of high dispersion. Therefore, the connectivity between the areas is defined by the three-dimensional circulation, which has temporal and spatial variations, though some structures are dominant in different regions and help to determine the provinces.

The areas in the northern region are defined by the persistent presence of small eddies in the Upper Gulf (UG), the Buffer Zone (BZ, which is part of the biosphere reserve due to the presence of endemic fish species), and the peninsular portion of the region (PE). Additionally, the central portion of the region, which is influ-

Table 1

<table>
<thead>
<tr>
<th>Region</th>
<th>Name</th>
<th>Acronyms</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Gulf of California</td>
<td>Upper Gulf</td>
<td>UG</td>
<td>Small eddies and slow flow</td>
</tr>
<tr>
<td>(NGC)</td>
<td>Buffer Zone</td>
<td>BZ</td>
<td>Small eddies on the peninsular coast and eastward (westward) flow in winter (summer) due to the influence of the anticyclonic (cyclonic) eddy</td>
</tr>
<tr>
<td>Peninsular eddies</td>
<td>Seasonal eddy</td>
<td>PE</td>
<td>Small eddies confined to the peninsular coast</td>
</tr>
<tr>
<td>The northern coast of Sonora</td>
<td></td>
<td>SO</td>
<td>Anticyclonic (cyclonic) eddy in the central portion of the NGC</td>
</tr>
<tr>
<td>Delfín Basin</td>
<td></td>
<td>DB</td>
<td>Intense flow to the south (north) in the anticyclonic (cyclonic) period</td>
</tr>
<tr>
<td>Midriff Archipelago Region</td>
<td>Ballenas–Salsipuedes Channel</td>
<td>BC</td>
<td>The confluence of flows: SE, BC and AG</td>
</tr>
<tr>
<td>(MAR)</td>
<td>East of the Ángel de la Guarda Island</td>
<td>AG</td>
<td>Preferential flow northward</td>
</tr>
<tr>
<td>North of the Tiburón Island</td>
<td></td>
<td>TI</td>
<td>Intense southward (northward) flow in the anticyclonic (cyclonic) period</td>
</tr>
<tr>
<td>Sills Zone</td>
<td></td>
<td>SZ</td>
<td>Intense and complex flows</td>
</tr>
<tr>
<td>Southern Gulf of California</td>
<td>Central Peninsular Región</td>
<td>CP</td>
<td>Slow flows with small eddies</td>
</tr>
<tr>
<td>(SGC)</td>
<td>South Peninsular Región</td>
<td>SP</td>
<td>Mesoscale eddies</td>
</tr>
<tr>
<td>La Paz Bay</td>
<td></td>
<td>PB</td>
<td></td>
</tr>
<tr>
<td>Guaymas Basin</td>
<td></td>
<td>GB</td>
<td></td>
</tr>
<tr>
<td>Farallón Basin</td>
<td></td>
<td>FB</td>
<td></td>
</tr>
<tr>
<td>Central Continental Región</td>
<td></td>
<td>CC</td>
<td>Intense southward (northward) flow in the anticyclonic (cyclonic) period</td>
</tr>
<tr>
<td>South Continental Región</td>
<td></td>
<td>SC</td>
<td></td>
</tr>
</tbody>
</table>
enced by the mesoscale eddy (SE, Fig. 3), is also considered. These circulation patterns can be differentiated from the northern coast of Sonora (SO), where the flows are more intense and narrowly connected with the large island area. In the Delfín Basin (DB), the patterns are complex due to the confluence of flows from the mesoscale eddy, the Ballenas–Salsipuedes Channel, and the eastern zone of Ángel de la Guarda Island. These characteristics define particle trapping (e.g., UG, BZ, PE, and SE) or dispersion (e.g., SO and DB) patterns in the region. The large island region exhibits intense flows and complex circulation patterns due to the exchange between the northern and southern zones (Fig. 3). In the eastern zone of Ángel de la Guarda Island, the surface flow is preferentially toward the northeast due to the influence of the intense flow among the islands during the cyclonic period; however, in the anticyclonic period, the intense flow branches off into two sections (northwest and southwest) due to the presence of the island. The northward branch flows over the Ángel de la Guarda Island area, whereas the deep flow moves primarily toward the north. In the northern zone of Tiburón Island, the flows move predominantly north during the cyclonic period but south during the anticyclonic period. In contrast, the circulation patterns are complex in the central portion of the region around the San Lorenzo and San Esteban sills (SZ). Under anticyclonic circulation conditions, surface flows toward the south are intense, whereas flows at the seabed are in the opposite direction and exhibit eddies such as the one at San Pedro Mártir. In the presence of cyclonic circulation, the patterns are similar except that the surface flow moves toward the north, and the flow at the seabed moves toward the south. While the circulation patterns are also complex in the Ballenas–Salsipuedes Channel, the flows are weak compared with the other provinces. Thus, this pattern can be associated with a particle retention zone.

The circulation patterns in the southern region are more structured compared with those in the large island region with the flows on the continental shelf being intense toward the south under anticyclonic circulation conditions and toward the north during the cyclonic period (Fig. 3). Conversely, the flows were weak on the peninsular coast. In contrast, the presence of eddies is persistent in the central region, though they were not always defined at the surface.

2.3. Method of particle dispersion and the connectivity matrix

The passive particle trajectory was calculated using an advection–diffusion scheme as described by Visser (1997) and Proehl et al. (2005):

\[ X(t + \delta t) = X(t) + X'_a(t) + R_x(6A_x\delta t)^{1/2}, \]

\[ Y(t + \delta t) = Y(t) + Y'_a(t) + R_y(6A_y\delta t)^{1/2}, \]

\[ Z(t + \delta t) = Z(t) + Z'_a(t) + R_z(6A_z\delta t)^{1/2} + \delta t\partial A_x/\partial Z. \]

Here, \( X, Y, \) and \( Z \) are the positions in the zonal, meridional, and vertical directions, respectively, of a particle for each 1-hour step (\( \delta t \)). \( X'_a, Y'_a, \) and \( Z'_a \) are the displacements obtained for the velocity field of the numerical model using the second-order Runge–Kutta interpolation method on the horizontal and the Euler method on the vertical. The particle velocity at each position was calculated using a bilinear interpolation. \( R_x, R_y, \) and \( R_z \) are random variables with uniform distributions, with a mean of zero, and a range between 1 and –1. \( A_x, A_y, \) and \( A_z \) are the horizontal and vertical coefficients of turbulent diffusion, respectively, with values of 100 and between 0 and 0.013 m² s⁻¹, respectively. These coefficients were obtained from the numerical model. The values of \( A_x \) were interpolated for each position of the particle.

In each area, between 6000 and 250,000 particles were released into the water column in accordance with the province dimensions. Each particle was advected for 28 days, which represents the larval stage duration (>2 weeks) of many important Gulf species, as reported by Calderon-Aguilera et al. (2003), Peguero-Icaza et al. (2011), and Soria et al. (2014). Soria et al. (2014) document many species (see their Table 1) with larval stage ranging from 2 to 4 weeks that spawn in different seasons of the year. The movement of the fluid transports the larvae during this phase. At the end of the advection period, the position of the released particles was quantified for each area, and the information was arranged in a connectivity matrix.

The connectivity matrix was defined as \( C_{ij}(t) \), where the vertical axes \( i \) denotes the particle liberation provinces, and the destination areas are shown on the horizontal axes \( j \). The particle retention in each province is shown on the matrix diagonal, and particle transport is shown outside of the matrix in percentages. The total percentage of the particles was obtained via horizontal integration. Retention or transport values less than 5% were excluded to improve clarity with regard to the connectivity matrices.

3. Results and discussion

The result of the integration of particles of different layers of the model for each area indicates the predominant connection among the provinces of the Gulf. In spite of the complexity of the three-dimensional circulation (Supplementary material), well-defined patterns are visible from the perspective of connectivity, as described in this section.

The connectivity among the different GC regions exhibits seasonal patterns, which is consistent with the characteristics of circulation in the Gulf. During the anticyclonic circulation period (November to March), most of the regions and provinces, particularly the northern region, transport particles toward the mouth of the Gulf, as shown in the connectivity matrix for January (Fig. 4a). In the presence of cyclonic circulation (June to September), the transport occurs toward the head of the Gulf, as in July (Fig. 4b).

For the circulation transition periods (April to May and October), the retentions are at their highest for most of the regions; therefore, dispersion is low (see the diagonal matrix elements for May: Fig. 4c). The connectivity in each province of the region is differentiated for each circulation period. Figs. 5 and 6 show the matrices in which the vertical axes correspond to periods of particle advection, and the horizontal axes correspond to the connectivity of a particular area with the remaining provinces.

In the northern region, the presence of the anticyclonic eddy and the intense flow on the continental shelf favor particle transport toward the south, where maximum incursion is observed up to the peninsular coast of the southern region (see Fig. 3). This dispersion pattern is consistent with that reported for surface of the Gulf (Peguero-Icaza et al., 2011; Marínone, 2012). However, the definition of smaller polygons allows the identification of small areas of high retention, for example, UG, BZ, PE and SE (Fig. 5a–d). This situation is associated with the presence of eddies, which tend to trap materials as documented with fish larvae among certain regions of the ocean (Rodríguez et al., 1999; Nishimoto and Washburn, 2002; Rodrigues et al., 2004; Fossheim et al., 2005). In contrast, the southern part of the region is dispersive (retention <20%) due to the intense flow on the continental shelf (SO; Fig. 5e) as well as the confluence of flows from the Ballenas–Salsipuedes Channel, the seasonal eddy and the eastern zone of Ángel de la Guarda Island atop the Delfín Basin (Fig. 5f).

In these areas, particle trapping in the water column is more effective in the presence of a cyclonic eddy (Fig. 5a–f), as has been observed on the surface layer of the region (e.g., Peguero-Icaza et al., 2011; Marínone, 2012). In general, more than 70% of the particles released in this region remain trapped during this period (except in the DB). This high retention can be explained by the
presence of the cyclonic eddy and the intense flow on the continental shelf toward the head of the Gulf (Fig. 3), which (in addition to favoring particle transport from the southern region) limit incursion toward the large island region. The coastal flow favors transport toward the south under anticyclonic circulation conditions. These results indicate that the northern coast of Sonora and the Delfín Basin are highly dispersive, whereas the central portion and the northern region tend to trap particles.

Particle retention is low in the large island region except for the Ballenas–Salsipuedes Channel, which shows percentages greater than 30% during the 4 months of the anticyclonic period and for the entire cyclonic period (Fig. 6d). The BC is characterized by an intense tidal current, weak residual flows, and mixing (López et al., 2006, 2008), all factors that limit the displacement of particles that are dominated by the residual flow (Marinone et al., 2008, 2011). In general, particle transport in the large island region occurs in both the north and the south due to the complex circulation pattern (Fig. 3). Surface transport is seasonal toward the south under anticyclonic circulation conditions and toward the north during the cyclonic period, including the Ballenas–Salsipuedes Channel (Marinone, 2012). The large island region exhibits a particularity in the eastern zone of Ángel de la Guarda Island (Fig. 6a), where particle transport is primarily toward the north during the 12 monthly periods. This behavior is associated with the branching of the coastal flow into two portions under anticyclonic circulation conditions due to the presence of the island, that is, toward both the northwest and the southwest (Fig. 2). The branch toward the northwest flows over the Ángel de la Guarda Island province and favors transport toward the north on the surface. At the seabed, the predominant flow moves toward the north (Marinone, 2008), which is consistent with other observations (López et al., 2006, 2008). In contrast, the intense flow that occurs among the large islands favors a surface flow toward the north during cyclonic circulation.

The southern region exhibits well-defined patterns. During the anticyclonic period, the greatest retentions (>30%) occur in the South Peninsular Region (SP, Fig. 6f) and in La Paz Bay (PB, Fig. 6g), where the flows were weak and above the basins of the region, that is, Guaymas Basin (GB, Fig. 6h) and Farallón Basin (FB, Fig. 6i), where the presence of eddies is strong. However, trapping is more effective (>30%) in the region during the cyclonic circulation period, except for the Central Continental Region (CC; Fig. 6j) where transport is observed up to the northern coast of Sonora. These results are consistent with the presence of the coastal
flow that defines high dispersion in the zone (e.g., CC and SC). This behavior is consistent with that reported previously in Lagrangian studies (Velasco Fuentes and Marinone, 1999; Marinone et al., 2011) and in surface connectivity studies (Marinone, 2012). Thus, it is a characteristic pattern of the water column. With particle transport occurring primarily among the provinces of the southern region, particle trapping in the entire region is greater (>67%) during the anticyclonic period.

During circulation transition periods, the average flows are weak and less organized compared with the flows during the cyclonic and anticyclonic periods (Fig. 3). One of the consequences of these circulation patterns is maximum particle retention for most of the areas (Fig. 4c), which has been observed in the surface connectivity of the Gulf (Marinone, 2012). The current work finds that particle trapping is greater during the transition period from anticyclonic to cyclonic circulation patterns (April–May; see the matrices in Figs. 5 and 6). In particular, maximum retentions were observed with >62% in the Upper Gulf, the seasonal eddy, and the northern areas of the northern region in May (Fig. 5a, d, and e); smaller retentions (<40%) were observed in the provinces of the large island region; and the largest retentions (>70%) were found in the southern region, with the exception of the Central Continental Region.

The connectivity matrices also provide information concerning the areas that receive greater particle contributions in different months. In general, the most effective trapping was observed in the central areas of the northern (SE) and southern regions (GB and FB; Fig. 4). This result is likely associated with the presence of eddies and the dimensions of the areas that are greater than the rest. In addition, these provinces retained the greatest amount of particles, as did smaller areas such as the UG, SP, and PB. These characteristics suggest that materials such as eggs and fish larvae cluster here.

Connectivity (obtained by integrating particles in the vertical) provides some general information on particle transport between areas or regions of the GC. However, the possible applications in the transport of larvae, nutrients and pollutants between the coasts or among the marine protected areas (MPA) of the Gulf have limitations due to the nature of these variables and the complex circulation of the Gulf. For example, spawning and recruitment processes of most marine organisms occur within the first few meters of the ocean. Therefore, as an example, we show in Figs. 7 and 8 the connectivity in the Gulf for the upper 60 m. Comparing Fig. 5 and 7 for the northern Gulf, a similar pattern is found as it is quite shallow.

The Upper Gulf is a spawning and recruitment zone for fish and other organisms such as blue shrimp (Calderon-Aguilera et al., 2003; Sánchez-Velasco et al., 2012). Recently, Sánchez-Velasco et al. (2012) reported that the diversity and abundance of fish larvae are greater in the UG than in other areas of the northern region (Sánchez-Velasco et al., 2009) at the start of the summer (June). However, Sánchez-Velasco et al. (2009) showed that both the diversity and the abundance of fish increase at the end of the summer (August), which suggests that these variables peak during the annual cycle. Sánchez-Velasco et al.’s (2009) hypothesis is consistent with the particle trapping in the UG (Fig. 7a), where an
Fig. 7. Same as Fig. 5 but for the 0–60 m connectivity.

Fig. 8. Same as Fig. 6 but for the 0–60 m connectivity.
increase was observed from June (56%) to September (63%), reached a minimum in December (14%), and then increased in January before reaching a second maximum during the circulation transition period in May (62%). The transport of the UG to other areas (where MPAs are located) is low (<20%) and only occurs in the cyclonic period, as observed for the northern coast of Sonora (Puerto Peñasco reserve network) and the Midriff Archipelago Region (Ballenas–Salsipuedes Channel and San Pedro Mártir Island).

For the upper 60 m (Fig. 8) between Ángel de la Guarda and Tiburon islands (SZ), the main surface transport is to the SGC during the anticyclonic period and toward the NGC during the cyclonic period (Fig. 8c). The Biosphere Reserve of San Pedro Mártir lies in this area and according to the results demonstrates low connectivity (<15%) with the UG in July and the northern coast of Sonora (<30%) throughout most of the cyclonic period. This result suggests that MPAs (UG, BC and San Pedro Mártir Island) may be exchanging biological material throughout the year.

Soria et al. (2014) studied patterns of surface connectivity San Pedro Martir during May and June. They reported that trapping is significant in May, and the dispersion is highly dynamic with transportation on the peninsula of Baja California and along the coast of Sonora to the UG, as suggested by our results. The Midriff Archipelago Region can be a key source for the recruitment of marine organisms in the NGC during the cyclonic period when trapping is more effective throughout the water column (>70%), while transport to the coasts and basins of the SGC occurs in the anticyclonic period.

Similar connectivity studies around the world have been used to design conservation strategies for different species and to understand the degree of recruitment or dispersion of eggs and larvae of different MPAs. For example, in the Irish Sea, a semi-enclosed sea similar to the GC, Van der Molen et al. (2007) reported excursions of a few hundred km including active behavior of some species. For the whole Mediterranean, Andrello et al. (2013) reported low connectivity for the Dusky grouper Epinephelus marginatus among several MPAs. They interpreted this as a potential for self-recruitment.

The connectivity between continental and peninsular coasts in the northern areas of the SGC was observed in July from the Central Continental Region (CC) to the Central Peninsular Region (CP) (see Fig. 8i) and during most of the anticyclonic period in the southern areas of the Southern Gulf of California (from CC to SP and PB); however, the main transport was towards the central Gulf basins of GB and FC. This connection between the Gulf coasts has been observed in the distribution of LFAs in mesoscale eddies in the SGC (Contreras-Catala et al., 2012; Sánchez-Velasco et al., 2013). Contreras-Catala et al. (2012) and Sánchez-Velasco et al. (2013) documented the presence of a mixture of coastal and oceanic larvae in anticyclonic and cyclonic eddies, respectively, within the Farallón Basin Region. They suggest that mesoscale eddies capture larvae near the coast and transport it around the periphery. This may facilitate recruitment between the coasts. Sánchez-Velasco et al. (2013) suggest that transport can last ~6 days given an eddy with geostrophic velocity of 0.4 m s⁻¹ and 70 km radius.

The seasonal patterns of connectivity found in this research are consistent with the distribution of certain larvae that follow the interdependence of the spawning process with the circulation and the environmental characteristics of the Gulf (Peguero-Icaza et al., 2008; Peguero-Icaza et al., 2011). For example, three species of larvae (Vinciguerra lucetia, Diogenichthys laternatus, and Bathyergus macrurus) are located exclusively in the southern region during the winter (Peguero-Icaza et al., 2008) when particle transport is limited toward the northern region, whereas the presence of other species (e.g., Gobulus crescentalis, Etrous crossoptus, and Lythrypnus dalli) predominates in the northern region during the cyclonic period (Peguero-Icaza et al., 2011) when retention is high (>70%) in the entire water column.

4. Conclusions

This work examined the three-dimensional connectivity in the entire GC using the output of a non-linear three-dimensional baroclinic model. The areas were defined based on the presence of certain structures (e.g., eddies or intense flows) that tend to trap or disperse materials in the water column. The results indicated a seasonal pattern in the connectivity that is consistent with the Gulf circulation characteristics.

The northern region was more dispersive under anticyclonic than cyclonic circulation conditions when particle trapping was more effective (>70%). The resolution of the provinces permitted the northern portion of the region (UG, BZ, PE, and SE) to be identified, such as the zone of greater trapping associated with the presence of eddies, whereas the southern portion of the region (SO and DB) was more dispersive (>80%); in particular, the Delfín Basin showed this pattern during the year.

In the large island region, particle dispersion was high due to the intense exchange between the northern and southern regions of the Gulf. The province with the greatest retention was the Ballenas–Salsipuedes Channel, which had more effective trapping during the cyclonic period than the anticyclonic period. A distinctive pattern was observed in the eastern zone of Ángel de la Guarda Island, where transport occurred predominantly toward the northern region and was associated with deep flow and the branching of the surface flow among the large islands during the anticyclonic region (or intense flow toward the north during the cyclonic period). These results are consistent with reports in the literature.

The southern region exhibited greater retention during the cyclonic period than the anticyclonic period. The continental shelf was the most dispersive (CC and SC), and the greatest connection with the northern region was observed at the northern portion of this zone (CC). In contrast, in the central (GB and FB) and peninsular (CP, SP and PB) zones, trapping was more effective due to the presence of eddies and weak flows, respectively. Finally, the maximum retention in each province (as defined in the different regions of the Gulf) occurred during the transition from anticyclonic to cyclonic circulation when the circulation patterns were weaker and more complex.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2014.02.002.

References


