Seasonal surface connectivity in the Gulf of California

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A three-dimensional numerical model is used to study seasonal connectivity in the Gulf of California. From the Eulerian velocity fields of the model, particle trajectories were calculated for the 12 months of the year using an advection/diffusion scheme. Connectivity was quantified for twelve Gulf provinces with different dynamic/circulation characteristics being defined by the Eulerian velocity field: strong or weak coastal currents, eddies, and areas of mixing and exchange. Retention occurred for 9–12 months of the year in the Upper Gulf, Eddy and Sonora regions of the northern Gulf because of the Gulf-wide eddy circulation, which implies high potential for the auto-recruitment of larvae in this province. High retention was also found on the peninsula side of the southern Gulf in association with weaker residual currents, again implying potential for self-recruitment. In contrast, low retention was observed on the mainland side of the central and southern Gulf, from which particles are exported to many areas by the faster residual currents enhancing the potential for recruitment of distant coastal species. Empirical Orthogonal Function analyses revealed a strong annual and semiannual evolution in accordance with the strong seasonality of the Gulf dynamics.

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1. Introduction

The Gulf of California (GC) has several important fisheries (Arvizu-Martínez, 1987) and is rich in biodiversity and regional endemism, particularly for invertebrates (Brusca, 2002). These characteristics result from the combination of different physical processes in the Gulf, including strong tidal currents, mixing, and large seasonal temperature variations, geomorphologic diversity and habitat types. Moreover, in response to the decline of some fisheries and threats to marine ecosystems, marine reserves have been used as a conservation tool, thereby increasing the pressure for their proper management (Cudney-Bueno et al., 2009) and requiring multidisciplinary studies. In particular, it is important to understand the degree of association or connection between different areas of the Gulf with respect to the fluxes of nutrients, contaminants and early larval stages of various organisms (Van der Molen et al., 2007). Circulation and its seasonal evolution play an important role in larval dispersal in any ocean. In the GC, we can expect a different degree of connectivity in areas where rectilinear residual currents dominate, such as in the eastern coast of the Gulf, compared to areas dominated by eddies or mesoscale structures.

Several connectivity studies addressed the GC, but they cover limited areas or seasons (Marinone et al., 2008; Sánchez-Velasco et al., 2009; Peguero-Icaza et al., 2011). Marinone et al. (2008) presented connectivity matrices for the northern Gulf, but limited their analysis to the depth band between the coastline and the 60 m isobath. The study was also limited to the summer season. The primary result of the Marinone et al. (2008) study was that connectivity was dominated by the seasonal circulation, and the flux of particles was downstream (along a cyclonic route).

From the distribution of fish larvae in the GC, Peguero-Icaza et al. (2008), Sánchez-Velasco et al. (2009) and Peguero-Icaza et al. (2011) found that larval fish assemblages were associated with areas of different environmental conditions. For example, during summer, the presence of the cyclonic surface circulation includes the eddy in the center and a northwestward coastal current on the mainland side that acts as a continuation of the inflowing current from the south and therefore carries nutrients and larvae to the northern Gulf. Sánchez-Velasco et al. (2009) and Peguero-Icaza et al. (2011) conducted seasonal connectivity studies in the northern Gulf between areas defined by larval fish assemblages, revealing different degree of particles retention within each larval fish assemblage with areas that depended on the season. However, these studies established connectivity between areas defined by the larval fish assemblages found in each particular cruise and were limited to the northern GC. Therefore, a general
connectivity study for the Gulf is still lacking, particularly for the southern Gulf.

For the entire GC, the winter and summer Lagrangian studies of Velasco and Marinone (1999) with a barotropic model and the monthly results by Cutiérrez et al. (2004) with the surface horizontal currents of a three-dimensional (3D) baroclinic model established the tracks of particles and their destination by visual inspection. Marinone et al. (2011) reported Lagrangian monthly trajectories in the entire GC for the complete year from the full 3D advection of particles released at the surface and calculated indices that quantify characteristics related to the retention and the dispersion of particles. These indices represent the net and total distances traveled by the particles, the number of particles that are trapped in an area of 12.5 × 12.5 km² and the time that the particles need to escape from a 50-km-radius circle surrounding the release point. The indices characterized the strong seasonal current along mainland Mexico and the trapping of particles in areas with eddies and in areas with slow currents (the peninsular side of the southern Gulf). However, the final destination of the particles was not defined and/or quantified in these studies.

The previous Lagrangian studies do not provide spatial connectivity, and the previous connectivity studies in the Gulf are limited in space (to the northern Gulf) and time (during summer or during particular cruises). Therefore, the objective of this study is to quantify the spatial connectivity for the entire GC for a typical year. The circulation of the Gulf is strongly seasonal: the northern GC is characterized by strong seasonal surface currents and a large basin-wide eddy (ED) and SO areas, with weaker currents in the southern GC. For the entire GC, the winter and summer seasons are characterized by stronger currents and tidals, as well as a dominance of downstream coastal currents. These two areas have similar characteristics described would not match every month of the year, as the circulation evolves in a seasonal cycle, particularly during the transitional periods.

The polygon for each area was fixed by visual inspection of the Eulerian low-frequency velocity field, which was obtained by filtering the hourly values by passing the fields through a 25 h running average filter three times (Yao et al., 1982). Fig. 2 shows four snapshots of the low-frequency circulation for the different areas. For clarity, only one in every four vectors is shown. The Upper Gulf (UG) is a marine protected area, and the numerical model shows small eddies that can lead to local retention. The coastal area close to the state of Sonora (SO) is characterized by strong seasonal currents (> 10 cm s⁻¹), and it is on the eastern side of the seasonal basin-wide eddy (ED) first observed by Lavín et al. (1997). East of Angel de la Guarda Island (AG) is an area where currents connect the ED and SO areas and deep currents flow up-gulf (López et al., 2008). SN and SS are the coastal areas of Sonora and Sinaloa, respectively, and are characterized by strong seasonal up-gulf and down-gulf coastal currents. These two areas have similar characteristics, but they are separated to maintain areas of reasonable size. For example, excursions from a particular lagoon or nursery area separated by a few hundreds of kilometers would not be distinguished in an area containing both the SN and SS areas. For the same reason, the area on the peninsular side was split into two areas, one off La Paz (LP) and the other containing Bahía Concepción (BC). The LP and BC areas are characterized by weaker currents and diffusivities are taken from the numerical model, and because the vertical diffusivity is not constant, a pseudo-advective term is introduced to prevent particles from walking from areas of high to low diffusivities. Therefore, the position of the particles is calculated as

\[ X(t + \delta t) = X(t) + \dot{X}(t) + \alpha h \sqrt{(2A h \delta t) / 3} \]  (1)

\[ Y(t + \delta t) = Y(t) + \dot{Y}(t) + \alpha v \sqrt{(2A h \delta t) / 3} \]  (2)

and

\[ Z(t + \delta t) = Z(t) + \dot{Z}(t) + \alpha w \sqrt{(2A h \delta t) / 3} + \delta \dot{z} \alpha v / \alpha Z, \]  (3)

where \((X, Y, Z)\) are the particle positions in the zonal, meridional, and vertical directions, respectively, at time \(t\), \(X, Y, Z\) are the advective displacements obtained by integrating the velocity field, \(\dot{V}(x,y,z) = \nabla u(x,y,z), \nabla v(x,y,z), \nabla w(x,y,z)\). The velocity at each particle position is calculated by bilinear interpolation of the instantaneous Eulerian velocity fields from the numerical model, which were saved every hour. \(R_x, R_y, R_z\) are random variables between \(-1\) and \(1\) (visser, 1997). \(Ah\) is the horizontal eddy diffusivity and is constant \((Ah = 100 \text{ m}^2 \text{s}^{-1})\), as in the Eulerian numerical model. In the particle tracking algorithm, the results are similar with different values of the horizontal diffusion coefficient, indicating that the dominant process is advection. \(Av\) is the vertical diffusivity, which is also taken from the Eulerian numerical model, and is calculated and interpolated for the individual particle positions at each time step. In the Eulerian numerical model \(Av\) is calculated following Kochergin (1987).

To calculate the connectivity matrices, it is necessary to define the release areas and to obtain the final destination of the particles. For a first characterization of the connectivity in the entire GC, twelve areas were defined (Fig. 1) according to local characteristics outlined in Table 1. These characteristics are based on the strongly seasonal circulation of the Gulf (Lavín et al., 1997; Lavín and Marinone, 2003); it is cyclonic and anticyclonic during summer and winter, respectively. It is clear that areas with the characteristics described would not match every month of the year, as the circulation evolves in a seasonal cycle, particularly during the transitional periods.

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smaller excursions (Marinone et al., 2011). The region off San Francisquito (SF) is at a branching zone of the circulation of the southern Gulf. Part of the flow remains in the south, and part continues to the northern GC through the area labeled TI, where a quasi-permanent anticyclonic gyre has been reported (Mateos et al., 2006), which is evident in Fig. 2. The Ballenas and Salsipuedes channel area (CB) is characterized by strong tidal currents, mixing and convergence-induced upwelling (López et al., 2006, 2008) but weak residual currents. Finally, because the primary interest is to provide the connectivity of areas of biological interest, the large central southern portion (CS) of the Gulf was not subdivided. The CS is characterized by mesoscale eddies (Figueroa et al., 2003; Zamudio et al., 2008).

Particles were seeded in each region at the first day of each month at the upper model layer and were subsequently transported using the full three-dimensional velocity field (see equations (1)–(3)). In each area, the particles were seeded homogeneously everywhere, and the number of particles in each area ranged from 9451 to 26,934, depending on the size of the area. After 28 days of drifting, the number of particles present in each region and their source area was recorded. The 28 day period was chosen to have the same length for all months (including February) and to cover the most realistic situations for biological applications because most species have a spawn–egg–larvae stage duration of less than approximately 4 weeks.

For the case of the connectivity of specific organisms, motility during their early life stages can play an important role in determining their final destination (Bradbury and Snelgrove, 2001; Armswoth and Roughgarden, 2005; Van der Molen et al., 2007). The results shown here do not include any larval behavior and should be taken as representatives of the connectivity of nutrients, pollutants, eggs and larvae that can be treated as passive or inert, neutrally buoyant or of limited locomotion. The dispersal of particles is due only to hydrodynamics; i.e., advection and diffusion. Areas dominated by eddy-like circulation, such as the northern Gulf, would tend to retain more particles, say nutrients and, potentially, recruitment. In contrast, areas of strong coastal currents would connect to more distant areas in the downstream direction, and the potential for larger larval dispersal would accordingly be greater. The technique for determining the source and destiny of larvae using maps of connectivity is useful in cases for which spawning areas are well-established. Particles can be seeded in those areas, and one can subsequently determine where they end up after some suitable period of time (Peguero-Icaza et al., 2008).

Table 1
 Connectivity areas and their main characteristics. Regions SN-SS and LP-BC have similar characteristics and are only divided to provide more reduced/precise geographical source and destination areas for the particles.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Characteristics/features</th>
</tr>
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<tbody>
<tr>
<td>UG</td>
<td>Upper Gulf</td>
<td>Slow residual currents and small eddies (Marinone et al., 2011)</td>
</tr>
<tr>
<td>SO</td>
<td>Sonora</td>
<td>Strong coastal current (Peguero-Icaza et al., 2011)</td>
</tr>
<tr>
<td>TI</td>
<td>Tiburon</td>
<td>Exchange area between north and south and eddy (Beier, 1997; Mateos et al., 2006)</td>
</tr>
<tr>
<td>SN</td>
<td>Sinaloa North</td>
<td>Strong coastal current (Lavín and Marinone, 2003)</td>
</tr>
<tr>
<td>SS</td>
<td>Sinaloa South</td>
<td>Strong coastal current (Lavín and Marinone, 2003)</td>
</tr>
<tr>
<td>LP</td>
<td>La Paz</td>
<td>Weak coastal current (Lavín and Marinone, 2003)</td>
</tr>
<tr>
<td>BC</td>
<td>Bahia Concepción</td>
<td>Weak coastal current (Lavín and Marinone, 2003)</td>
</tr>
<tr>
<td>SF</td>
<td>San Francisquito</td>
<td>Boundary of eddy/return current (Mateos et al., 2006)</td>
</tr>
<tr>
<td>CB</td>
<td>Channel</td>
<td>Mixing and upwelling, weak residual currents (López et al., 2006, 2008)</td>
</tr>
<tr>
<td>ED</td>
<td>Eddy</td>
<td>Cyclonic/anticyclonic seasonal eddy (Lavín et al., 1997)</td>
</tr>
<tr>
<td>AG</td>
<td>Angel de la Guarda</td>
<td>Exchange area among north, south and ED (Beier, 1997)</td>
</tr>
<tr>
<td>CS</td>
<td>Central South</td>
<td>Eddies (Figueroa et al., 2003; Zamudio et al., 2008)</td>
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</table>
Watson et al., 2010; Chiswell and Rickard, 2011). In this study, the connectivity of the entire Gulf is studied by defining areas of different hydro-dynamical behavior by visual inspection of the Eulerian velocity field.

3. Results and discussion

The final position of the particles released from the twelve areas and for the 12 months studied were plotted to visualize their final destination. As an example, Fig. 3 shows the cases for January and July, when the general circulation of the GC is well-defined as anticyclonic and cyclonic (Marinone et al., 2011), respectively. The corresponding plots for the 12 months studied are available in the Supplementary Material. Each frame shows the polygon defining the area where the particles were seeded, and the final position of the particles after 28 days. A visual inspection of the figure shows more dispersion of the particles during January than during July; more particles are found outside the area of seeding during January. For January, the areas that keep more particles (retention) are the UG, LP, BC, ED and CS. For July, the retention of particles occurs in the UG, SO, BC, ED and CS areas. The export of particles during January is notably large from the north and from the mainland side of the Gulf toward the south and toward the peninsular side, indicating large spatial connectivity. For July, a coastal up-gulf excursion is present on the mainland side.

According to Carrillo et al. (2002) and Palacios-Hernández et al. (2002), the transitional periods between the summer and winter circulation are between September and October and April and May, respectively. This transitional pattern is reproduced by the model (Marinone, 2003, 2008; Marinone, et al., 2011), and in these periods, the circulation reverses direction. Consequently, the months of September and May are the most "diagonal", meaning that dispersion is low. The potential for self-recruitment is high over all of the GC at these times.

By analyzing the areas that receive particles from other areas (i.e., the columns of Fig. 4), it is clear that the Upper Gulf (UG), Concepción Bay (CB), and San Francisquito (SF) areas do not capture particles throughout the year, and the Tiburon (TI) and Angel de la Conception (BC) areas retain particles for eight. The high retention in the coastal region of SO occurs because the currents there are actually the border of the seasonal eddy. The Channel Ballenas/Salsipuedes area (CB) has 6 months of retention (>30%), and this situation is due to the high degree of tidal mixing, which results in weaker residual currents according to our model results. Retention in LP, CS and BC is due to weaker currents in general (low frequency and tidal) throughout the year. The areas near the large islands, AG, SF, and TI, have fewer months of retention (3, 0, and 2 months respectively), and this finding is caused by strong currents that are produced by the bathymetric restrictions in that region, which is the exchange area between the northern and southern Gulf (López et al., 2006, 2008).

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Guarda (AG) areas only capture particles during 1 month. The UG and the CB retain particles, as mentioned above. However, SF, TI and AG do not retain particles; i.e., these three areas are transit areas. The Eddy (ED) region receives particles from AG from July to September, when the currents are cyclonic in the northern Gulf and up-gulf in the coastal southern Gulf, while during the anticyclonic period, ED receives particles from the UG. The SO region receives particles from the Eddy area during January and from TI, CB, and AG from May to August (i.e., from the central Gulf when the flow is up-gulf).

At the southern Gulf, the northern and southern Sinaloa areas (SN and SS) exchange particles directly in the downstream direction. That is, the SN feeds the SS during October—April, and the SS feeds the SN from July to September. The central southern (CS) area captures particles for many months from different areas. This area has eddies (Figueroa et al., 2003; Zamudio et al., 2008), is in the middle of the two coasts, and is the largest area.

Marinone et al. (2008) reported connectivity matrices during July for 21 areas along the coast in the northern Gulf between 0 and 60 m depth and found a downstream cyclonic connectivity, as in this study but with almost no retention. The matrices' areas were contained in the SO, UG and ED regions of this study. Marinone et al. found low retention because during July, the circulation is strong, and their study areas were much smaller than ours, meaning that the particles escaped in a few days. For example, in day Julian 224, which corresponds to mid-July. Fig. 2 show speeds of approximately 15 cm s⁻¹, which translates to a displacement of approximately 13 km day⁻¹. This finding implies that the particles surround almost the entire northern Gulf in 28 days. Our results differ slightly from those of Marinone et al. (2008) because the numerical model used here has an improved bathymetric resolution by a factor of three. This phenomenon produced smaller eddies in the UG area, where we found high retention. This area (UG) and SO are productive (Calderon-Aguilera et al., 2003; Sánchez-Velasco et al., 2009) and house marine reserves. The local retention may explain the enhancement in recruitment observed after the reserve establishment (Cudney-Bueno et al., 2009).

The twelve areas chosen are large, and there can be subdomains within each area in relation to the connectivity of different species, i.e., the source and the destiny of larvae. For well-known nurseries, spawning areas, marine reserves or banks of some species, the procedure described here (identifying the source and destiny of particles) can be applied on a case-by-case basis. Soria et al. (submitted for publication) studied the demographic connectivity of the rock scallop, Spondylus calcifer, in the northern Gulf of California during July. The source “points” from this study are located near the coast. The authors were interested in determining the possible sources of larvae for a marine reserve located in the north of the SO area. They found that the main sources of particles are two locations south of the same area (SO), i.e., the three points lay in the
same region. In this study, that would indicate local retention. For their study, the authors found the advection/dispersion of the particles downstream along the coastal current at the edge of the cyclonic gyre. Fig. 4 shows that SO retains 40–50% of particles in that same month. The SO area, as mentioned before, shows at least 30% particle retention for 9 months of the year.

Peguero-Icaza et al. (2011) reported connectivity among three large areas in the central-northern Gulf for the months of June, August, December, and February. The areas were defined from the degree of association of their larval fish assemblages and are different for each month and therefore are difficult to compare. However, their results are in accordance with the results from this study in that they report high retention and low exportation of particles to the south during summer, which is the cyclonic phase of the circulation when the currents in the central Gulf are to the north. In contrast, when the flow is predominantly anticyclonic and to the south, low retention occurred in the study of Peguero-Icaza, and most of the particles were exported to the south (lost from their domain).

Fig. 5 shows, as a synthesis of the connectivity matrices, the time average (Fig. 5a), the standard deviation (Fig. 5b), and the first (Fig. 5c and e) and second modes (Fig. 5d and f) of the empirical orthogonal functions (EOF). The EOF analysis is used only to extract a compact description of the spatial and temporal variability of the time series of connectivity (Emery and Thomson, 1997). For the time average (Fig. 5a), the areas in the diagonal with values ≥30% are UG, SO, LP, ED, and CS. Only SF has values smaller than 10% in the diagonal. Away from the diagonal, only BC receives particles (≥30%) from SF, and CS from BC. The areas that capture particles from more regions are CS, SO, and BC with 6, 5, and 4, respectively.

The first EOF has an annual periodicity and explains 48% of the variance; it reflects a large domination of the diagonal components of the matrix. Values with the same sign indicate that the regions retain/disperse particles in phase, and values with the opposite signs indicate that while one cell retains particles, the other cell disperses particles (with respect to the average). The LP and BC areas are out of phase of the rest of the regions. The second EOF mode explains 21% of the variance and shows a semiannual evolution. In this mode, all of the diagonal components are in phase (same sign). The seasonal evolution of the connectivity from just these two modes accounts for 69% of the variance.

Finally, connectivity in the Gulf depends on location and on the season. Areas of large retention with eddy-like circulation, such as the northern Gulf, would have more limited spatial connectivity and may experience low external recruitment and large self-recruitment. Areas of large excursion, as those of the coastal currents along the mainland side of the Gulf, would export particles far away from the origin in the downstream direction and the destiny of the particles largely depends on the season.
Fig. 4. The monthly connectivity matrices. The vertical axes correspond to the release areas, and the horizontal axes correspond to the arrival areas. The particles in the rows add to 100%. Only cells with more than 10% of particles are colored. The diagonal lines are visualizing aids to locate the different elements (cells) of the matrices.
4. Summary

Connectivity matrices were calculated for the Gulf of California for the 12 months of the year. The trajectories of the particles were obtained with an advection/diffusion scheme that uses the Eulerian velocity field from a three-dimensional numerical model. To calculate the connectivity matrices, the Gulf was divided into twelve regions of different hydrodynamic characteristics, as seen from the Eulerian velocity field. These regions are characterized by strong and/or weak coastal currents, eddies, mixing and exchange areas. The main findings are

- Large retention occurs in three regions of the northern Gulf of California, namely, the Upper Gulf, the Eddy and the Sonora areas. This situation occurs for 9–12 months of the year, and therefore the potential for auto-recruitment of larvae is large. In these areas, the retention happened because of the eddy-like seasonal circulation.
- High retention occurs in the southern part of the Gulf on the peninsular side because of the weak seasonal currents and also the potential for auto-recruitment is large.
- Large dispersion occurs off the mainland coastal areas in the central and southern parts of the GC, especially for the Sinaloa North and Sinaloa South areas, which export particles to numerous areas due to strong seasonal currents and therefore the potential of distant coastal species connectivity is large.
- The evolution of the connectivity from the EOF analyses is predominantly annual and semiannual with 48% and 21% of the variance, respectively.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.ecss.2012.01.003.

References


