



Numerical simulation of larval shrimp dispersion in the Northern Region of the Gulf of California

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Abstract

The trajectories of shrimp larvae in the northern part of the Gulf of California were studied from a Lagrangian point of view using a three-dimensional numerical model. The advection of particles was carried out over fortnightly periods starting at spring and neap tides. The northernmost region of the gulf has important shrimp fisheries and nursery areas have been located off the coast of Baja California at San Felipe (SF) and off the Sonora coast at Santa Clara (SC). Though the reproduction zone is believed to be south of these nursery areas, there is much that remains unknown about the zone and the routes used by shrimps to reach these areas. Passive and active simulations of shrimp larvae drift were carried out in order to study the possible areas of shrimp spawning and their migratory routes. The active migration schemes were based on assumptions that the larvae can be advected only: (1) during the day, (2) at night or (3) when the currents flow in the northward direction toward the nursery areas. It was found that the larvae in Santa Clara and San Felipe came from different production zones. No differences were found between the spring and neap tide scenarios except for the diurnal migration experiments. The distance traveled by shrimp larvae was always less than ~40–50 km, except in the cases when the larvae selected the appropriate direction to the nursery areas when the larvae travel ~140 km to SC and ~95 km to SF.

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1. Introduction

Bordered to the south by the Angel de la Guarda and Tiburon Islands, the northern region of the Gulf of California (GC, Fig. 1) harbors important shrimp fisheries. Two species of shrimp have been identified (Aragón-Noriega and Calderón-Aguilera, 2000): blue shrimp (*Litopenaeus stylirostris*) and brown shrimp (*Farfantepenaeus californiensis*), the blue being more significant. In general, shrimp spend their adult life offshore where spawning takes place. The larva stages (from eggs, nauplius, protozoa to mysis) occur offshore. The postlarvae stage is reached after approximately 14 days and is followed by migration to the nursery areas

(usually estuaries). Spawning occurs usually/especially during summer in the GC, and the shrimp are freely advected during this part of their life cycle until they have motile capacity.

Nursery areas of shrimp have been found in the Upper Gulf of California (UGC) where the postlarvae stay until they migrate into the open ocean (Aragón-Noriega and Calderón-Aguilera, 2000). One nursery area is located in Santa Clara (SC) off the Sonora coast and the other north of San Felipe (SF) off the Baja California coast (Fig. 1). These shrimp nursery areas are near-shore coastal regions and are not the usual protected estuaries. The National Institute of Fisheries located the spawning stokes off the mainland coast (Calderón-Aguilera et al., 2003). During summer, the general circulation of the region is cyclonic (Lavín et al., 1997; Marinone, 2003), it was anticipated that postlarvae found along the Baja California coast would be older than those from the Sonora coast simply because of the time required to

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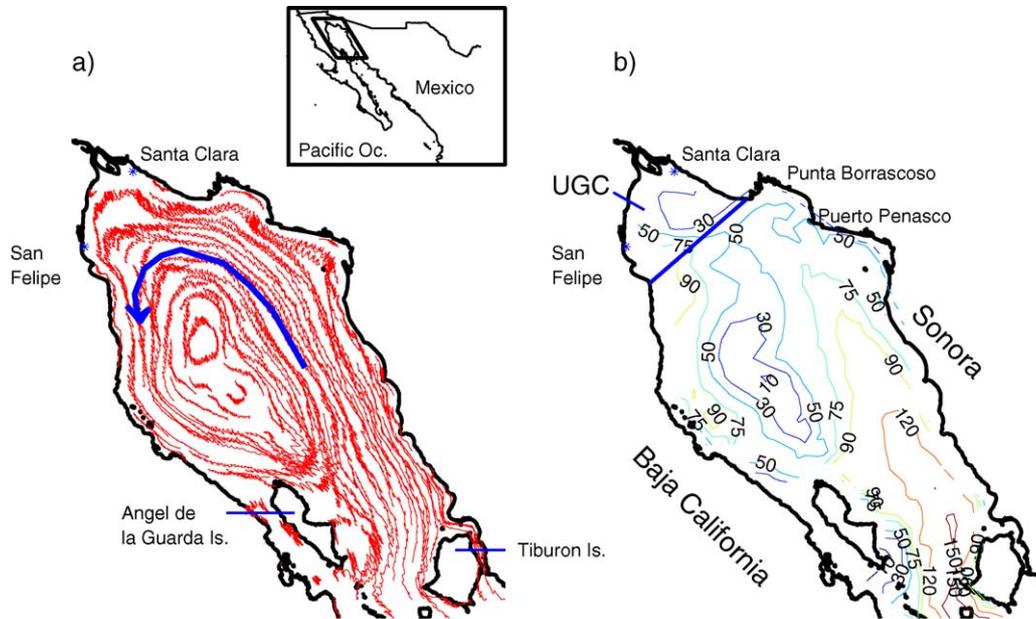


Fig. 1. The northern region of the Gulf of California. Santa Clara and San Felipe have been identified as nursery zones. UGC stands for Upper Gulf of California. (a) Passive particle trajectories, the initial time was during the spring tide of July 2001, and the integration period is 15 days. For clarity only every other one trajectories are shown. The blue arrow indicates the direction of the flow. (b) Net distance traveled by the particles in km.

travel a greater distance. However, Aragón-Noriega and Calderón-Aguilera (2001) reported finding younger larvae in SF than in SC, suggesting that they either come from spatially different reproductive units or that there exists a different circulation pattern.

To explore the above ideas, Calderón-Aguilera et al. (2003) used the surface currents from a numerical model to study the migratory patterns of shrimp larvae. By visual inspection of the Eulerian velocity fields, they predicted the possible migration routes used by larvae to reach the nursery areas and concluded that there are different stocks spawning at the nearby region.

The objective of this study is to determine the possible migratory routes (at egg and postlarvae stages) and the location of the reproductive units of shrimp from a Lagrangian point of view. In principle, this approach provides for the potential trajectories of floats, fluid parcels, contaminants, larvae, etc. Experiments with active and passive particles were performed with the aim of exploring the relative importance of the currents when compared to the mobile capacity of the postlarvae.

2. Model and experiments

The trajectories of the particles were obtained by time-integrating the horizontal velocity field obtained from the layerwise vertically-integrated Hamburg Shelf Ocean Model developed by Backhaus (1985), which solves also the fully prognostic temperature and salinity equations. The model domain has a mesh size of $2.5' \times 2.5'$ ($\sim 3.9 \text{ km} \times \sim 4.6 \text{ km}$) in the horizontal and 12 layers

in the vertical (nominal lower levels at 10, 20, 30, 60, 100, 150, 200, 250, 350, 600, 1000 and 4000 m). The model was implemented for the GC by Marinone (2003) and is described in detail there (and references therein).

The results shown in this article come from the model forced with: (a) tides; (b) winds; and climatological (c) hydrography at the mouth; and (d) heat and fresh water fluxes at the sea–air interface. As shown in Marinone (2003) the model reproduces the main seasonal signals of surface temperature, heat balance, tidal elevation and surface circulation in the northern gulf. Tidal currents have also been validated from several current meter observations (Marinone, 2000).

The trajectories of the particles were calculated integrating the system:

$$\begin{aligned} \frac{dx}{dt} &= (u_* + u_d), \\ \frac{dy}{dt} &= (v_* + v_d), \end{aligned} \quad (1)$$

with a second order Runge–Kutta method and a time step of 10 min, where (x, y) is the particle position, (u_*, v_*) is the background fluid velocity at each particle position, calculated by bilinear interpolation of the instantaneous Eulerian velocity fields from the numerical model, and (u_d, v_d) are small normally distributed random velocities used to incorporate diffusivity into the model motion. The components (u_d, v_d) were chosen to have a zero mean and standard deviation proportionate to the background velocity (u_*, v_*) . This increased diffusion simulates a stronger and more turbulent flow related to the instantaneous model velocity field.

Larvae were released every ~ 12 km on the numerical model grid over the whole northern region of the gulf, every 2 h for 24-h periods starting at spring tide and at neap tide. Then, each experiment was repeated 10 times while varying the random velocity (u_d, v_d). The integration period was 15 days; the required time to progress from egg to postlarvae stages and cover a fortnightly tidal cycle.

Calderón-Aguilera et al. (2003) located two nursery areas approximately 60 km from each other in the UGC; SF and SC. To implement these into the model, the nursery areas were defined as circular regions with a radius (R) of 25 km centered in SF and SC, respectively, in such a way that they do not overlap. This means that when particles arrive within 25 km of SF and SC, they are considered to have successfully reached the nursery areas. After identifying the particles that reach these areas, percentages, required time, distance traveled and the probability of the particles reaching the nursery areas were calculated.

The above experiments were done with passive advection of particles. Shrimp larvae, like other planktonic organisms, are capable of vertical migration (Rothlisberg et al., 1996) and use currents to move horizontally only in some “favorable” direction or only during the day or night according to some physical/chemical cue (e.g., Heron et al., 1994; Rothlisberg et al., 1995; Flierl et al., 1999). To simulate these conditions, a *biological component* was included and the particles were advected only upon compliance with set conditions. Implemented to determine the best strategy to reach the nursery areas, these conditions were that particles travel only (1) during the day, (2) at night, and (3) when the current direction is toward the UGC. The first two scenarios imply that the larvae hide descending in the water column and that the larvae obviously must have followed a successful strategy to reach the nursery areas from the production zone, located to the south. The third scenario was selected to investigate a more direct form of transit from the production to the nursery areas. Each one of these strategies was run in the model as in the passive cases.

3. Results

Fig. 1a shows the trajectories calculated with passive or purely advected shrimp larvae for the case starting at spring tides (July 2001). Fig. 1b shows contours of the mean net distance traveled by the larvae in 15 days. The mean net distance was calculated by averaging the net distance reached from all the repetitions of each experiment. As no significant difference was found between the spring and neap tide experiments, all trials were considered as repetitions of a single experiment. The trajectories show a basin wide cyclonic gyre with

two small cyclonic gyres in its center. Fig. 1b shows two areas where the distances traveled are larger than 75 km. These are located near the Baja California and Sonora coasts and to the east of Angel de la Guarda Island. At the center and northern parts of the gyre, where the nursery areas are located, the net distances traveled are less than ~ 30 km. The standard deviation of the distance traveled (not shown) by the particles is only between 2 and 5 km.

Aragón-Noriega (pers. comm.) and Licón-González (pers. comm.) suggested that the larvae come from a place near the Sonora coast, south of the nursery areas. The path of the trajectories of the passive particles shown in Fig. 1a matches this migration route, however, only those particles located inside the 50 km contour are capable of reaching the nursery areas.

3.1. Passive migrations

From the net displacements shown above, it can be concluded that the particles that arrive at the nursery zones in 15 days or less are only those closer than 40–50 km. Fig. 2a shows the trajectories of the particles that reach the nursery zones in at least one of the experiments; green for the SC zone and red for the SF zone. The trajectories displayed correspond to the experiment started during spring tide.

Fig. 2b shows contours of the average time used by the passive larvae to reach the nursery zones. The solid and dashed contours correspond to the particles that arrive to SF and SC, respectively. Shaded areas mark the regions where 90% or more of the seeded and released larvae reach the nursery areas (red for SF, green for SC). These shaded areas will be referred to as production or spawning zones. Both production areas are located to the east of the nursery zones. The SC nursery area also acts as a production area for SF, meaning that there is migration from SC to SF. Shrimp larvae arrive to SC and SF from a maximum of 34 km and 39 km away, and only 4.6% and 3.6% of the total particles seeded reach SC and SF, respectively (see Table 1).

3.2. Migration strategies

3.2.1. Diurnal migrations

Fig. 2c,d shows the results for the case in which the larvae are advected only during the day at spring tide. The percentage of larvae that reach the SC nursery area is slightly larger for the spring tide case (3.9%) than for the neap tide case (3.4%) (not shown). For SF, there is no difference between spring and neap tides and 3.0% of the particles reach the area. The larger migrations were toward SC (about 35 km and 26 km with spring and neap tide, respectively), while the displacements were ~ 10 km for SF. The larvae that reach the SC nursery area come from the southeast following the Sonora

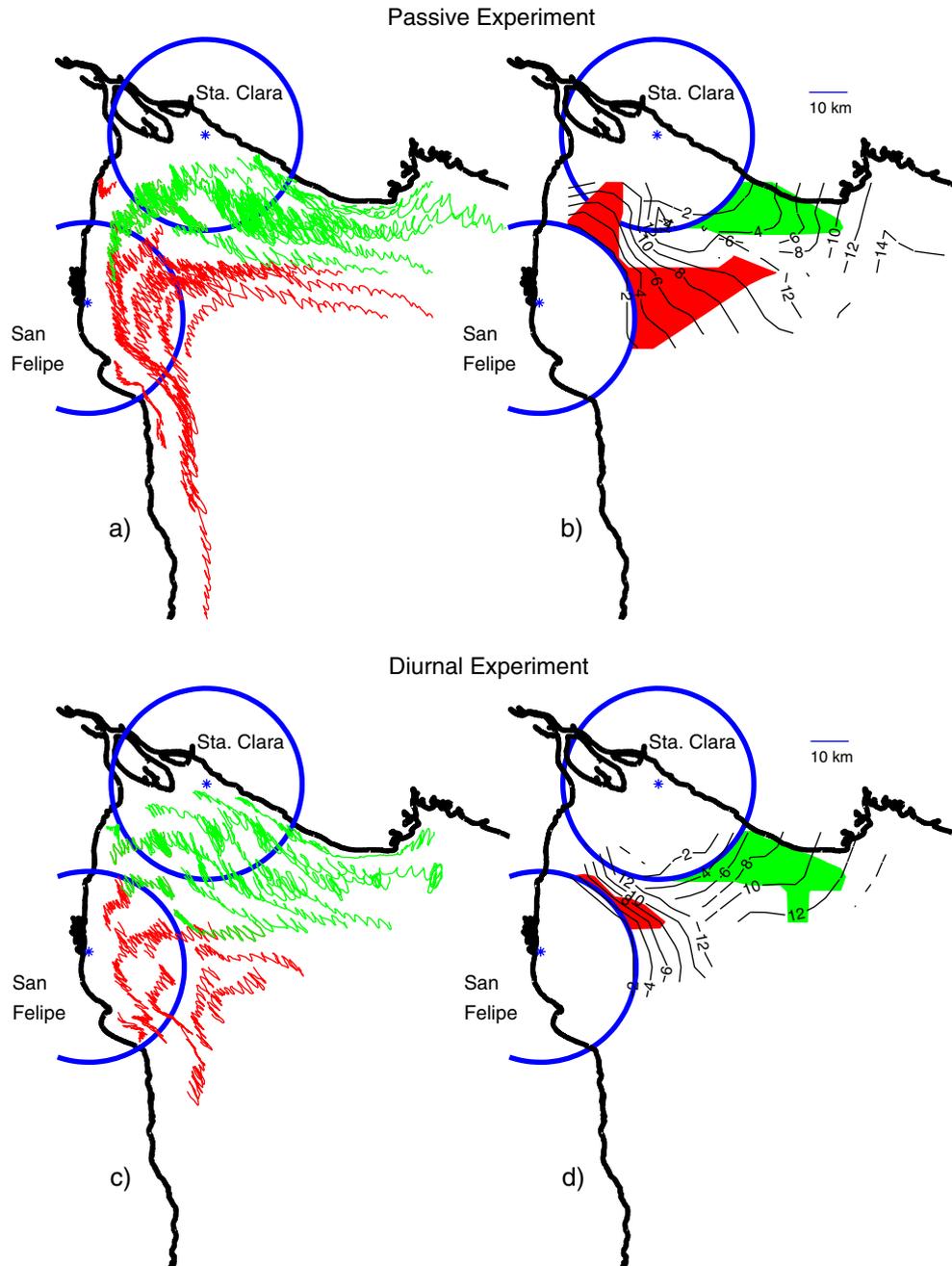


Fig. 2. Passive (a, b) and diurnal experiments (c, d). The circles indicate the nursery areas defined within a radius $R = 25$ km. (a) and (c) show trajectories that reach the nursery zones to San Felipe (in red) and Santa Clara (in green). (b) and (d) show the mean time used by the particles to reach the nursery areas: solid and dashed contours for SF and SC, respectively. The colored zones in (b) and (d) are the production areas and are defined as such only when 90% of the released particles of all repetitions reach the nursery areas.

coast, while those that reach SF come from the east during both spring and neap tides. The maximum required time for the particles to reach the nursery areas is 8 days to SF and 12 days to SC.

3.2.2. Nocturnal migrations

The experiments in which the larvae are allowed to travel only during the night are shown in Fig. 3a,b. As no difference was found between the spring and neap tide

cases, only the latter is shown herein. A small percentage of larvae reach the nursery areas (3.0% to SF and 1.7% to SC). As in the diurnal migration experiments, the larvae that reach SC come from the southeast, those that reach SF come from the east and, in both cases, particles travel less than 10 km. The production area is within the limit of the nursery area for SF, while there is no production area for SC. The required time to reach the zones is longer than 6 days.

Table 1
Percentage of the total seeded particles that reach the nursery zones of Santa Clara (SC) and San Felipe (SF), and their traveled distances

Experiments		% of particles		Distance (km)	
		Spring	Neap	Spring	Neap
Passive	SC	4.6	4.6	34	34
	SF	3.6	3.6	39	39
Diurnal	SC	3.9	3.4	35	26
	SF	3.0	3.0	10	10
Nocturnal	SC	1.7	1.7	10	10
	SF	3.0	3.0	10	10
With northward current	SC	12.0	12.0	140	140
	SF	10.0	10.0	95	95

The experiment's classification according to strategy is as follows: Passive—corresponds to a continuous advection of the particles, Diurnal and nocturnal—for advection of the particles allowed only during the day and night, respectively, and With northward currents—where the advection is allowed only when the meridional component of the velocity is to the north.

3.2.3. Migration to the northern part of the Gulf

The experiments in which the larvae are advected only when the meridional component of the velocity is to the north are shown in Fig. 3c,d during spring tide (no differences were found for the neap tide case). The percentage of particles that arrive in the nursery areas increases significantly (Table 1) and, the potential spawning areas increase considerably (Fig. 3d). The maximum migration distances now become 95 km for SF and 140 km for SC. There is no migration between nursery areas and, similar to previous experiments, there is no evidence of a common production area.

4. Discussion

Surely the successful migration depends not just on circulation conditions but also on the behavioral responses that the authors use in their scenarios, such as avoiding bad currents, or traveling only during the day or the night. A basin wide cyclonic gyre dominates the general circulation in the northern gulf from July to September (Ripa, 1997; Marinone, 2003), and it is also evident in Fig. 1a. The larger spawning events take place during this time of the year (Calderón-Aguilera et al., 2003).

Gutiérrez et al. (2003) described the Lagrangian circulation of the gulf and reported that, during July and August, the net traveled distances of passive tracers are less than 100 km per month. Here the time window was reduced to 15 days because this is the life cycle of the first planktonic stages of shrimp. In this time frame, the traveled distances attained by the advected particles are smaller in the northernmost part of the region, particularly near the nursery areas where the particle displacements are less than ~30 km. At these speeds,

passive larvae could only reach the nursery areas from 40–50 km away and from the coastal areas. The remainder would move toward the Baja California coast following the cyclonic gyre southwards (Fig. 1a). The identified spawning area has been located further south than those implied by the passive migrations. If the location of the production area is correct, the larvae need to have some active strategy in order to successfully reach the nursery areas.

Although the dominant semidiurnal tide amplifies in this region, no differences were found between the experiments with initial conditions on spring or neap tide and those during each tidal cycle. Even though the tidal excursion in this region is large, Gutiérrez et al. (2003) showed that the net displacement of the particle is determined by the general long-term circulation.

Younger larvae exist in the SF nursery area than in that of SC when the general summer circulation is cyclonic. An apparent paradox is created when this aforementioned fact is combined with the belief that a unique spawning area exists south of these regions in the GC. This inconsistency has motivated several studies, with in situ measurements and estimations using tidal Eulerian currents. However, the use of Eulerian fields to estimate the trajectories of particles of Lagrangian nature could lead to misleading conclusions, especially where large velocity gradients are present (Longuet-Higgins, 1969; Zimmerman, 1979). Aragón-Noriega (pers. comm.) estimated maximum displacements of ~4 km per day using a residual velocity of 0.05 m s⁻¹. At this rate, the particles will take about 14 days to travel from the spawning zone at Punta Borrascoso to the nursery areas. Using constant tidal velocities, without considering the path of the trajectory, of just 6 or 12 h per cycle (i.e., only in the upgulf direction), they estimated displacements of 13 km and 16 km, respectively, and the larvae would need just 4 days to travel the same distance. The Lagrangian predictions made in this work were done with the instantaneous velocity of currents at the particle position, so it is possible to adequately determine the origin and path of the particles from the spawning regions to the nursery areas.

Table 1 summarizes some of the findings of the different strategies of migration showing the percentage of the released particles that arrive at the nursery areas and the mean distance traveled by the larvae during spring and neap tides for both the SC and SF nursery areas. With the exception of the nocturnal case, the percentage of particles that reach SC is always larger than those that reach SF. For the experiments done with particles moving only toward the north, the amount of particles reaching the area increases significantly and is at a minimum when the particles only move during the night. Obviously, the longest migration occurs when the particles move toward the northern part of the gulf and the smallest migrations were found for the nightly advectons to SF.

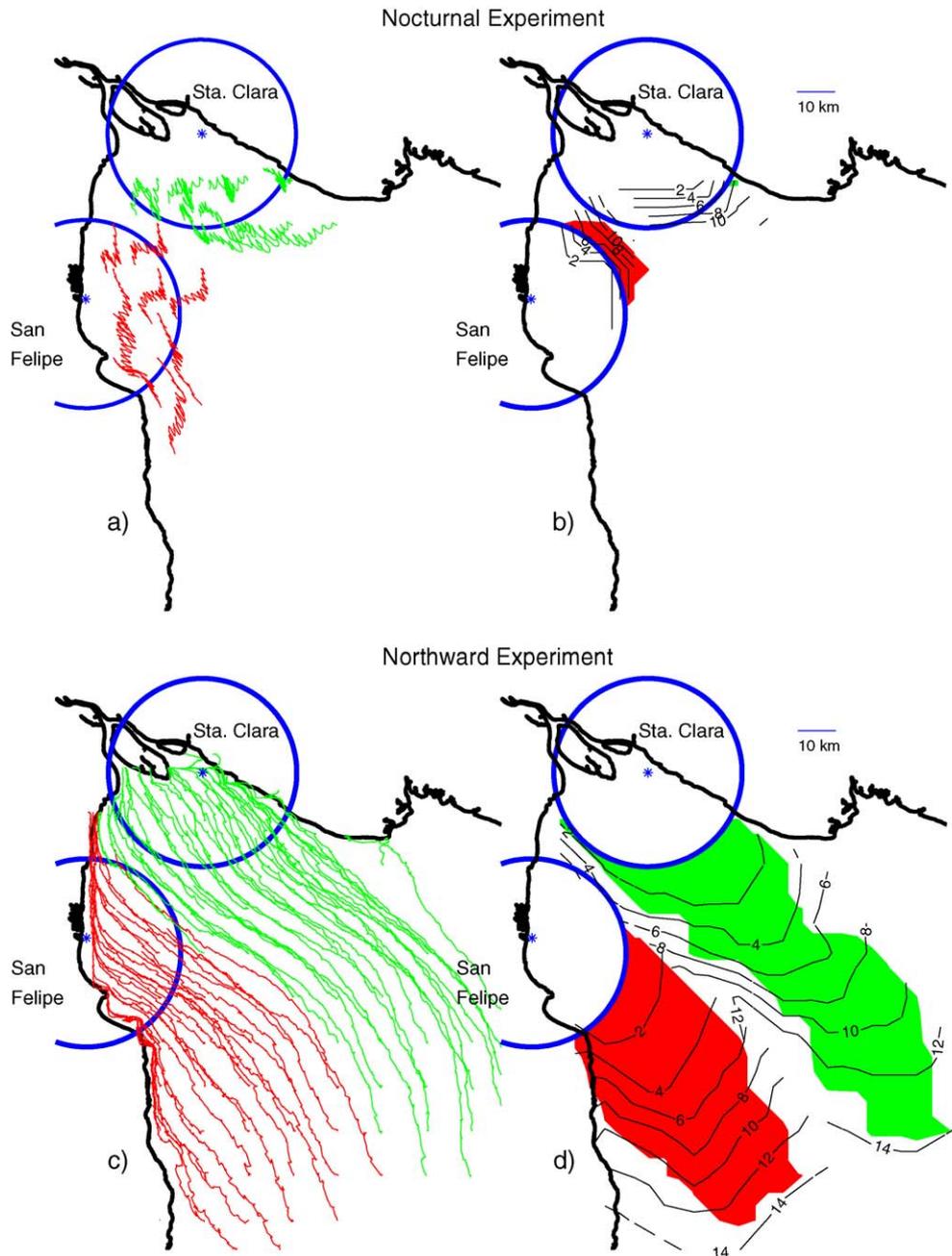


Fig. 3. Same as Fig. 2, but for the nocturnal (a, b) and northward (c, d) migration experiments, during spring and neap tide, respectively.

The differences between the day and night experiments depend upon the particular fortnightly period, as the phase of the tidal constituents have positive and negative influence over the 12-h, day and night period. As such, a different month could have yielded an opposite result, just as a different location could offer another outcome. For example, Rothlisberg et al. (1983) found that in the Gulf of Carpentaria, larvae traveling during the night can migrate over 160 km in two–three week periods. Hill (1994) found maximum migrations associated to the diel (24-h period) with the principal solar semi-diurnal tide (S2) (12 h) advecting particles for 6 h per night so that

they are locked to the same part of the S2 tidal induced current. For the day and night experiments presented in this work, 12 h of night and 12 h of day for a two-week-long summer cycle were selected. As our model currents include several tidal constituents, the advection is not locked to any one constituent (for example, particles will be advected 12.00 of 12.42 h of the principal lunar semi-diurnal tidal cycle, M2).

In this study, the larvae are advected with the same scenario for the whole integration period and no distinctions are made within the 15-day advective period. In reality, the larvae go from completely passive

(eggs) to a relatively or potentially active (postlarvae) behavior. Active migration has been documented for postlarvae and fish and it has been shown that they follow some external clue: e.g. plaice follow some geophysical clue, such as a geomagnetic field (Metcalfe et al., 1993). Some studies suggest a tidally active response from postlarvae shrimp (Heron et al., 1994; Rothlisberg and Church, 1994; Rothlisberg et al., 1995) and others indicate that postlarvae follow some odor or chemical cues (Forward et al., 2003, for premolt megalope, blue crab). In particular, blue and brown shrimps have been reported to be more active during the day and night, respectively (García and Le Restre, 1981).

From the experiments done, it was feasible to determine the possible source of larvae to SC and SF (shadow areas in Figs. 2 and 3). Shrimp larvae migrate to SC from the southeast following the Sonora coast and from the center of the upper gulf to SF. Punta Borrascoso was proposed as the spawning zone of the area by Aragón-Noriega (pers. comm.), but Licón-Gonzalez (pers. comm.) states that these larvae could come from places as far as Puerto Peñasco. In the present work, no evidence of larvae coming from Punta Borrascoso was found. It is also possible that these areas are fed by some small localized near-shore spawning populations, as suggested by Rothlisberg and Church (1994). This viable contribution should not be underestimated. If fishery management ignores the possibility that different spawning areas exist, it may well jeopardize the recruitment success of shrimp.

In conclusion, the larvae come from different spawning stocks to the nursery zones of SC and SF and, in order to arrive from more than 40–50 km, the larvae must use a northward traveling migration strategy following some spatial gradient (temperature, salinity, pressure, etc.) or a more complex one. These results should be taken as hypothesis as there is no data to validate them, but they can lead or help to a different sampling strategy of the interested researchers in fisheries.

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