Modelling of Sardine (Sardina pilchardus) Egg Dispersal in the Gulf of Cadiz

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1. Introduction

The Gulf of Cadiz is recognised to be an important sardine spawning ground. In recent years, surveys conducted by the Portuguese Sea and Fisheries Institute (IPIMAR) indicate that sardine egg presence in the Gulf has been increasing (Stratoudakis *et al.*, 2003). During one such cruise in November 2001, a small patch (~600 km^2) of sea surface water near to Cadiz was intensively sampled for sardine eggs, over the duration of one night. The location is just above the shelf break, water depths between 40 and 120 m. Results from this survey are shown in Figure 1.

Sardine eggs undergo several developmental stages; these may be simplified into Day 0 eggs (eggs aged less than 24 hours) and Day 1 eggs (aged over 24 hours). Figure 1b shows the distribution of Day 0 eggs observed at 3 m depth on the night of 12/13 November 2001; a small highly-concentrated patch of eggs is visible in the upper-left quadrant of the figure. In Figure 1c, which shows the simultaneous distribution of Day 1 eggs, the higher egg densities are found towards the lower-right quadrant, where they are clearly more dispersed in comparison with the Day 0s. Circulatory features observed in regional satellite images close in time to the study period (see Figure 5b) give support to the hypothesis that the spawning location of the Day 1 eggs may correspond to the present location of the Day 0 eggs. The objective of the present study is to further explore this possibility using a numerical modelling approach.

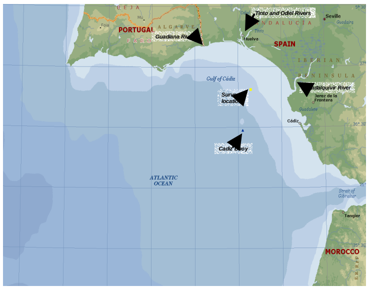

Figure 1a. Generalised map of the Gulf of Cadiz region included within the model domain. The sardine egg survey location is indicated, and also the position of the Cadiz buoy from which wind data were obtained.

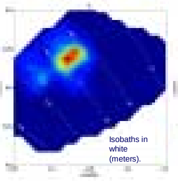
Isobaths in white (meters).

Figure 1b. The observed distribution of Day 0 sardine eggs 3 m below the surface, near to Cadiz on 12/13 November 2001.

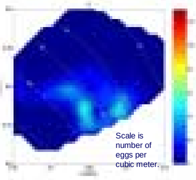
Scale is number of eggs per cubic meter.

Figure 1c. The observed distribution of Day 1 sardine eggs 3 m below the surface, on 12/13 November 2001.

Figure 2a (upper). 6-hourly model forcing wind velocity vectors at the location of the study site, west of Cadiz. Winds are light and generally easterly until 8 November when a moderate 3-day northerly pulse is initiated. After 11 November wind speeds decrease, but retain a northerly component until day 16.

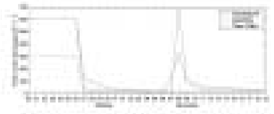

Figure 2b (lower). Daily river outflow values for the Guadalquivir River; Guadiana River; and the Tinto and Odiel Rivers, which converge at Huelva. Note ramping up of outflows until October 26.

Table 1. Model parameters.

Number of timesteps	NTIMES	5184
Internal (baroclinic) timestep	DT	500 s
External (barotropic) timestep	NDTFAST	30 s
Surface stretching	THETA_S	5
Bottom stretching	THETA_B	0.4
Thermocline depth	TCLINE	50 m

2. The model setup

ROMS 2.1 is used to simulate wind and buoyancy forcing in the Gulf of Cadiz over the first three weeks of November 2001. The model domain includes the entire Gulf of Cadiz region, extending between 34.5° and 39.0° N, and 5.5° and 10° W. Boundaries to the north, south and west, are open, whilst the eastern boundary that normally permits circulation between the Gulf and the Mediterranean Sea, is closed. Realistic bottom topography is utilised. Horizontal grid resolution is ~4 km, with 23 vertical levels permitting increased vertical resolution near the surface. Further model parameters are given in Table 1.

25 numerical floats are released into the model, in a diamond formation, at 1800 hours on 11 November, over the location of maximum sardine egg concentrations seen in Figure 1b. These floats allow the simulation of the egg dispersal in response to the environmental forcing.

Wind and river runoff are significant forcing mechanisms in the Gulf of Cadiz, particularly in the wintertime (Figure 2). National Centers for Environmental Prediction (NCEP; Kalnay *et al.*, 1996) wind speeds are used to force the model. NCEP air temperature, precipitation and shortwave solar radiation data are also used in the implementation of the ROMS 'bulk fluxes' routines. Fresh water is introduced at three point sources that correspond to the locations of the three main Gulf of Cadiz rivers: the Guadalquivir River (Alcalá del Río station); the Guadiana River (Pulo do Lobo station); and the Tinto-Odiel River System (12 % of the Guadiana outflow, following Cossa *et al.*, 2001). River inlets are each a single grid cell wide, and the inlet lengths vary between 11 and 14 grid cells. The river mass fluxes, with temperature 10 ° C and salinity 0 psu, are input at the top vertical level of the innermost grid cells of the inlets. Over the first 6 days of the simulation the discharges are artificially ramped up to increase the volume of fresh water within the domain.

The model is started from rest on 20 October 2001. Initialisation is achieved using Gulf of Cadiz winter stratification profiles for 2001 obtained from the World Ocean Atlas (Hankin *et al.*, 2001). Initial surface temperatures and salinities are 20.2 ° C and 36.2 psu, respectively, across the domain. At the three lateral boundaries facing the open ocean, an active/passive radiative boundary scheme is used for the inward and outward fluxes of momentum (Marchesiello *et al.*, 2001).

3. Response to forcing

Considerable confidence in the response of the model to the forcing may be gained from the results in Figure 3, which show the close agreement between model sea surface temperature (SST) and SST observations obtained from a buoy stationed at 36.47° N, 6.95° W in the Gulf of Cadiz (Figure 1a). These results indicate that the 'bulk fluxes' routines are performing well. Between 1 and 19 November surface waters cool by 2 ° C, in correspondence with the transition to winter. A sharp SST decline occurs 9 through 11 November, which is associated with the aforementioned changes in wind strength and direction (see Figure 2a).

The model surface salinity fields (averaged over one inertial period) in Figure 4 illustrate the surface structure of the river plumes and the effects of the wind forcing upon them, from 8 through 14 November, the period in which the float release occurs; black vectors denote the horizontal current velocities. During the first ~19 days of the simulation generally light easterly winds prevailed. These promoted the formation of a downstream (in the direction of Kelvin wave propagation) flowing coastal current, carrying fresh water from the three rivers. The image sequence shows that before the 3-day pulse of stronger northerly winds, the plumes have merged together, are attached to the coast, and display higher current velocities than in other parts of the domain. The signature of the Guadalquivir River is weak, however it augments that of the Tinto-Odiel at Huelva. The northerly wind pulse (up to 10 m s^{-1}) beginning on day 8 induces an upwelling response along the coastline, so that the plumes are advected offshore, broadening but not separating from the coast. Surface velocities across the domain increase. Close inshore eastward of Huelva there is a reversal of the direction of flow, so that an upstream flowing coastal current develops. This flow prevails after the relaxation of the wind on November 11. Examination of the current velocities at the location of the floats in the 12-November image indicates that they are strongly influenced by the situation resulting from the northerly wind pulse (compare with 8 November).

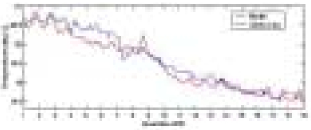

Figure 3. A time-series of SST measured at 36.47° N, 6.95° W by the Cadiz buoy, and a co-located model SST time-series showing good agreement.

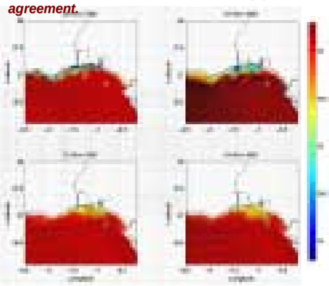

Figure 4. Model surface salinity fields for 8, 10, 12 and 14 November. The white 'O' marks the location of the float release.

4. Float results

The model yields the float movements shown in Figure 5a. The figure shows the start and end of the float tracks over-laid on an averaged (over one inertial period) model SST field from the 14 November. Over the given tracking period of 36 hours, the floats are displaced a distance of about 5 km, implying a speed of approximately 4 cm s^{-1}, in a southeasterly direction. This displacement compares favourably with the velocity estimates obtained from successive satellite SST images, shown in Figure 5b. The model floats move together as a block, with slight deformation of the formation occurring as a result of shear. Diffusivity of horizontal float motions is, for the present, not included within the model configuration.

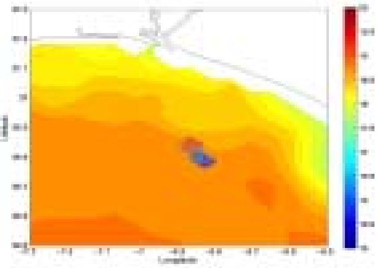

Figure 5a. Model SST field for 14 November 2001 over the Cadiz area. Red/Blue circles indicate the initial/final positions of floats released and tracked over 36 hours between 11 and 12 November 2001. SST values away from the coast are equivalent to the observations in Figure 5b; inshore, however, the model fails to fully capture the steep, sharp observed SST gradients – increased model resolution may improve this situation.

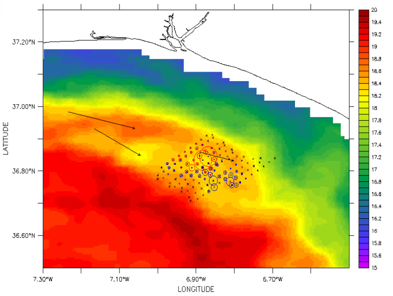

Figure 5b. AVHRR SST for 14 November 2001 over the Cadiz area. Arrows indicate the displacements of thermal structures observed between successive images from the 13 and 14 November. Red/Blue circles indicate the position and relative egg concentration of Day 0/1 eggs.

5. Application and future plans

The results from this modelling study add weight to the hypothesis that the observed Day 1 and Day 0 sardine eggs share a similar spawning location. However, the real value of this study is that it demonstrates the beneficial role that numerical modelling can play in the investigation of the mortality versus dispersion problem: fish stock assessment includes as input data estimates of spawning biomass inferred from egg concentrations; current methods for producing these estimates operate under the assumption that relative differences in egg concentrations between the developmental stages result from mortality alone, so that the effects of dispersion into or out of the sampling area are not accounted for. A better understanding of the role played by dispersion will improve our ability to produce such estimates.

In the short term, future plans for the further development of this particular configuration are: the inclusion of horizontal diffusivity in the float movements; improved representation of the wind field by interpolation of Cadiz buoy winds into the NCEP data (the orography of the southern Portuguese coast is known to produce an east-west tendency in the wind field, in comparison with that of the wider western Iberia Peninsula [e.g. Folkard *et al.*, 1997]).

However, there remains a pressing need for more and better in situ data, both biological and oceanographic. To this end, and looking further into the future, surveys similar to that reported here are being planned at IPIMAR, and their design will incorporate the experience gained from the present study. From the modelling perspective, we expect to collect sufficient information for both the initialisation and later validation of our configuration. This configuration will also include nesting in order to increase the resolution over our survey site or sites.

6. Acknowledgements

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7. References

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