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Modelling surface radioactive spill dispersion in the Alborán Sea

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Abstract

The Strait of Gibraltar and the Alborán Sea are the only connection between the Atlantic Ocean and the Mediterranean Sea. Intense shipping activities occur in the area, including transport of waste radionuclides and transit of nuclear submarines. Thus, it is relevant to have a dispersion model that can be used in an emergency situation after an accident, to help the decision-making process. Such dispersion model requires an appropriate description of the physical oceanography of the region of interest, with simulations of tides and residual (average) circulation. In this work, a particle-tracking dispersion model that can be used to simulate the dispersion of radionuclides in the system Strait of Gibraltar–Alborán Sea is described. Tides are simulated using a barotropic model and for the average circulation a reduced-gravity model is applied. This model is able to reproduce the main features of the Alborán circulation (the well known Western Alborán Gyre, WAG, and the coastal circulation mode). The dispersion model is run off-line, using previously computed tidal and residual currents. The contamination patch is simulated by a number of particles whose individual paths are computed; diffusion and decay being modelled using a Monte Carlo method. Radionuclide concentrations may be obtained from the density of particles per water volume unit. Results from the hydrodynamic models have been compared with observations in the area. Several examples of dispersion computations under different wind and circulation conditions are presented.

Keywords: Dispersion; Numerical modelling; Hydrodynamic models; Particle-tracking; Alborán Sea

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1. Introduction

The area of the Strait of Gibraltar has a high ecological value, being essential in marine and aerial migratory processes. As the only connection between the Mediterranean Sea and the Atlantic Ocean, marine turtles and mammals (dolphin, porpoise, sperm whale, killer whale) travel through the Strait and the Alborán Sea. Also, the region has a high tourist interest, since many kilometers of sand beaches in the area of the Strait and the Costa del Sol (Málaga) attract thousands of tourists each year. Finally, there are also some important towns. A release of radioactivity in the area as a consequence of an accident (or a deliberate release) can lead to relevant ecological and economic impacts.

Shipping activities in the area of interest are very intense, again due to the fact that it is the only connection between the Atlantic and the Mediterranean. There is a traffic over 70,000 merchant vessels per year, 30% of them declaring hazardous cargos. Transit of nuclear submarines and vessels transporting radioactive waste must also be considered. Only in the Strait of Gibraltar there are over 12,000 vessels per year (mostly passenger ferries) crossing between the north and south coasts (Nav42, 1998). Connections between the towns of Málaga and Almería (Spain) and the north African coast must be added (see Fig. 1 for locations).

It is usual to have adverse meteorological conditions in the Strait, with more than 54% of days of moderate to poor visibility and 13% of days with persistent fog conditions. Winds must be added, with frequent east and west gales. East winds (*levantes*) blow on an average of 165 days per year, predominantly from April to October, with an average speed of the order of 50 km/h. Maximum speed reaches 125 km/h. Gusts of winds can remain up to 7–10 days. West winds (*ponientes*) blow on an average of 60 days per year, from November to March predominantly. Minimum and maximum speeds are 30 and 90 km/h. West winds are not as persistent as *levantes*, lasting for about 12–36 h.

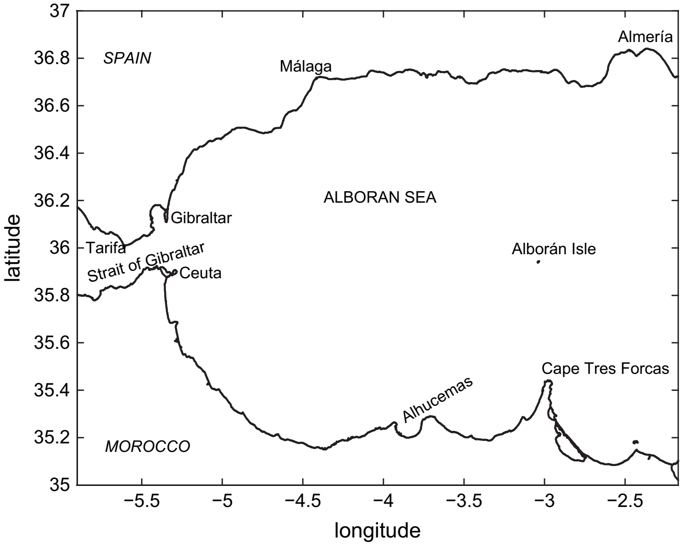

Fig. 1. Map of the Strait of Gibraltar and Alborán Sea.

The particular conditions in the area (intense traffic and adverse meteorology) make navigation difficult. Indeed, several accidents have occurred in the last years (Nav42, 1998). Due to the particular water circulation patterns in the area, a spill occurring in the Strait is introduced into the Alborán Sea basin in a time scale ranging from some hours to some days (Echevarría et al., 2002). Thus, the area of the Alborán Sea may be affected by an accident occurring not only inside the Alborán Sea itself, but in the Strait of Gibraltar as well. The objective of this work consists of describing a spill model that covers the Strait of Gibraltar and the Alborán Sea that can be applied to radioactive contaminants. This work may be considered as the natural continuation of Periáñez (2005a), where a radionuclide dispersion model covering only the Strait of Gibraltar was described.

The hydrodynamic is solved in advance. A 2D depth-averaged barotropic model is used to obtain tidal currents in the region. A reduced-gravity model is applied to obtain the average water circulation in the upper water layer, since only spills occurring at the surface will be considered by the moment. Tidal and average circulations are stored in files that will be read by the dispersion code to compute water current at any time and position. Dispersion is solved using a particle-tracking method. Thus, the spill is simulated by a number of particles, each of them equivalent to a number of units (for instance Bq), whose paths are followed in time. Radioactive decay and turbulent diffusion are simulated by means of Monte Carlo methods. Contaminant concentrations may be obtained at the desired time from the density of particles per water volume unit.

Some characteristics of the physical oceanography of the region are briefly described in the next section. The hydrodynamic and dispersion models are next presented. Some examples of calculations are then given and, finally, some discussion is included.

2. The Alborán Sea

The water circulation in the Strait of Gibraltar is characterized by a surface inflow of Atlantic water and a deep outflow of more dense Mediterranean water. Exchanged flows (Tsimplis and Bryden, 2000) are of the order of 0.7 sverdrup (1 sverdrup $= 10^6$ m^3/s) with a net inflow into the Mediterranean Sea of about 0.05 sverdrup. This net inflow compensates the excess of evaporation over precipitation and river supply in the Mediterranean. This description of the exchange as a simple two-layer system flowing in opposite directions is a good first approximation (Farmer and Armi, 1988; Echevarría et al., 2002). The surface circulation in the Alborán Sea is as follows. The Atlantic water penetrates the Strait of Gibraltar and reaches mean velocities of the order of 0.6 m/s. This water forms a jet that enters the Alborán Sea in a east-northeast direction. The jet flows along the Spanish coast and curves to the south. Part of it flows to the west, incorporating to an anticyclonic gyre, while the remainder flows to the African coast between Cape Tres Forcas and Alborán Isle (Perkins et al., 1990). This is known as the Western Alborán Gyre (WAG). Another gyre, more elusive, fills the eastern basin of the Alborán Sea: it is the Eastern Alborán Gyre (EAG) that is out of domain of our model. A detailed description may be seen for instance in Vargas-Yáñez et al. (2002), Vélez-Belchí et al. (2005) and references cited in these works, which include the classical works carried out since the 1970s.

The WAG fills the western Alborán Sea between the Strait of Gibraltar and the Alborán Isle (Perkins et al., 1990), thus extending some 200 km in the west–east direction. The WAG extends towards the south, reaching the coast of Morocco (Perkins et al., 1990; Werner et al., 1988). The vertical scale of the gyre is about 200 m. It has also been suggested (Preller,

1986) that a coastal feature (Cape Tres Forcas) acts as a barrier to the gyre growth. The variability of circulation in the Alborán Sea has been investigated by Vargas-Yáñez et al. (2002). These authors conclude, from their results and from the revision of previous works, that the gyre is the dominant circulation pattern in summer and the coastal mode is more likely in winter. In this coastal mode, the Atlantic current flows close to the African coast once it exits the Strait of Gibraltar and no gyre is apparent. Nevertheless, it has to be clearly pointed out that this bimodal behaviour is not perfectly defined, as can be seen for instance in the data presented by Heburn and La Violette (1990). In fact, there are transitions between the two commented behaviours (Vázquez-Cuervo et al., 1996; Vélez-Belchí et al., 2005 and references here included). In this work, the presence of the WAG and the coastal model will be sometimes referred as the usual summer and winter conditions, respectively. However, it must be kept in mind that an absolutely clear annual cycle does not exist. We will return to this point later.

With respect to the tides in the area, an important feature of the tidal flow in the Strait is that it can be considered, as a first approach, as barotropic. Indeed, 93% of the variance of current velocity in the semidiurnal band has a barotropic character in the Strait (Mañanes et al., 1998). Tsimplis and Bryden (2000) have pointed out that tidal currents are barotropic and larger than the mean inflow or outflow. The semidiurnal tide dominates ADCP records (acoustic Doppler current profiler) in the Strait, obscuring the expected two-layer character of the mean flow. The tidal signal is so strong that it reverses the currents near the bottom for a part of each tidal cycle. As a consequence, 2D depth-averaged models have already been applied to simulate surface tides in the Strait (Tejedor et al., 1999). Tsimplis et al. (1995) have even used a 2D barotropic model for simulating tides in the whole Mediterranean Sea. The success of these models indicates that the baroclinic component is of secondary importance.

In the case of the main tidal constituent, M_2, tide amplitude at the Atlantic entrance of the Strait is about 0.8 m. This amplitude decreases towards the east. Thus, at the Mediterranean entrance it is only about 0.3 m. The amplitude of the tide is reduced more in the Alborán Sea, reaching 0.09 m at the east limit of our domain (see map in Fig. 1). The associated currents decrease in a similar way: from tidal currents of the order of 1 m/s in the Strait to currents of a few cm/s in the Alborán Sea basin. Similar behaviour is observed for the S_2 constituent.

From this analysis it seems evident that tides are relevant, for the transport of pollutants in water, in the area of the Strait of Gibraltar. However, once those pollutants enter the Alborán Sea the main mechanism is the residual (average) circulation. Contaminants may remain trapped in the WAG, and an appropriate description of this average circulation is thus required for a realistic calculation of contaminant dispersion.

3. Model description

3.1. Hydrodynamics

The hydrodynamics of the area is described by means of two models: a barotropic model is used to calculate tides and a reduced-gravity model is applied to obtain the residual (average) circulation.

A 2D depth-averaged model is used to calculate tidal currents over the domain; as commented in the previous section, it is a good approach. Equations are standard and may be seen for instance in Periáñez (2005b). The solution of these equations provides the water currents at each point in the model domain and for each time step. Currents are treated by standard tidal analysis and tidal constants are stored in files that will be read by the dispersion code to calculate the advective transport of particles. The model includes the two main tidal constituents, M_2 and S_2. Thus, the hydrodynamic equations are solved for each constituent and tidal analysis is also carried out for each constituent separately.

Some open boundary conditions must be provided to solve the hydrodynamic equations. Surface elevations are specified, from observations, along open boundaries of the computational domain. A radiation condition is applied to the water velocity component that is normal to the open boundary (Jensen, 1998; Periáñez, 2005b).

Equations are solved using an explicit finite difference scheme. The computational domain (Fig. 1) extends from 35°00′N to 36°56′N and from 5°54′W to 2°10′W. Resolution of the grid is $\Delta x = 2972$ m and $\Delta y = 3341$ m. Water depths were downloaded from the NOAA Geodas database. Time step, limited by the CFL (Courant–Friederichs–Lewy) stability condition is $\Delta t = 10$ s. Once a stable periodic solution is achieved, tidal analysis is carried out to determine tidal constants that are used by the particle-tracking code.

The reduced-gravity model is the simplest model able to simulate the major features of circulation above the pycnocline. Essentially it is a two-layer model in which the lower layer is infinitely deep and at rest. Thus, the interface between the two layers may deform without any resulting motion in the lower layer. In spite of this relative simplicity, reduced-gravity models are used at present to study different problems in oceanography (Cummins and Lagerloef, 2004; Chern and Wang, 2005; Morales-Maqueda et al., 1999; Arruda et al., 2004).

Equations may be seen in the above indicated references. They are very similar to those of the barotropic motion, but the upper layer thickness replaces the surface elevation in the continuity equation and in the gravity term of the momentum equations. Also, the reduced gravity, g', replaces gravity, g, in these equations:

$$g' = g\frac{\rho_2 - \rho_1}{\rho_2} \quad (1)$$

where ρ_1 and ρ_2 are the densities of the upper and lower layers, respectively. The reduced gravity is fixed as 0.010 m/s^2, the same as in the model of Heburn and La Violette (1990).

The same numerical scheme as in the barotropic model was used to solve the reduced-gravity equations. The CFL stability condition is less restrictive in this case than in the barotropic model. Thus, time step for the explicit integration is increased to $\Delta t = 800$ s. The model is integrated specifying water currents along the open western boundary until a steady solution is achieved. The computed steady current and upper layer thickness over the domain are stored in files that will be read by the dispersion code.

Two average water circulation patterns have been obtained with the reduced-gravity model: one corresponding to the usual summer situation (existence of the gyre) and the other one corresponding to the usual winter situation (coastal circulation). As will be discussed in some more detail below, different circulation patterns are obtained by changing the surface inflow through the Strait of Gibraltar.

3.2. Particle-tracking dispersion model

The dispersion of radionuclides is calculated by using a particle-tracking method. Essentially, the radionuclide discharge is simulated by a number of discrete particles. The path followed by each particle is computed; turbulent diffusion being modelled as a three-dimensional random walk process. Advection is calculated through the addition of the tidal and the residual currents. Radioactive decay is also simulated using a Monte Carlo method (Periáñez and Elliott, 2002). The density of particles per water volume unit is finally computed to obtain radionuclide concentrations over the domain at the desired time. Both instantaneous and continuous releases of particles can be simulated. It must be noted that the particle-tracking model is three-dimensional, while the hydrodynamic module provides depth-averaged currents. Thus, a current profile is generated from the depth-averaged currents at each location by the dispersion code (see for instance Pugh, 1987), which is a common approach in rapid-response particle-tracking models (Riddle, 1998).

The effect of wind is included as usual in particle-tracking models. Thus, it is assumed that the water surface moves in the direction of wind at a speed equal to 3% of the wind speed 10 m above the sea surface. This current decreases logarithmically to zero at a depth usually defined as 20 m (Pugh, 1987; Proctor et al., 1994; Elliott, 1986).

Date and time of the discharge (and duration in the case of continuous releases) must be given. Thus, the appropriate phase of each tidal constituent at $t = 0$ must be specified. The values used in this model correspond to the origin of time, January 1, 2003 at 0:15 hours Greenwich time.

The adsorption of pollutants by suspended and bottom sediments can also be simulated with a particle-tracking model (Periáñez and Elliott, 2002). However, these processes are neglected in the present study since suspended matter concentrations are very low in the area, typically 0.1–0.5 mg/L (León-Vintró et al., 1999). Also, since the pycnocline is acting as a barrier for vertical mixing, interactions of pollutants with bed sediments can be neglected.

There is no stability criterion equivalent to the CFL condition in the particle-tracking calculations, although it is wise to ensure that each particle does not move through a distance that exceeds the grid spacing during each time step. Thus, time step was fixed as $\Delta t = 300$ s.

All the equations involved in the particle-tracking dispersion model, as well as the numerical aspects of their solution, may be seen for instance in Periáñez (2005b).

The dispersion code automatically reads six files which contain the topography of the Alborán Sea, amplitudes and phases of the two tidal constituents included in the model (M_2 and S_2), and the residual circulation (for gyre or coastal circulation modes). These files are generated by the hydrodynamic module that has been run off-line, as noted before. The user must also include some information for each simulation, related to the release characteristics. This information is summarized in Table 1. Wind conditions are also defined in a file that must be edited before running the model. Variable winds can be included.

The reduced-gravity model provides the residual current in the domain, as already noted. Nevertheless, residual currents are controlled by the water inflow through the Strait of Gibraltar that, as will be discussed in some more detail below, presents some variability. Thus, a factor that acts as a modulator of the residual current amplitude must be introduced. If 1 is used, the residual current for the average water inflow (for gyre or coastal modes) through the Strait is used in the calculations. These average currents may be slightly amplified or reduced by specifying values for the modulator larger or smaller than 1, respectively.

The dispersion model provides several output files. It gives the coordinates of each particle at several times during the simulation. Thus, snapshots of particles can be drawn to study the temporal evolution of the discharge. In particular, 12 snapshots at constant intervals along the simulation are provided. Another file contains a map of the final contaminant concentration over the domain computed from the density of particles per water volume unit. Optionally, the time evolution of radionuclide concentrations at desired points over the domain can be obtained.

Table 1
Information required by the model to be introduced by the user

Release point coordinates
Select instantaneous/continuous release option
Wind file name
Release date (day, month, year)
Release time, UTC (hours, minutes)
Select circulation mode (gyre/coastal)
Simulation time (days)
Magnitude of the release in the corresponding units
Radionuclide decay constant
Residual current modulator

4. Results

Results of the hydrodynamic models are presented first. Next, some examples of dispersion calculation are given.

Computed values of the amplitude and phase of the water surface elevation produced by the M_2 and S_2 tides have been compared with observed values (Tsimplis et al., 1995; Manzella and Elliott, 1991) at different locations in the Strait of Gibraltar and the Alborán Sea. Results are given in Table 2. Locations may be seen in the map in Fig. 1. It can be observed that generally there is a good agreement between the measured and computed tidal constants for both constituents.

A tidal chart for the M_2 tide is shown in Fig. 2. The same color joins points with the same tide amplitude (corange chart). The amplitude decreases quickly in the Strait of Gibraltar, from about 0.75 m in the Atlantic entrance to 0.30 in the section of Gibraltar. There is a further, although slower, amplitude reduction in the Alborán Sea, reaching only about 0.10 m at the eastern boundary. It can be seen that corange lines are oriented in a south–north direction, while cotidal lines (join points with the same tidal phase, not shown) are essentially in a northeast direction, in agreement with observations and the earlier computations by Tsimplis et al. (1995).

The spatial distribution of the M_2 current amplitude is presented in Fig. 3 as an example. The current amplitude in most of the Alborán Sea is about 0.03 m/s. Only in some specific areas larger currents are obtained. This is the case of the south–north section going from Cape Tres Forcas to Alborán Isle and the Spanish coast. Currents of the order of 0.06–0.09 m/s are computed close to the Cape, around Alborán Isle and close to the Spanish coast. This is

Table 2
Observed (subindex *obs*) and computed (subindex *comp*) amplitudes (A, cm) and phases (g, deg) of tidal elevations at several locations indicated in Fig. 1

Station	M_2				S_2			
	A_{obs}	g_{obs}	A_{comp}	g_{comp}	A_{obs}	g_{obs}	A_{comp}	g_{comp}
Tarifa	42	57	41	45	14	85	16	79
Ceuta	30	50	32	52	11	76	12	86
Málaga	17	59	18	42	7	72	8	77
Alhucemas	18	58	18	56	7	80	7	89
Almería	9	51	9	49	4	78	4	77
Gibraltar	30	46	29	41	11	72	12	77

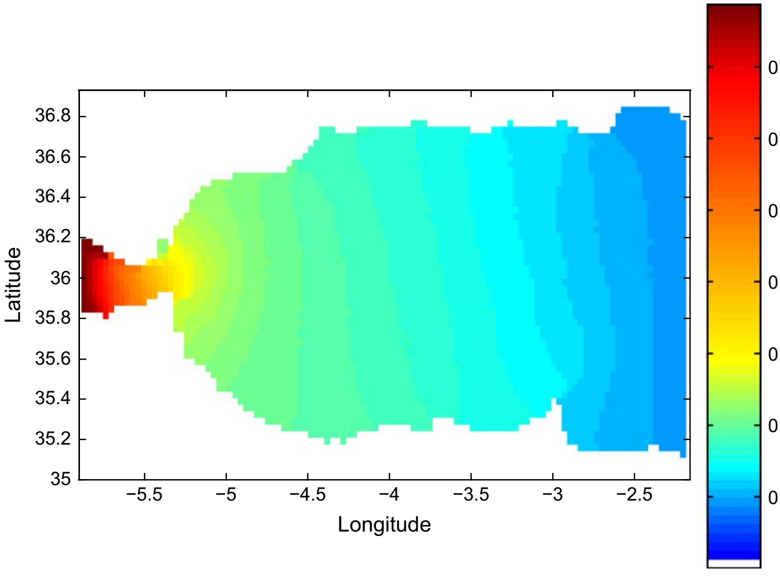

Fig. 2. Corange chart for the M_2 tide. Amplitude of the tide is given in meters.

in good agreement with the earlier computations presented by Tsimplis et al. (1995). Current amplitude increases as approaching Gibraltar Strait, where, as expected, maximum values are obtained. Indeed, currents of the order of 0.8 m/s are computed in some locations. For clarity reasons, however, the scale maximum in Fig. 3 is limited to 0.2 m/s. In the case of the S_2 tide, results show a similar decrease in the tide amplitude, from about 0.25 m at the Atlantic entrance of the Strait to about 0.04 m at the eastern open boundary of the domain. Current

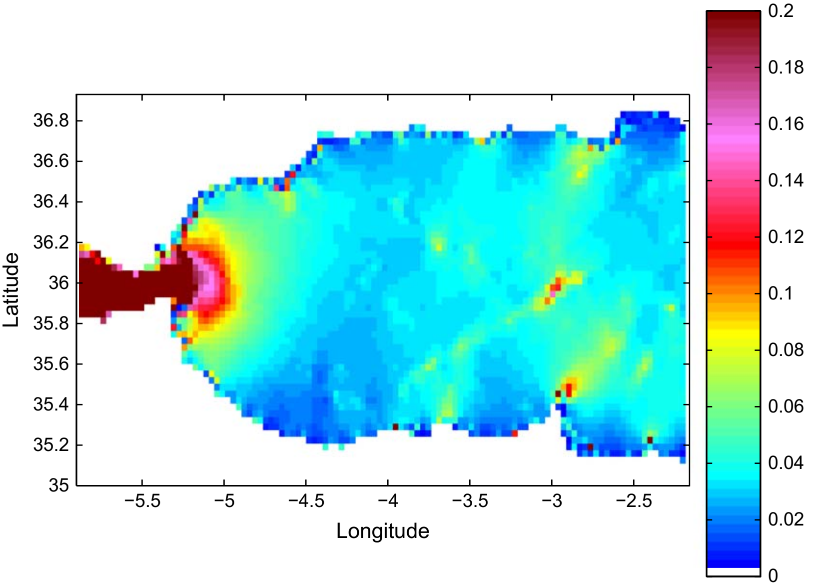

Fig. 3. Current amplitudes (m/s) for the M_2 tide.

amplitudes decrease from maximum values of the order of 0.25 m/s in the Strait of Gibraltar to currents weaker than 1 cm/s in the Alborán Sea.

Residual currents provided by the reduced-gravity model are presented in Fig. 4 for both circulation conditions (existence of the gyre and coastal mode). The different situations are obtained by simply changing the inflow through the Strait of Gibraltar. The collapse of the WAG may be related to its westward advection, that is caused by an enhanced transport towards the Atlantic in the deep water layer (Heburn and La Violette, 1990). Recently another mechanism (Vélez-Belchí et al., 2005), consisting of an eastward advection of the WAG, has been observed for its disappearance. It is also related to a decrease in the Atlantic inflow after an initial increase of water velocity in the Strait of Gibraltar. Nevertheless, other different mechanisms have been proposed to explain WAG disappearances (see discussion in Vélez-Belchí et al., 2005).

Usually in summer, the jet of Atlantic water entering through the Strait of Gibraltar flows towards the east along the Spanish coast and partially curves to the south before reaching Alborán Island. Part of this flow continues to the east between Cap Tres Forcas and Alborán Island and the remaining rotates towards the west, flowing along the African coast. A gyre

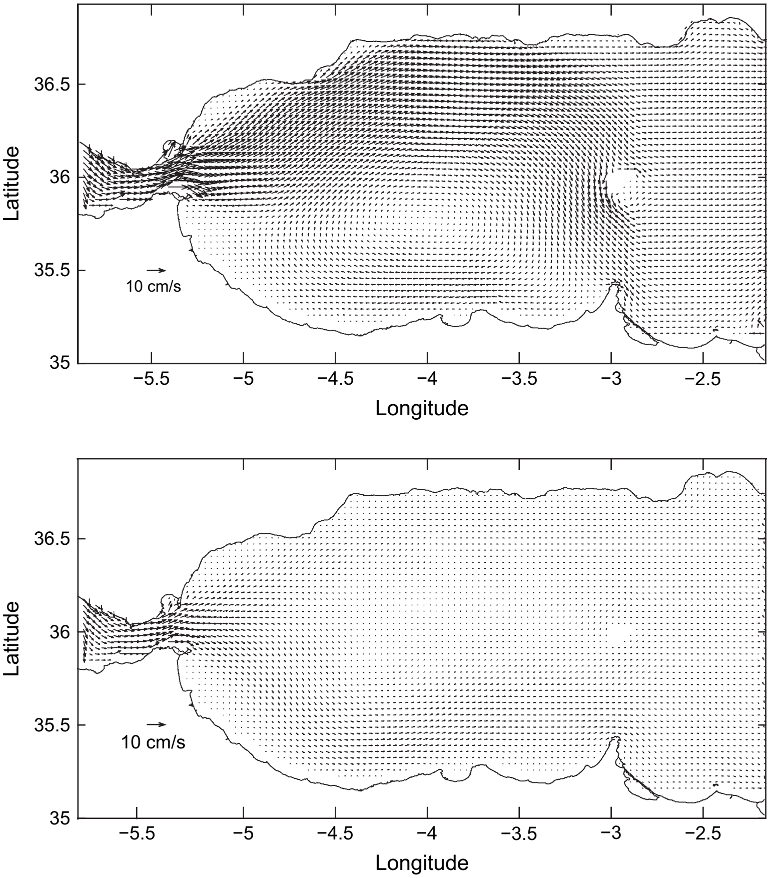

Fig. 4. Steady currents computed with the reduced-gravity model showing the WAG (up) and the coastal circulation mode (down).

of anticyclonic circulation is thus completed. During coastal mode circulation conditions, the Atlantic current flows close to the African coast once it exits the Strait of Gibraltar. These circulation patterns are in good qualitative agreement with those deduced from satellite thermal images that are shown in Fig. 5 (from Vargas-Yáñez et al., 2002). It can be observed in the July photograph that warmer water is accumulated in the centre of the WAG. In February the coastal jet flowing along the African coast is clearly seen. The computed thickness of the upper water layer is shown in Fig. 6 when the WAG is present. It can be observed that there is a depression of the interface in the centre of the WAG. Its magnitude and size are in agreement with previous calculations carried out with reduced-gravity models (Preller, 1986; Werner et al., 1988; Heburn and La Violette, 1990). The high pressure area makes water to rotate

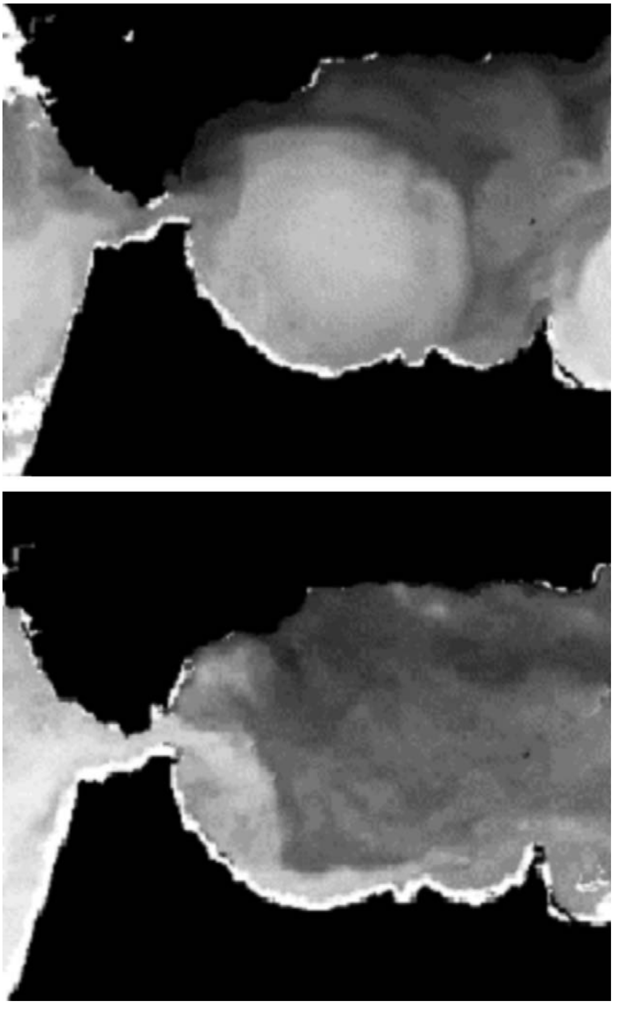

Fig. 5. Classic images of the western Alborán Sea as seen by the thermal sensor of the NOAA 7 satellite, showing classical circulation patterns in summer and winter. The darker tones refer to colder water, whereas lighter tones refer to warmer water. Images were obtained in July 1997 (up) and February 1998 (down) (Vargas-Yáñez et al., 2002). The gyre is clearly visible in the summer image.

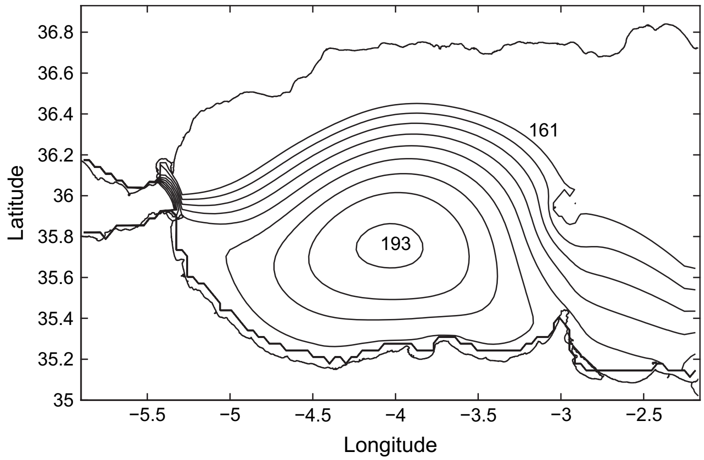

Fig. 6. Thickness (m) of the upper water layer computed with the reduced-gravity model. Distance between isolines is 4 m.

clockwise around it. It has to be commented, however, that the depression of the interface with respect to the remaining Alborán Sea calculated by all these models is smaller than that obtained during, at least, some measurement campaigns (Perkins et al., 1990).

The computed inflow through the Strait of Gibraltar is 0.86 and 0.54 sverdrup when the WAG is present and for the coastal mode circulation, respectively. Current-meter observations and recent models give a transport of about 0.8 sverdrup (Béranguer et al., 2005). In particular, Tsimplis and Bryden (2000) gave an estimation of 0.66 ± 0.47 sverdrup, where the large error is due to seasonal variability. Our results are in agreement with these estimates. Nevertheless, flows are affected by other factors as for instance atmospheric pressure differences between the Atlantic and the Mediterranean. Thus, the residual current modulator is introduced to be able to account for this variability.

Thus, it seems that, generally speaking, the present model gives a representation of the system that is realistic enough to implement on it the particle-tracking dispersion code. Some examples of dispersion calculations will be presented now.

Values of the diffusion coefficients have to be provided. The horizontal diffusion coefficient depends on the horizontal grid spacing. Following Dick and Schonfeld (1996):

$$K_h = 0.2055 \times 10^{-3} \Delta x^{1.15} \tag{2}$$

The present grid resolution gives $K_h = 2.0$ m^2/s. For the vertical diffusion coefficient a typical value of 0.001 m^2/s is used (Elliott et al., 2001; Dick and Schonfeld, 1996).

It has been assumed that the release occurred on July 1, 2005 at 0:00 hours UTC (just as an example of summer conditions, there is not any other particular reason to select this date and time). No wind is considered and the decay constant is set to zero (long-live radionuclide). The total activity discharged is 1×10^{12} Bq. Finally, the current amplitude modulator is 1 (average inflow through the Strait of Gibraltar). In the first experiment, the fate of a release occurring at the centre of the Strait of Gibraltar [grid cell (10, 30)] has been simulated. In this case the patch is introduced in the Alborán Sea by the Atlantic water jet and moves rapidly towards the east, in a trajectory that is initially parallel to the Spanish coast. Then curves to the south and the patch is divided by Alborán Island. The time required by the patch to reach the east boundary of the domain is about 50 days, which implies an average velocity of the order of 9 cm/s. Three of the 12 snapshots produced by the model are shown in Fig. 7 as an example. The 25 days elapsed between the first and third snapshots are in excellent agreement with the also 25 days taken by two neutrally buoyant Lagrangian floats, launched at meridian −4.88° (latitude 36.1°), to reach the passage between Cape Tres Forcas and Alborán Island (Vélez-Belchí et al., 2005). Very similar trajectories were also computed by the model of Preller (1986).

If the same experiment is repeated at a short temporal scale, simulating only the first 4 days, then the snapshots produced by the model show how the patch moves in the Strait forward and backwards because of tidal oscillations. These movements cannot be appreciated in longer simulations due to the longer time elapsed between snapshots.

A release of the same characteristics as before has been introduced in cell (20, 28) at the same time and date, which would correspond to an accident occurring close to the harbour

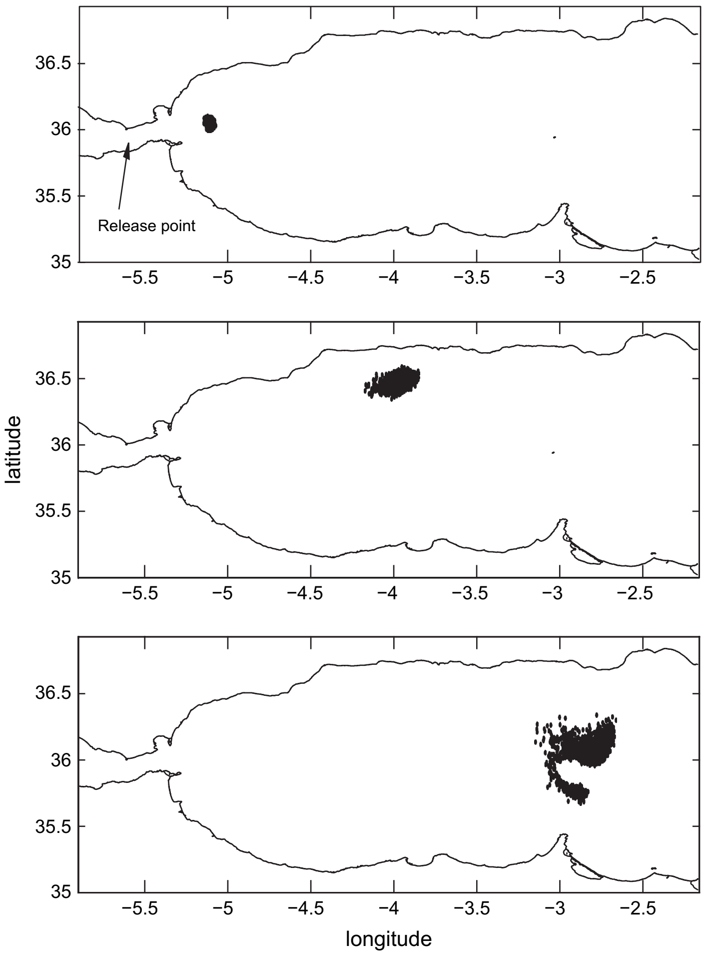

Fig. 7. Snapshots showing the position of particles: 2.5 (up), 12.5 (middle) and 27.5 (down) days after an instantaneous release in the central part of the Strait.

of Ceuta. The patch of course moves to the east, but in this case the complete patch crosses through the passage between Cape Tres Forcas and Alborán Island contaminating the African coast. The evolution of the patch may be seen in Fig. 8.

Another experiment consisted of simulating an accident in the central part of Alborán Sea [cell (55, 30)]. Now all particles remain trapped in the WAG. Indeed, the time required to complete a loop is of the order of 60 days. Some results may be seen in Fig. 9, where the anticyclonic rotation of the radioactive patch can be observed. As an example, the map of concentrations, computed from the density of particles per water volume unit, is presented in Fig. 10.

An accident occurring off Gibraltar harbour [cell (17, 35)] has been simulated to illustrate how the model works with a continuous release. The accident again occurs at 0:00 hours on July 1, 2005. The release lasts for 5 days and the movement of particles is computed during 30 days. A very elongated patch, in the direction of the mean current, that travels along the Spanish coast is observed (Fig. 11). Indeed, it can be seen that the Spanish coast would be

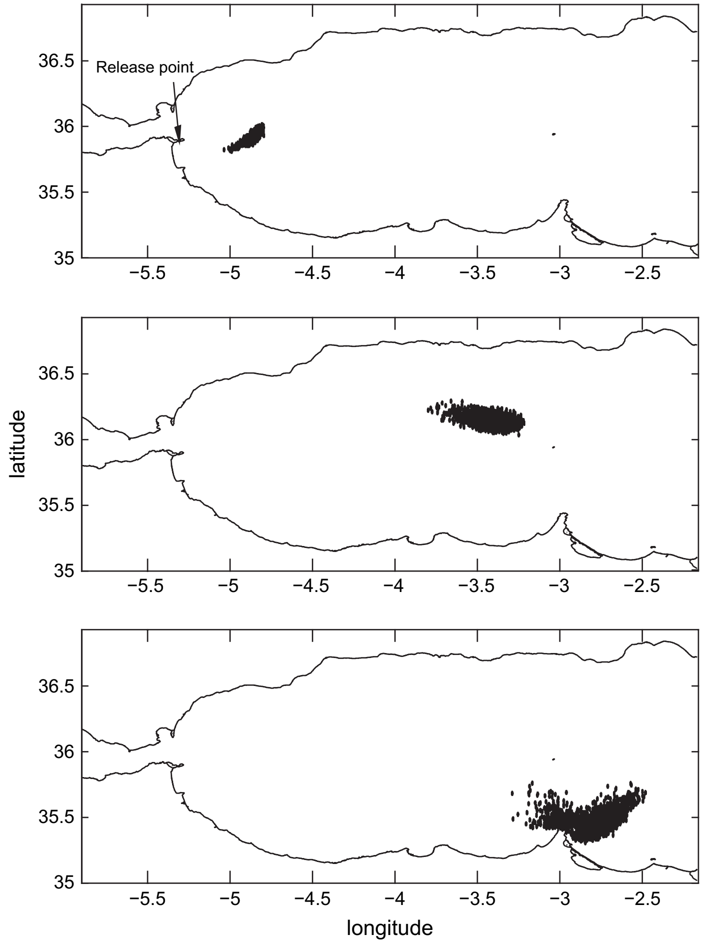

Fig. 8. Snapshots showing the position of particles: 4.2 (up), 20.8 (middle) and 37.5 (down) days after an instantaneous release occurring off the Ceuta harbour.

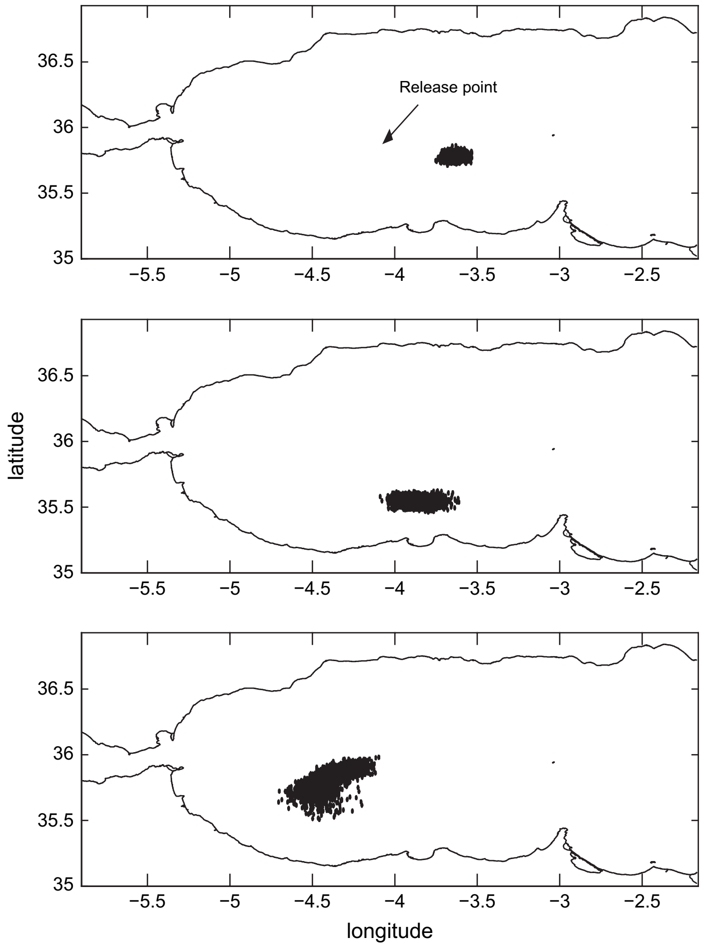

Fig. 9. Snapshots showing the position of particles: 15 (up), 30 (middle) and 55 (down) days after an instantaneous release in the central part of the Alborán Sea.

heavily contaminated from approximately $-5.25°$ to $-2.75°$ longitude after an accident occurring off the harbour of Gibraltar.

The effects of winds will be illustrated in what follows. The simulation shown in Fig. 7 (long-live radionuclide release occurring at the central part of the Strait of Gibraltar) has been repeated but with a 10 m/s wind blowing from the east. Results are presented in Fig. 12. If this figure is compared with Fig. 7, it can be seen that the wind tends to retain the contamination inside the Alborán Sea for a longer time. Also, a tail of particles is produced along the Spanish coast where some contamination is retained. Thus, this region would remain contaminated for a longer time as a consequence of the wind. Finally, it can also be seen that more intense mixing of contamination along a south–north direction is produced than under calm conditions. West winds, in the same direction as the average currents, produce the opposed effect: a faster contaminant flushing off from the region. It must be pointed out that it is not realistic to have these wind conditions persisting without change during such a long time. However, the aim of the experiment is simply to show the effect of winds on the

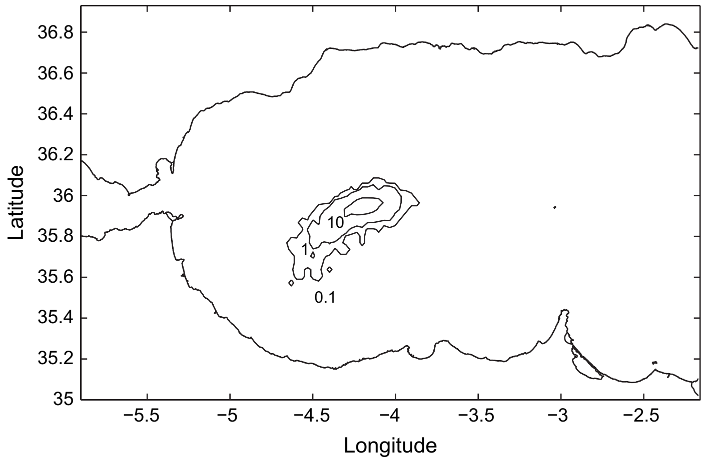

Fig. 10. Concentration map (Bq/m^3) obtained 60 days after the release in Fig. 9.

behaviour of the contamination patch. As has been commented before, the model may anyway deal with non-constant wind fields.

Finally an accident occurring during coastal circulation conditions has been simulated. The instantaneous release was supposed to occur on January 1, 2005 at 0:00 hours close to Ceuta harbour under calm wind, as in the experiment in Fig. 8. Results are presented in Fig. 13. It can be seen that the radioactive patch curves to the south and travels along the African coast. Nevertheless the speed of the patch is slower than when it is introduced in the Atlantic jet in the northern part of the sea (Fig. 7) if the WAG is present. Now the patch travels some 82 km in 90 days, that results in an average speed of 1 cm/s. Similar results are obtained if the release occurs inside the Strait of Gibraltar.

5. Discussion

The model described in this paper is a tool designed to support the decision-making process after a release of radioactivity in the sea, not for a theoretical study of the Alborán Sea physical oceanography. The difference is huge. Having a rapid response is essential in decision making after an emergency and, of course, increasing computation speed implies that simplifications have to be carried out in the model. Particularly, it is required to have water current fields computed in advance, so that it is not necessary to repeat hydrodynamic calculations (time consuming). Running time of the dispersion model is 5.4 s per day of simulation on a Pentium 4 PC, 3.2 GHz and 512 MB RAM. This is in the case of an instantaneous release (constant number of particles during the complete simulation).

In the opinion of the author, the most dramatic problem is related with the residual circulation in the Alborán Sea. As already mentioned, the WAG is usually present in summer while the coastal mode is more likely in winter. However, there are transition episodes between both situations and it cannot be guaranteed that the WAG will always be present during the summer, for instance. Moreover, fluxes through the Strait of Gibraltar change and for a given situation (for instance coastal mode), water velocities may vary.

Let us imagine that an accident occurs just now. How do we run the model? In other words: is just now the WAG present? Which is the water inflow through the Strait just now? Presently it

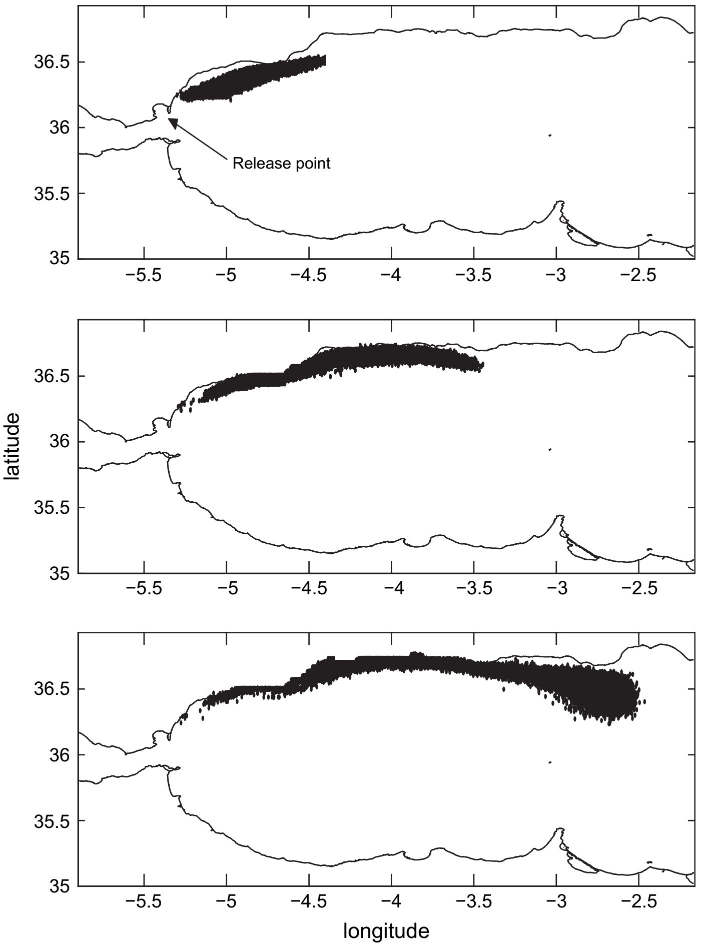

Fig. 11. Snapshots showing the position of particles: 7.5, 15 and 27.5 (from top to bottom) days after a continuous radionuclide release occurring off Gibraltar harbour.

is not possible to have an answer. Thus, it is recommended to carry out calculations under the most probable conditions in a first guess: WAG in summer, coastal mode in winter. Additional simulations may then be carried out using the other circulation mode and different current modulators (to increase and reduce water velocities). This method will, at least, allow to estimate if there is any chance that a given sensible point (a coastal town for instance) is affected by contamination.

6. Conclusions

A particle-tracking model that simulates the dispersion of radioactive spills in the Alborán Sea has been developed. The contamination release is simulated by a number of particles whose paths are computed. Diffusion and decay are simulated by a Monte Carlo method. The currents required to calculate the advective transport are obtained from appropriate hydrodynamic models. Radionuclide concentrations are obtained from the density of particles per water volume unit.

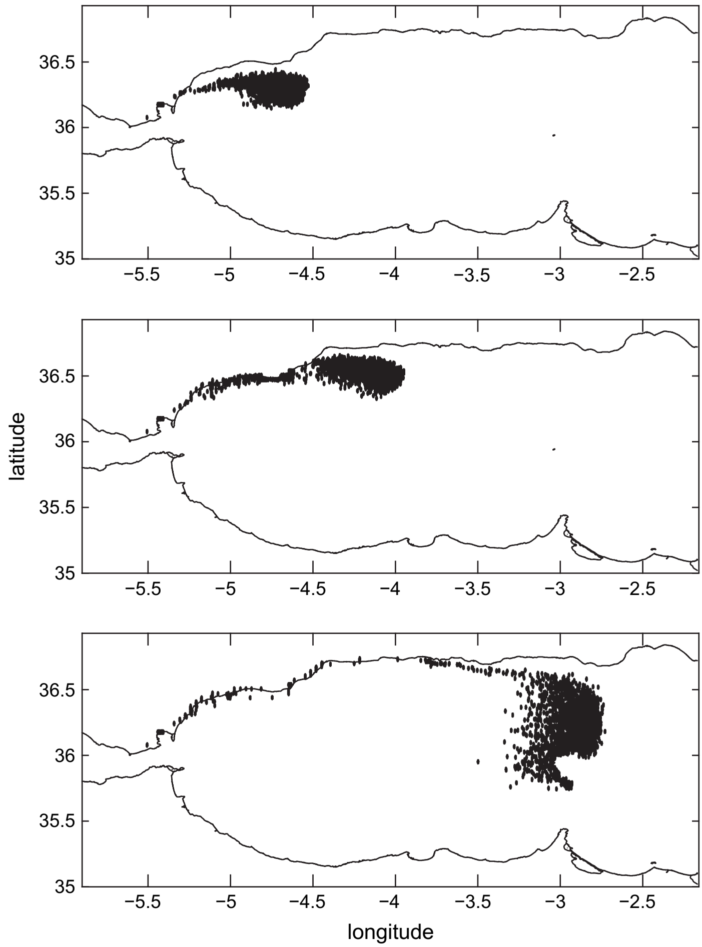

Fig. 12. Snapshots showing the position of particles: 2.5 (up), 12.5 (middle) and 27.5 (down) days after an instantaneous release of a long-live radionuclide in the central part of the Strait. A 10 m/s wind blowing from the east is included.

A 2D barotropic model is used to calculate tidal currents over the domain. This model provides the tidal constants that are used by the dispersion model to reconstruct the tidal current at any time and position in the model domain. This model has been validated through the comparison of computed tidal elevations and phases with measurements in the area.

The residual circulation is obtained from a reduced-gravity model. This is the simplest approach which is able to simulate the major features of circulation above the pycnocline. Essentially it is a two-layer model in which the lower layer is infinitely deep and at rest. It was not possible to carry out a quantitative validation of this model, but computed currents are, at least, in qualitative agreement with observations available in the region. In particular, the main circulation features (the WAG and the coastal mode) are reproduced by the model. Equations in both the models are solved by standard explicit finite difference schemes.

Some experiments concerning hypothetical radioactivity releases in the region have been carried out. The average speed of a radionuclide patch released in the Strait of Gibraltar as it travels towards the eastern boundary of the domain is of some 9 and 1 cm/s for usual

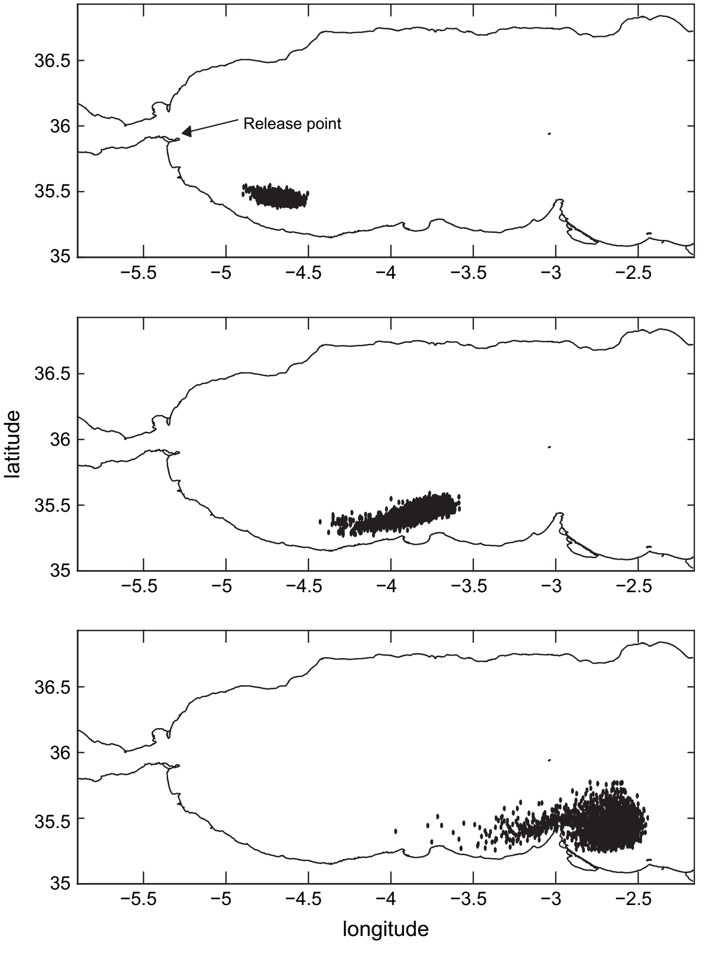

Fig. 13. Snapshots showing the position of particles: 22.5 (up), 25 (middle) and 90 (down) days after an instantaneous release of a long-live radionuclide off Ceuta harbour with the coastal mode for residual circulation (usual winter conditions).

summer and winter conditions, respectively (existence of the gyre and coastal circulation mode). If the accident occurs in the central part of the Alborán Sea, particles are trapped in the WAG (if present). The time required to complete a rotation has been estimated to be two months.

The simulation of a continuous release has been illustrated with the case of an accident occurring off Gibraltar harbour. The model predicts that a significant portion of the Spanish coast is contaminated.

Winds have a significant effect on the dispersion patterns in the area. Thus, dominant east winds tend to retain contaminants inside the Alborán Sea, also enhancing mixing along the transverse direction (north–south). On the other hand, west winds produce a faster cleaning of the sea.

As a final conclusion, it can be said that this kind of model is a very useful tool that may be used to support the decision-making process in response to an emergency situation.

In the near future, the reduced-gravity model will be replaced by a two-layer model able to simulate deep outflow from the Alborán Sea to the Atlantic. This way, the model could deal not only with accidents occurring at the surface, but also at any depth (for instance leakage from a sunken nuclear submarine).

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