A rapid response model for simulating radioactivity dispersion in the Strait of Gibraltar

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GISPART (GIbraltar Strait PARticle Tracking model) is a three-dimensional particle-tracking code that simulates the dispersion of radionuclides in the Strait of Gibraltar. It consists of a hydrodynamic module that is run off-line to determine tidal constants and residuals in the domain. This information is stored in files that are read by the dispersion module to reconstruct water movements. A Lagrangian approach is used, thus, a radionuclide release is simulated by a number of particles, whose paths are computed individually. Radionuclide concentrations are obtained from the density of particles per water volume unit. Some examples of the results are shown. Matlab GUIs (graphical user interfaces) allow an easy application of the model and visualization of results.

Introduction

The objective of this paper is to develop a Lagrangian radionuclide dispersion model for the Strait of Gibraltar, connecting the Mediterranean Sea and the Atlantic Ocean. This is relevant because of the intense shipping activities in the Strait, which include the transport of radioactive materials and the transit of nuclear submarines. Shipping routes are complex, with intersections of longitudinal routes with some 12000 annual transverse round trips Algeciras-Ceuta, Algeciras-Tanger and Tarifa-Tanger (Fig. 1). Also, the port of Algeciras is the most important in Spain, with 60.7 Mt of cargo handled in 2003. Fishing activities in the area must also be considered. It is usual to find adverse meteorological conditions in the Strait (poor visibility, persistent fog conditions and strong winds) and thus several accidents have been reported in the area, including collisions and groundings.

The area of the Strait of Gibraltar, as the only connection between the Atlantic Ocean and the Mediterranean Sea, has a high ecological and tourist value, and there are also some important towns. Indeed, the Natural Park of the Strait was created in 2003, which includes a marine and a terrestrial part. Over 1900 marine species of flora and fauna have been described, many of them under strict protection due to their endemic character and/or rareness. Also, the Strait is essential in marine and aerial migratory processes. Thus, a radioactivity release into the Strait as a consequence of an accident (or a deliberate release) can lead to a large ecological and economic impact. As a consequence, it is relevant to have an operative radionuclide dispersion model that could be used in the assessment of contamination after an accident in the Strait. Such a model, denoted GISPART (GIbraltar Strait PARticle Tracking model), is available at www.personal.us.es/rperianez.

In the following section, the model will be briefly described and next some examples of results are shown.

Description of the model

The GISPART model consists of two sub-models. First, a hydrodynamic module is run off-line. This provides the tidal constants and residuals that are required to reconstruct water movements in the model domain, which are stored in files that are read by the dispersion module to compute advective transport. Once the hydrodynamic module has been adequately calibrated and all information required by the dispersion computations is stored, it is not necessary to repeat the hydrodynamic calculations. This is an advantage over coupled hydrodynamic and dispersion models.

Hydrodynamic module

An important feature of the tidal flow in the Strait is that it can be considered barotropic as a first approach.[1] As a consequence, 2D depth-averaged models have already been applied to simulate surface tides in the Strait.[2] The barotropic hydrodynamic equations are solved over the model domain using finite differences. Surface elevations are prescribed from observations along open boundaries and radiation conditions are used to determine the current component that is normal to the open boundary. A quadratic law for bottom friction is applied. Details on the equations and numerical schemes may be seen elsewhere.[3]

Hydrodynamic calculations are carried out separately for the two main tidal constituents, M_2 and S_2. Thus, spring-neap tidal cycles can be simulated. Once a stable periodic solution is achieved, standard tidal analysis is carried out and residual transport is calculated for each constituent. Tidal constants (amplitudes and phases) for

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each point in the domain and residual transports for each tidal constituent are stored in files to be read by the dispersion code. Results from the hydrodynamic calculations have been validated through an extensive comparison of tidal amplitudes, phases and current magnitudes and phases with observations for 16 points in the domain (Table 1). More details may be seen elsewhere.[4]

Dispersion code

The dispersion of radionuclides is calculated using a particle-tracking method. Essentially, the pollutant discharge is simulated by a number of discrete, passive, particles. The path followed by each particle is computed, turbulent diffusion being modeled as a three-dimensional random walk process. Radioactive decay is also simulated using a Monte Carlo method.[5] The density of particles per water volume unit is finally computed to obtain radionuclide concentrations over the Strait 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.[6] The spatial resolution of the dispersion model is $\Delta x = \Delta y = 2500$ m and time step is $\Delta t = 600$ s.

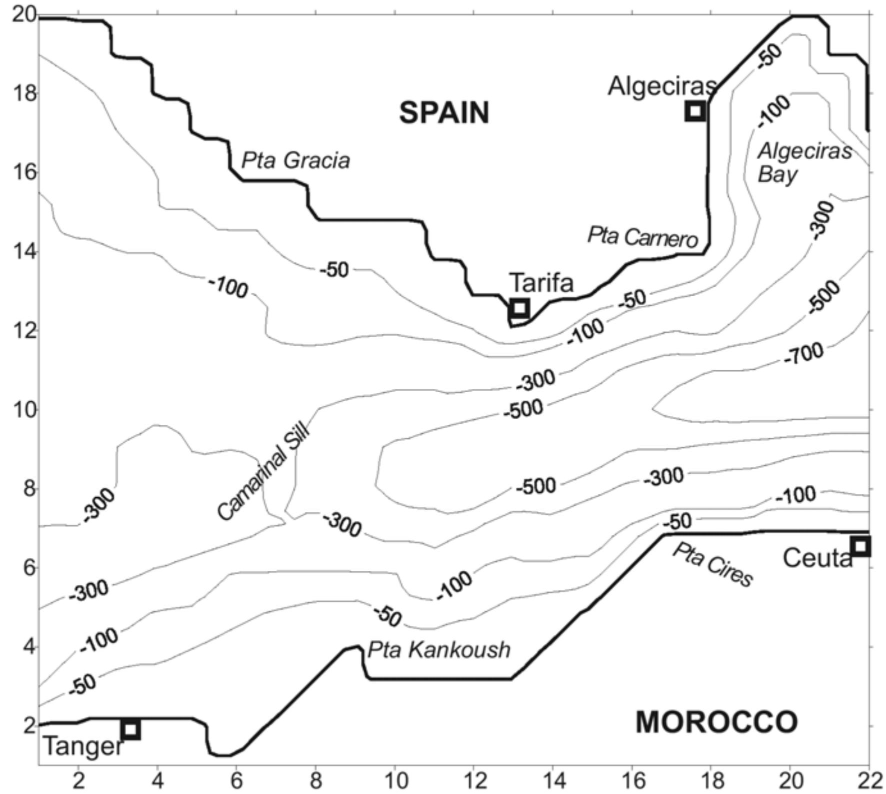

Fig. 1. Map of the computational domain showing some important towns (squares). Each unit in the *x* and *y* axis is the grid cell number (thus equals to 2500 m)

Table 1. Observed and computed amplitudes (in cm) and phases (in deg) of tidal elevations at several points in the Strait[4]

Station	M_2				S_2			
	A_{obs}	G_{obs}	A_{comp}	G_{comp}	A_{obs}	G_{obs}	A_{comp}	G_{comp}
Pta Gracia	64.9	49	70.5	57	22.3	74	24.8	81
Pta Kankoush	51.8	69	52.7	59	20.1	90	18.9	86
Tarifa	41.5	57	46.2	52	14.2	85	17.4	77
Pta Cires	36.4	47	38.5	56	14.1	74	14.3	82
Algeciras	31.0	48	25.0	48	11.1	74	10.0	71
Pta Carnero	31.1	48	25.6	46	11.5	71	10.4	69
Ceuta	29.7	50	25.0	50	11.4	76	10.0	72

Advection is computed solving the following equation for each particle:

$$\frac{d\mathbf{r}}{dt} = \mathbf{q} \quad (1)$$

where **r** is the position vector of the particle and **q** is the current vector (due to wind and tide) at the particle position, solved in components u and v. The maximum sizes of the horizontal and vertical steps due to turbulent diffusion, D_h and D_v, respectively, are:

$$\begin{aligned} D_h &= \sqrt{12 K_h \Delta t} \\ D_v &= \sqrt{2 K_v \Delta t} \end{aligned} \quad (2)$$

where K_h and K_v are the horizontal and vertical diffusion coefficients, respectively. More details about the practical aspects of the computation may be seen elsewhere.[3]

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 taken[6] as 20 m.

Date and time of the discharge (and duration in the case of continuous releases) must be specified since the fate of the release will depend on the tidal state when it took place. 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 being January 1, 2003 at 0:15 hours Greenwich time.

The adsorption of radionuclides by suspended sediments can be neglected since suspended matter concentrations in the Strait of Gibraltar are very low, typically in the range[7] of 0.1–0.5 mg/l. Also, average depth is 350 m and, as a consequence, interactions of radionuclides with bed sediments can be neglected as well.

Graphical user interfaces

Matlab GUIs have been created to allow an easy use of the model. The first, main, GUI is used to introduce all the information required by the model, that is summarized in Table 2. Optionally, the time evolution of contaminant concentration at desired points over the domain can be obtained. The release point and the point where the time evolution of particles is obtained (if the option is selected) can be introduced as grid coordinates or, alternatively, from another GUI simply clicking at the point with the mouse.

If the graphic button is pressed, the output GUI is opened (Fig. 2). Twelve snapshots at constant intervals during the simulation may be plotted to show the evolution of the radionuclide patch over time.

Table 2. Information required by the model to be introduced by the user

Release point coordinates
Select instantaneous/continuous release option
Wind speed
Wind direction
Release date (day, month, year)
Release time, UTC, (hours, minutes)
Simulation time (days)
Magnitude of the release in the corresponding units
Radionuclide decay costant

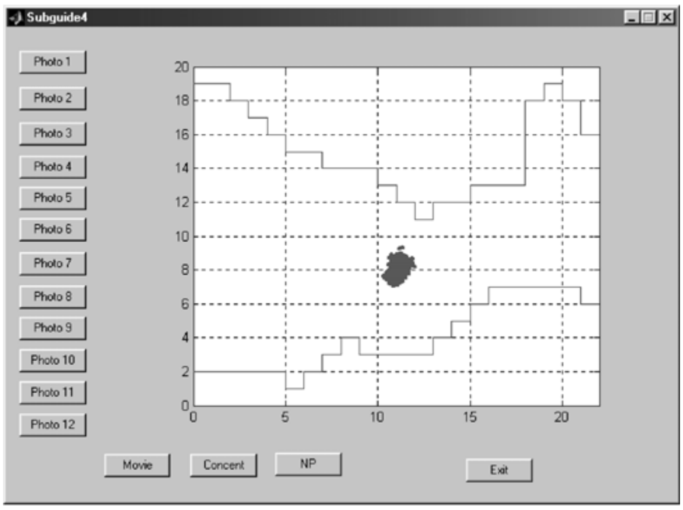

Fig. 2. Output GUI

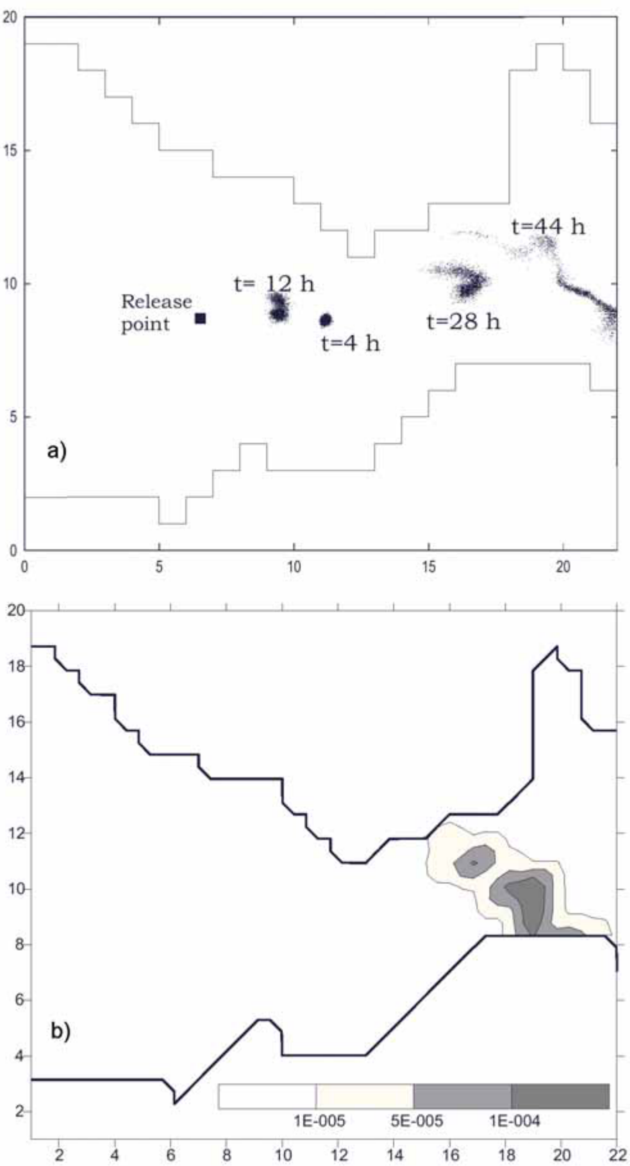

Fig. 3. Dispersion of an instantaneous release. The position of particles at different times after the release is shown (a); Computed surface concentration in arbitrary units per m^3 48 hours after the release (b). It has been obtained from the density of particles

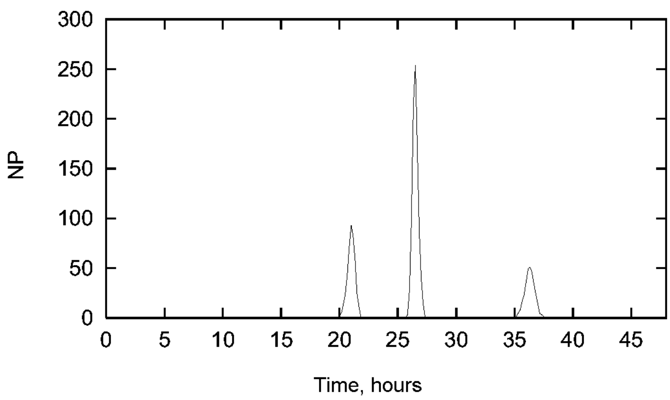

Fig. 4. Time evolution of the number of particles inside grid cell (15, 9)

Photographs may be seen one by one or as a movie. Another graphic consists of a map of the final radionuclide concentration over the Strait (concent button) computed from the density of particles per water volume unit.[3] If the option was selected, the time evolution of particles at the selected point may be finally seen (NP button).

Results and discussion

Typical results obtained from the particle-tracking model are presented in Fig. 3. Conservative particles (i.e., no decay) are considered in the simulations here. An instantaneous discharge of a long-lived radionuclide was introduced into a grid cell in the area of Camarinal Sill during high water at Tarifa and with no wind. 3000 particles are used in the simulation, whose tracks are followed during two days. The position of each particle at four different times after the release is shown in Fig. 3a. The concentration of the radionuclide in arbitrary units (for instance Bq) per m^3 at $t=48$ hours is also presented in Fig. 3b. There is a net transport towards the Mediterranean Sea due to the residual currents, although the patch moves forward and backward following tidal oscillations. This can be also seen in Fig. 4, where the time evolution of the number of particles inside an arbitrary grid cell [in this case (15, 9)] is shown. The patch moves three times over this point, producing three peaks in the number of particles at 21, 26 and 36 hours after the release. The highest peak, 254 particles, is observed 26 hours after the release. In this simulation $1.0 \cdot 10^6$ units (Bq for instance) were released, thus the peak implies a maximum concentration equal to $9.2 \cdot 10^{-5}$ units/m^3. For the following peak, at $t=36$ hours, the concentration is reduced in a factor 5 due to the spreading of the patch.

The movement of a patch is obviously influenced by wind conditions. West winds, directed in the same direction as the residual circulation, produce a faster movement to the eastern part of the Strait, while east winds tend to retain particles into the Strait. Since the particle-tracking model is three-dimensional, shear diffusion is automatically included and the patch size increases in the direction of wind.

An example of the simulation of a continuous release is presented in Fig. 5. The release occurs at same point and tidal conditions as before (cell (7, 9) and high water at Tarifa), and under calm wind. The position of particles 44 hours after the release is shown in Fig. 5. This can be compared with the 44 hours patch in Fig. 3. Now there is a plume extending from the release point to the eastern part of the Strait. It is interesting to observe that four patches with larger concentrations of particles are apparent in the plume. They correspond to particles released during slack water, that remain concentrated and move together.

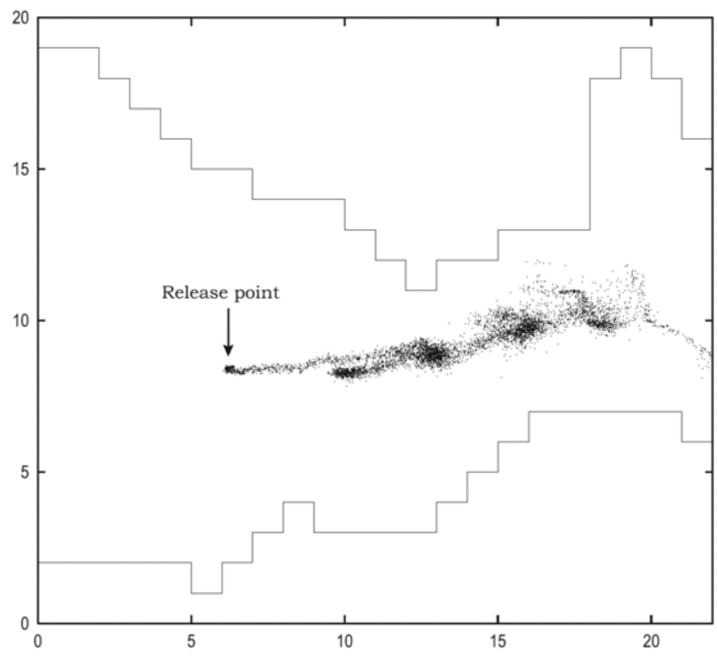

Fig. 5. Position of particles 44 hours after the beginning of a continuous release at grid coordinates (7, 9)

Conclusions

A particle-tracking model for simulating radioactivity dispersion in the Strait of Gibraltar has been developed. The model solves the depth-averaged hydrodynamic equations for the M_2 and S_2 tidal constituents off-line. Dispersion is solved using a Lagrangian approach, diffusion and decay being simulated by means of a Monte Carlo method. Matlab GUIs have been created to introduce run parameters and visualize results in an easy way. Some examples on the dispersion of contaminants have been provided. Generally, the fate of a patch depends on the tidal state when the release was carried out and on wind conditions. East winds oppose the residual current and tend to retain contaminants in the Strait, thus greater radionuclide concentrations occur. Under calm conditions and, especially, west winds, the Strait is flushed off rapidly.

References

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