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Short Communication

GISPART: a numerical model to simulate the dispersion of contaminants in the Strait of Gibraltar

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Abstract

GISPART is a three-dimensional particle-tracking code to simulate the dispersion of contaminants 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 several files that are read by the dispersion module to reconstruct water movements. Several application cases are presented, including instantaneous and continuous releases as well as different wind conditions, to show the information that can be extracted from the model.
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Keywords: Gibraltar Strait; Particle tracking; Numerical modelling; Pollutants

Software availability

Program name: GISPART (GIbraltar Strait PARticle-Tracking model)
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Hardware: Compatible PC 200 MHz or higher
Programe code: Fortran
Cost: Free
Availability: http://www.personal.us.es/rperianez or contact R. Periáñez

1. Introduction

Recently, there has been an increasing interest in the development of pollutant dispersion models for the marine environment to use for decision making purposes after contaminant spills. In particular, particle-tracking methods are well suited for problems in which high contamination gradients are involved, since they minimize the effects of numerical diffusion. Also, they can be used to rapidly assess contaminant dispersion if the hydrodynamics are simulated previously off-line. Particle-tracking models have been used to simulate the dispersion of passive tracers (Gomez-Gesteira et al., 1999; Harms et al., 2000), radionuclides (Schonfeld, 1995; Periáñez and Elliott, 2002), oil spills (Proctor et al., 1994a,b) and even contaminated milk (Elliott et al., 2001) in several coastal water environments.

The objective of this paper consists of giving a brief description of a new Lagrangian pollutant dispersion model developed for the Strait of Gibraltar, connecting the Mediterranean Sea and the Atlantic Ocean. This is a relevant topic because of the intense shipping activities in the Strait, which include the transport of radioactive material from/to the nuclear fuel reprocessing plants of Sellafield and Cap de la Hague (in UK and France, respectively), the transit of nuclear submarines, as well

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as massive transport of chemical contaminants. Shipping routes are complex, with intersections of longitudinal routes with some 2000 annual transverse round trips Algeciras–Ceuta, Algeciras–Tanger and Tarifa–Tanger (see 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. The area of the Strait of Gibraltar has a high ecological and tourist value, and there are also some important towns. Thus, a contamination release into the Strait as a consequence of an accident (or a deliberate release) can lead to a large ecological and economic impact.

2. Model description

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, and 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. Model equations are summarized in Appendix.

2.1. Hydrodynamic module

An important feature of the tidal flow in the Strait is that it can be considered barotropic, as a first approach
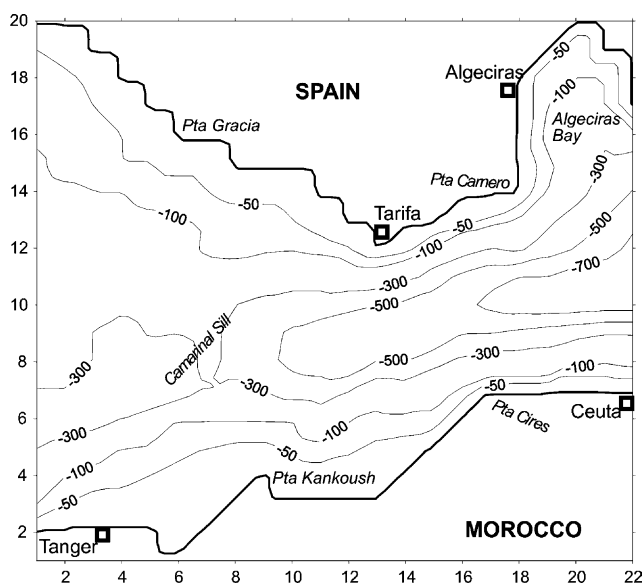

Fig. 1. Map of the computational domain showing some important towns (squares). Each unit in the x and y axes is the grid cell number (thus equal to 2500 m).

(Mañanes et al., 1998; Tsimplis and Bryden, 2000). As a consequence, 2D depth-averaged models have already been applied to simulate surface tides in the Strait (see for instance Sánchez and Pascual, 1988; 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.

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.

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 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. Although not presented here, results are, in general, in good agreement with observations (Periáñez, 2004).

2.2. Dispersion code

The dispersion of contaminants is calculated using a particle-tracking method. Essentially, the pollutant 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. Decay of particles is also simulated using a Monte Carlo method (Periáñez and Elliott, 2002). This process is relevant, for instance, in the case of radioactive contaminants. The density of particles per water volume unit is finally computed to obtain contaminant 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 (see for instance Pugh, 1987). The spatial resolution of the dispersion model is $\Delta x = \Delta y = 2500$ m and time step is $\Delta t = 600$ s.

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 as 20 m (Elliott, 1986; Pugh, 1987; Proctor et al., 1994a).

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 h 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 Strait, typically 0.1–0.5 mg/L (León-Vintró et al., 1999). Also, the average depth is 350 m (reaching 900 m in the eastern part) and, as a consequence, interactions of pollutants with bottom sediments can be neglected too.

2.3. Input data

The dispersion code automatically reads 6 files that contain the topography of the Strait, amplitudes and phases of the two tidal constituents included in the model (M_2 and S_2), and the residual circulation. These files are provided 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.

2.4. Model output

The model provides several output files. It gives the coordinates of each particle at several times during the simulation. Twelve snapshots at constant intervals during the simulation are plotted to show the evolution of the pollutant tracers over time. Another file contains a map of the final contaminant concentration over the Strait computed from the density of particles per water

Table 1
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
Contaminant decay constant

volume unit. Optionally, the time evolution of contaminant concentration at desired points over the domain can be obtained.

3. Application cases

An example of the type of results that can be obtained from the particle-tracking model is presented in Fig. 2. Conservative particles (i.e. no decay) are considered in the simulations here. Instantaneous discharge of a pollutant was inputted into a grid cell in the area of Camarinal Sill during high water at Tarifa and with no wind. Three thousand particles are used in the simulation, whose tracks are followed during 2 days. The position of each particle at four different times after the release is shown in Fig. 2 (top). The concentration of the pollutant in arbitrary units per m^3 at $t = 48$ h is also presented in Fig. 2 (center). 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 also be seen in Fig. 2 (bottom), 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 h after the release. The highest peak, 254 particles, is observed 26 h after the release. In this simulation 1.0×10^6 units of contaminant were released, thus the peak implies a maximum concentration equal to 9.2×10^{-5} units/m^3. For the following peak, at $t = 36$ h, the concentration is reduced by a factor 5 due to the spreading of the patch. From the center of the patch after 48 h an average velocity of the pollutant of 17 cm/s towards the Mediterranean can be estimated. This number can be compared with the mean speed of the Atlantic inflow equal to 23 cm/s measured by Tsimplis and Bryden (2000).

The movement of a patch is obviously influenced by wind conditions. This can be clearly seen in Fig. 3. The same simulation described above has been repeated but with 15 m/s east and west winds, which is common in the Strait. The position of particles 28 h after the release for both simulations is shown in Fig. 3, which can be compared with the 28 h patch in Fig. 2. 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 produced and the patch size increases in the direction of wind.

An example of the simulation of a continuous release is presented in Fig. 4. 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 h after the release is shown in Fig. 4. This
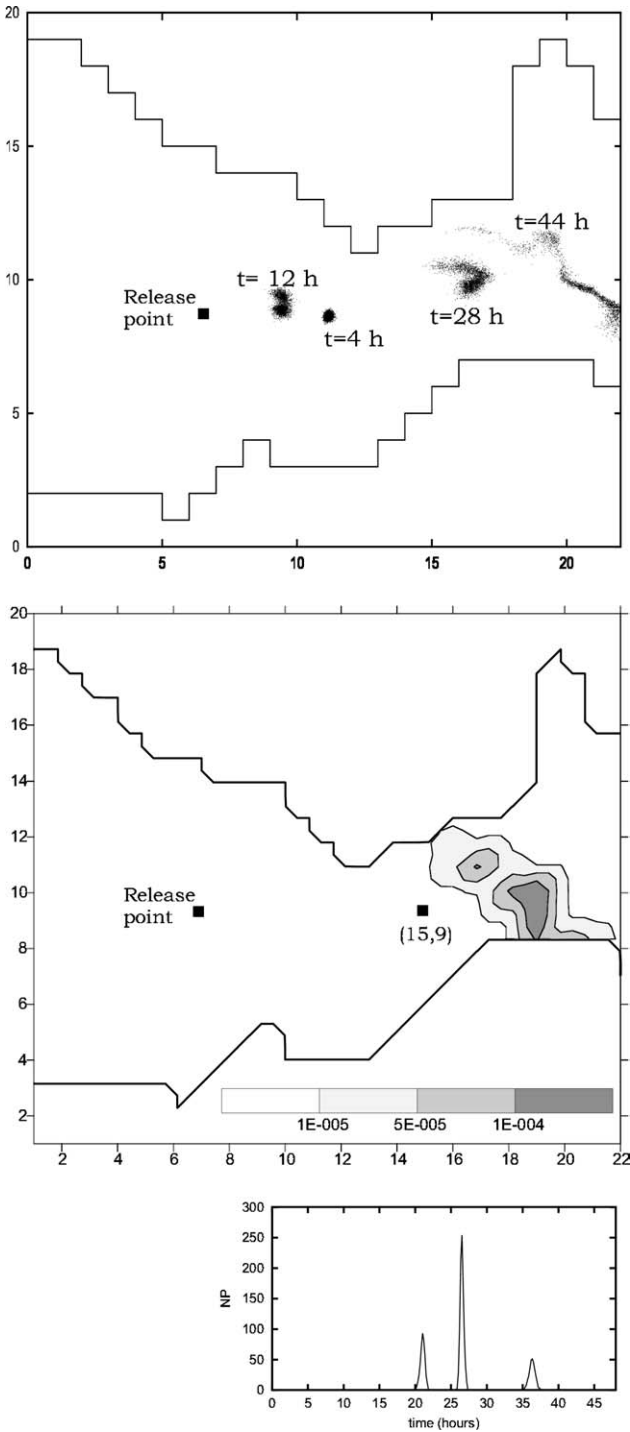
Fig. 2. Up: Dispersion of an instantaneous release. The position of particles at different times after the release is shown. Center: Computed surface concentration in arbitrary units per m^3 48 h after the release. It has been obtained from the density of particles. Down: Time evolution of the number of particles inside grid cell (15,9), whose position is indicated in the central panel.

can be compared with the 44 h patch in Fig. 2. 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
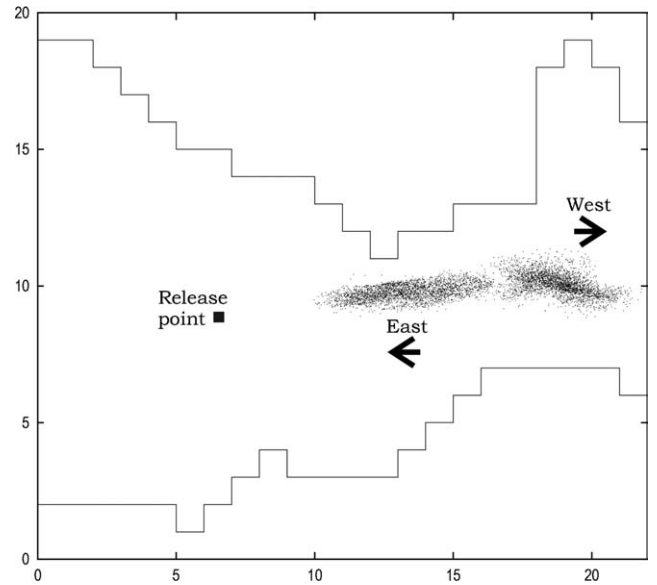

Fig. 3. Position of particles 28 h after an instantaneous release at grid cell (7,9) with 15 m/s winds from the east and west. The release point and wind directions are indicated.

apparent in the plume. They correspond to particles released during slack water, which remain concentrated and move together.

Finally, an accident has been simulated at Algeciras harbor. This is a relevant topic, as mentioned in Section 1. The accident consisted of an instantaneous release occurring during high water at Tarifa. This would be the most critical accident, since contaminants are retained into Algeciras Bay. Only in the case of winds blowing from the north would contaminants be flushed out of the bay. The position of particles for calm conditions and a 15 m/s northern wind, 14 days and 2 days after the
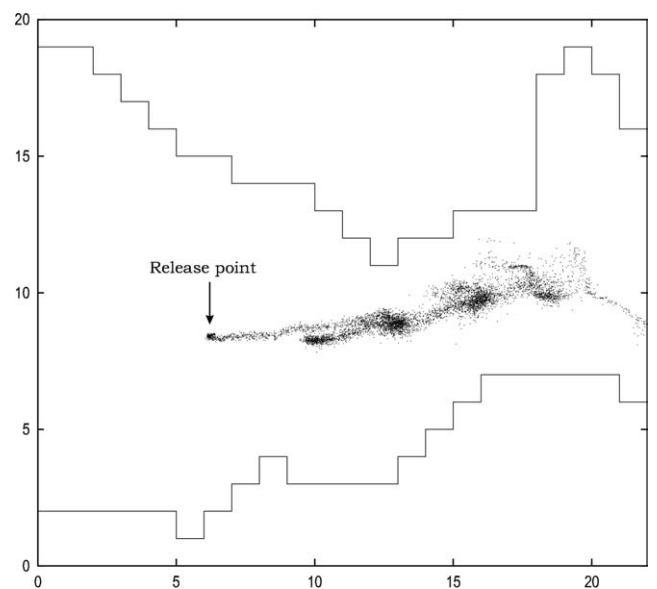

Fig. 4. Position of particles 44 h after the beginning of a continuous release at grid coordinates (7,9).

release respectively, is presented in Fig. 5. It can be seen that for calm wind essentially all the contamination is retained in the bay (this would also be the case for east and west winds). In the case of north winds, contaminants are transported to the axis of the Strait. From this area they are flushed out by longitudinal currents.

As an indication, the running time for an instantaneous release (3000 particles are tracked) is approximately 10 s per day of simulation on a 333 MHz Pentium 2 computer.

4. Conclusions

A particle-tracking model for simulating pollutant 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. Tidal analysis is carried out and tidal constants and
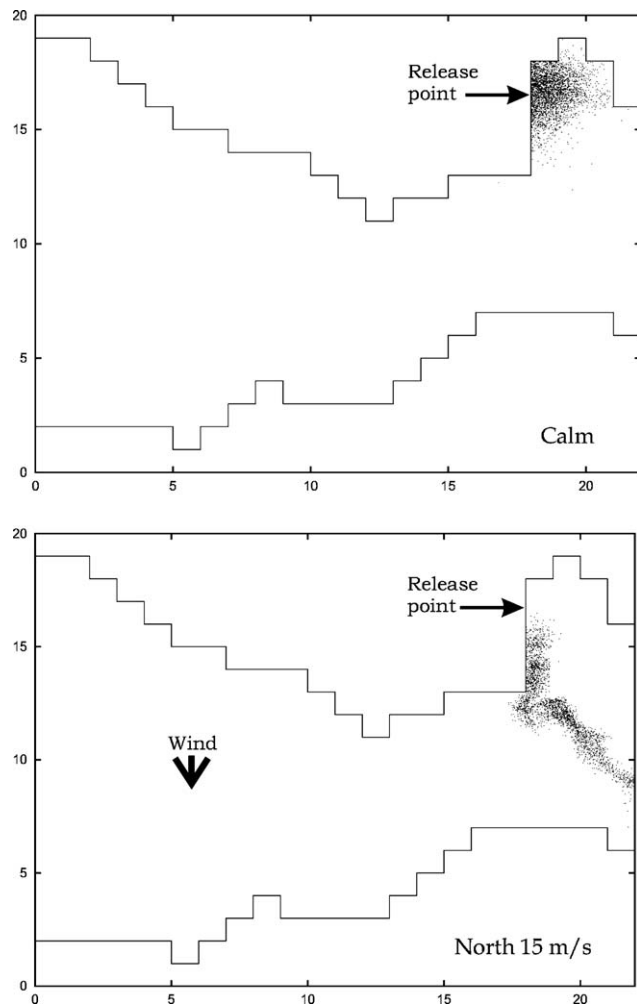

Fig. 5. Position of particles after an accident at Algeciras harbor, 14 days after the accident in the case of calm conditions and 2 days after the accident in the case of a 15 m/s north wind. The release point and wind directions are indicated.

residuals are stored in files that are read by the dispersion model. Dispersion is solved using a Lagrangian approach, diffusion and decay being simulated by means of a Monte Carlo method. The dispersion model is three-dimensional, thus standard vertical profiles for the tidal and wind-induced currents have been used to define the variation of currents with depth.

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 contaminant pollution occurs. Under calm conditions and, especially, west winds, the Strait is flushed off rapidly. The most critical accident would take place at, or near, Algeciras harbor. In this case contamination stays in Algeciras Bay, only if wind blows from the north sector a faster flushing of contaminants out of the bay occurs.

Appendix

The depth-averaged hydrodynamic equations are written as:

$$\frac{\partial z}{\partial t}+\frac{\partial}{\partial x}(Hu)+\frac{\partial}{\partial y}(Hv) = 0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial z}{\partial x}-\Omega v+\frac{\tau_u}{\rho H} = A\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial z}{\partial y}+\Omega u+\frac{\tau_v}{\rho H} = A\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

where u and v are the depth-averaged water velocities along the x and y axes, D is the depth of water below the mean sea level, z is the displacement of the water surface above the mean sea level measured upwards, $H = D + z$ is the total water depth, Ω is the Coriolis parameter ($\Omega = 2w\sin\beta$, where w is the earth rotational angular velocity and β is latitude), g is acceleration due to gravity, ρ is water density and A is the horizontal eddy viscosity. τ_u and τ_v are friction stresses.

The surface current is deduced from the depth averaged one:

$$u_s = \frac{m+1}{m}\overline{u} \tag{4}$$

where $\overline{u}$ is the depth-averaged current provided by the hydrodynamic model and $m = 6$. The current speed at a level z' below the sea surface is:

$$u_{z'} = u_s \left(\frac{D - z'}{D} \right)^{1/m} \tag{5}$$

The wind-induced current at any depth is:

$$u_{z'} = \begin{cases} u_0 - \dfrac{u^*}{\kappa} \ln\left(\dfrac{z'}{z_0}\right) & \text{if } z' < 20\,\text{m} \\ 0 & \text{if } z' \geq 20\,\text{m} \end{cases} \tag{6}$$

where u_0 is the surface wind-induced current, $\kappa = 0.4$ is the von Karman constant, u^* is a friction velocity and z_0 is the sea surface roughness length. The friction velocity can be estimated as

$$u^* = 0.0012W \tag{7}$$

for a wide range of conditions, where W is wind speed 10 m above the sea surface. Of course, these current profiles are solved in the u and v components.

Advection is computed solving the following equation for each particle:

$$\frac{d\mathbf{r}}{dt} = \mathbf{q} \tag{8}$$

where $\mathbf{r}$ is the position vector of the particle and $\mathbf{q}$ 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:

$$\begin{aligned} D_h &= \sqrt{12 K_h \Delta t} \\ D_v &= \sqrt{2 K_v \Delta t} \end{aligned} \tag{9}$$

where K_h and K_v are the horizontal and vertical diffusion coefficients respectively.

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