IL NUOVO CIMENTO Vol. 30 C, N. 2 Marzo-Aprile 2007
DOI 10.1393/ncc/i2006-10239-y

Particle exchange and residence times in the North Western Mediterranean

D. Cianelli([1])([2]), F. Diaz([2]), Y. Leredde([3]), P. Marsaleix([4]) and F. Carlotti([2])

([1]) *Dipartimento di Scienze per l'Ambiente, Università "Parthenope" Via de Gasperi 5, 80133 Napoli, Italy*
([2]) *Laboratoire d'Océanographie et de Biogéochimie, Centre d'Océanologie de Marseille Campus de Luminy, Case 901, 13288 Marseille cedex 09, France*
([3]) *Laboratoire de Dynamique de la Lithosphère, Université Montpellier 2, CC. 60 place E. Bataillon, 34095 Montpellier cedex 5, France*
([4]) *Pôle d'Océanographie Côtière de l'Observatoire Midi-Pyrénées, Laboratoire d'Aérologie 14 Avenue Edouard Belin, 31400 Toulouse, France*

(ricevuto il 21 Settembre 2006; revisionato il 13 Dicembre 2006; approvato il 29 Dicembre 2006; pubblicato online il 3 Aprile 2007)

Summary. — The effects of the hydrodynamic processes on the distribution of passive drifters in the Gulf of Lions (GoL) have been investigated using a Lagrangian approach coupled with a 3D circulation model (Symphonie). We consider passive drifters, for which transport processes are determined solely by the 3D flow fields, which are in turn primarily forced by the North Mediterranean Current (NMC) and by the Rhône fresh-water inputs. The model reproduces 600 3D Lagrangian trajectories of particles released along the coastal area of the GoL during the winter period (January-February). The GoL has been divided into four sectors, each corresponding to a zone playing a strategic role in the hydrodynamics of the study area. The macroscopic characteristics of the transport on the shelf zone are analyzed in terms of total concentration and residence times of the cluster released in the basin. Particle distributions are strongly related to the mesoscale and sub-mesoscale hydrodynamic structures on the shelf and to the offshore circulation associated with the NMC. Two crucial areas are identified: a dispersive zone, corresponding to the central part of the continental shelf, and a wide offshore zone, representing an area of both aggregation and transition.

PACS `92.10.Sx` – Coastal, estuarine, and near shore processes.

1. – Introduction

In coastal areas mesoscale hydrodynamic structures (10 s to 100 s of km) are crucial for basin-scale particle transport. Investigating the relationships between particle distribution and mesoscale structures provides a rationale to estimate pollutant dispersion and oil spills fate [1,2], as well as to understand the influence of such physical structures on the dynamics of local ecosystems [3,4]. The north-western Mediterranean Sea and especially the Gulf of Lions (GoL) represent an interesting site to study the influence of water mass circulation and estuarine inputs on particle transport. A strong mesoscale circulation associated with the North Mediterranean Current (NMC) penetrates the GoL from the northeastern side splitting into two branches: a southern one following the continental slope, and a northern one occasionally entering the shelf zone following a northwestern direction [5, 6]. The modelling efforts carried out during the last 15 years over this area have been mainly focused on the fresh-water plume dynamics (*e.g.* [7-9]), on the mesoscale circulation and distribution of water masses (*e.g.*, [10, 6]) and on the interactions of coastal currents with a shallow shelf [11,12]. The GoL has also relevant biological implications as it is a major anchovy spawning area in the northwestern Mediterranean Sea [13], owing to its relative high primary production over the year [14].

The main goals of the present work are to understand how the hydrodynamic features of the GoL may determine the development of retention/dispersive areas and to provide a preliminary estimate of particle transport during the winter period (January-February). To this aim we investigate particle drift in relation to physical forcing variations by means of a 3D hydrodynamic model (Symphonie) of the GoL [7, 9] coupled with a Lagrangian module. The Lagrangian approach represents a suitable tool by which to study transport processes over an entire basin [15-17] and to simulate complex and interactive processes acting at different scales [18, 19]. Here we present a first step considering passive drifters for which the transport processes are determined uniquely by the velocity fields of the model circulation. By estimating the residence times we then characterize the exchange processes on the shelf zone.

2. – Materials and methods

The Symphonie hydrodynamic model is basically a three-dimensional primitive equation model of the coastal ocean. The three components of the velocity field, surface elevation, temperature and salinity are computed on a C Arakawa grid with horizontal mesh of 3 km; the vertical resolution consists of a generalized sigma coordinate system with 25 levels [10]. Turbulence closure is achieved through a prognostic equation for the turbulent kinetic energy and a diagnostic equation for the mixing and dissipation length scales [20]. A leap-frog scheme is used for the time stepping; the computation costs are limited thanks to a time splitting technique which permits computing separately the vertical shear of the current and its depth-averaged component with appropriate time steps [21]. On the basis of the surface boundary conditions, the momentum flux equals the wind stress, whereas the heat flux results from the atmospheric and radiative fluxes. The solar flux penetrates the water column with a decreasingly exponential law and the salinity flux takes into account the balance between evaporation and precipitation. Open boundary conditions are the same used in Estournel *et al.* [10], *i.e.* a radiation condition (*e.g.* [22]). The external forcings are of three types: river discharges, atmospheric fluxes and large-scale inputs at lateral open boundaries. The real fresh-water inputs from the most important rivers (Rhône, Hérault, etc.) are updated at high frequency (from 3 to 24 hours); the atmospheric forcings are provided by the 3-hours averaged outputs of the weather-forecast model Aladin (Météo-France). The restoring terms of the open boundary scheme allow forcing the model with the features of the general circulation at the regional scale; this latter, clearly identified as the NMC, is given by the regional-scale model MOM (*e.g.* [23]).

To compute the trajectories in the three-dimensional flow field of the Symphonie model a Lagrangian particle routine has been developed. The Lagrangian simulations are based on the output velocity fields from Symphonie with a temporal resolution of 3 h.

We consider purely passive floaters, and their simulated walks are computed assuming that the velocity is constant over the sampling interval. Given the properly Eulerian velocity fields, the Lagrangian particles are advected with the flow. At each point, the velocity field is computed by linearly interpolating the nearest grid points along the three spatial dimensions. Once the particle position is known, additional local variables—such as temperature, salinity, density and turbulent kinetic energy—are interpolated using the values computed by Symphonie on the neighbouring grid points.

Following [24] and [17] the transport properties on the shelf area are evaluated computing the total particle concentration $C(t)$ and the residence time T. $C(t)$ is the ratio between $N(t)$, which is the number of particles inside the region at time t, and the total number of particles initially released in the same region (N_0). The difference between N_0 and $N(t)$ gives the number of particles already exited from the domain $N_{\mathrm{out}}(t)$. The residence time T is computed as

$$T = \lim_{t\to\infty} T^*(t), \tag{1}$$

$$T^*(t) = t\frac{N(t)}{N_0} + \sum_{i=1}^{N_{\mathrm{out}}} \frac{t_{\mathrm{out}}(i)}{N_0}\,, \tag{2}$$

where T^* represents the average time taken by the drifters to exit from the release area for the first time and $t_{\mathrm{out}}(i)$ is the exit time of each particle that has already left.

3. – Results

Figure 1a shows the modelled domain, comprised between longitude 2°58′ and 7°38′ E and latitude 40°50′ and 43°50′ N and the corresponding bathymetry. To classify the different zones of the GoL as aggregative or dispersive, we divided our research area into four sectors: sector A corresponds to the shelf zone approximately delimited by the isobath of 200 m; sector B marks the boundary between the offshore and coastal zones; sectors C bounds the area where the predominant physical structure is the return branch of the NMC cyclonic flow. Sector D is a narrow strip representing the external boundary of the modelled domain; owing to the boundary conditions set in the Symphonie model [10], we consider all particles entering sector D as leaving the domain.

Basing on preliminary tests providing the main direction of particle transport, the single release coordinates in the x, y and z reference frame have been fixed deterministically for both sectors A and B, in the area between Cap Creus and Saint-Tropez (fig. 2a). The initial distribution in sector A covers (almost homogeneously) the continental shelf up to the 200 m bathymetric line. In sector B the initial coordinates have been set basing on a regular lattice overlapping with both a limit zone between the shelf and offshore dynamics (from 5°12′ to 5°25′ E), which is the most interesting area owing to the intrusion of the NMC in the GoL (see the velocity fields in fig. 1b). Particle concentration in sector A is much higher than in sector B because our experimental design was aimed at understanding if this sector A could be considered an aggregation area or not. The simulations of a 600 particles cluster, released at time step $t = 0$ (t_0) in the layer 0–25 m, have been run between January 1st and February 25th 1999, time span for which the Symphonie model has been validated using field data from the oceanographic cruise Moogli 3 [23].

At the initial state, particles are scattered along the GoL near shore in sector A and within a large area comprised between the coast and 42°50′ N and between 5°12′ and

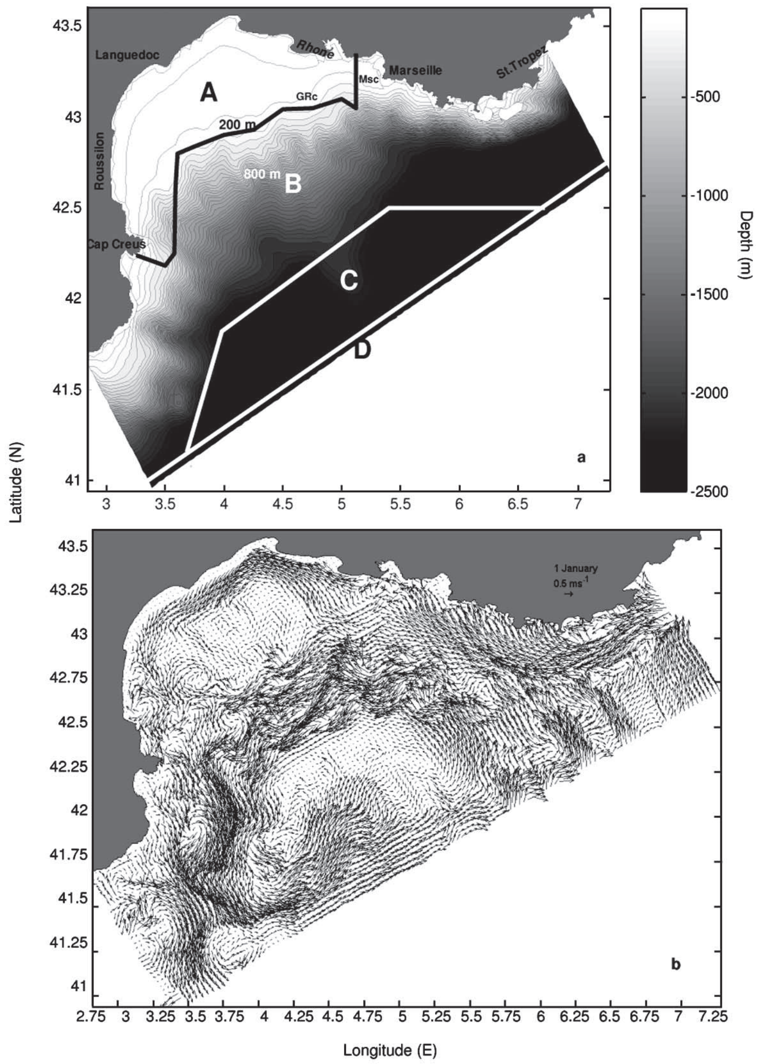

Fig. 1. – a) The modelled domain divided into four sectors and the corresponding bathymetry (interval isolines 50 m); b) the cyclonic structure of the large-scale circulation and the north-western intrusion of the NMC in the GoL visible in the horizontal velocity field (at 20 m depth) on January 1st.

6°55′ E in sector B (fig. 2a). At t_0 the presence of NMC along the continental slope and its intrusion on the eastern side of the shelf is relevant, the horizontal velocities in the central part of the continental shelf are much weaker (less than 10 cm s^{-1}) than those observed for the cyclonic circulation, which reaches values greater than 60 cm s^{-1} (fig. 1b). Consequently, this zone of the shelf appears relatively cut off from the rest of the studied area. One month later (fig. 2b and 3a), most of the particles initially spread from sector A predominantly remain over the continental shelf; a certain aggregation may be observed in the East of the Rhône River delta (ca. 43°30′N-5°00′ E), where the fresh-

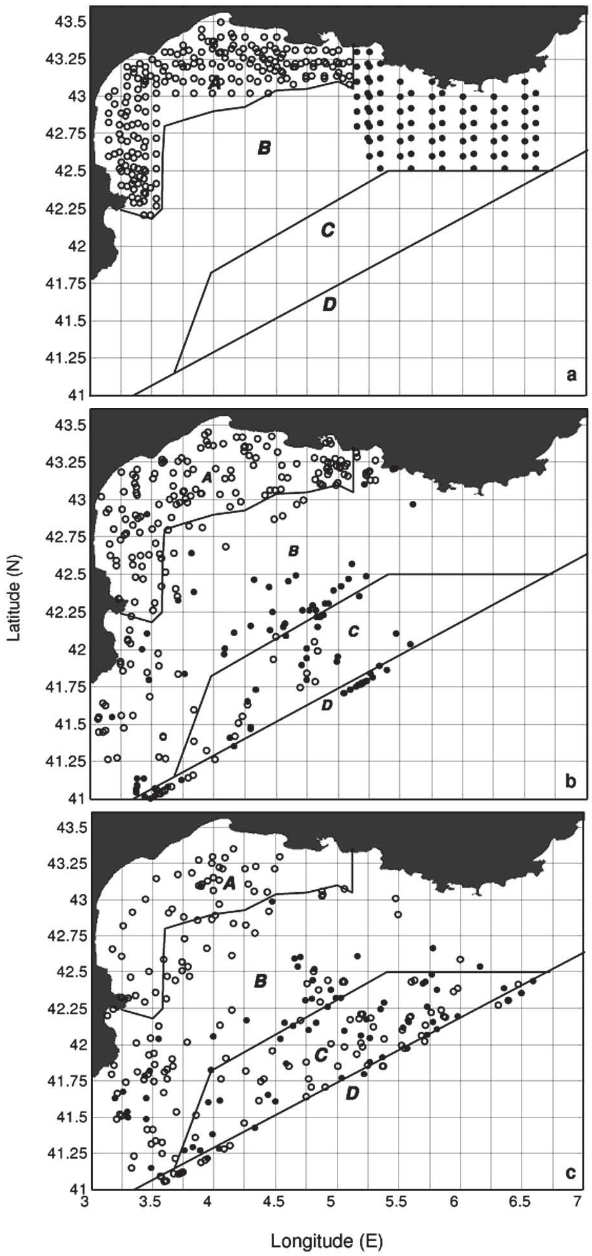

Fig. 2. – The evolution of particle distribution released from sectors A (○) and B (•) at a) initial time step; b) after one month from the release; c) after two months from the launch. For graphical purposes only a subset of 300 particles is shown.

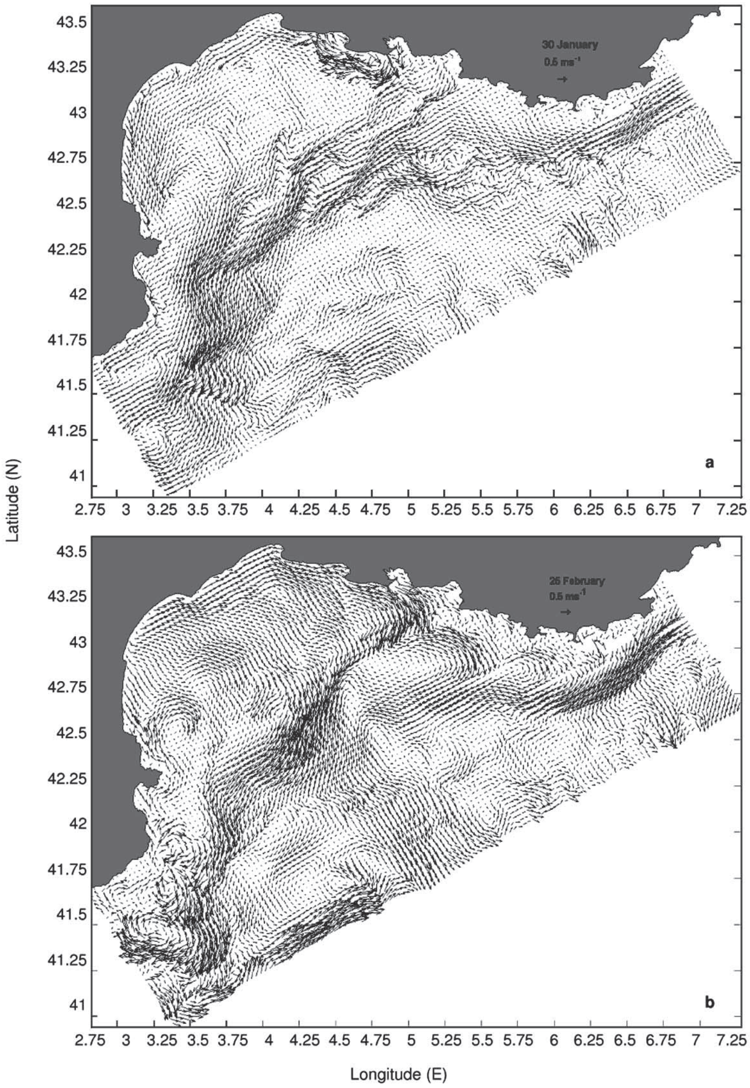

Fig. 3. – The horizontal velocity field at 20 m depth: a) after one month from the release; b) after two months from the launch.

water inputs were lower than usually in this season. Of the remaining particles originated from sector A, some are found offshore in sector B, while only a few of them penetrate in the eastern zone of sector B. At the same time, almost all drifters launched from sector B leave their initial zone and move much offshore in sectors B and C. This intermediate repartition principally results from the intense westward circulation of the NMC and its associated offshore gyre: the main flow of the NMC is still present along the continental slope (typical transport values are 1.7–1.8 Sv [5]), where the strongest currents are found (maximum typical values $\sim 70\,\mathrm{cm\,s^{-1}}$). Moreover, the bathymetric effects due to the presence of the edge between the Marseille and the Grand Rhone canyons (fig. 1a: Msc

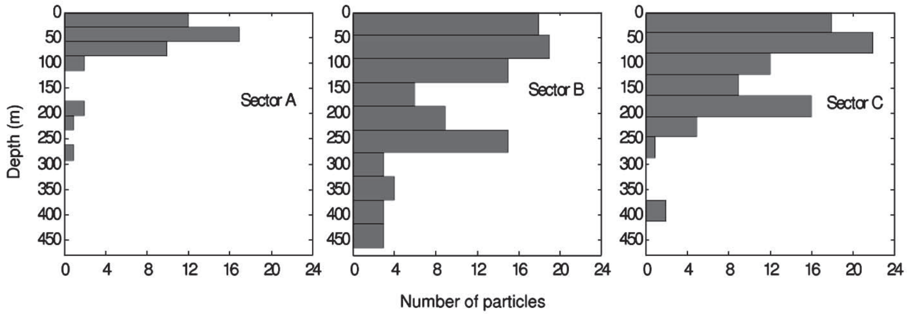

Fig. 4. – Histograms of vertical distribution at the end of simulation for sectors A, B and C.

and GRc, respectively) mark the separation of the NMC in two branches separated by a zone of weak currents. At the end of the simulation (February 25th, fig. 2c and 3b), part of the particles initially launched in sector A remains on the continental shelf. During the second half of February the coexistence of seasonal north to northwesterly winds, blowing with velocities greater than 10 knots, generate strong upwellings along the Languedoc-Roussillon coast [10] inducing an absence of particles in the littoral zone of the GoL and a particle aggregation towards the central part of the shelf. The remaining stock drifts from sector A principally towards the offshore sectors B and C. Particles launched from the western side of sector A firstly move northeastward towards the central part of the shelf, with a speed of order of $30\,\mathrm{cm\,s^{-1}}$, advected by the eastern counter-current observed by Petrenko [5], and then depict an anticyclonic eddy, as measured at the same location and with similar spatial scales under conditions of Mistral and Tramontane northerlies winds [10]. On the contrary, the particles launched from sector B are exclusively observed offshore in sectors B and C. During winter, offshore currents are typically oriented to the southwest thus the particles found in the southern part of sector B cover the whole span of the regional cyclonic circulation by drifting firstly south-westward within the main branch of the NMC, then north-eastward within the return current. Their path mark the deep water formation area observed during the Moogli 3 cruise [23] due to the intense cooling and evaporation induced by the northerlies winds blowing during February.

Figure 4 shows the vertical distribution of the sample previously considered on February 25th for sectors A, B and C. The number of particles in sector A (fig. 4a) decrease from the surface down to ca. 280 m. This zone is a typical shallow-water area, thus the majority of particles are concentrated in the surface layer (0–100 m). The intrusion of the NMC on the eastern side of the GoL and its spreading from the slope up to the 100 m isobath [5] is here clearly visible. In sector B (fig. 4b) particles reach a maximum depth of ~ 460 m, with a number of particles in the layer 0–250 m much greater than in the other ones. The mean depth (~ 160 m) of the particles reflects the vertical size of this mixing layer that almost exactly matches the observed core of the NMC during Moogli 3 (see table 3 in [5]) in this area. The weak stratification, the winds from the north and the occurrence of dense water formation enhance the vertical dispersion of particles in the mixed layer and only few particles are found deeper in the water column. Moving offshore in sector C (fig. 4c), the number of particles decreases from the surface to a maximum depth around 410 m; as generally observed in the other sectors, a large proportion of particles is found in a surface layer reaching ca. 200 m. This latter distribution probably results from distinct processes occurring in this sector, such as the Mediterranean Deep Water formation (*e.g.* [25]) and

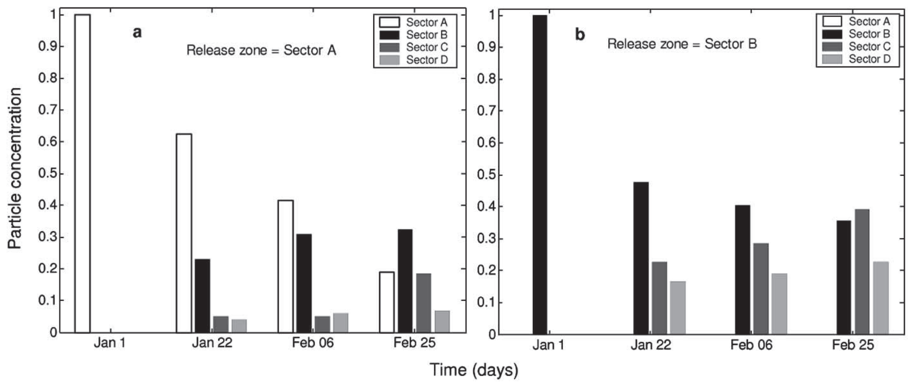

Fig. 5. – Time evolution of particle concentration in the release area and particle redistribution in the different sectors: a) particles initially released from sector A; b) particles initialliy released from sector B.

the presence of a return cyclonic branch of the NMC flowing north-eastward.

The bar diagram in fig. 5 shows the exchanges between the continental shelf and the offshore sectors of the GoL. The plot points out the time evolution of the tracers concentration in the release area, as well as their redistribution in the neighbouring sectors as time goes by. The particle concentrations for sectors A and B (C_{A} and C_{B}, respectively) are computed as described in sect. **2**. At t_0, when 436 particles are spread over sector A (fig. 5a), the particle concentration in this sector $C_{\mathrm{A}} = 1$ exponentially decreasing when the particles start to leave the origin area. After three weeks the majority of the particles remains confined to the continental shelf and only a minimum amount is transported to the offshore areas ($C_{\mathrm{A}} = 0.63$), whilst at the end of simulation the highest concentration of particles is found in sector B. A different repartition is observed for the group of particles (164) initially released in sector B (fig. 5b). Throughout the simulation period, they mainly remain in the release sector (on Feb. 6th, $C_{\mathrm{B}} \cong 0.43$) and only few of them drift towards the offshore sector C. On the whole, by the end of the simulation only few particles exit from the modelled domain reaching sector D. It is worth noting that, in about 60 days, no particle starting from sector B reaches the shelf zone.

A proxy of the aggregative or dispersive character of the shelf area (sector A) is obtained calculating the residence time T for two crucial shelf zones: the upwelling one along the Languedoc-Roussillon coast and the Rhône river delta (A_1 and A_2, respectively). Since a particle, once left its release area, may eventually re-enter it, we define as in [17] a buffer zone corresponding to the area comprised between the limit of sector A and the 800 m isobath (see fig. 1a). When a particle remains in the buffer, it is considered as still on the shelf and the relative residence times is computed; on the contrary, if the particle goes beyond the buffer it is assumed to be definitely leaving the shelf area. In the upwelling zone, 150 particles have been released and the estimated residence time is $T^*{}_{\mathrm{A1}} \cong$ 54 days; almost the same value is found on the Rhône delta area, where the residence time $T^*{}_{\mathrm{A2}}$ is about 52 days. These T^* correspond to the initiation of the asymptotic behaviour of theorethical residence time curves; more detailed investigation should be carried on longer time series, for which no model validations with *in situ* data are yet available.

Calculated T^* values should therefore be considered as an underestimate indicating that the two shelf areas are able to retain the particles approximately two months on average.

4. – Conclusions

The coupling between a Lagrangian approach and the 3D circulation model allows us to preliminary analyse the distribution of passively drifted particles induced by the winter hydrodynamic structures and meteorological forcings in the GoL. By reconstructing the single 3D Lagrangian trajectories we evaluate the contribution of the realistic hydrodynamics in the gain and loss of particles through the shelf and the offshore zone of the GoL during the winter period.

Starting at the beginning of January from an initial distribution evenly covering the whole coastal area of the GoL and a wide offshore zone eastern of the GoL, we obtain at the end of February two major distribution areas separated by the NMC. The coastal area shows a dispersive character: by the end of the simulation, less than one third of the particles originated from sector A remains on the shelf (fig. 2), while a relevant number is transported towards sectors B and C. The second distribution area is identified in the central offshore zone, between sector C and the south of sector B. This area can be properly defined as both a retention area, because particles entering the NMC cyclonic gyre are confined in it, and a transition area, since NMC sustains particle drift towards the western margin of the basin. In our simulations, almost the 50% of the initial shelf population is found in sector A after one month from the release, showing that the local hydrodynamic structures only initially work as a potential retention system for the shelf population. On the other hand, during the same period sector B favours particle transport mainly owing to the presence of the main branch of the NMC, particles trapped in it being quickly drifted to the offshore zone. On the whole, a large part of the particles released in sector B are drifted by an east to west transport, developing their trajectories in the central part of the cyclonic gyre; only few of them finish their paths nearby the release point.

The estimate of residence times of shelf particles is strictly linked to the marked shelf-offshore transport directions. Particles entering the offshore branch of the NMC current are not able to re-enter the shelf, and after ~ 55 days only 20% remains in the release area. Drifters launched from the western side of the GoL are captured by the strong eastern counter-currents favoured by the numerous intrusions of the NMC on the shelf and on its western side [5]. Before the end of January, the weak surface currents in correspondence of the Rhône River aggregate the particles around the river mouth. After this date, the fresh-water inputs rapidly increase (above $3000\,\mathrm{m^3\,s^{-1}}$) until the end of February, directing the drifters towards the western area of sector A. At the same time, the development of sub-mesoscale eddies favours the retention of particles in front of the Roussillon coast, while the occurrence of northwesterly winds inducing coastal upwellings (*e.g.* [26]) drives the cluster towards the central part of the shelf.

The present analysis represents the first attempt to characterise particle transport in the GoL. The results are in agreement with a previous study (*e.g.* [10]) showing that the hydrodynamic circulation in the GoL is mainly affected by the direction and strength of wind as well as by river discharge. The evidence that none of the particles initially released offshore enters the shelf area hints at the presence of a physical barrier hampering such transport. On these grounds it is evident that, at least in winter conditions, the seasonal features of the wind-induced shelf circulation, the fresh-water inputs and the NMC (flowing deep (250–300 m) and fast ($70\,\mathrm{cm\,s^{-1}}$) close to the coast) favour a shelf-offshore and an east-to-west particle exchange, whilst an offshore-shelf transport is inhibited. These outcomes provide new elements to understand the interactions between the local hydrodynamics and the ecosystems dynamic of the GoL and they also highlight which are the zones meriting special focus in coastal zone management program.

* * *

The authors acknowledge Prof. E. Zambianchi for helpful discussions and the modellers team of the Pôle d'Océanographie Côtière at the Laboratoire d'Aérologie (Toulouse, France). Comments from an anonymous referee improved an earlier version of the manuscript. This work has been performed in the framework of the "French Programme National d'Environnement côtier".

REFERENCES

[1] Mariano A. J., Griffa A., Ozgokmen T. M. and Zambianchi E., *J. Atmos. Ocean. Techn.*, **19** (2002) 1114.
[2] Berloff P. S. and Mc Williams J. C., *J. Phys. Ocean.*, **32** (2002) 797.
[3] Lévy M., Mémery L. and Madec G., *Deep-Sea Res.*, **47** (2000) 27.
[4] Oschlies A., *J. Geophys. Res.*, **107** (C5) (2002) 10 1029/2000JC000275.
[5] Petrenko A., *Ocean. Acta*, **26** (2003) 323.
[6] Petrenko A., Leredde Y. and Marsaleix P., *Cont. Shelf Res.*, **25** (2005) 7.
[7] Estournel C., Kondrachoff V., Marsaleix P. and Vehil R., *Cont. Shelf Res.*, **17** (1997) 899.
[8] Estournel C., Broche P., Marsaleix P., Devenon J. L., Auclair F. and Vehil R., *Est. Coast. Shelf Sci.*, **53** (2001) 25.
[9] Marsaleix P., Estournel C., Kondrachoff V. and Vehil R., *J. Mar. Syst.*, **14** (1998) 99.
[10] Estournel C., Durrieu de Madron X., Marsaleix P., Auclair F., Julliand C. and Vehil R., *J. Geophys. Res.*, **108** (C3) (2003) 7.
[11] Auclair F., Marsaleix P. and Estournel C., *Ocean. Acta*, **24** (2001) 529.
[12] Echevin V., Crepon M. and Mortier M., *J. Phys. Ocean.*, **33** (2003) 188.
[13] García A. and Palomera I., *Sci. Mar.*, **60** (1996) 155.
[14] Diaz F., Raimbault P., Boudjellal B., Garcia N. and Moutin T., *Mar. Ecol. Prog. Ser.*, **211** (2001) 51.
[15] Cesari R. and Tampieri F., *Nuovo Cimento C*, **20** (1997) 425.
[16] Blanke B., Arhan M., Madec G. and Roche S., *J. Phys. Ocean.*, **11** (1999) 2753.
[17] Falco P., Griffa A., Poulain P. and Zambianchi E., *J. Phys. Ocean.*, **30** (2000) 2055.
[18] Carlotti F. and Wolf K. U., *Fish. Ocean.*, **7** (1998) 191.
[19] Guizien K., Brochier T., Duchêne J. C., Koh B. S. and Marsaleix P., *Mar. Ecol. Prog. Ser.*, **311** (2006) 47.
[20] Gaspar P., Gregoris Y. and Lefevre J. M., *J. Geophys. Res.*, **95** (1990) 179.
[21] Blumberg A. F. and Mellor G. L., in *A description of a three-dimensional coastal ocean circulation model*, edited by Heaps N. S. (AGU, Washington, DC) 1987, pp. 1-16.
[22] Oey L. Y. and Chen P., *J. Geophys. Res.*, **97** (C12) (1992) 20087.
[23] Dufau-Julliand C., Marsaleix P., Petrenko A. and Dekeyser I., *J. Geophys. Res.*, **109** (C11002), (2004) doi:10.1029/2003JC002019.
[24] Buffoni G., Falco P., Griffa A. and Zambianchi E., *J. Geophys. Res.*, **102** (C8) (1997) 18699.
[25] Madec G. and Crépon M., in *Thermohaline-driven deep water formation in the Northwestern Mediterranean Sea*, edited by Chu P. C. and Gascard J. C. (Elsevier Oceanography Series) 1991, pp. 241-266.
[26] Millot C., *J. Mar. Syst.*, **20** (1999) 423.