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Hydrodynamic characterization of the Arcachon Bay, using model-derived descriptors

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Abstract:

A numerical model (MARS-2D) was developed, with the aim of describing the hydrodynamics that prevail in Arcachon Bay. Direct model results as well as derived mixing and transport time-scales (tidal prism, local and integrated flushing times, age of water masses), were used to understand the behaviour of water masses and exchanges between the Bay and its frontiers. Particular attention was paid to the processes that drive the hydrodynamics (tides, wind and rivers), in order to understand their respective influence.

The Arcachon Bay hydrodynamic system appears primarily to be highly influenced by tides; secondarily, by winds. About two third of the lagoon total volume is flushed in and out at each tidal cycle, which represent a mean tidal prism of 384 millions of cubic meters. The percentage of seawater flushed out during the ebb, that returns into the lagoon during the following flood flow is very high (return flow factor=0.95). This pattern leads to calculated integrated flushing times (IFT) ranging from 12.8 to 15.9 days, respectively, for the winter 2001 and summer 2005 simulations (two contrasting climatological situations: in summer, light northwesterly winds and low discharges in the rivers and, in winter, stronger southwesterly winds and higher river flows). Moreover, it has been found that northerly and westerly winds tend to reduce the flushing time, whilst southerly and easterly winds tend to hinder the renewal of the water in the Bay. The behaviour of the waters originating from the two main rivers of the lagoon, was studied also by means of the mean age assessment, under varying conditions of river flow and wind regime.

Keywords: Hydrodynamics; Residual fluxes; Tidal prism; Flushing time; Age of seawater; Tracer; Arcachon Bay

1. Introduction

The understanding of any marine system functioning incorporates the study of the hydrodynamics responsible for the transport, together with the dilution of its different constituents (biota, suspended sediments, nutrients, contaminants, etc.). Nonetheless, the perception of the system as a whole is sometimes arduous especially for coastal areas with a meandering coastline, strong bathymetric gradients and large intertidal areas. This observation is probably one of the reasons that caused researchers to develop tools and concepts that allow a more synoptic description of the hydrodynamics of a system, such as (for example) the tidal prism, the transit time, the residence time, the flushing time or the age of water masses (Takeoka, 1984 ; Brooks et al., 1999 ; Deleersnijder et al., 2001 ; Monsen et al., 2002 and Shen & Haas, 2004). The interest of such proxies is that they generally derive from classical hydrodynamic model, making easier the comparison of different systems hydrodynamics.

Arcachon Bay (44°40'N, 1°10'W) is a semi-confined triangular-shaped lagoon, located in the southeast of the Bay of Biscay (the Aquitaine and Landes coast, Figure 1); its surface is about 174 km^2 at high tide, and about 65% of this surface emerges at low tide. The tidal cycle is semi-diurnal with a weak diurnal inequality; tidal amplitude ranges between 0.8 and 4.6 m for neap and spring tides, respectively, whilst the mean depth is 4.6 m. The Bay communicates with the sea through two main mouths, separated by the Arguin Bank. Many little streams run into the lagoon, but the two main rivers, the Eyre and the Porges Canal, contribute for more than 95% (73% and 24% respectively) of the total annual freshwater inflows. The mean monthly flows range respectively from 8.4 to 38.6 m^3 s^{-1} and from 1.8 to 12.9 m^3 s^{-1}, for the Eyre and the Porges canal, with the maxima occurring in February and the minima in August.

Offshore of Arcachon Bay, the narrowness of the shelf and the local topography lead to very weak barotropic tidal currents as well as weak tidal (Eulerian) residual currents (Lazure & Dumas, 2008). The mixed layer depth ranges typically from 10 to 20 m during spring, when thermal stratifications are more frequent than salinity stratification. Nonetheless, under particular conditions of winds (northwesterly), the Gironde river plume can reach that area (Puillat et al., 2006). Hence, water mass circulation in this area is governed mainly by winds and, secondarily, by density currents (Lazure & Jegou, 1998 ; Puillat et al., 2006 and Lazure & Dumas, 2008).

In this study, the hydrodynamic model MARS-2D was used, together with the above-mentioned concepts, in order to describe the physics that prevail in the Arcachon Bay. Likewise, to understand the water mass movements and exchanges between the Bay and its frontiers. Particular attention was paid to the hydrodynamic main drivers (tides, wind and rivers), in order to understand their respective influences.

2. Materials and methods

2.1. The MARS model

The hydrodynamic model developed for Arcachon Bay is MARS (Model for Applications at Regional Scale). A detailed description of the model is provided in Lazure & Dumas (2008), whilst the way in which the model accomodates with wet/dry zones, is given in the Appendix. Due to the small water depth of the lagoon, the somewhat low freshwater inputs and the strong tidal currents, the water column is well-mixed all along the year, in Arcachon Bay (Robert et al., 1987). Use of the MARS-2D model was selected, assuming that horizontal current component does not vary significantly from the surface to the bottom; similarly that the vertical current acceleration is negligible when compared to gravitational acceleration.

The model is forced by sea surface elevation (at the boundaries) and atmospheric conditions (throughout the domain). Boundary conditions for the sea surface elevation are provided by a succession of four nested models with decreasing extensions (see inset, to Figure 1). The global hydrodynamic tidal solution FES99 (Lefèvre et al., 2002) provides water height variations to the largest model. In contrast to the sea surface elevation, the temperature and salinity at the model boundaries are considered as being constant (temperature of 10°C and salinity of 35.2). Air temperature, atmospheric pressure, nebulosity, as well as relative humidity, were provided by climatological datasets and wind speed and direction by the Meteo-France (the Ferret Cape weather station). All the results presented in this study originate from the more detailed model (limits : 44°21'N-44°54'N and 0°57'W-1°27'W). Cell dimensions are 235×235 m. The time-step varied between 60 and 200 seconds.

Several measurement campaigns were necessary to provide a relevant bathymetry to the model. For the internal part of the lagoon, the soundings from L'Yavanc (1995) were used whilst, for the inlet area and the open ocean, data came from the SMNG (Service Maritime de Navigation de la Gironde) and from SHOM (Service Hydrographique et Océanographique de la Marine).

Model validation was performed following the methods described in Smith & Rose (1995) and Piñeiro et al. (2008). Water elevation validation was performed using tide gauge measurements (L'Yavanc, 1995), as well as model predictions from the SHOM. Simulated currents were compared to Acoustic Doppler Current Profiler data, recorded during June 2002 along 10 transects located on the main channels of the Bay. The simulated salinity was compared also to *in-situ* measurements (Ifremer-ARCHYD database). Currents and salinity data were vertically-averaged, in order to be compared with the 2D-simulations. The location of all the measurements stations (water elevation, ADCP and salinity) are shown in Figure 1.

Simulations characteristics

The influence of tides, winds and rivers were assessed by running several simulations, under various tidal, wind and river flows conditions. Realistic simulations, involving real tide series, with measured wind speeds and directions as well as gauged river flows as forcing variables, were run. The time-series recorded at the Cape Ferret station by Météo-France, during winter 2001 and summer 2005, were selected since they represent two contrasted situations : in summer, light northwestely winds and low water discharges in rivers and, in winter, stronger southwesterly winds and higher river flows. Eyre river flow datasets were provided by the DIREN (Governmental Environment Agency); all the small streams were estimated on the basis of the Eyre flows, by means of linear regression. In addition to these realistic simulations, the influence of wind and the rivers was estimated using comparisons between a reference "no wind / no rivers" run, together with simulations involving schematic cases of winds (four cardinal directions, with constant speed of 5 and 10 m s^{-1}) and river flows (low discharges or flood river flows).

2.2. Hydrodynamics and transport time-scales

Currents, surface water elevation variations, tidal shape and propagation inside the Bay, were studied using direct results from the MARS-2D simulations. Residual Eulerian fluxes (RF) were computed as the product of the current speed by the water depth, at each time-step, integrated over a tidal period. The tidal prim was calculated as the difference between high and low tide volumes, assuming the Ferret Cape meridian (1°15'W) as the separation line between the lagoon and the ocean.

The water renewal of the lagoon was studied on the basis of a commonly-used descriptor, the flushing time or turnover time, defined as the time necessary for a significant portion of a water parcel to be replaced by water coming from outside the lagoon boundaries, i. e. from the ocean or the rivers. Following the method described in Koutitonsky et al. (2004), the hydrodynamic model was used to simulate the renewal of the lagoon : at time t=0, beginning at high tide, a dissolved passive tracer was set to one (unity) all over the lagoon domain and to zero elsewhere. Then, no further introduction of tracer was performed during the simulation. The time necessary for the tracer concentration to fall below 37% (*i. e.* e^{-1}) of initial concentration was recorded for all the lagoon cells. This time will be subsequently called the local flushing time (LFT). Furthermore, the time for the mean concentration of the constituent, over the whole lagoon domain to fall below 37% of the initial concentration, was recorded as the integrated flushing time (IFT).

Age of riverine water masses was used to estimate the mean time spent by water originating from the two main rivers, before reaching different locations in the lagoon. Deleersnijder et al.'s general theory of age (2001) was used, involving passive tracers and taking into account both advection and mixing/diffusion processes.

3. Results

3.1. Model validation

Table 1 summarises the results for the model 'goodness-of-fit' analysis i. e. linear regressions, between simulations and observations.

3.2. General study of currents and tides

Current speeds are weak (below 0.5 m s^{-1}) within the intertidal zone and outside Arcachon Bay; they are stronger within the main channels and the inlets. Strongest currents (2.3 m s^{-1} in the North and South mouths) were simulated some 3 hours after high tide and the weakest currents were found, as expected, during high or low tides.

Figure 2 shows a general residual circulation directed from the Bay towards the ocean (*i. e.* ebb-dominated) within the mouths, as well as in the Teychan and Ferret channels. In contrast, inward residual fluxes (flood-dominated) were simulated along the Pyla coast and in the Piquey Channel. Finally, residual fluxes are almost nil in the innermost parts of the lagoon and do not exhibit any clear directional tendency.

The tidal prism and the study of the tidal wave shape are presented in Table 2. During a mean tide, 64% of the Bay total volume is flushed in and out. The tidal wave shape varies, according to the neap or spring tide cycle : it appears quasi-symmetrical during spring tides and asymmetrical during neap tides. In this last case, the ebb duration was always found to be shorter than the flood. Thus, strongest currents are observed always during the ebb. This asymmetry, together with the time-lag between high and low tides, together with the current directional changes, creates an hysteresis phenomena *i. e.* a net water retention during the increasing tidal phases and a net water expulsion during the decreasing tidal phases (data not shown here).

The influence of wind on the tidal prism were weak, with induced variations never exceeding 3%. It appeared nevertheless, that northerly and easterly winds tend to reduce the tidal prism (-10 millions of cubic meters, when compared to the 'no wind' simulation), whilst westerly and southerly winds tend to increase the tidal prism (+10 millions of cubic meters, when compared to the 'no wind' simulation).

3.3. Flushing time

In the absence of any wind and river inputs, the IFT calculated for Arcachon Bay is 18.9 days. Best renewal was found in the case of strong northerly and westerly winds (respectively, 13.3 and 15.9 days for a 10 m s^{-1} wind speed). Worst renewal was found when light easterly and southerly winds are blowing (respectively 17.9 and 17.4 days for a 5 m s^{-1} wind speed). The impact of rivers resulted in being approximately as important as the wind impact, since the calculated IFT were 14.8 and 17.4 days, respectively, for flood and low freshwater flow conditions (no wind simulation). Hence, winter 2001 weather conditions (stronger winds coupled with higher river flows) led to a shorter IFT, than summer the 2005 situation : 12.8 and 15.9 days, respectively. Figure 3 presents the spatial repartition of flushing times (LFT), for the two realistic simulations. As expected, the waters located near the lagoon inlets or the river mouths are rapidly renewed and exhibit low values (LFT of below one day) whilst the inner parts of the lagoon takes more than 20 days to be significantly renewed.

3.4. Age of riverine water masses

Figure 4 presents the mean age maps, for water masses originating from the two main rivers (Eyre and Porges rivers). Waters coming from the Eyre or the Porges spend nearly the same amount of time, before reaching the Eyrac station, Arguin Bank and Buoy 7. Seasonal variation in river flows lead to considerable variations in the mean age. For instance, waters coming from the Eyre and reaching the Arguin Bank, are about 10 days older during the summer of 2005 than during the winter of 2001. It is important to remember that, whatever location within the Bay, the levels of dilution are logically much higher for the Porges river, than for the Eyre : Porges tracer concentrations never exceed 5.5% of the initial concentration, even during river flood periods. In comparison, Eyre river flows are sufficient to maintain relatively high tracer concentrations (40% at maximum), during winter, for areas close to the river mouth.

4. Discussion

The Arcachon Bay hydrodynamic system appears to be influenced primarily by tides and, secondarily, by winds. The model simulates a tidal wave shape sensibly different, whether it is a neap (asymmetry, with the ebb being shorter than the flow) or a spring tide (symmetry). This pattern is observed typically in coastal zones where the tide is highly modified by non-linear effects, caused by meandering coastlines and the presence of shallow water areas. Within the Bay, the flood tide progresses (respectively regresses during the ebb) uniformly along the tidal wave front, without being concentrated within any particular pathway; this contrasts what might have been expected, with respect to the lagoon complex channel network. This “piston-like” functioning is somewhat similar to estuarine hydrodynamics. The study of residual fluxes and maximum currents distribution allows, moreover, to a spatial split of the Bay into two parts : (a) the inner lagoon with low currents and residual fluxes, without any dominant direction; and (b) the southwesterly part of the lagoon (approximately from the lagoon mouths, up to the Teychan and Ferret channels), where strong currents occur with residual fluxes directed towards the open ocean. RF is an Eulerian descriptor allowing one to assess, in shallow areas and when water flow is close to be one-dimensional (for the channels and the intertidal zones), the residual water flow direction and the quantity of the displaced water. Even if it remains illusory to reach a conclusion of the sediment dynamics, on the sole basis of the simulated residual fluxes and maximum currents, they nonetheless provide relevant information on the directions and quantities of water masses displacements, in shallow water areas and when water flow is close to being one-dimensional. It is then likely that the inner lagoon will be more subjected to sediment deposition, than the outer lagoon; this seems to have higher hydrodynamic capacities, to flush out the suspended sediments. These results are in accordance with the results obtained by L’Yavanc (1995), deduced from two bathymetry surveys (1865 and 1992), *i. e.* a sediment erosion zone, in the southwestern part of the lagoon , together with a sediment deposition zone in the more internal parts of the system.

The prevailing wind, together with the river flows, appeared to be of great importance in the renewal of the Bay. The constant backward and forward tidal motion makes the waters which have just exited to the open ocean, re-entering during next flood inside the Bay; this does not facilitate their renewal. Thus, the wind assumes major importance outside the Bay, where the tidal currents are weak, by pushing the waters out from the lagoon influence. Conversely, rivers play an important role in the renewal of the innermost parts of the Bay. Sanford et al. (1992) proposed an equation linking the IFT, the basin volume, the tidal prism, the tidal period and *b*, the return flow factor. Considering the model results obtained, the return flow factor *b* for the Arcachon Bay would range between 0.94 and 0.95; this underline, once again, the considerable part of the water masses that re-enter the lagoon, after being flushed out. For comparison, Cucco & Umgeisser (2006) estimated the mean return flow factor to be 0.66 for Venice lagoon (a micro-tidal regime), futher, Gillibrand (2001) found a mean return flow factor of 0.32, for a meso-tidal Scottish Fjord, the Loch Fyne, whilst Moore et al. (2006) obtained 0.8 for the Okatee Estuary, South Carolina (a meso-tidal area). It is noteworthy that the return flow factor seems not to be correlated strictly to the tidal amplitude.

LFT maps have revealed the strong heterogeneity of the flushing times, inside the Bay. If one considers confinement as a sensitivity factor for the lagoon ecosystem, the different parts of the Bay are obviously not on an equal footing, with respect to accidental pollutions. Thus LFT maps may be viewed as useful tools, to undertake protection and management policies.

The calculation of the age of water masses has permitted quantification of the mean time spent by freshwater originating from the two main rivers, before reaching different locations in the lagoon. Simulations have shown that river flows and winds influence, significantly, the progression of the river plumes in the Bay. The mean age maps describe the domain of the river influence, on a spatial scale and, complemented with the concept of time-variability; this may be, to the opinion of the authors, of valuable interest in the study of the Arcachon Bay biochemistry.

The use of the MARS-2D model permits significant progress in developing a knowledge of the hydrodynamic functioning of the lagoon. The calculation of derived mixing and transport time-scales has added a more global concept of the system, to the direct model results. Such data might be of some interest for the next research step, *i. e.* the study of the Arcachon Bay ecosystems and the biogeochemical cycles.

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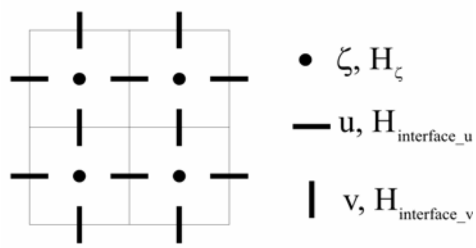
Appendix

The model assumes a wetting and drying capability which is mass preserving. It is based on an absolute land boundary over which sea can never spill, which splits the domain into two sets of points : points that are always dry and points that are wet or dry, namely the oceanic domain. The equations solved in the oceanic domain, are the same that are solved either at permanently wet cells, or at cells that are wetting or drying periodically (hereafter named cells of the transient zone). The point is just to exhibit within this transient zone a criteria from which one can determined whether a given interface's cell (at point u or v in the Arakawa C grid) is dry or wet, so that the corresponding variable can be set to zero. In the model, it is based upon two considerations :

in the transient zone the bottom topography is defined slightly differently as usual (*i. e.* the interface cell topography is set to the mean of the two bottom position of adjacent zeta points $H_{\mathrm{int}erface\_u} = 0.5(H_{\zeta}{}^{+} + H_{\zeta}{}^{-})$; here the topography at the middle of the cell (i*. e.* at the zeta point) is set to the deepest of the four adjacent interfaces (*i. e.* $H_{\zeta} = \max(H_{\mathrm{int}erface\_u}{}^{+}, H_{\mathrm{int}erface\_u}{}^{-}, H_{\mathrm{int}erface\_v}{}^{+}, H_{\mathrm{int}erface\_v}{}^{-})$). Thus, one might see the bottom within the cell as flat rather than sloped.

the flow section at the interface is computed either with respect to the mean of the water elevation of adjacent cells (i.e. $D_{\mathrm{int}erface} = H + 0.5(\zeta^{+} + \zeta^{-})$), or in case this ends up with negative flow section (in wetting or drying phase), with the maximum of both water elevations (*i. e.* $D_{\mathrm{int}erface} = H + \max(\zeta^{+}, \zeta^{-})$)



Arakawa C-grid. Position of the variables

This automatically ensures, without any further test, that the flow stops once the cell is fully dry, or begins when water elevations is sufficient to spill in the neighbour cell (*i. e.* water elevation exceeds the value of the bottom). Moreover, as long as the continuity equation is written and solved in the flux form, it ensures the mass preserving property: everywhere in the domain, even the for cells that are drying or wetting, an outflow flux of a given cell is the exact inflow flux of its neighbour.

Tables

Table 1. Regression parameters for observed vs. predicted values. a is the slope, b is the intercept, df, the degrees of freedom, r^2, the coefficient of determination (expresses how much of the variance in observed value is explained by the simulated values) and RMSD, the root mean squared deviation (expresses the mean deviation of simulated values with respect to the observed ones, in the same unit as the model variable).

Variable	a	Significance of test a =1	b	Significance of test b =0	df	r^2	RMSD
Water elevation	1.000	$p < 0.001$	0.258	$p < 0,001$	1727	0.924	0.403 m
Current	0.613	$p < 0.001$	0.098	$p < 0.05$	37	0.675	0.2 m s^{-1}
Salinity	0.868	$p < 0.001$	4.477	$p < 0.001$	191	0.755	2.25

Table 2. Simulated tidal prism (P), total lagoon volume (V_{tot}), instantaneous maximum water flows at the Arcachon Bay exit (F_{exit}), flood (D_{flood}) and ebb (D_{ebb}) mean duration at the Eyrac station, and tidal amplitude at the Eyrac station (Amp), for three different tidal amplitudes.

	Mean neap tide	Mean tide	Mean spring tide
High tide V_{tot} (10^6 m^3)	721	807	892
Low tide V_{tot} (10^6 m^3)	457	423	400
P (10^6 m^3)	264	384	492
F_{exit} ($m^3.s^{-1}$)	15 400	24 000	30 680
D_{flood}	6h 48’	6h 32’	6h 12’
D_{ebb}	5h 38’	6h 01’	6h 13’

Amp (m)	2.10	3.11	3.80

Figures

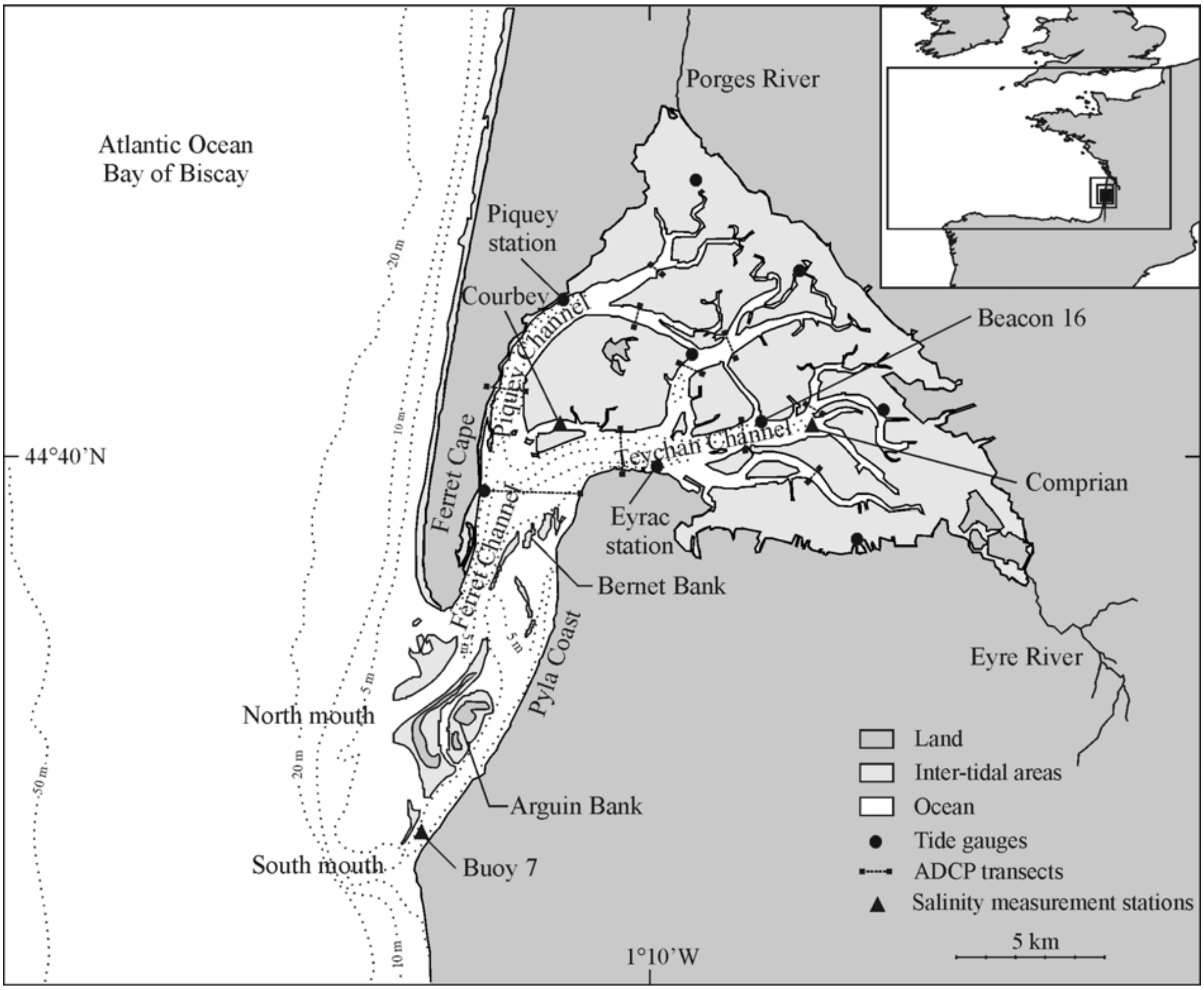


Figure 1.

Figure 1. The Arcachon lagoon. The extents of the four nested models are shown in the inset. Depth contours (50, 20, 10 and 5 m) are given in dotted line.

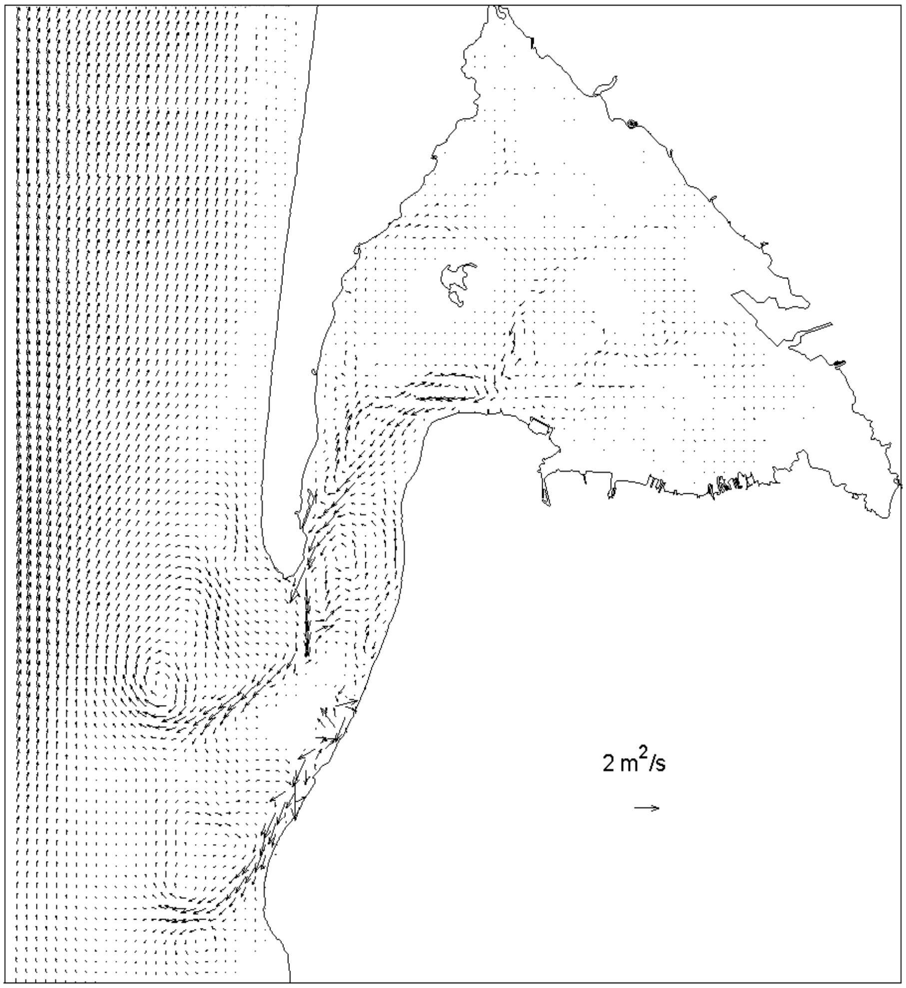


Figure 2.

Figure 2. Simulated Eulerian residual fluxes (expressed in m^2 s^{-1}) for a mean tide.

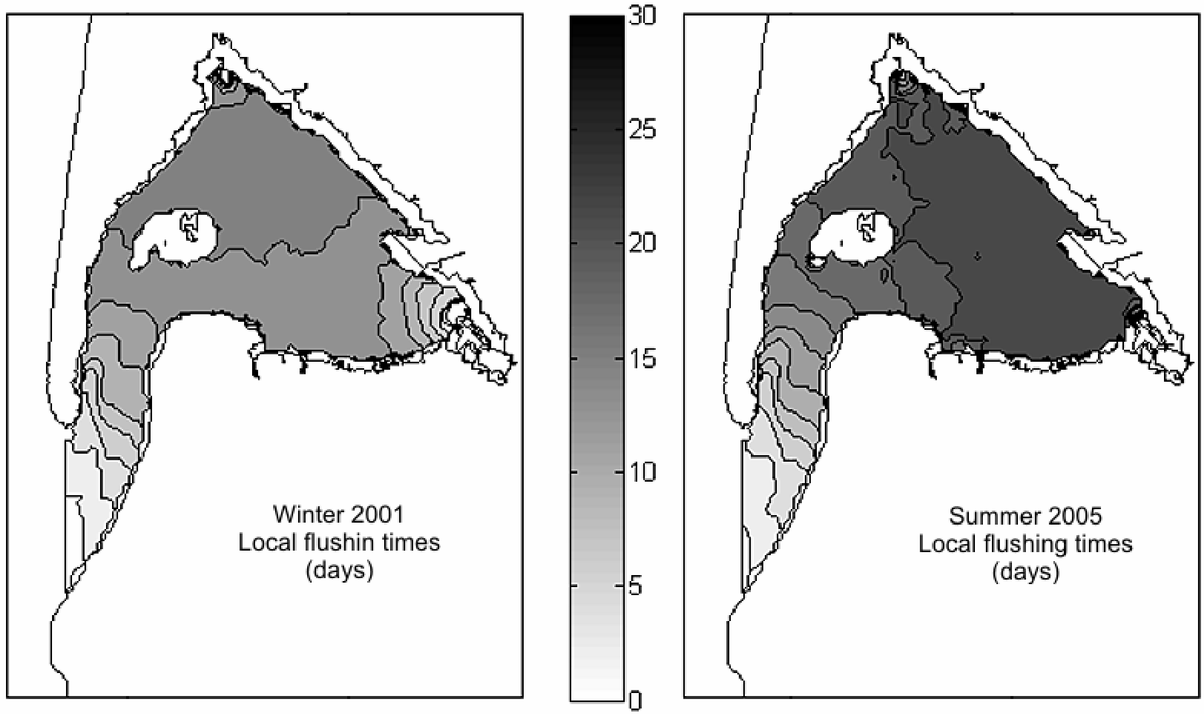


Figure 3.

Figure 3. Local flushing time maps (in days), calculated for two contrasted weather conditions: the winter of 2001 and the summer of 2005.

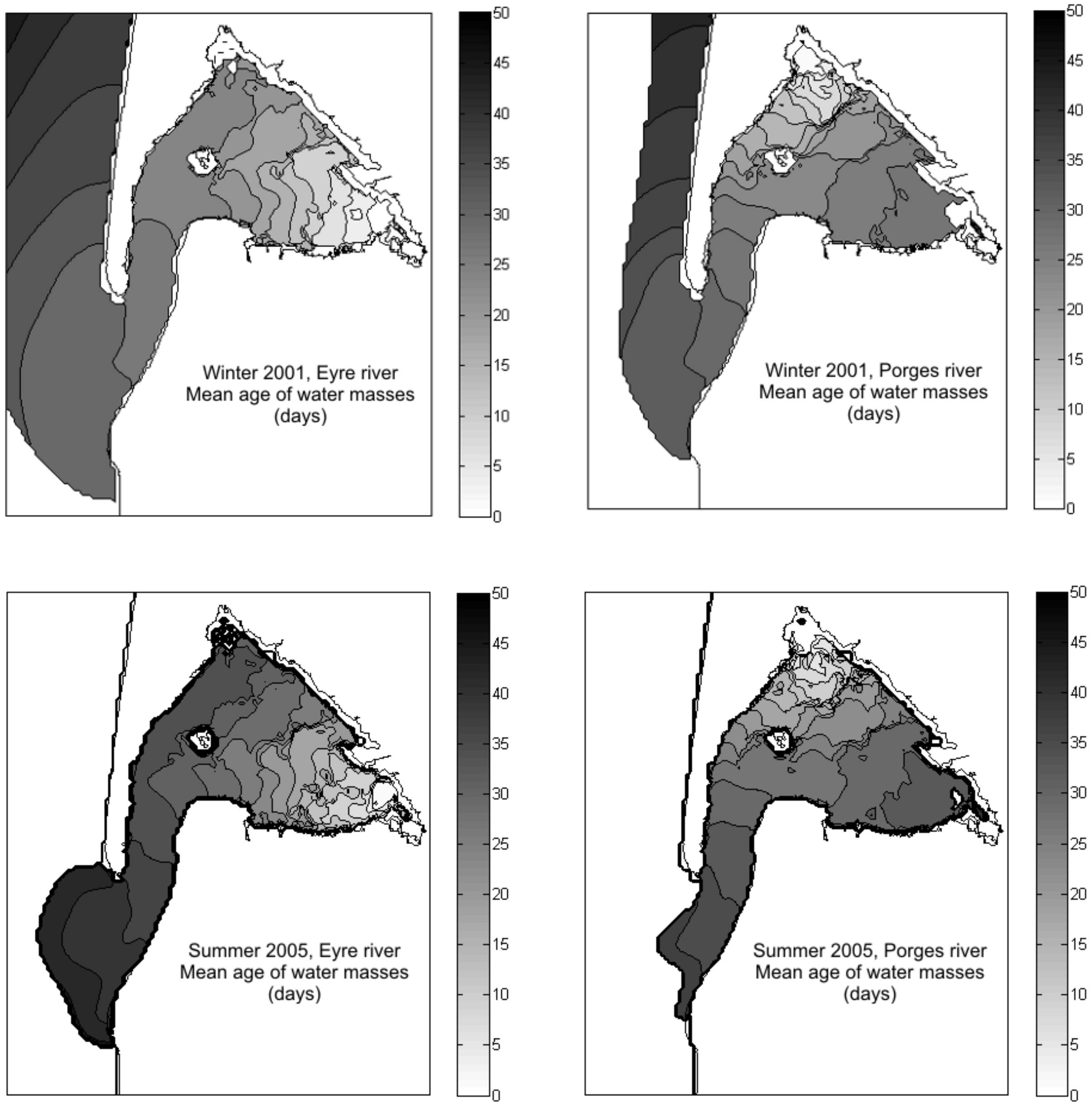


Figure 4.

Figure 4. Mean age (in days) of water masses originating from the two main rivers, for two contrasted meteorological situations: the winter of 2001 (upper panel) and the summer of 2005 (lower panel). The results are reported after the river plumes had reached a 'stable' extension, *i. e.* after 80 days of simulations.