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Circulation in a semi-enclosed bay under influence of strong freshwater input

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A high horizontal resolution 3D hydrodynamic model was applied to a semi-enclosed bay (Gulf of Fos, western Mediterranean Sea) in order to describe the specific circulation patterns driven by winds and to infer the scales of residence times. Freshwater inputs to this bay come from the Rhône river and navigation channels. Idealised simulations under typical wind forcing conditions were performed and are described in this paper. They revealed several features of the exchanges of water masses in the Gulf of Fos, in particular the intrusion of the Rhône river plume generated by south winds. During northern wind conditions, surface waters flushed out of the system. To compensate for this outflow, bottom currents transporting marine waters took the opposite direction. Residence times in the different areas of the gulf were also investigated. A realistic simulation was performed under actual conditions of Rhône river discharges, meteorological forcing and impact of the surrounding general circulation. Model outputs, mainly salinity fields, were compared to 10-day observations acquired during a multidisciplinary cruise that took place in May 2001. Model results and observations were in good agreement and showed a massive inflow of the Rhône river plume waters into the Gulf of Fos during a south wind event. Sensitivity studies showed that the salinity field was strongly dependent on the wind direction and on the local freshwater discharges.

Keywords: Coastal oceanography; Numerical modelling; River plume; Wind-induced circulation; Rhône; Mediterranean Sea; Gulf of Lion; Gulf of Fos

1. Introduction

Estuarine and coastal waters are intensely affected by pollutants released into the environment by

wastewater and industrial discharges or storm water overflow discharges (Beer, 1997). Effects include an increased loading in anthropogenic contaminants which can result in eutrophication (Peierls et al., 1991; Nixon, 1995; Howarth et al., 1996). Many estuarine ecosystems receive more nutrients than they can assimilate and the excess nutrients stimulate the production of organic material, which drives the

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autotrophy–heterotrophy balance (trophic state) to harmful levels. Eutrophication does not only depend on the nutrient load but also on physical factors such as mixing and transport processes dominated by tide, river flow and winds. In regions of restricted exchanges, knowledge of the time scales for transport and removal of materials that enter the water bodies is especially important for estimating not only the system responses to nutrients, but also the lag time between management and system improvements (Dettmann, 2001; Monsen et al., 2002). Microtidal systems have a low mixing capacity, which depends mainly on the wind and the river flow. In these estuarine systems, river flow is often considered to control buoyancy, ‘nutrification,’ time of residence, stratification and gravitational circulation, salinity and bottom oxygen depletion. As the response of these parameters to the river flow and wind forcing is strongly non-linear, the use of empirical or numerical models is necessary to estimate water properties, water exchanges, residence times, etc. A wide range of models have been used, from a simple box-model taking the effects of wind and tides into account in a simplified way (Brown and Arellano, 1980; Hagy et al., 2000) to more complex numerical models describing transport processes at fine spatial resolution (Signell and Butman, 1992; Brooks et al., 1999; Delhez and Deleersnijder, 2001).

The goal of our paper is to apply a 3D hydrodynamic model to a microtidal estuarine system in order to simulate the interactions between wind-driven processes and river flows, which act simultaneously on the residence time of the water masses and consequently on the productivity of the system.

After a presentation of the Gulf of Fos (GOF), the site of study, and of the 3D model, idealised simulations are presented to show the influence of the different wind conditions on the freshwater inputs in the gulf. A realistic simulation is then described and compared to experimental observations of the MOD-ELFOS2 cruise.

2. Site of study

The GOF is a semi-enclosed basin, covering 42 km² and having a mean depth of 8 m, located in the Gulf of Lion (northwestern Mediterranean Sea)

(Fig. 1). Bathymetry is characterized by a navigation channel in the central part of the gulf. This channel is 24 m deep and around 200 m wide. Outside this channel, the water depth decreases slowly from 12 m to the shore line. The southern part of the channel has a moderate slope directed off shore to a depth of 60 m. This gulf has experienced numerous extensions and transformations since the early 1960s due to harbour activities such as the construction of three new docks in the northern part and the regular dredging of the circulation channel.

Meteorological conditions are characterized by two main wind regimes. The first one is a northwestern wind called the Mistral which blows continental cold and dry air masses down the Rhône valley. The Mistral is known to be responsible for coastal upwellings in this region (Millot, 1981). The second dominant wind blows from the southeast. It is less frequent than the Mistral and, as it originates offshore, can induce high wave breaking near the shore. These two wind regimes do not show any periodicity. Days with no wind correspond to less than 4% of the total year (Météo-France data). Tidal amplitudes are weak (mean amplitude of about 20 cm) and associated currents are extremely low (Albérola et al., 1995). Thus, the GOF can be classified as a microtidal system controlled by aperiodic wind forcing.

The gulf is influenced by freshwater inputs mainly originating from:

- the Rhône river, whose plume can penetrate the gulf by passing along the ‘They de la Gracieuse’ under southeastern wind conditions (Estournel et al., 1997). The Rhône river is one of the largest rivers of the world (rank 42 for outflows, Welcomme, 1985), equivalent to the Rhine, and is the largest flowing into the Mediterranean Sea. Mean freshwater discharge is around 1700 m³ s⁻¹.
- three channels flushing into dock 1: Arles Canal, Rhône Canal and Vigueirat Canal. The total inflow of these channels was estimated to vary between 12 and 92 m³ s⁻¹ (Port Autonome de Marseille, personal communication).
- the Etang de Berre releasing brackish water from the east through the Caronte channel. The water budget of the Etang de Berre is controlled by freshwater inputs from a hydroelectric power plant located to the north. The water inputs from the

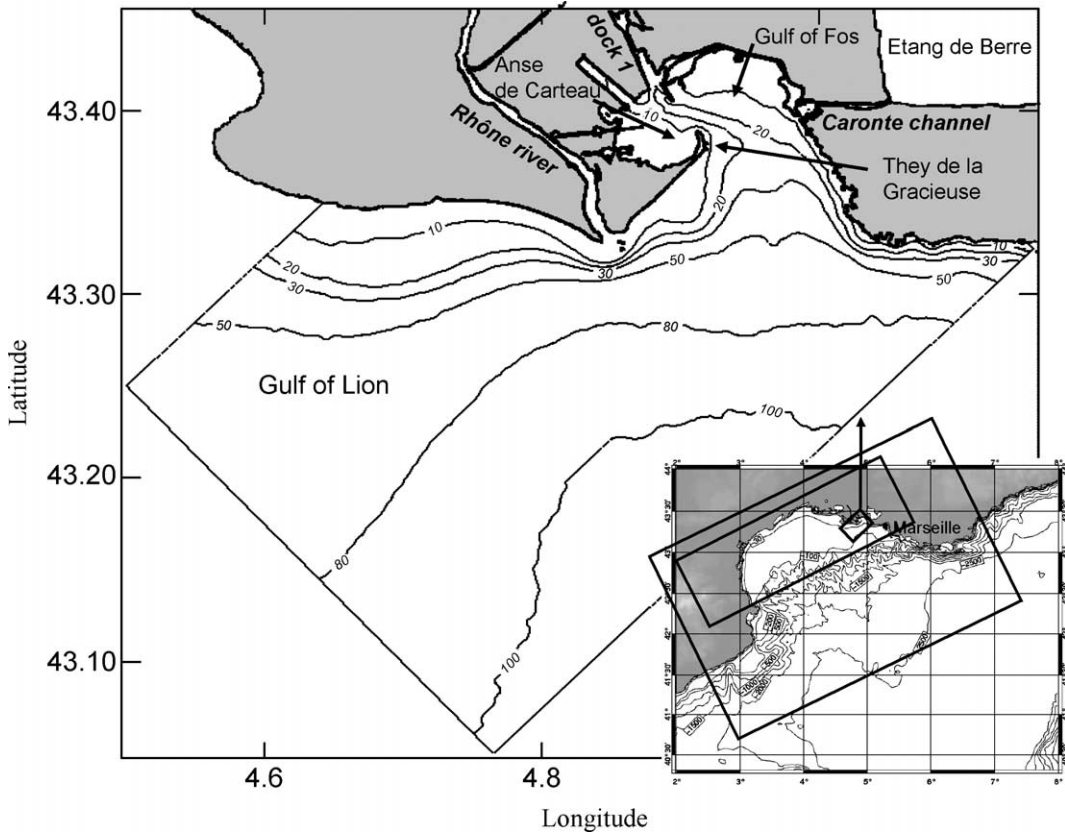


Fig. 1. Gulf of Fos bathymetry and main freshwater sources. The insert indicates the three model's domains: the domain of the Gulf of Fos model, continental shelf model and regional model.

Caronte channel to the GOF are highly variable due to the conjunction of barometric and tidal action, wind-driven forcing and freshwater inputs from the power station. Inputs around $260 \text{ m}^3 \text{ s}^{-1}$ have been measured with surface and bottom salinities of 4 and 24, respectively (Nérini, 2000).

Other freshwater inputs exist, for instance, through a dam separating the Rhône river from the GOF in the west (C. Vella, personal communication). These discharges are of minor importance and will be neglected in this study.

The GOF is largely influenced by the offshore wind-driven circulation that prevails on the continental shelf of the Gulf of Lion (Estournel et al., 2003) and by sporadic intrusions of the Northern Current onto the shelf (Millot, 1990; Auclair et al., 2001; Echevin et al., 2003).

3. The numerical model

3.1. Description of the model

SYMPHONIE is a three-dimensional primitive equations coastal ocean model (Estournel et al., 1997) which has recently been used to study the wind-induced circulation in the Gulf of Lion (Estournel et al., 2003; Auclair et al., 2003), the intrusion of the Northern Current onto the continental shelf (Auclair et al., 2001) and the Rhône river plume circulation (Marsaleix et al., 1998; Estournel et al., 2001).

The current components, free surface elevation, temperature and salinity are computed on a C staggered grid (Arakawa and Suarez, 1983). A generalized topography following a coordinate system is used. Compared to simple sigma coordinate, the generalized sigma coordinate allows the slope of the

iso-level surface to be limited over steep topography in order to avoid large truncation errors on the pressure gradient computation (Mellor, 2002; Auclair et al., 2000). The turbulence closure scheme is based on a prognostic equation for the turbulent kinetic energy and on a diagnostic equation for the mixing and dissipation length scales (Bougeault and Lacarère, 1989). A leap frog scheme is used for the time stepping. The time splitting technique of Blumberg and Mellor (1987) has also been implemented in the model. This technique allows the vertical shear of the current and the depth-averaged horizontal components to be computed separately with appropriate time steps.

3.2. Initial and boundary conditions

The modelling of the circulation in the GOF required a high-resolution grid that limited the domain. The influence of the open sea circulation was taken into account through a classic downscaling method using three levels of grid nesting.

First of all, a simulation of the circulation of the Gulf of Lion was computed with a coarse grid ($\Delta x=3$ km, 25 vertical levels) and a larger domain (Fig. 1). Outputs of current, temperature, salinity and surface height were performed every 3 h. These outputs were used to initialize and to force a shelf model ($\Delta x=1$ km, 25 vertical levels) at its open boundaries. Outputs of this second run were used in the same way for initialization and forcing of the high-resolution model of the GOF ($\Delta x=200$ m, 10 vertical levels), whose grid will be discussed in the following sub-section.

The largest model was initialized and forced using the method described by Estournel et al. (2003). The characteristics of the grids and the main modelling parameters are shown in Table 1 for the three domains.

In the three models, Rhône freshwater discharge was achieved with a channel connected to the mouth of the river. Water temperature and salinity as well as the hourly discharges, which were provided by the Compagnie National du Rhône, were specified at the upstream boundary of the channel. Other freshwater inputs were similarly introduced into the GOF model at the end of dock 1 and at the mouth of the Caronte channel.

Sea surface momentum and heat fluxes were calculated from the surface pressure, air temperature, relative humidity and wind velocity of the high-

Table 1
Main modelling characteristics

General characteristics:			
Advection scheme	mixed upwind centered scheme (Beckers, 1995)		
Turbulent scheme	Gaspar et al. (1990)		
Open boundary conditions	characteristics and relaxation		
Bottom roughness	10^{-2} m		
Coriolis parameter	Beta-plan		
Domain's characteristics	GOF model	Shelf model	Regional model
Horizontal grid scale	200 m \times 200 m	1 km \times 1 km	3 km \times 3 km
Number of generalized sigma levels	10	25	25
Horizontal diffusion	1 m ² s ⁻¹	10 m ² s ⁻¹	30 m ² s ⁻¹
External time step	1.8 s	3.5 s	6 s
Internal time step	22.2 s	69.2 s	150 s

resolution meteorological model ALADIN (Pailleux et al., 2000) from Météo-France with the bulk formulae (Geernaert, 1990) using the sea surface temperature from the ocean model.

3.3. The GOF model grid

The GOF model grid consists of 150×220 nodes with a grid increment of 200 m. The bathymetry was computed from the 35 000 bathymetry points from marine chart no. 6684 provided by EPSHOM (the main establishment of the French Navy's Hydrographic and Oceanographic Department). A 45° anticlockwise rotation of the grid axes from the geographic axes allowed full representation of south-westward offshore plumes induced by Mistral wind events (see Section 4.3).

The water column was described by 10 vertical grid levels. To describe the plume flow, the vertical levels were narrowed near the surface.

The results showed in the following sections were obtained with the GOF model.

4. Idealised simulations and analyses of water exchanges in the GOF

Wind is an important factor that influences the exchanges between the GOF and the marine water

Table 2
Forcing for the four idealised simulations

Simulation	Wind		Discharge (m^3s^{-1})		
	Speed (ms^{-1})	Direction ($^\circ$)	Rhône	Dock 1	Caronte channel
1	5	120	1700	0	0
2	10	200	1700	0	0
3	8	330	1700	50	210
4	variable wind conditions		1700	0	0

masses from the Gulf of Lion. Moreover, wind drives freshwater input from the Rhône river plume on certain occasions and is also responsible for the dispersal of the local inflows from the Caronte channel and dock 1. The following section shows modelling results for southern winds driving surface exchanges at the gulf entrance and for northern wind

driving bottom exchanges during upwelling events. Transitional wind events will add some insights into the characteristic time scales associated with water renewal. Four idealised simulations were made under uniform wind conditions over the domain, a representative stratification of spring conditions and a nominal Rhône river freshwater outflow of $1700 \text{ m}^3 \text{ s}^{-1}$. The model results correspond to outputs from a 2-day simulation, whose duration was sufficient for the Rhône river plume to develop in the region of the mouth and in the GOF. The forcing parameters are given for the four simulations in Table 2.

4.1. Moderate southeastern wind situation

Southeastern winds are often associated with storms and high waves. In the Gulf of Lion, these

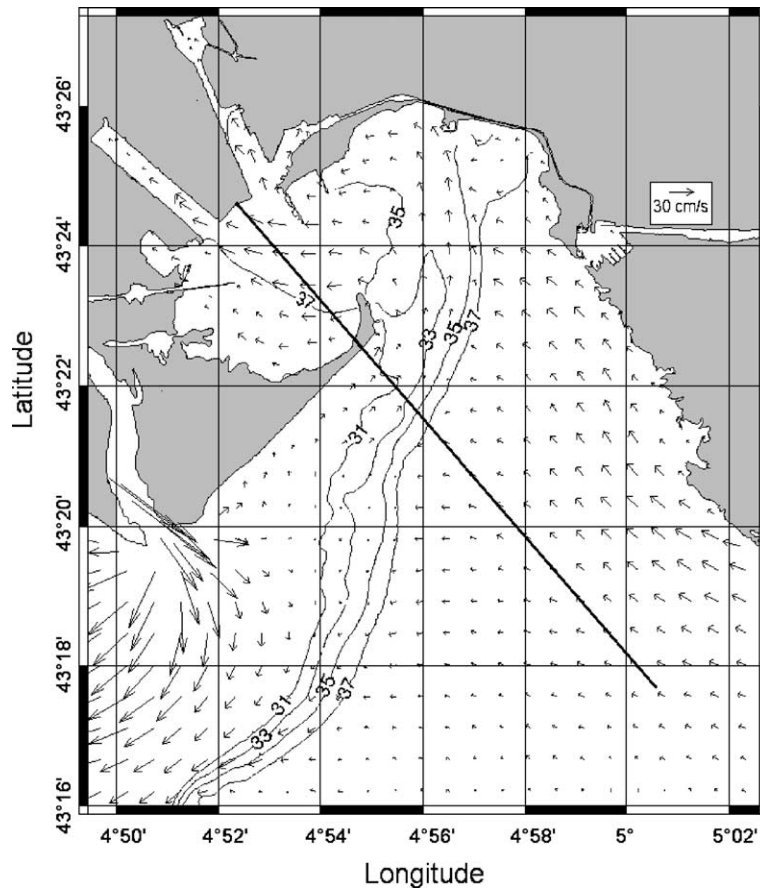


Fig. 2. Simulated surface salinity and currents averaged over an inertial period under a moderate southeastern wind. The straight line corresponds to the vertical cross section shown in Fig. 3.

winds induce a general situation of downwelling along the coast, an elevation of the water level and an anticlockwise coastal current. For strong winds, this coastal current dominates the internal dynamics of the Rhône plume and drives freshwater masses westward along the coast (Estournel et al., 1997). In that case, the interactions with the GOF are reduced. The balance between the wind and the Rhône river outflow influences freshwater inputs into the GOF as observed from satellite imagery (Demarcq and Wald, 1984) and from model results (Estournel et al., 1997). The modelling results were obtained with a 1-km mesh which is probably too large to correctly reproduce the intrusions into the GOF.

In the present simulation the model was forced by a southeastern wind field of low intensity (5 m s^{-1} , 120°) and by an average Rhône river discharge. An intrusion of the Rhône river plume along the ‘They de la Gracieuse’ can be observed in Fig. 2. Offshore, a wind-driven coastal jet taking a southeast–northwest direction in the southern part of the GOF maintained the plume against the ‘They de la Gracieuse.’ Some parts of the plume entered the gulf and diluted northwards.

A northwest–southeast vertical section of salinity (Fig. 3) shows a thin saline layer (2 m deep) along the ‘They de la Gracieuse.’ Conversely, downwelling

movements and turbulent mixing drove a complete dilution of the freshwater masses in the northern parts of the gulf, shown by the dropping of the isohalines with depth.

4.2. South-southwest wind situation

South-southwest winds are less frequent in this region. Based on Météo-France data, statistics over the 1973–1996 period show that 200° oriented winds have an occurrence of 48 per 1000 per year in this area. Nevertheless, this wind is crucial because it generates large inputs of Rhône waters into the GOF (Kondrachoff, 1995). The freshwater inputs and the associated impacts on stratification can play a major role on the functioning of the GOF ecosystem as shown by Arfi (1980) who used thermal infrared pictures and field measurements of primary production to observe a mass production of phytoplankton linked to a persistent south-southwest wind event. We simulated such a wind event (10 m s^{-1} , 200°) under an average Rhône river outflow. The eastern region of the gulf was subjected to a high sea surface desalination corresponding to a significant inflow of Rhône river freshwaters (Fig. 4). Surface salinity values varied from 30 to 35. A downwelling occurred on the east coast of the GOF, generating an increase of

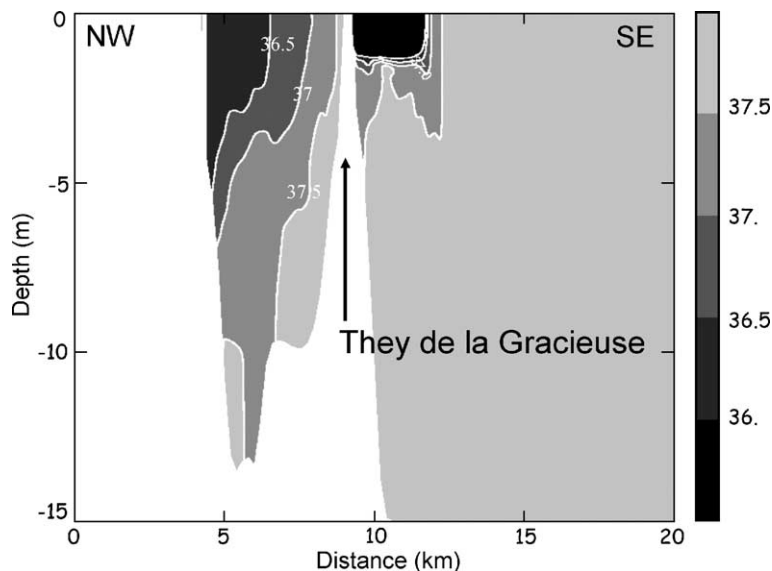


Fig. 3. Vertical cross section in salinity from the Anse de Carteau (left) to offshore region of the ‘They de la Gracieuse’ (right) as indicated in Fig. 2.

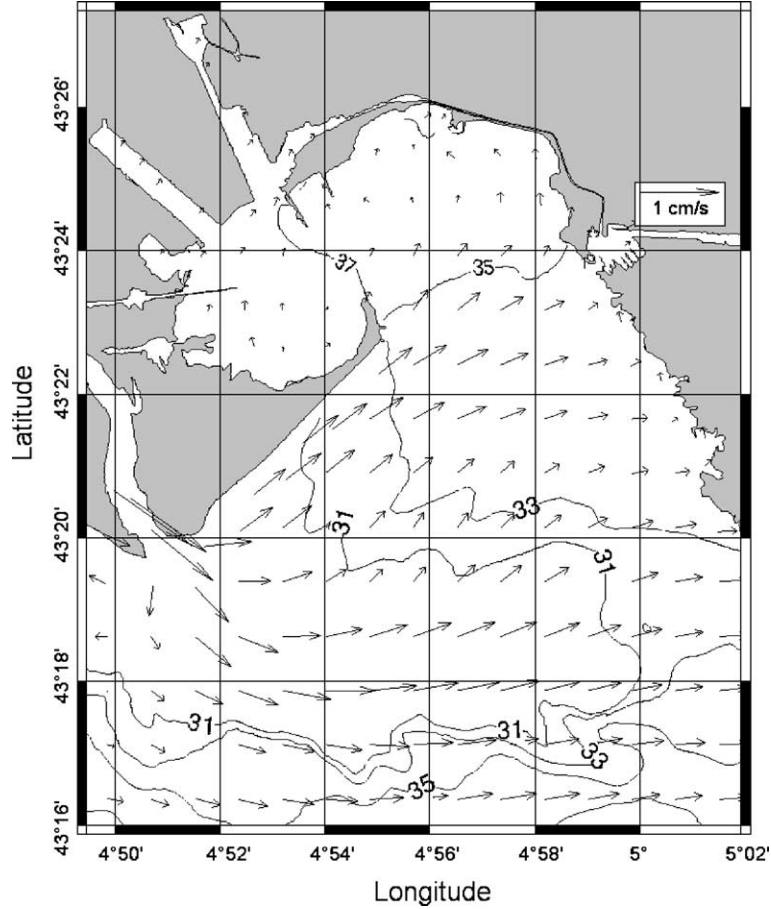


Fig. 4. Simulated surface salinity after 2 days of south-southwest wind conditions.

the surface layer depth. The 10-m-deep surface layer was nearly homogeneous with warm ($T \approx 20^\circ$) and brackish ($S \approx 34.5$) water. The vertical current reached 0.5 mm s^{-1} at 5 m depth. In the most northern part of the GOF, the surface layer occupied the whole water column and salinity was around 35.

4.3. Northwestern wind situation

Northern to northwestern winds are the dominant wind regimes in this region. A simulation was performed with a northwestern wind (8 m s^{-1} , 330°). A freshwater input of $50 \text{ m}^3 \text{ s}^{-1}$ was imposed in dock 1, corresponding to a medium outflow. This northwestern wind induces inputs from the Etang de Berre through the Caronte channel. Indeed, water level rises in the southern part of the Etang de Berre.

Conversely, it drops in the GOF near the Caronte channel. This creates a pressure gradient that produces a water incursion into the GOF. To describe this phenomenon we used a brackish water input of $210 \text{ m}^3 \text{ s}^{-1}$ at a salinity of 5 corresponding to an extreme case already observed by Nérini (2000). Fig. 5 shows the surface salinity field describing the three plumes resulting from the Rhône river, dock 1 and Caronte channel discharges. As the Rhône river plume was oriented southwards near the mouth and southwestwards offshore, as previously shown by Estournel et al. (1997) and Arnoux-Chiavassa et al. (1999), no Rhône river water entered the GOF. The freshwater input from dock 1 induced a surface salinity reaching 35 in the Anse de Carteau and along the 'They de la Gracieuse.' Under these conditions, horizontal mixing between water masses from the Etang de Berre and

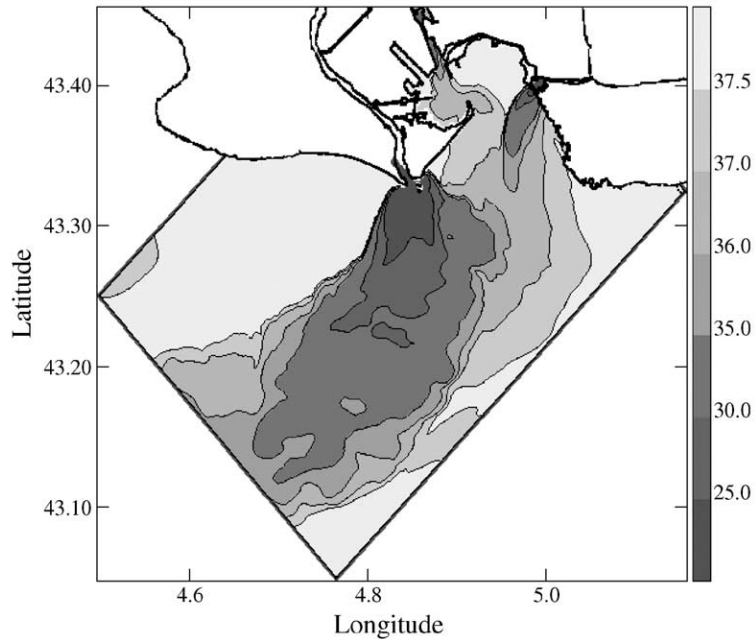


Fig. 5. Simulated surface salinity after 2 days of northwestern wind conditions. Note that isovalues are irregularly spaced.

the GOF water was restricted to the southern part of the gulf.

Northwestern winds favour upwelling formation along straight coastlines in the Gulf of Lion as shown from satellite temperature imagery (Millot, 1981) and through model results (Johns et al., 1992). At a smaller spatial scale in the GOF, the simulation showed that the topographical complexity induced vertical water motions with fast surface water temperature variations. Unfortunately, the small dimensions of the GOF did not allow AVHRR images to be used to analyse this phenomenon. Fig. 6 presents the computed surface temperature field after 2 days of wind forcing. A cold water front was observable along the northern and eastern coastlines and corresponded to an upwelling situation. Conversely, warmer water masses were located along the southern coastline in the Anse de Carteau, corresponding to a downwelling situation. Fig. 7 shows bottom currents which flow northwards along the navigation channel towards the docks and correspond to a compensatory current driven by the general outflow of surface waters off the GOF. These currents drive colder marine waters into the GOF. A total flushing of the GOF water masses can thus rapidly occur under Mistral conditions.

4.4. Bending wind situation

A simulation of 7 days was run under variable wind conditions from south to north in order to analyse the spatial and temporal scales of a drainage event after massive input of Rhône river waters. This event was observed during a multidisciplinary cruise in May 2001 (MODELFOSS2 cruise, see Section 5). Residence times of the water masses were estimated for this event. A constant Rhône river outflow of $1700 \text{ m}^3 \text{ s}^{-1}$ was imposed at the river mouth. Southwestern winds (10 m s^{-1} , 200°) were applied for the first 36 h, inducing the entrance of plume waters eastwards into the GOF (Section 4.2). Wind direction was then linearly changed from 200° to 120° during the following 12 h. A southeastern wind (5 m s^{-1} , 120°) was then applied for the next 48 h, driving the estuarine waters to the western part of the GOF. Finally, after a clockwise rotation of wind from southeast to northwest over 24 h, a northwestern wind (8 m s^{-1} , 330°) was stabilized for the last 48 h, producing superficial water outflow from the GOF.

At the end of day 4, after the southwestern and southeastern wind events, Rhône river waters covered the total GOF surface as shown on the salinity field in

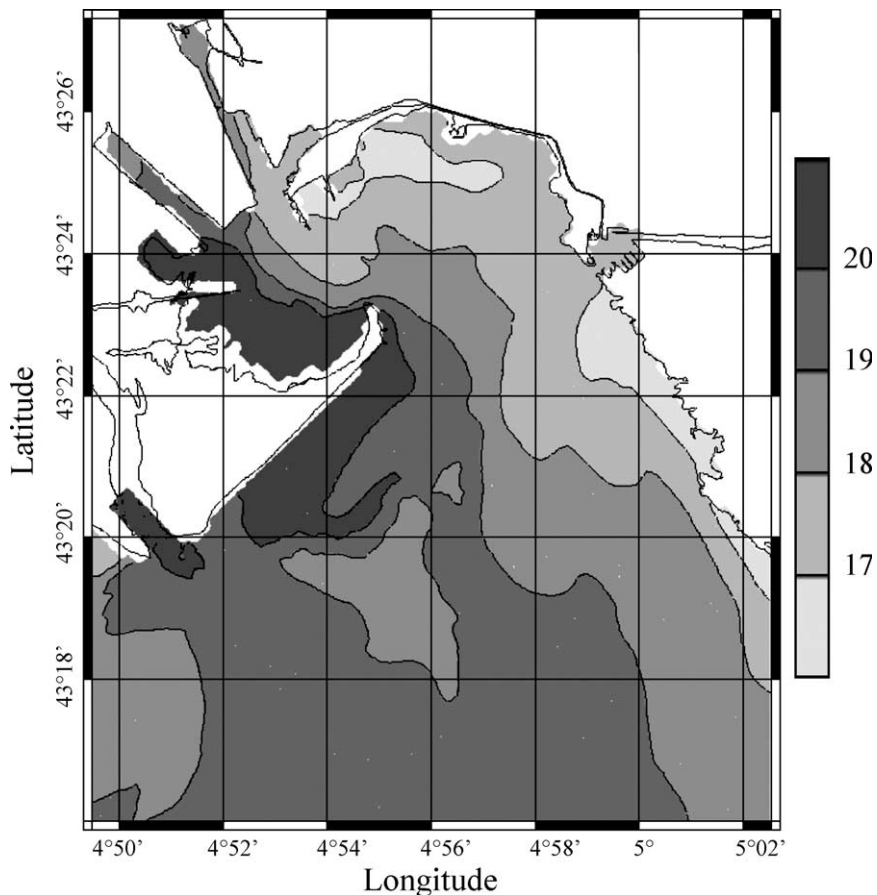


Fig. 6. Simulated surface temperature ($^{\circ}\text{C}$) after 2 days of northwestern wind conditions.

Fig. 8a. The Anse de Carteau was the last site influenced by the Rhône river waters as demonstrated from the 1-day time lag in salinity decrease observed between site A, located in the northern part of the GOF, and site B, located in the Anse de Carteau (Fig. 9). On day 5, the wind turned from southeast to northwest. During this rotation, all plume waters were driven to the eastern part of the GOF. Northwestern winds, stabilized on day 6, produced a surface water outflow. At 09:00 on day 6, surface water renewal was already visible through marine water pools located in the northern part of the gulf (Fig. 8b) and driven by the bottom water motions shown in Fig. 7. At the end of day 7, the upwelling produced water renewal in the major part of the GOF (Fig. 8c). Some freshwaters were still trapped in the Anse de Carteau. Time scales of responses to the variability of atmospheric forcing

were higher in this western part of the GOF: 20 h were necessary to change the salinity from 35 to 36 (only 2 h at site A) (Fig. 9a). The GOF can roughly be considered as the juxtaposition of two cells with different features in the process of water renewal. The eastern part experiences fast water renewal due to an upwelling circulation, while the western part behaves like a confined system due to the narrowing of the coastline between the 'They de la Gracieuse' and the northern dikes.

5. MODEL FOS2 experience

A multidisciplinary cruise was carried out in the GOF during May 2001. Drastic changes in salinity field were observed in response to variable wind

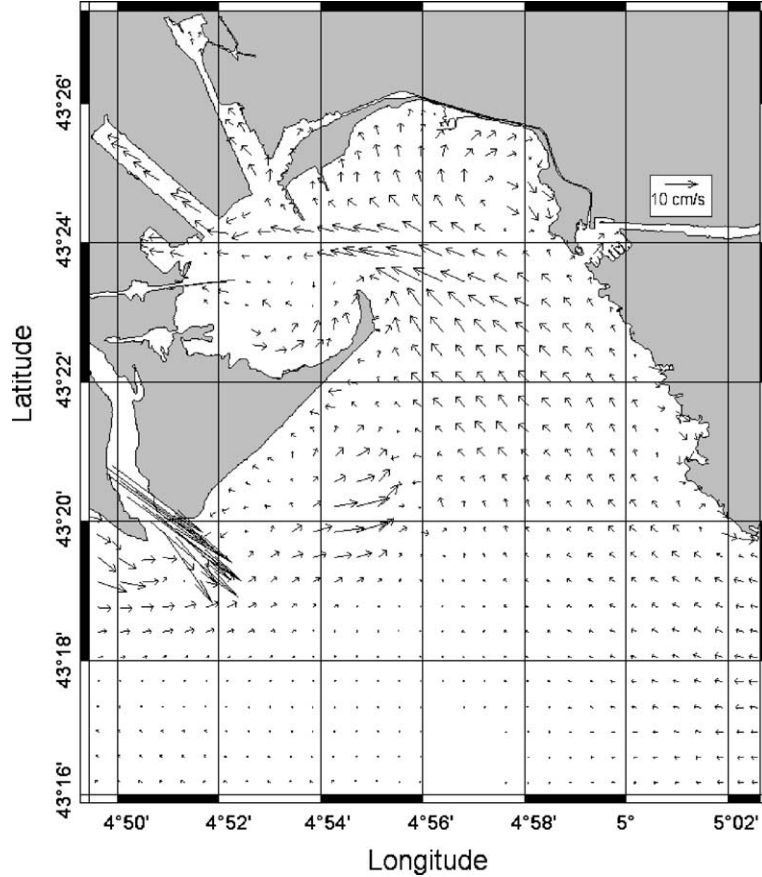


Fig. 7. Simulated bottom currents averaged over an inertial period after 2 days of northwestern wind.

conditions. A numerical simulation with real forcing was performed in order to explain the observed variability and to validate model results.

5.1. Materials and methods

The MODELFOSS2 cruise took place on board *R/V Tethys II* between May 9 and 17, 2001. The overall objective of this cruise was to determine the relations between physical, biogeochemical and biological processes in relation with eutrophication conditions. A network of 24 stations was repeatedly sampled using a CTD profiler (Seabird 911 equipped with rosette and 12-l Niskin bottles) between May 10 and 16, 2001. Sampling was always performed over a 10-h period at most. Only data related to this study are shown here, the remainder will be published in a forthcoming article.

A meteorological buoy (Aanderaa 3227) equipped with underwater salinity temperature probes was moored at station 24 in the Anse de Carreau for safety reasons. Wind speed and air temperature together with water salinity and temperature data at 1-m, 4.5-m, 6.6-m and 8.6-m depths were recorded. The sampling rate was set to 5 min.

The initial state of the simulation of the regional model was calculated thanks to the method described by Estournel et al. (2003). This method requires a background vertical profile for temperature and salinity. This was deduced from subsurface measurements taken during the RHOFI cruise that took place a few days before MODELFOSS2 and extended by Levitus climatology. Rhône river outflows from the Rhône river database (Compagnie Nationale du Rhône: www.cnr.tm.fr) were given hourly. The reference simulation of the GOF model

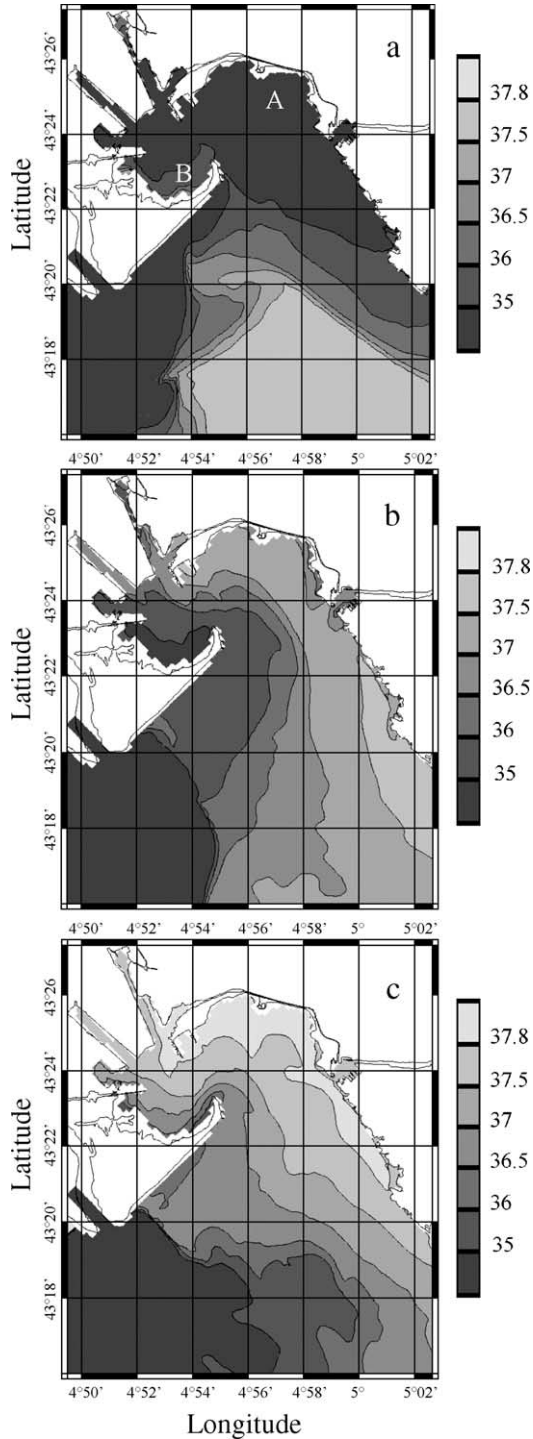


Fig. 8. Contour plots of surface salinity (a) day 5 at 00:00, (b) day 6 at 09:00 and (c) day 8 at 00:00. Note that isovalues are irregularly spaced.

was forced by the wind speed measured at the buoy and by the wind direction provided by Météo France and measured at Marseille Marignane airport, 30 km east of the GOF. Since no measurements were available, water outflows were considered to be $50 \text{ m}^3 \text{ s}^{-1}$ (a medium value) for dock 1 and $0 \text{ m}^3 \text{ s}^{-1}$ for the Caronte channel.

5.2. Hydraulic and meteorological conditions

Rhône river discharge decreased progressively from 2800 to $2000 \text{ m}^3 \text{ s}^{-1}$, a mean value around which it oscillated till the end of the cruise (Fig. 10a).

Meteorological data showed two different periods of winds. The first one, between May 9 and 13, was characterized by a low wind intensity (3 m s^{-1} on average) and a variable wind direction (Fig. 10a and b). May 13 was a transition period during which the wind strengthened. During the second period, between May 14 and 17, wind speed was around 10 m s^{-1} and the direction alternated between south and south-southeast. During that period, winds peaked at 12 m s^{-1} on May 15 at 03:00 and on May 16 at 09:00.

5.3. Temporal evolution of salinity field compared to observations

5.3.1. Observed salinity field

Fig. 11(a–d) shows the spatially interpolated surface salinity field measured during the cruise. Stabilized conditions with salinity ranging between 33 and 38 prevailed during the first period (May 10–13) characterized by low wind (Fig. 11a–c): marine waters were present southeast of the GOF while brackish water masses spread in the southwestern region and in the Anse de Carteau. Fig. 12 presents temporal changes in salinity measured at station 24 located in the Anse de Carteau (indicated on Fig. 11a). High variability in surface salinity was recorded during this period (with a minimum of 29.5). The system appeared highly stratified with much higher salinity waters at 4.5-m depth. In the course of May 13, salinity increased in the surface layers at station 24, corresponding to a mixing of the whole water column.

From May 13 on, salinity strongly decreased over the whole GOF (Fig. 11d). A first low-salinity water

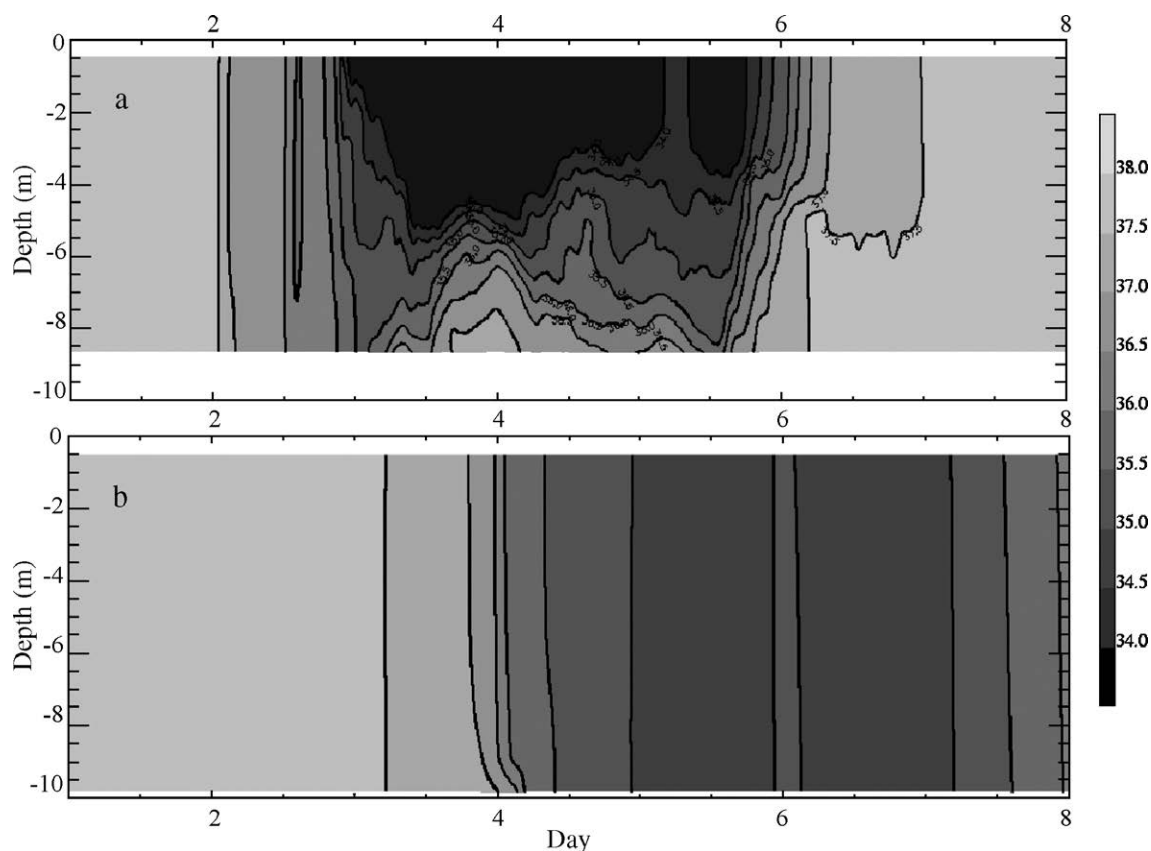


Fig. 9. Temporal evolution in vertical salinity at site A located northeast in the Gulf of Fos (a) and at site B in the Anse de Carteau (b). Positions of site A and B are given on Fig. 8a.

cell (salinity lower than 25) typical of southeastern wind events appeared along the ‘They de la Gracieuse’ and a second one in the northern part of the GOF. At station 24 on May 14 (Fig. 12), drastic decreases of about 10 units in salinity at 1 m depth and of 8 units at 4.5 m depth were recorded. On May 16, the lowest salinity of the cruise was recorded over the GOF (not at station 24 where salinity conditions increased by 2 units, probably following a strengthening of southern winds, driving surface water northwards).

5.3.2. Simulated salinity field

The general trend of the simulation during the period is in good agreement with the observations. Fig. 11e shows the surface salinity field corresponding to May 11 at 06:00. Plume water intrusion from the southwest was correctly simulated even though the

modelled salinities were slightly lower than the observations. Freshwater discharge from dock 1 was responsible for the low salinity simulated in the Anse de Carteau. Stratification at station 24 was relatively well reproduced (Fig. 12). From May 13 onwards, the Rhône river plume penetrated the GOF due to the more intensive wind, which turned south. This plume hugged the coastline of the ‘They de la Gracieuse’ on May 14 (Fig. 11f) as shown in the data (Fig. 11d). Later on, both simulation and observations showed that freshwaters influenced the northern part of the GOF and finally the Anse de Carteau, with a 12-h time lag in the model (Fig. 12). On May 15, a stabilized situation was encountered at station 24 with a salinity of 32 at 1 m depth, i.e., 4 units higher than in the observed data. The observed salinity increase at station 24 on day 16 was qualitatively well reproduced by the model.

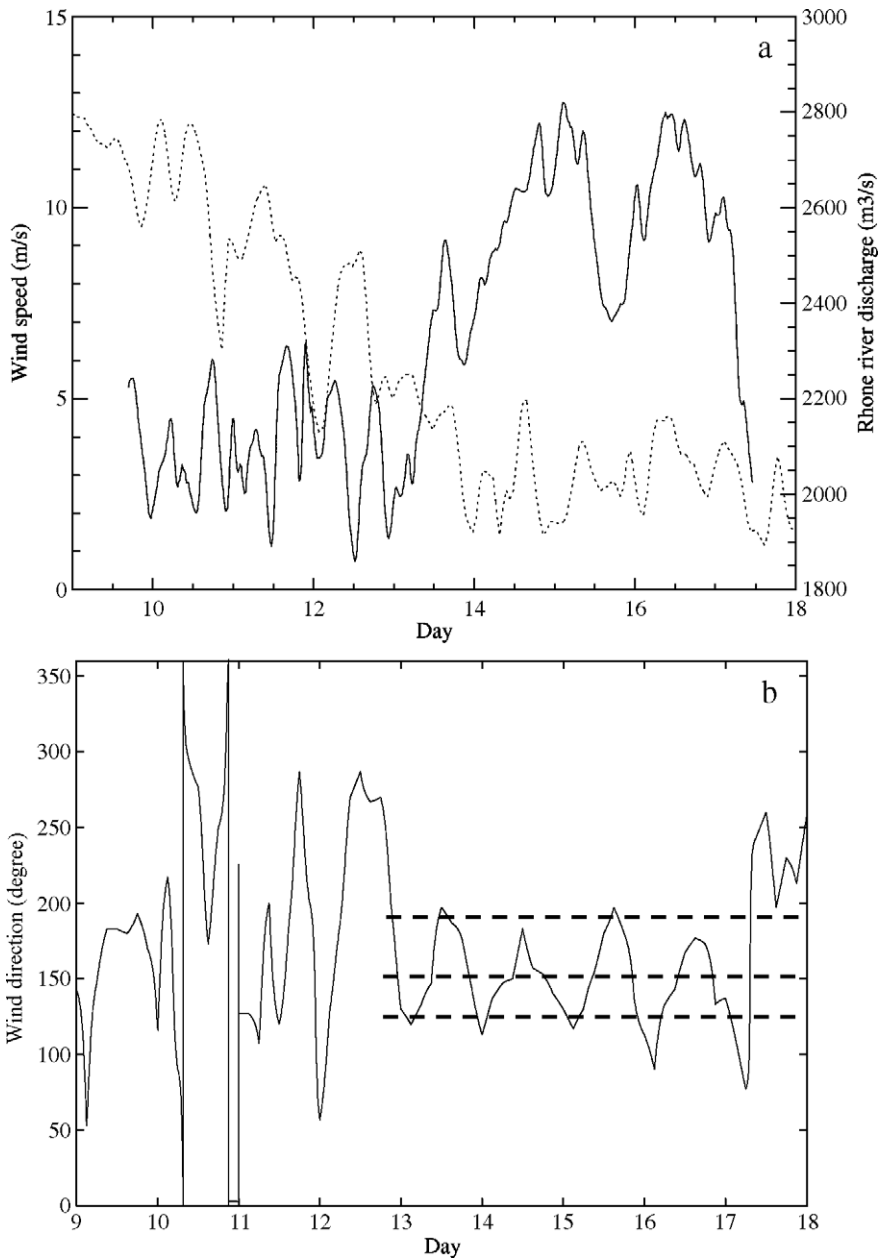


Fig. 10. 10 m interpolated wind speed measured at station 24 in the Gulf of Fos (Aanderaa buoy, solid line) and Rhône river outflow (dashed line) (a), wind direction recorded at Maignane airport (solid line) (b) (the dashed lines indicate wind directions applied to sensitivity tests).

5.4. Sensitivity studies

The GOF is a complex area where the forcing terms of the water circulation are not regularly

monitored. The following tests aimed at appraising the sensitivity of the model to these forcing parameters and at estimating the accuracy required to forecast large variations of salinity.

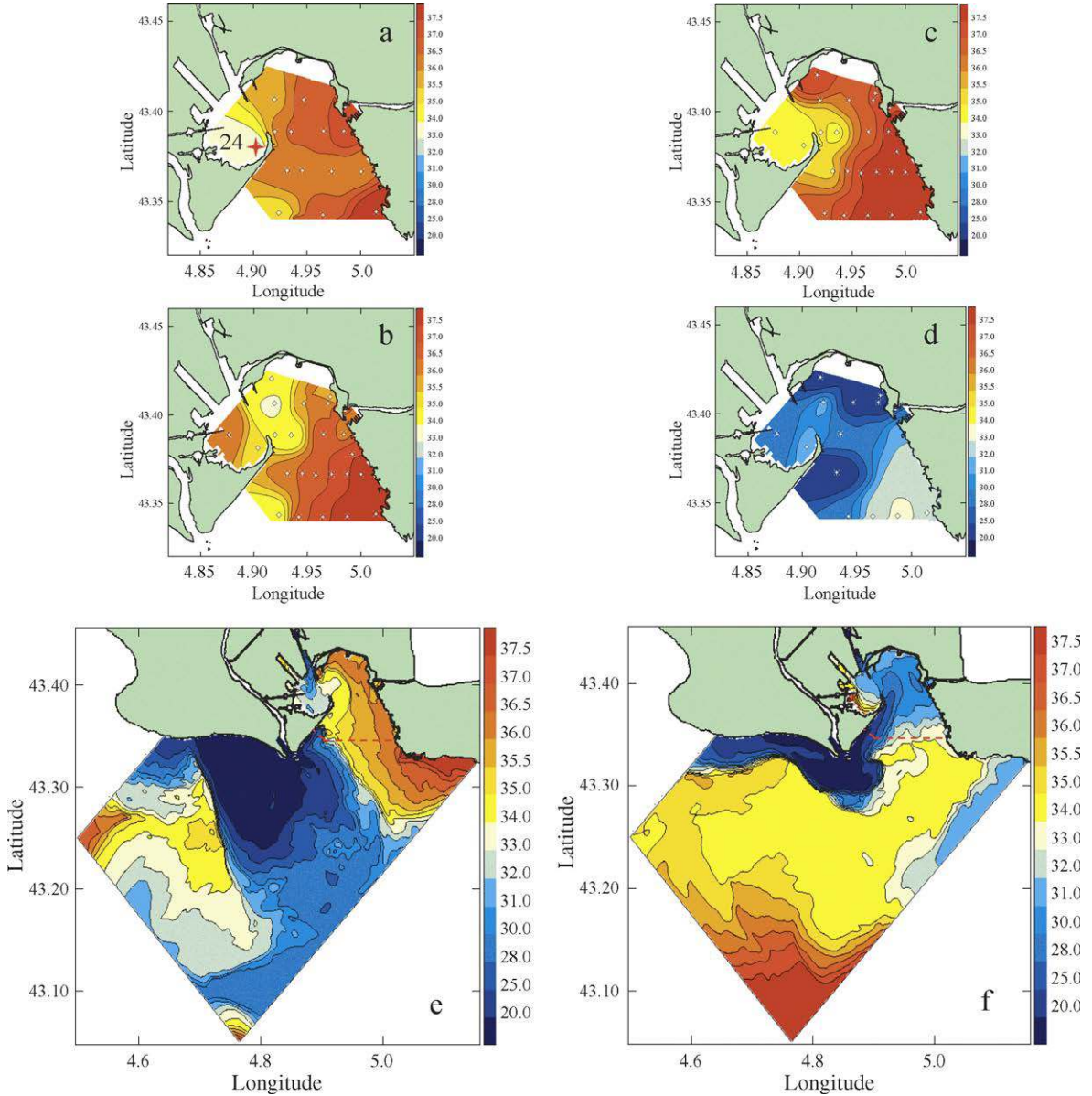


Fig. 11. Spatio-temporal variability in surface salinity interpolated over the model grid and measured during the MODELFOSS2 cruise at different dates: May 10 (a), May 11 (b), May 12 (c) and May 14 (d). Surface salinity simulated for May 11 at 06:00 (e) and May 15 at 00:00 (f). Position of station 24 is given in graph (a). Note that isovalues are irregularly spaced.

5.4.1. Sensitivity to local freshwater inflows

5.4.1.1. *Caronte channel.* Freshwater inflows from the Caronte channel are highly variable and are not regularly measured. The inflows used in this sensitivity study corresponded to data from the hydro-

electric power plant (Electricité de France, personal communication). Salinity of the Caronte channel waters was fixed at 10. With this new input, the plume simulated during the first period between May 11 and 12 showed salinity between 32 and 34, while this salinity was about 36 in the reference simulation.

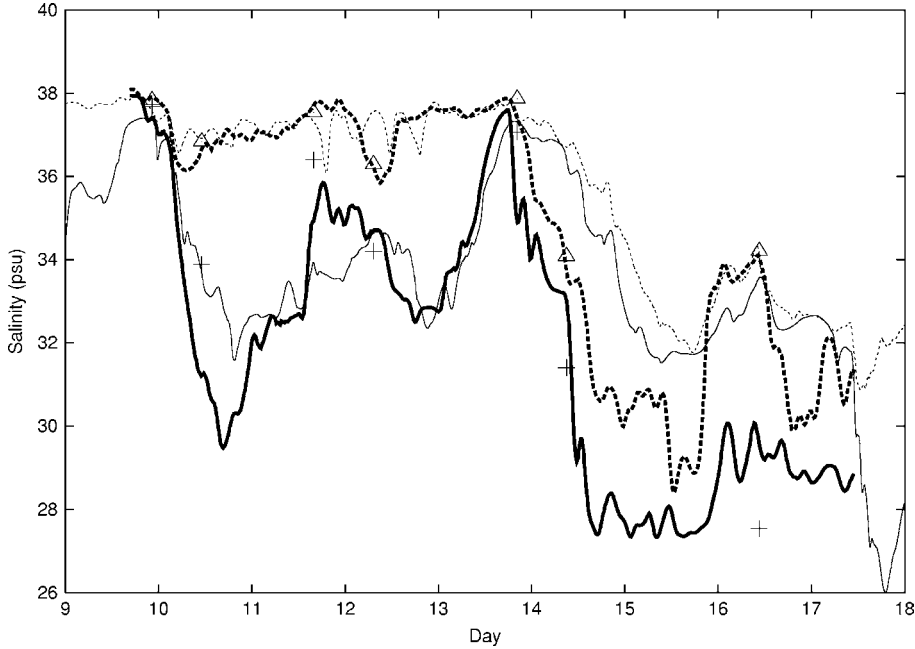


Fig. 12. Comparison between observed salinity (thick solid and dashed lines at, respectively, 1-m and 4.5-m depths) and modelled salinity (fine solid line at 1 m and fine dashed line at 4.5 m) at station 24 in the Anse de Carteau. Crosses correspond to CTD measures at 1-m depth and triangles at 4.5-m depth.

During the second period, these inputs were swept along northwards by the Rhône river plume and the wind-driven circulation. On May 15 at 00:00, a freshwater spot appeared in the north with surface salinities of 28 (Fig. 13a). This spot, composed of a combination of Rhône and Caronte channel waters, seemed to correspond to the observations even if the data showed values close to 20. The salinity at station 24 was more adequately represented in this simulation, which showed a lower salinity than in the reference simulation (Section 5.3.2) (Fig. 14a). As a consequence, it can be stated that waters from the Caronte channel can penetrate the Anse de Carteau.

5.4.1.2. Dock 1. The reference simulation showed that freshwater inputs from dock 1 could influence the salinity structure of the western part of the GOF. Because the range of input data given by the harbour authorities was broad, a sensitivity analysis was performed. Instead of the high value of $50 \text{ m}^3 \text{ s}^{-1}$ used for the reference simulation, a smaller inflow of $10 \text{ m}^3 \text{ s}^{-1}$, corresponding to a minimal value of this inflow, was tested. The two drastic decreases at station

24 on May 10 and 12 were consistently simulated but their amplitude was less pronounced (Fig. 14a). The extension of dock 1 plume was reduced, the plume influencing only the nearby area. During the second period, no change in model results was observed using the two different inflows, which confirms the lesser impact of dock 1 waters during this period. Nevertheless, these inflows play a major role in cases of low and/or northern wind conditions.

5.4.2. Sensitivity to wind direction

The shape and the position of the Rhône river plume are highly sensitive to wind direction, as shown in Section 4 and as observed by Forget et al. (1990) using VHF radar measurements of radial currents near the Rhône river mouth, especially when wind speed is high. As the wind direction applied in the model did not correspond to local measurements (the meteorological station is 30 km to the east of the GOF), the sensitivity to this parameter was also studied. In order to estimate the sensitivity to wind direction, three new runs were performed with constant wind direction during the second period from May 13 on, when the

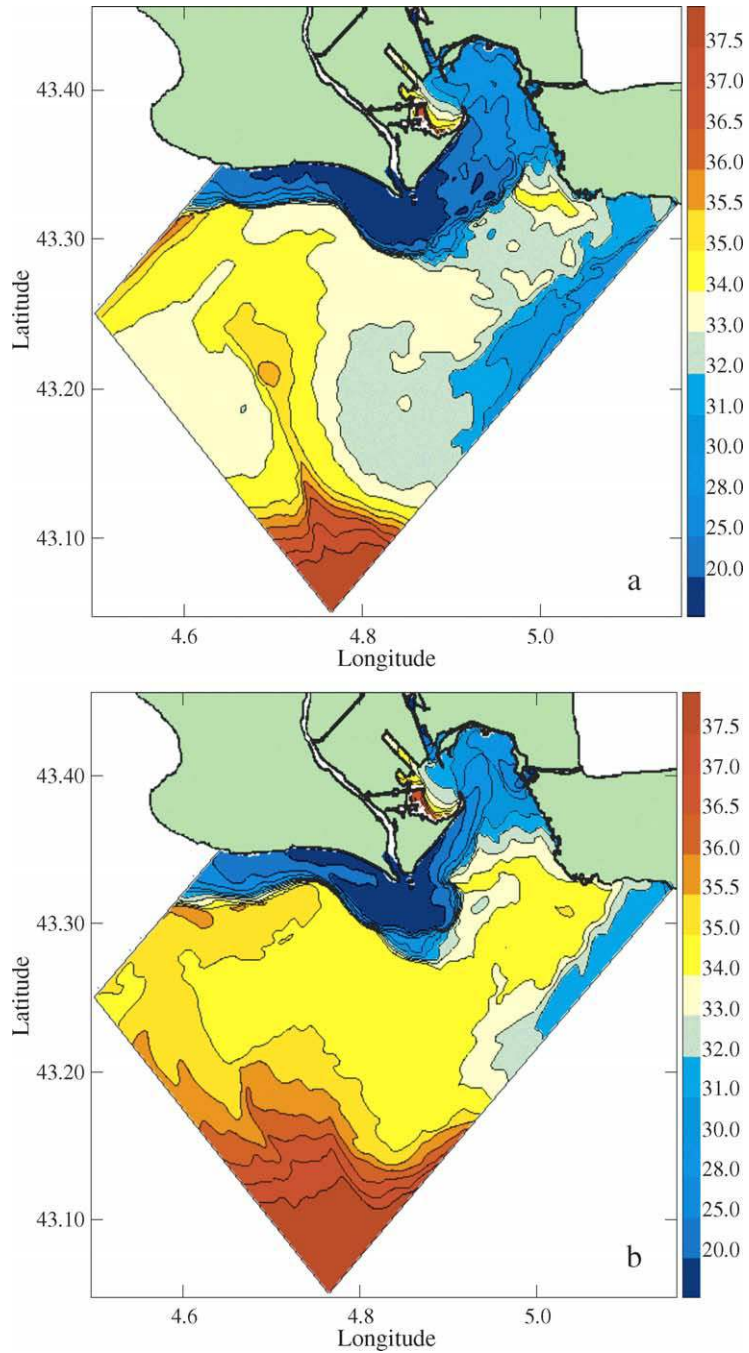


Fig. 13. Surface salinity simulated. (a) with freshwater inputs from the Caronte channel (eastern part of the Gulf of Fos) for May 15 at 00:00, (b) under constant wind conditions (150°) for May 14 at 12:00.

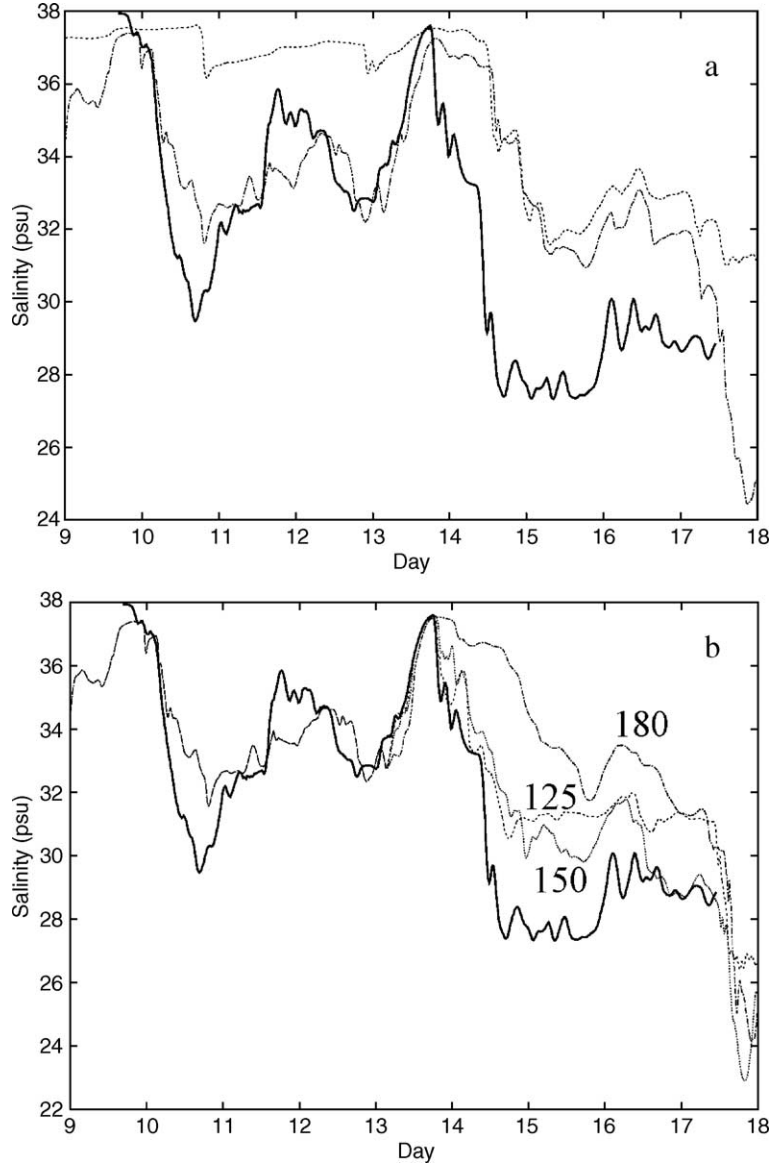


Fig. 14. Observed salinity at 1-m depth at station 24 (solid line) and modelled salinity (a) with freshwater inflows from the Caronte channel (dashed line) and dock 1 inflows fixed at $10 \text{ m}^3 \text{ s}^{-1}$ (dotted line), (b) under constant wind conditions for different directions: 125° (dashed line), 150° (dotted line) and 180° (dashed dotted line).

wind speed became high and the wind direction variable. Two simulations were realized with extreme values (considering measurements presented in Fig. 10b), i.e., 125° and 180° and a third one with a mean value of 150° . The simulations showed that wind directions of 125° and 150° privileged the intrusion of Rhône river waters into the GOF, first along the

coastline near the 'They de la Gracieuse' and then towards the western part of the gulf. The intrusion into the Anse de Carteau was faster and showed no time lag (Fig. 14b). Salinity values were lower at station 24 and thereby closer to observed values. In both simulations, the position of the Rhône river plume along the 'They de la Gracieuse' was adequately

reproduced. For the simulation realized with a 150° wind direction, a spot with lower salinity at the northern part of the GOF was reproduced (Fig. 13b). However, this freshwater cell was characterized by higher salinities than these observed.

For 180° constant wind direction, the plume divided into two main branches: the first one flowed westwards and the second one eastwards along the coast. This wind situation was less favourable for drastic Rhône river inflows into the GOF.

6. Concluding remarks

Sensitivity analysis performed on idealised simulations (Section 4) and a realistic simulation (Section 5.1) showed the overall impact of winds and freshwater inflows on the hydrological behaviour of the GOF.

Low winds and northwestern winds favour the extension of freshwater inflows from dock 1 and the Caronte channel. These intrusions can affect distant sites when local outflows and winds are high. Sensitivity studies in Section 5 showed that during low wind conditions such as those encountered during the first part of the MODELFOSS2 experiment, dock 1 waters extended as far as the southern part of the Anse de Carteau. In the case of southeastern winds, the situation is different: intrusion of Rhône river plume waters into the GOF depends on the balance between outflow and wind intensity. For strong wind and low outflow conditions, intrusions will be limited to a few kilometres along the 'They de la Gracieuse' while moderate winds can drive Rhône waters up to the northern tip of the gulf.

Sensitivity studies to the westward coastal current linked to the general circulation in the Western Mediterranean (not shown) were also performed. The characteristics of this current, especially its depth, were perturbed at the eastern boundary of the largest model, leading to a more or less important intrusion of a secondary branch onto the continental shelf offshore of Marseille (Auclair et al., 2003). These sensitivity studies revealed that the influence of this current was much lower than the two other driving forces (wind and freshwater outflows).

Compared to field observations, the realistic simulation performed for the MODELFOSS2 period

gave good quality results, qualitatively reproducing the spatial variability in salinities during the cruise and the vertical stratification variation at reference station 24. Some discrepancies were detected between surface salinities, especially in the Anse de Carteau. They could be due to uncertainties in local outflows and wind directions, as shown in Section 5. The vertical resolution could also explain a part of the disagreement between model results and observations. Although the bay is quite shallow, 10 vertical levels could be too coarse to describe the great stratification in this region. Indeed, a sensitivity study (not presented here) showed that the difference between model outputs and observations at station 24 could be slightly reduced by increasing the vertical resolution.

Hydrodynamic processes related to water renewal produced by northern winds in the GOF were described by the model. The outflow of surface waters is compensated by upwelling processes occurring in the northern part of the GOF. A northward bottom current is canalized along the navigation channel towards the docks. The idealised simulations allowed two different areas in the GOF to be described with specific time responses to wind events. In cases of flushing events, water renewal in the eastern part of the GOF is faster than in the western part due to topographic complexity, inducing larger residence times in the latter part. These two areas with different hydrodynamic features have to be considered separately in the context of eutrophication studies. Furthermore, the Anse de Carteau, the western part of the GOF, hosts a commercial shellfish farm producing mussels on fixed rope structures averaging 2500 metric tonnes annually and the particularly high shellfish production rates are partly due to the specific hydrodynamic conditions of this site (Grenz et al., 1991).

In presenting these results our intent was to underline that, even at small spatial scales, hydrodynamics can be complex in microtidal systems influenced by wind driven processes. The use of the 3D model applied to the GOF gave an accurate description of processes that influence residence times. The results presented here, especially the real case simulation corresponding to the MODELFOSS2 cruise in May 2001, will be used to explore the biogeochemical variables measured during that period in a dynamic way.

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