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3D modelling of seasonal evolution of Loire and Gironde plumes on Biscay Bay continental shelf

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Abstract – A 3D model of the Atlantic shelf has been developed and applied to study shelf dynamics and evolution of hydrology. The model takes the combined effects of tide, wind, river discharges and surface heat flux into account. Time scales vary from 1 day to several years. Following a brief description of the model and forcing variables, the behaviour of the Loire and Gironde plumes is described, first for winter and spring, then over a period of several years, under realistic forcing. The results show that plume evolution depends on the high variability of river runoff and winds. Model simulations performed over 7 years (1990 to 1996) have highlighted several features of these plumes: 1) In early winter and periods of high river runoff, plumes usually spread northwards and along shore. 2) During winter, vertical stratification is weak on the shelf. 3) Near the bottom, low-salinity water spreading hardly varies, reaching about the same extent each year. The low-salinity waters are located in the north of each estuary, often not reaching the 50 m isobath. 4) When river discharges are reduced and prevailing winds are from the north-west, the northward spreading of plumes may be stopped. In that case, plumes may be driven offshore or southwards. This path change usually occurs in spring. Salinity gradients become weaker under mixing and spreading effects. The low-salinity strip along the shore seldom builds up again, and the shelf circulation of water masses becomes mainly wind-driven. © Elsevier, Paris

river plume / modelling / shelf dynamics / Bay of Biscay

Résumé – Modélisation 3D de l'évolution saisonnière des panaches de la Loire et de la Gironde. La dynamique du plateau continental Atlantique et l'évolution de l'hydrologie sont étudiérs par un modèle mathématique 3-D. Les effets combinés de la marée, du vent, des apports fluviaux et des échanges thermiques entre l'océan et l'atmosphère sont pris en compte. Les échelles de temps varient de la journée à plusieurs années. Après une description rapide du modèle et des paramètres forçants, on étudie l'évolution des panaches fluviaux de la Loire et de la Gironde durant l'hiver et le printemps et leur variabilité interannuelle. Celle-ci est directement liée aux variations des débits et des vents. Les simulations des années précédentes (1990 à 1996) ont mis en évidence plusieurs caractéristiques des panaches : (1) En période de crue (début de l'hiver), les panaches se propagent vers le Nord et restent collés à la côte. (2) En hiver, les stratifications sont faibles. (3) Près du fond, l'influence des panaches est moins variable et relativement constante chaque année. Les dessalures se situent au nord de chaque estuaire et ne dépassent quasiment jamais l'isobathe 50 m. (4) Au printemps quand les débits faiblissent et que le vent est de secteur NW, la progression des panaches vers le Nord est stoppée et ceux-ci sont déviés vers le large ou repoussés vers le Sud. Les gradients de salinité faiblissent sous l'effet du mélange ou de l'étalement. La reconstitution ultérieure d'une bande côtière stable est très rare et les masses d'eaux sur le plateau sont alors principalement soumises à la circulation induite par les vents. © Elsevier, Paris

panache / modélisation / dynamique du plateau continental / golfe de Gascogne

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1. INTRODUCTION

In recent years, study of the transport and behaviour of some trace elements like cadmium, entering Bay of Biscay near-shore waters through river discharges, has become necessary because of the contamination risk for coastal shellfish farms. To this end, a national oceanographic programme (PNOC) was conducted from 1992 to 1995. The programme's main objectives included the understanding and description of circulation processes, mixing and long-term transport of water masses on the Atlantic continental shelf.

Current measurements on the continental shelf have been highly sporadic, usually lasting less than 1 month. Detailed analysis of these measurements [12, 15] shows a low contribution from tides to the long-term transport. A north-westward residual component of about 4 $cm \cdot s^{-1}$ was measured in spring 1987. Lehay [14] showed that that current may have been wind-driven. However, Pingree and Le Cann [15] assessed the potential role of large-scale thermal process and showed that the strong current generated over the shelf break may be apparent over the outer and mid-shelf areas.

Some numerical models have been developed to describe several processes and their effects on hydrology. Most of them deal with tidal dynamics: barotropic tide [13, 16] and internal waves [17]. These models have confirmed the location of some thermal fronts near the coast and at the shelf break. They have also indicated related processes: turbulence due to barotropic tidal currents near the coast and internal tidal mixing at the shelf break.

A 3D model has been used both to assess long-term transport on the shelf and as an initial approach to highlighting the role played by each dynamic process [6]. The calculated Eulerian tidal residual currents are very weak over a large part of the shelf (< 1 $cm \cdot s^{-1}$), except in some coastal zones such as western Brittany, Bourgneuf Bay or around Belle-Ile island [6]. Therefore, at depths greater than 30 m, the subtidal transport will depend on winds or the density gradient.

Wind is often the main driving force of long-term transport in coastal zones. As demonstrated by Pingree and Le Cann [15], the NW/SE winds generate the largest vertically integrated currents since the wind direction is parallel to the coast. Therefore, transport is limited when winds are westerly or south-westerly. Near the coast, wind-driven circulation is more complex because of depth variations and land influences. The inflows and outflows lead to a reversal of deep currents and induce vertical movements. Jegou and Lazure [6] have shown that vertical movements induced by upwelling-favourable winds are stronger and clearer when tidal currents are weak. Thus, the Landes and Vendée coasts and, to a lesser degree, the southern part of Brittany are the most sensitive areas. Upwellings are not generated under the same wind directions on either side of the Loire estuary because of the coastline orientations: north-westerly to northerly winds in the south of the Loire, westerly winds along the Brittany coast.

The last forcing examined is that of density gradients generated by differences in both temperature and salinity. Horizontal temperature gradients may be sharp in thermal fronts due to tidal stirring and upwelling events, and can induce significant horizontal transport locally in spring and summer.

In shelf areas, the highest salinity gradients are usually due to large freshwater discharges from large rivers [18]. The Loire and Gironde are the two main rivers on France's Atlantic coast. Their annual mean freshwater outflow is about 900 $m^3 \cdot s^{-1}$ each, with peak runoffs in winter or spring often surpassing 3 000 $m^3 \cdot s^{-1}$. River discharges may induce high density currents during the runoff period [3, 18]. Near the estuary mouth, low salinity water flowing out forms a surface-layer plume with characteristic current directions, i.e. downstream at the surface and upstream at the bottom. Because of its lower density, the buoyancy plume has a free surface above the surrounding, more saline waters. This generates pressure gradients, causing its entrainment and lateral spreading towards the right (in the northern hemisphere) due to the earth's rotation.

In the absence of strong external forcing, the model [6; Lazure, unpublished data] reproduces quite well the northward propagation of the Loire and Gironde plumes and their confinement along the coast. The density gradients caused by these estuarine discharges create baroclinic coastal currents. In the frontal zone, these currents follow isopycnal lines. Their velocities may reach 20 $cm \cdot s^{-1}$. Nevertheless, the spreading of plumes is highly dependent on wind stress since their buoyancy usually confines them near the surface layer. Model simulation [6] showed that in the case of strong, opposing north winds, the poleward spreading of plumes may be stopped and reversed south-westwards. Therefore, separating different forcing enabled us to conclude that the development and evolution of river plumes are governed by the dynamics of seasonal forcing conditions.

A brief description of the numerical model and the forcing variables is followed by a discussion of the results under realistic forcing conditions. Daily salinity fields were calculated for a period of 7 years. They provide input on seasonal and year-to-year evolution of the Loire and Gironde plumes. The behaviour of the Loire and Gironde plumes during winter and spring 1994 is described. The year 1994 was an interesting one indeed, due to extremely high freshwater discharge rates and meteorological conditions marked by periods of high winds and a residual westerly wind.

2. THE MODEL

The numerical model developed uses a 3D finite difference scheme [10; Lazure, unpublished data]. It consists of the entire set of primitive equations, allowing calculation of currents, temperature, salinity and dispersion of dissolved elements within the hydrostatic assumption.

The equations are solved with a split external–internal mode technique [2]. The model has a free surface and the vertical levels are determined using a 'sigma coordinate' system allowing a constant number of calculation points on the water column. Vertical eddy viscosity and diffusivity are calculated by the resolution of the turbulent kinematic energy equation and the use of an algebraic formula for the mixing length [7].

The simulation domain is presented in *figure 1.* It extends from the coast to approximately the 200 m isobath in the west and from the English Channel entrance in the north (49° N) to the Gulf of Cap Breton in the

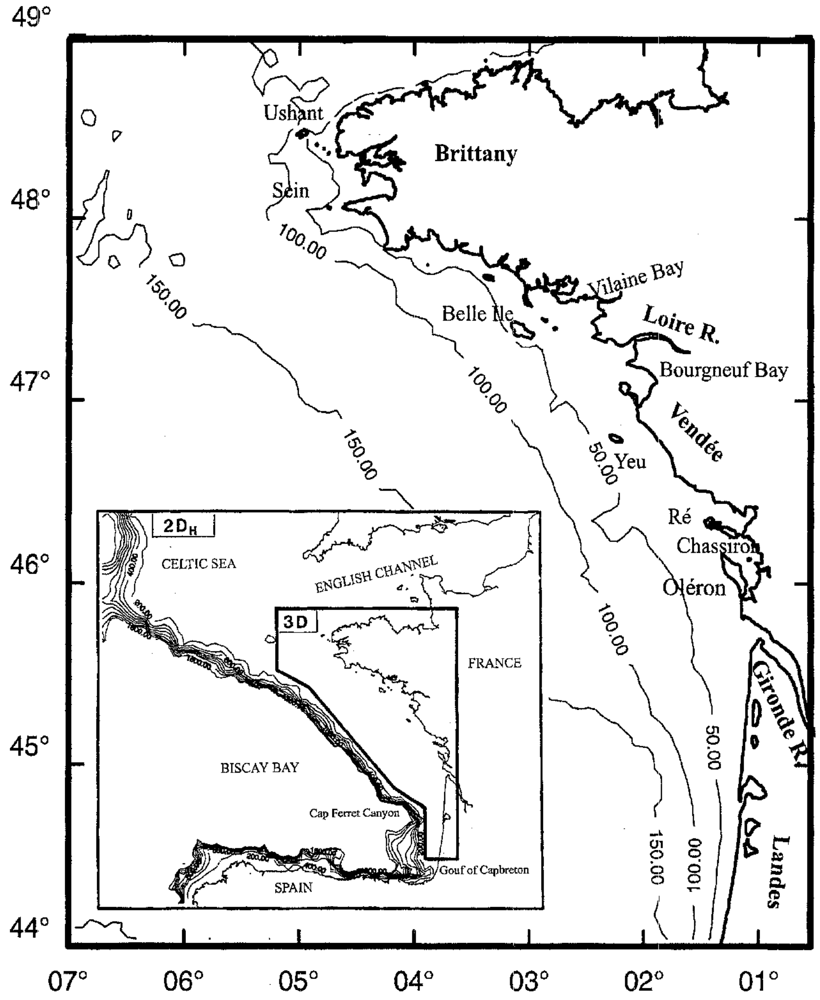

Figure 1. The 2D numerical model area and the 3D model subdomain of the Atlantic shelf.

Figure 1. Domaines du modèle 2D et du modèle 3D du plateau Atlantique.

south (43° 50' N). The numerical grid has a uniform spacing of 5 km ($\Delta x = \Delta y = 5$ km) like that of similar models developed for other continental shelves [4, 8]. It has 100 points on the x-axis, 117 in y and 10 evenly divided levels on the vertical plane. The time step is around 900 s.

2.1. Initial and run conditions

The simulation covers 7 years, starting on 1 January 1990 and ending at the end of 1996. The total run took about 5 days on a SUN Ultra Sparc 1 workstation. Because of a lack of data, a homogeneous initial salinity field (S = 35.5) and temperature (11 °C) were used.

2.2. Boundary conditions

The open boundary conditions are produced by a larger model extending from Portugal to the North Sea (*figure 1*). This model is 2D (vertically integrated), in spherical coordinates, with a grid size of about 10 km. It is forced by tide at its open offshore boundaries and by wind fields at the surface. This extended model was run to study mean transport due to tide and winds and to provide efficient boundary conditions for the 3D nested model.

At the upper boundary, heat transfer at the ocean–surface interface is calculated using climatological values: air temperature, cloudiness and specific humidity. At the open boundary, an horizontal extrapolation of the calculated temperature was adopted.

The Loire and Gironde discharges are imposed in their own estuaries. At the open boundary, when currents enter the domain, salinity is related to the sea water value (35.5) with a time scale of 15 days.

For the past 19 years, analysis of wind data recorded by Meteo-France in three coastal stations (Belle-Ile, Chassiron, Cap Ferret) shows high variability of wind speed and direction. Differences between meteorological stations along the Atlantic coast are small, winds are almost homogenous in direction from the north to the south of the model domain, but wind speed decreases from north to south. Therefore, in an initial approach, the wind measured at Chassiron may be considered as representative of the mean wind stress for the entire French Atlantic shelf.

3. RESULTS OF SIMULATIONS UNDER REALISTIC FORCING

3.1. Winter and spring 1994

3.1.1. Wind and river discharge variability

The mean wind stress pattern was calculated, day by day, for the last 19 years to assess seasonal variations (*figure 2*). It exhibits a seasonal cycle with a marked directional change in the spring period between late March and early April. This period is that of transition, in average years, between prevailing south-westerly winds in winter and north-westerly winds in spring.

A comparison of average pattern (top right) with individual years reveals great inter-annual variability (*figure 2*). In 1993 winds were particularly weak and could be considered as having little effect on transport. On the contrary, in 1994 there were significant periods of strong winds, as in April, and a residual westerly direction. Nevertheless, the 1994 wind-stress pattern resembles the average pattern, in direction, except when south-westerly winds re-occurred during 1 month in spring. In winter, from January to March, winds at Chassiron station (*figure 3*) were mainly south-westerly with some westerly events. The beginning of April was characterised by a marked directional change in wind stress. Winds turned north-westerly, growing stronger, then northerly in the last 2 weeks of April. Wind stress in April was about twice that of both February and March. A new directional change occurred in early May with moderate south-westerly winds, once again followed by northerly winds in June.

A daily average data curve of freshwater discharges over a period of 10 years is given in *figure 3a*. Data were obtained from the Hydrological Services (S.H.C). This curve shows that freshwater discharges from the Loire and Gironde Rivers are usually synchronous. High discharges occur in winter and sometimes in early spring, often with the maximum peak in February or March and the lowest level in August and September. Inter-annual variations of freshwater discharges may be quite important. For instance, winter river discharges may exceed twice the average winter runoff in some years, such as 1988, 1994 or 1995. Conversely, there are some years with very low inputs of freshwater, as in 1992. The year-to-year freshwater supply fluctuations may modify the properties of water masses on the shelf.

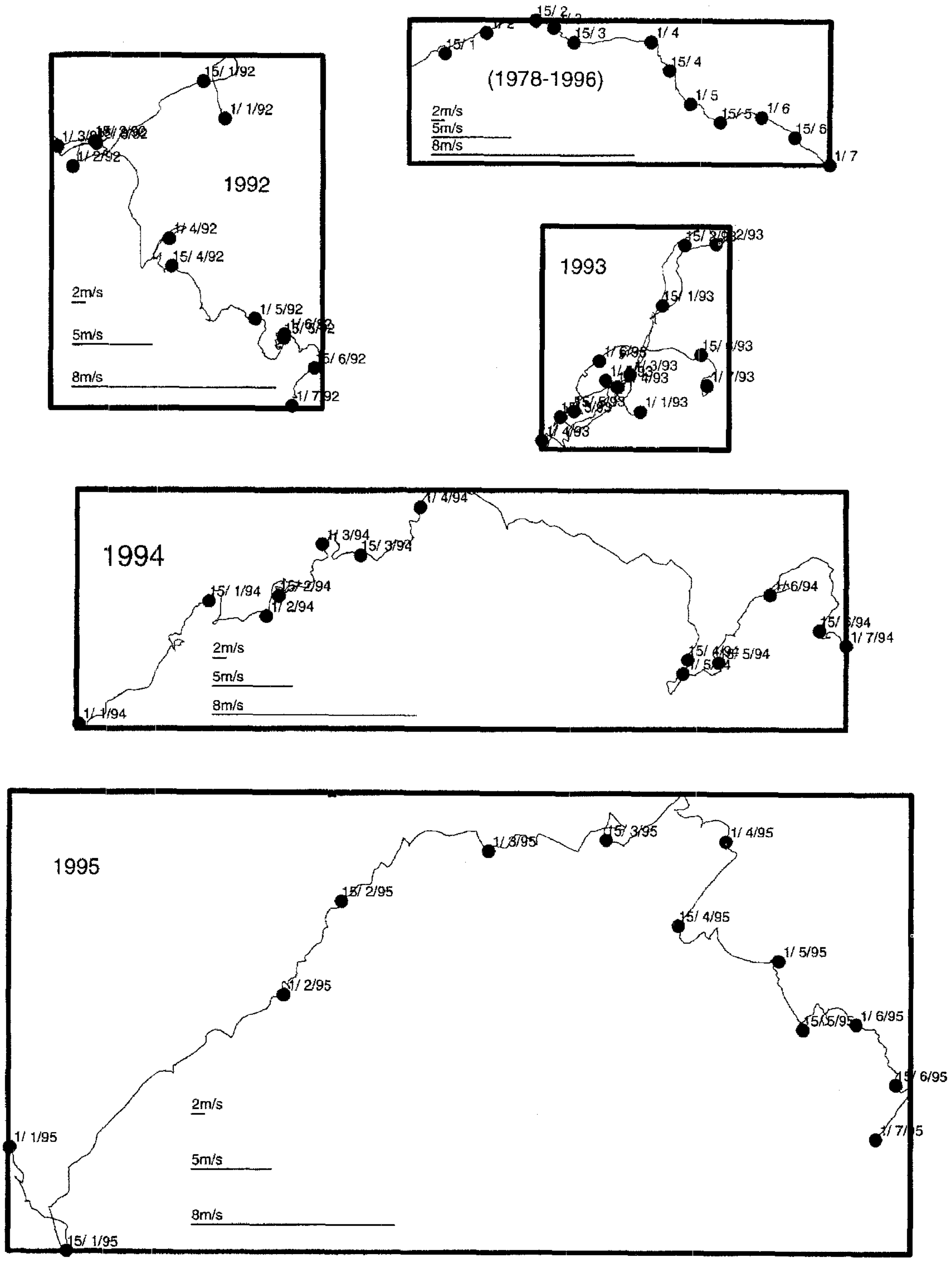

Figure 2. Progressive vector diagrams of wind stress at Chassiron (calculated with data from Meteo-France). The scale indicates the equivalent wind-stress integration over 15 days for three different wind speeds.

Figure 2. Hodographes intégrés de la tension du vent à Chassiron (calculée à partir des données de Météo-France). L'échelle représente l'intégration de la tension de vent pendant 15 jours pour trois vitesses de vent constantes.

The freshwater discharge curve (*figure 3b*) shows that a long period of water runoff occurred in 1994 from January to March with rates above 2 680 $m^3 \cdot s^{-1}$ for the Loire and 2 400 $m^3 \cdot s^{-1}$for the Gironde. The highest values occurred at the beginning of January and at the end of February with peaks above 3 000 $m^{3} \cdot s^{-1}$. In March, Loire and Gironde runoffs dropped to 1 000 $m^3 \cdot s^{-1}$. Discharges were again high during the last 2 weeks of April with a higher peak for the Gironde River. Then during May, the Loire and Gironde decreased to 1 000 $m^3 \cdot s^{-1}$ once more.

Seasonal and inter-annual variability in outflow and wind stress precludes the use of averaged meteorological data for realistic simulations. Therefore, the simulations are run with real, recorded forcing conditions, enabling model results to be compared with in situ measurements.

3.1.2. Near-surface salinity and current fields in 1994

The calculated salinity and current fields were averaged over 1 month to filter out daily or weekly fluctuations, to point out the seasonal evolution of hydrodynamics during winter and spring, when plumes occur.

In January, high discharges (*figure 4*) that had started in December 1993 created a low salinity strip about 50 km wide, close to the coast. Due to the combined effects of south-westerly winds and density-driven circulation, low salinity water was advected polewards. At the edge of the plumes, surface currents can reach 10 $cm \cdot s^{-1}$. Outside of this low salinity strip, the currents flowed northwards on the southern part of the shelf and were inverted southwards, north of 46° N. West of the Brittany coast, currents show complex patterns persisting through winter and spring, whereas winds and discharges are highly variable. This indicates that these currents are tidally-driven, contrary to those in the model's southern regions.

In February (*figure 4b*), the salinity pattern was almost the same. Freshwater spreading poleward was visible in the south Brittany area. The 35 isohaline extended about 60 km along the coast in 1 month's time, corresponding to a mean daily speed of 2 $km \cdot d^{-1}$. High runoff and cross frontal mixing made the coastal freshwater strip meander. The winds being lower than in January, density-driven currents could be clearly identified. These currents are perpendicular to the main salinity gradient and increase with it. During calm periods, they have the characteristics of coastal baroclinic currents.

During March (*figure 4c*), the previous trend continued to develop, while runoff decreased greatly. Low salinity progressed northwards and the width of the coastal strip continued to grow. The meandering trend was confirmed and a small, clockwise surface eddy appeared south of Belle-Ile.

In April (*figure 4d*), the winds reached their maximum force during the first 2 weeks and strongly modified the salinity field. Due to the upwelling-favourable north-westerly wind, surface currents were directed westwards in the Ekman layer: the freshwater was thus advected offshore, destroying the coastal strip. The slight increase in runoff was not sufficient to maintain the freshwater close to the coast. As shown later, the offshore spreading of freshwater occurred in the first 20 m and induced a haline stratification over most of the continental shelf. A pocket of low salinity water could be found south of Belle-Ile.

In May (*figure 4e*), the winds were weak and the residual wind stress was quite similar to that in February. Outside of the plumes, the surface currents were directed south-east. In the low salinity area, most of the surface currents followed salinity contours, indicating that density-driven circulation was probably predominant. Salinity increased in southern Brittany but decreased slowly on the outer shelf off the Gironde estuary. A large cyclonic eddy was formed west of Belle-Ile and south Brittany. This eddy advected low salinity water north-westwards along the Brittany coast.

In June (*figure 4f*), the north-westerly wind increased offshore advection of freshwater. The cyclonic gyre was advected southwards. South of the Gironde estuary, the strong southward current is induced by wind. The opposite currents near Cap Ferret canyon are questionable, since the proximity of the model's boundary may induce spurious effects such as unrealistic salinity gradients which would tend to drive water northwards.

3.1.3. Vertical structures

Figure 5 shows a west–east salinity transect in front of the Gironde estuary (45° 40' N). On the left, salinity cross sections were derived from shipboard measurements during the CALIBSAT 3 (1–2 February 1994, top left) and CALIBSAT 4 (8–13 July 1994, bottom left) surveys [5]. Model salinity calculations are presented for the same period in *figure 5* (right-hand side). The transition between a weak stratification in winter and a two-layer structure in summer is clear and provides a good way to test agreement between model and measurements.

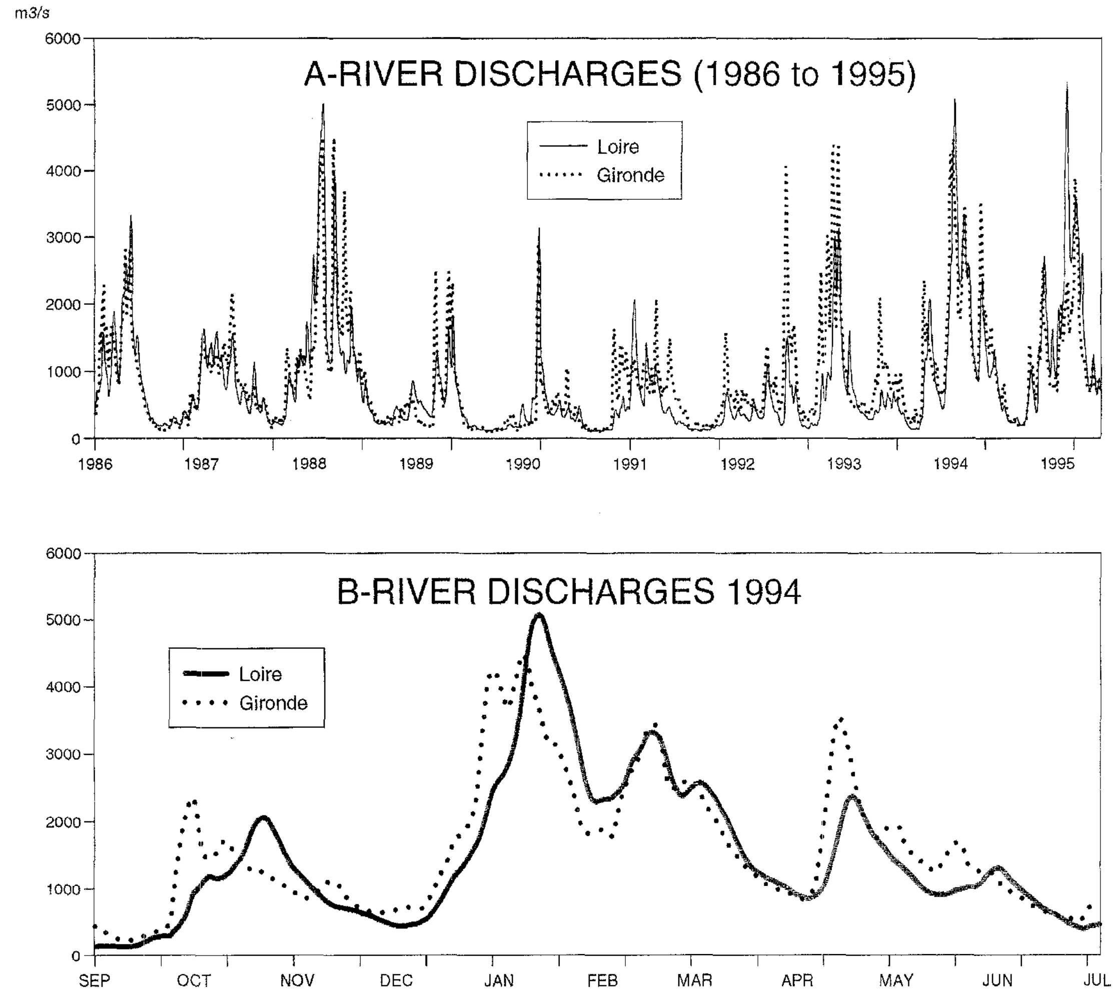

Figure 3. Loire and Gironde discharges (A) from 1986 to 1995; (B) in winter and spring 1994.

Figure 3. Débits de la Loire et de la Gironde (A) de 1986 à 1995 ; (B) durant l'hiver et le printemps 1994.

In winter, downwelling-favourable winds and high turbulence levels confined low salinity waters on the inner shelf and prevented stratification. It can be observed that the model predicted a slightly stronger stratification than observed.

In summer, the spreading of freshwater over the shelf occurred in the first 30 m. The model reproduces this strong stratification well. Although not within the scope of this paper, it should be noted that a thermocline occurred at that time over most of the shelf and increased the stability of the column.

3.1.4. Near-bottom salinity and current fields

Winter and early summer near-bottom current and salinity fields are shown in *figure 6*. Contrary to surface structures, monthly variations were low near the bottom. The coastal water was fresher during both months and appeared to be quite stable. South of the Gironde estuary, the freshwater influence was always very weak.

Bottom layer currents were weaker than those at the surface. Both situations show that near the coast, within the coastal strip, the currents flowed southwards and fol-

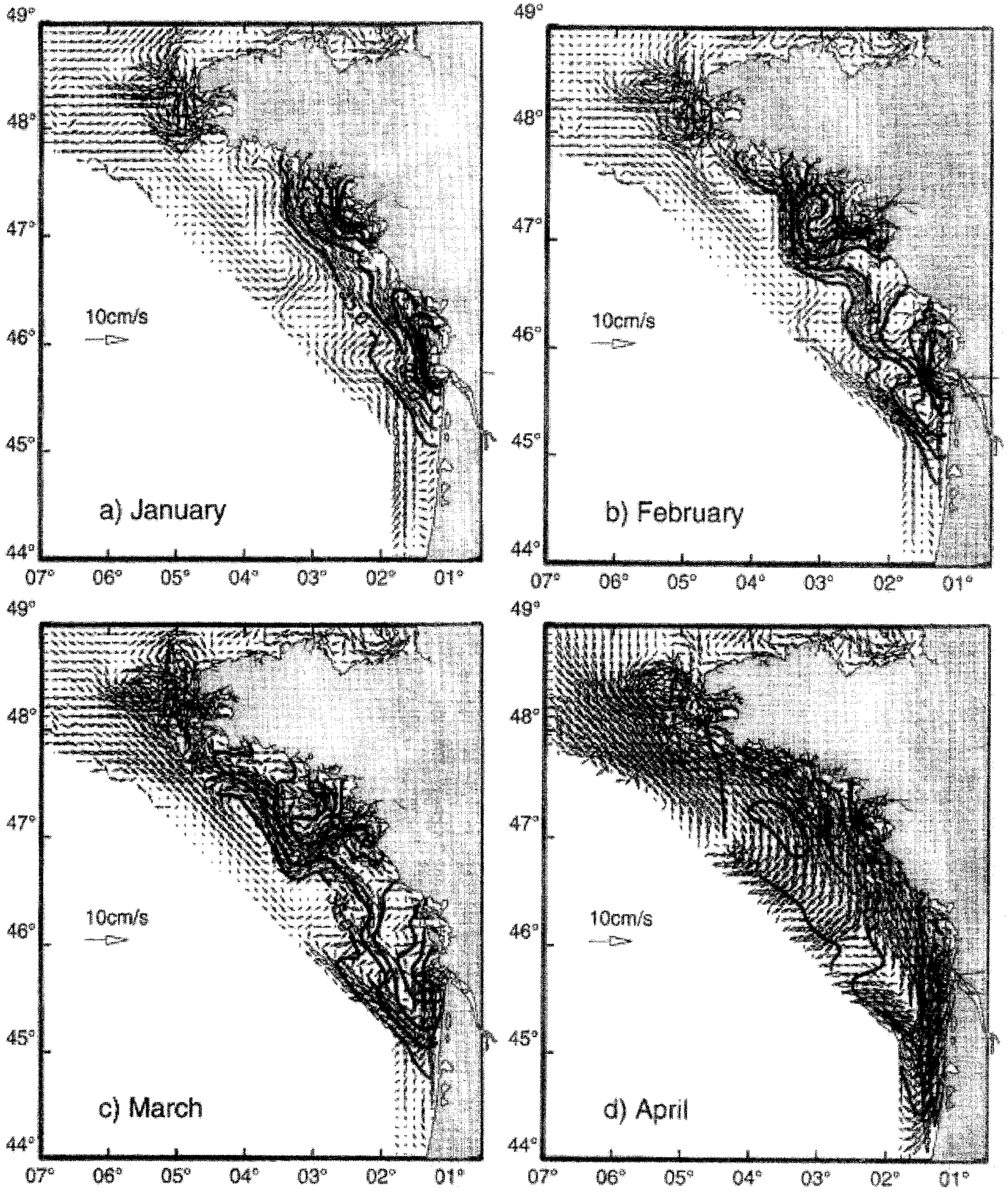

Figure 4. Evolution of computed near-surface salinity and currents during 1994 winter and spring.

Figure 4. Évolution des salinités et des courants calculés en surface au cours de l'hiver et du printemps 1994.

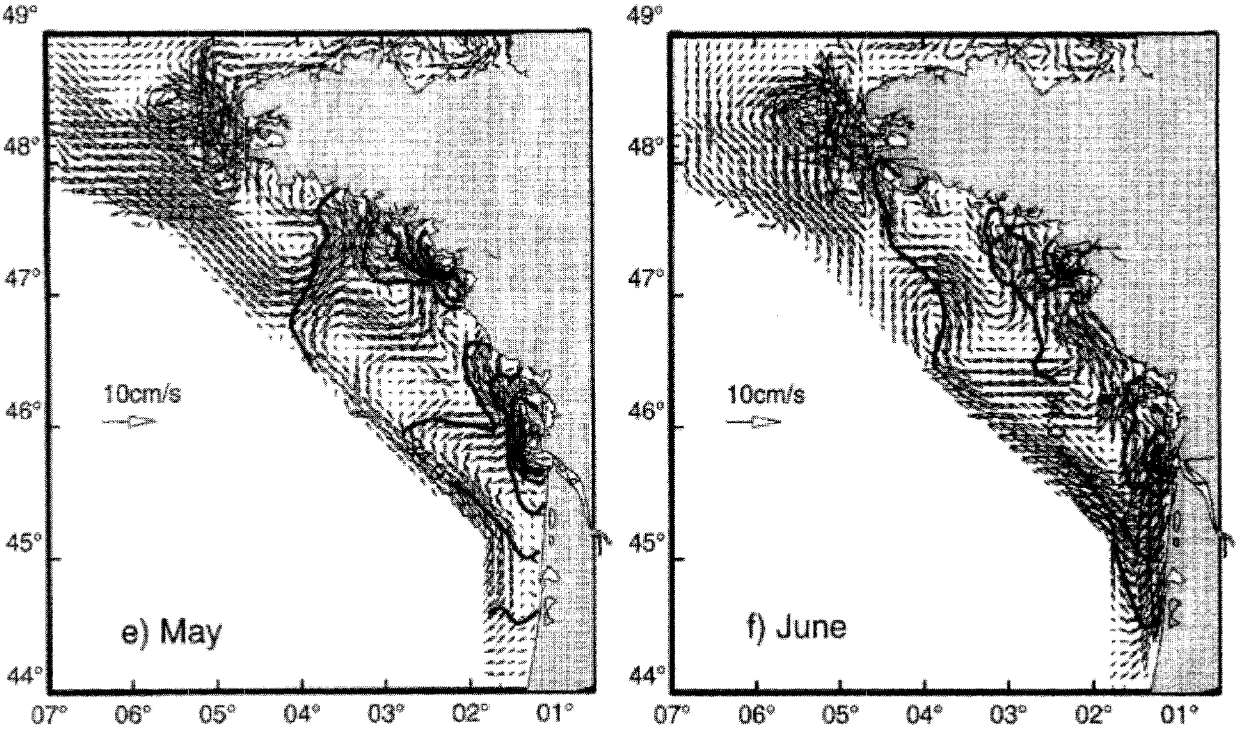

Figure 4. Continued.

Figure 4. Suite.

lowed isohalines. These currents flowed in the opposite direction of those at the surface, indicating a density-driven mechanism. Near the estuaries, the bottom waters were pumped into a classic estuarine circulation scheme. Outside the coastal strip, on the mid- and outer shelves, the currents were also directed south-eastwards, but were stronger in June than in February. As at the surface, strong northward currents on the southern outer shelf (Cap Ferret canyon) in June were questionable.

3.2. Inter-annual variations

Model simulations were run for 7 realistic years (1990 to 1996). The results were compared during winter and spring, at the same periods. This provides a description of the simulated response of the Loire and Gironde plume behaviour related to the history of different river inputs and wind-stress conditions. As seen in *figures 2* and *3*, freshwater rates during the runoff period and the wind-stress diagram can be rather different from year to year. The winds in 1992 (*figure 2*) differ from the mean wind (top right) because the south-westerly winds were absent during the first 2 months and the northerly wind component prevailed thereafter. Conversely, 1993 may be considered as a special year because the winds were almost continuously weak during the first 6 months and showed no definite residual tendency. The winds in 1995 were very similar to winds in 1994, with a more pronounced northerly tendency.

The Loire and Gironde discharges also varied greatly over the 4 years (*figure 3a*). The year 1992 can be considered as very dry. During the previous autumn and winter of 1992, the mean runoff for the Loire and Gironde were only 310 and 490 $m^3 \cdot s^{-1}$, respectively, whereas they were 1 660 and 1 690 $m^3 \cdot s^{-1}$ in 1994. Contrary to wind behaviour, the runoffs in 1993 were close to average, 880 and 1 290 $m^3 \cdot s^{-1}$ for previous autumn and winter. As already shown, 1994 was an exceptional year and 1995 was quite similar, with a mean discharge of 1 800 and 1 490 $m^3 \cdot s^{-1}$. for the Loire and Gironde.

In early May 1992 (*figure 7*), the salinity field was very different from that of 1994. The plumes were heavily deflected southwards. The south Brittany coast, excepting

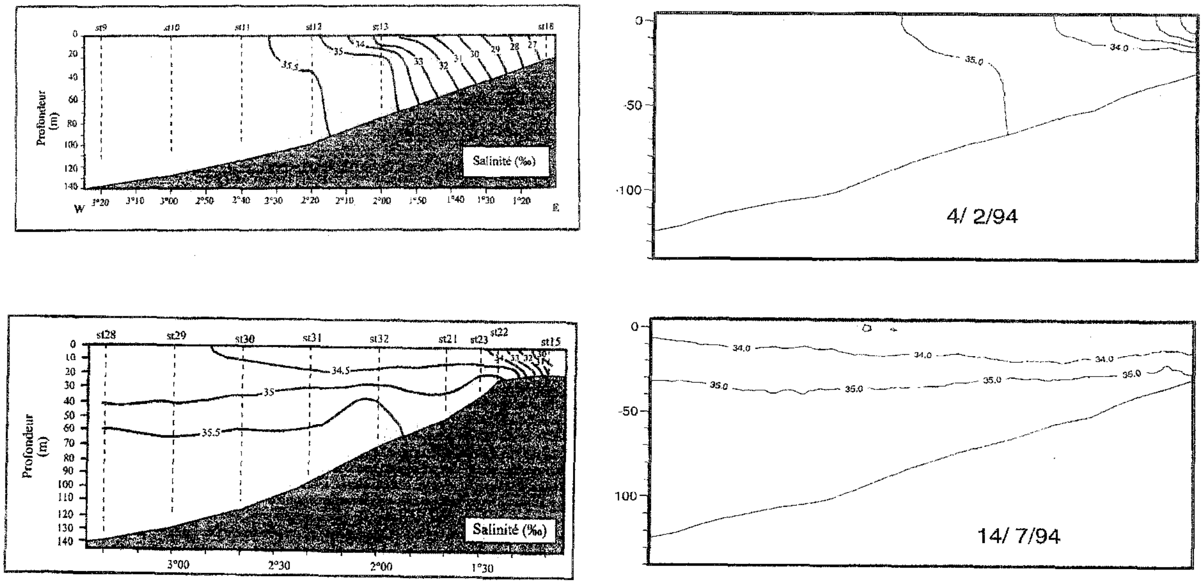

Figure 5. Vertical sections of salinity off the Gironde estuary. Left: measurements of the CALIBSAT 3 (top) and CALIBSAT 4 (bottom) surveys. Right: computed cross section.

Figure 5. Coupes verticales de salinité devant l'estuaire de la Gironde. A gauche : salinités mesurées durant la campagne CALIBSAT 3 (en haut) et CALIBSAT 4 (en bas). A droite salinités calculées par le modèle.

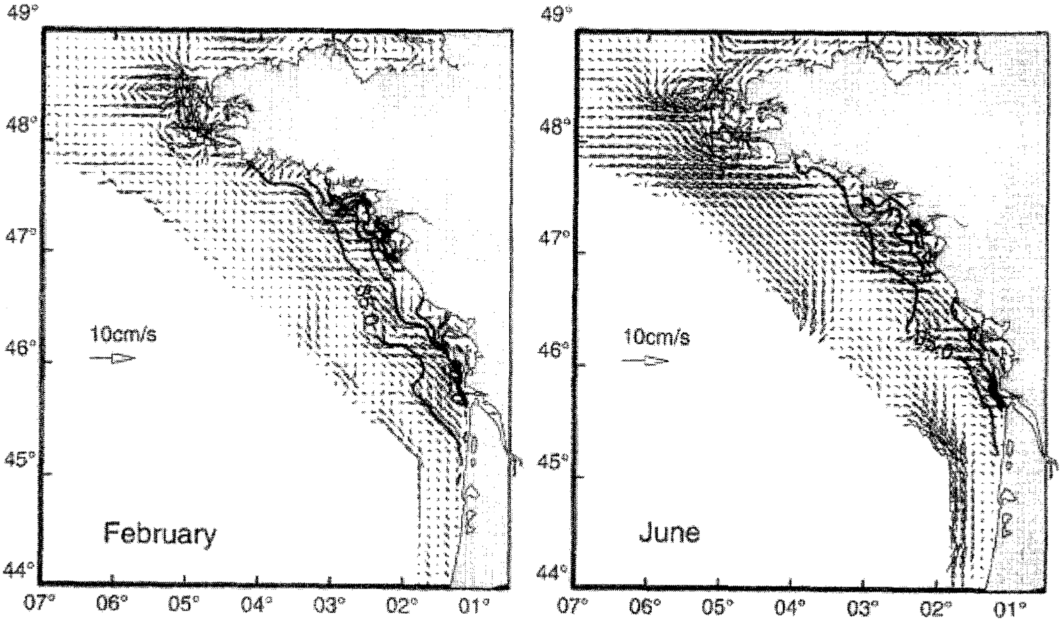

Figure 6. Evolution of computed near-bottom salinity and currents during February and June 1994.

Figure 6. Évolution des salinités et courants calculés près du fond en février et juin 1994.

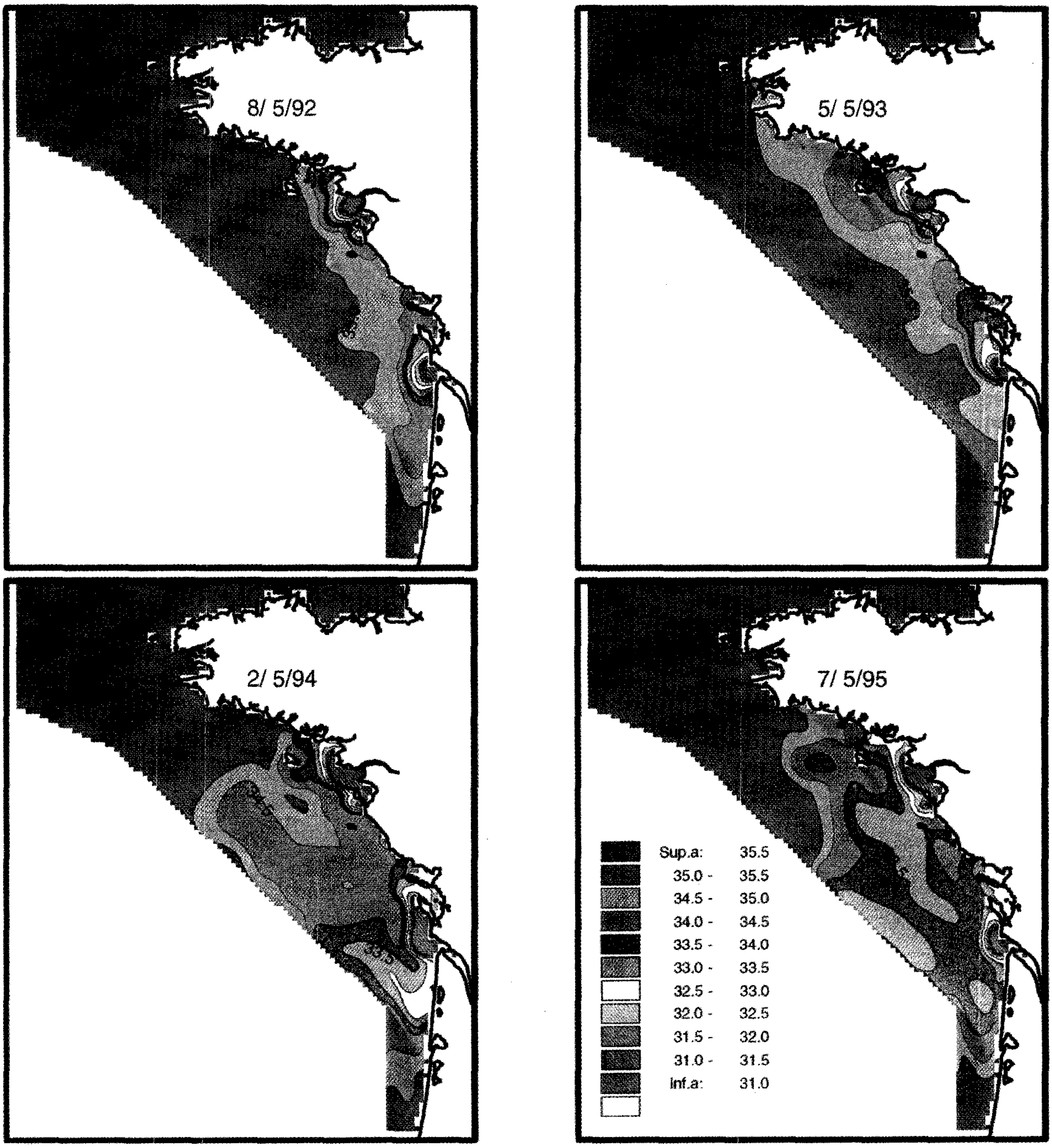

Figure 7. Computed near-surface salinity fields in early May for different years.

Figure 7. Salinités calculées près de la surface au début Mai pour différentes années.

the Vilaine Bay, was outside of the Loire's influence. The Gironde plume spread along the Landes coast. This feature seems to be due to the combined effects of weak run-off, which was not sufficient to create a strong poleward baroclinic current, and moderate north-westerly winds from mid-March.

At the beginning of May, plumes were often driven southwards and dispersed offshore by winds except when wind stress had been weak for a long time, such as in 1993 (*figure 7*). Under these conditions, the plumes still spread northwards along the coast and low salinity waters mainly driven by density gradients reached the western part of Brittany. However, the mid- and outer shelf remained unaffected by the Loire and Gironde influences.

The greatest offshore spreading of low salinity waters on the shelf occurred in years of very large river discharges, such as 1994 and 1995. In this case, the isohaline 34.5 extended over the major part of the shelf area connecting the Loire and Gironde plumes and over the shelf break, as in 1995 (*figure 7*). However, due to the boundary's location, the model cannot accurately simulate such circumstances. The spring conditions of these years led to strong vertical stratification extending over a large part of the shelf.

Thus, the realistic model simulations enable us to describe the behaviour and the features of the Loire and Gironde plumes on the shelf under different conditions of river runoff and winds. Low salinity waters of plumes principally affect the near-shore in the northern part of estuary mouths, forming an along-shore strip between the Gironde and Belle-Ile in winter. The south Brittany, Vendée and Landes coasts and the shelf are occasionally reached, depending on the freshwater supply and wind stress.

4. CONCLUSIONS

The evolution of low salinity waters generated through Loire and Gironde freshwater inputs have been simulated over several realistic years using a 3D model of the Atlantic shelf. The model simulation results were studied for winter and spring seasons, when river runoff occurs.

Simulation has shown that river runoff generates a baroclinic coastal current in winter. Late March or early April clearly marks the change between winter conditions (freshwater extending northwards on the inner shelf) and summer conditions (freshwater spreading offshore and mixing with seawater). The low salinity water masses can reach the shelf break in some years and may be driven outside the model domain by north-westerly winds.

These qualitative results are due to the seasonal cycle of river runoff and wind stress: usually maximum runoff and downwelling-favourable winds in the winter season, and decreased runoff and upwelling-favourable winds in the spring. Spreading direction and offshore dispersal of plumes depend on the balance between the strength of density-driven currents and that of wind stress. Thus, in winter, winds may enhance the northward density-driven spreading of plumes while in spring they often oppose and frequently reverse this transport, dispersing river-induced low salinity waters offshore. Therefore, in spring, wind appears to be the main forcing element for water renewal.

Seasonal and inter-annual fluctuations of the freshwater supply and wind stress lead to high variability of the low salinity expanse on the shelf. In winter, the along-shore extent of the low salinity strip generally covers the coastal area between the Gironde's mouth in the south and Belle-Ile island in the north. The maximum southward extent is along the Landes coast and occurs during strong upwelling-favourable wind events. The maximum northward extent was observed south of Sein Island in western Brittany whenever wind stress was weak during the runoff period, as in 1993. The maximum offshore extent occurred with abnormally high runoffs and strong upwelling-favourable winds, as in 1994 or 1995. In those years, the Loire and Gironde plumes were connected and a large part of the shelf was influenced by low salinity, thus vertically stratified.

Winter and spring circulation of water masses is very similar on the south-east United States continental shelf (South Atlantic Bight, SAB). Twelve rivers along 400 km of coastline produce a total runoff varying from 1 000 to 4 000 $m^3 \cdot s^{-1}$ in spring (March and April). In winter, river discharges from the coast form a frontal zone which extends about 20 km offshore [1]. Low salinity water forms a southward baroclinic current which is intensified in winter by wind stress. During spring, prevailing north-eastward winds (upwelling-favourable) induce offshore transport in the shallow near-surface Ekman layer. Cross-shelf transport of low salinity water masses takes about 2 months [9].

On the inner shelf, in both cases, the driving forces seem very similar, i.e. a balance between the pressure gradient (due to freshwater inputs), Coriolis force and wind stress. However, over the mid- and outer shelf, the SAB is influenced by the Gulf Stream, which induces a northward pressure gradient, whereas the circulation over the French outer shelf and shelf break, although not very well known, is probably less intense.

The variability of Loire and Gironde plume spreading as described by the model could not be entirely validated because of the limited amount of suitable data. However, the model has shown seasonal and year-to-year fluctuations of salinity fields which may lead to chemical and biological modifications of water masses on the shelf. Therefore, the priority for the next step of Atlantic shelf study is to enhance the model's accuracy though verifications and improvements. Current measurements will allow model accuracy in simulating density currents to be checked. Interfacing the model with a meteorological model will take account of more realistic meteorology. Finally, the model's domain will be extended offshore for a better simulation of plumes when they spread outside the shelf.

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