Hydrodynamics of the North Brittany coast: a synoptic study

Marée
Manche Ouest
Courant résiduel
Mélange

Tide
English Channel
Residual current
Mixing

Pierre GARREAU

Laboratoire Hydrodynamique et Sédimentologie, Institut Français de Recherche pour l'Exploitation de la Mer, Centre de Brest, B.P. 70, 29280 Plouzané, France.

ABSTRACT

The tidal hydrodynamics of the northern coast of Brittany is determined by numerical modelling. Long term transportation and mixing are considered for the whole zone. To define areas sensitive to eutrophication (from the hydrodynamic point of view) physical criteria are discussed. An application is carried out for the bay of Lannion and the bay of Saint-Brieuc.

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RÉSUMÉ

Conditions hydrodynamiques sur la côte Nord-Bretagne

Un modèle numérique de marée est appliqué à la côte nord de la Bretagne. Le transport et le mélange à grande échelle de temps sont examinés sur l'ensemble de la zone. Des critères sont proposés pour définir les zones qui, du point de vue hydrodynamique, peuvent être sensibles à l'eutrophisation. La baie de Lannion et celle de Saint-Brieuc font l'objet d'une approche plus détaillée.

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INTRODUCTION

Every year, eutrophication phenomena appear on the European continental shelf. Along the coast of Brittany, sensitive areas are observed, such as the bay of Lannion, whereas other coastal zones remain clean of *Ulvea* or toxic phytoplankton proliferation. Water mass confinement in particular bays is one of the relevant factors for the definition of ecological sensitivity. The aim of this paper is to examine the tidal hydrodynamics of the North Brittany coastal zone, particular attention being paid to vertical and horizontal mixing and long term advection in embayments. Instead of using an advection-dispersion model, such physical properties are derived from a depth-averaged numerical model.

The dynamics of the English Channel has been intensively studied (Pingree, 1980) and the tidal spectroscopy is already wellknown for the sea surface elevation (Le Provost and Fornerino, 1985; Chabert d'Hières and Le Provost, 1978) and for current velocities (Fornerino, 1982). The semi-diurnal tide is the major feature of the zone. The instantaneous peak current amplitudes are about 1 m s^{-1} and the mean tidal range varies from 5 m (at the mouth of the English Channel) to 9 m (at the end of the bay of Mont Saint-Michel). Because of non-linearities, the generated tidal residual current is locally strong, typically 0.2 m s^{-1}. In this process study only the M2 tide and its harmonics are considered and all meteorological forcing has been removed. The model is of the 2D depth averaged type and is briefly described in the second part. Physical parameters concerning mixing and advection are discussed in the third part. Finally an application is reported for the bay of Saint-Brieuc and the bays of Morlaix and Lannion.

EQUATIONS AND NUMERICAL MODEL

The numerical model used in this study consists of a vertical integration of the complete Navier-Stokes equations using the Boussinesq approximation to incorporate the Reynolds stresses. To take into account the strong depth variations and the important surface tidal amplitude, all non-linear terms are conserved.

The zonal and meridional depth-averaged velocities are respectively u (x, y, t) and v (x, y, t). Let z (x, y, t) be the instantaneous sea surface elevation. Therefore the set of equations governing the water movement are :

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial z}{\partial x}+A\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-g\frac{u\sqrt{u^2+v^2}}{Kr^2(H+z)^{4/3}}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}-fu=-g\frac{\partial z}{\partial y}+A\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-g\frac{v\sqrt{u^2+v^2}}{Kr^2(H+z)^{4/3}}$$

$$\frac{\partial z}{\partial t}=-\frac{\partial (H+z)u}{\partial x}-\frac{\partial (H+z)v}{\partial y} \qquad (1)$$

The depth at rest is H (x, y), the Coriolis factor is f and the gravitational acceleration is g. The bottom friction is parametrized by a quadratic law and a Strickler formulation ($Kr = 25\ m^{-1/3}\ s^{-1}$). The turbulent diffusion coefficient A is assumed constant ($A = 90\ m^2\ s^{-1}$).

The numerical model is a finite difference scheme using the alternating direction-implicit (ADI) method (Lendertsee, 1967). The code used was developed by Salomon (Lazure and Salomon, 1991) and includes an automatic treatment of flooding and drying bank. To obtain an efficient resolution of bays and islands, the grid size is 500 m long. Such a semi-implicit model is unconditionally stable for linear equations. Introducing advection and quadratic friction generates a numerical instability. The time step constraint is approximated by

$$\Delta t < \frac{2g\Delta x^2}{Kr^2 H^{4/3}\,|U|}$$

This estimation is in agreement with the range of the time step limit found during different numerical experiments. In deeper regions (H = 80 m), the strength of the current remains strong (about $1\ m\ s^{-1}$); therefore the stability criterion is very constrained. Practically the time step is 11.5 s.

Geographically the model extends from the Aber Benoît (4°40' West) to the bay of Mont-Saint-Michel (1°20' West) as shown in Figure 1. In the Channel islands zone, Jersey is situated on the northern boundary (49°10'). The depth at the western end of the model is relatively deep (*i.e.* about 80 m), whereas that of the coastal zone is less than 30 m. The depth in the entire Channel islands region is typically less than 30 m. The coastline is very indented and capes, bays or reefs are expected to influence the mesoscale circulation.

Practically the domain is a rectangle of 245 x 85 km and the number of grid point is 490 x 170. Only to the north and west are there open boundaries and the tidal forcing (*i. e.* the sea surface disturbance) applied is computed by a similar model which describes the whole North European Shelf behaviour of the M_2 tide (Salomon and Breton, 1990). The mean level variation, the M_2 sea surface movement and all higher harmonics generated inside the domain are included in the boundary forcings. This is an essential condition in regard to the residual motion and this technique allows us to bring the seaward limit nearer to the coast. Let $\vec{n}$ be the vector normal to the boundary. It is also assumed that $\partial\vec{u}/\partial\vec{n} = 0$.

Although harmonics prediction is not the objective of this study, the tidal charts for M_2 and M_4 are shown in Figure 2. The semi-diurnal lunar amplitude grows from West (2.25 m) to East (4.25 m) and the phase lag between Mont-Saint-Michel bay and the Aber Benoît is about two hours. The results compare favourably with data and earlier works (*see* references quoted in introduction). Nevertheless, our model does tend to overestimate slightly the M_2 amplitude. This slight discrepancy of 5 % is also present in the boundary conditions. The explanation can be found in the fact that the damping is not only a function of the M_2 tide alone but of all significant constituents. Other semi-diurnal and diurnal astronomical waves are not included in this simplified study. The quarter-diurnal component (M_4)

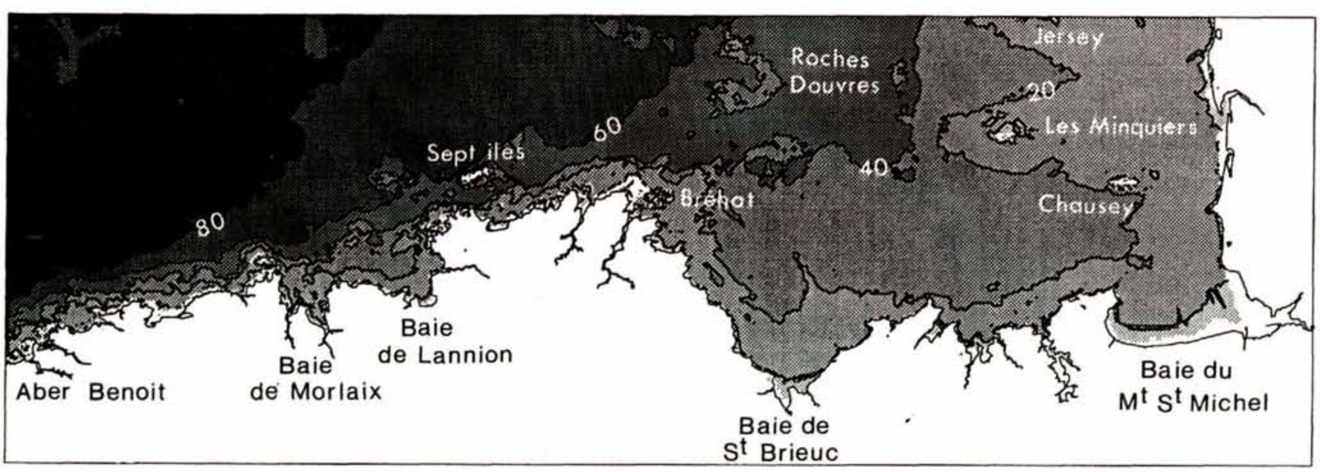

Figure 1

Bottom topography and situation of the zone.

Situation géographique et topographie du fond.

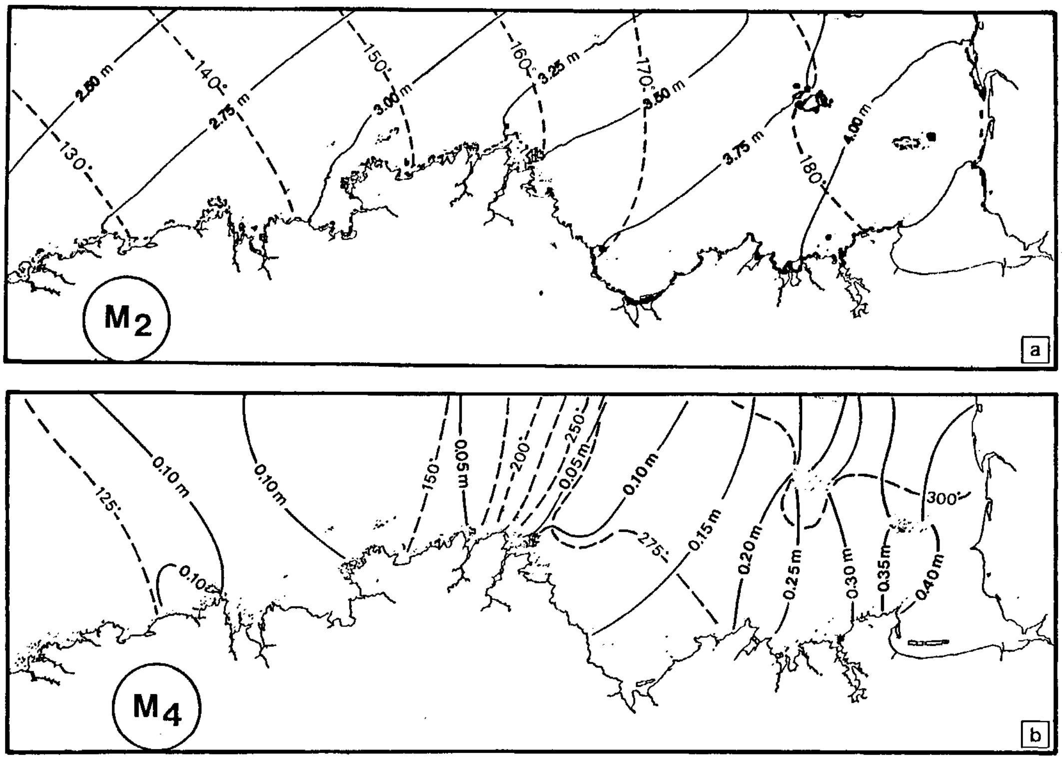

Figure 2

Computed amplitude (in metres) and phase (in degrees) of the M_2 tide and of the first harmonic M_4.

Carte cotidale (amplitude en mètres et phase en degrés) pour les ondes M_2 et M_4.

prediction is very close to measurements and former modelizations. The difference is less than 0.01 m in Saint-Servan (near Saint-Malo), in Saint-Helier (Jersey) and Roscoff and the phase is correct. Because of the same non-linear origin, we believe that some confidence can be given to residual currents. With regard to the objectives of this study (*i.e.* estimation of mixing and long term advection), the assumption has been made that the M_2 tidal effects are correctly reproduced in the model.

PHYSICAL PROPERTIES AND BIOLOGICAL PROCESSES

In such a macrotidal environment, the spatial variation of the biological activity is directly linked to the dynamic properties of water bodies. The description of the transportation of plankton, nutrients or dissolved matters by the tide is classically treated by adding the advection-dispersion equation to dynamics or by using a random walk procedure. Both approaches are efficient when the position, the duration and the quantity of release are known. The approach developed herein is more synoptic and the instantaneous depth-averaged velocity field is used to interpolate some physical criteria which allow the mixing and the advection to be estimated. The time scale of biological processes such as phytoplankton or seaweed proliferation is greater than that of the tide (*i.e.* 12 h 24 mn). Therefore, except for the maximum depth-averaged velocity, all parameters describe a mean property. From the physical point of view, an ecologically sensitive area is a zone of low-mixing high confinement of water bodies and sometimes of strong stratification. A strong tidal current does tend to prevent eutrophication phenomena. The parameters considered include:

- the maximum depth average velocity;
- the residual Lagrangian velocity;
- the seasonal stratification parameter;
- the dispersion capacity.

The biologist often requires the definition of a characteristic time scale for water renewal. Many definitions (residence time, flushing time, transit time, age, *etc.*) exist in the literature (Hidetaka, 1984) and the difficulty is to circumscribe the problems to be solved. The first stage is to specify the volume of water which is assumed to exchange materials with a "clean open sea". This volume is either a bay (geographical criterion) or a residual gyre around a bank or near a cape (hydrodynamics criterion) or a sensitive area (ecological criterion). The second stage is to characterize the release. Is the discharge of matter localized in time and space or continuous ? Finally, is the dissolved matter conservative or not ? From the above, it is obvious that the definition of a characteristic time in synoptic studies is not available. Nevertheless, in this paper, a time scale is derived from the mean Lagrangian velocity and applied to the bay of Saint-Brieuc.

The maximum depth average velocity

During a complete tidal period, the hodograph of the depth-averaged velocity vector is described by a closed curve named the tidal ellipse (*see* Fig. 3). At a given time the velocity is a maximum and in most locations the tidal current never vanishes. In the whole area the polarization is cyclonic, except perhaps when the currents are rectilinear as between Bréhat and Chausey or in the western part of the domain.

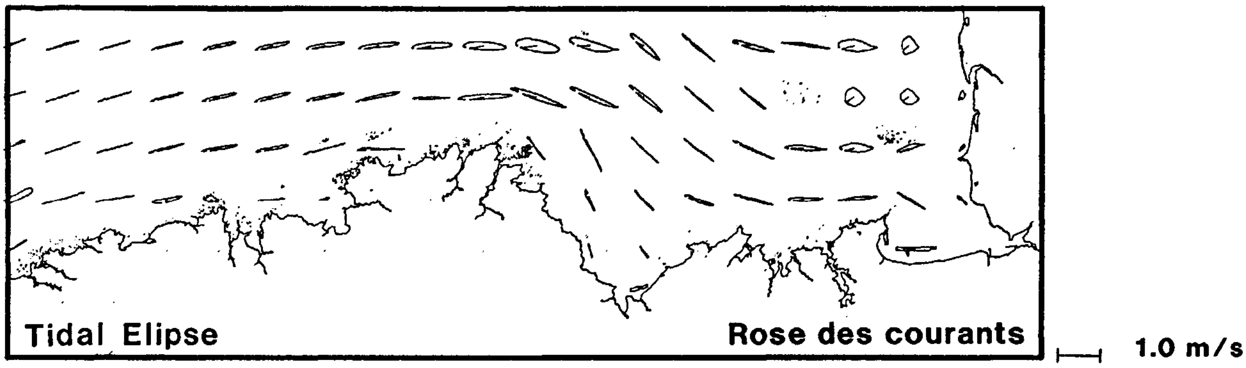

Figure 3

Tidal ellipse.

Ellipse de marée.

The maximum current occurs between Bréhat and Roches Douvres as shown in Figure 4, and is generally about 1.5 m s^{-1} and locally about 2 m s^{-1}. Another area where strong tidal currents prevail is located near capes and in the channels between the islands and mainland (see the Sept Iles area, for instance). On the other hand, because the bays are generally semi-enclosed the tidal current at the head is very slow except when the tidal flat is very extended as in the eastern part of the bay of Mont-Saint-Michel.

Consequently, despite an important tidal range the currents are relatively small at the far end of embayments, where biological species which need calm water can find favourable environments.

If the time variation of the current is assumed nearly sinusoidal, an approximation of the tidal excursion along the major axis of the tidal ellipse can be calculated using the map of maximum velocity (U_{max}). The amplitude of the displacement of a water particle during a tidal period (T = 44712 s) is in the range of :

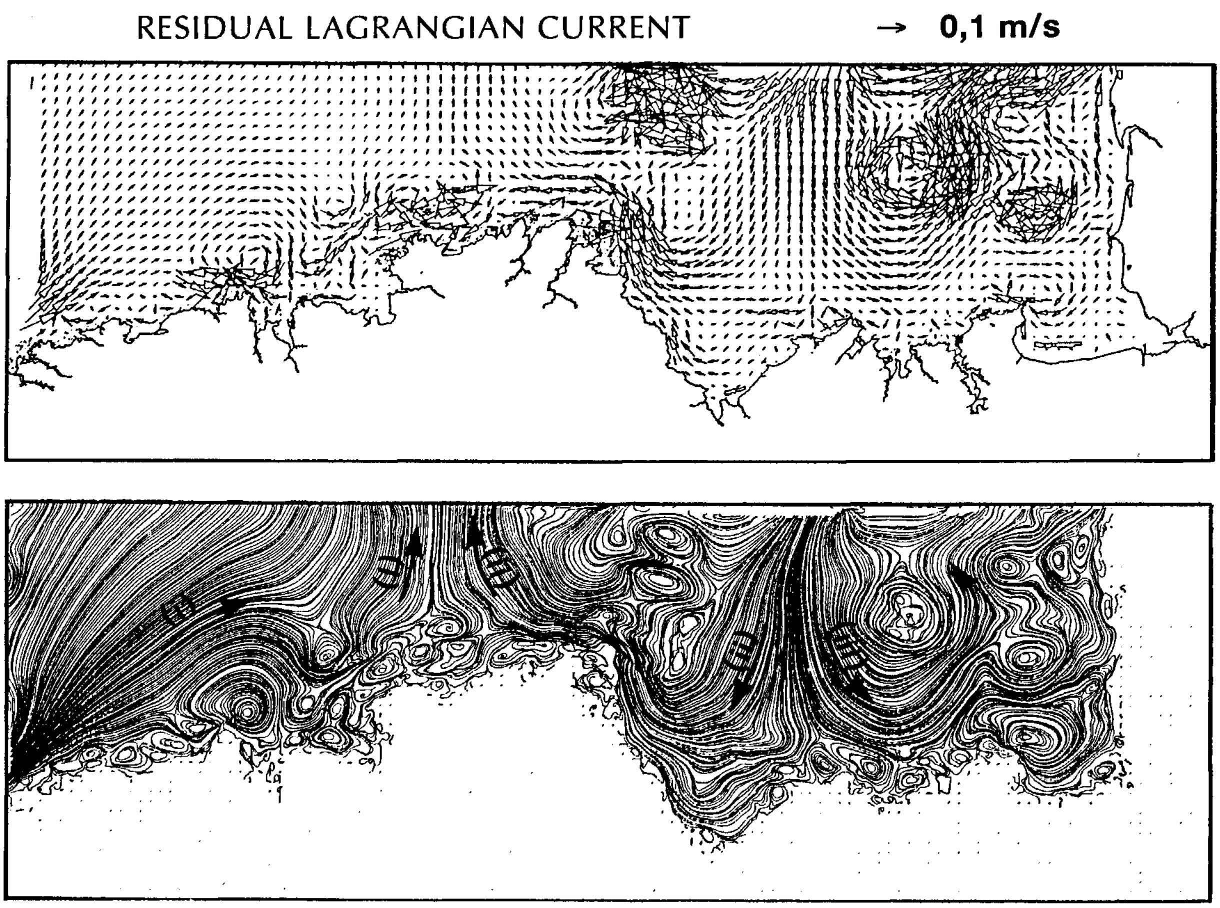

Figure 5

Residual Lagrangian velocity fields (a) and derived long-term trajectories (b).

Champs de courant résiduel lagrangien (a) et trajectoire à long terme associée (b).

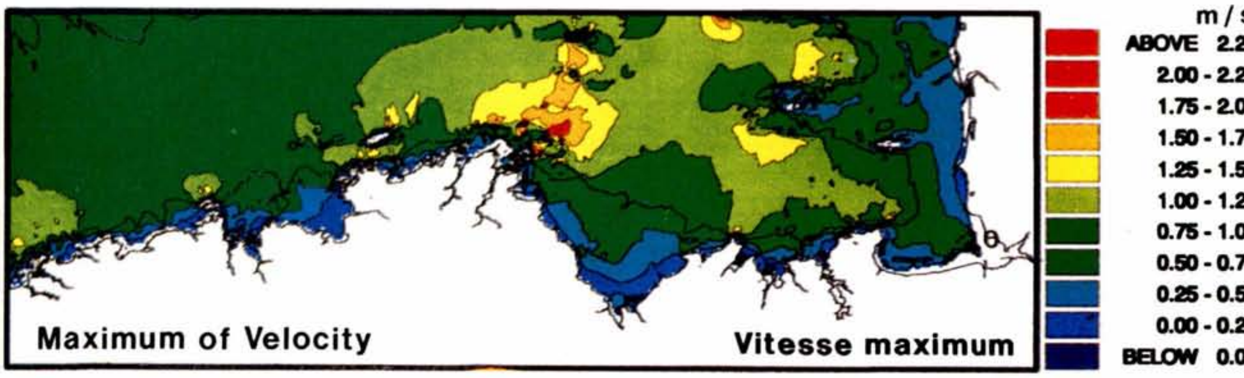

Figure 4

Maximum of instantaneous velocity during a M_2 tidal cycle.

Maximum de vitesse atteint par le courant au cours d'un cycle de marée.

$$E = \frac{T.U_{max}}{2\pi}$$

For instance, between Bréhat and Roches Douvres the tidal displacement amplitude of a water parcel can reach 15 km ($U_{max} \approx 2$ m s^{-1}), whereas in the bay of Lannion the latter is less than 2 km ($U_{max} \approx 0.25$ m s^{-1}).

Finally the zones of strong currents are generally well mixed (horizontally and vertically) but the long-term advection (estimated below) is not necessarily important.

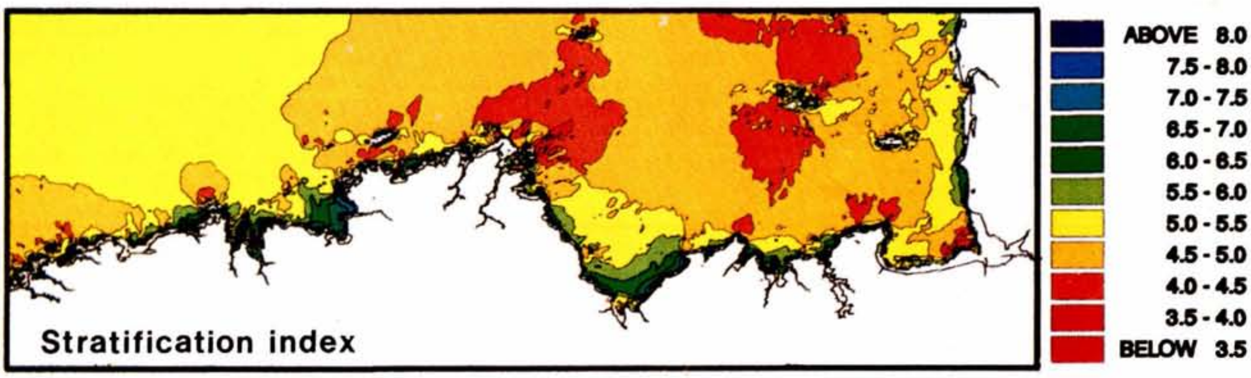

Figure 6

Stratification parameter $Log_{10}\left(\frac{H}{|u|^3 C_d}\right)$ *derived from the numerical model of M_2 tide.*

Paramètre de stratification $\mathrm{Log}_{10}\left(\frac{H}{|u|^3 C_d}\right)$ estimé à partir du modèle numérique.

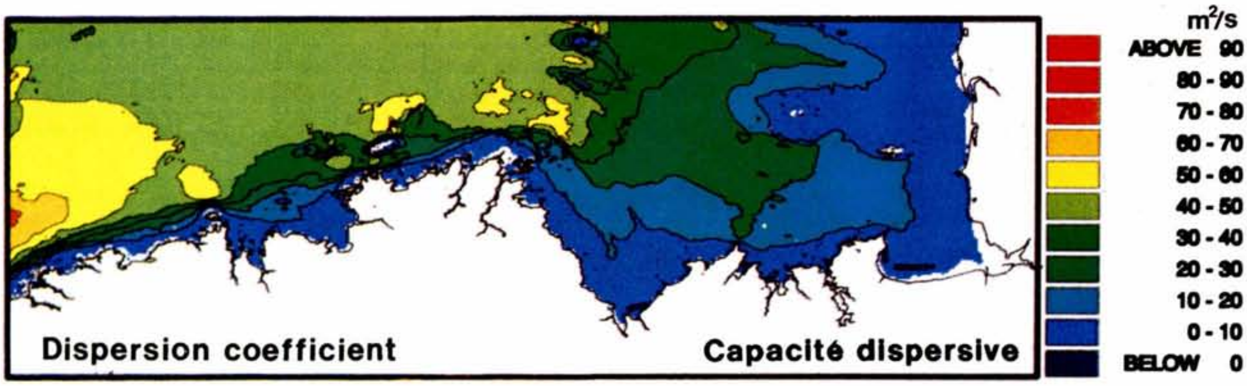

Figure 7

Estimation of the horizontal dispersion coefficient due to vertical shear.

Coefficient de dispersion horizontale due au cisaillement vertical.

Residual Lagrangian velocity

Long-term transportation of dissolved matter is generally poorly described by the mean Eulerian velocity (*i.e.* at fixed position) because the latter can differ highly from the Lagrangian mean velocity (*i.e.* following a marked particle). The difference was named Stokes velocity by Longuet-Higgins (1969). Using a numerical model it is a straightforward matter to evaluate by numerical integration and bilinear interpolation the track and thus the mean Lagrangian velocity. The known drawback of this kind of computation is that the residual Lagrangian velocity for one starting position varies with the starting time (Foreman *et al.*, 1992).

Another way is performed here. During a tidal cycle, the trajectory of a water parcel is a curve and it is possible to calculate the mean position (*i.e.* the barycentre) of the track. For one particle, this barycentre is moving as the mean motion. In more mathematical formalism, it is always possible to consider that the instantaneous position $\overline{x(t)}$ of a water column is the sum of a mean position $\overline{X(t)}$ [*i.e.* tidally averaged] and a perturbation $\overline{\zeta(x,t)}$ which describe oscillating tidal movement. That is :

$$\overline{x(t)} = \overline{X(t)} + \overline{\zeta(x,t)}$$

$$\text{where } \overline{X(t)} = \frac{1}{T}\int_{t-T/2}^{t+T/2} \overline{x(t)}\, dt$$

$$\text{and } \int_{t-T/2}^{t+T/2} \vec{\zeta}\,(x,t)\, dt = 0.$$

The long-term movement is defined as the velocity of the displacement of the mean position. An approximation of this concept (*i.e.* the barycentric method as described in Salomon *et al.*, 1988) is performed herein. The reader will find some theoretical considerations in the work of Andrew and McIntyre (1978). The result is a velocity field independent of any starting time (Fig. 5 *a*). The residual Lagrangian current is intensified near capes and around islands or reefs. This residual velocity can reach locally 0.20 m s^{-1}, but is generally less than 0.05 m s^{-1}. The long-term trajectories computed using the residual Lagrangian current (Fig. 5 *b*) show two scales of residual dynamics. The first concerns small eddies (diameter < 20 km) generated by local topography or coastlines. If they are situated in low mixing area (as at the far end of a bay), they can efficiently trap water and pollutants. The bay of Lannion is a typical example of these patterns.

The second scale divides coastal waters into three different circulations :

1) Oceanic water coming from the Celtic Sea flows along the coast to the Sept Iles, then heads to the north.

2) Water coming from the north, between Jersey and Roches Douvres, describes an anticyclonic gyre before flowing northwards near the Sept Iles region.

3) Finally, a cyclonic gyre exists around Jersey, Chausey and Les Minquiers.

Each water mass has characteristic physical properties (*i.e.* temperature, salinity, *etc.*). Because of different depths and residence times, it is possible to observe the thermal response of these three circulations to seasonal variation (Jégou and Salomon, 1992). The first one is from "oceanic behaviour" and the mean thermal amplitude of temperature between summer (typically 16°C) and winter (typically 10°C) is only about 6°C. The last one is more continental and the thermal amplitude is greater, typically 12°C. In February the mean sea-water temperature is approximately 8°C and in August 20°C in the bay of Mont-Saint-Michel. Radionuclides released in La Hague from a nuclear fuel reprocessing plant situated in the North Cotentin is an efficient tracer. The results found by Guéguéniat *et al.* (1988) confirm this large-scale circulation. From a physical point of view the apparent "wall" which separates Celtic water from more continental circulation is something of a curiosity. The northward flow is not trapped by a topographic variation and the most interesting way to explain this important feature of the North Brittany coastal dynamics is perhaps by considering the M_2 and M_4 standing wave structures.

Stratification parameter

During spring and summer, the surface heat fluxes tend to increase the stability of the water column and to create a seasonal thermocline. In contrast the turbulence generated by the bottom friction tends to break down the thermocline generating process. Large depth and low currents are conducive to thermocline generation, whereas shallow depths and strong flows destroy the stability of the water column.

Based on energy considerations, Simpson and Hunter (1974) pointed out a useful ratio u^3/H as stratification index. Using a numerical model, Pingree (1980) applied this concept to predict the thermocline extension in the English Channel. Remote sensing was in agreement with critical value proposed for the Celtic Sea and the English Channel. The same formulation is applied herein but in the international system of units instead cgs. Thus the stratification index is defined as

$$S = \mathrm{Log}_{10}\left(\frac{H}{|u|^3\, C_d}\right)$$

where $|u|$ is the modulus of the instantaneous velocity and C_d is a non dimensional drag coefficient commonly used in numerical model for the M_2 tide. Following Pingree (1980) in the English Channel, the value of the drag coefficients and of the critical value of S are:

$C_d = 2.5\ 10^{-3}$
$S = 5.5$.

Values greater than 5.5 correspond to possible stratification. The whole area is vertically well mixed and no seasonal thermocline is expected for mean tide (*see* Fig. 6). Near the coast the observed high values are the consequence of small depths, therefore the effects of swell-induced bottom mixing will become locally important. Nevertheless, during neap tides and for favourable meteorological condition a transitory stratification occurs in the far end of the bay of Lannion and of the bay of Saint-Brieuc.

Horizontal dispersion

When considering horizontal dispersion by tidal and residual currents, two mechanisms are classically involved. The first is the consequence of a purely horizontal advective process is named "differential convection" or sometimes "Lagrangian chaos" (Zimmerman, 1986) and is a consequence of the horizontal variability of velocities due to the shape of coastline or topography. The second deals with vertical shear producing horizontal dispersion (Bowden, 1983). It is assumed herein that the greater part of the differential convection is taken into account in the Lagrangian circulation described above. Therefore the turbulence generated by small eddies shown Figure 5 *b* is excluded from the determination of an horizontal coefficient of dispersion.

In vertically well mixed water the vertical shear effect is a key component of horizontal mixing and the order of magnitude of the longitudinal dispersion coefficient K_x is given by Bowden (1983). It is :

$K_x \approx uH$

For tidal currents, this value is tide-averaged and in the case of an elliptical pattern of velocities the rate of dispersion parallel to the minor axis would be different (*i.e.* less) than that parallel to the major axis. For short diffusion time (*i.e.* one tidal period) and small patch dye experiments Talbot and Talbot (1974) agree in many cases with this range for a horizontal dispersion coefficient. Therefore in this global approach the mean eulerian flow $\overline{(H+z)u}^{\,t}$ is used as an order of magnitude for K_x. The result is shown in Figure 7. Dispersion is in the range of 10 $m^2 s^{-1}$ to 70 $m^2 s^{-1}$ and is particularly weak at the end of bays. Nevertheless it is important to note that from the large-scale point of view, mixing is already described by Lagrangian residual eddies shown in Figure 5 *b*. This kind of turbulence certainly prevails in the eastern part of the domain.

APPLICATION

To illustrate the usefulness of this approach, two embayments are examined in greater detail. Figure 8 *a* shows the full resolution of the mean Lagrangian velocities in the vicinity of the bay of Morlaix and of the bay of Lannion. In the west, the residual currents are stronger and a small-scale anticyclonic eddy is generated by a cape effect behind the Ile de Batz. The cyclonic gyre in the centre of the zone is a consequence of a shoaling bank. Both structures contribute to the renewal of the

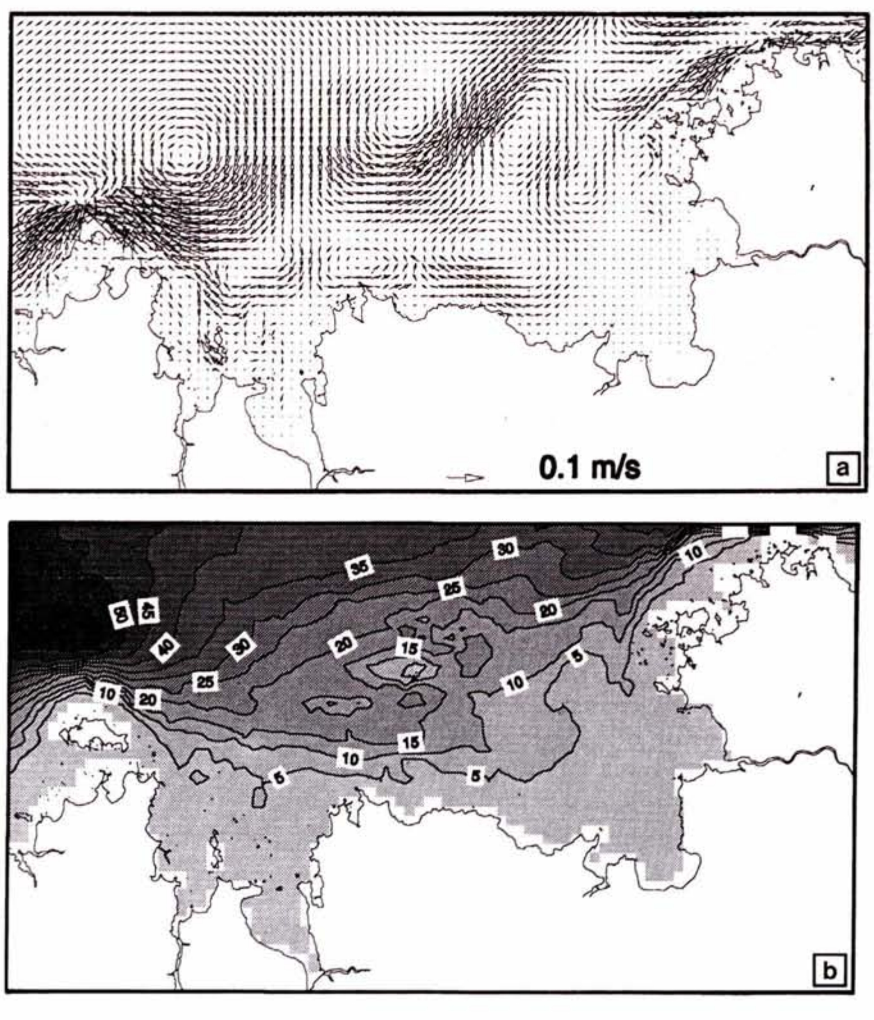

Figure 8

Long-term dynamics of the bay of Morlaix and the bay of Lannion. Residual Lagrangian velocity (a) is compared to horizontal dispersion [given in $m^2 s^{-1}$] (b).

Dynamique à long terme en baie de Morlaix et en baie de Lannion. Vitesse résiduelle lagrangienne (a). Coefficient de dispersion horizontale [$m^2 s^{-1}$] (b).

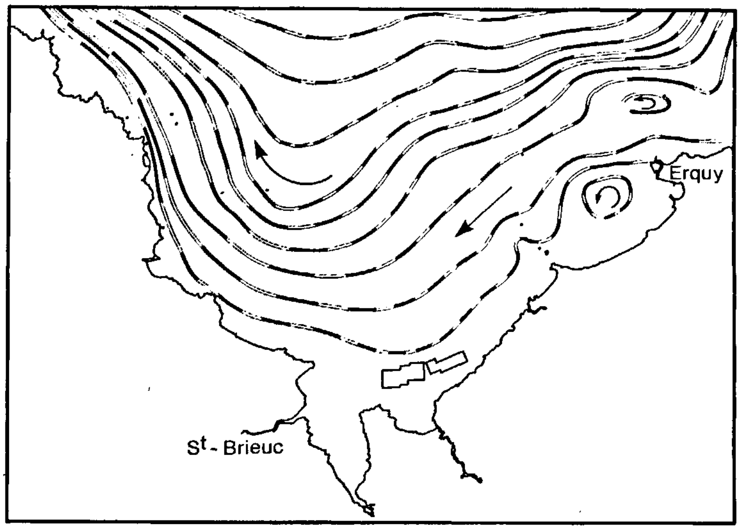

Figure 9

Timing of the water masses motion in the bay of Saint-Brieuc. One segment corresponds to one day.

Transit des masses d'eau dans la baie de Saint-Brieuc. Un segment correspond à un jour de trajet.

water in the western part. Moreover this water is advected into a stronger mixing zone. In contrast, the eastern region (*i.e.* the bay of Lannion) is characterized by a slow residual current and a low dispersion coefficient (Fig. 8 *b*). The physical approach is in agreement with observation: the dynamics of the bay of Lannion is conducive to eutrophication.

The bay of Saint-Brieuc is largely open and the residual circulation is simpler than in the former embayment. The water flows increasingly strong from east to west and two eddies are situated near the Cap d'Erquy. The timing of the water mass movement in the bay is shown in Figure 9. Each black or white segment of tracks corresponds to one day of long-term advection. A simple addition permits the evaluation of transit time. Typically the duration of the transit from east to west is twenty or thirty days long. Note the acceleration of the displacement in the western part of the bay). The results are in agreement while Thouzeau and Le Hay (1988) who study the behaviour of *Pecten maximus* larvae. From an ecological point of view, the eastern region is certainly more sensitive to pollutant.

CONCLUSION

The numerical model described herein is an efficient tool for obtaining an overview of long-term circulation and mixing in a zone largely dominated by tidal dynamics. In eutrophication or phytoplankton proliferation, biological processes are closely related to physical properties of the water movement and to nutrient input. This kind of work permits comparison between ecologically sensitive areas and the local dynamics and hence the prediction of future problems. However, this does not replace more local studies at the scale of a bay, but gives objective information concerning the choice of the boundary of a sub-model.

Acknowledgements

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