

Modelling the nitrogen cycle in the Channel: a first approach

Channel
Box-model
Nitrogen
Phytoplankton

Manche
Modèle en boîtes
Azote
Phytoplankton

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ABSTRACT

A simple model of the nitrogen cycle in the Channel is proposed. Based on the long-term circulation, this box-model permits the description of the spring phytoplankton bloom in the whole Channel. Spring western thermal stratification has not been taken into account; consequently, the earliest phytoplanktonic development is observed in the eastern Channel, followed by the western, deeper part. This model also shows the influence of nutrient supply from the rivers on the Channel ecosystem, and particularly the influence of the river Seine on the chlorophyll concentrations along the eastern French coast. Comparison of calculated data with measurements shows a fairly good agreement in the eastern Channel but discrepancies are encountered for the western part. These problems are discussed and improvements of the model are proposed.

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RÉSUMÉ

Modélisation du cycle de l'azote en Manche

Un modèle simple du cycle de l'azote en Manche est proposé. Utilisant la circulation à long terme, ce modèle en boîtes permet la description du bloom phytoplanktonique dans toute la Manche. La stratification thermique printanière à l'Ouest n'étant pas prise en compte, le développement phytoplanktonique est précoce en Manche orientale et plus tardif dans la partie occidentale, plus profonde. Notre modèle souligne également l'influence des apports en sels nutritifs par les rivières sur l'écosystème de la Manche, et particulièrement l'influence de la Seine sur les teneurs en chlorophylle le long de la côte française de Manche orientale. La comparaison des valeurs calculées avec les mesures montre un assez bon ajustement à l'Est, mais des divergences sont rencontrées en Manche occidentale. Ces problèmes sont discutés et des améliorations du modèle sont proposées.

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INTRODUCTION

Modelling the cycle of elements such as nitrogen can be applied to an epicontinental sea like the Channel in order

to extract the main trends of the annual cycle. Furthermore, in coastal zones, the model permits the study of a possible eutrophication and of processes which govern it.

The Channel is a very interesting area for this type of study because its ecosystem is influenced by continental inputs and particularly by nutrient supply from the rivers. Of particular interest is the fate of these inputs in connection with the long-term circulation, which is now better known and modelled. This circulation individualizes interesting areas like the Normano-Breton gulf, where eddies lead to high residence times. The western Channel, where a seasonal thermocline appears in summer, is also to be distinguished from the eastern part, where waters are considered as completely mixed throughout the year.

The purpose of this paper is to present the results of a simple model of the nitrogen cycle in the Channel. In this first approach, we have focused solely on winter inorganic nitrogen concentrations and on the spring phytoplankton bloom. This model has been elaborated with the help of *Elise* software developed at IFREMER (Menesguen, 1991).

HYDRODYNAMIC SUBMODEL

Long-term circulation

Our model is based on the results of a 2D-numerical model of tides in the Channel, developed by Salomon and Breton (1991) and used to compute the long-term tidal circulation.

With the help of long-term trajectories issued from this model, a division of the Channel into a unique layer of 34 boxes has been proposed, for use in the ecological model (Fig. 1). Each box is assumed to be homogeneous, and advective residual fluxes between boxes are automatically calculated by *Elise* software.

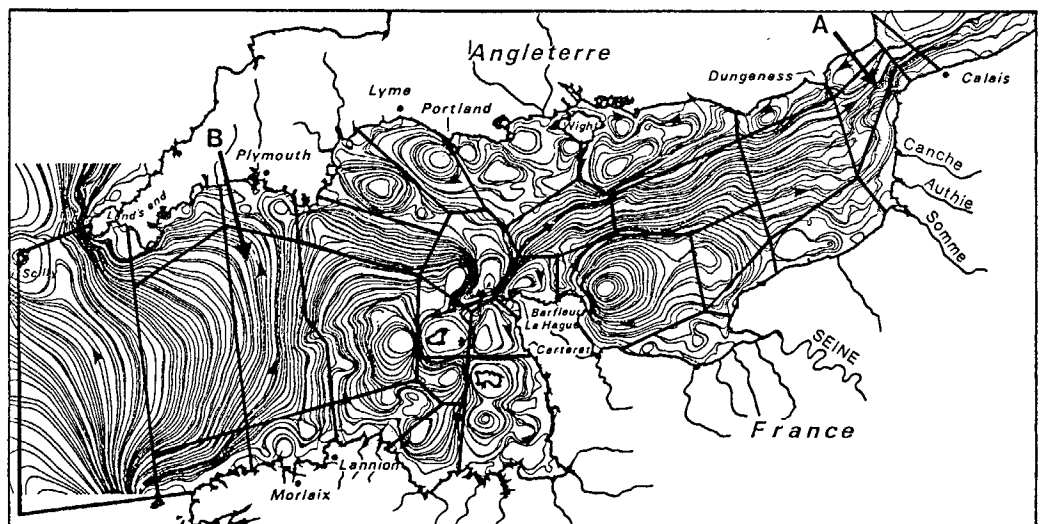
Boxes have been designed according to the following considerations:

- identification of coastal zones, where nutrient supply from the continent may be important;
- alignment of box faces along (or perpendicular to) trajectories;
- isolation of eddies, as in the gulf Normano-Breton, where high residence times are suspected to enhance biological production.

Figure 1

Residual circulation (after Salomon and Breton, 1991) and definition of the boxes in the Channel. Boxes A (Dover Strait) and B (western Channel) are used for calibration. The main rivers discharging into the Channel are shown.

Circulation résiduelle (d'après Salomon et Breton, 1991) et définition des boîtes dans la Manche. Les boîtes A (Pas-de-Calais) et B (Manche occidentale) sont utilisées pour la calibration. Les principales rivières se déversant dans la Manche sont figurées.



Dispersion

As only residual currents have been taken into account for advective fluxes, tidal mixing has been considered as dispersion. *Elise* software considers horizontal dispersion in two ways: as parallel to residual currents (with a coefficient K_x); and as perpendicular to them (K_y).

Calibration of these dispersion coefficients between boxes has been achieved using a steady-state simulation for a conservative tracer: salinity. The inputs to the model are water originating in the Atlantic Ocean (salinity equal to 35.3) and the main rivers discharging into the Channel, with a salinity equal to zero (Fig. 1). Flow rates of the rivers have been set to the monthly values actually measured during the year 1980, if available, and otherwise to interannual monthly averages. The most important river is the Seine, whose catchment area accounts for about 2/3 of the totality of the catchment areas of the rivers flowing into the Channel (Taylor *et al.*, 1981).

Results of the simulation obtained with coefficients of dispersion respectively equal to $500 \text{ m}^2 \cdot \text{s}^{-1}$ for K_x and $100 \text{ m}^2 \cdot \text{s}^{-1}$ for K_y show a relatively good agreement with historical average values [C.I.E.M., 1933 (Fig. 2 a and b)]. The main characteristics of the salinity isolines are respected. The model gives decreasing values of salinities from the Atlantic Ocean to the North Sea. Moreover, we can notice low salinities areas:

- in the Normano-Breton gulf, due to fresh water inputs and low dispersion with central Channel;
- in the bay of Seine and all along the eastern French coast, as the result of inputs from the river Seine. Water coming from the Seine flows along the French coast as far as the Dover Strait, forming with inputs from the rivers Somme, Canche and Authie the "coastal river" (Brylinski *et al.*, 1991). The "coastal river" represents low-salinity and nutrient rich waters flowing between the continent and offshore waters.

Discrepancies between results of the model and data can be explained either by the lack of some river inflows in the model, especially on the English coast or, and mainly by the lack of precision due to box-models, which underlines the great influence of water coming from the Atlantic Ocean.

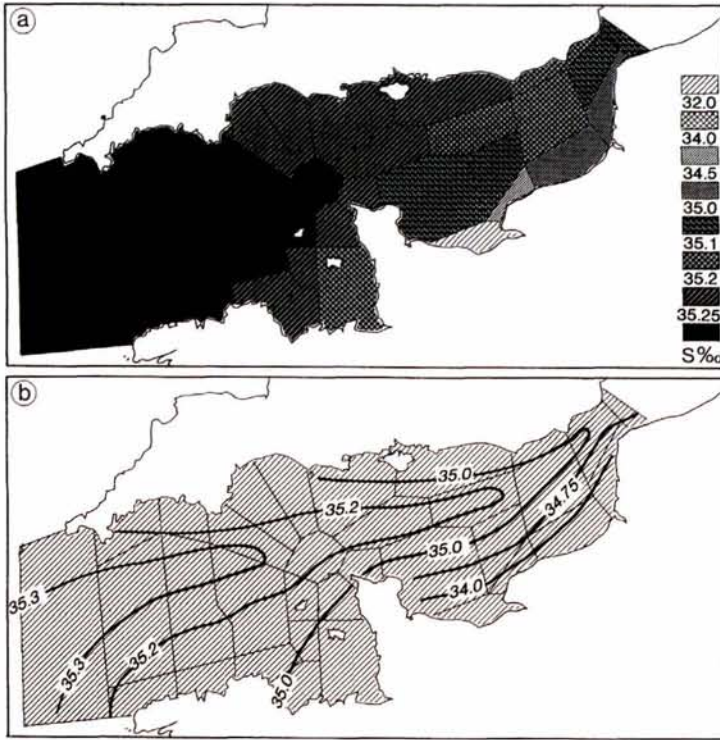


Figure 2

Computed salinity at day 45 (a). Historical monthly average values of salinity [C.I.E.M., 1933 (b)].

Salinité simulée à la date 45 (a). Valeurs moyennes mensuelles historiques de salinité [C.I.E.M., 1933 (b)].

BIOLOGICAL SUBMODEL

Conceptualization

This model and its equations are inspired by the model described in Chapelle (1991).

In this first approach, the nitrogen cycle has been described on the basis of four state variables only (Fig. 3):

- inorganic nitrogen;
- phytoplanktonic nitrogen;
- detrital nitrogen in the water;
- benthic organic nitrogen.

Four forcing variables have been taken into account:

- photoperiod (daily values);
- daily light intensity at noon (daily values);
- temperature (monthly averages);
- non-chlorophyllous extinction coefficient (monthly averages).

Surface light intensity has the same value for all boxes and has been measured at Caen (Normandy) for the year 1980. Total light intensity has been halved because only visible light is used by phytoplankton for photosynthesis. Concerning the temperatures, we have used the results of a thermal model of the Channel (Agoumi, 1982). Extinction coefficients (k_{NC}) have been taken from Agoumi (1985). These coefficients are time-varying (seasonal pattern) and spatially-varying, decreasing from the coastal areas to the offshore zone. The eastern Channel is more turbid than the western. For example, in the central part of the Dover Strait, extinction coefficients vary from 0.2 m^{-1} in winter to 0.05 m^{-1} in summer, and from 0.4 to 0.1 m^{-1} in the coastal area of this zone.

The processes involved in the model are the following:

- phytoplankton growth and mortality. Growth is limited either by light or by nutrient concentration. According to

Liebig's law, the growth rate is driven by the minimum of light and nutrient limitations. The light limitation is of Steele's type, the nutrient limitation is of classic Michaelis type;

- phytoplankton sinking, depending on nutritional limitation of the cells (Titman and Kilham, 1976) and on turbulence. In a first approximation, turbulence has been parametrized with the help of extinction coefficients:

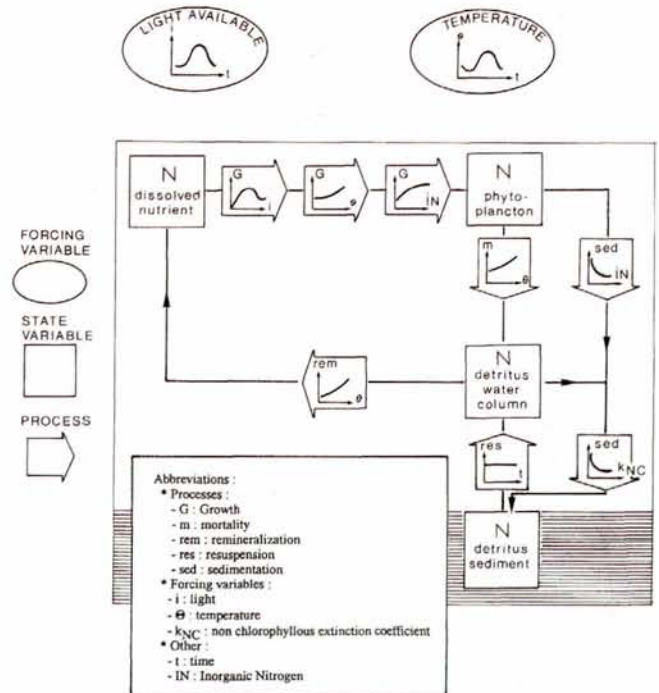


Figure 3

Conceptual scheme of the biological model.

Schéma conceptuel du modèle biologique.

Table

Equations governing the processes occurring in a box and values of the parameters of the model.

Équations régissant les processus écologiques dans une boîte et valeurs des paramètres du modèle.

X_1 : inorganic nitrogen ($\mu\text{mol.l}^{-1}\text{ N}$)

X_2 : phytoplanktonic nitrogen ($\mu\text{mol.l}^{-1}\text{ N}$)

X_3 : detrital nitrogen in the water ($\mu\text{mol.l}^{-1}\text{ N}$)

X_4 : organic benthic nitrogen ($\mu\text{mol.m}^{-2}\text{ N}$)

$$\frac{dX_1}{dt} = r_{\min} \times f_T \times X_3 - \mu_{\max} \times f_T \times \min(f_N, f_L) \times X_2 \quad (1)$$

$$\frac{dX_2}{dt} = [(\mu_{\max} \times f_T \times \min(f_N, f_L) - m_P \times f_T - \frac{v_{SP}}{h}) \times X_2] \quad (2)$$

$$\frac{dX_3}{dt} = m_P \times f_T \times X_2 + \frac{(r_{\text{sus}} \times X_4)}{h \times 1000} - (r_{\min} \times f_T + \frac{v_{\text{SMO}}}{h}) \times X_3 \quad (3)$$

$$\frac{dX_4}{dt} = (v_{\text{SP}} \times X_2 + v_{\text{SMO}} \times X_3) \times 1000 - r_{\text{sus}} \times X_4 \quad (4)$$

h : box depth (m)

θ : temperature ($^{\circ}\text{C}$)

Action of the temperature: $f_T = \exp^{k_T \times \theta}$ (Arrhenius' formulation)

Action of the light: $f_L = \iint \left(\frac{I_{z,t}}{I_{\text{sat}}}\right) \times \exp^{(1 - I_{z,t}/I_{\text{sat}})} \times dz \times dt$ (Steele's formulation)

Light intensity at depth z : $I_{z,t} = I_{0,t} \times \exp^{-k_L \times z}$

Light extinction coefficient: $k_L = k_{\text{NC}} + 0.054 \times (X_2)^{2/3} + 0.0088 \times X_2$ (Riley's formulation)

Action of nutrients: $f_N = \frac{X_2}{X_2 + k_N}$ (Michaelis' formulation)

Sedimentation velocity:

- of phytoplankton: $v_{\text{SP}} = [v_{\text{SPmin}} \times \text{Neff} + v_{\text{SPmax}} \times (1 - \text{Neff})] \times \text{Teff}$

Effect of nutrients: $\text{Neff} = (f_N)^{1/5}$

Effect of turbulence: $\text{Teff} = 1 - 0.8 \times \left(\frac{k_{\text{NC}}}{k_{\text{NCmax}}}\right)^2$

- of detrital nitrogen: $v_{\text{SMO}} = v_{\text{SMOmax}} \times \text{Teff}$

Parameter	Definition	Unit	Value	Reference
μ_{\max}	Maximum growth rate at 0 $^{\circ}\text{C}$	d^{-1}	0.6	Paasche (1973)
k_T	Coefficient in Arrhenius' formulation	$^{\circ}\text{C}^{-1}$	0.07	Eppley (1972)
I_{sat}	Optimal light intensity	W.m^{-2}	70	Mortain-Bertrand <i>et al.</i> (1988)
k_N	Half-saturation constant for inorganic nitrogen	$\mu\text{mol.l}^{-1}\text{ N}$	1.5	Eppley <i>et al.</i> (1969)
m_P	Mortality rate at 0 $^{\circ}\text{C}$	d^{-1}	0.05	calibration
v_{SPmin}	Minimal sedimentation velocity of phytoplankton	m.d^{-1}	0.5	Smayda (1970)
v_{SPmax}	Maximal sedimentation velocity of phytoplankton	m.d^{-1}	2	id.
v_{SMOmax}	Maximal sedimentation velocity of detrital nitrogen	m.d^{-1}	1	calibration
r_{\min}	Mineralization rate at 0 $^{\circ}\text{C}$	d^{-1}	0.05	Vinogradov <i>et al.</i> (1973)
r_{sus}	Resuspension rate	d^{-1}	0.01	calibration

sinking is considered to be minimized by turbulence when extinction coefficients reach their maximum in winter. k_{NCmax} is the maximal value for k_{NC} ;

- detrital nitrogen remineralization and sinking. Sinking depends on turbulence, in the same way as for phytoplankton. Remineralization is a temperature-dependent, first order process;

- resuspension of benthic organic nitrogen. Benthic detrital nitrogen is resuspended in the water column, with a constant rate.

Finally, the time variations of the different state variables are expressed as follows :

$$\frac{d(\text{Ninorg})}{dt} = \text{remineralization-growth} \quad (1)$$

$$\frac{d(\text{Nphyto})}{dt} = \text{growth-mortality-sinking} \quad (2)$$

$$\frac{d(\text{Ndet})}{dt} = \text{mortality + resuspension} - \text{remineralization - sinking} \quad (3)$$

$$\frac{d(N_{org})}{dt} = \text{sinking } (N_{phyto} + N_{det}) - \text{resuspension} \quad (4)$$

Table 1 gives the detailed equations and the values of the parameters of the model. Some parameters have been calibrated qualitatively with the help of *in situ* data found in the literature (Bentley, 1984; Dupouy, 1982).

Boundary conditions

The model has been run until yearly periodicity has been reached for all the state variables in every box, provided

that all the forcing variables and the boundary conditions have been considered as pure yearly periodical functions.

Concerning inputs from the ocean, the values retained are the concentrations of inorganic nitrogen and phytoplankton near the Ushant front, because water flowing into the whole Channel, as indicated by the residual circulation, comes from this area. These values are extrapolated from Morin *et al.* (1991) on the Armorican shelf.

Values of state variables in the rivers have been set to zero, except for inorganic nitrogen. Measurements from year 1980 have been retained if available, and interannual average values otherwise.

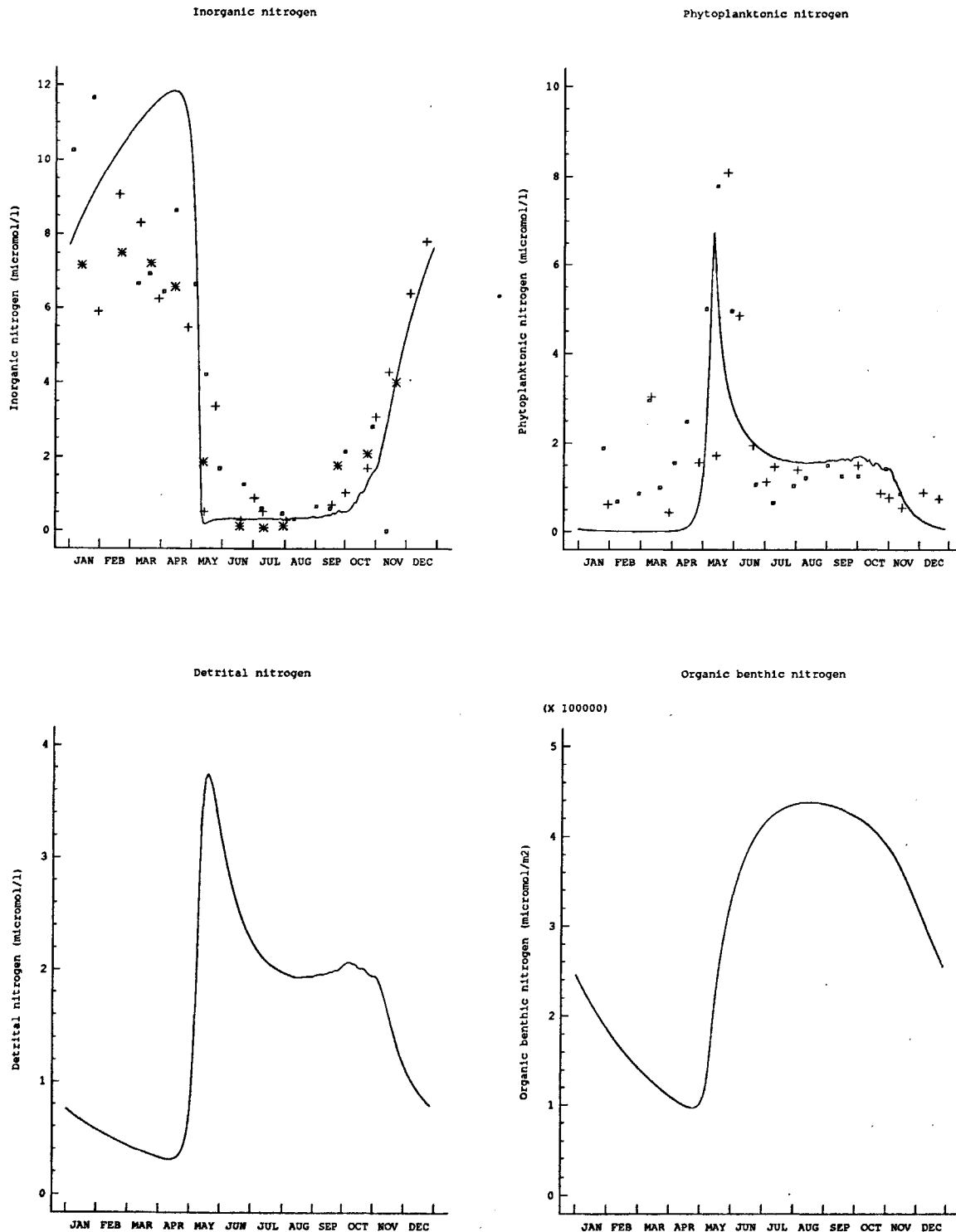


Figure 4
 Annual evolution of the different state variables in the Dover Strait (box A). Data measured in 1979 (+), 1980 (□) and 1991 (*).
 Évolution annuelle des différentes variables d'état dans le Pas-de-Calais (boîte A). Données mesurées en 1979 (+), 1980(□) et 1991(*).

RESULTS

Comparison between simulated and observed data

Results of the model have been compared with measurements in the Dover Strait on the one hand, and in the western Channel on the other hand. Data in the Dover Strait and in the western Channel have been collected during transects between Boulogne and Folkestone (Bentley, 1984) for the years 1979 and 1980, and between Roscoff and Plymouth (Dupouy, 1982), in 1980 and 1981.

Data collected for *Fluxmanche* programme in 1991 have been also taken into account in the Dover Strait. We considered that the ratio gChl *a*/mol.N in phytoplankton cells was equal to 1 (Antia *et al.*, 1963).

We have only focused on inorganic nitrogen concentrations in winter and on the intensity and the timing of the spring phytoplankton bloom, because this first model does not take into account zooplankton, which strongly influences the system after the first bloom by grazing.

Results of the simulation give maximal winter concentrations for inorganic nitrogen of approximately

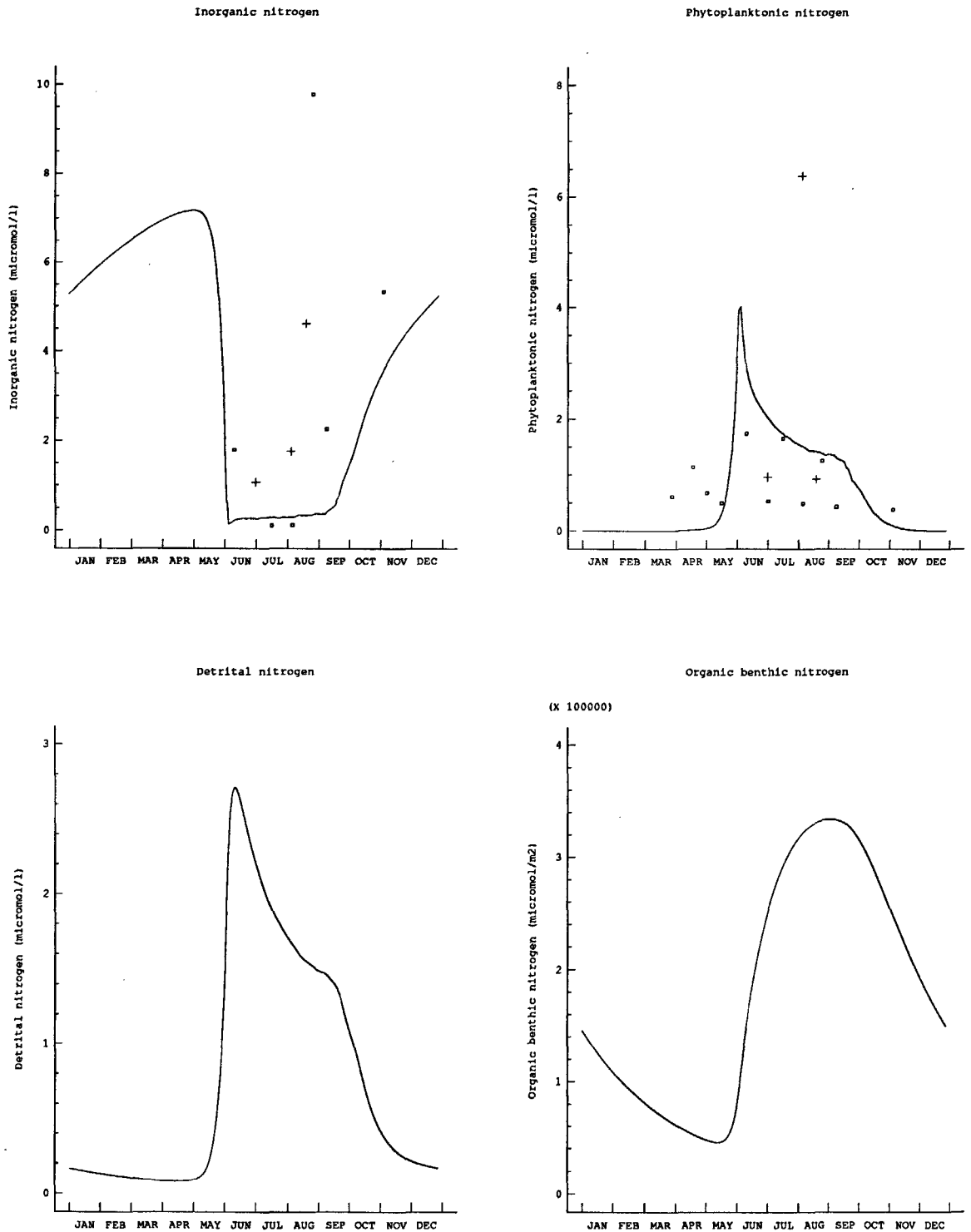


Figure 5

Annual evolution of the different state variables in the central part of the western Channel (box B). Data measured in 1980 (□) and 1981 (+).

Évolution annuelle des différentes variables d'état dans le Pas-de-Calais (boîte B). Données mesurées en 1980 (□) and 1981 (+).

12 $\mu\text{mol.l}^{-1}$ in the Dover Strait (Fig. 4) and 7 $\mu\text{mol.l}^{-1}$ in the western Channel (Fig. 5). Chlorophyll concentrations show peaks at about 7 $\mu\text{g.l}^{-1}$ for the box A and at 4 $\mu\text{g.l}^{-1}$ for the box B, respectively at the beginning and at the end of May. The bloom leads to an increase in detrital and organic benthic nitrogen.

Comparison between results of the model and data in a central box of the Dover Strait shows a relatively good agreement. On the contrary, the model does not represent the evolution of the system in the western Channel. Calculated values are higher than observed data for phytoplankton.

Evolution of the phytoplankton bloom

The purpose here is to describe the global evolution of phytoplankton concentrations in the whole Channel during the bloom.

Phytoplanktonic development is beginning at day 120 in the eastern Channel, particularly on the French coast, because of lower depths and nutrient inputs from the rivers, especially from the river Seine (Fig. 6 a). On the English coast, development is limited by high turbidity and mostly by reduced nutrient supply. Shallow depths

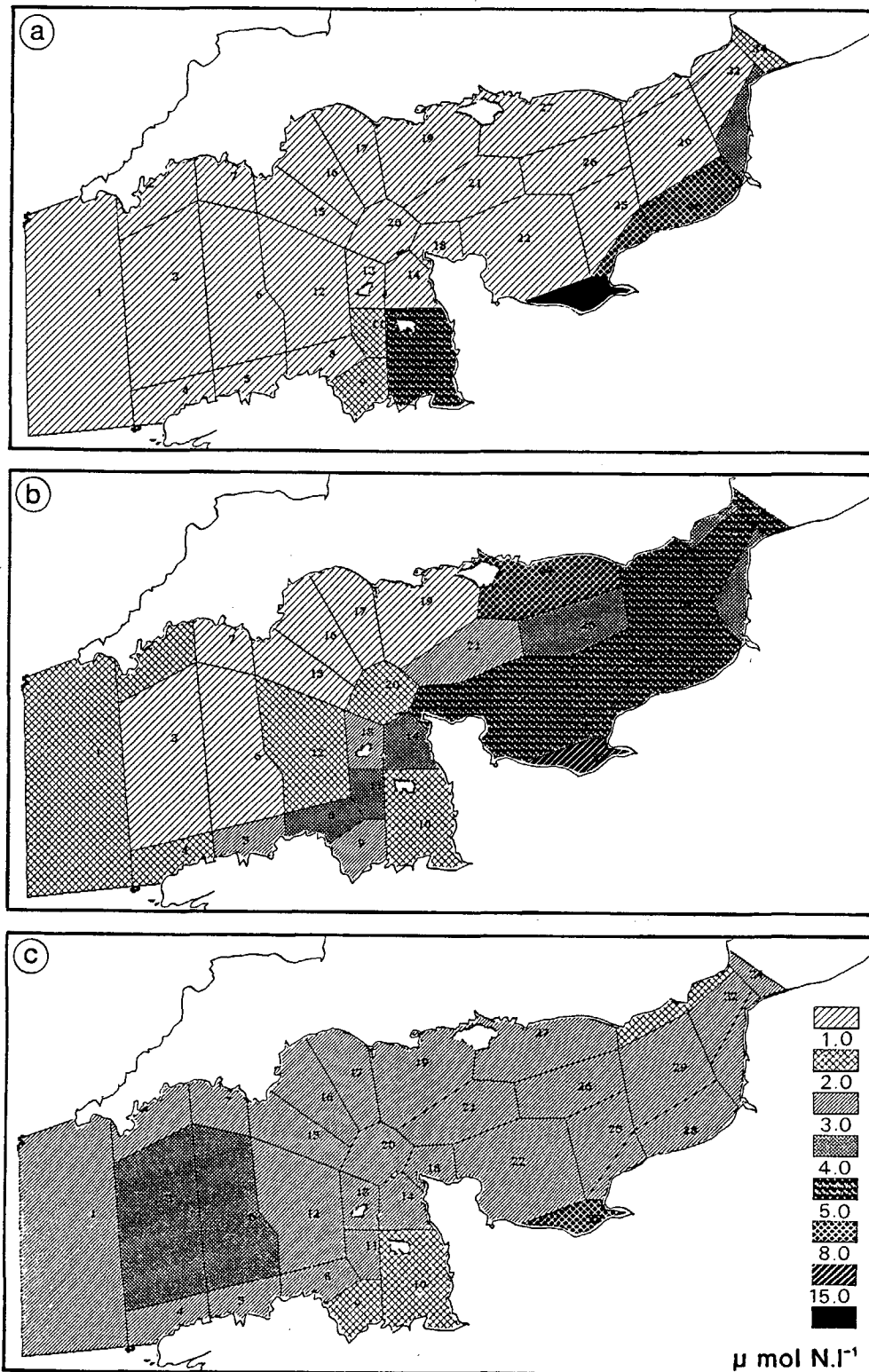


Figure 6
 Evolution of the phytoplankton spring bloom:
 a) day 120; b) day 140; c) day 160.
 Évolution du bloom phytoplanktonique printanier :
 a) jour 120; b) jour 140; c) jour 160.

also imply an early phytoplanktonic development in the Normano-Breton gulf.

Twenty days later, phytoplanktonic development is spreading over the whole eastern Channel. In the western Channel, chlorophyll concentrations are increasing (Fig. 6 b).

At day 160, chlorophyll contents are more important in the West than in the East, except for the bay of Seine, where inputs maintain high phytoplankton concentrations (Fig. 6 c).

DISCUSSION

The global evolution of the phytoplankton bloom shown by the model is relatively correct, especially in the eastern Channel. The influence of zooplankton on phytoplankton concentrations could be important mainly after the bloom, inducing predator/prey oscillations during summer with intense nutrient regeneration.

Concerning the western Channel, we did not consider the thermal stratification, which permits an earlier phytoplanktonic development. Discrepancies between model results and data in the western Channel can be also explained by the large variability observed in measured data collected in the area. As for inorganic nitrogen concentrations, Armstrong *et al.* (1970; 1972; 1974) have noticed great interannual variations. Winter concentrations vary between 5 and 13 $\mu\text{mol.l}^{-1}$ from one year to another in the central part of the western Channel. Nevertheless, Pingree *et al.* (1977) consider a mean nitrate concentration of about 5 $\mu\text{mol.l}^{-1}$ in winter in the waters off Plymouth. The same remarks can be made concerning chlorophyll contents. Holligan and Harbour (1977) found a concentration of roughly 4 $\mu\text{g.l}^{-1}$ in April, in the surface layer of a stratified water column.

However, values of inorganic nitrogen and chlorophyll concentrations seem to be too high in the western part of the system, and that can be also due to the influence of the estimated inorganic nitrogen concentrations of Atlantic waters entering the western Channel ecosystem.

Moreover, physical phenomena like resuspension, sedimentation and turbidity may have an important influence and consequently may require an explicit mathematical formulation. Agoumi (1985) showed the influence of the non-chlorophyllous extinction coefficient on the system.

CONCLUSION

The model provides a synoptic description of a phytoplankton bloom in the whole Channel. The phytoplankton bloom begins earlier in shallow, nutrient-rich areas of the eastern Channel than in the western part of the sea. We can notice the influence of fresh water inputs, especially those from the river Seine, on planktonic development, particularly along the eastern French coast. The Normano-Breton gulf appears also to be an interesting zone where high residence times, low depths and nutrient supply from the rivers lead to an early and enhanced spring bloom, in comparison with other parts of the western Channel.

Further improvements of the model will take into account thermal stratification in the western Channel and zooplankton grazing; more attention will be paid to resuspension, sedimentation and turbidity.

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