Services du Premier Ministre
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GECONCERTEERDE ONDERZOEKSACTIES

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Shear effect dispersion in a shallow tidal sea

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Introduction

The hydrodynamics of shallow continental seas like the North Sea is dominated by long waves, tides and storm surges, with current velocities of the order of 1 m/s . The currents generate strong three-dimensional turbulence and vertical mixing, resulting, in general, in a fairly homogeneous distribution of temperature, salinity and concentrations of marine constituents over the water column.

Vertical gradients of concentrations may exist in localized area where vertical mixing is partly (and temporarily) inhibited by stratification or during short periods of time - a few hours following an off-shore dumping, for instance - before vertical mixing is completed. However such cases are very limited in space and time and, in most problems, it is sufficient to study, in a first approach, the horizontal distribution of depth-averaged concentrations.

If c denotes the concentration of a given constituant, the three-dimensional "dispersion" equation, describing the evolution of c in space and time, can be written (e.g. Nihoul, 1975).

$$\frac{\partial c}{\partial t} + \underset{\sim}{\nabla}.(c\underset{\sim}{v}) = Q + I - \underset{\sim}{\nabla}.(\underset{\sim}{\sigma} c) + D \qquad (1)$$

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In eq. (1),

i) $\underline{\nabla}.(c\underline{v})$ represents advection and can be separated in two parts corresponding respectively to the horizontal transport $\underline{\nabla}.(c\underline{u})$ and to the vertical transport $\frac{\partial}{\partial x_3}(cv_3)$; $\underline{u} = v_1\,\underline{e}_1 + v_2\,\underline{e}_2$ denoting the horizontal current velocity.

ii) Q represents the rate of production (or destruction) of the constituent by volume sources (or sinks).
[*In most practical applications, inputs and outputs are located at the boundaries – in which case, they appear in the boundary conditions and no in* Q *–, or are localized quasi-instantaneous releases which may be conveniently taken into account in the initial conditions. In the following, one shall assume that this is the case and one shall set* $Q = 0$] .

iii) I represents the rate of production (or destruction) of the constituent by (chemical, ecological, ...) interactions inside the marine system and I is, in general, a function of coupled variables c' , c'' , ...
[*A marine constituent is said to be passive when its evolution is not affected by such interactions. In the following, to simplify the formulation, one shall restrict attention to passive constituent and set* $I = 0$. *The generalization of the theory to a system of interacting constituents presents no fundamental difficulty (Nihoul and Adam, 1977)*].

iv) $-\underline{\nabla}.(\underline{\sigma}c)$ represents "migration". (sedimentation, horizontal migration of fish, ..., e.g. Nihoul, 1975).
[*Migration, at least in the most frequent case of sedimentation, can easily be taken into account (e.g. Nihoul and Adam, 1977). However, to avoid overloading the analysis, one shall assume, in the following, that the constituent is simply transported by the fluid and that the migration velocity* σ *is zero*].

v) D represents turbulent diffusion and can be separated into a vertical turbulent diffusion and a horizontal turbulent diffusion.
[*The horizontal turbulent diffusion is negligible as compared to the horizontal advection. The horizontal dispersion which is observed in the sea is mainly the result of the horizontal transport of the*

constituent by irregular and variable currents constituting a form of "pseudo horizontal turbulence" extending to much larger scales than the "proper" three-dimensional turbulence (e.g. Nihoul, 1975). In that case, D *can be simply written*

$$D = \frac{\partial}{\partial x_3} \left(\mu \frac{\partial c}{\partial x_3} \right) \tag{2}$$

where μ *is the vertical turbulent diffusivity*].

In the scope of the hypotheses made above, eq.(1) can be written, in the simpler form

$$\frac{\partial c}{\partial t} + \underset{\sim}{\nabla}.(c\underset{\sim}{u}) + \frac{\partial}{\partial x_3} (cv_3) = \frac{\partial}{\partial x_3} \left(\mu \frac{\partial c}{\partial x_3} \right) \tag{3}$$

The velocity field $\underset{\sim}{v} = \underset{\sim}{u} + v_3 \underset{\sim}{e}_3$ is given by the Boussinesq equations and in particular, one has

$$\underset{\sim}{\nabla}.\underset{\sim}{u} + \frac{\partial v_3}{\partial x_3} = 0 \tag{4}$$

Depth-averaged dispersion equation

Let

$$\bar{c} = H^{-1} \int_{-h}^{\zeta} c \, dx_3 \quad ; \quad \hat{c} = c - \bar{c} \tag{5) ; (6}$$

$$\bar{\underset{\sim}{u}} = H^{-1} \int_{-h}^{\zeta} \underset{\sim}{u} \, dx_3 \quad ; \quad \hat{\underset{\sim}{u}} = \underset{\sim}{u} - \bar{\underset{\sim}{u}} \tag{7) ; (8}$$

with

$$\int_{-h}^{\zeta} \hat{c} \, dx_3 = 0 \quad ; \quad \int_{-h}^{\zeta} \hat{\underset{\sim}{u}} \, dx_3 = 0 \tag{9) ; (10}$$

and

$$H = h + \zeta \tag{11}$$

where h is the depth and ζ the surface elevation.

One has

$$\frac{\partial \zeta}{\partial t} + \underset{\sim}{u}.\underset{\sim}{\nabla}\zeta = v_3 \qquad \text{at} \quad x_3 = \zeta \tag{12}$$

$$\frac{\partial h}{\partial t} + \underset{\sim}{u}.\underset{\sim}{\nabla}h = - v_3 \qquad \text{at} \quad x_3 = - h \tag{13}$$

Integrating eqs.(1) and (4) over depth, inverting the order of integration with respect to x_3 and of derivation with respect to t, x_1 or x_2 and using eqs.(12) and (13) to eliminate the corrections due to the variable limits of integration, one obtains (e.g. Nihoul; 1975)

$$\frac{\partial}{\partial t}(H\overline{c}) + \underset{\sim}{\nabla}.(H\,\overline{c}\,\overline{\underset{\sim}{u}}) + \underset{\sim}{\nabla}.\int_{-h}^{\zeta} \hat{c}\,\hat{\underset{\sim}{u}}\,dx_3 = 0 \tag{14}$$

$$\frac{\partial H}{\partial t} + \underset{\sim}{\nabla}.(H\,\overline{\underset{\sim}{u}}) = 0 \ . \tag{15}$$

In the right-hand side of eq.(14), one should have the difference between the fluxes of the constituent at the free surface and at the bottom. The hypothesis is made here that there is no exchange between the water column and the atmosphere and between the water column and the bottom sediments.

In this case, combining eqs.(14) and (15), one gets

$$\frac{\partial \overline{c}}{\partial t} + \overline{\underset{\sim}{u}}.\underset{\sim}{\nabla}\overline{c} = \Sigma \tag{16}$$

where

$$\Sigma = H^{-1}\underset{\sim}{\nabla}.\int_{-h}^{\zeta} (-\,\hat{c}\hat{\underset{\sim}{u}})\,dx_3 \tag{17}$$

Σ contains the mean product of the deviations $\hat{c}$ and $\hat{\underset{\sim}{u}}$ around the mean values $\overline{c}$ and $\overline{\underset{\sim}{u}}$. The observations reveal that this term is responsible for a horizontal dispersion analogous to the turbulent dispersion but many times more efficient. This effect is called the "shear effect" because it is associated with the vertical gradient of the horizontal velocity $\underset{\sim}{u}$ (e.g. Bowden, 1965 ; Nihoul, 1975).

Parameterization of the shear effect

Substracting eq.(16) from eq.(1), one obtains

$$\frac{\partial \hat{c}}{\partial t} + \underset{\sim}{\bar{u}}.\underset{\sim}{\nabla}\hat{c} + \underset{\sim}{\hat{u}}.\underset{\sim}{\nabla}\hat{c} + \Sigma + v_3 \frac{\partial \hat{c}}{\partial x_3} + \underset{\sim}{\hat{u}}.\underset{\sim}{\nabla}\bar{c} = \frac{\partial}{\partial x_3}\left(\mu \frac{\partial \hat{c}}{\partial x_3}\right) \qquad (18)$$

Because of the strong vertical mixing, one expects the deviation $\hat{c}$ to be much smaller than the mean value $\bar{c}$. This is not true for the velocity deviation $\underset{\sim}{\hat{u}}$ which may be comparable to $\underset{\sim}{\bar{u}}$; the velocity increasing from zero at the bottom to its maximum value at the surface. One may thus assume that the first four terms in the left-hand side of eq.(18) are negligible as compared to the sixth one $\underset{\sim}{\hat{u}}.\underset{\sim}{\nabla}\bar{c}$. The fifth term, representing vertical advection, is undoubtedly even smaller than the four neglected terms and eq.(18) reduces to

$$\underset{\sim}{\hat{u}}.\underset{\sim}{\nabla}\bar{c} = \frac{\partial}{\partial x_3}\left(\mu \frac{\partial \hat{c}}{\partial x_3}\right) \qquad (19)$$

The physical meaning of this equation is clear : weak vertical inhomogeneities are constantly created by inhomogeneous convective transport and they adapt to that transport in such a way that the effects of advection and vertical turbulent diffusion are in equilibrium for them.

Integrating eq.(19) with the condition that the flux is zero at the free surface, one obtains

$$H\underset{\sim}{\hat{r}}.\underset{\sim}{\nabla}\bar{c} = \mu \frac{\partial \hat{c}}{\partial x_3} \qquad (20)$$

where

$$\underset{\sim}{\hat{r}} = H^{-1} \int_{\zeta}^{x_3} \underset{\sim}{\hat{u}}\, dx_3 \qquad (21)$$

Integrating by parts and taking into account that $\underset{\sim}{\hat{r}} = 0$ at $x_3 = \zeta$ and $x_3 = -h$ (cfr eq.10), one gets

$$\Sigma = H^{-1}\, \underset{\sim}{\nabla}.(H\underset{\sim}{R}.\underset{\sim}{\nabla}\bar{c}) \qquad (22)$$

where $\underset{\sim}{\underset{\sim}{R}}$ is the shear effect diffusivity tensor, i.e. :

$$\underset{\sim}{\underset{\sim}{R}} = H \int_{-h}^{\zeta} \frac{\underset{\sim}{\hat{r}}\,\underset{\sim}{\hat{r}}}{\mu}\, dx_3 \qquad (23)$$

To determine $\underset{\sim}{\underset{\sim}{R}}$, one must know the turbulent eddy diffusivity μ and the function $\underset{\sim}{\hat{r}}$, i.e. the velocity deviation $\underset{\sim}{\hat{u}}$.

Vertical profile of the horizontal velocity

The evolution equation for the horizontal velocity vector $\underset{\sim}{u}$ can be written, after eliminating the pressure (e.g. Nihoul, 1975)

$$\frac{\partial \underset{\sim}{u}}{\partial t} + \underset{\sim}{\nabla}.(\underset{\sim}{u}\,\underset{\sim}{u}) + f\underset{\sim}{e_3} \wedge \underset{\sim}{u} + \frac{\partial}{\partial x_3}(v_3 \underset{\sim}{u}) = - \underset{\sim}{\nabla}\left(\frac{p_a}{\rho} + g\zeta\right) + \frac{\partial}{\partial x_3}\left(\nu \frac{\partial \underset{\sim}{u}}{\partial x_3}\right) \qquad (24)$$

where f is equal to twice the vertical component of the earth's rotation vector, p_a is the atmospheric pressure, g the acceleration of gravity and ν the vertical turbulent viscosity.

In eq.(24), one has neglected the effect of the horizontal component of the earth's rotation vector (multiplied by $v_3 \ll u$) and the horizontal turbulent diffusion (because horizontal length scales are always much larger than the depth).

The observations indicate that, in shallow tidal seas, the turbulent viscosity ν can be written as the product of a function of t, x_1 and x_2 and a function of the reduced variable $\xi = H^{-1}(x_3 + h)$ (e.g. Bowden, 1965).

Let

$$\nu = H^2\, \sigma(t, x_1, x_2)\ \lambda(\xi) \qquad (25)$$

where σ and λ are appropriate functions.

The asymptotic form of ν for small values of ξ is well-known from boundary layer theory :

$$\nu = k\, u_*\, (x_3 + h) = k\, u_*\, H\, \xi \qquad (26)$$

where k is the Von Karman constant and u_* the friction velocity given by

$$u_*^2 = \|\underset{\sim}{\tau}_b\| \qquad ; \qquad \underset{\sim}{\tau}_b = \left[\nu \frac{\partial \underset{\sim}{u}}{\partial x_3} \right]_{x_3 = -h} \tag{27};(28)$$

Hence

$$\sigma H = k u_* \tag{29}$$

and

$$\lambda(\xi) \sim \xi \qquad \text{for} \qquad \xi \ll 1 \,. \tag{30}$$

In a well-mixed shallow sea, where the Richardson number is small and the turbulence fully developed, it is reasonable (e.g. Nihoul, 1975) to take

$$\mu \sim \nu \,. \tag{31}$$

This hypothesis will be reexamined later.

It is convenient to change variables to (t, x_1, x_2, ξ) in eq.(24). In the final result (Nihoul, 1977), the non-linear terms combine with additional contributions from the time derivative to give three terms, related respectively to the gradients of velocity, depth and surface elevation. These terms are found negligible almost everywhere in the North Sea (Nihoul and Runfola, 1979). Thus although depth-integrated two-dimensional hydrodynamic models of the North Sea may not discard the non-linear terms[1], if one excludes localized singular regions like the vicinity of tidal emphydromic points, the "local" vertical distribution of velocity may be described, with a very good approximation, by a linear model.

Then, the governing equation for the velocity deviation $\hat{\underset{\sim}{u}}$ can be written

$$\frac{\partial \hat{\underset{\sim}{u}}}{\partial t} + f \underset{\sim}{e}_3 \wedge \underset{\sim}{u} = \sigma \left\{ \frac{\partial}{\partial \xi} \left[\lambda \frac{\partial \hat{\underset{\sim}{u}}}{\partial \xi} \right] - \frac{\underset{\sim}{\tau}_s - \underset{\sim}{\tau}_b}{\sigma H} \right\} \tag{32}$$

---

1. It can be shown that these terms are essential in determining the residual circulation (Nihoul and Ronday, 1976b).

where

$$\underset{\sim}{\tau}_s = \left[\nu \frac{\partial \underset{\sim}{u}}{\partial \xi} \right]_{x_3 = \zeta} \tag{33}$$

is the wind stress (normalized with water density).

It is possible to find an analytical solution of eq.(32) giving $\underset{\sim}{\tilde{u}}$ in terms of $\underset{\sim}{\tau}_s$, $\underset{\sim}{\tau}_b$ and their derivatives with respect to time ; the coefficients depending on the functions $s(\xi)$, $b(\xi)$ and $f_n(\xi)$ $(n=1,2...)$ defined by (Nihoul, 1977)

$$s(\xi) = \int_0^{\xi} \frac{\eta}{\lambda(\eta)} \, d\eta \tag{34}$$

$$b(\xi) = \int_{\xi_0}^{\xi} \frac{1 - \eta}{\lambda(\eta)} \, d\eta \tag{35}$$

$$\frac{d}{d\xi} \left[\lambda \frac{df_n}{d\xi} \right] = - \alpha_n f_n \tag{36}$$

with

$$\int_0^1 f_n^2(\xi) \, d\xi = 1 \tag{37}$$

$$\lambda \frac{df_n}{d\xi} = 0 \quad \text{at} \quad \xi = 0 \quad \text{and} \quad \xi = 1 \, . \tag{38}$$

One should note here that, in the definition of $b(\xi)$, the lower limit of integration is not set equal to zero but to $\xi_0 = \frac{z_0}{H} \ll 1$ where z_0 is the "rugosity length". z_0 can be interpreted as the distance above the bottom where the velocity is conventionally set equal to zero, ignoring the intricated flow situation which occurs near the irregular sea floor and willing to parameterize its effect on the turbulent boundary layer as simply as possible. In the North Sea, the value of z_0 , which varies according to the nature of the bottom, is of the order of 10^{-3} m $(\ln \xi_0 \sim - 10)$ [e.g. Nihoul and Ronday, 1976a].

Although $\xi_0 \ll 1$, it cannot be systematically put equal to zero because the linear variation of the vertical eddy viscosity near the bottom leads to a logarithmic velocity profile which is singular at $\xi = 0$. However, in the present description, the difficulty exists only for the function b and the eigenfunction $f(\xi)$ may be determined on the interval $[0,\xi]$.

In a shallow tidal sea like the North Sea, it is readily seen, comparing the orders of magnitude of the different terms, that one obtains a very good approximation with only the first two terms in the series expansion of $\underset{\sim}{\hat{u}}$, i.e. (Nihoul, 1977)

$$\underset{\sim}{\hat{u}} = \underset{\sim}{v}_s[s(\xi) - \bar{s}] + \underset{\sim}{v}_b[b(\xi) - \bar{b}]$$

$$- \left[\frac{s_1}{\alpha_1 \sigma} \dot{\underset{\sim}{v}}_s + \frac{b_1}{\alpha_1 \sigma} \dot{\underset{\sim}{v}}_b\right] f_1(\xi) \qquad (39)$$

where $\bar{s}$ and $\bar{b}$ are the depth-averages of s and b , s_1 and b_1 two numerical coefficients $\left(s_1 = \int_0^1 s\, f_1\, d\xi \; ; \quad b_1 = \int_0^1 b\, f_1\, d\xi\right)$; α_1 the eigenvalue corresponding to $f_1(\xi)$ and where

$$\underset{\sim}{v}_s = \frac{\underset{\sim}{\tau}_s}{\sigma H} \quad ; \quad \underset{\sim}{v}_b = \frac{\underset{\sim}{\tau}_b}{\sigma H} \qquad (40);(41)$$

A dot denotes here a total derivative with respect to time

$$\left[\dot{\underset{\sim}{v}}_s = \frac{d\underset{\sim}{v}_s}{dt} = \frac{\partial \underset{\sim}{v}_s}{\partial t} + f\, \underset{\sim}{e}_3 \wedge \underset{\sim}{v}_s \quad \text{and similarly for } \underset{\sim}{v}_b\right] .$$

Knowing the function $\lambda(\xi)$, one can determine $\underset{\sim}{\hat{u}}$ by eq.(39), $\underset{\sim}{\hat{r}}$ by eq.(21) and $\underset{\approx}{R}$ by eq.(23).

Parameterization of the bottom stress

The functions $\underset{\sim}{\hat{u}}$, $\underset{\sim}{\hat{r}}$ and $\underset{\approx}{R}$ depend on the vectors $\underset{\sim}{v}_s$, $\underset{\sim}{v}_b$ and their derivatives. These can be determined by eqs.(27), (29), (40) and (41) from $\underset{\sim}{\tau}_s$ and $\underset{\sim}{\tau}_b$.

The surface stress $\underset{\sim}{\tau}_s$ can be calculated from atmospheric data, the bottom stress $\underset{\sim}{\tau}_b$ is not given and must be determined by the no-slip condition at the bottom, i.e.

$$\hat{\underset{\sim}{u}} = - \overline{\underset{\sim}{u}} \qquad \text{at} \qquad \xi = \xi_0 \tag{42}$$

Eq.(42) provides a differential equation for $\underset{\sim}{\tau}_b$ in terms of $\underset{\sim}{\tau}_s$ and $\overline{\underset{\sim}{u}}$.

In shallow tidal seas like the North Sea, the terms including $\dot{\underset{\sim}{v}}_s$ and $\dot{\underset{\sim}{v}}_b$ are generally negligible and can only play a part during a relatively short time, at tide reversal (Nihoul and Runfola, 1979). The dominant term is, in fact, the term containing the bottom stress. The effect of the wind stress appears as a first order correction and the "memory" effect involving the derivatives $\dot{\underset{\sim}{v}}_s$ and $\dot{\underset{\sim}{v}}_b$ as a second order correction. One thus has

$$\overline{\underset{\sim}{u}} \sim \overline{b}\ \underset{\sim}{v}_b \qquad \text{(zeroth order)} \tag{43}$$

$$\overline{\underset{\sim}{u}} \sim \overline{b}\ \underset{\sim}{v}_b + \overline{s}\ \underset{\sim}{v}_s \qquad \text{(first order)} \tag{44}$$

$$\overline{\underset{\sim}{u}} \sim \overline{b}\ \underset{\sim}{v}_b + \overline{s}\ \underset{\sim}{v}_s + (s_1 \dot{\underset{\sim}{v}}_s + b_1 \dot{\underset{\sim}{v}}_b)\ \frac{f_{1,0}}{\alpha_1 \sigma} \qquad \text{(second order)} \tag{45}$$

Eq.(43) yields the well-known semi-empirical quadratic bottom friction law. Indeed, combining eqs.(27), (29) and (43), one finds

$$\|\underset{\sim}{\tau}_b\| \sim \frac{\sigma H}{\overline{b}}\ \|\overline{\underset{\sim}{u}}\| \sim \left(\frac{\sigma H}{k}\right)^2 \quad \Rightarrow \quad \sigma H \sim \frac{k^2}{\overline{b}}\ \|\overline{\underset{\sim}{u}}\| \tag{46}$$

i.e.

$$\underset{\sim}{\tau}_b = \frac{k^2}{\overline{b}^2}\ \|\overline{\underset{\sim}{u}}\|\ \overline{\underset{\sim}{u}} \tag{47}$$

$\frac{k^2}{\overline{b}^2}$ is the so-called "drag coefficient".

At the first order, one gets another classical formula (e.g. Groen and Groves, 1966; Nihoul, 1975) :

$$\underset{\sim}{\tau}_b = \frac{k^2}{\overline{b}^2}\ \|\overline{\underset{\sim}{u}}\|\ \overline{\underset{\sim}{u}} - \frac{\overline{s}}{\overline{b}}\ \underset{\sim}{\tau}_s \tag{48}$$

The second order parameterization is better understood if the last term in the right-hand side of eq. (45) is eliminated using eqs (32), (34), (35),

(36) and (39). One has, indeed

$$\frac{\partial \bar{\underline{u}}}{\partial t} + f\, \underline{e}_3 \wedge \bar{\underline{u}} = -\sigma \left[\frac{\partial}{\partial \xi}\left(\lambda \frac{\partial \hat{\underline{u}}}{\partial \xi}\right)\right]_{x_3 = -h} + \frac{\underline{\tau}_s - \underline{\tau}_b}{H}$$

$$\sim -(s_1 \dot{\underline{v}}_s + b_1 \dot{\underline{v}}_b)\, f_{1,0} \sim -\alpha_1 \sigma\, (\bar{\underline{u}} - \bar{s}\, \underline{v}_s - \bar{b}\, \underline{v}_b)$$

i.e., using (46) to estimate σH ,

$$\tau_b \sim \frac{k^2}{\bar{b}^2} \|\bar{\underline{u}}\| \bar{\underline{u}} - \frac{\bar{s}}{\bar{b}} \underline{\tau}_s + \frac{H}{\alpha_1 \bar{b}} \left(\frac{\partial \bar{\underline{u}}}{\partial t} + f\, \underline{e}_3 \wedge \bar{\underline{u}}\right)$$

With a typical drag coefficient of the order of $2\ 10^{-3}$ (e.g. Nihoul and Ronday, 1976), one finds, using characteristic values for the North Sea,

$$\frac{k^2}{\bar{b}^2} \|\bar{\underline{u}}\| \bar{\underline{u}} \sim 0(2\ 10^{-3}\ \bar{u}^2) ,$$

$$\frac{H}{\alpha_1 \bar{b}} \frac{\partial \bar{\underline{u}}}{\partial t} \sim \frac{H}{\alpha_1 \bar{b}} f\, \underline{e}_3 \wedge \bar{\underline{u}} \sim 0(10^{-4}\ \bar{u}) .$$

Thus, the "acceleration" terms containing $\frac{\partial \bar{\underline{u}}}{\partial t}$ and $f\, \underline{e}_3 \wedge \bar{\underline{u}}$ (i.e. the terms arising from the time derivatives of $\underline{v}_s$ and $\underline{v}_b$) are not expected to play an important role except perhaps during relatively short periods of weak currents (when tides reverse, for instance). The total effect of the acceleration terms depends really on the local conditions. Obviously, (fig. 1) if the current velocity vector rotates clockwise during a tidal

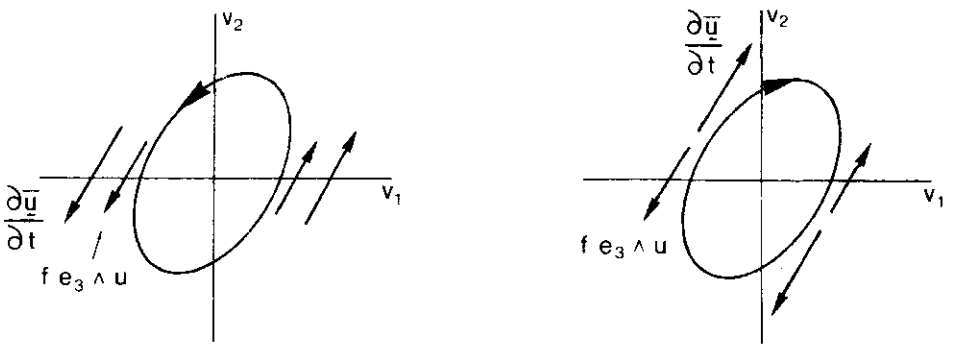

fig. 1.

period, the two terms tend to oppose each other and their global contribution may remain always very small. On the other hand, if the current velocity vector rotates counter-clockwise (as it is often the case in the Southern Bight) the two terms reinforce each other and have a definite - although limited - effect on the velocity profile and the related relationship between the bottom stress and the mean velocity (fig.2, fig. 3).

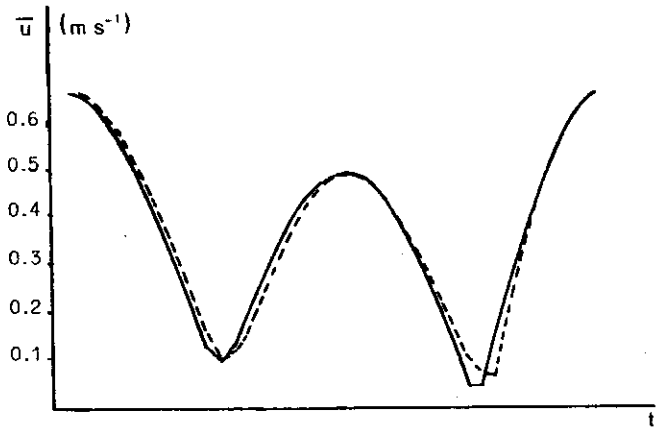

fig. 2.

Amplitude of the mean velocity

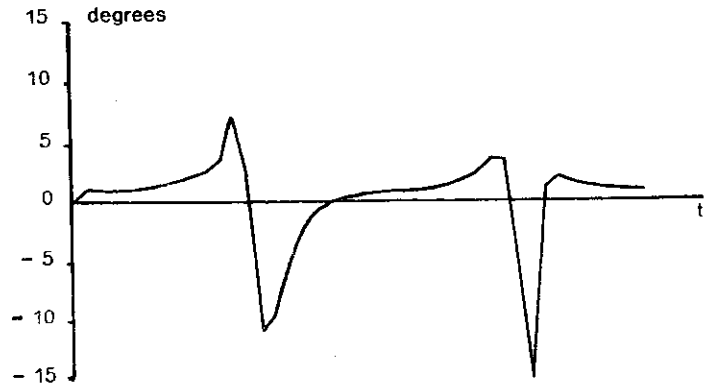

fig. 3.

Phase of the mean velocity

Comparison between the mean velocity $\bar{u}$ computed at the test point 52°30' N , 3°50' E in the North Sea by a depth-averaged two-dimensional model using an algebraic parameterization of τ_b (full line) and by the tree-dimensional model subject to the condition of zero velocity at the bottom (dash line) [Nihoul and Runfola, 1979].

Most hydrodynamic models of shallow seas restrict attention to the determination of the depth-mean velocity $\underset{\sim}{\bar{u}}$. The two-dimensional time dependent evolution equation for $\underset{\sim}{\bar{u}}$ is obtained from eq.(24) by integration over depth. It includes the surface elevation ζ and the bottom stress $\underset{\sim}{\tau}_b$ and thus constitutes with eq.(15) and eq.(43) (or 44) a closed system for the depth-averaged circulation (e.g. Nihoul, 1975).

The determination of the vertical velocity profile can be carried simultaneously using eq.(39).

One can go a step further and devise a three-dimensional model based on the depth-averaged equation, the local depth-dependent equation for the velocity deviation $\underset{\sim}{\tilde{u}}$ and the refined parameterization of the bottom stress given by eq.(49) ; the acceleration corrections being taken into account when required in the numerical calculation. (Nihoul and Runfola, 1979).

The model gives H, $\underset{\sim}{\bar{u}}$, $\underset{\sim}{\tau}_b$, $\underset{\sim}{\tilde{u}}$, $\underset{\sim}{\hat{f}}$ and $\underset{\approx}{R}$.

Substituting in eq.(16) one obtains explicitly the dispersion equation for the mean concentration $\bar{c}$.

Coefficients of the shear effect dispersion

Shear effect dispersion is described by eq.(16) where Σ is given, in terms of the functions $\underset{\sim}{\hat{f}}$ and μ, by eqs.(22) and (23). The functions $\underset{\sim}{\hat{f}}$ and μ can be determined by eqs.(21), (25), (31) and (39) provided the function λ is known. Thus the parameterization of the shear effect - as well as the determination of the vertical profile of velocity - reduces to the choice of a single scalar function.

The function

$$\lambda = \xi(1 - 0.5\ \xi) \tag{50}$$

appears to cover a wide range of situations in the North Sea and other shallow tidal seas (e.g. Bowden, 1965 ; Nihoul, 1977).

In this case, the eigenfunctions and the eigenvalues of eqs.(36), (37) and (38) are given by

$$f_n = (4n + 1)^{1/2}\ P_{2n}(\xi - 1) \tag{51}$$

$$\alpha_n = n(2n + 1) \tag{52}$$

where P_{2n} is the Legendre polynomial of even order 2n.

Integrating eq.(39), one obtains, in this case,

$$\underset{\sim}{\hat{r}} = \underset{\sim}{v}_s \, S(\xi) + \underset{\sim}{v}_b \, B(\xi) + \frac{\dot{\underset{\sim}{v}}_s + 2\dot{\underset{\sim}{v}}_b}{\sigma} F(\xi) \tag{53}$$

with

$$S(\xi) = 4 \ln 2(\xi - 1) + 2(2 - \xi)\ln(2 - \xi) \tag{54}$$

$$B(\xi) = - 2 \ln 2(\xi - 1) + \xi \ln \xi - (2 - \xi)\ln(2 - \xi) \tag{55}$$

$$F(\xi) = \frac{5}{36} (\xi^3 - 3 \xi^2 + 2 \xi) \tag{56}$$

The shear effect diffusivity tensor can then be written, using eqs.(25) and (31)

$$\underset{\sim}{R} = \int_{\xi_0}^{1} \frac{\hat{\underset{\sim}{r}} \, \hat{\underset{\sim}{r}}}{\sigma\lambda} \, d\xi$$

$$= \frac{\gamma_{ss}}{\sigma} \underset{\sim}{v}_s \underset{\sim}{v}_s + \frac{\gamma_{sb}}{\sigma} (\underset{\sim}{v}_s \underset{\sim}{v}_b + \underset{\sim}{v}_b \underset{\sim}{v}_s) + \frac{\gamma_{bb}}{\sigma} \underset{\sim}{v}_b \underset{\sim}{v}_b$$

$$+ \frac{\gamma_{sf}}{\sigma^2} (\underset{\sim}{v}_s \dot{\underset{\sim}{v}}_s + 2 \underset{\sim}{v}_s \dot{\underset{\sim}{v}}_b + \dot{\underset{\sim}{v}}_s \underset{\sim}{v}_s + 2 \dot{\underset{\sim}{v}}_b \underset{\sim}{v}_s) \tag{57}$$

$$+ \frac{\gamma_{bf}}{\sigma^2} (\underset{\sim}{v}_b \dot{\underset{\sim}{v}}_s + 2 \underset{\sim}{v}_b \dot{\underset{\sim}{v}}_b + \dot{\underset{\sim}{v}}_s \underset{\sim}{v}_b + 2 \dot{\underset{\sim}{v}}_b \underset{\sim}{v}_b)$$

$$+ \frac{\gamma_{ff}}{\sigma^3} (\dot{\underset{\sim}{v}}_s + 2 \dot{\underset{\sim}{v}}_b)(\dot{\underset{\sim}{v}}_s + 2 \dot{\underset{\sim}{v}}_b)$$

with

$$\gamma_{ss} = \int_{\xi_0}^{1} \frac{S^2}{\lambda} \, d\xi \sim 0.048 \qquad \gamma_{sf} = \int_{\xi_0}^{1} \frac{SF}{\lambda} \, d\xi \sim - 0.015 \qquad (58), (59)$$

$$\gamma_{sb} = \int_{\xi_0}^{1} \frac{SB}{\lambda} \, d\xi \sim 0.090 \qquad \gamma_{bf} = \int_{\xi_0}^{1} \frac{BF}{\lambda} \, d\xi \sim - 0.031 \qquad (60), (61)$$

$$\gamma_{bb} = \int_{\xi_0}^{1} \frac{B^2}{\lambda} \, d\xi \sim 0.196 \qquad \gamma_{ff} = \int_{\xi_0}^{1} \frac{F^2}{\lambda} \, d\xi \sim 0.005 \qquad (62), (63)$$

Application to the Southern Bight of the North Sea

In the Southern Bight of the North Sea, the depth is small and the bottom stress $\underset{\sim}{\tau}_b$, maintained by bottom friction of tidal currents, wind induced currents and residual currents is always fairly important. One can estimate that, in general, the characteristic time σ^{-1} is one order of magnitude larger than the characteristic time of variation of $\underset{\sim}{v}_s$ and $\underset{\sim}{v}_b$ (Nihoul and Ronday, 1976 ; Nihoul, 1977).

The terms of eq.(57) which contain the derivatives $\dot{\underset{\sim}{v}}_s$ and $\dot{\underset{\sim}{v}}_b$ - the coefficients of which are already smaller than the others - may then be neglected.

The shear effect diffusivity tensor reduces then to

$$\underset{\approx}{R} = \frac{H}{\|\underset{\sim}{v}_b\|} \left[\beta_1 \underset{\sim}{v}_b \underset{\sim}{v}_b + \beta_2 (\underset{\sim}{v}_s \underset{\sim}{v}_b + \underset{\sim}{v}_b \underset{\sim}{v}_s) + \beta_3 \underset{\sim}{v}_s \underset{\sim}{v}_s\right] \tag{64}$$

with

$$\beta_1 \sim 1.2 \quad ; \quad \beta_2 \sim 0.6 \quad ; \quad \beta_3 \sim 0.3 \tag{65) (66) (67}$$

In weak wind conditions ($\underset{\sim}{v}_b \leqslant 10^{-2}\ \underset{\sim}{\bar{u}}$), the first term in the bracket is largely dominant and, using eq.(43), one obtains, with a good approximation

$$\underset{\approx}{R} = \alpha \frac{H}{\bar{u}} \underset{\sim}{\bar{u}}\ \underset{\sim}{\bar{u}} \tag{68}$$

$$\Sigma = H^{-1} \underset{\sim}{\nabla}.\left[\alpha \frac{H^2}{\bar{u}} \underset{\sim}{\bar{u}} (\underset{\sim}{\bar{u}}.\underset{\sim}{\nabla}\bar{c})\right] \tag{69}$$

with

$$\alpha \sim 0.14 \tag{70}$$

However, in weak wind conditions, the approximation which consists in neglecting the derivatives $\dot{\underset{\sim}{v}}$ and $\dot{\underset{\sim}{v}}$ is less justified and, furthermore, one may question the validity of eq.(50). If the wind is too weak to maintain turbulence in the sub-surface layer, one may expect, in some cases, a turbulent diffusivity which, instead of growing continuously from the

bottom to the surface, instead passes through a maximum at some intermediate depth to decrease afterwards to a smaller surface value. This type of behaviour is described by the family of curves

$$\lambda = \xi(1 - \delta\xi) \qquad (71)$$

Eq.(50) corresponds to the case $\delta = 0.5$. Values of δ from 0.5 to 1 correspond to lower intensity turbulence in the surface layer and the limiting value $\delta = 1$ would correspond to the case of an ice cover and the existence, below the surface, of a logarithmic boundary layer analogous to the bottom boundary layer.

In the Southern Bight of the North Sea, it is reasonable to assume that δ does not differ significantly from 0.5 and, in any case, never reaches extreme values close to 1. Nevertheless, to estimate the maximum error one can make on α , it is interesting to compute the coefficients β_1, β_2 and β_3 for some very different values of δ.

One finds

δ	0.5	0.7	0.9
β_1	1.2	1.5	2
β_2	0.6	0.8	1.3
β_3	0.3	0.5	1
α	0.14	0.17	0.23

The increase of the coefficients β_1, β_2, β_3 and α with δ is obviously associated with more important variations of u over depth i.e. with larger values of $\hat{u}$.

One should note also that the existence of a vertical stratification, even a weak one, reduces the turbulent diffusivity ($\mu = \eta\nu$ with $\eta < 1$) and contributes similarly to increase the value of α (e.g. Bowden, 1965).

In the Southern Bight of the North Sea, eventual modifications of the magnitude ($\eta < 1$) or of the form ($\delta > 0.5$) of the turbulent diffusivity are not likely to be very important and eq.(68) can presumably be used with $\alpha = 0.14$ or some slightly higher value obtained by calibration of the model with the observations.

Vertical concentration profile

When $\overline{c}$ has been calculated, it is possible to compute the deviation $\hat{c}$ by eq. (20). Changing variable to ξ and using eqs. (25) and (31), one gets

$$\frac{\partial \hat{c}}{\partial \xi} = \frac{\hat{\underline{r}}}{\lambda} \cdot \frac{\nabla \overline{c}}{\sigma} \tag{72}$$

with, from eq. (9),

$$\int_0^1 \hat{c} \; d\xi = 0 \; . \tag{73}$$

Restricting attention to the dominant terms, one finds

$$\hat{c}(\xi) = [H(\xi) \; \underline{v}_s + G(\xi) \; \underline{v}_b] \cdot \frac{\nabla \overline{c}}{\sigma}$$

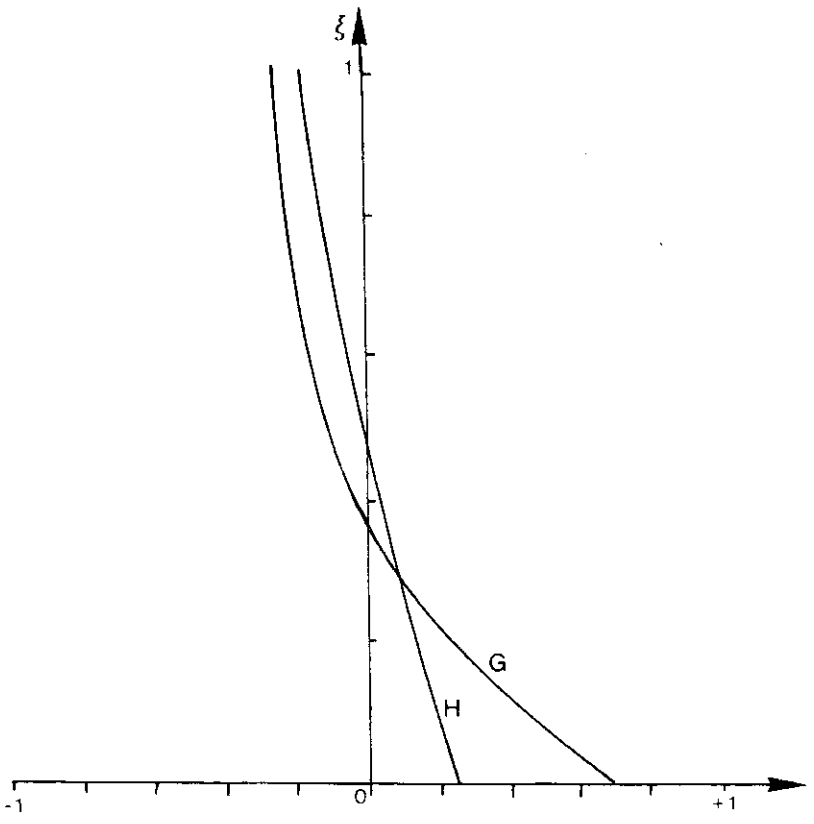

fig. 4.

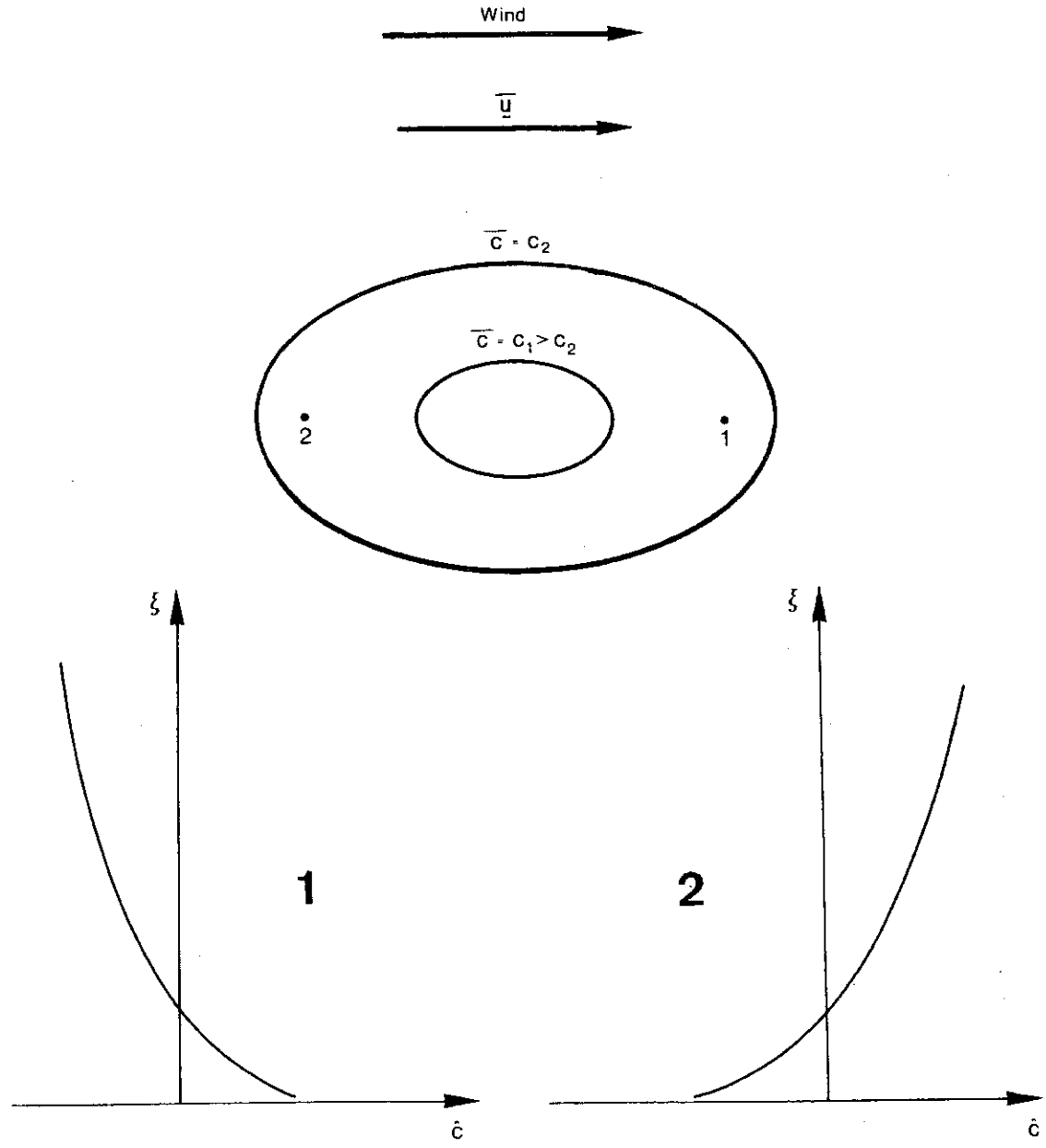

fig. 5.

where

$$H(\xi) = 4\ \{P(\xi) + \ln(2-\xi)\ \ln\frac{\xi}{4} + \ln 2\ (4\ \ln 2 - 1 - \ln\xi) - 2\} \qquad (75)$$

$$G(\xi) = -\ 2\ \{2\ L_2(\tfrac{1}{2}) + \ln\frac{2-\xi}{2}\ \ln\frac{\xi}{2} + \ln(2)\ \ln(2) + 2\} \qquad (76)$$

and

$$P(\xi) = L_2(\frac{\xi}{2}) + 2\, L_2(\frac{1}{2}) - \overline{L}_2 \qquad (77)$$

$$L_2(x) = \text{Dilo}\,(1-x) = \sum_{\nu=1}^{\infty} (-1)^{\nu} \frac{(x-1)^{\nu}}{\nu^2} \qquad (78)$$

The functions H and G are shown in fig.4. They are both negative near the surface and positive near the bottom. This is what one should expect from a physical point of view. Higher velocities near the surface carry water masses farther. If this transport is directed towards increasing mean concentrations the corresponding inflow of lower concentration fluid decreases the local concentration below the mean value $\overline{c}$. If the transport in the upper layer is directed towards decreasing mean concentrations, the corresponding inflow of high concentration fluid increases the local concentration above the mean value $\overline{c}$. The opposite situation occurs near the bottom. This is illustrated in fig. 5 showing the concentration profiles at two points situated downstream and downwind and respectively upstream and upwind on the same isoconcentration curve following a dumping.

The combination of eqs.(16) and (42) with a three-dimensional hydrodynamic model provides a three-dimensional dispersion model for the calculation of the evolution with time and the spatial - horizontal and vertical - distribution of any passive buoyant marine constituant.

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Air-sea interactions

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Introduction

Of late years, the investigation of air-sea interactions and the study of their effect on the dynamics of the ocean and the atmosphere have gained considerable importance.

Much work is at the moment being devoted to the measurement and parameterization of the different transfers occuring at the air-water interface. These consist mainly of fluxes of mass (water vapour, gases, pollutants), heat (short and long wave radiation, latent and sensible heat), momentum and mechanical energy.

At the local scale, these fluxes act as boundary conditions on the oceanic and atmospheric systems. They supply almost all the energy for circulations and turbulence in the ocean. They determine the state of the sea and of the water immediately below the interface. (A very important part of all the solar radiation absorbed below the bottom of the atmosphere is stored temporarily in the upper layers of the ocean). This portion of the sea being most under their influence is also the place where a very important biological activity occurs, which constitutes a crucial link in the food chain in the sea. Besides, they determine the state of the atmospheric lower layers, their stability, and their temperature, moisture and velocity distributions.

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1. Aspirant F.N.R.S.

Moreover, these fluxes are also of primary importance at the large scale : the climate of the earth is a very intricate system involving land, sea and air. As constant transfers occur continuously between the different components, the dynamics of the climate must take the oceanic and atmospheric dynamics into account, with all their interactions.

In this paper, we will present some of the work we are at present undertaking in this field.

In a first paragraph, the radiative and turbulent energy fluxes will be detailed ; several methods of measurement we are using will be described and compared, and the first experimental results will be presented.

In a second paragraph, some features of the atmospheric boundary layer and the ocean mixed layer and thermocline will be depicted. The general equations governing both phenomena will be introduced and different modelling approaches we are using will be described.

A last paragraph will introduce a large scale air-sea interaction problem and present some preliminary results: the ocean dynamics of the Gulf of Guinea (laying stress on the upwelling problem), and its possible connection with the climate of the Sahel area.

1.- Energy transfers and their measurement

1.1.- THE BASIC ENERGY TRANSFERS

A general view of the various energy fluxes involved in air-sea interactions is shown in figure 1. The two broad classes of exchanges are clearly depicted : radiative and turbulent.

1.1.1.- Radiative transfers

The basic source of energy is the sun. Its light undergoes many transformations before reaching the sea level. Diffusion and absorption by atmospheric molecules and clouds may reduce in a considerable way the energy arriving at the surface. Some light is also reflected by the sea surface (albedo), so that the remaining energy really absorbed in the upper layers of the ocean may vary within wide limits according to the season, time of the day and cloudiness.

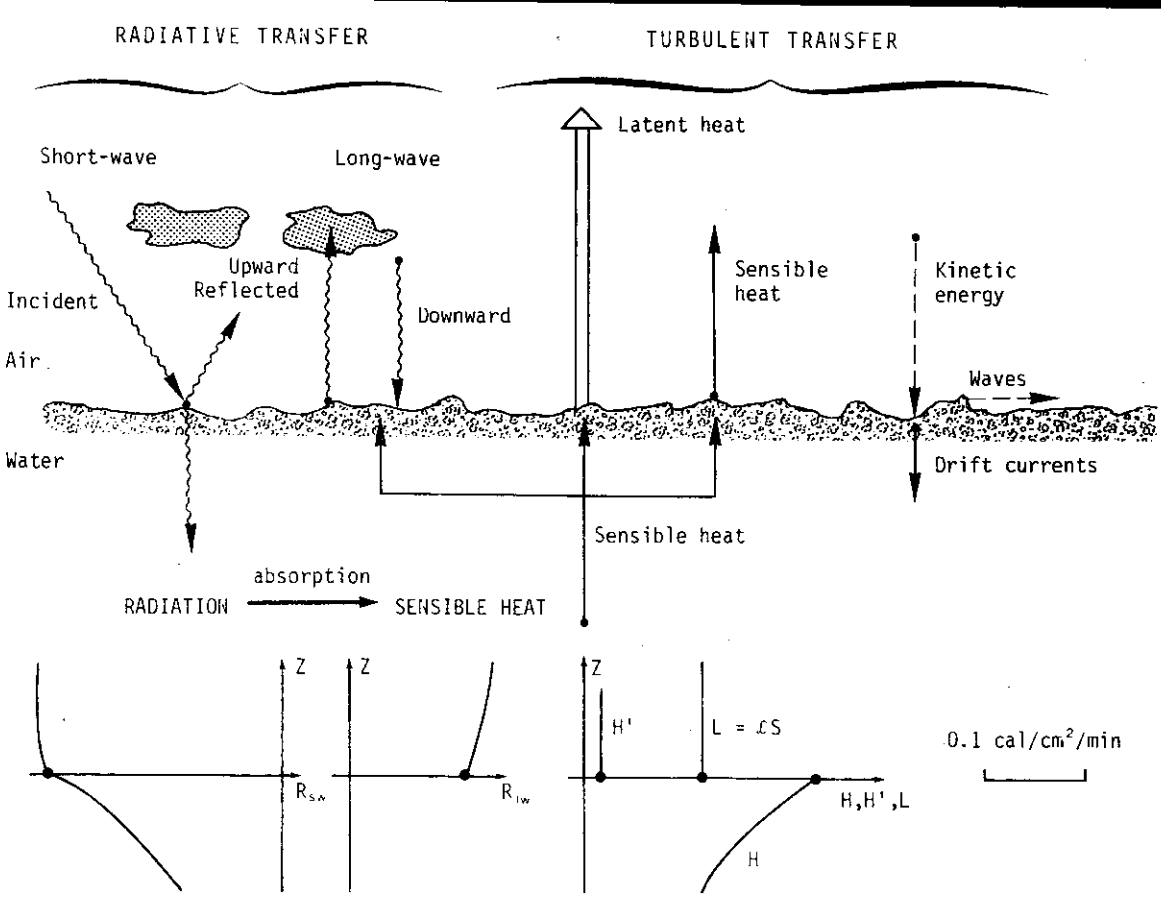


fig. 1.

Schematic display of energy transfers and transformations in the vicinity of the ocean-atmosphere interface, and the corresponding upward fluxes, assuming a steady-state situation.

In the infra-red part of the spectrum, a more complex equilibrium is reached between thermal emission from the sea surface and from the atmosphere above it. This is due to the high absorptive power of water vapour, of course present in large quantities in the marine atmosphere.

1.1.2.- Turbulent transfers

Friction on the sea surface generates turbulence in the air, enabling a turbulent transfer of energy. Some quantity of heat is exchanged in this way between the sea surface and the air, but the biggest part of the energy is extracted from the sea surface by evaporation of water, thus by transfer of latent heat.

Some part of the mechanical energy of the air is also transferred to the ocean (waves, current, oceanic turbulence).

The oceanic medium, subject to all these atmospheric inputs responds in its own way. The characteristics of its surface are modified (temperature, roughness), and this can in its turn affect the lower atmosphere. This is the basic feed-back mechanism of air-sea interactions.

This brief survey of the main exchanges between the atmosphere and the ocean makes the complexity of the problem in its generality obvious. This is the reason why most of the modelling approaches have to divide the task into smaller ones.

1.1.3.- Energy balance at the sea level

If S_0 denotes the solar incoming radiation flux and α the albedo of the sea surface, the following relation states that the sum of all energy fluxes is equal to zero :

$$I_0 - I_L^{\uparrow} + I_L^{\downarrow} - H - E + W = 0 \qquad (1)$$

(a positive sign means a gain of energy for the surface)
where

$$I_0 = S_0 \ (1 - \alpha) \ ,$$

$I_L^{\uparrow}$ is the infra-red emission of the surface, $I_L^{\downarrow}$ is the infra-red emission from the atmosphere, H is the sensible heat flux (to the atmosphere), E is the latent heat flux (to the atmosphere), W is the sensible heat flux in the sea (positive upwards).

1.2.- THE ESTIMATION OF THE FLUXES

1.2.1.- Radiative transfers

Measurements of radiative fluxes are difficult at sea mainly because of sea spray. After a few days in normal conditions, the sensors are covered with a film of salt, and a close watch on the instruments must be kept to ensure enough accuracy in the measurements. For that reason, only solar radiative flux can be obtained in coastal stations without much trouble. The albedo of the sea surface can now be fairly well determined

from tables of sea surface reflectivity as a function of sun height, cloud cover and sea state (Krauss, 1972). Because of the sea spray, radiative measurements at sea can only be performed during special compaigns when a constant survey of the equipment is possible. The global or net radiative fluxes (upwards-downwards, both visible and infra-red) can then be measured. The only problem is to keep the sensor horizontal and to take into account the solid angle under which the sensor "sees" the boat.

1.2.2.- Turbulent transfers

There is no simple and direct way of measuring the turbulent energy fluxes, and indirect methods must be used. We shall briefly describe here four methods used to determine the fluxes at the local scale. They are :

a) drag coefficient formulas
b) similarity and surface layer theory
c) direct measurement of fluctuation covariances
d) spectral methods

a) *Drag coefficient*

This is the simplest way of estimating the fluxes. The only quantities needed are the wind speed at some standard level (usually 10 m) above the sea surface, the air temperature and humidity at the same level, and the sea surface temperature.

In the turbulence theory, the fluxes are given by :

$$\tau = \rho_a \, u_*^2 \qquad (2)$$

$$H = - \rho_a \, C_{p_a} \, u_* \, T_* \qquad (3)$$

$$E = - \rho_a \, L \, u_* \, q_* \qquad (4)$$

where τ is the surface stress or flux of momentum, H and E are the sensible and latent heat fluxes, ρ_a is the density of the air, C_{p_a} is the heat capacity of the air at constant pressure, L is the latent heat of vaporization of the water, u_* is the friction velocity in the air, T_* and q_* are the temperature and humidity scales of turbulent fluctuations.

The first drag coefficient C_D is defined as the square of the ratio of the friction velocity u_* to the wind speed V measured at the standard level, i.e. :

$$u_* = C_D^{\frac{1}{2}} V_{10} \ .$$

The other coefficients C_E and C_H can be introduced in a similar way. The drag formulas are thus :

$$\tau = \rho_a \ C_D \ V_{10}^2 \tag{5}$$

$$H = - \rho_a \ C_{p_a} \ C_H \ V_{10} \ (T_{10} - T_w) \tag{6}$$

$$E = - \rho_a \ L \ C_E \ V_{10} (q_{10} - q_w) \tag{7}$$

where T_{10} is the air temperature at 10 m height, q_{10} is the air humidity at 10 m height, T_w is the water temperature, q_w is the specific humidity of saturated air at the water temperature (this quantity is determined from T_w and the tables of thermodynamic properties of water vapour).

In fact, the drag coefficients C_D, C_E and C_H simply relate the measurable quantities to unmeasurable ones. These coefficients have been carefully determined in special measurement campaigns by a best fit to the observed flux data. Unfortunately, there is a wide variety of C_D in the literature. We present here one of the latest version reported by Friehe and Gibson (1978). If

$$\Delta T = T_w - T_{10} \ ,$$

$$C_D = 10^{-3} \times (0.63 + 0.066 \ V_{10}) \tag{8}$$

$$C_H = \begin{cases} 10^{-3} \times (2 + 0.97 \ V_{10} \ \Delta T) \\ 10^{-3} \times (1.46 \ V_{10} \ \Delta T) \end{cases} \quad \text{if} \quad V_{10} \ \Delta T \begin{cases} < 25 \text{ m s}^{-1} \text{ K} \\ > 25 \text{ m s}^{-1} \text{ K} \end{cases} \tag{9}$$

$$C = 10^{-3} \times 1.32 \tag{10}$$

(V_{10} in m s^{-1}, T in Kelvins).

As a rule, the C_D's are increasing with increasing wind speed, because of the increasing roughness length z_0 of the sea.

This is the simplest way of obtaining valuable estimates of the fluxes. However, a non negligible scatter of C_D values among different authors may question the general applicability of the method.

b) *Similarity theory — Surface layer formulas*

The original similarity theory of Monin and Obukov published in 1954 has been widely used recently since the determination of the functions by Businger (1973). The theory stipulates that the vertical non dimensionalised wind, temperature and humidity gradients are only function of a non dimensional height $\xi = z/L$, where L is the Monin-Obukov length scale, defined as :

$$L = \frac{\overline{T}\, u_*^2}{kgT_*} \tag{11}$$

g is the acceleration of gravity and $\overline{T}$ the mean temperature, k is the Von Karman constant (k = 0.35).

Thus

$$\begin{cases} \dfrac{kz}{u_*}\dfrac{\partial \overline{u}}{\partial z} = \phi_M(\xi) \\ \dfrac{kz}{T_*}\dfrac{\partial \overline{T}}{\partial z} = \phi_H(\xi) \\ \dfrac{kz}{q_*}\dfrac{\partial \overline{q}}{\partial z} = \phi_E(\xi) \end{cases} \tag{12}$$

The ϕ_i (i = M,H,E) have now a well known analytical form (Businger, 1973).

The relations (I.12) can be integrated from 0 (or z_0) to the standard level of measurement (usually 10 m), yielding the integrated form ψ_i of the ϕ_i . We have then :

$$
\begin{cases}
u_* = \dfrac{k\, V_{10}}{\ln \dfrac{z}{z_0} - \psi_M} \\[2ex]
T_* = \dfrac{k(T_{10} - T_w)}{0.74 \ln \dfrac{z}{z_0} - \psi_H} \\[2ex]
q_* = \dfrac{k(q_{10} - q_w)}{0.74 \ln \dfrac{z}{z_0} - \psi_E}
\end{cases}
\qquad (13)
$$

We obtain in this way an implicit set of equations that can be solved iteratively to have L , u_* , T_* and q_* from the observed V_{10} , T_{10} , T_w and q_w . The fluxes can then be obtained directly from equations (2) to (4). It is important to note that in order to use equations (13), an adequate value of z_0 must be determined independently, generally as a function of V_{10} .

c) *Direct method*

With fast response sensors and a fixed, stable frame of reference, the fluctuating eddies in the air may be resolved and the turbulent fluxes can be directly expressed as the covariances of the fluctuations of the vertical wind component and the other quantity. Thus :

$$
\begin{cases}
\tau = - \rho_a \, \overline{u'w'} \\[2ex]
H = \rho_a \, C_{p_a} \, \overline{T'w'} \\[2ex]
E = \rho_a \, L \, \overline{q'w'}
\end{cases}
\qquad (14)
$$

(Here an overbar denotes a time average over an adequate period, generally of the order of a few tens of minutes, and primes denote fluctuations around the mean).

Comparing (I.2 to I.5) with (I.14) leads immediately to :

$$\begin{cases} \overline{u'w'} = - u_*^2 \\ \overline{T'w'} = - u_* T_* \\ \overline{q'w'} = - u_* q_* \end{cases} \qquad (15)$$

which can be used to define the velocity, temperature and humidity scales u_* , T_* and q_* .

This technique may be considered as an absolute measurement of the fluxes (a reference one), but it needs sensors able to respond to frequencies up to a few Hz in order to pick up the portion of the flux due to small eddies. In the atmosphere, this implies a sampling frequency of the order of 10 Hz.

The other important point is that the verticality of the sensor must be accurately set, and must remain unchanged. Equations (I.14) show that w' is the leading factor. Even a very small deviation of the sensor from the vertical should induce the effect of u or v in the measured w (since generally $\overline{u} \simeq \overline{v} \gg \overline{w}$). This implies the use of a fixed rigid support for the instrument (a pile e.g.) and excludes any simple system (as usual buoys or boats).

d) *Spectral method*

This promising method will be briefly outlined here. For details, one can refer to Champagne et al. (1977).

In the inertial subrange of turbulence, the spectrum of wind fluctuations follows the Kolmogorov's law :

$$S_u(n) = \alpha_1 \, u^{\frac{2}{3}} \, \varepsilon^{\frac{2}{3}} \, n^{-\frac{5}{3}} \qquad (16)$$

where α_1 is a constant $\simeq 0.55$, ε is the dissipation rate, n is the frequency measured at a fixed point in space.

In neutral conditions, the wind profile follows the logarithmic law :

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz} \quad .$$

As the turbulent energy balance in the stationary case is

$$- \overline{u'w'} \frac{\partial u}{\partial z} = \varepsilon ,$$

we have

$$u_* = (k \varepsilon z)^{\frac{1}{3}} .$$

In the non-neutral case, it can be shown that this relation becomes :

$$u_* = \left[\frac{k \varepsilon z}{\left[1 + 0.5 \left|\frac{z}{L}\right|^{2/3}\right]^{3/2}} \right]^{1/3} \qquad (17)$$

As ε can be found from (16), equation (2) gives an evaluation of the momentum flux if L is known.

A similar procedure can be followed for temperature and humidity : the spectrum of temperature fluctuations follows the law

$$S_\theta(n) = \beta_\theta \chi_\theta u^{\frac{2}{3}} \varepsilon^{-\frac{1}{3}} n^{-\frac{5}{3}} \qquad (18)$$

where β_θ is a constant $\simeq 0.4$, χ_θ is the dissipation rate for temperature fluctuations (to be determined). The use of a similar hypothesis for the temperature profile leads to the following expression for the temperature scale :

$$T_* = - \left[\frac{k z \chi_\theta}{2 u_* \phi_H} \right]^{\frac{1}{2}}$$

where ϕ_H is the similarity function for heat.

The heat flux is then found by equation (3).

A quite similar relation is also established for q_*, but at the present time, no experimental confirmation exists for it.

e) *Comparison of the methods*

Table 1 summarizes the needs and advantages of each method.

The last two methods require instruments capable of measuring frequencies over 1 Hz in the fluctuations. The ideal instrument for this purpose is the sonic anemometer. The Gill anemometer we have can also be used, if it is not too close to the sea surface.

Table 1

Comparison of the methods used to determine the turbulent fluxes

Method	Data needed	Instrument needed	Comments	Maximum expected error
A. Drag coefficient	T_{10} , T_w, V_{10} , q_{10} + choice of drag coefficients formulas	Simple instruments measuring mean values	Very fast method	± 40 %
B. Similarity Monin-Obukov	T_{10} , T_w, V_{10} , q_{10} + estimated z_0	Use of buoy possible.	Iterative method	± 40 %
C. Direct covariance	u, v, w, T, q	Fast response instruments to measure fluctuating quantities. Fixed frame of reference (tower or mast fixed on bottom) Vertical must be accurately defined.	Basic technique of flux determination Difficult method at sea.	± 10 %
D. Spectral	u, T, q	Fast response instruments to measure fluctuating quantities. Fixed frame of reference not necessary. Vertical wind speed not needed. Use of buoy should be possible.		± 20 % (?)

1.3.- A FEW RESULTS

A buoy has been operated in common by the Institut Royal Météorologique (I.R.M.), the University of Liège, and the University of Louvain-La-Neuve, during two summer campaigns at STARESO, the oceanographic station of the University of Liège in Calvi, Corsica.

The available data are summarized in table 2.

Table 2

Data measured by the I.R.M. buoy in Calvi

Campaign	Period of recording	Measured parameters
Summer 1977	14-7-77 to 10-8-77 (with interruptions)	Wind speed, Air temperature } at 6 m height; Sea surface temperature at - 2 m
Summer 1978	9-7-78 to 9-8-78	Wind speed, Wind direction, Air temperature } at 6 m height; Wind speed, Air temperature } at 2 m height; Water temperature at - 2 m

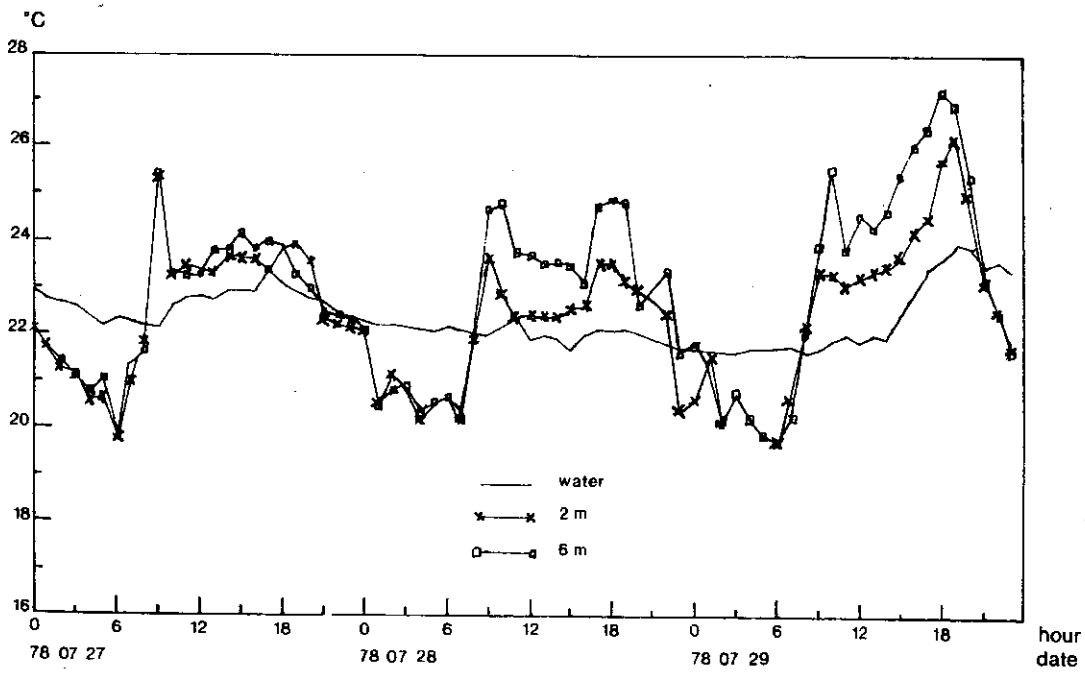


fig. 2.

Sample of observed temperatures in the Bay of Calvi with the I.R.M. buoy

Figures 2 and 3 show a sample of the measured data. Figure 4 shows the estimated fluxes for the 1978 summer campaign.

The reader may refer to the work of Clement (1979) for complete fluxes calculations and comparisons. The complete set of data is available at the I.R.M.

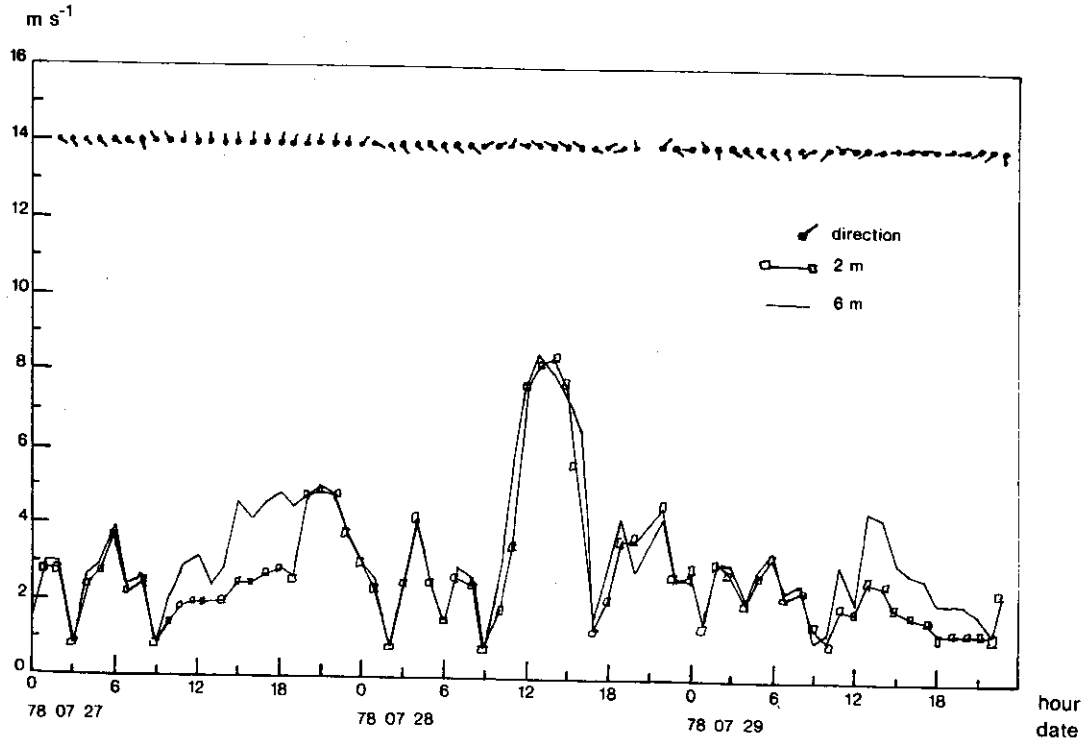


fig. 3.

Sample of observed wind speed and direction in the Bay of Calvi with the I.R.M. buoy

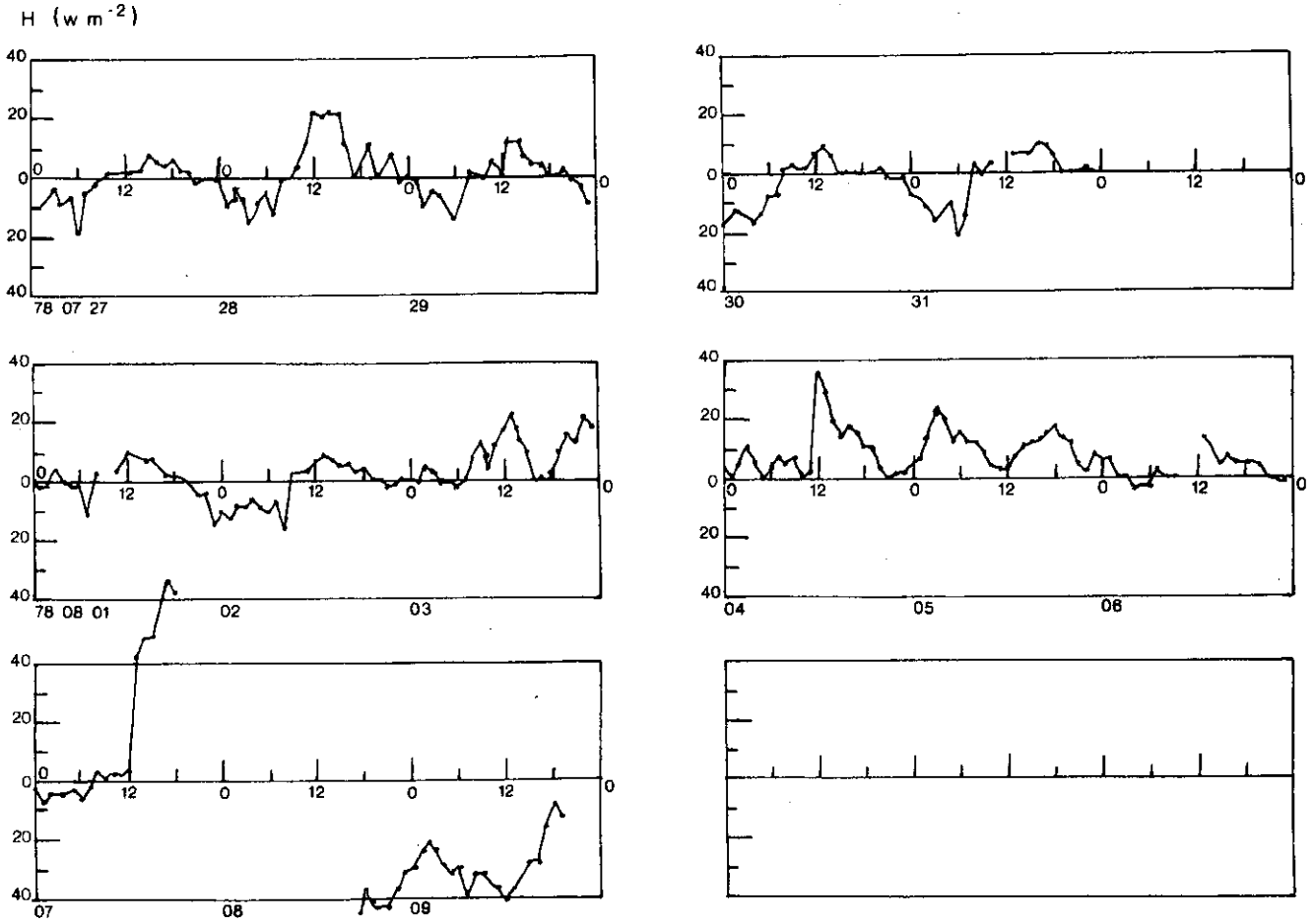


fig. 4.

Estimated heat fluxes from 27-07 to 09-08-1978

2.- The boundary layers in the atmosphere and the ocean

In the preceding section, several processes occuring close to the sea surface (at a few meters height) have been described in order to measure the turbulent fluxes at the interface.

As mentioned in the introduction, the fluxes act also as lower boundary conditions for the atmospheric boundary layer, i.e. the layer in which turbulent exchanges of momentum, heat and moisture take place. Typically, this layer is from 500 to 1500 meters high. Above this level, the friction of the sea surface is no more felt, and the air flux is normally non turbulent.

They act also as boundary inputs for the upper layers of the ocean. However, the ocean has a much larger thermic and dynamic inertia than the atmosphere, and very often exhibits an important stratification which acts as a barrier for the exchanges with lower water layers. This stratification is mainly due to heat and salinity.

Before starting with the equations used to model the atmospheric boundary layer and the upper layers of the ocean, it is interesting to have a look at the general characteristics of the ocean vertical thermal structure.

2.1.- MAIN FEATURES OF THE VERTICAL THERMAL STRUCTURE OF THE OCEAN

In this section, we shall not consider the recently discovered phenomenon of fine-scale stratification or microstructure in the ocean, although this could lead to a reconsideration of the modelling problem, but emphasize the coarser general structure of the oceanic waters. (Further informations about microstructure can be found in Fedorov, 1978).

In low and mid latitude areas, the mean vertical structure of the waters (disregarding annual or higher frequencies fluctuations) can be schematized by the existence of three different layers :

a) a surface layer, 50 to 200 m deep, where the temperature is close to its value at the surface ;

b) a layer in which the temperature decreases with depth and which extends itself below the first and down to 1000 m almost. This is the main or permanent thermocline.

c) deeper, the temperature gradient dies away : we are in the domain of the deep waters.

There are also some differences between the equatorial and mid-latitude areas : in the former ones, the waters are highly stratified and a well defined thermocline can be found ; in the latter ones, there is also a thermocline, but not so important and often deeper.

However, polar areas, many lakes and some enclosed seas (as the Mediterranean Sea) do not exhibit a permanent thermocline. This mean global structure is mainly the result of the large scale energetic exchanges with the atmosphere and the general oceanic circulation.

The layers close to the sea surface (0 - 100 m) undergo the influence of the exchanges with the atmosphere, and these have several well or less marked periodicities (seasonal, diurnal, synoptic,..). Heat fluxes depend locally on the season, hour of the day and atmospheric conditions. Mechanical energy transfers, depending mainly on the wind, can also exhibit a periodicity of a few days (synoptic, i.e. related to the development of atmospheric perturbation in our latitudes, e.g.). The advection can also take an important part locally.

In connection with the seasonal variations of the fluxes in mid and high latitude areas, a seasonal thermocline develops at the bottom of a layer often close to homogeneity in temperature. This thermocline appears in spring, develops in summer and dies away at the end of autumn. The temperature difference between the upper warm layers and the underlying fluid is more important at mid-latitude than in polar areas. In low latitude areas, the seasons are not so distinct, and there is almost no variation across the year.

Finally, diurnal or synoptic variations in the fluxes can also induce diurnal or transitory thermocline structures. In special circumstances, a succession of transitory thermoclines can be observed above the seasonal thermocline, related to the evolution of the fluxes in the preceding days.

It should again be noticed that polar areas, some lakes and enclosed seas as the Mediterranean Sea have only seasonal, diurnal and transitory thermoclines.

One important problem, and also one of the best documented, is the study of the effect of a gust of wind causing mixing in the upper layers and entrainment of the underlying fluid. The new mixed layer can enclose old thermoclines and even reach the seasonal thermocline and modify it.

Figure 5 shows an example of a well develop mixed layer due to a sudden rise in wind force. The profiles were taken at STARESO, Calvi, Corsica.

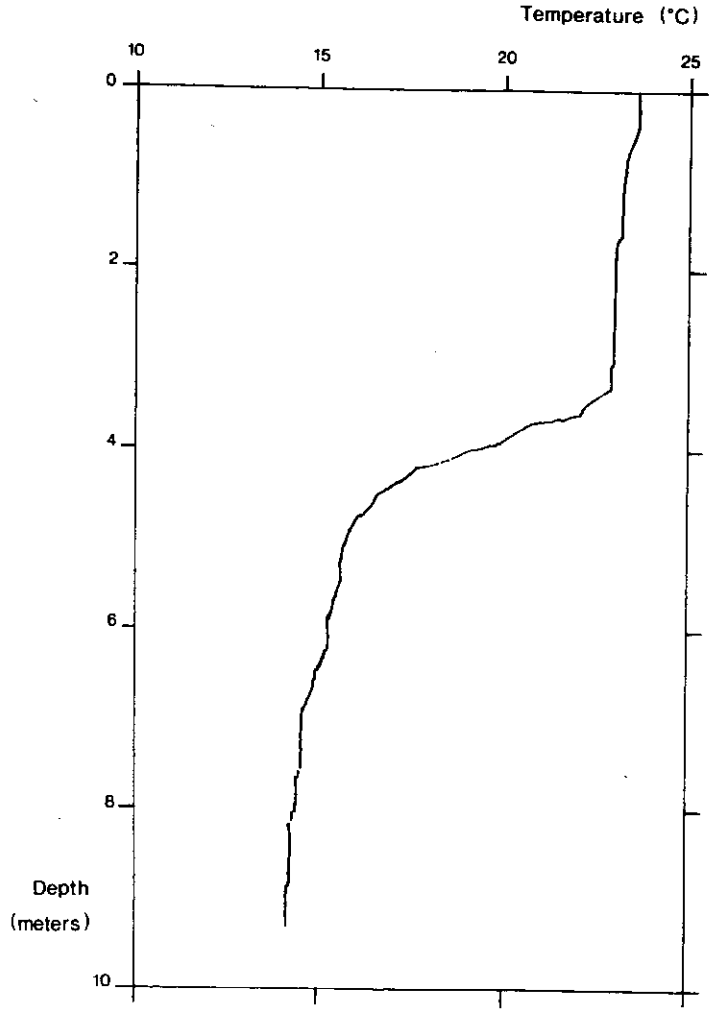


fig. 5.

Vertical structure of the water temperature off Calvi, Corsica, after the passage of a gust of wind (10 m/s) [18-07-77]

One of our present aims is to model the dynamics of the upper oceanic layers at the different time scales. If the question of the mixed layer deepening is well documented, its later evolution and restructuration still set unresolved experimental and theoretical problems.

2.2.- BOUNDARY LAYER MODELLING

The fundamental hypotheses used for the modelling of the atmospheric boundary layer and of the oceanic upper mixed layer and thermocline are the following :

1) The Boussinesq approximation.

In the ocean

$$\rho = \rho_0[1 - \alpha(T - T_0) + \beta(S - S_0)] \ , \quad \rho_0 = \rho\,(S_0, T_0)$$

where T is the temperature and S the salinity. In the atmosphere, a similar formula is introduced, involving potential temperature and water-vapour content.

2) The parameters are decomposed into a mean value (denoted by an overbar) and turbulent fluctuations. The equations for the mean values of the parameters are considered, as well as the equation for turbulent kinetic energy.

Nowadays, second order closure models are being developed. These consider also the equations for all second order covariances and use closure hypotheses for these equations. However, they involve many computation problems and in a first time, we will restrict ourselves to the former, simpler but more direct approach.

3) Horizontal homogeneity is also assumed. This hypothesis is realistic in the marine atmospheric boundary layer, because of the absence of topography. In the ocean, it is also realistic if we consider areas far enough from coastal areas and bottom effects.

We get in this way :

$$\frac{\partial u}{\partial t} = f(v - v_g) - \frac{\partial}{\partial z}\,\overline{u'w'} \tag{19}$$

$$\frac{\partial v}{\partial t} = -\,f(u - u_g) - \frac{\partial}{\partial z}\,\overline{v'w'} \tag{20}$$

$$\frac{\partial T}{\partial t} = -\,\frac{\partial}{\partial z}\,\overline{w'T'} + \frac{R}{\rho_{0_w} c_{p_w}} \qquad \text{(ocean)}$$

or (21)

$$\frac{\partial \theta}{\partial t} = -\,\frac{\partial}{\partial z}\,\overline{w'\theta'} + \frac{R}{\rho_{0_a} c_{p_a}} \qquad \text{(atmosphere)}$$

$$\frac{\partial S}{\partial t} = - \frac{\partial}{\partial z} \overline{w'S'} \qquad \text{(ocean)}$$

or

$$\frac{\partial q}{\partial t} = - \frac{\partial}{\partial z} \overline{w'q'} \qquad \text{(atmosphere)} \tag{22}$$

$$\frac{\partial e}{\partial t} = - \overline{u'w'} \frac{\partial u}{\partial z} - \overline{v'w'} \frac{\partial v}{\partial z} + \overline{w'b'} - \frac{\partial}{\partial z} \left[\frac{\overline{p'w'}}{\rho_0} + \frac{\overline{u'^2 + v'^2 + w'^2}}{2} w' \right] - \varepsilon \tag{23}$$

The frame of reference is dextrorsum, with z positive upwards. The overbars have been omitted for mean speeds (u,v), temperature, or potential temperature in the atmosphere (T,θ), salinity (S), humidity (q) and turbulent kinetic energy (e). f is the Coriolis parameter and (u_g, v_g) the geostrophic wind or current. ρ_0 and c_p are related to the air, or the sea water, R is the divergence of the radiation flux, b' denotes the fluctuations of buoyancy b defined as $b = -\frac{\rho - \rho_0}{\rho_0} g$. An equation for buoyancy can be written instead of (21) and (22).

The right-hand side terms of the last equation have the following physical meaning :

$- \overline{u'w'} \frac{\partial u}{\partial z} - \overline{v'w'} \frac{\partial v}{\partial z}$ is the turbulence production due to shear in the mean wind or current ,

$\overline{b'w'}$ is a source or a sink of turbulent kinetic energy due to the buoyancy forces ,

$\frac{\partial}{\partial z} \left[\frac{\overline{p'w'}}{\rho_0} + \frac{\overline{u'^2 + v'^2 + w'^2}}{2} w' \right]$ is a transport term of turbulence,

ε is the turbulent kinetic energy dissipation ($\varepsilon > 0$).

Closure hypotheses have to be introduced now in order to solve the system. We also need initial and boundary conditions for the different variables.

We will examine the particular cases of the atmospheric and oceanic boundary layers.

2.2.1.- Atmospheric boundary layer

The turbulent diffusivities K_M , K_θ and K_q are introduced :

$$- \overline{u'w'} = K_M \frac{\partial u}{\partial z} \quad ; \quad - \overline{v'w'} = K_M \frac{\partial v}{\partial z} \tag{24}$$

$$- \overline{w'\theta'} = K_\theta \frac{\partial \theta}{\partial z} \tag{25}$$

$$- \overline{w'q'} = K_q \frac{\partial q}{\partial z} \tag{26}$$

In this case, if we neglect the divergence of the radiation flux, equations (19) to (22) become :

$$\frac{\partial u}{\partial t} = f(v - v_g) + \frac{\partial}{\partial z} \left(K_M \frac{\partial u}{\partial z}\right) \tag{27}$$

$$\frac{\partial v}{\partial t} = - f(u - u_g) + \frac{\partial}{\partial z} \left(K_M \frac{\partial v}{\partial z}\right) \tag{28}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K_\theta \frac{\partial \theta}{\partial z}\right) \tag{29}$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} \left(K_q \frac{\partial q}{\partial z}\right) \tag{30}$$

These four equations can be solved numerically if initial profiles of u , v , θ and q are given as well as the temperature and humidity time evolution at the sea level. The K 's are used as parameters. Many kinds of ABL models have been devised assuming various forms of K(z) profiles. The interest reader can find a review of K(z) specifications in Yu (1977), Coantic (1978) and Schayes (1979).

A not complicated and realistic K formulation is based on equation (II.5). The introduction of the diffusivities and several hypotheses lead to :

$$\frac{\partial e}{\partial r} = K_M \Bigg(\underbrace{\left[\frac{\partial u}{\partial z}\right]^2 + \left[\frac{\partial v}{\partial z}\right]^2}_{(a)} \underbrace{- 1.35 \frac{g}{\theta} \frac{\partial \theta}{\partial z}}_{(b)} \Bigg) + \underbrace{1.2 \frac{\partial}{\partial z}\left[K_M \frac{\partial e}{\partial z}\right]}_{(c)} - \underbrace{\varepsilon}_{(d)} \tag{31}$$

where we find again the expressions for turbulent kinetic energy production

by wind shear (a), production or removal due to buoyancy (b), diffusion (c) and dissipation (d).

The dissipation ε is frequently expressed as

$$\varepsilon = c\, e^{\frac{3}{2}}\, \ell \qquad \text{(c is a constant)}$$

and K_M is defined by

$$K_M = c\, \ell\, e^{\frac{1}{2}}$$

The set of equations is then closed if we specify the mixing length ℓ. Various formulations exist among which the one of Blackadar is frequently used :

$$\ell = \frac{kz}{1 + \frac{kz}{\lambda}} \quad \text{or} \quad \frac{1}{\ell} = \frac{1}{\lambda} + \frac{1}{kz}$$

where

$$\ell = 2.7 \times 10^{-4} \left|\frac{U_g}{f}\right| \qquad (U_g \text{ is the geostrophic wind}).$$

Up to this point, the model fits mainly continental ABL simulation. On land, turbulent processes are dominating due to the normally large temperature oscillation of the night and day sequence. Large instabilities can develop during the day, triggering convection. On the other hand, over the sea, the daily temperature oscillation (at sea level) is very much smaller, and instability does not develop in daytime (unless advection of cold air over warm water occurs).

Therefore, radiative and evaporation phenomena are as important as turbulent ones over the marine ABL and we must take the radiative term into account in (29).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K_\theta \frac{\partial \theta}{\partial z}\right] + \frac{R}{\rho_{O_a} c_{p_a}} \tag{32}$$

$$R = -\frac{\partial}{\partial z}(F^{\uparrow} - F^{\downarrow}) \tag{33}$$

R is the heating rate due to the divergence of the radiation flux density. $F^{\uparrow}$ is the total radiative flux upwards, and $F^{\downarrow}$ the total radiative flux downwards at the considered level.

The F's are computed by integrating the absorptivity - emissivity of water vapour at all levels above or below the considered level. For example $F^{\downarrow}$ is given by :

$$F^{\downarrow}(z_1) = \int_{z_1}^{\infty} \sigma T^4 \frac{d\varepsilon(z_1, z)}{dz} dz \qquad (34)$$

where σ is the Stefan constant (black body) and ε is here the emissivity of water vapour between levels z_1 and z. A similar equation is used for $F^{\uparrow}$.

Such a radiative model should simulate the marine ABL in a reasonably good way as far as advective phenomena are not important.

Let us notice two points now :

- this model does not take any condensation of water vapour into account, i.e. the presence or formation of clouds above the BL (medium and high clouds) and in the BL (low clouds), which affect considerably the radiative balance of the system. These important problems have not yet found a good solution. They are often parameterized in a crude way in order to avoid very long computation time.
- if horizontal homogeneity cannot be assumed, one has to turn to a two-dimensional or even a full three-dimensional model. This is however needed to represent phenomena as sea breaze along a coast, or non uniform meteorological situations, which unfortunately are not rare.

Input data for the models consist of initial profiles of wind, temperature and humidity, and the evolution of the sea temperature. These data are obtainable from standard radiosoundings and special tethered balloon soundings for the lowest level ($z \leq 500$ m)

2.2.2.- Oceanic upper layer

Although the general equations are similar, the approach of the problem has been to a slight extent different in the case of the oceanic mixed layer and thermocline. Efforts have been made to solve equations (19) to (23) using similar techniques as in the atmosphere, but much emphasis has been laid on integrated models, capable of simulating the time evolution

of the upper mixed layer characteristics (depth, mean temperature and salinity). The reason for this is perhaps the lack of interest for the exact determination of current profiles, e.g., as long as their horizontal variability is not taken into account, and also the will of developing simple models of the oceanic response to atmospheric inputs which could be used as subroutines in more general problems.

Before developing these two approaches, we shall give the expression of the boundary fluxes at the top boundary and below the bottom of the mixed layer.

a) Top boundary $z = 0$

1. $\overline{u'w'_0}$, $\overline{v'w'_0}$: the determination of the stress has been detailed in part 1. A friction velocity u_* can also be introduced in the water $|\tau| = \rho_{0_w} u^2_{*_w}$ and it is related to the friction velocity in the air

$$u_{*_w} = \left[\frac{\rho_{0_a}}{\rho_{0_w}}\right]^{\frac{1}{2}} u_{*_a} \qquad (35)$$

τ is directed as the wind.

2. $\rho_0 c_p \overline{w'T'_0}$ is determined from eq. (1). Usually, one considers that some part r of the solar incoming radiation is absorbed at the surface, and that the remaining part (1-r) is absorbed with depth according to a law $\sim e^{\gamma z}$. The possibility of precipitation with a temperature differing from that of the sea water is also introduced. Thus

$$\rho_0 c_p \overline{w'T'_0} = H + E + I^{\downarrow} - I^{\uparrow} - I_0 r - \rho_0 c_p P(T_p - T_s) \qquad (36)$$

P is the precipitation rate, T_p the precipitation temperature and T_s the sea surface temperature

$$R = \frac{\partial I}{\partial z} = (1-r)\ \gamma\ e^{\gamma z} I_0 \qquad (I_0 \text{ positive } \downarrow) \qquad (37)$$

$$3. \quad \overline{w'S'_0} = S_0 P - \frac{E}{\rho_0 L} \qquad (38)$$

where P is the precipitation rate, $\frac{E}{\rho_0 L}$ the evaporation rate and S_0 the salinity of the surface.

4. The buoyancy flux can be obtained from 2 and 3 :

$$\overline{w' b_0'} = \frac{\alpha g}{\rho_0 c_p} \left[H + E + I^{\dagger} - I^{\dagger} - I_0 r - \rho_0 c P (T_p - T_s) \right] - \beta g (P - \frac{E}{\rho_0 L}) S_0 \qquad (39)$$

5. $$\overline{\frac{1}{2} w' (u'^2 + v'^2 + w'^2) + \frac{p' w'}{\rho_0}} \quad . \qquad (40)$$

This is the flux of the turbulent velocity and pressure fluctuations. Near the surface, it must be equal to the rate of working by the wind, and is usually parameterized as $- c_1 u_*^3$ where c_1 is a proportionality factor.

b) Bottom boundary.

Below the mixed layer, the turbulence and turbulent fluxes vanish. If we integrate the equations, this process leads to special boundary conditions detailed below.

2.2.2.1.- Non integrated models

Mixing length hypotheses are also used in the ocean. The main problem is to find a good parameterization for the eddy diffusivities. In Mellor and Durbin's model (1975)

$$- (\overline{u'w'} , \overline{v'w'}) = e^{\frac{1}{2}} \ell S_M \left(\frac{\partial u}{\partial z} , \frac{\partial v}{\partial z}\right)$$

$$- \overline{w'T'} = e^{\frac{1}{2}} \ell S_T \frac{\partial T}{\partial z}$$

where $S_M(R_i)$ and $R_T(R_i)$

$$\left[R_i = \frac{\frac{\partial b}{\partial z}}{\left[\frac{\partial u}{\partial z}\right]^2 + \left[\frac{\partial v}{\partial z}\right]^2} \right]$$

take the effect of static stability on the eddy coefficients into account. The $S(R_i)$'s have been estimated using higher order closure hypotheses and laboratory experimental results.

A simplified turbulent kinetic energy balance neglecting diffusion and assuming local equilibrium is also used.

$$- \overline{u'w'} \frac{\partial u}{\partial z} - \overline{v'w'} \frac{\partial v}{\partial z} + \overline{b'w'} - \varepsilon = 0$$

$$\varepsilon = c\, e^{\frac{3}{2}}\, \ell^{-1}$$

where c is a constant and ℓ is defined as

$$\frac{1}{\ell} = \frac{1}{-Kz} + \frac{1}{\ell_\infty}$$

and

$$\ell_\infty = - c' \frac{\int_{-\infty}^{0} e\, z\, dz}{\int_{-\infty}^{0} e\, dz}$$

where c' is another constant.

These models make no assumption concerning the existence of a mixed layer. They give realistic profiles with mixed layers and thermoclines, but they require much computation work and leave some important physical processes apart.

2.2.2.2.- Integrated models

If we assume that there exists a well mixed layer (temperature, salinity, and to a lesser extent, current), we obtain the so-called slab models, and equations can be integrated over the mixed layer depth h (from $-h$ to 0) :

$$h \frac{du}{dt} = f v h - \overline{u'w'_0} + \overline{u'w'_{-h}} \qquad (41)$$

$$h \frac{dv}{dt} = - f u h - \overline{v'w'_0} + \overline{v'w'_{-h}} \qquad (42)$$

$$h \frac{dT}{dt} = - \overline{w'T'_0} + \overline{w'T'_{-h}} + \frac{1}{\rho_0 c} I_0 (1-r)(1 - e^{-\gamma h}) \qquad (43)$$

$$h \frac{dS}{dt} = - \overline{w'S'_0} + \overline{w'S'_{-h}} \qquad (44)$$

$$h\frac{de}{dt} = Prod + \int_{-h}^{0} \overline{b'w'dz} - \left[\frac{\overline{p'w'}}{\rho_0} + \overline{\frac{w'}{2}(u'^2 + v'^2 + w'^2)}\right]_0$$

$$+ \left[\frac{\overline{p'w'}}{\rho_0} + \overline{\frac{w'}{2}(u'^2 + v'^2 + w'^2)}\right]_{-h} - Diss \qquad (45)$$

Here, u, v, T, S and e denote the values of the variables in the mixed layer, and geostrophic current has been omitted.

These equations involve the fluxes at the bottom boundary of the mixed layer. Taking into account the fact that discontinuities are possible at the bottom of the mixed layer for temperature, salinity, current and kinetic energy, the bottom boundary fluxes can be expressed as :

$$\overline{u'w'}_{-h} + W_e u = 0 \qquad (46)$$

$$\overline{v'w'}_{-h} + W_e v = 0 \qquad (47)$$

$$\overline{w'T'}_{-h} + W_e(T - T_b) = 0 \qquad (48)$$

$$\overline{w'S'}_{-h} + W_e(S - S_b) = 0 \qquad (49)$$

$$\left[\frac{\overline{p'w'}}{\rho_0} + \overline{\frac{w'}{2}(u'^2 + v'^2 + w'^2)}\right]_{-h} + W_e e - W_e \frac{1}{2}(u^2 + v^2) = 0 \qquad (50)$$

where the subscript $_b$ denotes the values in the layers below the mixed layer.

The value W_e appearing in the equations is the rate of entrainment of the underlying fluid into the mixed layer, and it is equal to the time derivative of the mixed layer depths when this is increasing. However, when the depth of the mixed is decreasing, it is assumed to be completely decoupled from the ocean interior and $W_e = 0$. The physical meaning of this assumption is the fact that the ocean mixed layer cannot demix. This can be collected in a formal way using the Heaviside function

$$\theta(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{if } x \leq 0 \end{cases},$$

$$W_e = \frac{dh}{dt}\,\theta\left(\frac{dh}{dt}\right) \quad .$$

If we introduce equations (46) to (50) into equations (41) to (45), we get after a little algebra :

$$\frac{d}{dt}(h\,u) - f\,v\,h = \frac{\tau_{0x}}{\rho_0} \tag{51}$$

$$\frac{d}{dt}(h\,v) + f\,u\,h = \frac{\tau_{0y}}{\rho_0} \tag{52}$$

$$h\,\frac{dT}{dt} = -\,W_e(T - T_b) - \overline{w'T'_0} + \frac{1}{\rho_0 c}\,I_0(1-r)(1 - e^{-\gamma h}) \tag{53}$$

$$h\,\frac{dS}{dt} = -\,W_e(S - S_b) - \overline{w'S'_0} \tag{54}$$

$$W_e\left\{\frac{h}{2}\left[\alpha g(T - T_b) - \beta g(S - S_b)\right] + e - \frac{1}{2}(u^2 + v^2)\right\} = \mathrm{Prod}_S + c_1 u_*^3$$

$$+\,\frac{h}{2}\,\overline{b'w'_0} - \frac{h}{2}\,\frac{\alpha g}{\rho_0 c}\,I_0(1 - r)\left[1 - \frac{2}{\gamma h} + e^{-\gamma h}\left(1 + \frac{2}{\gamma h}\right)\right] - \mathrm{Diss} \tag{55}$$

Equation (II.27) is used as a balance, i.e. $h\,\frac{de}{dt} \simeq 0$. The production of turbulent kinetic energy is zero in the layer since there is no shear (u assumed constant). Shear can act at the bottom of the layer [third term on the left hand side of (55)], and also in a thin layer close to the surface and driven mainly by wind (Prod_S). Prod_S can be parameterized by $c_2 u_*^3$ where c_2 is a proportionnality factor. Production at the surface and turbulent flux can be taken together and $u_{**}^3 = c_1 u_*^3 + c_2 u_*^3$ used as a new turbulent velocity scale.

The problem now is to find a good parameterization for the energy dissipation. As the turbulent kinetic energy has three major sources :

- Production plus flux at the surface = $u_{**}^3 = \mathrm{Prod}_{surf}$
- Production due to shear at the bottom = $W_e\,\frac{1}{2}(u^2 + v^2) = \mathrm{Prod}_{shear}$
- Production due to buoyancy flux at the surface = $\frac{h}{2}\,\overline{b'w'_0}$ (if $\overline{b'w'_0} > 0$) = Prod_{buoy} ;

the dissipation rate is written as a sum of three parts corresponding to each particular source :

$$\text{Diss} = (1 - \phi_1)\ \text{Prod}_{\text{shear}} + (1 - \phi_2)\ \text{Prod}_{\text{surf}} + (1 - \phi_3)\ \text{Prod}_{\text{buoy}} .$$

Again, e is assumed to be of the order of u_{**}^2 (or u_*^2). This leads to

$$W_e \left\{ \frac{h}{2} [\alpha g(T - T_b) - \beta g(S - S_b)] + c\, u_{**}^2 - \phi_1 \frac{1}{2} (u^2 + v^2) \right\}$$

$$= \phi_2\, u_{**}^2 + \frac{h}{4} \left[(1 + \phi_3)\ \overline{b'w'_0} - \frac{1 - \phi_3}{\overline{b'w'_0}} \right]$$

$$- \frac{h}{2} \frac{\alpha\, g}{\rho_0 c}\ I_0 (1 - r) \left[1 - \frac{2}{\gamma h} + e^{-\gamma h} \left(1 + \frac{2}{\gamma h} \right) \right]$$

In the first applications, ϕ_1, ϕ_2 and ϕ_3 were taken as constant. Recently, Kitaĭgorodskii developed the model for particular cases of deepening and by comparison with well documented laboratory data, he got expressions of ϕ_1 and ϕ_2 as a function of the bulk Richardson number

$$Ri_{**} = \frac{h[\alpha g(T - T_b) - \beta g(S - S_b)]}{u_{**}^2} .$$

Such models can describe the time evolution of the mixed layer if they are well calibrated.

Further improvements we would like to develop are the following :

- the development of an integrated model in parallel with a non integrated one. This will shed some light on the general validity of the parameterization of the integrated model.
- the modification of these models to introduce other effects as internal waves, e.g.
- the search for stationary or quasi-stationary solutions for this problem, and their conditions of existence.

3.- Climatic problems related to air-sea interactions

3.1.- DEFINITION OF THE PROBLEM AND JUSTIFICATION

The necessity of a better understanding of climate and climatic changes has become evident nowadays. As climatic fluctuations are governed by the climatic system components, in which the oceanic system takes a prominent part, it is understandable that the European Commission for Research in the field of climatology asks the oceanographers to undertake more research dealing with climatic problems.

Among these, some play a leading part because of their serious social and economic consequences : coldest winters for a long time in England (1962-63), USSR, Turkey (1971-72) ; highest summer temperatures and following drought in USSR, Finland and Western Europe ; persistent drought in the major countries of the Third-World : Chile (1960-69), Mexico, Sahel and Cape Verde Islands (1968-73) ; catastrophic floods all over the world (even in the central Australian desert).

The W.M.O. (World Meteorological Organization) understood it well, and its efforts to solve these problems are constant, for example through international research programs as IDOE (International Decade of Ocean Exploitation), GARP (Global Atmosphere Research Program), GATE (GARP Atlantic Tropical Experiment), WAMEX (West African Monsoon Experiment).

The problem of drought in the Sahel related to the upwelling phenomenon in the Gulf of Guinea that we are investigating is well at its place in this context.

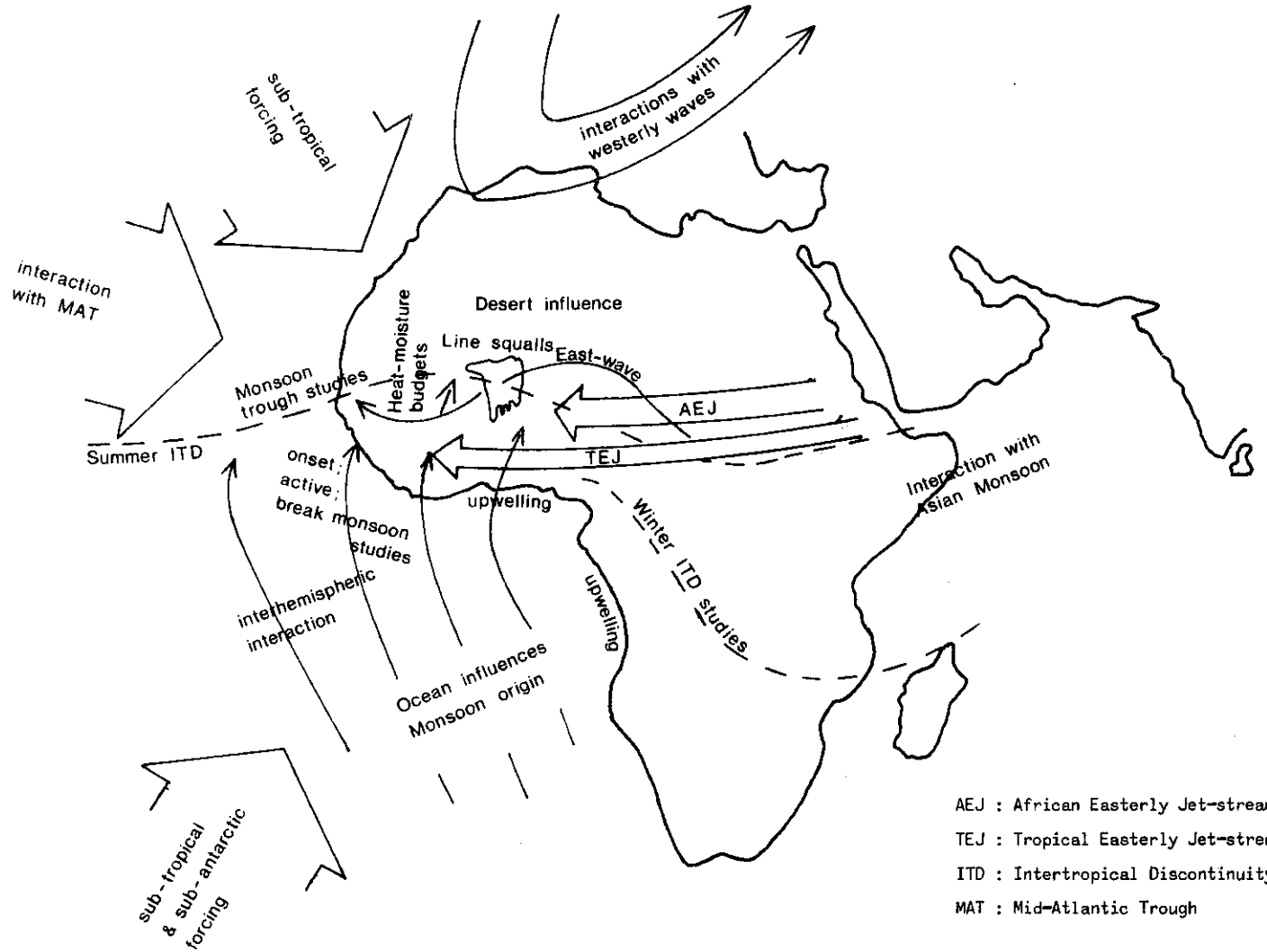
Many arguments plead in favour of this study, which are of :

1. Geographical nature :

The tropical situation of this zone first, and secondly, the proximity of the equatorial region allow theoretical studies required by meteorologists about the energetic equator fluctuations and the equatorial atmospheric and oceanic circulations (cfr. GARP), especially the ascending branch of the Hadley cell;

2. Physical nature :

- On the one hand, the existence of monsoon winds due to ocean-continent thermal gradients because of the permanent conflict between air masses under the direct influence of Açores, St. Helene and Libye anticyclones, and Saharian and equatorial troughs,



AEJ : African Easterly Jet-stream (mid-troposphere)

TEJ : Tropical Easterly Jet-stream (high troposphere)

ITD : Intertropical Discontinuity

MAT : Mid-Atlantic Trough

After WAMEX (1976).

fig. 6.

- and on the other hand, the occurence of coastal and oceanic upwelling in the Gulf of Guinea just under the fetch zone of monsoons, are the best way to an adequate approach of any study of the ocean-atmosphere-continent hydrological cycle, and thus, of the pluviosity in the Sahel.

Moreover, interactions with extratropical zones (figure 6) support the interpretation of the extratropical role which is to be played by this region : eventual correlations for climatic anomalies between the Mediterranean Basin and the Sahel zone ; European and American atmospheres pollution by saharian sands, and who knows, tomorrow, perhaps with dust, CO_2 and ashes due to the burning of the bush used by the sahelian traditional agriculture ? In the same way, the incursions in the Sahel of the high latitudes circulation must be noticed, as well as the reject of the subtropical anticyclone belt towards mid-latitudes.

The basic idea of this study is the following : as precipitations are function of the water-vapour content of the air masses over the continent, the variation in the intensity of oceanic evaporation related to any loss all along the ocean-atmosphere-continent hydrodogical cycle could explain the abnormal deficit of pluviosity in the Sahel area, and thus, the increasing risk of drought and aridification.

3.2.- THE UPWELLING IN THE GULF OF GUINEA

In order to understand the generation and the development of the upwelling in the Gulf of Guinea, we try to discern the eventual role of local effects from that of external effects :

- are the fundamental causes of purely oceanic origin (trade wind regime variation exciting a Kelvin wave propagating eastward along the equator),
- or are they of local character with south-west trade winds (monsoons), topographic effects and irregular coastline (existence of capes and bights) playing the fundamental part ?

The mathematical model used is the following :

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \beta y v - g'\frac{\partial h}{\partial x} + \frac{\tau_x}{\rho H} + A\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\beta y u - g'\frac{\partial h}{\partial y} + \frac{\tau_y}{\rho H} + A\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}\,[(H+h)u] + \frac{\partial}{\partial y}\,[(H+h)v] = 0$$

where u, v and h describe perturbations of horizontal circulation and upper layer thickness (fluctuations of pycnocline) ; β is the Rossby parameter, $\tau_{x,y}$ the components of the surface wind stress in the east and north directions, respectively. g' is the reduced gravity

$$g' = g\,\frac{\rho_2 - \rho_1}{\rho_2} \quad .$$

ρ $(= \rho_1)$ is the density of the upper layer, H is its mean thickness and A the horizontal eddy viscosity coefficient.

Introducing non dimensional parameters, we get

$$\frac{\partial u}{\partial t} + a_1 u\,\frac{\partial u}{\partial x} + v\,\frac{\partial v}{\partial y} = yv - a_1\,\frac{\partial h}{\partial x} + a_2\,\frac{\tau}{\rho} + a_3\,\frac{\partial^2 u}{\partial x^2} + a_4\,\frac{\partial^2 u}{\partial y^2}$$

$$\frac{\partial v}{\partial t} + a_1 u\,\frac{\partial v}{\partial x} + v\,\frac{\partial v}{\partial y} = -\,yu - \frac{\partial h}{\partial y} + a_2\,\frac{\tau}{\rho} + a_3\,\frac{\partial^2 v}{\partial x^2} + a_4\,\frac{\partial^2 v}{\partial y^2}$$

$$\frac{\partial h}{\partial t} + a_1 u\,\frac{\partial h}{\partial u} + v\,\frac{\partial h}{\partial y} + a_1 (H+h)\,\frac{\partial u}{\partial x} + (H+h)\,\frac{\partial v}{\partial y} + a_1 u\,\frac{\partial H}{\partial x} + v\,\frac{\partial H}{\partial y} = 0$$

where

$$a_1 = \frac{L_y}{L_x} \quad ,$$

$$a_2 = \beta^{-\frac{1}{2}}\, g^{-\frac{3}{4}}\, (H+h)^{-\frac{7}{4}} \quad ,$$

$$a_3 = A\,\frac{W^2}{L^2}\,\beta^{\frac{1}{2}}\, g'\,(H+h)^{-\frac{3}{4}} \quad ,$$

$$a_4 = A\,\beta^{\frac{1}{2}}\,[g'(H+h)]^{-\frac{3}{4}} \quad ;$$

$$W = \frac{\sqrt{g'(H+h)}}{\beta\, L_x} \quad ;$$

L_x and L_y are the zonal and meridional length scales respectively.

The dimensional analysis shows that, for a constant H (50 m), the wind forcing term a_2 plays the fundamental role :

$$\frac{a_1}{a_2} \sim 10^{-3} \quad , \quad \frac{a_3}{a_2} \sim 10^{-6} \quad , \quad \frac{a_4}{a_2} \sim 10^{-7} \ .$$

With such a model, we can predict, as soon as meteorological forcings are known, the intensity and the duration of the upwelling, and further, if a thermal equation is associated, the sea surface temperature (SST), that could allow the quantification and the analysis of energetic exchanges (latent and sensible heat) in the Gulf of Guinea, and consequently, an approach of the hydrological cycle and its influence on the pluviosity in the Sahel.

Preliminary results confirm the general theoretical characteristics already described by O'Brien et al. (1978) :

- eastward propagating perturbation along the Equator, generating an upwelling of 12 m on the tenth day, with an east-west perturbation velocity $u = - 0.41$ m/s ;
- full upwelling in the entire Gulf of Guinea on about day 50, with the maximum value centered at the Equator.

3.3.- DATA ANALYSIS AND INTERPRETATION

The theoretical study is completed by the analysis of climatic data (precipitations and run-off in the Sahel, SST in the Gulf of Guinea).

Up to now, the only available data are precipitations for 20 stations and a 69 years period (figure 7). The curve on figure 8 is somewhat like that of Bunting et al. (1976) and shows periods of extreme drought (1913, 1940, 1070). Bunting et al. used only five stations. Our curve uses more stations and is thus better for the zonally averaged means, as recommended by the WMO, because of the high spatial variability of convective rainfall in the Sahel region. The great difference is the peak for the year 1966. However, this value is doubtful and must be related to the surprising maximum monthly value of April 1966 (208 mm, i.e. 26 % of the total annual rainfall in 1966).

fig. 7.

Rainfall stations in West Africa used in the zonal mean

So, the only values for the 4 months period - june to september - are considered further. The choice of this period can be justified as follows :

1. 91 % of the rainfall occur during these 4 months (Bunting et al., 1976);

2. the maximum pluviosity cannot occur in april, but in july and (or) august, when the ITF (Intertropical Front) reaches its northest position, whereas, even in may, the ITF lies in Conakry (9°30'N), far south from the Sahel zone, whose lowest latitude station is Maidugury (10°47'N);

3. rainy monsoon winds blow over the upwelling zone in the Gulf of Guinea during this chosen period.

The resulting curve (figure 9) is more similar to that of Bunting et al. (1976) and depicts the general tendency of a decreasing pluviosity during the last thirty years.

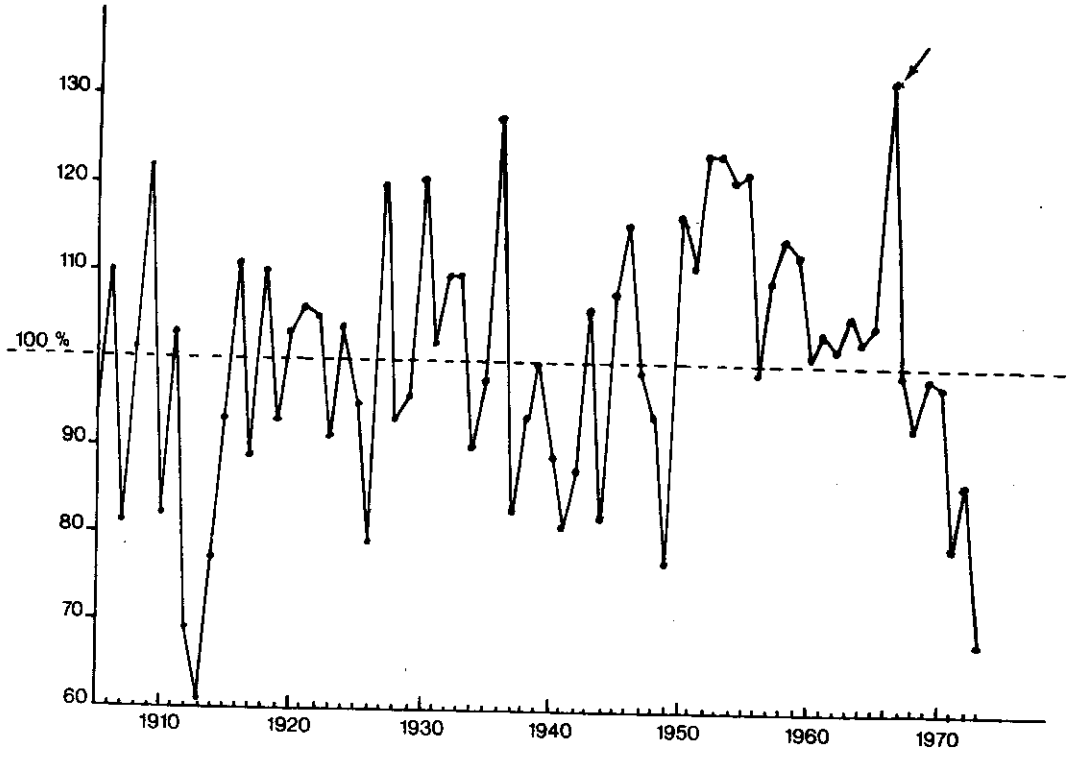


fig. 8.

Mean annual rainfall for the 20 sahelian stations expressed as a percentage of the normal 1905-1973.

Fourier analysis has been performed for the annual means, and the spectrum shows peaks at several frequencies (figure 10 and table 3).

Table 3

Period (years per cycle) observed by spectral analysis of zonal mean rainfall in the Sahel (Bah, Bunting et al.) and temperatures in Central England (Mason). Values of % of total variance are underlined.

MASON (1976)	23	14.5	11.5	7.6	5.2	3.5	3.1	2.8	2.5	2.2	2.1	
	8		< 4								10	
BUNTING et al. (1976)	40	20	10	6.7	5.0	4.0	3.3	2.9	2.5	2.2	2.1	
	7.2	10.5	12.4	10.3	5.7	5.5	8.9	9.9	12.7	12.7	9.7	
BAH (1979)	34.5	11.5	6.9	4.9	4.3	3.9	3.5	3.1	2.8	2.5	2.4	2.2
	13.2	11.7	3.2			5.1		9.8	5.1		7.5	

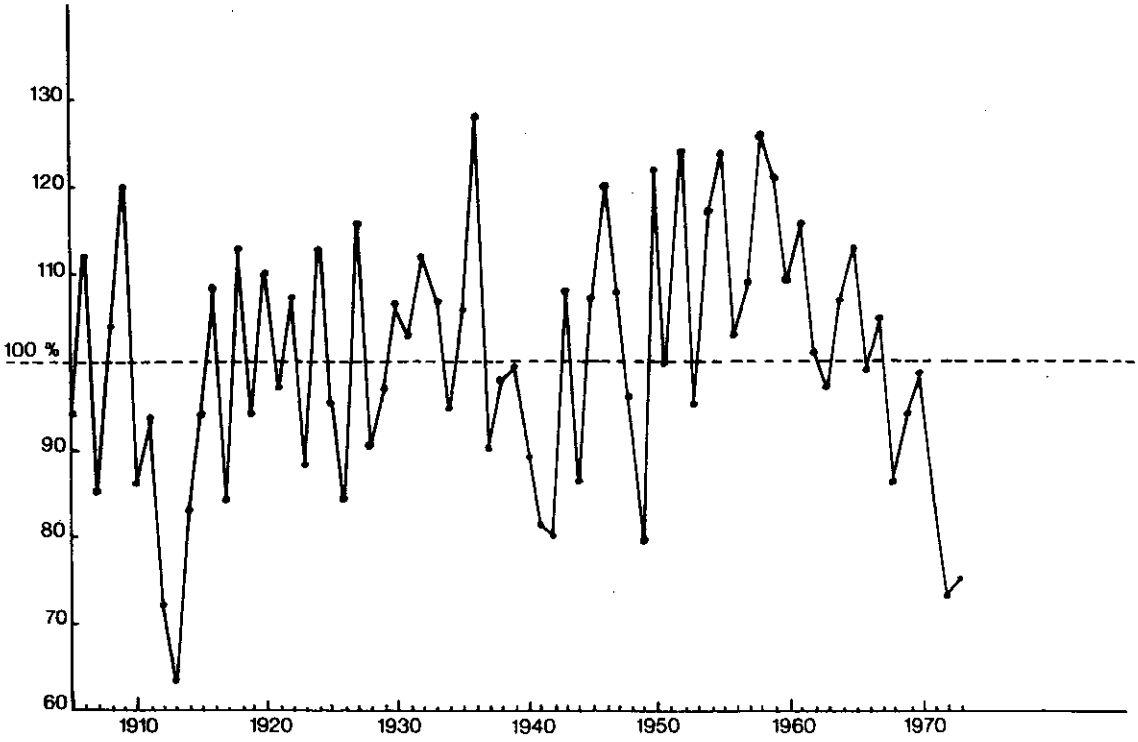


fig. 9.

Mean rainfall for the 4-months period (June, July, August, September) expressed as a percentage of the corresponding normal 1905-1973.

The 11.5 years periodicity may be identified with the semi-period of the "double sunspot cycle" or Hale cycle.

The 7.1. years peak suggests the periodicity of 8 years observed over Lake Victoria, which is very regular and which may be associated with solar activity.

Lower periodicities could perhaps be related to the cycles of suspended particles, CO_2, ice blocks, sea level pressure, coastal upwelling easterly perturbations, Arctic temperature anomaly, or other climatic features.

These preliminary results should be confirmed by further studies. Nevertheless, it is surprising to notice that Bunting et al (1976), as well as Mason (1976) obtain similar periodicities, especially at high frequencies, with temperature data series in Central England (1668-1975) (table 3).

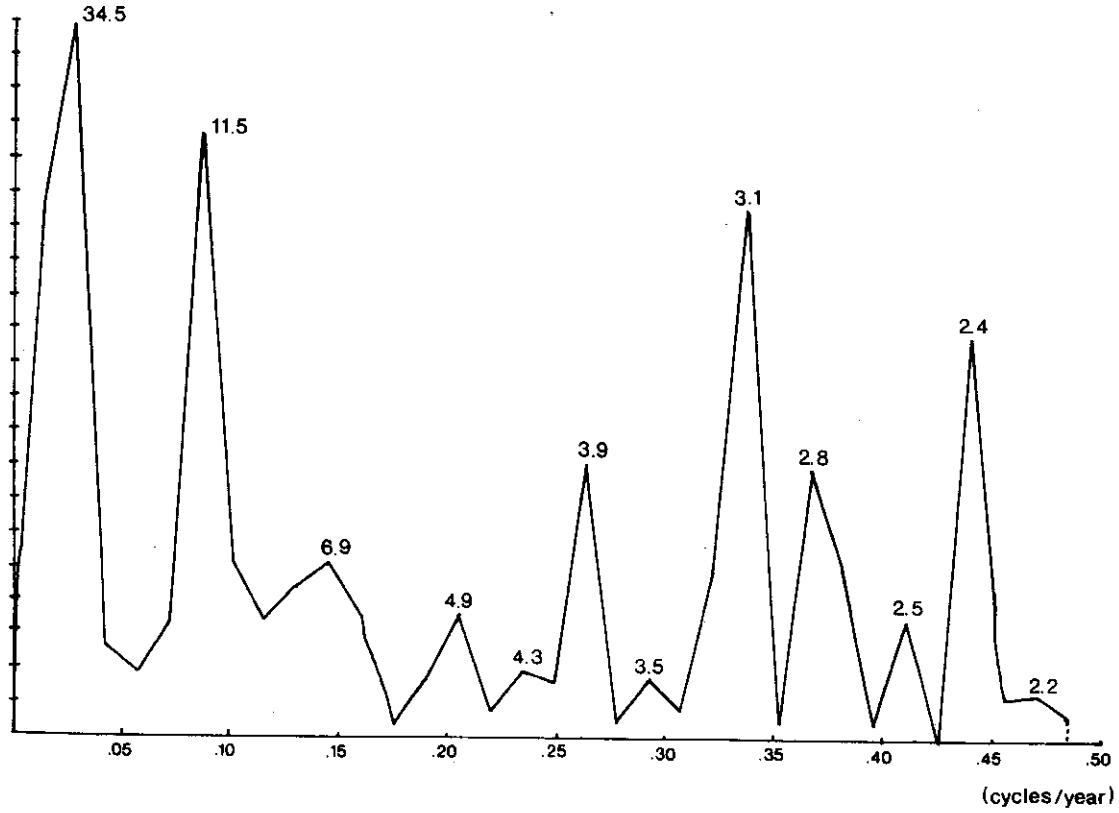


fig. 10.

Power spectrum of the zonal mean rainfall record

Does this result imply that mid-latitudes and subtropical latitudes are under the influence of the same high frequency phenomena at short climatic scales ? Or could there be some interaction, may be linear, between meteorological and climatic phenomena of these different latitudes ?

There is another hypothesis : the persistence of polar air masses in the subtropical atmosphere in the form of cold air drops, and thus, the influence of polar front fluctuations on the climatology of the Sahel. If so, there is a need for further studies of the possible correlations between climatic phenomena of subtropical zones and corresponding phenomena not only in the Mediterranean Basin (Helbig, 1976), but also in higher latitude zones.

For fitting purpose, Bunting et al (1976) gave the curve :

$$R = -12.7 + 12.9 \sin \frac{2\pi(t + 12)}{180},$$

but they underlined that it provides no basis for forecasting. The curve we propose is the following, and it contains 84 % of the total variance :

$$R = -6.62 \cos\left(\frac{2}{69}\pi t - 63°56\right) - 7.63 \cos\left(\frac{4}{69}\pi t - 33°62\right)$$
$$- 7.02 \cos\left(\frac{4}{23}\pi t - 49°33\right) + 4.72 \cos\left(\frac{12}{23}\pi t - 58°35\right)$$
$$- 6.64 \cos\left(\frac{46}{69}\pi t - 57°4\right) - 4.71 \cos\left(\frac{50}{69}\pi t - 6°\right)$$
$$- 5.07 \cos\left(\frac{20}{23}\pi t + 2°97\right) + 3.84 \cos\left(\frac{20}{69}\pi t + 47°6\right)$$
$$- 3.71 \cos\left(\frac{14}{69}\pi t + 58°77\right) - 3.73 \cos\left(\frac{44}{69}\pi t + 41°67\right)$$
$$- 3.77 \cos\left(\frac{52}{69}\pi t - 54°56\right)$$

where R is the % deviation from the 1905-1973 mean and t is the time in years.

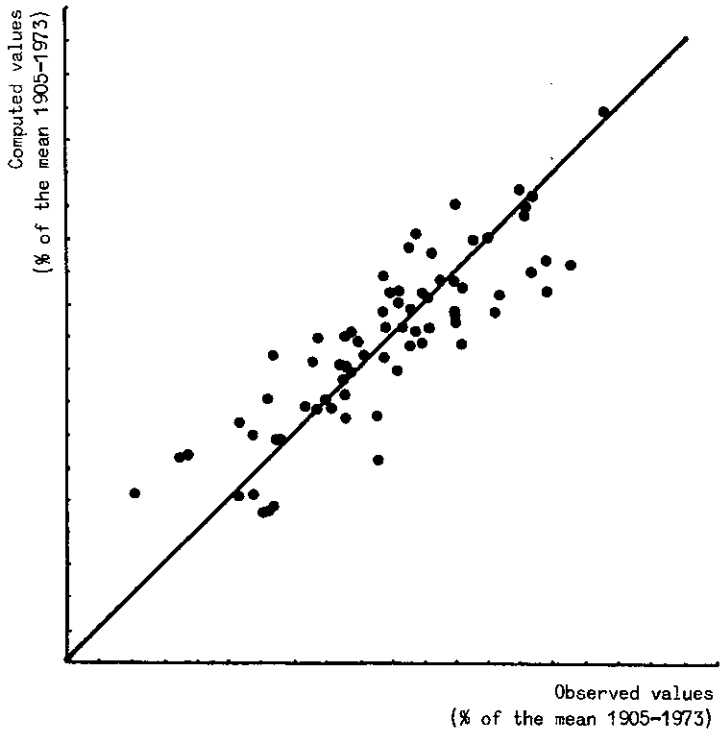


fig. 11.

Observed values versus computed values for R

Computed values and observed ones are plotted on figure 11.

We intend to perform the same analysis on SST data series, as soon as they become available, in order to get significant periodicities of anomalies eventually related to continental rainfall variations.

An efficient collaboration could be established with IRM (Institut Royal Météorologique de Belgique) and LMD (Laboratoire de Météorologie Dynamique, Palaiseau, France).

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Hydrodynamic models for very shallow coastal seas

Application to the Belgian coast

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Introduction

In the past, hydrodynamic models successfully reproduced the sea surface motion induced by tides and storm surges. Unfortunately, the simulation of horizontal currents was not very satisfactory because the discretization of the coast and of the bottom topography was too crude (spatial steps of about 30 km).

To improve the quality of the calculated current pattern, the numerical representation of the geometry must be refined : sand banks, beaches, flood and ebb channels have to be taken into account in the model.

Another application of hydrodynamic models is the prediction of dynamic effects of coastal engineering projects. A refinement of the grid allows a better resolution of the horizontal and vertical geometry.

The simulation of tides in a very shallow region with an irregular topography requires suitable and accurate numerical schemes. In this paper, two hydrodynamic models of the Belgian coast are presented. The first one is based on an explicit scheme, the second one on a semi-implicit scheme. Comparisons with the observations are made, and different boundary conditions at the Western Schelde mouth are tested.

1.- Mathematical formulation of depth-averaged hydrodynamic models

The equations of a depth averaged model are (e.g. Nihoul, 1975) :

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(H\bar{u}) + \frac{\partial}{\partial y}(H\bar{v}) = 0 \qquad (1)$$

$$\frac{\partial (H\bar{u})}{\partial t} + \frac{\partial}{\partial x}(H\overline{uu}) + \frac{\partial}{\partial y}(H\overline{uv}) = H\left(f\bar{v} - g\frac{\partial \zeta}{\partial x}\right) - k\bar{u}\sqrt{\bar{u}^2 + \bar{v}^2} + \text{disp. terms} \qquad (2)$$

$$\frac{\partial (H\bar{v})}{\partial t} + \frac{\partial}{\partial x}(H\overline{uv}) + \frac{\partial}{\partial y}(H\overline{vv}) = -H\left(f\bar{u} + g\frac{\partial \zeta}{\partial y}\right) - k\bar{v}\sqrt{\bar{u}^2 + \bar{v}^2} + \text{disp. terms} \qquad (3)$$

where

$$\bar{u} = \frac{1}{H}\int_{-h}^{\zeta} u \, dz \ ,$$

$$\bar{v} = \frac{1}{H}\int_{-h}^{\zeta} v \, dz \ ,$$

$$H = h + \zeta \ ,$$

ζ is the sea-surface elevation above the equilibrium level, f the Coriolis parameter, g the acceleration of gravity and k the bottom friction coefficient.

The dispersive terms in equations (2) and (3) result from turbulent and shear effects. They can be parameterized as follows :

$$H\nu\left(\frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2}\right) \quad ; \quad H\nu\left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2}\right)$$

with ν a coefficient of "viscosity" used to formulate the dispersive terms.

Equations 1, 2 and 3 will be solved with appropriate initial and boundary conditions :

1. initial conditions

   $\bar{u}$, $\bar{v}$ and $\zeta = 0$ at $t = 0$

   for all grid points, except along open sea boundaries where the elevations or currents are prescribed ;

2. boundary conditions

Along the coasts : $\frac{\partial \bar{v}}{\partial n} = 0$

with $\underset{\sim}{n}$ the normal at the coast.

Along open sea boundaries, the elevations or (and the currents must be given (see § 3).

2.- Main features of the Belgian coastal models

The hydrodynamic models cover the Belgian coast, part of the Dutch coast up to the Eastern Schelde, and are limited in the Western Schelde at Vlissingen. The seaward extension is of about 30 kilometers (see fig. 1).

The mean equilibrium depth is very small (10 meters), and the maximum is $h_{max} \sim 25$ m. The bottom topography is rather unequal : narrow and deep flood and ebb channels, sand banks, etc...

The observations (Van Cauwenberghe, 1973) show that the spatial variation of currents is mainly related to the shape of the bottom, and that the characteristic lengths for $\bar{u}$ and $\bar{v}$ are much smaller than those related to ζ variations. Consequently, the advective terms are of some importance, and must be suitably reproduced espacially when the spatial step (Δx) is small.

3.- Influence of the open sea boundary on the hydrodynamic of the southern North Sea

Daubert and Graffe (1967) investigated existence conditions for linear and non-linear long-waves equations. The linear form of equations (1) to (3) requires only one-point boundary conditions, so only ζ at the open sea boundaries. For the non-linear case, two-points boundary conditions are required when the flow is directed into the region of computation, and one-point boundary conditions when it is directed out of this region.

In the case of a real fluid, the problem of boundary data is a problem of sensitivity of boundary elevations to the internal velocity field. According to Abott et al. (1973) : *If the dynamic effects dominate over resistance effects, two-points data will be desirable over all inflow segments,*

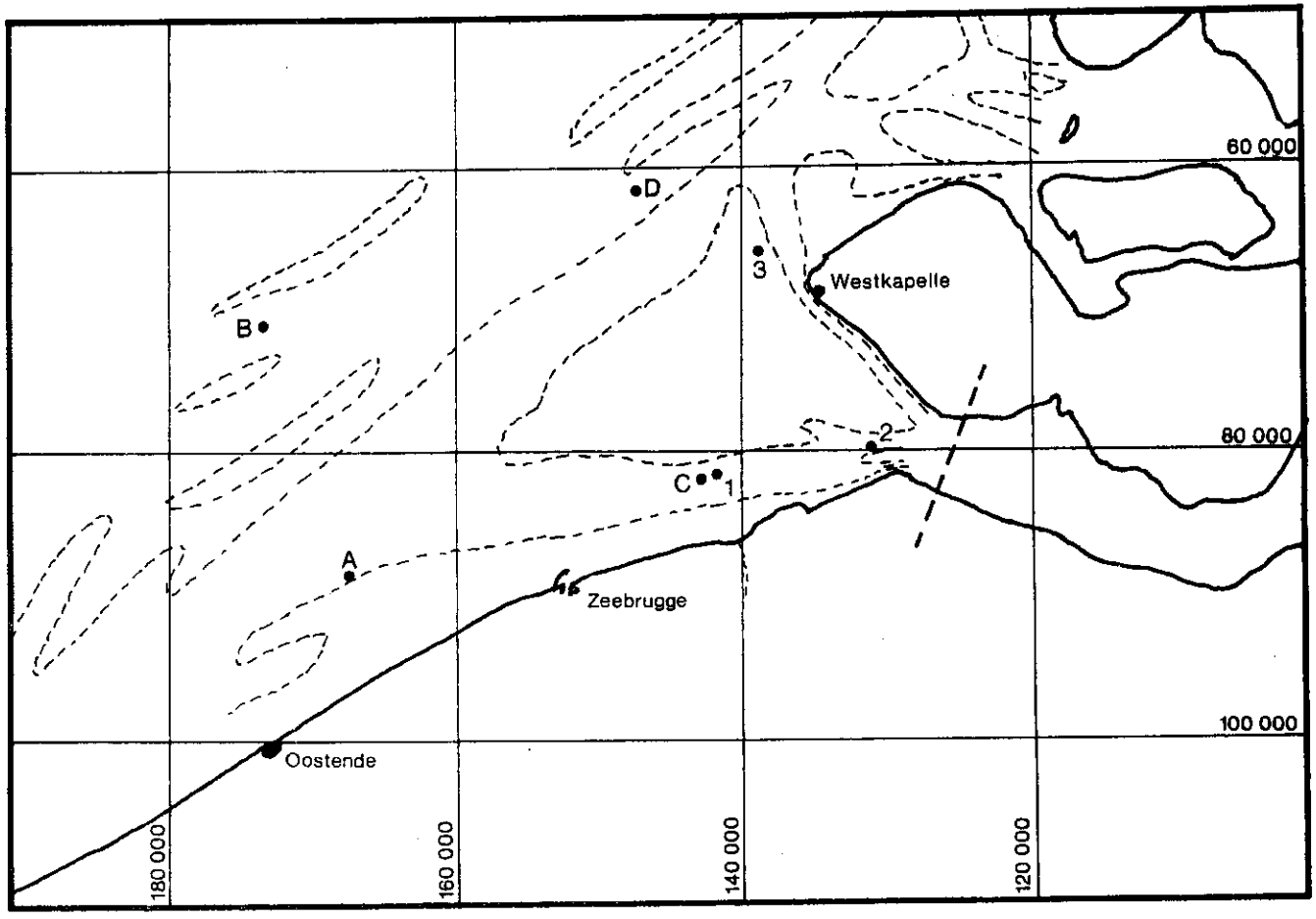

fig. 1.

Positions of the stations of comparison

whereas the dominance of resistance effects implies the practical sufficiency of one-point data throughout.

For the open sea boundaries, the inertial terms are small compared to the pressure and frictions terms : one-point boundary conditions are prescribed and they are derived from other computations and observations. Along these open sea boundaries, equations of motion are assumed to be linear.

In order to visualize the importance of the nature of the boundary condition near Vlissingen on the dynamics of the horizontal and vertical motions, two numerical simulations are performed : the first one with a condition on the sea elevation, the second one with a condition on the water transport. Fig. 2 shows the current roses at some references points (see Fig. 1), the elevation and the flow for a cross section close to Vlissingen (the dotted lines are related to a forced elevation and the solid lines to a forced flow at Vlissingen).

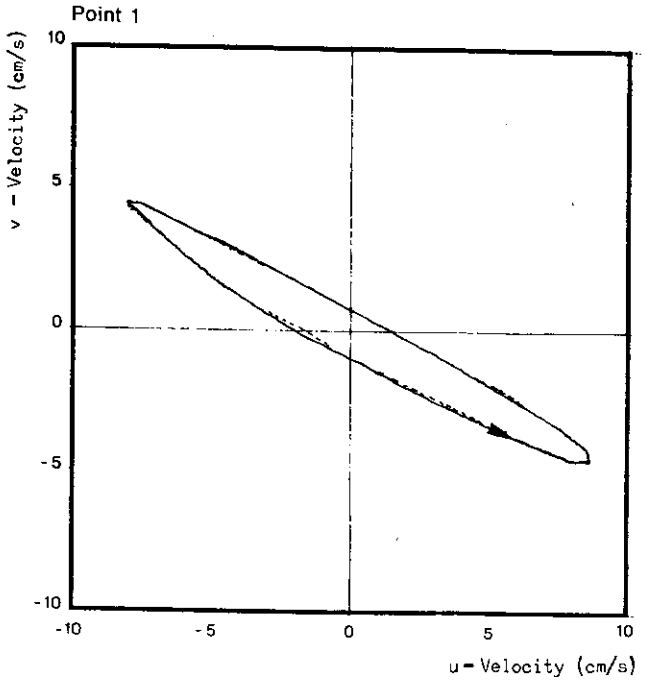

fig. 2a.
Current roses

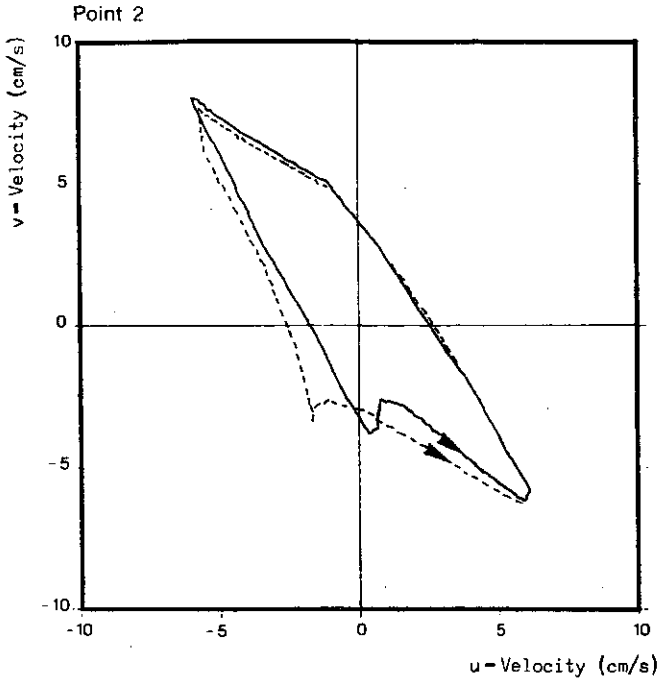

fig. 2b.

Current roses

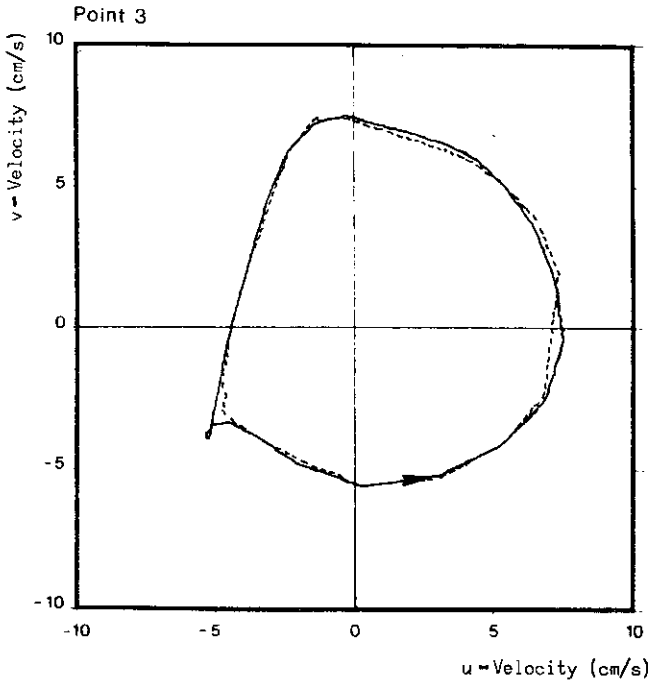

fig. 2c.

Current roses

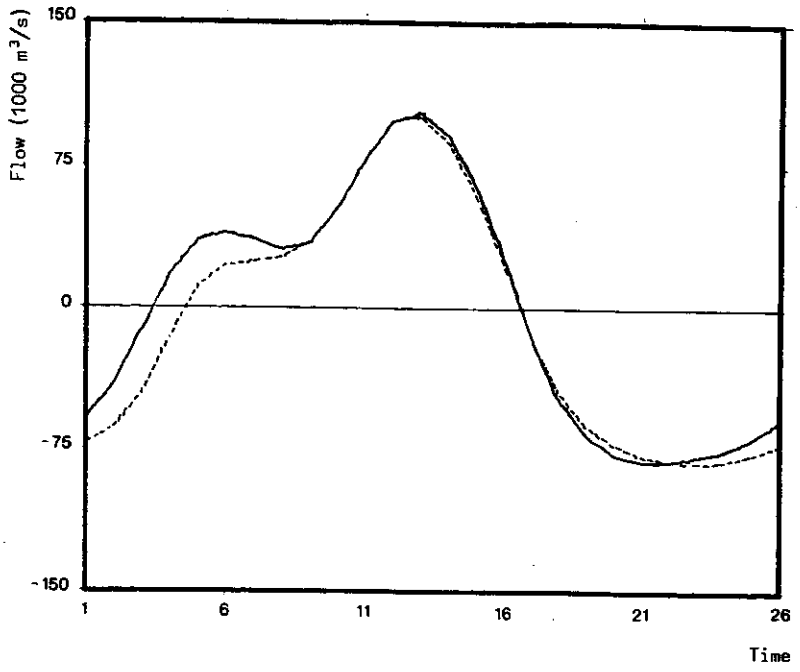

fig. 2d.

Inflows and outflows in cross section close to Vlissingen

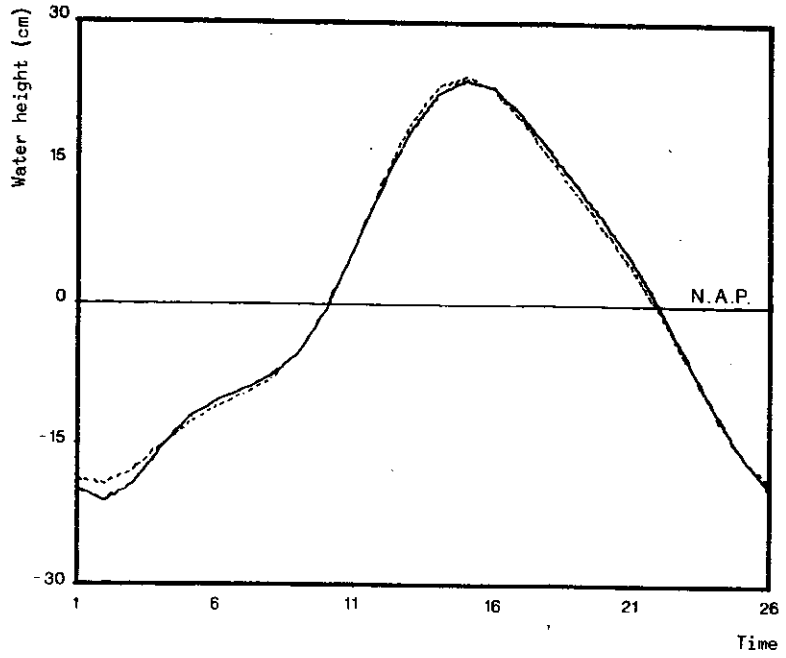

fig. 2e.

Sea elevations at Vlissingen

From these diagrams, one may deduce that the inflows or outflows are more sensitive than the elevations to the nature of the open sea boundary conditions. The Western Schelde influences the velocities in a sector of about 25 kilometers. An analysis of these simulations shows that the best boundary condition in the cross section near Vlissingen must be a double-point condition (a condition on the water transport).

4.- Accuracy of numerical schemes

The previously mentioned schemes had the following truncation errors : for equations with advection terms,

truncation error = $0(\Delta t) + 0(\Delta x)$,

for equations without advection terms,

truncation error = $0(\Delta t) + 0(\Delta x^2)$.

This accuracy is adequate to simulate long-waves in rather deep-coastal seas (e.g. the North Sea and the Southern Bight), where the advection terms are small compared to the others.

Along the Belgian coast, the topography is very irregular and the depth small. For this reason, the advection and the friction terms generate strong harmonics of the fundamental forced wave.

In a first approach, the discretization of the advective terms is non centered. This formulation induces a numerical viscosity ($\nu_{num} \sim \frac{\bar{u}}{2} \Delta x$) which is larger than that produced by turbulence and shear effect. There results a weak damping and smoothing of the solutions.

As hydrodynamicists are also confronted with practical problems (e.g. modifications of the current pattern due to dams and harbours) one must develop more accurate numerical schemes where the artificial viscosity is weak and the higher harmonics are suitably reproduced.

5.- An explicit predictor-corrector

In 1978, Ronday showed that the first order schemes under-estimate the first harmonic of the semi-diurnal lunar tide. To simulate accurately the

higher harmonics of periodic tidal waves and the hydrodynamic perturbations, one must develop a more precise scheme.

As shores and sand banks arising at low tide complicate the resolution of the equations, only an explicit scheme (e.g. Flather and Heaps, 1975) can simulate these phenomena in a simple and "cheap" way. The simpliest scheme that may answer all these requirements is an explicit predictor-corrector.

The predictor is merely the previously used scheme (without the dispersive terms) and its role is the stabilization of the whole scheme. In the corrector step, the discretization of the derivatives are all centered and the viscosity coefficient has a more realistic value. An estimate of the critical time step is

$$\Delta t_c \sim \frac{\Delta x}{\sqrt{2 g h_{max}} + \bar{u}_{max}}$$

This predictor-corrector scheme has been successfully applied to the simulation of tides in the English Channel (Ronday, 1978). Unfortunately, difficulties appeared when it was applied to the Belgian coastal region : a local unexpected instability arose above the Walcheren Island near the open boundary, after one half period of the lunar tide. This instability may be due to over-simplified open sea boundary conditions in this area.

6.- Limitations of explicit and semi-implicit schemes

To improve the quality of the numerical simulations, one must refine the representation of the bottom topography. Unfortunately, some important problems arise from the reduction of the spatial step Δx : memory occupation and computation time.

6.1.- MEMORY OCCUPATION

If x is divided by two, the memory occupation is multiplied by four. As the core of the computer is limited, the refinement of the grid will also be limited.

6.2.- COMPUTATION TIME

For the previous described schemes, the stability condition is very restrictive : the critical time step is proportional to the spatial step. To study the same area, if the spatial step is reduced by a factor two, the computation time is approximatively multiplied by eight. Consequently, the tidal simulation with a precise explicit scheme (predictor-corrector) and a very fine grid becomes very expensive. This smallness of the time step - due to stability requirements - is not fully justified because the characteristic times of $\bar{u}$, $\bar{v}$ and ζ do not need such a temporal accuracy. For this reason, it is attractive to develop semi-implicit schemes.

The main advantage of semi-implicit schemes is the less restrictive stability condition. Leendertsee (1967) developed a semi-implicit scheme accurate to the first order in time and to the second order in space. The instability of his numerical code is due to a particular formulation of the bottom stress. In a first approach, we have developed a simplier semi-implicit scheme accurate to the first order in time and in space, where the stability condition is not related to the bottom stress. The time step must verify the following condition :

$$\frac{\Delta t}{\Delta x} < \frac{2}{|\bar{u}|_{max} + |\bar{v}|_{max}}$$

This computation code is applied to a region covering a large part of the Belgian coast, and the chosen numerical grid is characterized by a small spatial step : $\Delta x = 500$ meters. The open sea boundaries are deduced from the previous predictor-corrector simulation.

To analyse the advantages (or disadvantages) of this new code, the same tide is simulated by means of two codes : the first one is explicit (see § 3), the second one is semi-implicit. The explicit scheme has a time step $\Delta t = 20$ s , the semi-implicit $\Delta t = 200$ s . Figures 3 and 4 show the comparisons between the two simulations (the solid lines are related to the semi-implicit scheme, and the dotted lines to the explicit one). The elevations (fig. 3) and current roses (fig. 4) are compared at four reference points.

The analysis of these figures shows that the elevations are identical and the velocities very similar. As the computation time is five times

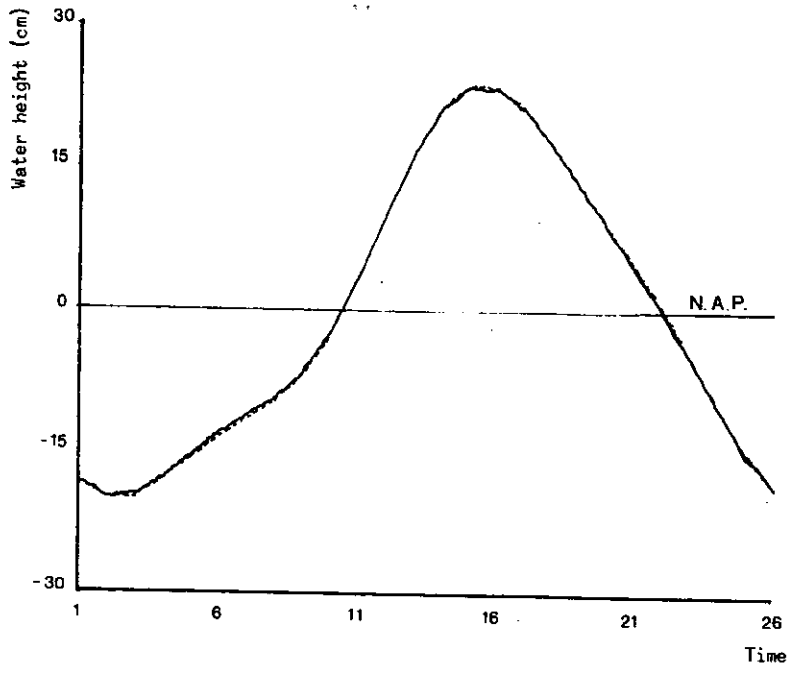

fig. 3a.

Sea elevations for station A

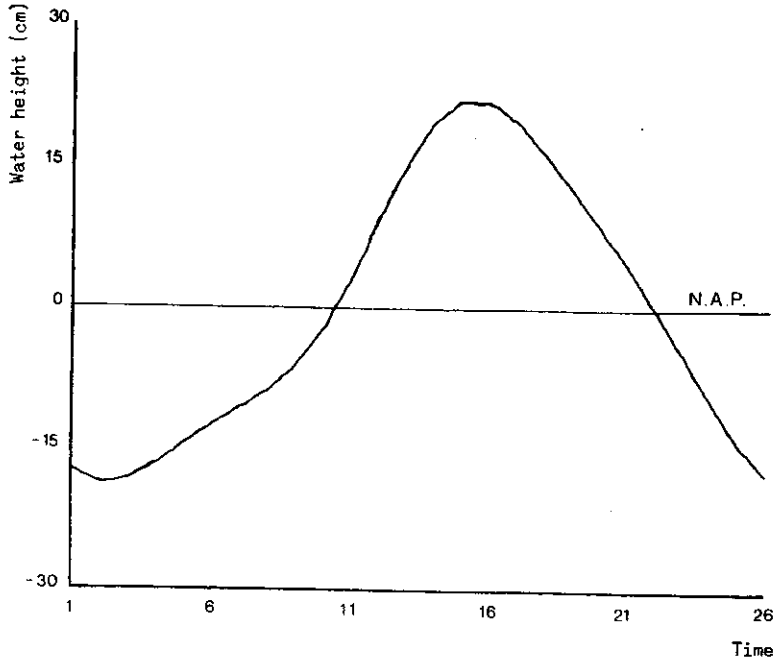

fig. 3b.

Sea elevations for station B

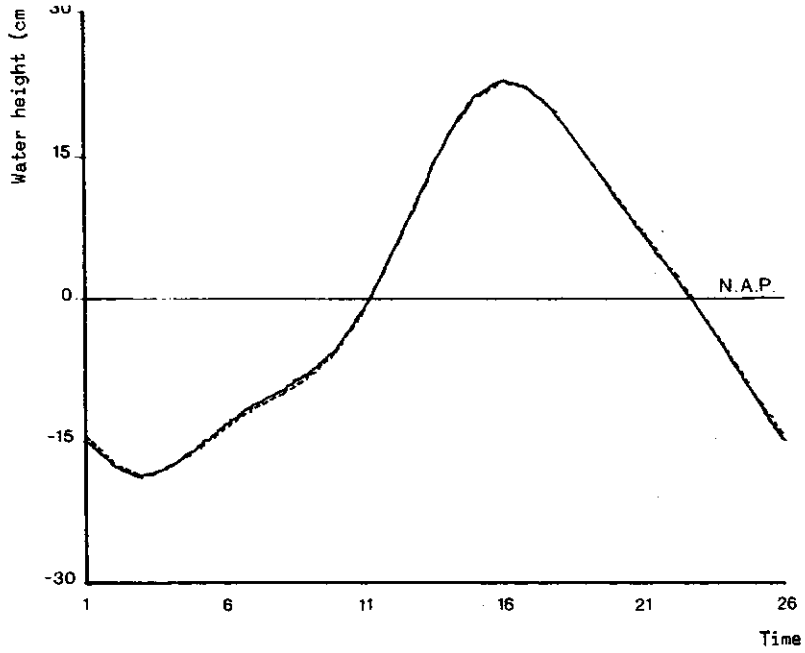

fig. 3c.

Sea elevations for station C

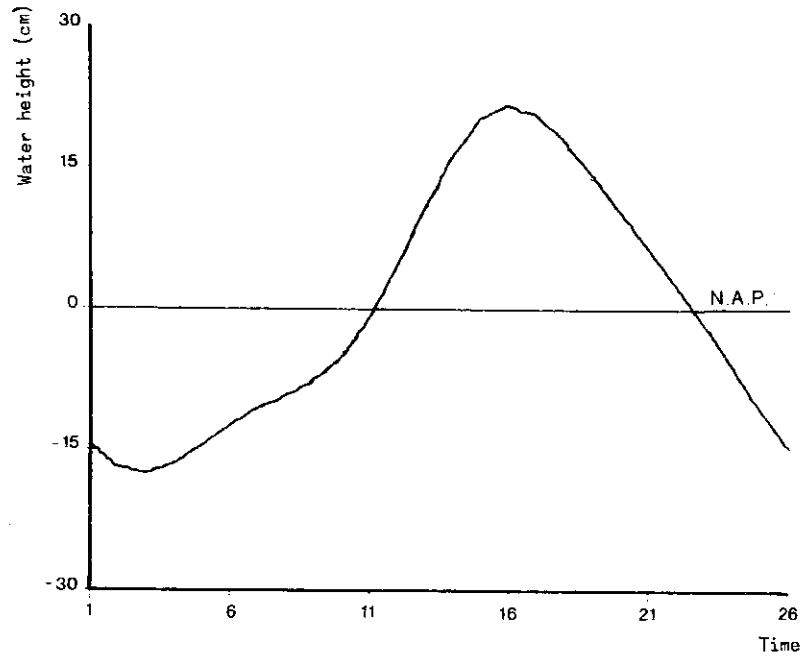

fig. 3d.

Sea elevations for station D

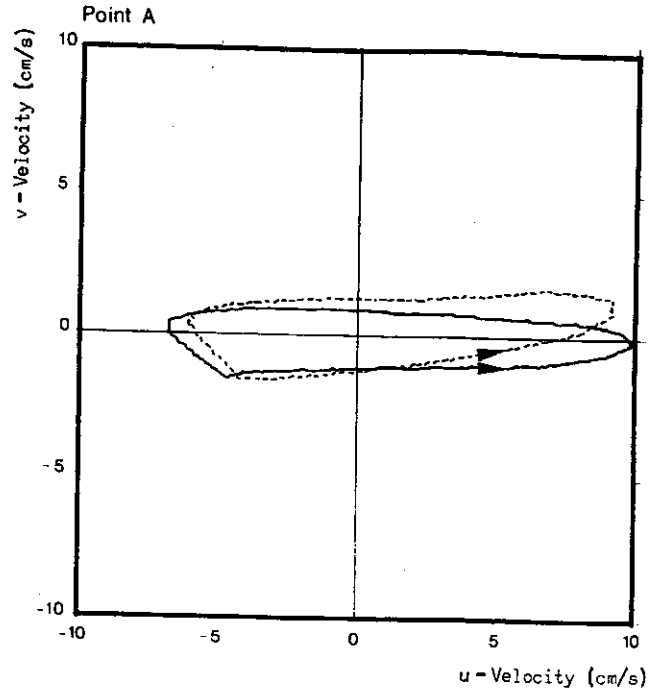

fig. 4a.

Current roses

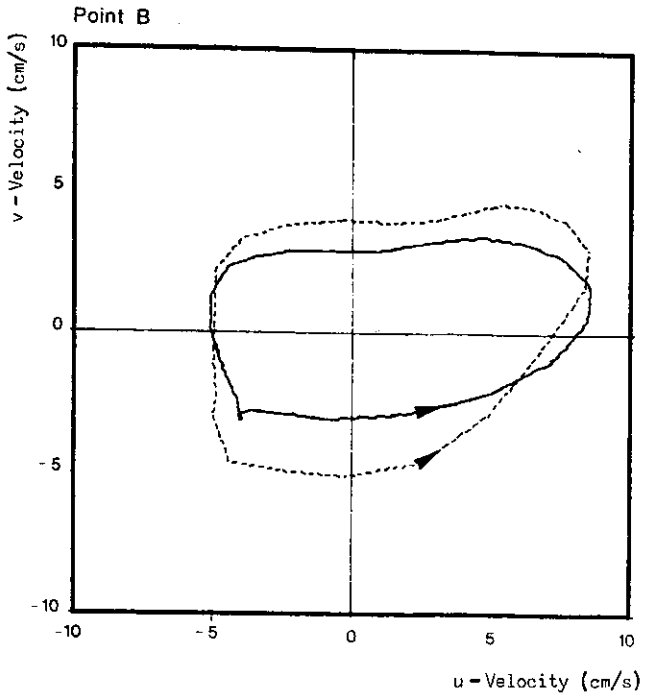

fig. 4b.

Current roses

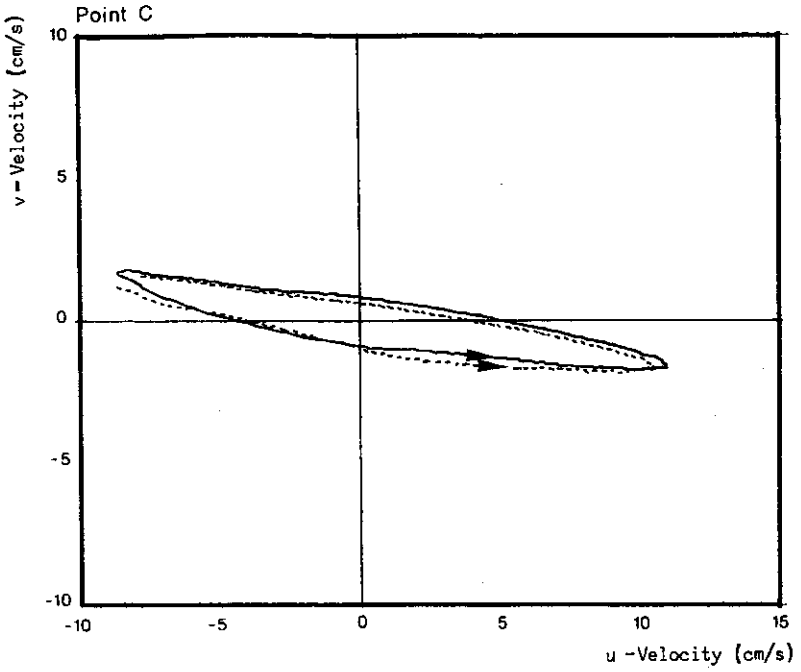

fig. 4c.

Current roses

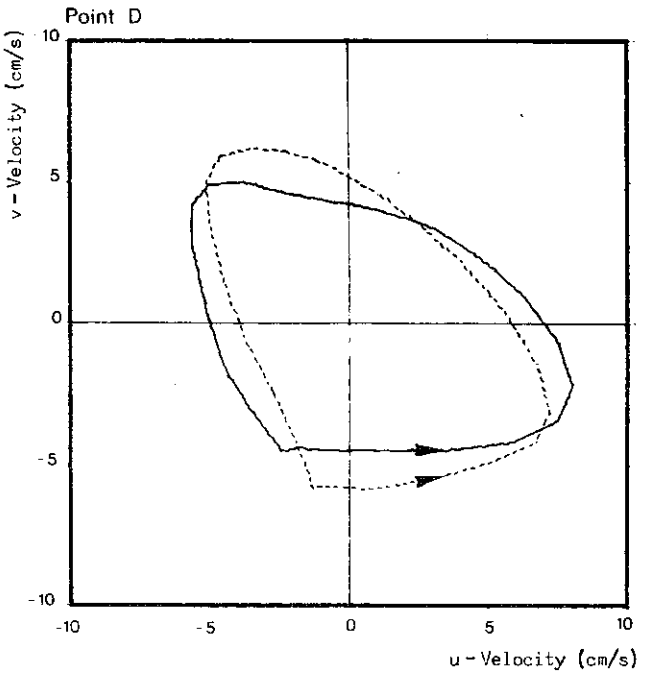

fig. 4d.

Current roses

higher with the explicit code and the quality of the results rather equal, one can conclude that the semi-implicit model is the most economical. Unfortunately, this code cannot be easily adapted to areas where sand banks are merging at low tide.

Conclusions

To study the prediction of dynamic processes in relation with coastal engineering projects and the generation of tidal harmonics, one must apply a predictor-corrector procedure. Unfortunately, it is very expensive when the refinement of the bottom topography is required. This technique is also adapted for areas where sand banks are merging at low tide.

For deeper areas, the simple semi-implicit model is very convenient and inexpensive if the bottom topography is not too irregular.

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Fate of heavy metals in experimental aquatic food chains
Uptake and release of Hg and Cd by some marine organisms
Role of metallothioneins

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When trying to model aquatic food webs one might be tempted to associate a flux of pollutants - say heavy metals - to the fluxes of carbon or nitrogen linking the different parts of the system. Restricting to major questions, one needs know the level of contamination of prey and predator, the rate of entry from food or directly from water, the rate of loss, the possible effects of abiotic factors (chemical speciation, partition of the metal between water column and suspended particulate matter, temperature, salinity, oxygen content, etc). Toxicity must be evaluated at all levels including man and terrestrial animals. The task seems enormous and laboratory experiments only give a partial answer. However they should be planned with the aim to understand the general scheme and to probe real systems for assessment, asking pertinent questions. The data briefly presented here have been collected with this general framework in mind.

1.- Relative uptake of heavy metals from water and food by aquatic organisms : a simple and useful laboratory set-up to study Hg distribution in a two levels food chain *Tubifex tubifex* and *Lebistes reticulata*

The reason to use the chain *Tubifex tubifex* and *Lebistes reticulata* (guppy) is that these freshwater animals are easy to keep alive and readily available at low cost. The experiments (Bouquegneau and Mercenier,

to be published) have been carried out in a 100 ℓ tank separated in three compartments by two plastic gauze screens (2 mm mesh size); water circulation and aeration is maintained by a conventional aquarium pump (250 ℓ/hour) with no filter. Two lots of 35 guppies are kept in the two first compartments; a cluster of about 20 g of Tubifex worms is kept in an open container in the third compartment. The fishes and the worms were intoxicated at the same time for 12 days by adding 10 or 50 ppb of mercury ($HgCl_2$ or CH_3HgCl). One group of fishes was fed until refusal with the intoxicated worms, the other group with non-intoxicated worms kept in a spare aquarium. The water Hg concentration was kept constant by addition of $HgCl_2$ or CH_3HgCl each 24 h and Hg content in the three groups of animals was followed in samples taken each day using the Coleman Mercury Analyser System MAS 50 and the technique described by Hatch and Ott (1968). This experimental set-up allows to simultaneously follow the Hg uptake by direct contamination (from water) and by direct plus indirect contamination (from water + food) under identical experimental conditions, taking into account for instance the possible direct intoxication from the pollutant released from faeces and the role of organic matter, dissolved or particulate, since the water was non filtered. The results are shown in figure 1.

Important Hg concentration in both fish lots and in the prey is observed but no significant difference in the uptake kinetics of both groups of guppies. The conclusion after careful analysis of the data is that the main route of uptake is direct contamination from water and that the percentage of Hg assimilated from food must be small — but higher for CH_3HgCl than for $HgCl_2$. This can be shown by fitting the experimental data to a curve of the type proposed by Pentreath (1975) :

$$C_t = C_{ss} \ (1 - e^{-kt}) \qquad (1)$$

where C_t is the Hg concentration at time t , C_{ss} the concentration at the steady state,

$$k = \frac{0.693}{t_{b\frac{1}{2}}}$$

with $t_{b\frac{1}{2}}$ being the "biological half-time". The $t_{b\frac{1}{2}}$ (days) and C_{ss} (ppm) values are given in table 1.

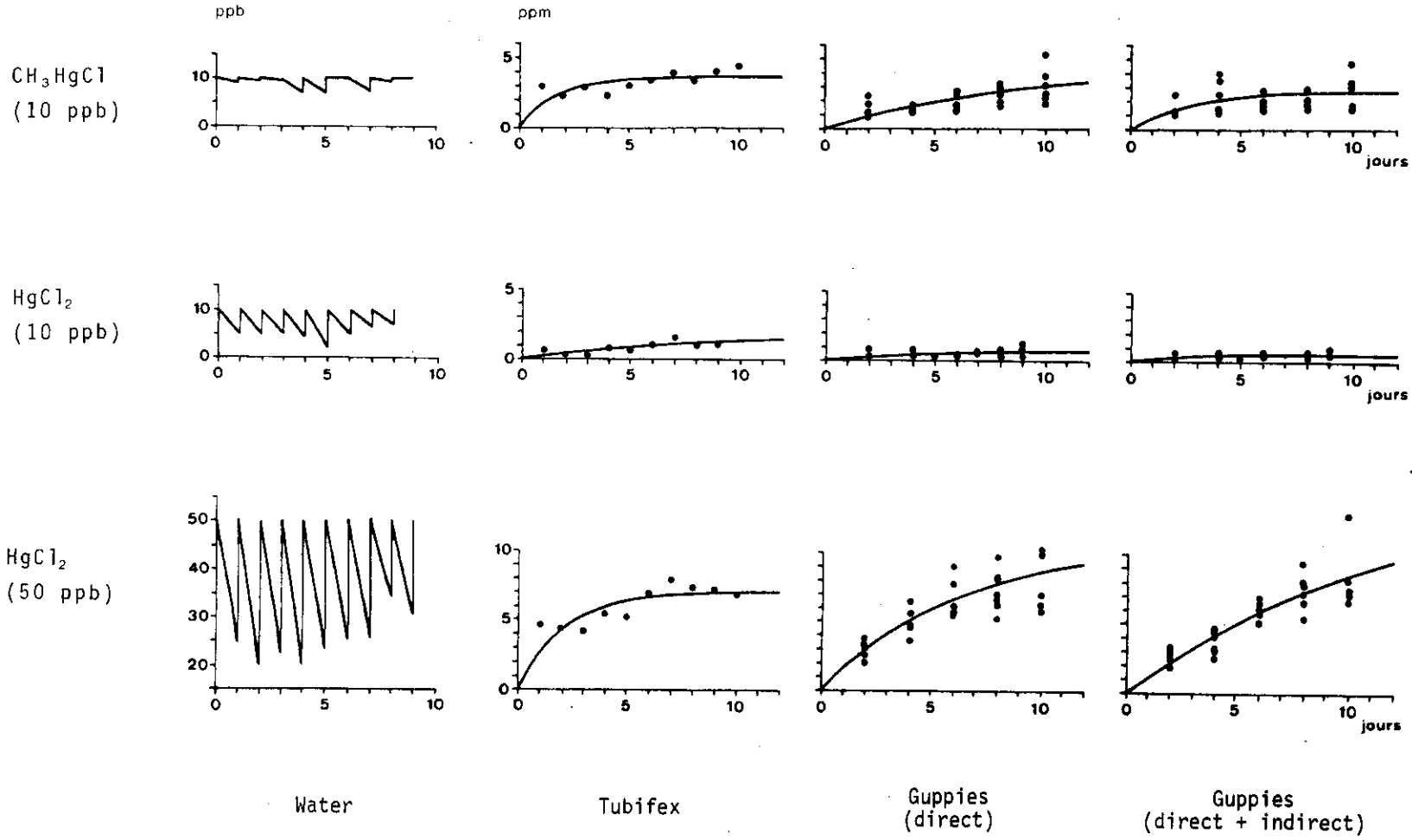

fig. 1.

Evolution of mercury content of water and organisms during intoxications by 10 or 50 ppb of mercury added daily to the aquarium water.

Table 1

Biological half-times $t_{b\frac{1}{2}}$ and concentrations at steady state C_{ss} calculated from curves of figure 1

	Tubifex		Guppies (dir.+ind. intoxication)		Guppies (dir. intoxication)	
	$t_{b\frac{1}{2}}$	C_{ss}	$t_{b\frac{1}{2}}$	C_{ss}	$t_{b\frac{1}{2}}$	C_{ss}
10 ppb CH_3HgCl	1.2	3.7	5.9	4.4	1.9	2.8
10 ppb $HgCl_2$	6.1	2.0	2.8	0.7	1.7	0.55
50 ppb $HgCl_2$	1.4	6.8	4.3	10.9	8.6	15.5

The significance of the calculated $t_{b\frac{1}{2}}$ values will be discussed later in this paper. The faster uptake of CH_3HgCl compared with $HgCl_2$ can be explained by the high solubility of CH_3HgCl in lipids and because it is mainly eliminated by the liver (bile) attached to low molecular weight molecules able to be reabsorbed in the intestine (Norseth, 1971). $HgCl_2$ is mainly excreted by the kidneys (Bouquegneau, 1975).

The fact that contamination from water is the main entry route for fish in this experiment fits with the observations of Bouquegneau (1973-1975) showing that Hg easily penetrates through the gills, in non-fed animals (*Anguilla anguilla* adapted to sea-water and *Myoxocephalus scorpius*) and accumulates in the body tissues. $HgCl_2$ induces the formation of metallothioneins and under acute intoxication, death is observed by rupture of the NaCl balance (Bouquegneau, 1975, 1977). Metallothioneins have also been detected in Tubifex intoxicated as described above. That the effect observed because of ingestion of contaminated food is small is in general agreement with observations made by other experimenters on experimental food chains, taking into account that is most cases direct and indirect contamination were combined, because of faeces and excretion products, in an uncontrolled way.

A review of the matter is presented in a paper by Bouquegneau and Noël-Lambot (1977) who point out that the lowest trophic levels *in situ* or in the laboratory (see f.ex. Aubert et al., 1972, 1974, 1975) are generally the most exposed to contamination by heavy metals.

If heavy metals assimilated from food contribute only partially to the contamination of aquatic predators it remains to evaluate the order of magnitude of this route of entry. We will show how we propose to deal with this problem in the next chapter.

2.- Determination of percentages of ingested heavy metals assimilated from food by aquatic animals in three two levels food chains : *Dunaliella bioculata – Artemia salina; Tubifex tubifex – Lebistes reticulata* and *Patella vulgata – Serranus cabrilla*

The experiments on fish (Bouquegneau et al., to be published) made in a two compartment aquarium as described under § 1 but the pump is fitted with a large charcoal-glass fiber filter to retain suspended matter and to remove the greatest part of the metals released by excretion or bacterial activity on faeces. In one compartment predators were fed with non-intoxicated food and in the other they received contaminated food. Both batches were sampled and their content in heavy metals substracted.

Blank experiments with no pollutants were also carried out. The *Patella vulgata* prey was collected in the industrially polluted area of the Bristol Channel and contained about 50 ppm Cd (w.w). The data on the planktonic chain were obtained in the following way : 100 artemias in a 25 cm plastic tube ϕ 6 cm, obturated at one end with a 1 mm mesh gauze were fed through the gauze on a batch of intoxicated algae during 1 hour per day during 8 days. The number of ingested cells was measured with a Coulter-counter. The water containing the algae was then filtered and 100 artemias in another plastic tube were exposed each day to that water for 1 h again and then fed on non-intoxicated algae for 1 h . The tubes containing the artemias either intoxicated directly only on intoxicated directly and by ingestion of contaminated food where then placed together in a stirred and aerated sea-water tank to complete the direct intoxication resulting from the presence of faeces. The heavy metal content of both algae and artemias per gram wet weight was measured by atomic absorption spectrophotometry.

The percentagesof assimilated ingested heavy metal are obtained by substracting the metal concentrations of the animals intoxicated indirectly

only from that of the predators intoxicated both directly and indirectly and dividing by the amount of food metal ingested.

Table 2

Percentage of ingested heavy metals assimilated by *Artemia salina*, *Lebistes reticulata* and *Serranus cabrilla*

Dunaliella bioculata - *Artemia salina* food chain	
$CuCl_2$	non detectable
$ZnCl_2$	non detectable
$CdCl_2$	3.5 %
$HgCl_2$	5.7 %
CH_3HgCl	28.8 %
Tubifex tubifex - *Lebistes reticulata* food chain	
$ZnCl_2$	10.6 %
$CdCl_2$	0.1 %
$HgCl_2$	0.1 % - 1.4 %
CH_3HgCl	37.1 % - 53.2 %
Patella vulgata - *Serranus cabrilla* food chain	
Cd (see text)	0.8 %

The results are summarized in table 2. The data show the very low percentages of ingested metals assimilated by artemias and fishes except in the case of methylmercury where 30 to 50 percent revealed to be assimilated probably retained in lipids. The low values obtained for the other pollutants are quite interesting since it is known that a large fraction of the heavy metals present in the tissues is bound to proteins and that the percentage of ingested proteins assimilated by fishes can be taken to be about 80 %. This might indicate that heavy metals inhibit either the hydrolysis of their protein carrier or the transport through the digestive tract of peptides and amino acids to which they remain attached.

3.- Study of the direct accumulation and elimination of mercury in some marine and freshwater organisms

3.1.- THE UPTAKE OF $HgCl_2$ FROM SEA WATER BY *Serranus cabrilla* (Med. Sea)

The direct accumulation of mercury from water by fish through the gills generally flattens out in a plateau with time, as if mercury intake was compensated by loss (excretion, etc.). If this is true the curve can be represented by equation (1) (see § 1) and biological half-times can be calculated. On the other hand release of Hg by intoxicated fish can be measured by exposing the animals to non-contaminated sea-water. Obviously the calculated biological half-times from the uptake curves and those obtained from experimental evidence must coincide. If they do not, then the significance of equation (1) has to be questioned.

Table 3 shows results which confirm the validity of equation (1) and of the assumptions of Pentreath (1975) who proposed this simple treatment of the results.

Table 3

Biological half-times of mercury in some sea water fishes

Species	Pollutant	$t_{b\frac{1}{2}}$	References
Anguilla anguilla	CH_3Hg^+	1000 d	Jarvenpaa et al., 1970
Anguilla anguilla	$HgCl_2$	80 d	Bouquegneau, 1975
Pleuronectes platessa	$HgCl_2$	162 d	Pentreath, 1976a
Pleuronectes platessa	CH_3HgCl	300 d	Pentreath, 1976b
Raja clavata	$HgCl_2$	277 d	Pentreath, 1976c
Raja clavata	CH_3HgCl	no loss detectable	Pentreath, 1976c
Serranus scriba	CH_3HgNO_3	267 d	Miettinen et al., 1972

Some recent experiments by Radoux and Bouquegneau (1979) on the uptake of Hg ($HgCl_2$) by *Serranus cabrilla* show contradiction between the biological half-times $t_{b\frac{1}{2}}$ calculated and measured.

The fishes (19 to 48 g) caught off Calvi's Bay (Corsica at the Oceanographic Station of the University of Liège) were intoxicated in 80 ℓ aquaria containing aerated non filtered natural (S = 30 ‰) sea water (21 °C)

to which 100 ppb Hg ($HgCl_2$) was added. Water was changed and polluted every day. The fishes were not fed. Four were taken as samples before the experiment and after 1, 2, 4 and 10 days intoxication. The remaining fishes were divided in two batches : one continued to be intoxicated, the other was placed in aquaria containing unpolluted sea-water, filtered on charcoal glass fibers filters. The Hg concentration was measured as indicated page 86. The kinetics of uptake and experimental release is shown in figure 2 for the whole body.

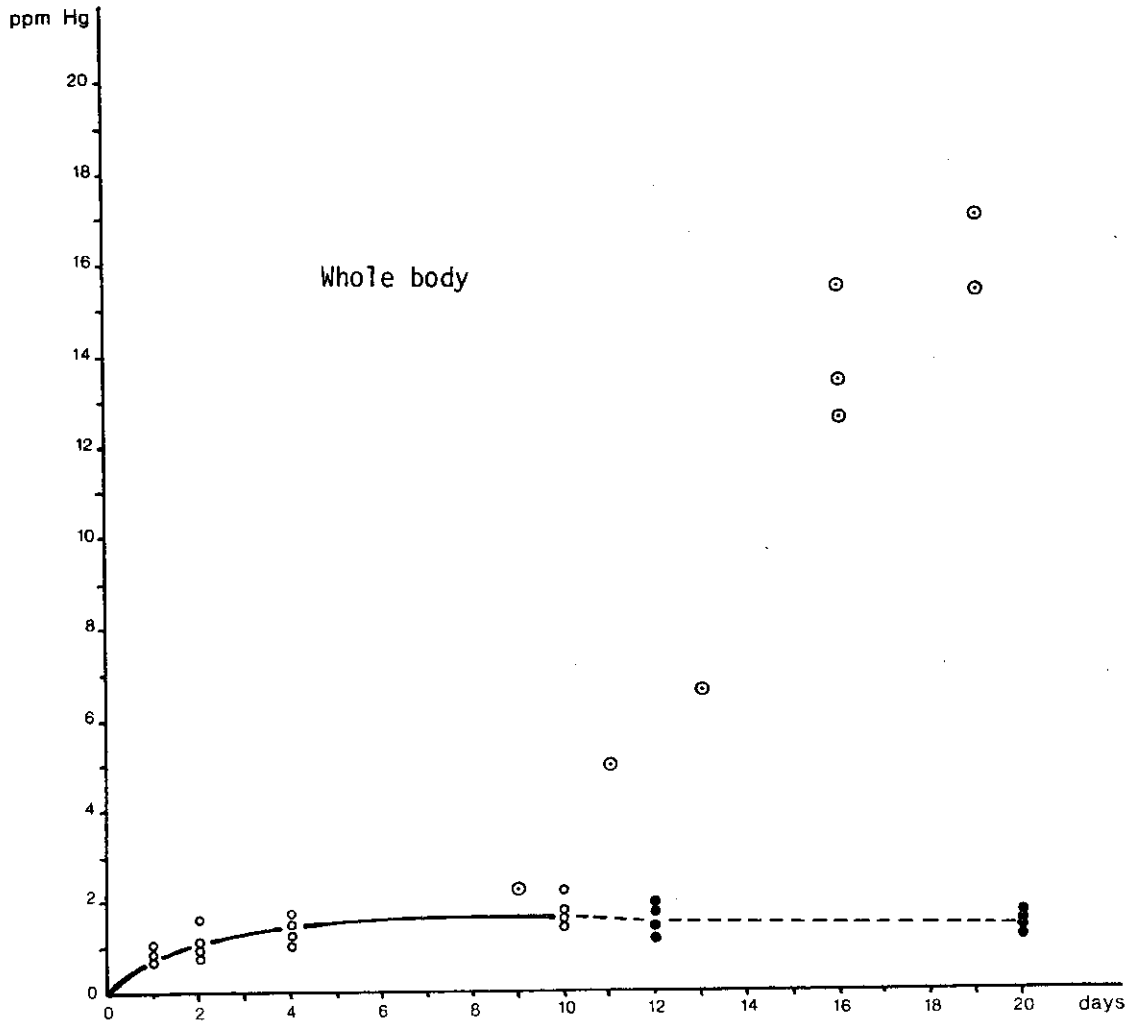

fig. 2.

Kinetics of uptake (———) and release (- - - -) of mercury in the whole body of *Serranus cabrilla*.

o Intoxicated fishes still alive

⊙ Dead fishes

● Intoxicated fishes put back in clean water

After Radoux and Bouquegneau (1979).

The slow elimination (broken line) suggests a $t_{b\frac{1}{2}}$ of about 100 days of the order of magnitude found for other marine species as indicated in table 3.

However if one uses the curve representing the uptake kinetics of fig. 2 it can be shown that it fits equation

$$C_t = 1.7\ (1 - e^{-0.5\ t})$$

suggesting a $t_{b\frac{1}{2}}$ of only 1.36 day (0.693/0.5). After eleven days of intoxication the concentration of Hg in fishes surviving in polluted water seems to be uncontrolled, the data (all corresponding to dead fishes) fit a curve seemingly parallel to the initial rate of mercury uptake.

Radoux and Bouquegneau (1979) have followed the kinetics of accumulation and experimental release in the organs of the fishes and find the same sort of discrepancy between calculated $t_{b\frac{1}{2}}$ and observed ones.

To conclude it looks as if the accumulation kinetics does not reflect a rapid elimination of the pollutant but rather a decrease of the rate of entry at least during 10 days of exposure. The limiting process has not been identified but might be linked to the production of a protective mucus layer which in some cases was observed, but unfortunately not quantified, especially on the gills. If the protective mechanism fails, the uptake kinetics would rapidly become linear in the experimental conditions and lead to death, for example by breakdown of osmoregulatory homeostasis as shown by Bouquegneau (1977) in sea-water adapted eels.

3.2.- THE UPTAKE OF $HgCl_2$ FROM SEA WATER BY *Crenilabrus ocellatus* (Med. Sea)

The same experimental protocol has been used as for *Serranus cabrilla* by Velissarides and Bouquegneau (to be published). Accumulation in gills, digestive tract plus attached organs and muscles is shown in figure 3 at the 50 ppb $HgCl_2$ level and the accumulation in the whole body is given in figure 4 together with the experimental release curve. The experimental biological half-time is long for the whole body and of the order of magnitude quoted in table 3. Gills eliminate Hg faster than the digestive tract, but muscles show an extremely slow rate of elimination if not a continuously slow accumulation.

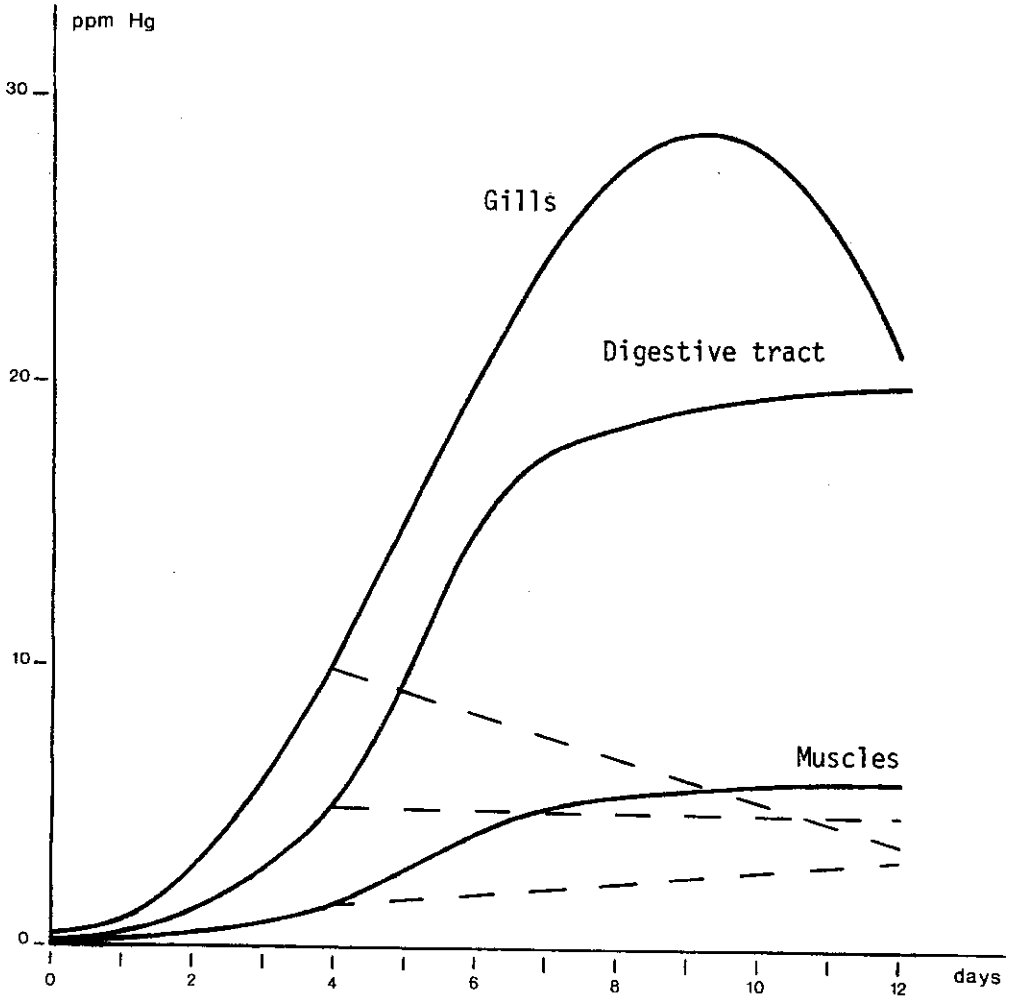

fig. 3.

Kinetics of uptake and release of mercury by gills, digestive tract and muscles of *Crenilabrus ocellatus* intoxicated in sea water containing 50 ppb Hg ($HgCl_2$) [broken line = release]

The accumulation curves are not at all classical, being sigmoïd and do not fit equation (1).

During 4 or 5 days accumulation proceeds slowly and might correspond to diffusion of Hg in the gill tissues where it attaches to -SH groups. The increase that follows is possibly related to the production in the animal of storage sites, probably metallothioneins. Extracts of the digestive tract plus attached organs shows indeed the presence of proteins with molecular weight 10 000 during this period of intoxication. To

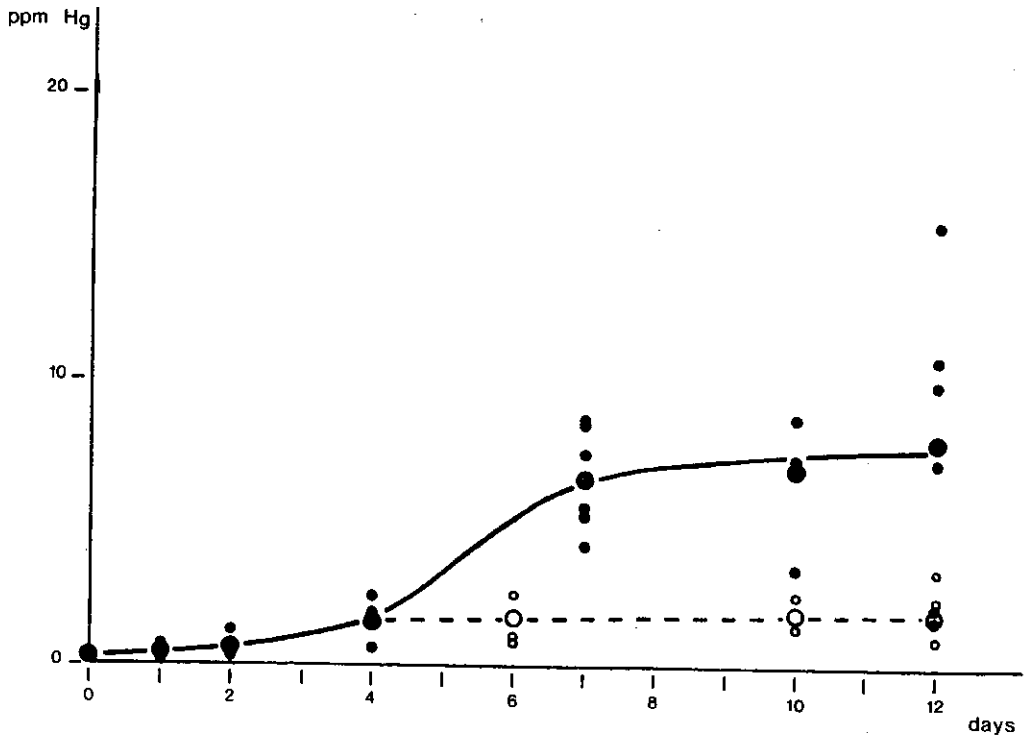

fig. 4.

Kinetics of uptake (———) and release (– – –) of mercury by *Crenilabrus ocellatus* exposed to 50 ppb Hg ($HgCl_2$).

explain the plateau of the sigmoïd curve one is left to admit either that the gills become less permeable to Hg or capable of excreting the pollutant at a greater rate. Further studies are obviously required to answer these questions but it remains interesting to point out that an accumulation curve of the Michaelis-Menten type is by no ways universal.

3.3.- THE UPTAKE OF $HgCl_2$ AND CH_3HgCl FROM FRESH WATER BY *Lebistes reticulata*; EFFECT OF ORGANIC PARTICULATE (AND DISSOLVED) MATTER

To investigate the kinetics of direct uptake and release of $HgCl_2$ and CH_3HgCl by *Lebistes reticulata*, Mercenier and Bouquegneau (to be published) have intoxicated unfed fishes in fresh water renewed each day, containing 50 ppb $HgCl_2$ or 10 ppb CH_3HgCl . Release was measured after three and ten days in unpolluted water filtered on charcoal and glass fiber. The calculated $t_{b\frac{1}{2}}$ were respectively 3 and 13 days, the observed $t_{b\frac{1}{2}}$ was 10 to 12 and 40 to 60 days. The same sort of argument as for *Serranus*

cabrilla might be proposed : possible protective action by mucus or unknown limiting mechanism of uptake of Hg .

However if one compares the values of $t_{b\frac{1}{2}}$ with those obtained in the experiments described in fig.1, when the mercury level was adjusted each day, the fishes being kept in the same water still other values are found. Further if one now compares the uptake curves when the water is renewed each day with those corresponding to the uptake when the guppies are fed on tubifex (fig.5) it is clear that the level of intoxication is much lower in this last case. The difference can be explained in this

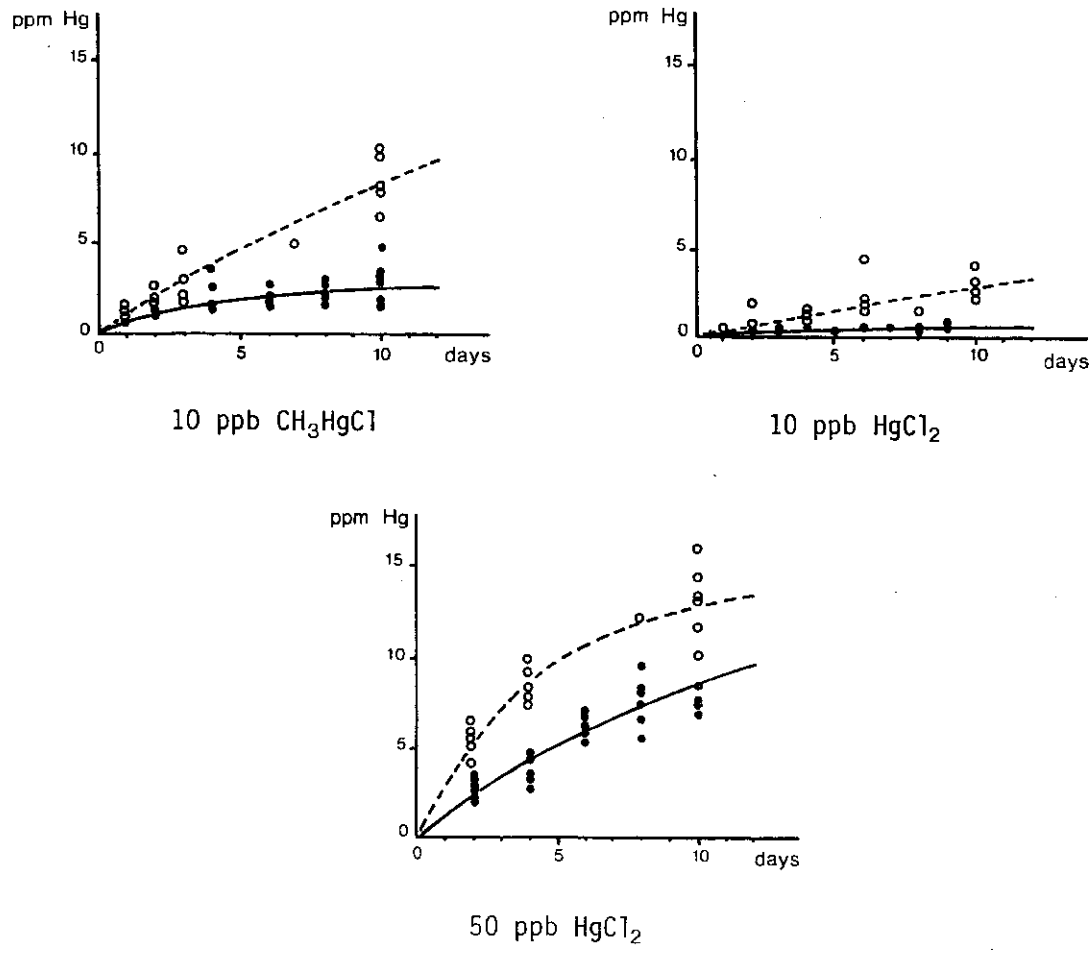

fig. 5.

Comparison between uptake kinetics of mercury by guppies whether the water is renewed (- - - -) or the mercury level is adjusted each day (———) ; the fishes are fed on Tubifex.

instance by the presence of suspended and dissolved organic matter to which Hg combines in a way or another. The metal available to the fishes is in lower concentration the higher the content in organic matter.

Mercenier and Bouquegneau have filtered the aquarium water on Millipore filter, type GS 0.22 µm , to retain the so-called particulate matter and the filtrate was passed on an Amicon UM2 membrane to separate molecules at the 2000 molecular weight level.

Typical results are given in table 4.

Table 4

Aquarium water renewed each day (fishes unfed) : 50 ppb HgCl					
Sampling date	Hg concentration	% Hg on suspended matter	% Hg in solution		
			Total	MW > 2000	MW < 2000
Day 9 , $t_{0\,h}$	50 ppb	2	98	71	29
$t_{24\,h}$	21 ppb	9	91	79	21
Aquarium water not renewed (fishes fed)					
A.- 50 ppb $HgCl_2$ adjusted each day					
Day 1 , $t_{24\,h}$	25 ppb	78	22	63	37
10 , $t_{24\,h}$	27 ppb	67	33	72	28
B.- 10 ppb CH_3HgCl					
Day 1 , $t_{0\,h}$	10 ppb	2	98	66	44
9 , $t_{24\,h}$	10 ppb	36	64	0	100

It thus appears that when the water is renewed and fishes not fed about 90 % of the $HgCl_2$ remains in solution and that this value drops to 20 and 30 % when large amounts of organic matter is present. In the case of CH_3HgCl in the same conditions, the amount in solution remains much higher. The distribution at the 2000 MW level varies with time and after a few days no CH_3HgCl can be found on molecules with a molecular weight higher than 2000 .

In conclusion the factor $t_{b\frac{1}{2}}$ seems to reflect not only the rate of elimination or excretion of the animal but also possible protective mechanisms reducing the uptake rate, as well as the competition between the fish and organic matter to trap the pollutant. At equal concentration,

CH_3HgCl will accumulate faster in fish than $HgCl_2$ because the affinity of the former for suspended organic matter and high molecular weight dissolved organic matter is lower. This means also that at equal total metal concentration water heavily loaded with organic matter is less toxic than water containing no organic detritus or dissolved organic substances.

3.4.- THE EFFECT OF SALINITY ON THE TOXICITY AND THE ACCUMULATION OF Hg IN THE CASE OF THE EURYHALINE CRAB *Eriocheir sinensis*

Bouquegneau and Hibaude (to be published) have used *Eriocheir sinensis*, animal capable of living either in fresh water or sea water, to investigate the influence of salinity on the direct accumulation of Hg and the corresponding toxicity.

The animals are adapted during 15 days to the chosen salinity : natural sea water (Atlantic, S = 33.6 ‰ , 0.07 ppb Hg), the same diluted twice with tap water, tap water. The intoxication experiments are carried out in polyethylene tanks [2.5 ℓ per crab, water being renewed every two days (100 ppb $HgCl_2$) or four days (10 ppm $HgCl_2$), 15 °C]. The animals were not fed during the tests.

Lethal toxicity tests show that at the 10 ppm level 100% mortality is attained after 24 h for fresh water (FW) adapted animals and after 40 days for sea water (SW) adapted ones. Further when SW adapted crabs are intoxicated in freshwater (hypoosmotic shock) 100% mortality is reached after 24 h , and when FW adapted crabs are intoxicated in sea water (hyperosmotic shock) 100% mortality is observed after 19 days. In absence of $HgCl_2$, there is no mortality during the same time lapses. In thus seems clear that at given $HgCl_2$ concentration and for the same animal, mercury is more toxic in freshwater than in sea water. Either the pollutant accumulates faster in freshwater, or the metal affects osmoregulation mechanisms (*Eriocheir sinensis* is in hyperosmotic conditions in diluted media, but isosmotic at high salinities : Schoffeniels and Gilles, 1970).

Both hypothesis have been tested in the folowing.

3.4.1.- Accumulation of Hg by *Eriocheir sinensis* in function of salinity.

The Hg load in gills (anterior and posterior), hepatopancreas, viscera, muscles, carapace and legs has been followed in time at two $HgCl_2$

concentrations 10 ppm and 100 ppb . Figure 6 shows the evolution of the total load of the animals with time at 10 ppm $HgCl_2$ in sea water (SW), SW/2 and fresh water (FW).

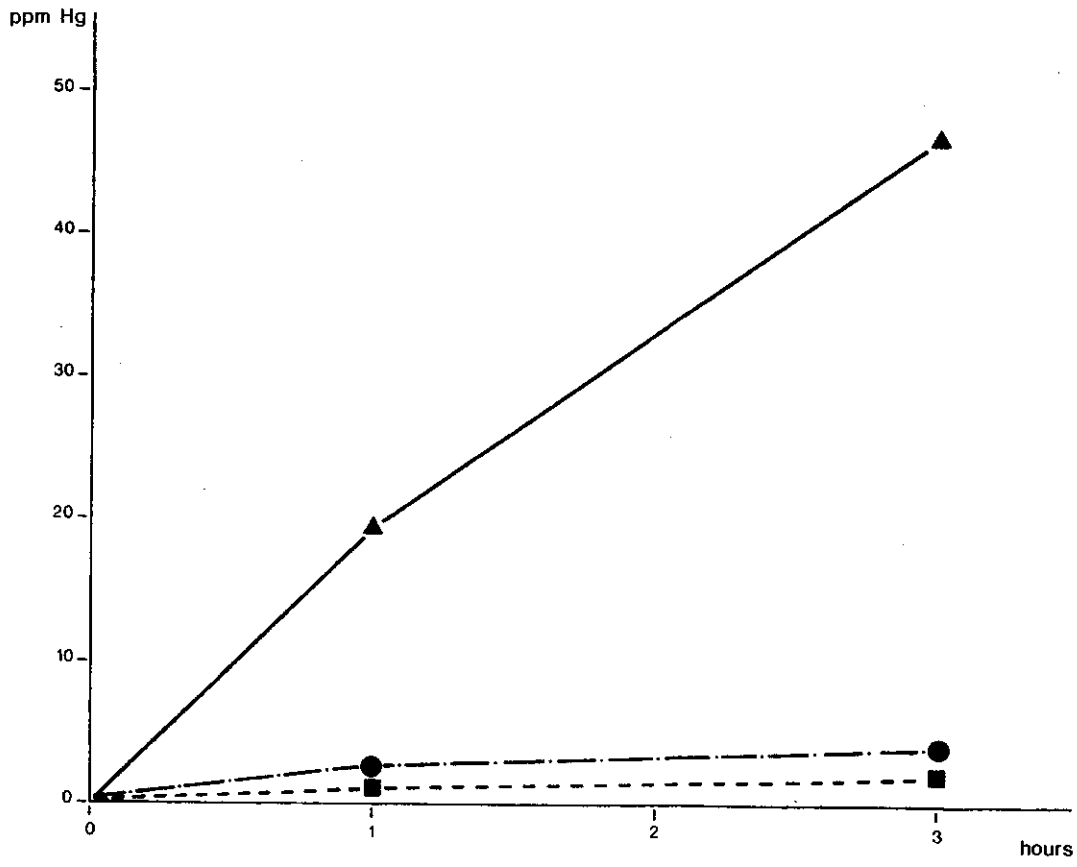

fig. 6.

Mercury uptake by *Eriocheir sinensis* living in various salinity ranges and intoxicated at the 10 ppm Hg level ($HgCl_2$).

▲ FW ● SW/2 ■ SW

Accumulation in FW is 20 times more important than in SW . The concentration factor in FW is 21 times that observed in SW and 2.5 times that obtained in SW/2 .

Figure 7 gives the kinetics of Hg accumulation at 100 ppb for the whole body load. In FW , accumulation is fast during the first day and ends in a plateau, mortality reading 100 % on the 6th day. In SW and SW/2 , accumulation is much retarded but increases continuously at levels higher than in FW although only 6 % mortality is attained after 16 days. The difference between the effects in FW and SW could be explained either by

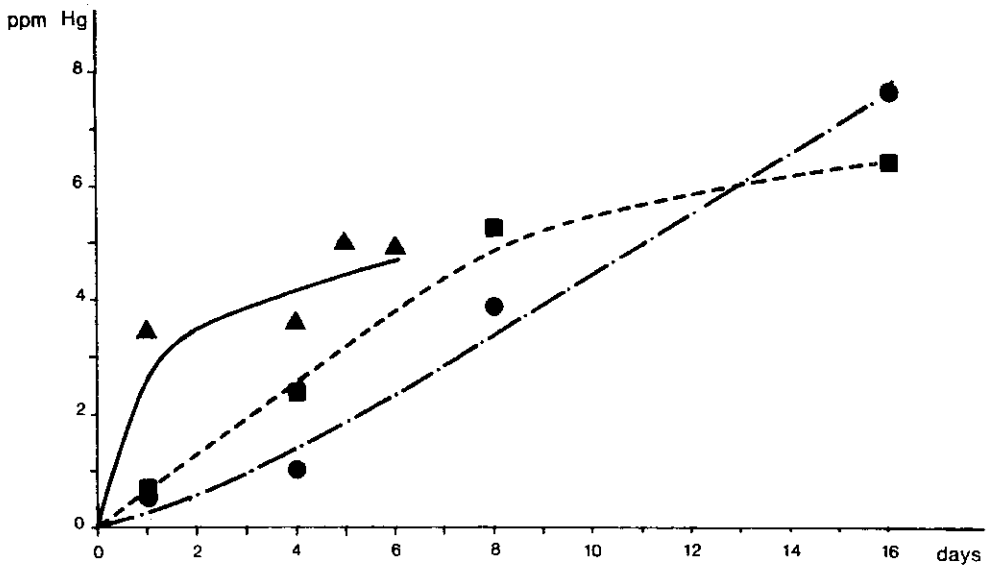

fig. 7.

Uptake kinetics of mercury by *Eriocheir sinensis* adapted to various salinity ranges and intoxicated in water containing 100 ppb Hg ($HgCl_2$)

▲ FW ● SW/2 ■ SW

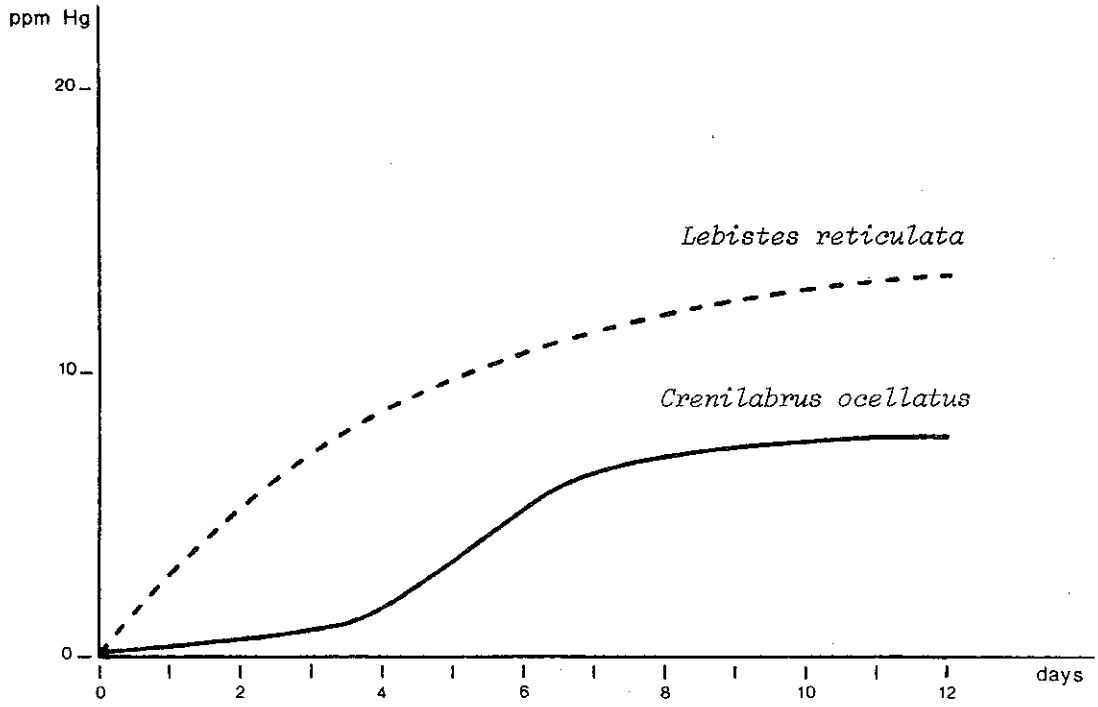

fig. 8.

Uptake kinetics of mercury by *Crenilabrus ocellatus* and by *Lebistes reticulata* living in water containing 50 ppb Hg ($HgCl_2$)

the fact that Hg loss is faster in FW than in SW but there is actually no experimental evidence to support this idea. On the other hand if one considers the results (figure 8) showing the difference between Hg accumulation in *Lebistes reticulata*, freshwater fish, and *Crenilabrus ocellatus*, seawater fish, similar differences in the accumulation curves do appear and have been explained by the appearance of metallothioneins in *Crenilabrus ocellatus*, proteins capable of retaining large amounts of Hg , reducing its toxicity. Extracts of crab organs (gills, hepatopancreas and muscles) passed on Aca 54 column show that in fresh water Hg is attached to proteins of molecular weight greater than 50 000 . The same observation is made for hepatopancreas and muscles of crabs adapted to sea water. However in the gills of the animals kept in sea water, 54 % of the Hg is bound to low molecular weight proteins, in the range of metallothioneins. It thus appears that, in sea water, mercury binds to low molecular weight proteins in the gills, which favours non toxic accumulation in these organs.

3.4.2.- Effect of Hg on osmoregulation in *Eriocheir sinensis* adapted to fresh water

Water content, Cl^- , Na^+ and K^+ concentrations have been followed in crabs living in fresh water containing 10 ppm Hg , that is in highly toxic conditions inducing death within 24 hours.

The results compared to observations on non-intoxicated animals can be summarized as follows :

- an important entry of water in the gills, with subsequent dilution of the interior of the animal; the extracellular internal space increases, the ion concentrations in the plasma decrease.
- an outflow of Na^+ through the gills; this, which perhaps initiates all other events, could be the consequences of a modified passive permeability for Na^+ or/and an inhibition of active transport [see Bouquegneau (1977)] at the level of the Na - K - ATPase.
- an outflow of Cl^- through the gills and parallel to the outflow of Na^+ .
- a diminution of the K^+ concentration in the gills, K^+ being lost to the exterior.

The system seems to evolve towards an osmotic equilibrium, the ionic pumps being blocked. During this process important changes of the cellular volume are induced and elevated concentrations of NaCl in the intracellular space of the gill epithelium can be observed. All these abnormal phenomena probably lead to the death of the animal, uncapable of maintaining its hyperosmoticity in diluted media.

These observations lead to the conclusion that the salinity might have to be considered carefully when dealing for instance with animals living in estuaries and adapted to withstand osmotic stresses. It looks as if they were more vulnerable in diluted sea-water or freshwater, which fits with observations made by Jones (1973). Species migrating from or to freshwater habitats to or from the sea might also be affected by abiotic effects of this type.

4.- Cadmium accumulation by marine animals; the role of metallothioneins

The natural cadmium concentration of sea water is below 0.1 ppb . Levels two orders of magnitude higher are however reported in coastal regions (Abdullah and Royle, 1974; Chan et al., 1974).

4.1.- TOXICITY OF CADMIUM

Cadmium toxicity is relatively well documented for mammals (Friberg et al., 1974) but few data are available for the other groups.

Measurements of acute toxicity of cadmium in the case of aquatic animals indicate lethal thresholds varying from less than 0.1 ppm to more than 50 ppm of cadmium in water (Eisler, 1971 ; Ashanullah, 1976). As a general rule, marine animals are much more resistant to cadmium than freshwater species. It can also be observed that fish are often more resistant than invertebrates. The toxic effects described for marine animals in the case of long-term exposure to cadmium also vary according to the species : effects on growth and reproduction (D'Agostino and Finney, 1974 ; Stebbing, 1976 ; Reish and Carr, 1978 ; Mirkes et al., 1978), on blood composition (Larsson, 1975), on skeleton formation (Bengtsson, 1975), ...

Toxic effects of cadmium result from its high affinity for organic substances with -SH groups (Vallee and Ulmer, 1972). By binding to proteins and specially to enzymes, cadmium disturbs thus many cellular mechanisms.

4.2.- BIOACCUMULATION OF CADMIUM

We shall report here some studies on the accumulation of cadmium by various marine organisms when exposed, naturally or experimentally, to high levels of this metal. In our experiments, cadmium was directly added to sea-water. Indeed, many data seem to indicate that uptake of this metal from water would be more important than from food (Kerfoot and Jacobs, 1974, cited by George et al., 1978 ; Berg and Weiss, 1975 ; Bouquegneau et al., 1976).

Direct uptake involves all surfaces in contact with water. In fish the gills seem the most important pathway. In the intestine, absorption, in the case of Cd is further limited by the existence, as we have shown in many fish species, of corpuscules rich in $CaCO_3$ and capable of adsorbing relatively large amounts of Cd and lowering the metal content of the water passing the digestive tract.

In fish exposed for long time to relatively high cadmium concentration in water (as in the experiment presented in table 5), cadmium is predominantly accumulated in the viscera (particularly in liver and kidneys) whereas muscles concentrations are always very low (generally below 1 ppm wet weight).

It must be noticed that in this case of drastic intoxication, the highest concentration is recorded in the liver but that at lower Cd levels, for example in the case of intoxications under field conditions, the maximum Cd concentration is attained in the kidneys.

In comparison with control fishes, the values presented in table 5 are exceptionally high. Indeed, under natural conditions, cadmium concentrations in fish tissues are generally below 1 ppm, except in the kidneys and in the liver where values of some ppm can sometimes be attained. Table 5 further shows that viscera are more exposed than muscles. After 180 days exposure ti 13 ppm Cd , the liver, in spite of its little weight fraction (1.2 % of the total body weight), contains more than 50 %

Table 5

Cadmium concentrations (mean ± standard error, µg/g wet weight or ppm wet weight) in various organs of sea-water adapted eels exposed during 180 days to 13 ppm Cd in sea water. (n = 3).

Organs	Cd concentration (µg/g)	Weight of organs (g)	Cd load	
			(µg)	% of total body load
Muscles	1,0 ± 0,1	76,1	76,1	9,1
Skin	3,1 ± 0,1	10,6	32,9	4,0
Bones	< 4,0	6,6	(6,6)	0,8
Digestive tract:				
oesophagus	23,8 ± 3,6			
stomach	19,8 ± 3,3	2,1	92,5	11,1
duodenum	72,6 ± 23,4			
intestine	60,0			
Liver	387,2 ± 41,5	1,2	464,6	56,0
Bile	4,5 ± 1,4	0,1	0,4	< 0,1
Kidneys	155,6 ± 34,7	0,7	108,9	13,1
Adipose tissue	11,6 ± 1,3	0,7	8,1	1,0
Plasma	1,4	0,6	0,8	< 0,1
Blood cells	7,8	0,3	2,3	0,3
Gills	31,3 ± 0,9	0,5	15,6	1,9
Spleen	74,2 ± 17,1	0,2	14,8	1,8
Air-bladder	6,5	0,2	1,3	0,2
Heart	35,0 ± 9,5	0,1	3,5	0,4
Brain	5,5	< 0,1	< 0,5	< 0,1
Total body *	8,29 ± 0.53	100	828,9	100

* The Cd load of each organ is calculated from its Cd concentration and its weight percentage [see also Noël-Lambot and Bouquegneau (1977)].

of the Cd body load; muscles, representing 76 % of the body weight, only contain 9 % of the total Cd load.

Owing to this very low Cd accumulation capacity of fish muscles, it is very improbable that sea pollution by Cd, to the contrary with Hg pollution, might ever lead to metal levels in fish dangerous for man. Therefore a control of the Cd concentration in fish caught for human consumption does not seem to be required. However, the control of the Cd content of the viscera would be useful in the case of small species eaten

whole and in the case of fish used to make flour. As it will be shown in the next pages, this control also seems to be very necessary for many invertebrates and especially for the molluscs.

Fig.9 shows the kinetics of accumulation and release of cadmium by the whole body of sea-water adapted eels. This figure illustrates two very important characteristics of cadmium bioaccumulation, not only in fish but also in some invertebrates (*vide infra*).

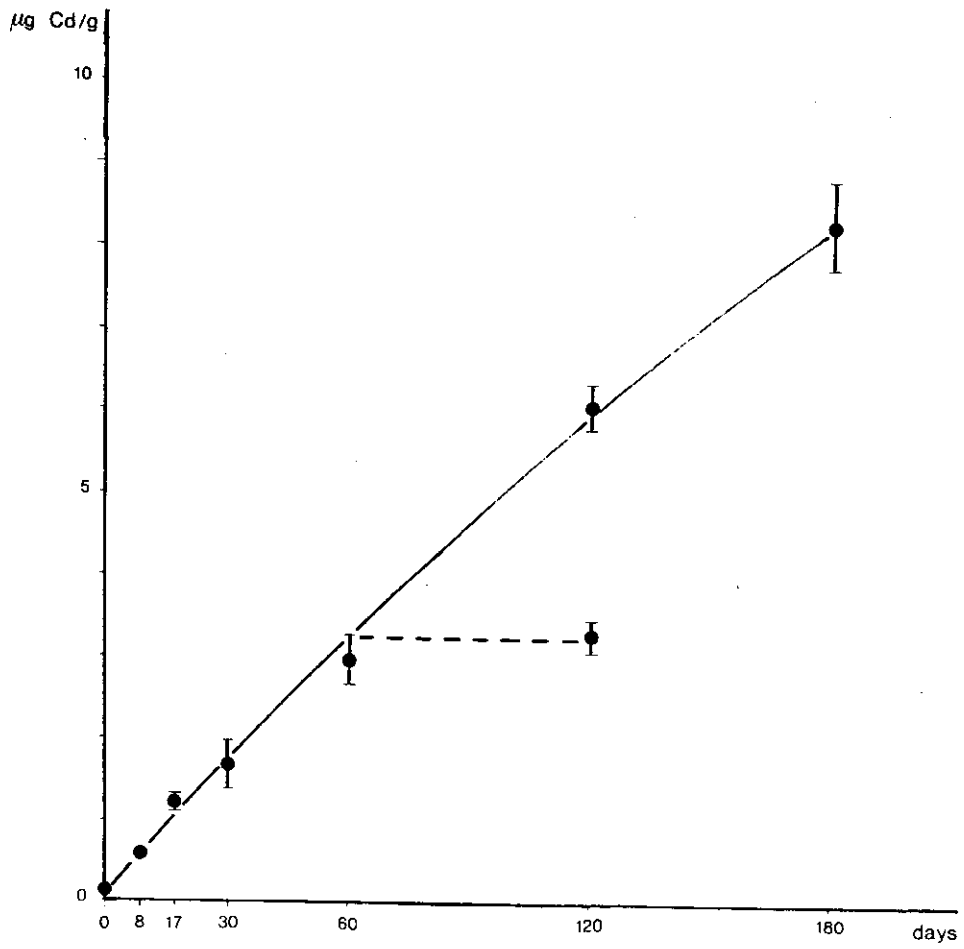

fig. 9.

Accumulation and release of cadmium (Cd concentration of the whole body) : continuous line.
Cadmium concentration of animals kept in non polluted water after an initial intoxication : broken line.
Each point represents the mean calculated for 2 or 5 specimens ± standard error.

1. Cadmium loading can occur over a very long period of time. In fig. 9, a steady state is not achieved within 180 days.
2. Cadmium is very slowly lost from the tissues when organisms previously intoxicated are returned to clean water. In many cases, binding of cadmium in the tissues may be considered as an almost irreversible phenomenon.

Identical characteristics of Cd accumulation are displayed by other marine organisms. It is the case of the limpets *Patella vulgata* and *Patella caerulea* (Noël-Lambot, 1979).

According to the evidence accumulated in our laboratory, most molluscs species seem to have an enormous capacity for Cd accumulation. When they are exposed for long time to very low levels of cadmium, they can thus accumulate very high quantities of this metal. It is specially the case of the species *Patella vulgata* (limpet) and *Purpura lapillus* (dog whelk) as shown in table 6. This table presents the Cd concentrations of several invertebrates collected from unpolluted waters and from

Table 6

Mean cadmium concentrations (in ppm wet weight) in some species caught off unpolluted or polluted waters (see in text)

	Unpolluted water	Polluted water
Molluscs		
Patella vulgata (shell length < 3 cm)	-	22.1
Patella vulgata (shell length > 3 cm)	0.9	53.9
Patella vulgata : muscle	0.6	38.6
Patella vulgata : viscera	1.4	78.3
Nucella lapillus	3.0	93.1
Littorina littorea	0.6	7.9
Littorina obtusata	-	16.7
Sepia officinalis : muscle	0.4	0.2 *
Sepia officinalis : liver	12.9	42.7 *
Hydrozoaires		
Actinia equina	< 0.5	0.5
Annelids		
Arenicola marina	-	6.0

* Specimen from Hinkley Point on Bristol Channel.

an area well known for its pollution by cadmium, the Bristol Channel (Portishead or Weston-super-Mare, England). Cadmium concentration in water of both these localities is near to 5 ppb (Preston, 1973 ; Abdullah and Royle, 1974). It can be seen that in molluscs, as in fish, Cd concentration is also higher in viscera than in muscle but muscles from molluscs nevertheless can present considerable Cd concentrations. In the case of *Patella vulgata*, a species with a high capacity for Cd bioaccumulation, it can also be observed that the old specimens show much higher Cd concentrations than the young ones. In fact, a direct relationship links Cd concentration and body size (Noël-Lambot et al., in preparation). This phenomenon is most probably a consequence of the very long exposure time and continuous accumulation of the metal by this species (see above).

From a practical point of view, this influence of the size of *Patella vulgata* on Cd concentration as also on concentrations of other metals such as Zn and Cu (for both elements we have observed an inverse relationship between concentration and body size) suggests that the use of organisms as indicators of pollution may present some problems. Indeed, differences in metal tissue concentrations between populations of a same species may reflect real differences in environmental concentrations but they also may be due to differences in body size. Moreover, it is known that environmental variables such as salinity, temperature, position of the organism in the water column, season, coexistence of several metals and presence of chelating agents also may affect the uptake of metals by organisms (Eisler and Gardner, 1973 ; Vernberg et al., 1974 ; Phillips, 1976 ; George and Coombs, 1977 ; George et al., 1978 ; this report page 12 and 14). It is essential to bear all this in mind when biological indicators are used to monitor environmental contamination by trace metals. We should also take in consideration the wide variety of responses already quoted but evident from table 6 which might mislead the experimentor so that one have to consider whether biological toxicity tests promoted by some are realistic. Anyway in the case of surveyance of marine food, molluscs should deserve special attention. Everything seems to converge to make these organisms often used as seafood have the highest Cd content compared to other animals :

1. the tissues of many molluscs have a high affinity for Cd,
2. commercially exploited molluscs live in coastal water, more exposed to Cd pollution,
3. the animals are generally eaten whole, that is viscera included, site of heavy accumulation.

As already quoted, the toxicity and bioaccumulation of the Cd^{++} ion result from its ability to form stable complexes with many cellular components, especially proteins where it attaches to -SH groups. We will study this problem in more detail in the next section.

4.3.- CADMIUM BINDING WITHIN THE CELLS : THE METALLOTHIONEINS

In several tissues from Cd-intoxicated animals, especially in those with high Cd concentrations such as liver, kidney and intestine in fish or in organs of the molluscs *Patella spp.* and *Nucella lapillus*, most of the metal accumulated is bound to metallothioneins which are soluble proteins with very particular properties (Kojima and Kägi, 1978). The presence of those proteins in the tissues can be shown by gel filtration technique. Fig.10 and 11 show the results for the soluble fraction of eel liver and of the whole of the soft tissues of limpet. On these figures, the chromatographic fraction called "MT" corresponds to metallothioneins. It can be seen that this fraction binds most of Cd present in the soluble extract and in some tissues such as liver, kidneys and digestive tract of fish, it also contains high amounts of Zn and Cu. Note that for many tissues, metallothioneins do not seem to be a normal constituent. Generally these proteins only appear in the cell after Cd administration. In some tissues such as in fish liver, they however are detected in the absence of any experimental intoxication (Noël-Lambot et al., 1978a) ; in these tissues, they probably play a role in the metabolism of Zn and Cu.

Isolation and characterization of metallothioneins can be performed as described in previous papers (Bouquegneau et al., 1975 ; Noël-Lambot et al., 1978a ; Frankenne et al., in preparation). The method includes the following steps : homogenization of the tissue followed by centrifugation, acetone fractionation of the supernatant, gel filtration on LKB Ultrogel AcA 54, ion exchange chromatography (DEAE Cellulose).

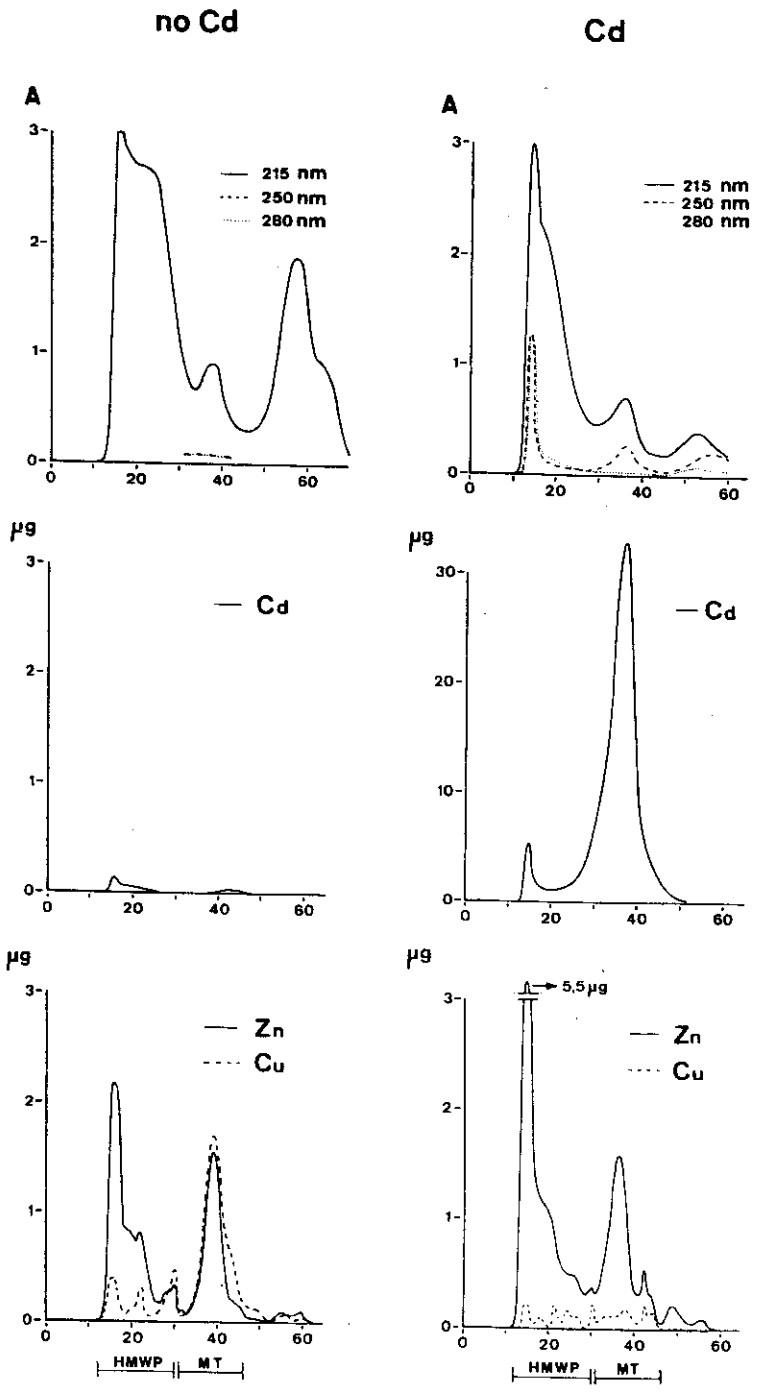

fig. 10.

Elution profiles on Sephadex G-75 column (76 × 3 cm) of liver soluble fraction obtained from non Cd-intoxicated eels or from eels intoxicated during 180 days in sea water containing 13 ppm Cd . Metals concentrations in the elution fractions are expressed in μg per fraction and per gram of organ.
Fractions volume : 10 mℓ . [After Noël-Lambot et al. (1978a).]

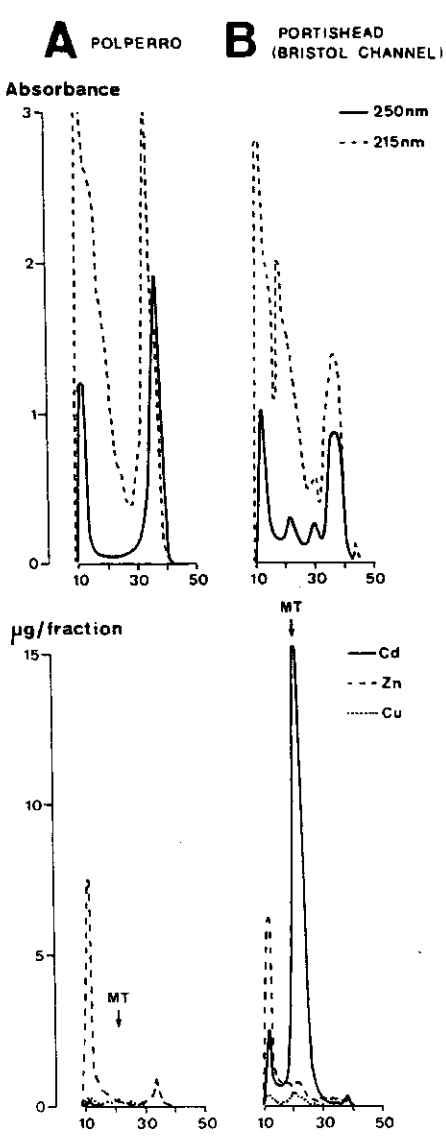

fig. 11.

Elution profiles on LKB Ultrogel AcA 54 column (2.6 × 33.5 cm) of the soluble extracts from limpets (*Patella vulgata*) collected from unpolluted water (A) or from Cd polluted water (B). Metals concentrations in the elution fractions are expressed in µg per fraction and per 1.2 g of tissue. Fraction volume : 5 mℓ .
[After Noël-Lambot et al. (1978b).]

The amino acid composition of the purified metallothioneins can be determined using the procedure of Benson and Patterson (1965). Metallothioneins also can be studied by spectroscopy and by electrophoresis on polyacrylamide gel electrophoresis.

The above methodology has been used for isolation and characterization of metallothioneins from the liver of the eel *Anguilla anguilla*, from the tissues of the mussel, *Mytilus edulis* and the limpet, *Patella vulgata*.

The metallothioneins isolated from all these different sources are not identical but they all are characterized by a low molecular weight (close to 10 000), a very high metal content (about 10% in weight), an unusual U.V. spectrum showing a maximum absorbance at 250 nm, a very particular amino acid composition with a high content in cysteine and the absence or a low content in aromatic amino acids (tyrosine, phenylalanine, tryptophan), histidine and arginine. Moreover, in all the tissues studied, we have observed the occurrence of two or more metallothioneins with electrical charges in the same experimental conditions (Noël-Lambot et al., 1978a ; Frankenne et al., in preparation).

For what regards all these properties, metallothioneins from the various aquatic animals studied here are very similar to those of mammals.

Metallothioneins, originally isolated and characterized from equine kidney by Margoshes and Vallee in 1957, have extensively been studied in mammals (for a literature review, see Webb, 1975 ; Bouquegneau and Noël-Lambot, in press), but very few informations are available about the other zoological groups and particularly about the invertebrates (Noël-Lambot, 1976 ; Howard and Nickless, 1977 ; Brown et al., 1977 ; Noël-Lambot et al., 1978b ; Overnell, personal communication). Until now, the studies of these proteins from an ecotoxicological point of view were very scarce (Brown et al., 1977 ; Noël-Lambot et al., 1978b).

In mammals, metallothioneins are generally considered to have a function in the metabolism of the essential metals Zn and Cu and in the detoxication of Cd and Hg. The metallothioneins of many aquatic animals display similar general properties and play a considerable role in the accumulation of both Hg and Cd.

4.3.1.- Metallothioneins and the accumulation of cadmium

An example of the part played by metallothioneins in Cd accumulation is given in fig.12. This figure has been drawn from data obtained from chromatographic analysis of eel liver samples. Cd was measured in the

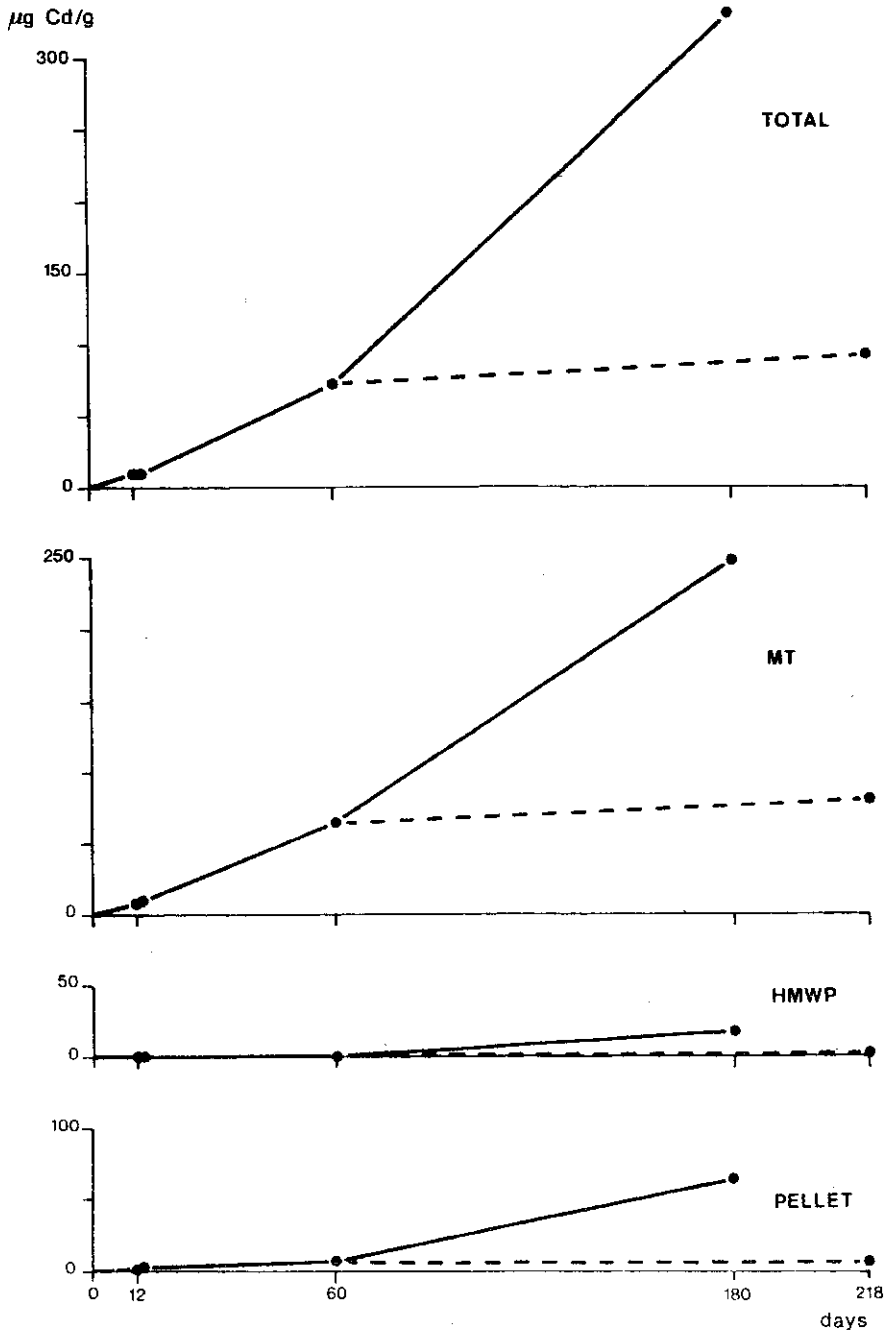

fig. 12.

Cd accumulation in the whole liver of the eel and various cellular fractions of this organ during a chronic intoxication in sea water containing 13 ppm of Cd .
MT = metallothioneins; HMWP = soluble proteins of high molecular weight.
All the concentrations are expressed in µg of Cd per g of wet tissue.
Broken line corresponds to animals transferred to unpolluted water after an initial intoxication.

centrifugation pellet and in the elution fraction obtained by chromatography of the supernatant (see above, fig.10).

As shown in fig.10, the Cd accumulated during a chronic intoxication is associated with two main fractions : the first one is quite heterogen and corresponds to the soluble proteins of high molecular weight (HMWP), the second one corresponds to metallothioneins (MT).

From fig.12 it is clear that the Cd loading of the liver occurs over a very long period of time. During the same time, Cd bound to metallothioneins (MT) raises to a considerable extent whereas Cd bound to the other soluble proteins (HMWP) and to the pellet is little affected. Therefore, the Cd-thionein complex represents the major form in which the metal is present in livers with heavy Cd load.

Owing to the chemical properties of metallothioneins, the amount of Cd bound to these proteins may be considered as a good indicator of their abundance so that the increase with time of the Cd contained in the MT fraction (fig.12) corresponds in fact to an increase in metallothioneins concentration (Noël-Lambot et al., 1978a).

It seems evident that the increase of the amount of metallothioneins with time corresponds to an equivalent increase of Cd-binding sites and thus to a more and more extensive capacity of Cd storage.

Quite similar results can be obtained with limpets naturally or experimentally exposed to Cd (Noël-Lambot et al., 1979).

The induced production of metallothioneins might thus be if not the main, one of the most important mechanisms responsible for the continuous accumulation of Cd in marine organisms, at least in certain of their organs.

We have already indicated that the total Cd concentration of many tissues does not decrease, or only very little when the animals are exposed to clean water again. Fig.12 shows that the intracellular distribution of the metal does not change either. The largest part of tissular Cd thus persists as Cd-thionein, although the cause of their formation has disappeared. The persistance of Cd-thioneins would however be linked to a continuous important turnover of the apoprotein as shown by Chen et al. (1975).

Metallothioneins can be considered as very efficient traps for Cd, screening other proteins from its toxic effects as is for Hg (Bouquegneau

et al., 1975). They do not disappear when intoxication ends but are rapidly distroyed after death (probably by bacteria or simply by proteolytic enzymes) as indicated in preliminary results. Cd is then returned to the water column either as free ionic species or complexed ones with renewed potential toxicity.

All tissues are not capable of producing metallothioneins and if they possess the capacity to do so a certain threshold of intoxication must be reached before these proteins do appear.

This threshold varies from one tissue to another, the tissues with the lowest threshold being also those storing the greatest amount of metal.

These tissues (viscera, in particular liver and kidney from fish and other vertebrates, soft parts of molluscs) should be used for surveyance work. They can be considered as good indicators of Cd pollution in natural conditions where it is difficult to estimate since very little is known about the effect of speciation of Cd on its toxicity, besides the effects of suspended matter and abiotic factors as discussed in the first part of this work for mercury.

We have mentioned that, as in mammals, metallothioneins in fish not only associate with Cd (or Hg) but also with various amounts of Cu and Zn. This problem will be discussed next.

4.3.2.- Metallothioneins and the metabolism of Zn and Cu

We have observed that under natural conditions, the Zn and Cu concentrations in the eel liver are very variable but closely related to each other. The study of the distribution of these metals in the soluble fraction of liver extracts shows that the amounts of Zn and Cu associated with metallothioneins, and also the concentration of these proteins, are directly dependent on the Zn and Cu concentrations in the whole liver. On the other hand, the metal content of the other hepatic components are little affected by these variations. These results suggest that metallothioneins have an important role in storage of excess Zn and Cu in fish. It must be quoted that this intervention of metallothioneins in the metabolism of the essential metals Zn and Cu seems to be limited to vertebrates.

Indeed, molluscs metallothioneins never bind important amounts of Zn or Cu , even in animals exposed to high amounts of both metals. In molluscs as in some other invertebrates there exists an other storage and detoxication mechanism for Zn and Cu . The metals are inclosed in vesicles within the cell. These vesicles act, as metallothioneins do in way for Cd and Hg , by preventing contact of excess metal with vital constituents (Coombs and George, 1978).

4.3.3.- Metallothioneins and the adaptation to cadmium during a long-term intoxication

Fig.13 compares the concentration and the distribution of Cd in tissues of animals intoxicated either at a lethal dose or a sublethal one (chronic intoxication). These data show that animals can die from Cd intoxication although the Cd concentrations in their tissues are far below the one observed after long periods of chronic intoxication during which the animals adapt. In the first case, the then lethal concentration is reached in a few hours. The toxic effect of Cd is thus not necessarily linked to very high tissue concentrations.

In animals adapted at low external Cd concentrations, Cd binds to metallothioneins and as already said becomes toxically inert : figure 13 shows that the Cd concentration in other cellular compartments remain relatively low. This examplifies the screening effect of metallothioneins. The drawback is that this protective mechanism is also the cause of an important bioaccumulation. The heavily loaded animals are a potential danger for others. Fortunately in aquatic food chains it seems that transfer through predators remains small. Nevertheless by continuous absorption of contaminated food, chronic intoxication only displaces Cd from one metallothionein to another and the metal will be returned to the environment at the death of either prey and predator.

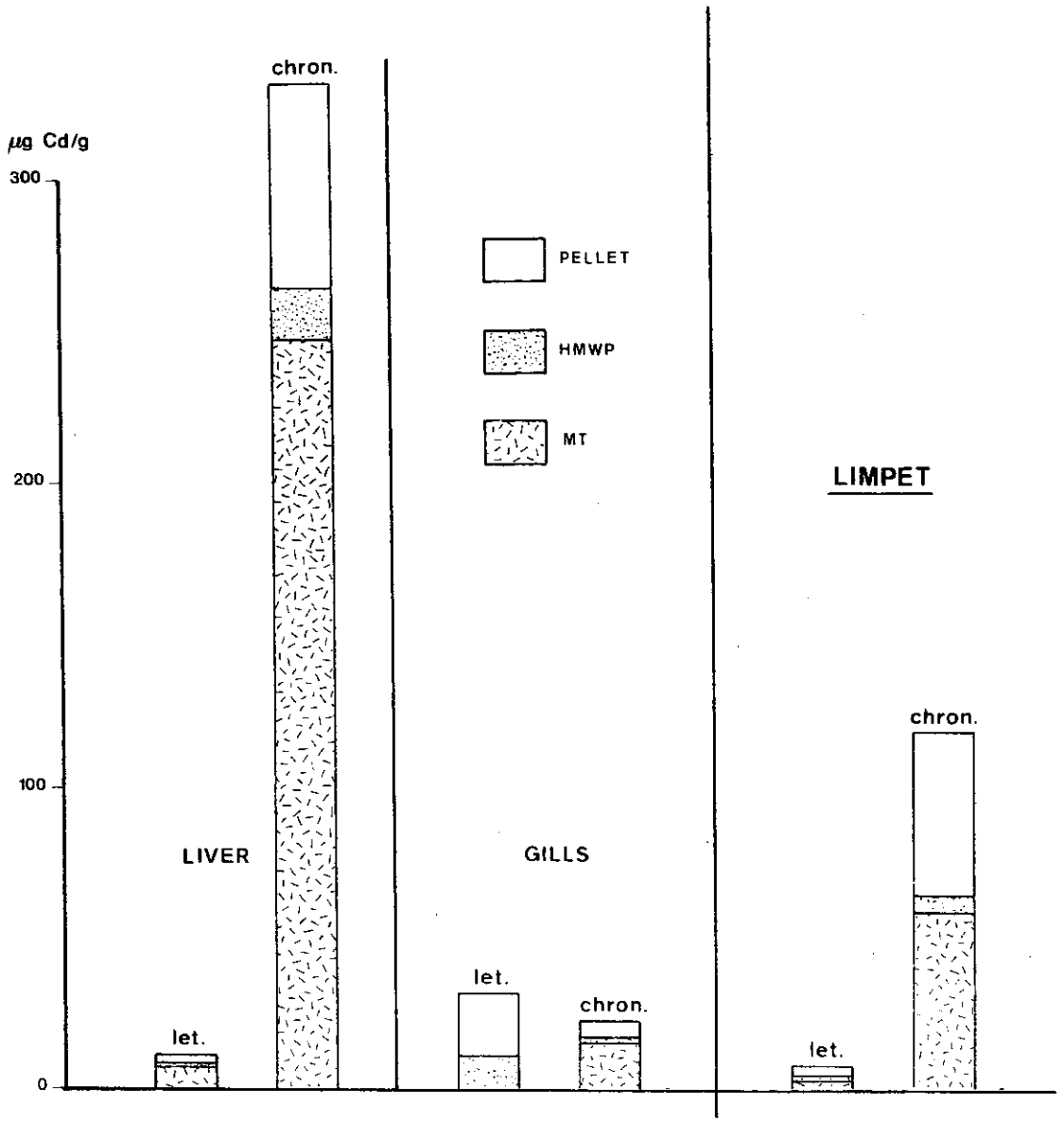

fig. 13.

Intracellular distribution of the cadmium accumulated during a lethal (let.) or chronic (chron.) intoxication. Cd concentrations (in µg Cd per g tissue) in the pellet, the soluble proteins of high molecular weight (HMWP) and the metallothioneins (MT).
Experimental conditions :

eel liver : 5 hours in 200 ppm Cd (n = 3) or 180 days in 13 ppm Cd (n = 2)
eel gills : 5 hours in 200 ppm Cd (n = 1) or 68 days in 13 ppm Cd (n = 2)
Patella vulgata : 48 hours in 2 ppm Cd (n = 3) or *in situ* intoxication (Portishead) n = 1 .

Note that the animals exposed to short time lethal Cd concentrations were still living when collected.

Conclusion

Going back to the introduction to this paper, one might ask in how far some of the questions have been answered. Regarding Hg^{++}, Cd^{++} and also Cu^{++} and Zn^{++}, transfer through the food chain is much less efficient than direct uptake from sea water. Only a few percentage of the metal ingested in food is assimilated except for CH_3HgCl because of its high solubility in lipids.

A relationship with carbon and nitrogen fluxes is only apparent because direct intoxication is repeated at each step of the food chain and increases with the age of animal at constant exposure. Practically, as much metal ingested with food is excreted. The direct route of entry shows kinetic differences between species and is modulated by abiotic effects (salinity, partition of metal between suspended matter and living matter, chemical speciation, etc). The significance of biological half-times calculated from uptake curves versus time is to be questioned because these other factors. The fact that some marine organisms if not all possess the capacity to fix heavy metals like Hg^{++} or Cd^{++} on metallothioneins which are continuously produced in chronically intoxicated animals leads to large accumulations with little or unknown effects on physiology but long retention times. It thus finally looks as if the heavy metal concentrations in the sea were under biological control as it is for many other systems (CO_2 and related substances, SiO_2, aluminium, etc.). If living matter or detritus resulting from living matter is the important sink for heavy metals where their trapped life span or residence time depends on the age of the animal and the time it takes to return the metals to soluble forms eventually toxic, then this will either affect the marine foodweb because of different resistance levels for different species, or it will not. On the other hand if we consume seafood we will in some extent eat what we tried to throw away. It is nice to know that man in some countries eats between 50 and 150 µg Cd per day (Karhausen, 1973; Friberg et al., 1974) from which 1.6 to 3 µg are really assimilated. This corresponds to eating one gram of limpets intoxicated in heavily Cd contamined (5 ppb in water) coastal zones. But who would eat limpets? If heavy metals like Cd or Hg distribute between sea living matter and detritus containing also land matter, the knowledge of the distribution of the metals between these compartments including species soluble in

water is of importance ; could one show for instance that detritus compared to living cells bind more metals, or that organic complexes are less or more toxic than ions ? Any evaluation to predict the fate of heavy metals in the marine environment either in a steady state or not would have to answer that question as well as how fast coastal waters diffuse to open oceans, deep currents and how fast chemicals are returned to the surface. This looks more important to the authors than to try and find model reduced food chains or single animals or plants to be used as unfallible tests for water quality. They believe it urgent to design more and more realistic laboratory experiments and to look at the ecosystem in a global way including its physics, its chemistry and biology, however crude the approach and to define the general rules of the game between it and the increasing amount of heavy metals dumped in the sea. We have little or no time to go in the details of species responses and far more detailed biochemical or physiological events. It might for instance be better to realize that heavy mortality in phytoplankton because of release of large amounts of nitrates and phosphates from land, because of agriculture, is in favour of a less toxic environment for fish and other animals regarding heavy metal potential toxicity and to ponder what would happen if this release was stopped and not the heavy metals release linked to industrial waste.

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The determination of trace metals in sea water and suspended matter by classical anodic stripping (Zn, Cd, Pb, Cu) or differential pulse anodic stripping voltammetry with a hanging mercury drop electrode (Zn, Cd, Pb, Cu, Sb and Bi).

An approach to speciation.

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1.- Sampling methodology

Sampling appears to be the most hazardous step in the determination of trace metals at the ppb level in sea-water because of contamination problems. Classically, Niskin bottles can be used with Téflon coated messengers and hydrowire ; water can be collected with Teflon centrifugal pumps. The next step is filtration which usually is carried out on Millipore filters (0.45 µm pore size), the final product being stored on board the ship at -20°C in polyethylene bottles carefully washed with pure HCl and tridistilled water. Filtration can also be carried out after thawing before analysis in the laboratory on land. Contamination is of course possible at any step and the ship itself is probably the main cause of trouble if not some other ship leaving behind herself a cload of Zn, Cu, Pb, etc from propellers, zinc anodes, paint, engine exhausts among other sources. Airborn material, careless handling by unskilled experimenters, the depth at which the sample is taken versus the ship's draught, the location on board of sampling system, atmospheric conditions, non homogeneity of the water, etc are all possible causes of difficulties piling up in an almost infinite list. To make sampling and filtrations more reliable the following system has been tested by

Gillain (personal communication) and shown to give far more better results than those described above which get easily out of control. Better results means that in some cases the trace metals concentrations are one order of magnitude lower than with the conventional methods.

The principle is to continuously collect small samples of water from a very large volume screened from atmospheric pollution. A peristaltic pump draws continuously 6 ℓ water per min at 5 m depth (2 m below the ship's keel);[in the North Sea (Southern Bight) the water column is taken as homogeneous] through a PVC tube previously soaked in 6 N HCl , rinsed with tridistilled deionized water. The ship is adrift and the tube is on the lee side so that it meets water masses not polluted by the vessel. A second peristaltic pump draws 0.5 ℓ per min from the main flow which is returned to the sea. The unfiltered sea water is kept in a 5 ℓ polyethylene bottle and magnet stirred continuously. Pure nitrogen (0.3 kg/cm^2 pressure) is used to drive the water to an ultrafiltration kit (0.45 µm millipore filter) where the liquid is stirred to reduce filter clogging and filtration proceeds under nitrogen pressure. The filtered samples are collected in 1 ℓ bottles each finally representative of about 60 ℓ water, excess water from the filter being discarded by simple bypass. The samples are immediately frozen at -20°C. Thawing is carried out in the laboratory immediately before analysis.

2.- Analytical techniques

2.1.- CLASSICAL ANODIC STRIPPING VOLTAMMETRY

The method has been described in detail by Duyckaerts and Gillain (1977). It allows to measure Cu, Pb, Cd and Zn not only in sea-water but also in plankton and/or suspended matter, first lyophilized and then ashed with microwave activated oxygen, followed by dissolution in concentrated HCl.

The interesting point is that besides being very sensitive (0.5 to 0.1 ppb), the method allows an approach to speciation. Carried out at *in situ* pH it gives an evaluation of the ionic species (I) ; at pH 3 metals forming "weak" complexes are released (II) ; at pH 3.5-4 samples first irradiated by U.V. during 12 hours at pH 1 show the release of

"strongly" complexed cations (III). The differences (II) - (I) and (III) - (II) can be used together with (I) to approach speciation.

2.1.- DIFFERENTIAL PULSE ANODIC STRIPPING VOLTAMMATRY

Differential pulse anodic stripping voltammetry receives considerable attention as a convenient technique for the simultaneous determination of heavy metals at the microtrace level. A review of its application to sea-water together with a complete description of the technique adapted by the authors has been recently described by Gillain et al. (1979).

The method can be used to perform the same sort of analysis as indicated for classical anodic stripping but the sensitivity is about one order of magnitude higher (0.05 to 0.01 ppb).

Further it can be used in well controlled conditions to determine simultaneously Zn, Cd, Pb, Cu, Sb and Bi.

Gillain et al have shown that a very good resolution of the peaks can be obtained by carefully studying the effects of both pH and NaCl concentrations. The optimal conditions, illustrated by fig.1, show the

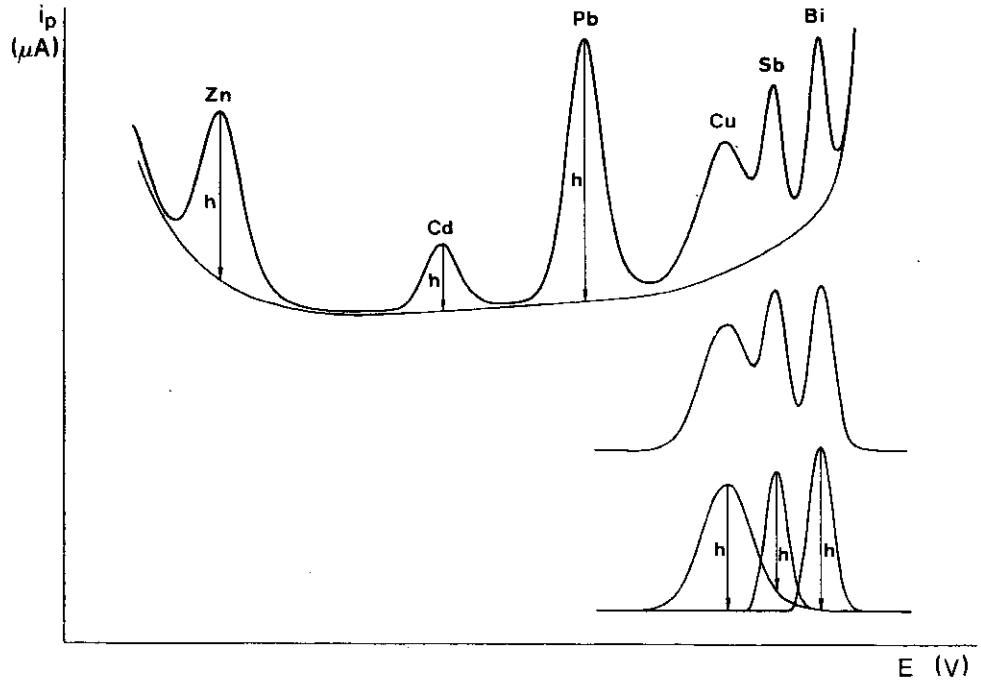

fig. 1.

Evaluation of stripping peaks (differential voltammetry) to measure simultaneously Zn , Cd , Pb , Cu , Sb , Bi .

results obtained at pH 1 and NaCl 2M concentration and how the height of the peaks are determined. The pH and the NaCl concentrations are adjusted by adding suprapure HCl and NaCl to the sea-water samples. The analysis takes only 2 hours.

Under these conditions it should be kept in mind that the metal concentrations which are measured correspond to the sum of the ionic species and the weakly bound ones, or if U.V. irradiation is used, to the sum of all species.

Typical values for North Sea water samples (ionic + weakly bound species) are given in table 1 together with indications on the precision of the method.

Table 1

Metals	Concentration (ppb)	Standard deviation (ppb)
Zn	5.2	0.26
Cd	0.6	0.06
Pb	6.2	0.70
Cu	4.3	0.40
Sb	0.4	0.06
Bi	0.3	0.04

3.- Results

3.1.- METALS IN SOLUTION

The data presented here correspond to samples taken during September, October and November 1978 in the coastal region off the Belgian coast between Dunkerque and the Scheldt estuary (51°07'20"-51°20'40"N, 51°25'00"-51°39'25"N ; five transects). The depth of sampling is 5m, the improved sampling system is used on board as well as the differential pulse technique in the laboratory.

Table 2 gives the mean values for Zn, Cd, Pb and Cu, as well as the extreme concentrations detected (20 samples per cruise).

Table 2

Mean values and extreme values (µg/ℓ) for Zn, Cd, Pb, Cu off the Belgian coast

	Metals	(I) pH *in situ*		(II) pH 3		(III) U.V. irradiation	
		Mean	Range	Mean	Range	Mean	Range
September 1978	Zn	0.48	0.10 - 1.50	2.48	1.00 - 5.43	6.7	2.6 - 14.5
	Cd	0.02	0.01 - 0.05	0.05	0.03 - 0.09	0.10	0.04 - 0.23
	Pb	0.75	0.10 - 1.60	2.55	0.90 - 5.80	5.10	0.90 - 9.10
	Cu	0.55	0.30 - 1.10	1.45	0.45 - 2.46	2.50	0.60 - 4.70
October 1978	Zn	2.45	0.50 - 4.30	6.60	2.50 - 10.0	10.6	2.5 - 23.0
	Cd	0.03	0.01 - 0.10	0.09	0.04 - 0.30	0.11	0.04 - 0.32
	Pb	0.70	0.30 - 1.30	2.50	1.10 - 4.80	5.10	3.00 - 9.70
	Cu	1.00	0.30 - 2.00	2.15	1.20 - 4.30	3.20	1.10 - 8.50
November 1978	Zn	1.60	0.35 - 3.60	4.0	1.80 - 8.50	6.5	2.5 - 10.6
	Cd	0.03	0.01 - 0.06	0.08	0.03 - 0.10	0.10	0.05 - 0.18
	Pb	1.50	0.20 - 1.90	3.40	2.20 - 4.50	5.00	2.30 - 7.90
	Cu	0.60	0.20 - 1.90	1.70	1.10 - 4.00	2.50	0.80 - 6.00

Note : (I), (II), (III) refer to concentrations of heavy metals in ppb ; (I) corresponds to ionic species, (III) to the total amount of metal, (II) - (I) to the weakly bound species, (III) - (II) to the strongly complexed cations (see text).

The values of column (II) (ionic species + weakly bound ones) are lower but not systematically, considering the ranges, with the data published in 1979 by the authors for 5 samples from the North Sea taken with conventional methods in 1977 (table 3).

Table 3

Metals	Metal content (ppb)				
	1	2	3	4	5
Zn	7.00	2.66	14.20	22.00	14.00
Cd	0.40	0.30	0.20	0.95	0.30
Pb	1.80	7.44	7.26	3.60	6.38
Cu	2.82	9.70	5.70	8.00	9.12
Sb	0.30	0.45	0.82	0.30	0.42
Bi	0.20	0.68	0.55	0.20	0.28

It is too early to compare the new results with the thousands of data collected in the North Sea off the Belgian coasts since 1971 (J.C. Nihoul and I. Elskens, 1978) because the bettered sampling technique has not been used long enough to detect the general pattern of distribution, the seasonal fluctuations, which considerably affect the amounts of heavy metals in this region.

At the international level, some intercomparisons can be made. For instance the mean values obtained by Duinker and Kramer in 1975 by polarographic analysis in the vicinity of the Rhine estuary (ppb) are given in table 4.

Table 4

	Mean	Range
Zn	9.9	3 - 20
Cd	0.20	0.10 - 0.30
Pb	2.5	1.7 - 3.3
Cu	1.7	1.0 - 2.5

These data were obtained at pH 3 and should be compared to column (II) in table 2.

Abdullah and Royle (1972) report polarographic results after preconcentration on chelating resin for mean values (10 samples) collected in the North Sea (table 5). The results again have to be compared with the data of column (II) of table 2 (ppb).

In 1973, Dutton and Jefferies, using atomic absorption spectroscopy after extraction with APDC-MIBK (ammonium pyrrolidine dithiocarbamate-methylisobutylketone)give the following values (ppb) for North Sea samples collected in May-June 1971 in a region rather close to the one investigated where we obtained the results quoted table 2 :

	Mean	Range
Zn	6.3	3 - 16
Cd	0.5	0.1 - 6.2
Pb	-	-
Cu	1.4	1 - 3

Table 5

		Mean	Range
Liverpool Bay	Zn	11.86	2.3 - 47.6
	Cd	0.27	0.14 - 0.74
	Pb	1.74	0.66 - 4.17
	Cu	1.45	0.30 - 3.03
Tardigan Bay	Zn	7.46	3.6 - 19.6
	Cd	1.11	0.50 - 2.41
	Pb	2.24	1.12 - 3.53
	Cu	1.72	0.98 - 4.02
Bristol Channel	Zn	10	3.6 - 21.4
	Cd	1.13	0.28 - 4.20
	Pb	1.2	0.40 - 5.00
	Cu	2.10	1.00 - 4.70

More recently, Burda et al.(1978) found at station 60°00'N, 0°30'E in the North Sea, after concentration on chelating resin and analysis by fluorescence : Zn 5.7 ppb, Pb 1.2 ppb, Cu 2.7 ppb (mean of 3 samples).

These results are difficult to compare to those of table 2 , as is with those of Abdullah et al., Dutton et al., because of the extraction or preconcentration techniques used. However they should also be compared in first analysis with column (II) of table 2.

Valenta et al.(1977) find at 13 km off the Island of Walcheren, probably in 1976, using anodic stripping for Cd : 0.028 ppb, Pb : 0.077 ppb, Cu : 1.22 ppb.

Although all these informations fall practically within the range of the determinations given in table 2 or are within the same order of magnitude, there is a rather wide scattering of the results indicating either unproper sampling or analytical techniques, correct measurements but referring to metals involved in different complexes or speciation, seasonal changes, horizontal inhomogeneity of water, effects related to biological activities (plankton - blooms, etc), local effects because of river discharge, dumping, atmospheric effects related to rain, transport of airborn material, etc.

Only long temporal series, correlated to other major events in the ecosystem will allow to understand the meaning of these fluctuations, provided proper intercalibration is carried out to ascertain the funda-

mental equivalent validity of the different methods actually used not only in the analytical chemistry laboratory but on board the ships used to collect the samples.

3.2.- METALS IN SUSPENDED MATTER

After calcination under microwave activated oxygen, the material soluble in suprapure concentrated HCl is analysed by the same techniques at sea-water ; 70% of Sb being lost during ashing, there is no reason to adjust the NaCl concentration. The results of table 6 refer to samples collected in September, October and November 1978 as reported for the data on the metals in solution.

Table 6

Concentration (ppm)
(Dry weight)

		Zn	Cd	Pb	Cu
September 1978	Mean	202	1.40	42	32
	Range	48 - 500	0.40 - 2.70	12 - 115	13 - 66
October 1978	Mean	130	0.78	35	38
	Range	13 - 300	0.30 - 1.70	3 - 110	22 - 75
November 1978	Mean	107	0.80	30	32
	Range	21 - 240	0.40 - 2.00	1 - 60	4 - 70

The values are of the same order of magnitude as those reported by Duinker and Nolting in 1973 as minimum values in the region of the Scheldt and Rhine estuaries :

Zn : 100 - 200 µg/g Cu : 30 - 50 µg/g	minimum values
Zn : 4800 µg/g Cu : 800 - 1000 µg/g	maximum values

The maximum values observed by Duinker and Nolting are probably due to the input of the Rhine.

Conclusions

Anodic stripping voltammetry is well suited for sea-water trace metal analysis ; it further allows to have an insight into chemical speciation however rudimentary : ionic species, weakly bound ones, strongly bound ones, by only changing one parameter, that is pH. This subdivision of the total metal content might prove very usefull to biologists if some differences appear at the toxicity level, or rate of accumulation of heavy metals, depending on a crude knowledge of speciation. This is the case as indicated in the paper of Bouquegneau et al. on "The fate of heavy metals in aquatic food chains, uptake and release of Hg and Cd by some marine organisms, role of metallothioneins" in this same issue.

It is obvious that atomic absorption analysis after extraction by solvents or by chromatography on chelating ion exchange resins will give different results.

This together with the problem of uniformization of sampling techniques are extremely important points ; intercalibration, choice of analytical method, preparation of standardized samples, etc are topics about which chemists interested in marine chemistry and related problems should come to a world-wide agreement.

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Benthic studies of the Southern Bight of the North Sea and its adjacent continental estuaries

Progress Report I

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Introduction

The North Sea and its estuaries are amongst the best known areas in the world as far as benthos is concerned. Nevertheless, there is still much basic knowledge missing. The efforts of the marine biology group of our institute are concentrated on several basic aspects of benthic ecosystems, including the systematics of marine nematodes, the ecology of meio- and macrobenthos, the measurement of benthic activity and the interactions between benthic systems and the overlying water column. This report synthesizes some of the studies that have been made during the last three years in the field of benthic ecology.

In investigations of the North Sea our efforts are directed mostly towards the measurement of structural parameters of populations and community organisation, such as density, biomass and diversity, because these parameters yield a maximum amount of information per unit effort. Because our research originated as part of a system analysis programme, the rates of change in the values of the state variables were required to characterize the system. However, our poor knowledge of benthic microbial processes and inadequate logistic support on board, our research

vessel forced us to abandon the idea of direct measurement of these fluxes; instead we now try to infer them from the proportionality which, within certain limits, exists between the magnitude of the structural parameters and the fluxes within the system. Though this approach is valid for the meio- and macrobenthic compartments of the system, there remains a need for a set of holistic measures to characterize the overall behaviour of the benthic system. This is not within the scope of our North Sea research for the moment, but methods for the measurement of aerobic community respiration and nutrient regeneration are now being developed in lagoonal situations (the Sluice Dock of Ostend) and will hopefully be applied to the North Sea in near future.

Benthic communities are more difficult to sample than planktonic communities but have some important advantages as the benthos is a stabler system in both the temporal and spatial domain. For sampling purposes it can be considered as being two-dimensional in most situations and types of problems. This eliminates the necessity to sample the vertical dimension which requires a large additional effort in order to avoid aliasing, giving spurious results in some situations (Platt & Denman, 1975). Patchiness in the horizontal plane is, at least in large areas of the North Sea, also less intense in the benthos than in the plankton. Analysis of the variance of benthic processes in the time domain as performed by e.g. spectral analysis can elucidate the periodicities in the system, but requires the establishment of long time series, a task not easilly fulfilled in marine situations. Consequently, such long time series ara rare and even for important or key species there are only a few census programs going on. The COST 47 project of the EEC will increase considerably the available data, but on the whole governmental agencies remain rather inhibited in their attitude towards such lengthy and costly programs.

The establishment of long time series is useful for purposes other than the characterization of the system in the time domain as well. The prediction of future states of ecological systems with the tools of system analysis has been reasonably successful for certain compartments but probably requires frequent monitoring to remain effective. However, it is doubtful whether such an approach will be successful when characteristics of single biological populations are to be predicted. This is not

only because modelling techniques are inadequate but it is also inherent in the nature of biological interactions which are stochastic phenomena with a highly variable outcome or indeed no directed outcome at all. When prediction cannot be based on dynamic model, it can only depend on a statistical model (Poole, 1978), and the estimation of the parameters of such models requires large numbers of accurate observations. The recognition of this problem and its implications for the management of marine systems led us to a high frequency monitoring program of a meiobenthic community in brackish water which started in 1968 and is still being continued.

Although monitoring is a regular part of our North Sea studies now, earlier work in the Southern Bight was concentrated on the description of characteristic species-assemblages of both meio- and macrobenthos (Van Damme & Heip, 1977; Govaere et al., 1977). From these studies we now have basic information on the distribution of species and their abundance and biomass in this area. Additional base-line studies are concerned with a large area of accumulating sediments to the south-west of the mouth of the Western Scheldt where particulate material from this heavily polluted river is deposited. Large-scale harbour constructions risk to change the hydrodynamical regime of the area with possible redistribution of sediments. Other human activities with possible important consequences include the exploitation of sand banks in the region, which threatens to become increasingly important, and possible thermal and radioactive pollution by the French nuclear power plant at Gravelines at the entrance of the Channel.

Macrobenthos of the delta region in The Netherlands has been studied qualitatively by Wolff (1973), who made an extensive survey of the area. Efforts of our group are restricted to the hard-bodied meiofauna of three of the estuarine branches, Lake Grevelingen, the Eastern Scheldt and the Western Scheldt. These investigations started only recently and a number of quantitative samples has been collected in collaboration with several Dutch institutions (Rijkswaterstaat Vlissingen, Delta Institute of Hydrobiological Research Yerseke and Biological Research Group Ems-Dollard estuary in the north. The investigations are still in a descriptive phase but have allowed us to draw a fairly consistent picture of the meiofauna of these estuaries. In order to approach the meiobenthic

compartment dynamically the dominant species of nematodes and harpacticoid copepods from these areas are now being cultured in the laboratory in order to establish generation times, number of offspring, etc., in controlled conditions, with the eventual goal of obtaining an adequate picture of the energy flow through these populations.

Material and methods

SAMPLING

The localisation of the stations will be given per study area. In subtidal stations three macrofauna samples were taken with a 0.1 m^2 Van Veen grab. The material in each grab was immediately collected in a bucket, without sieving, and fixed with formalin to a final concentration of 4 %. In very shallow estuarine stations or stations exposed at low tide, samples were handcollected with plastic cores covering a surface of 77.8 cm^2, pushed 15 cm into the sediment. 15 cores were collected into 3 buckets on the spot.

In our earlier work, meiofauna samples were taken by subsampling a Van Veen grab. Two plastic cores covering a sufface area of 10.2 cm^2 were pushed through a small hatch in the upperside of the grab into the collected sediment. From April 1978 onwards a modified Reineck-boxcorer (Farris and Crezee, 1976) was used. Four subsamples were taken from each box-core. Two replicates for meiofauna were fixed with warm formalin (70° C) to a final concentration of 4 %. The two other cores for chemical and sediment analysis were immediately frozen.

At some stations samples were taken by SCUBA divers with the same 10.2 cm^2 inner surface plastic cores. The overlying water was removed gently and collected, and the cores were subdivided into 2 cm-slices and fixed. Reineck-cores from the same locality were also divided into 2 cm-slices to allow comparison.

In shallow water (~3.5 m) samples could be collected with a 'meio-sticker', a telescoping tube (max. length : 5.5 m) equiped with a head into which a plastic core can be screwed in. Inside the head, a valve-spring-combination opens when the tube is lowered and closes when the sample has been taken. (Govaere & Thielemans, in press).

In the laboratory the meiobenthos samples were elutriated from sand using the trough-method (Barnett, 1968; Heip, 1976a). The material was collected on sieves with mesh sizes of 250 µm and 38 µm.

The extraction of the organisms from muddy sediments from the smaller fraction was done using a density-gradient centrifugation technique (Bowen et al., 1972; de Jonge & Bouwman, 1977).

Macrobenthos samples were gently rinsed on a sieve with round meshes of 0.87 mm. All material was restored in formalin for further determination.

SYSTEMATICAL METHODOLOGY

Permanent benthos can be subdivided following Mare (1942) and Hulings and Gray (1971), into meiobenthos and macrobenthos. Members of the higher taxonomical groups Hydrozoa, Turbellaria, Nematoda, Gastrotricha, Oligochaeta, Polychaeta (interstitial forms), Mollusca, Harpacticoida, Ostracoda, Tardigrada and Halacarida are commonly considered to belong to the meiobenthos; young stages of larger Oligochaeta, Polychaeta and Mollusca are temporary meiobenthos (McIntyre, 1969).

In the meiobenthos, Nematoda and Harpacticoida are systematically studied. Of the macrobenthos, the Polychaeta, Mollusca, Crustacea (Mysidacea, Tanaidacea, Isopoda, Cumacea, Amphipoda, Decapoda) and Echinodermata were identified to species. Nemertinea, Oligochaeta and Phoronida were only counted.

BIOMASS

Meiofauna was weighed with an accuracy of 0.1 ug with a Mettler ME 22/BA 25 Microbalance. The organisms were transmitted into pre-dried small aluminum recipients. Each of those was put into a covered small petri-dish and dried again at 110° C for 2 hours. Thirty minutes after drying, the recipient was weighed.

Macrobenthic organisms were divided into size classes. From the length-measurements and the length-weight regressions calculated by Govaere (1978) for species of the Southern Bight, we obtained the wet weight and the ash-free dry weight per species.

SEDIMENT ANALYSIS

A subsample of the sediment was oven-dried at 110° C during 2 hours. After homogenization 25 g was used for further analysis. The gravel fraction was separated from the rest by a 2 mm-mesh size sieve. The sand-mud fraction was stirred mechanically for 20 min. over an 18-sieves set with diminishing mesh sizes (1000, 850, 710, 600, 500, 420, 355, 297, 250, 210, 180, 149, 125, 105, 90, 74, 63 and 53 µm).

The fraction remaining on each sieve was weighed with an accuracy of ± 10 µg and a cumulative f.d., using phi-units, was plotted. For classification of the sand fraction of the sediment the Wentworth-scale was used. The terminology for the degree of sorting of this fraction is similar to that used by Wolff (1973) and Govaere (1978).

Table 1

Wentworth scale			Sorting coefficient $\sigma\phi$	
ϕ-units	µm	Name	ϕ-units	Name
0 - 1	500 - 1000	coarse sand	0.35	very well sorted
1 - 2	250 - 500	medium sand	0.35 - 0.50	well sorted
2 - 3	125 - 250	fine sand	0.50 - 2.00	less well sorted
3 - 4	62 - 125	very fine sand	2.00	poorly sorted

MATHEMATICAL METHODS

All results are expressed with their standard error.

To measure species diversity H in samples we used the Brillouin formula (Pielou, 1975) :

$$H = \frac{1}{N} \log \frac{N!}{n_1\, n_2\, n_3 \ldots n_s}$$

where H is expressed in bits per individual, N is the total number of individuals, n_i the number of individuals belonging to i^{th} species ($i = 1, \ldots, s$).

Eveness e refers to the equitability of the allocation of individuals between the species. The lower the e, the higher is the dominance of one (or several) species in the sample. It must be borne in mind

that calculation of eveness depends on knowledge of the number of species in the community, and that when only a few species are present, sample estimates will be biased to too low values.

$$e = \frac{H}{H_{max}}$$

where e is the equitability or eveness (range : 0 to 1), H is the observed species diversity,

$$H_{max} = \log_2 S$$

where S is the observed number of species.

Results and discussion

THE BELGIAN COASTAL ZONE OF THE NORTH SEA

Localisation and co-ordinates of the sampling stations are given in fig. 1 and table 2. Three areas were investigated :

(1) A near coastal zone with the majority of 18 regularly monitored stations concentrated along the Belgian eastern coast (Ostend - Knokke) and the mouth of the Scheldt estuary.

(2) A zone in a sand exploitation-area (ZB-stations)

(3) A near coastal zone along the Belgian west coast (De Panne - French border), which is a wintering area of the common scoter, *Melanitta nigra* L. (z-stations) and where water from the Channel is entering the North Sea.

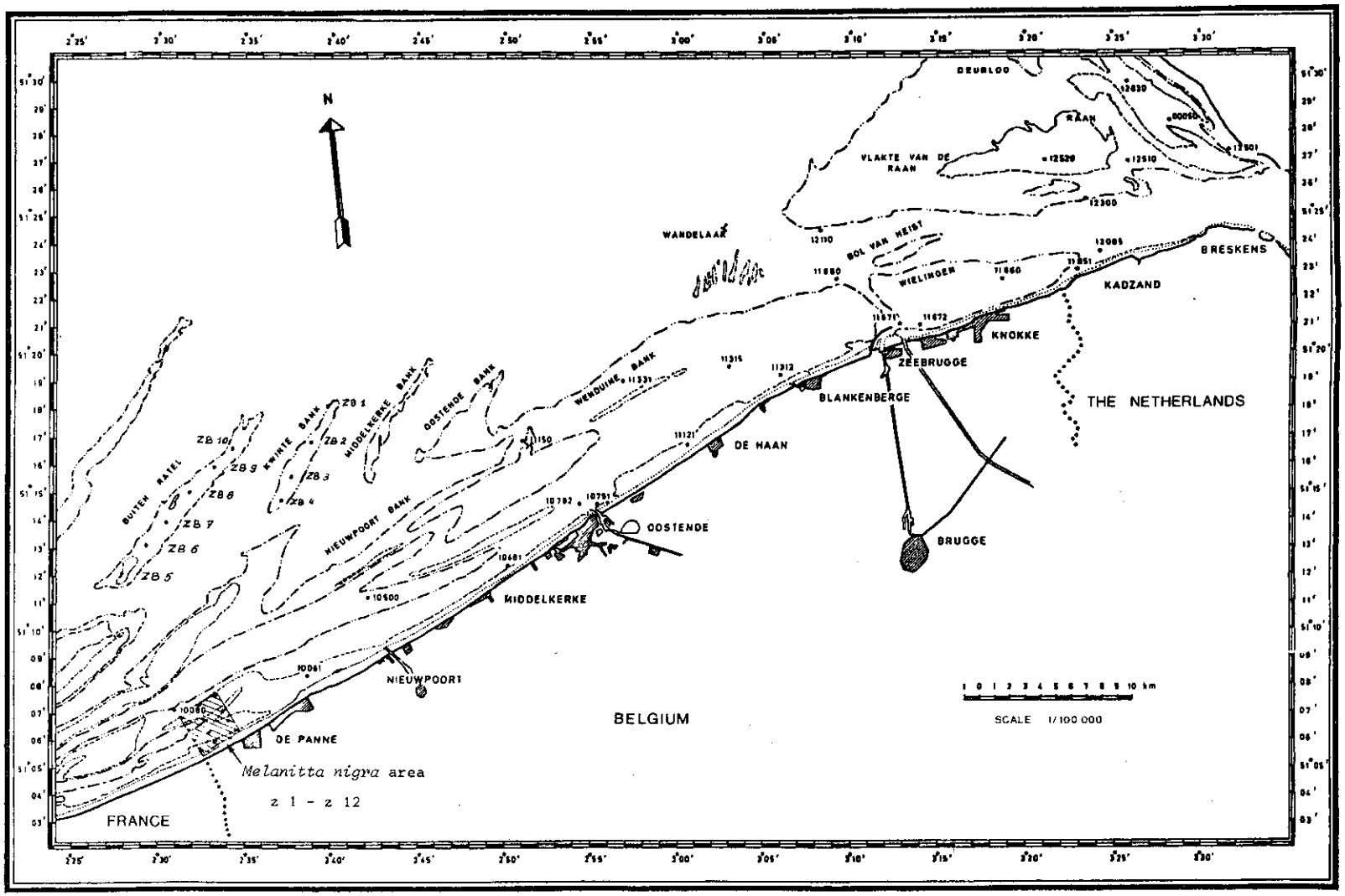

fig. 1.

Localisation of the stations in the Belgian coastal zone

Table 2

Co-ordinates of the stations in the Belgian coastal zone and the mouth of the Scheldt Estuary

Near coastal zone stations		
	N lat.	E long.
10080	51° 07' 10"	02° 35' 00"
10061	51° 08' 21"	02° 31' 40"
10500	51° 11' 06"	02° 42' 09"
10481	51° 12' 20"	02° 50' 14"
11150	51° 16' 32"	02° 51' 08"
10971	51° 14' 35"	02° 55' 25"
10792*	51° 14' 25"	02° 54' 50"
11331	51° 19' 01"	02° 56' 51"
11121	51° 16' 40"	03° 00' 30"
11315	51° 19' 30"	03° 03' 00"
11312	51° 19' 10"	03° 06' 00"
12110*	51° 24' 04"	03° 07' 00"
11880	51° 22' 38"	03° 09' 15"
11671*	51° 21' 00"	03° 12' 40"
11672	51° 21' 00"	03° 14' 00"
11860	51° 22' 38"	03° 18' 41"
11851	51° 23' 02"	03° 22' 56"
12085*	51° 23' 40"	03° 24' 20"
12300	51° 25' 31"	03° 23' 24"
12520*	51° 26' 58"	03° 21' 02"
12510	51° 26' 55"	03° 21' 45"
12830	51° 29' 49"	03° 25' 45"
00050*	51° 28' 25"	03° 28' 07"
12501	51° 27' 17"	03° 31' 33"

Sandbank stations		
	N lat.	E long.
ZB 1	51° 17' 30"	02° 39' 30"
ZB 2	51° 16' 42"	02° 38' 57"
ZB 3	51° 15' 40"	02° 37' 40"
ZB 4	51° 14' 48"	02° 37' 08"
ZB 5	51° 12' 05"	02° 27' 52"
ZB 6	51° 13' 08"	02° 29' 20"
ZB 7	51° 14' 08"	02° 30' 30"
ZB 8	51° 14' 57"	02° 31' 38"
ZB 9	51° 15' 45"	02° 32' 40"
ZB 10	51° 16' 28"	02° 33' 58"
Melanitta nigra L. stations		
z 1	51° 05' 50"	02° 32' 30"
z 2	51° 06' 10"	02° 33' 40"
z 3	51° 06' 25"	02° 34' 40"
z 4	51° 06' 20"	02° 32' 10"
z 5	51° 06' 40"	02° 33' 10"
z 6	51° 06' 55"	02° 34' 00"
z 7	51° 06' 50"	02° 31' 35"
z 8	51° 07' 15"	02° 32' 50"
z 9	51° 07' 25"	02° 33' 30"
z 10	51° 07' 20"	02° 31' 20"
z 11	51° 07' 40"	02° 32' 25"
z 12	51° 08' 00"	02° 33' 20"

* Samples taken in summer 1976 only. The 18 other stations were sampled in June-September 1977 and March-April - June - September 1978.

Sediment analysis

The mean values for the sediment analysis of samples from six cruises covering all 18 near-shore stations is given in table 3. The stations can be divided into 3 groups (table 4).

Table 3

Medium grain size (ϕ-units and mm), skewness Sk_q, sorting $\sigma\phi$ of the sandfraction and the mud- and gravelpercentage per station. Mean values of six campaigns : 06-09/1977; 03-04-06-09/1978.

Station	Med. grain size ϕ-units	mm	$\sigma\phi$	Sk_q	% mud	% gravel
10061	2.484	0.193	0.404	0.358	4.3	-
10080	2.100	0.239	0.381	0.297	0.3	1.3
10481	2.758	0.148	0.426	0.389	31.4	0.2
10500	2.501	0.177	0.411	0.289	22.7	2.5
10791	2.689	0.157	0.422	0.373	57.7	1.1
11121	2.528	0.174	0.413	0.347	14.2	-
11150	2.008	0.252	0.374	0.209	14.8	0.5
11312	2.751	0.149	0.426	0.382	61.8	-
11315	2.576	0.168	0.416	0.374	53.2	-
11331	2.992	0.134	0.433	0.333	61.3	-
11672	2.512	0.179	0.410	0.357	21.7	-
11851	2.823	0.129	0.435	0.390	59.1	0.1
11860	2.450	0.185	0.407	0.324	31.2	0.5
11880	2.451	0.202	0.385	0.265	54.7	2.2
12300	2.398	0.196	0.402	0.326	33.9	0.1
12501	2.347	0.198	0.401	0.341	2.9	-
12510	2.411	0.192	0.404	0.343	11.2	0.7
12830	2.507	0.180	0.410	0.327	15.1	1.7

Table 4

				Md (mm)	Mud (%)
(1)	Sand stations (n = 3)	< 5 %	mud-content	0.210	2.54
(2)	Muddy-sand stations (n = 8)	5 - 32 %	mud-content	0.180	20.29
(3)	Sandy-mud stations (n = 7)	> 32 %	mud-content	0.162	54.53

The mean medium grain size of the sand fraction (Md) decreases with increasing percentage of mud. The muddy-sand and the sandy-mud stations are mostly concentrated along the eastern coast. The sediment of the stations of the other areas (ZB- and z-st.) consists mostly of fine sand with a low mud-content.

An analysis of variance of these data shows that the medium grain size is stable in time (table 5). This is not true for the mud-content.

Table 5

Anova table for the medium grain size of the sandfraction, mud-content, real and transformed values of the number of nematodes for the 18 monitored stations

Source of variation	df	Mean grain size				Mud-content			
		SS	MS	Fs		SS	MS	Fs	
Date	3	0.003	0.001	0.75	n.s.	5752	1917	4.27	⁎
Station	17	0.073	0.004	3.21	⁎	30912	1818	4.05	⁎
Error	51	0.068	0.001			22847	449		
Total	71	0.143				59561			

Source of variation	df	Number of Nematodes: Real values				Number of Nematodes: Transformed log (N + 1) values			
		SS	MS	Fs		SS	MS	Fs	
Date	3	$36\ 10^6$	$12\ 10^6$	4.06	⁎	2.1090	0.7030	2.07	n.s.
Station	17	$82\ 10^6$	$5\ 10^6$	1.64	n.s.	10.5042	0.6179	1.82	n.s.
Error	51	$15\ 10^7$	$3\ 10^6$			17.2876	0.3390		
Total	71	$27\ 10^7$				29.9007			

⁎ Significant at 1 % level

Meiobenthos

Meiobenthos was only studied at the near coastal zone in the east.

Taxonomic group diversity

The most abundant taxon is the Nematoda followed by the Copepoda Harpacticoida, Polychaeta, Turbellaria and occasionally Ostracoda and Halacarida. The mean group-diversity is relatively low (table 6). This

Table 6

Mean number of higher taxonomic groups present per station group and per sampling series

	July 76	June 77	Sept. 78	April 78	Mean + St. E.
Sand	3.5	3.7	4.3	3.0	3.6 ± 0.3
< 32 % mud	3.0	2.6	3.5	2.4	2.9 ± 0.2
> 32 % mud	2.0	3.0	3.1	2.4	2.6 ± 0.3
Mean	2.7	2.9	3.2	2.8	3.0 ± 0.1

low diversity indicates the high stress conditions of this shallow zone with high velocity and turbidity pollution effects, etc...

In the sand-stations the diversity is always higher than in mud-stations. The mean diversity for the coastal area is 3.0 with the highest value in late summer. This value is slightly higher than the one found by Van Damme and Heip (1977) for the same zone. They found an average of 1.5-2.3 taxonomic groups in the winter-summer periods over 5 years.

Density

The mean density of the Nematoda over the four sampling periods is 1.6 10^6 ind..m^{-2} or 97 % of the total meiofauna (table 7). They are followed by Harpacticoid Copepods (24,000 ind. m^{-2} or 1.14 %) and Polychaeta (20,000 ind. m^{-2} or 0.92 %).

Table 7

Nematoda

Density per station (ind./10 cm^2) and mean density and biomass per sample serie ($\mu g/10\ cm^2$)

Station	June 1977	Sept. 1977	March 1978	April 1978	Mean ± St. Err.
10061	770	1790	560	430	890 ± 310
10080	1230	210	440	110	500 ± 250
10481	3680	5370	1420	960	2860 ± 1030
10500	4360	2710	1220	700	2250 ± 820
10791	2770	2450	90	3610	2230 ± 750
11121	3140	4280	1050	770	2310 ± 840
11150	110	80	340	290	200 ± 70
11312	2420	6240	170	470	2320 ± 1400
11315	760	1440	410	700	830 ± 220
11331	180	360	170	110	300 ± 50
11672	250	7660	20	860	2200 ± 1820
11851	1680	5180	650	4000	2880 ± 1040
11860	80	330	2320	3750	1620 ± 870
11880	410	320	710	10	360 ± 140
12300	1410	90	190	2170	960 ± 500
12501	90	3040	1430	1420	1500 ± 600
12510	40	4390	300	460	1300 ± 1040
12830	1870	5560	8750	700	4220 ± 1830
Mean	1400	2860	1150	1200	1650
St. Err.	330	580	470	300	260
Biomass	840	1720	690	720	990

Analysis of variance on the log (N + 1)transformed data shows that within station variance is larger than between station variance, and that these populations are in this sense stable both in space and time. However, when untransformed data are used the analysis shows a significant influence of time, and in fact density is higher in September than in other months (table 5). The highest densities were found in muddy sand stations (mean = 2.1 10^6 ind. m^{-2}). No correlation was found between density and the percentage of mud in the sediment.

Vertical distribution was investigated for three stations : 11315, 11851 and 12501, both on SCUBA samples and on Reineck-boxcore samples. Fig. 2 shows the vertical profile of nematode density per 2 cm-layer.

In the mud-stations 11315 and 11851 (resp. 53 % and 59 % mud) the majority of the nematodes is found in the upper 4 cm layer (93-99 %).

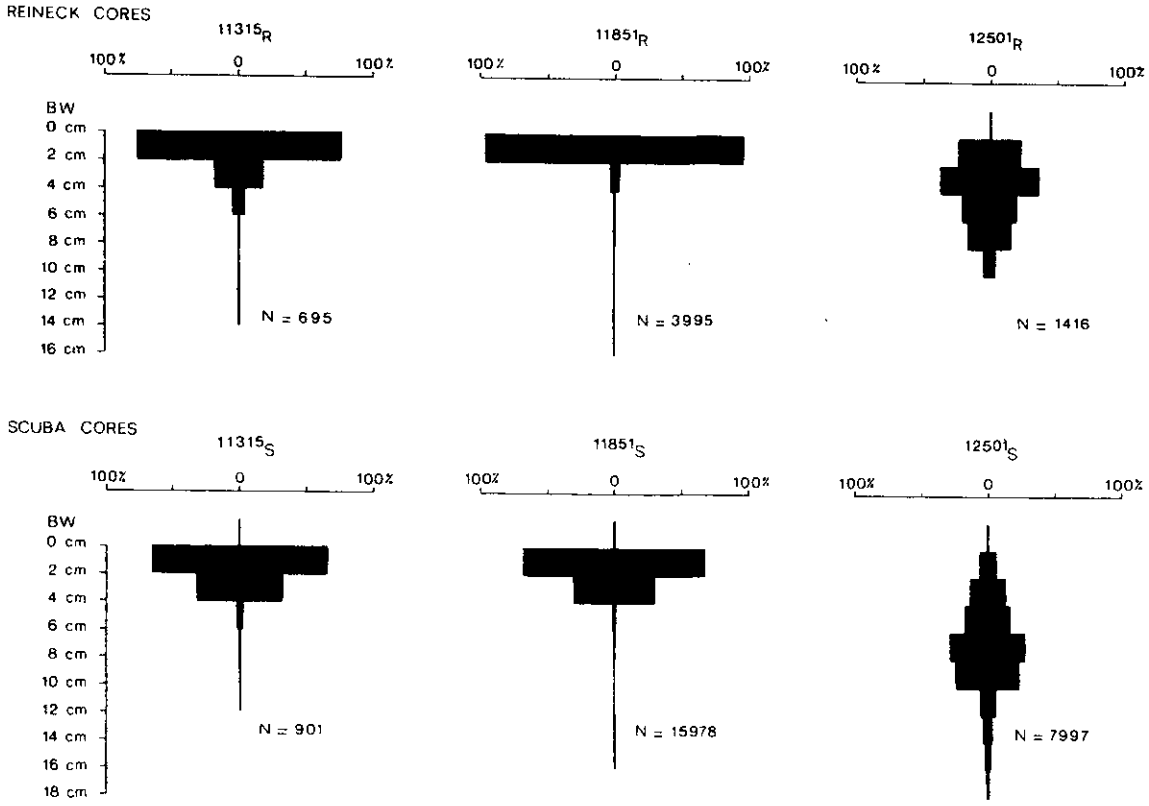

fig. 2.

Comparison of vertical distribution of Nematoda between REINECK-samples (R) and SCUBA-samples (S) at three coastal stations (N : number of individuals per 10 cm^2)

The sediment of station 12501 is fine sand with a medium diameter of 0.199 mm. In this typical sand station the nematodes penetrate the deeper layers in considerable numbers (table 8). This agrees with recent findings of several authors (e.g. Heip et al., 1977) who found non-negligible numbers of nematodes even at more than 20 cm depth), and contrasts with the opinion commonly held only a few years ago that nematode numbers below 4-5 cm are negligible even in sandy semiments.

Table 8

Comparison of the vertical distribution of Nematoda in different areas (percentage of total)

	JUARIO (1975) German Bight silty sand	BISSCHOP (1977) Southern Bight muddy sand	HOLVOET (1978) Western Scheldt muddy sand	This study	
				Mudst.	Sandst.
0 - 2 cm	70 - 86	50 - 68	63 - 69	65 - 96	6 - 23
2 - 4 cm	9 - 21	11 - 24	18 - 26	2 - 32	13 - 37
4 - 6 cm	5 - 12[1]	7 - 39	7 - 9	0.2 - 4	17 - 20
6 - 8 cm		1 - 10	2 - 5[2]	0.2 - 0.6	16 - 28
8 - 10 cm				0.1 - 0.2	5 - 24

1. 4 - 7 cm
2. 6 - 10 cm

Biomass

Biomass is not only dependent on density, but also on speciescomposition and on the reproductive state of the population. The mean biomass of an individual nematode in this area is 0.6 + 0.1 µg dry weight per individual (range 0.2 - 1.35 µg dwt; Bisschop, 1977). The mean biomass per sampling period is given in table 7 and the overall mean for the 4 cruises is nearly 1 g dwt. m^{-2}. This value is close to that found by Van Damme and Heip (1977) for this zone (± 1.5 g dwt. m^{-2}).

Species composition

The numbers of species is higher in sand-stations (20-30 species) than in mud-stations (4-12 species). Nematode communities in mud are

dominated by the *Sabatieria pulchra*-group (up to 95 %), *Daptonema tenuispiculum* (up to 71 %), *Paramicrolaimus conothelis* and species belonging to the genera *Theristus* and *Monhystera*. Their importance decreases in the sand-stations and other species become more important, such as *Spirinia parasitifera, Richtersia inaequalis, Ascolaimus elongatus, Microlaimus marinus, Tubolaimoides tenuicaudatus* and *Enoplolaimus propinquus*. (see table 9).

Table 9

Nematoda of the Southern Bight
Density (♂,♀, juveniles, damaged and total) and Feedingtype

	♂	♀	juv.	D	Tot.	Ft[3]
Aegialolaimus sabuliccla Allgen, 1933	9	8	20		37	1A
Odontophora armata Allgen, 1929	9	20	25		54	1B
Odontophora Bütschli, 1874 *spec.*	1	19	33		53	1B
Leptolaimus de Man, 1876 *spec.*	4	1	2		7	1A
Dagda bipapillata Southern, 1914	1				1	2A
Dagda Southern, 1914 *spec.*			1		1	2A
Camacolaimus longicaudatus de Man, 1922			2		2	2A
Camacolaimus de Man, 1889 *spec.*	1		2		3	2A
Terschellingia longicaudata de Man, 1880		1			1	1A
Metalinhomoeus de Man, 1907 *spec.*	2		2		4	1B
Rhadinema flexile Cobb, 1920	1	1	1	1	4	2B
Tubolaimoides tenuicaudatus Allgen, 1934	3	36	14		53	2A
Linhomoeus Bastian, 1865 *spec.*			1		1	2A
Eleutherolaimus Filipjev, 1922 *spec.*	1		4		5	1B
Sphaerolaimus Bastian, 1865 *spec. 1* [1]	1				1	2B
Sphaerolaimus Bastian, 1865 *spec. 2* [1]			1		1	2B
Cylindrotheristus longicaudatus Filipjev, 1922	1	4	15		19	1B
Cylindrotheristus normandicus de Man, 1880	6	9	25	1	41	1B
Daptonema tenuispiculum (Ditlevsen, 1918) Lorenzen, 1977	172	141	72		385	1B
Monhystera Bastian, 1865 *spec.*	39	8	78		125	1B
Paramonhystera Steiner, 1916 *spec.*	1	2			3	1B
Theristus mirabilis De Coninck & Stekhoven, 1933	12	13	26		51	1B
Theristus parasetosus De Coninck & Stekhoven, 1933	1				1	1B
Theristus Bastian, 1865 *spec.*	31	19	105		155	1B
Cobbia de Man, 1907 *spec.*	1				1	2A
Xyala striata Cobb, 1920		1			1	1B
Cyartonema Cobb, 1920 *spec.* [2]	3	1	8		12	1B
Onyx perfectus Riemann, 1966	1	1	6		8	2A
Onyx Cobb, 1920 *spec.*		4	13		17	2A

Table 9

(continuation)

	♂	♀	juv.	D	Tot.	Ft[3]
Spirinia parasitifera Bastian, 1865	3	3	11	4	21	2A
Spirinia Gerlach, 1963 *spec.*			5		5	2A
Microlaimus honestus de Man, 1922	2	2	11		15	2A
Microlaimus marinus Schulz, 1932	13	5	39		57	2A
Microlaimus de Man, 1922 *spec.*	6	13	25		44	2A
Paramicrolaimus conothelis Lorenzen, 1973	35	28	115		178	2A
Desmodora de Man, 1889		1			1	2A
Monoposthia mirabilis Schulz, 1932		1	2		3	2A
Monoposthia de Man, 1889 *spec.*		1			1	2A
Richtersia inaequalis Riemann, 1966	1	2	16	1	20	1B
Richtersia Steiner, 1916 *spec.*	2	7	36	3	45	1B
Sabatieria Rouville, 1933 *spec.*	204	328	477		1009	1B
Dichromadora hyalocheile De Coninck & Stekhoven, 1933	9	5	1		15	2A
Dichromadora Kreis, 1929 *spec.*	1	1	1		3	2A
Neochromadora poecilosoma Mickoletzky, 1924	1	1	1		3	2A
Neochromadora quinquepapillata Stekhoven, 1935	13	10	5		28	2A
Chromadorina Filipjev, 1918 *spec.*	2	3	8		13	2A
Prochromadorella Mickoletzky, 1924 *spec.*	1				1	2A
Paralongicyatholaimus macramphis Lorenzen, 1972	3	2	3		8	2A
Anticoma Bastian, 1865 *spec.*			2		2	1A
Halalaimus longicaudatus Filipjev, 1927			1		1	1A
Halalaimus de Man, 1888 *spec.*	8	11	23	2	44	1A
Enoploides Ssaveljev, 1912 *spec.*			5		5	2B
Enoplolaimus propinquus de Man, 1922	1	2	1		4	2B
Viscosia viscosa Bastian, 1865	3	2	11		16	1B
Viscosia de Man, 1890 *spec.*	11	2	42	3	58	1B
Fam. Chromadoridae Filipjev, 1917	8	12	23	3	46	-
Not identified, damaged species	6	4	67	45		

1. *Sphaerolaimus* Bastian, 1865 *spec. 1* : aff. *S. makrolasius* Schulz, 1932
   spec. 2 : aff. *S. ostrae* Filipjev, 1918

2. *Cyartonema* Cobb, 1920 *spec.* : aff. *C. flexile* Cobb, 1920
   aff. *C. germanicum* Juario, 1972

3. Ft = Feeding type
   1A : Selective deposit feeders
   1B : Non-selective deposit feeders
   2A : Epigrowth feeders
   2B : Omnivorous with capacity for predation and predators

Macrobenthos

The macrobenthic fauna was studied in three zones :

- Zone 1 : The near coastal zone and the mouth of the Scheldt estuary

(Vanosmael, 1977). In this zone, monitoring of 18 stations is still going on.

- Zone 2 : Two sandbanks, in an exploited and a non-exploited zone, were compared (Rappé, 1978).
- Zone 3 : A wintering-area of the common scoter, *Melanitta nigra* L. (Van Steen, 1978).

Zone 1 : The near coastal zone

Density and Biomass

Density varies between 80 ind. m^{-2} (st. 11671) and 31000 ind. m^{-2} (st. 12085) (table 10). In this last station and in st. 00050 the high density is due to the abundant mollusc *Mysella bidentata*. In the other stations, the most abundant taxon is generally the Polychaeta.

Out of 82 species found the most frequent are *Cistena cylindraria, Modiolus modiolus, Mysella bidentata, Nephtys cirrosa, N. hombergii, Tharyx marioni* and *Abra alba*. They were found in more than 50 % of the 40 replicates (table 11).

Biomass is calculated by means of species-specific regression curves between length and size (Govaere, 1978). The highest values are 42.67 g and 21.00 g ash free dry weight m^{-2} (resp. in st. 12085 and 00050), the lowest value is in st. 11671 with 0.004 g ash free dwt. m^{-2}. *Nephtys* spp., *Cystena cylindraria, Macoma baltica* and *Abra alba* are the most important species in terms of biomass.

Species diversity is quite stable (mean H = 2.1), the high dominance of *C. cylindraria* and *M. bidentata* is reflected in the eveness value of some stations (see also table 10).

Similarity

Using the Czekanowski-index for continuous data to study the similarity between replicates and between stations, and using the Mc.Connaughy-index for species affinity, Vanosmael (1977) found the macrofauna of replicates from the same station to be quite similar, and a rather high homogeneity of the macrofauna species composition over the whole area.

Table 10

Macrobenthos of the coastal zone of the Southern Bight
Density per taxonomical group and total density (ind./m^2), biomass in wet weight (g ww m^{-2}) and ash free dry weight (g Adwt m^{-2}), diversity H and evenness e per station

Station	Polychaeta	Mollusca	Crustacea	Echinodermata	Others	Total	g ww m^{-2}	g Adwt m^{-2}	H	e
10791	210	30	20	0	0	260	4.20	0.35	2.30	0.75
11851	1350	520	20	0	340	1830	24.55	1.75	2.01	0.45
12520	1400	130	10	0	0	1540	1.55	1.30	2.20	0.37
12501	360	520	160	3	160	1200	5.35	0.65	2.51	0.69
11671	20	50	20	0	0	80	0.05	0.004	0.80	0.63
12110	1160	120	70	3	0	1350	12.00	1.20	2.50	0.67
11331	60	110	10	0	0	180	1.25	0.15	2.05	0.83
11121	80	30	30	0	0	140	2.60	0.20	2.84	0.94
10972	1350	170	30	3	10	1570	18.65	1.50	2.71	0.65
12085	5960	24580	10	0	230	30780	1046.75	42.65	0.89	0.24
11315	110	130	20	0	0	260	8.95	0.45	2.23	0.79
11880	2380	700	10	0	310	3400	23.10	1.55	1.49	0.39
00050	3800	5630	100	5	190	9720	228.65	21.00	2.64	0.53
Mean	1400	2520	40	1	100	4020	106.00	5.60	2.10	0.61
St. Err.	490	1880	10	0.5	40	2340	80.20	3.40	0.18	0.06

Table 11

Macrobenthos of the Southern Bight
Absolute number and frequency per species for 40 replicates

Species	Number	Frequency	Species	Number	Frequency
POLYCHAETA			MOLLUSCA		
Harmothoe lunulata	90	2	*Modiolus modiolus*	618	29
Harmothoe ljunglmani	2	1	*Mysella bidentata*	9163	29
Lagisca extenuata	6	2	*Montacuta ferruginosa*	31	4
Pholoe minuta	68	4	*Cerastoderma edule*	14	6
Sthenelais boa	5	2	*Venerupis pullastra*	1	1
Eteone longa	90	9	*Petricola pholadiformis*	1	1
Eteone flava	1	1	*Donax vittatus*	9	7
Hesionura augeneri	38	2	*Macoma balthica*	23	11
Anaitides mucosa	161	5	*Tellina fabula*	10	1
Eumida sanguinea	335	5	*Tellina tenuis*	3	3
Microphthalmus similis	20	3	*Abra alba*	370	21
Gyptis capensis	4	1	*Spisula solida*	4	2
Autolytus prolifer	4	1	*Spisula elliptica*	2	1
Autolytus edwardsi	1	1	*Sphenia binghami*	3	3
Websterinereis glauca	3	2	*Thracia papyracea*	1	1
Eunereis longissima	13	2	CRUSTACEA		
Nephtys cirrosa	95	21	*Crangon crangon*	12	10
Nephtys hombergii	92	21	*Carcinus moenas*	11	1
Nephtys caeca	1	1	*Gastrosaccus spinifer*	34	4
Clycera capitata	4	1	*Mysida sp.*	1	1
Lumbrinereis latreilli	1	1	*Schistomysis kervillei*	4	3
Protodorvillea kefersteini	1	1	*Gammarus sp.*	10	4
Scoloplos armiger	219	17	*Melita obtusata*	4	1
Spio filicornis	169	17	*Nototropis falcatus*	7	5
Polydora ciliata	11	3	*Urothoe grimaldii*	5	3
Polydora pulchra	9	2	*Bathyporeia guilliamsoniana*	2	2
Pygospio elegans	8	6	*Bathyporeia elegans*	12	5
Spiophanes bombyx	73	13	*Microprotopus maculatus*	6	2
Polydora ligni	48	10	*Corophium sp.*	1	1
Scolelepis foliosa	1	1	*Corophium volutator*	1	1
Scolelepis bonnieri	7	4	*Pariambus typicus*	6	4
Magelona papillicornis	45	14	*Pseudocuma longicornis*	6	4
Caulleriella alata	1	1	*Diastylis rathkei*	39	15
Tharyx marioni	169	25	ECHINODERMATA		
Chaetozone setosa	1	1	*Ophiura texturata*	1	1
Ophelia limacina	5	3	*Ophiura albida*	1	1
Capitella capitata	148	18	*Echinocardium cordatum*	3	3
Capitomastus minimus	4	2	NEMERTINEA		
Notomastus latereeus	17	3	*Nemertinea spp.*	170	9
Heteromastus filiformis	79	12	PHORONIDA		
Cistena cylindraria	3484	33	*Phoronida spp.*	24	4
Lanice conchilega	309	15	OLIGOCHAETA		
Protodrillus sp.	10	2	*Oligochaeta spp.*	196	13
Saccocirrus papillocercus	2	1			

However, the classification of stations in relation to the sediment composition was not clear.

Zone 2 : Sandbank-zone

Two cruises (Oct. '77 and March '78) were to compare two sandbanks, the Buiten Ratelbank and the Kwintebank. A part of the latter is used for sand exploitation. The macrofauna study of this bank is still going on.

In eight stations the sediment consists of fine sand, but in station ZB 7 and ZB 1 we found medium and coarse sand respectively.

Density, biomass and species composition are quite similar on the two sandbanks, both in October and March. Mean density (biomass) for Oct. '77 and March '78 was resp. 200 (0.36 g) and 120 ind. m^{-2} (0.21 g ash free dwt. m^{-2}).

These values are rather low when compared with the surrounding area. The most abundant species were *Hesionura augeneri, Nephtys cirrosa, Spio filicornis, Scolelepis bonnieri, Ophelia limacina* (all Polychaeta), Archiannelida, the Mysid *Gastrosaccus spinifer,* the Tanaid *Tanaissus lilljeborgii* and the Amphipod *Bathyporeia elegans.* Diversity was also quite similar and mean values of 2.1 (October) and 1.5 (March) were found.

Zone 3 : Melanitta nigra-zone

Every year, from November till February a large population (up to 8500 ind.) of the common scoter, *Melanitta nigra* L., which feeds mainly on Mollusca, is wintering off the Belgian west coast.

Density of the macrobenthos varies between 190 and 26200 ind. m^{-2}, biomass between 0.6 and 33.3 g ash-free dwt. m^{-2}. Except for one station (z 8) the Mollusca were the most important taxon in terms of biomass. The most important species are *Tellina fabula, Abra alba, Mysella bidentata, Venerupis pullastra* and *Macoma balthica.*

Mean biomass for the whole area was 95.7 g wet weight m^{-2}. Based on the estimated daily food-consumption rate per scoter and the average number of days the population remains in this area, the food consumption during the winter period was estimated at 7.5-18 % of the stock.

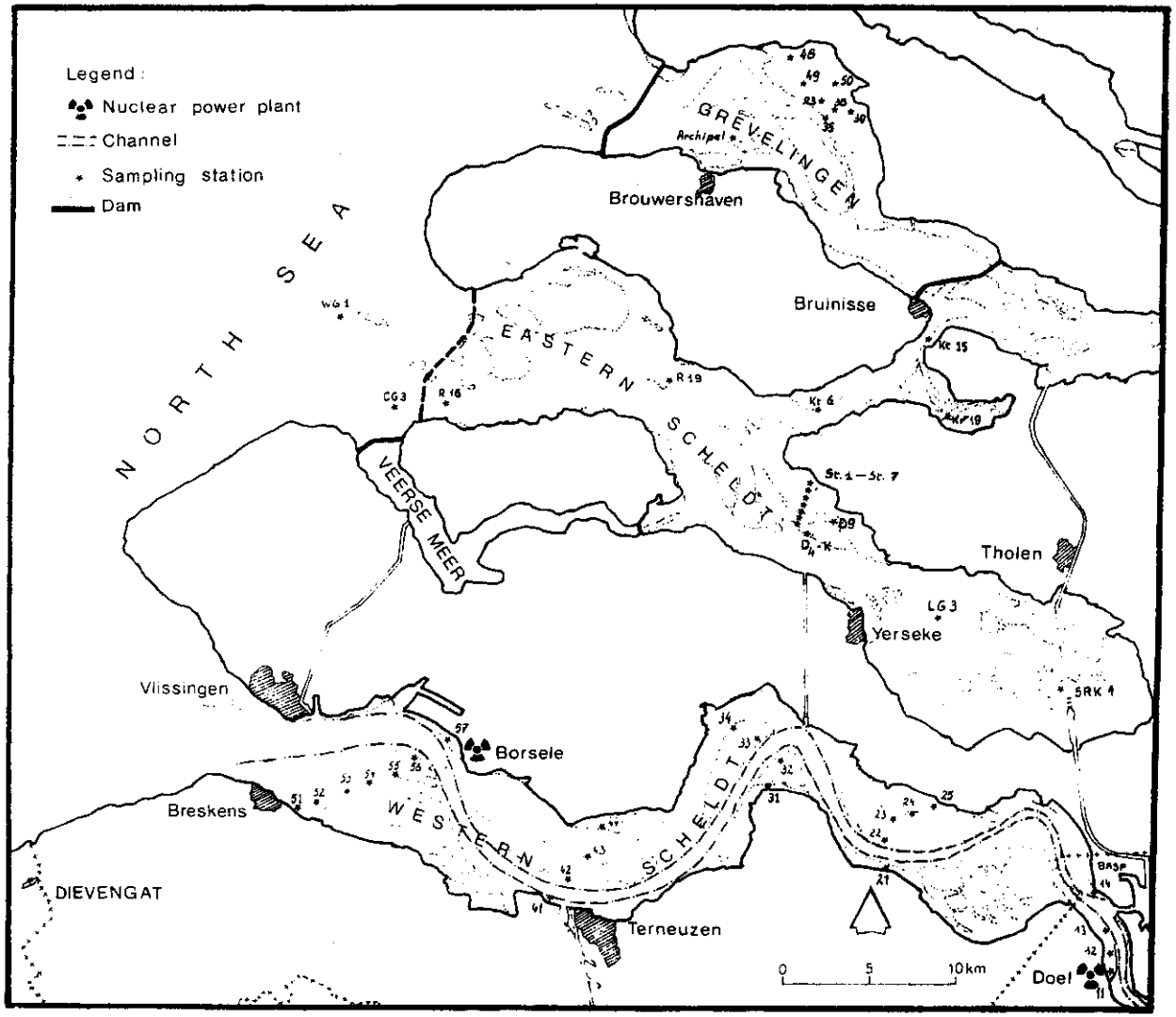

fig. 3.

Localisation of the stations in the Western Scheldt, Eastern Scheldt, Lake Grevelingen and Dievengat.

The delta region of the Scheldt, Meuse and Rhine in the Netherlands (fig. 3) has been the subject of intensive biological surveys since the establishment of the Delta Institute of Hydrobiological Research at Yerseke. One of the few gaps remains the study of hard-bodied meiofauna, although de Man already studied nematodes in this area at the beginning of the century. Some of the soft-bodied taxa were studied qualitatively by Den Hartog (e.g. 1966), Bilio (1966), Wolff et al. (1974) and Boaden (1976). Our data give the first quantitative information about Nematoda and Harpacticoida, but many of them are preliminary. These data are supplemented by data of the Ems-Dollard estuary in the north of the Netherlands.

The Western Scheldt estuary

Five transects from Doel (mesohaline) at the Belgian-Dutch border to Vlissingen at the mouth are currently being studied. Stations are situated mostly in the shallow sandy parts of the river; because the deeper channels are being frequently disturbed by the intense traffic and periodical dredging they do not allow the development of stable populations. Density of nematodes is extremely low at Doel (164 ind./10 cm^2 in 1978) whereas it varies between 1096 ind./10 cm^2 and 1691 ind./10 cm^2 in the other transects in September 1978, with a tendency of increasing towards the mouth (fig. 4). However, very high densities are found in the salt marsh of Saaftingen (WSS1 and WSS2) and in the river near it at Valkenisse. The density of all meiobenthic taxa is given in table 12, averaged for the transect, for September 1978, except for Doel, where a yearly average is given. The number of higher taxa increases towards the mouth of the river, from only 4 at Doel (Nematoda, Polychaeta, Oligochaeta and Copepoda) to 10 at Vlissingen, the only transect where Hydrozoa and Tardigrada are present. Harpacticoid density is rather low in all transects and varies between 1000 and 2000 ind./m^2, but up to 35,000 ind./m^2 are found in the salt marsh at Saaftingen and 21,000 ind./m^2 occur at the mouth. In this last transect there is a rich fauna with typical interstitial forms such as *Kliopsyllus constrictus*, *Paramesochra similis*, *Paraleptastacus espinulatus*, *Evansula pygmaea* and *Arenocaris bifida*. Other common

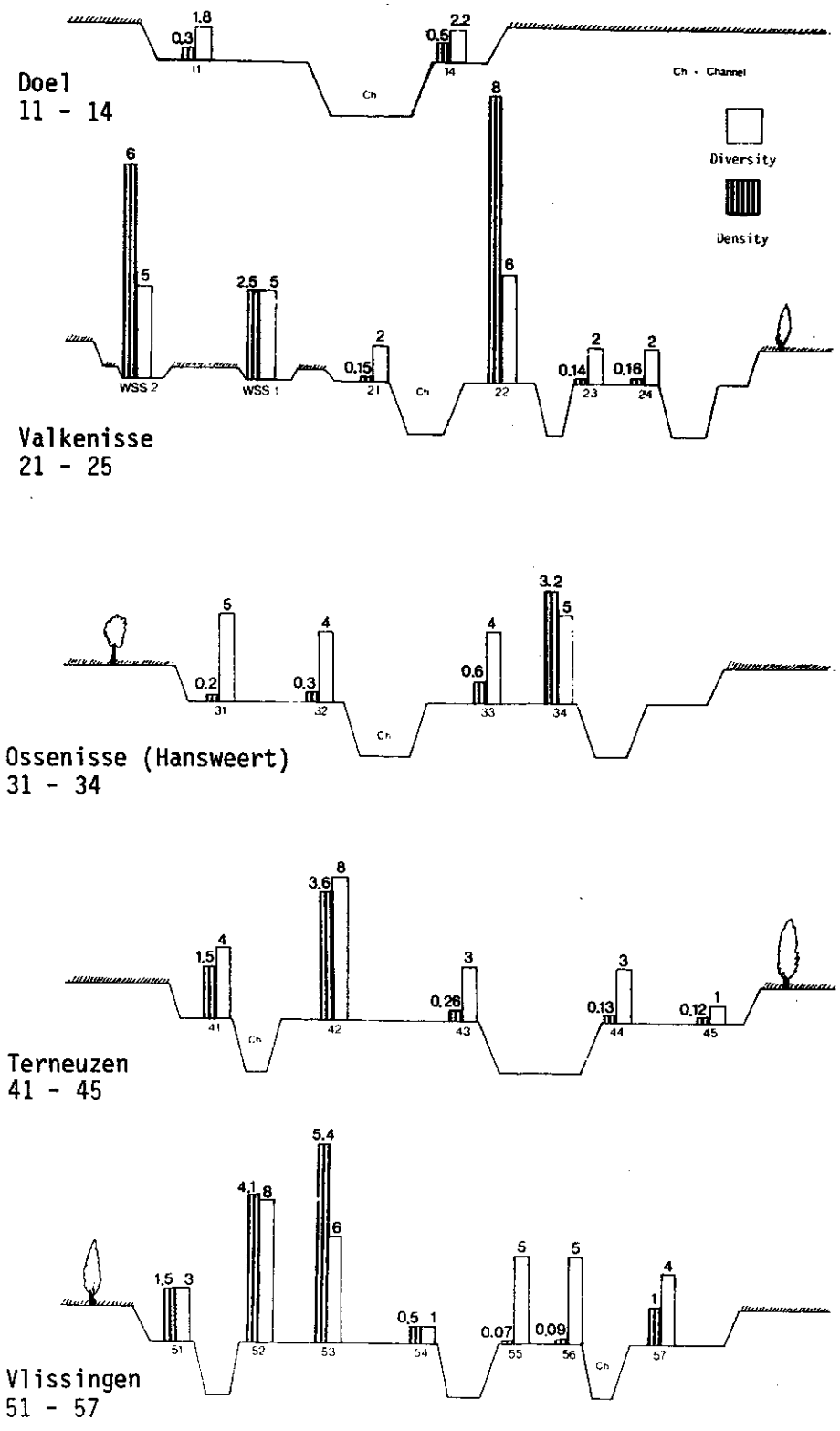

fig. 4.

Taxonomic group diversity and nematode density (ind. 10^6 m^{-2}) in the Western Scheldt Estuary

Table 12

Mean density (ind./10 cm^2) and average number of taxa per sample in five transects along the Western Scheldt estuary in September 1978

	Doel[1]	Valkenisse	Ossenisse	Terneuzen	Vlissingen
Hydrozoa	-	-	-	-	1.0
Turbellaria	-	3.3	6.8	1.5	6.3
Nematoda	164	2087	1096	1348	1691
Gastrotricha	-	-	3.8	6.0	50.9
Oligochaeta	1.0	5.8	1.8	1.5	6.1
Polychaeta	2.5	0.3	-	6.8	0.6
Mollusca	-	1.0	1.3	4.8	1.4
Harpacticoida	0.2	1.8	5.8	2.3	20.4
Ostracoda	-	5.3	0.3	7.3	6.0
Tardigrada	-	-	-	-	4.3
Total	178	2104	1115	1378	1788
Taxa per sample	2.2	3.0	4.0	4.3	4.4
Taxa per transect	4	7	7	8	10

1. Average over 1977-1978

species include *Canuella perplexa*, *Halectinosoma herdmani*, *H. gothiceps*, *Pseudobradya minor*, *P.* cf. *beduina*, *Tachidius discipes*, *Stenhelia palustris*, *Asellopsis intermedia* and *Euterpina acutifrons*. The same species, but in lower overall density, occur in the transects near Terneuzen and Ossenisse, whereas at Valkenisse only one species is present (*Stenhelia palustris*). In the salt marsh of Saaftingen only *Nannopus palustris*, *Stenhelia palustris* and *Platychelipus littoralis* were found in December 1978.

However, in the detailed study of the Doel transect by Holvoet (1978), harpacticoid copepods occurred, but only in 5 out of 64 samples taken at 9 stations on both sides of the river in 1977-1978. They belonged to only three species : *Asellopsis intermedia* (2 females at one station and one date), *Nitocra typica* (one male at one station and one date) and *Stenhelia palustris* (4 individuals at four stations and four dates). Mean nematode density over all these samples was 164,000 ind./m^2 , an extremely low figure. Density was consistently low at the BASF stations situated on the right bank near the BASF chemical plant, but fluctuated wildly at the WS stations situated near the outlet of the

thermal effluents from the nuclear power plant at Doel. Biomass was low as well (mean value 24 mg dwt./m^2 for all stations and samples), and so was diversity, with an average value of 1.5 bits, but a significantly higher diversity at the BASF-stations. Populations in the WS-stations are very unstable though the taxocene is quite similar in both station-groups. Dominant species are *Trichotheristus mirabilis*, *Mesotheristus setosus* and *Chromadorita nana*, which account for 61 % of the fauna. Other important species are *Enoplolaimus litoralis*, *Tripyloides marinus*, *Ascolaimus elongatus* and *Microlaimus spec.* These seven species account for 72 % of the fauna.

The Eastern Scheldt estuary

Preliminary studies of the harpacticoid copepods and nematodes of this fully marine estuary have been made by Janssens de Varebeke (1977), Surkyn (1977) and Willems (unpublished). Nematodes were studied from Van Veen samples and SCUBA diver samples from 10 stations covering the whole estuary in August 1976 (fig. 3). Although 97 species were found, only seven of them occur in more than five stations and they account for 73 % of all individuals which were found during the investigation. These seven species are *Theristus spp.*, *Viscosia viscosa*, *Sabatieria spec.*, *Odontophora armata*, *Cylindrotheristus spec.*, *Cyatholaimidae spec.* and *Axonolaimus spec.* Species occurring at less than five stations are probably too rare to be sampled adequately : 39 species were found at only one station, 10 species at only two stations. Only one species has both high density and is rare : *Dichromadora hyalocheile*, although only occurring at three stations, was extremely numerous in CG3, a station situated outside the estuary, where only 5 species were found. Usually, the average number of species per sample varies between 14 and 25 and is lower in Van Veen samples than in SCUBA diver samples, when this could be compared. In the North Sea station WG1, where extremely strong currents occur, 15 species were found in the Van Veen grab but 23 in SCUBA diver samples; in station SRK 4, at the head of the Eastern Scheldt, these figures are 15 and 34 respectively. Diversity varied between 0.6 bits in CG3 (see above) and 3.3 bits in LG3. When these extreme stations are not included the average value is 2.7 ± 0.2 bits per individual.

Density of nematodes was only estimated in the SCUBA diver samples. In the muddy station SRK 4 3285 ind./10 cm^2 were found but only 92 ind./10 cm^2 in station WG1 at the mouth of the estuary. This very low value is probably due to the very strong currents in this area forcing the nematodes to remain deeper into the sediment (sampling was to 10 cm depth).

Surkyn (1977) studied 7 intertidal stations forming a transect from high to low water level and one subtidal station on the same transect in August 1976. Although there is a trend of increasing density towards the low water level, at least in the upper 4 cm of the sediment, overall density was not significantly different in the intertidal stations (930 ± 253 ind./10 cm^2) when compared to the subtidal station (1829 ind./10 cm^2). The same is true for biomass where values of 1.02 ± 0.29 g dwt./m^2 (intertidal) and 1.85 g dwt./m^2 (subtidal) were found.

Harpacticoid copepods from the same transect were also studied. There was no clear trend in density, nor a significant difference between intertidal and subtidal stations. An overall average is 119 ± 36 ind./10 cm^2. Foorteen species were found during this study; dominant were *Asellopsis intermedia, Harpacticus flexus, Hastigerella spec., Halectinosoma herdmani, Pseudobradya minor* and *Enhydrosoma propinquum*, which together account for 96 % of all individuals found. Mean diversity of the whole transect was 1.8 ± 0.7 bits/ind. Willems (unpublished) determined 18 species in the subtidal stations covered in the study of Janssens de Varebeke (1977). Although quantitative information is lacking, important species appear to be *Canuella perplexa*, which occurs throughout the whole estuary but not in the mouth, *Paraleptastacus espinulatus, Kliopsyllus constricta, Halectinosoma herdmani* and *H. gothiceps, Pseudobradya beduina* and *Longipedia spp.*

Lake Grevelingen

The meiofauna of this landlocked marine lake (the estuary was closed in 1971) has been studied by Goossens (1976), Surkyn (1977) and Heip et al. (1977). It is the subject of an ongoing detailed study by Willems (in preparation). Surkyn (1977) studied seven stations, in a former intertidal area now permanently submerged, from samples taken in August 1976. In this area 18 species of harpacticoids were found with an overall

average density of 200 ± 94 ind./10 cm^2. Dominant species are *Canuella perplexa, Ameira parvula, Harpacticus flexus, Ectinosoma spec., Longipedia minor* and *Pseudobradya minor*, accounting for 94 % of all individuals. Mean diversity was 1.9 ± 0.8 bits/ind. Goossens (1976) found *Asellopsis hispida* to be dominant in the shallow sandy station Archipel in November 1974, with a density of 416 ± 44 ind./10 cm^2 on a total of 655 ± 67 ind./10 cm^2 (n = 4) as estimated with small cores (Heip et al., 1977).

The average density of nematodes in the area studied by Surkyn (1977) was 1291 ± 335 ind./10 cm^2, with a corresponding biomass of 1.4 g dwt./m^2. However, density at Archipel was considerably lower : 853 ± 105 ind./10 cm^2 as estimated from large cores (Heip et al., 1977). In this station the dominant species of nematodes were *Prochromodorella ditlevseni, Theristus problematicus, Microlaimus spec., Anticoma limalis, Enoploides cephalophorus* in the upper layers whereas *Sabatieria spec., Cobbia spec.* and *Theristus spec.* occurred deeper in the sand.

The Ems-Dollard estuary

The harpacticoid copepods of five station groups along a 40 km transect from the head to the mouth of this estuary, which is situated on the Dutch-German border, have been studied by Vaeremans (1977). Density, biomass and diversity of the harpacticoids showed a trend of increasing values towards the mouth (table 13).

Table 13

Mean density (ind./10 cm^2), biomass (mg dwt./m^2) and diversity (bits/ind.) of Harpacticoid Copepods at six station groups along the Ems-Dollard estuary

	Uithuizer Wad	Eemshaven	Hoog Watum	Reiderplaat	Heringsplaat	Oost-Fr. plaat
Density	77 ± 48	79 ± 12	34 ± 20	33 ± 7	36 ± 22	21 ± 7
Biomass	106 ± 45	122 ± 20	43 ± 29	33 ± 7	32 ± 11	22 ± 16
Diversity	1.5 ± 0.2	2.2 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	0.9 ± 0.2	0.3 ± 0.1
Nr. species	21	13	16	10	7	6
Nr. stations	14	16	6	13	4	17
Nr. dates	2	3	2	2	1	4
Distance	40 km	38 km	28 km	10 km	8 km	1.4 km

Outside the mouth of the estuary, at the Uithuizer Wad in the Wadden Sea, the taxocene is dominated by *Harpacticus flexus, Tachidius discipes, Asellopsis intermedia, Canuella perplexa, Enhydrosoma propinquum, Halectinosoma herdmani* and *Microarthridion littorale*. This is the same community as found at Eemshaven, although *Halectinosoma herdmani* appears to be more common there, and at Hoog Watum. At Reidersplaat two other species appear or become dominant : *Paronychocamptus nanus* and *Nannopus palustris*, whereas other species disappear : *Canuella perplexa, Paronychocamptus curticaudatus* and *Asellopsis intermedia*. Reidersplaat is situated in the Dollard itself and a general impoverishment of this area is apparent : only three species remain important at Heringplaat (*Paronychocamptus nanus, Stenhelia palustris* and *Nannopus palustris*) and the same three species characterize Oost-Friese plaat. In November 1976 only one species *Stenhelia palustris*, survived the huge input of organic material at that time at this site. It occurs throughout the estuary, but remains rare as long as conditions are favourable for other species, and it could serve as an indicator species.

The nematodes of this area are being investigated by Bouwman (in press) who found the following species to be important in the polluted area : *Eudiplogaster pararmatus, Hypodontolaimus geophilus, Mesotheristus setosus, Anoplostoma viviparum* and *Sabatieria vulgaris*.

The Dievengat

This shallow polyhaline brackish water pond in northern Belgium has been the subject of intense meiofauna research since 1968 dealing with harpacticoid copepods, ostracods and nematodes (e.g. Heip, 1976; Heip et al., 1978). These investigations aim at the establishment of long time series, spatial patterns and the elucidation of the dynamics of the dominanat populations in the field. It is mentioned here because many of the species occurring in the Dievengat are important in other brackish water areas as well. Dominant harpacticoid copepods are *Paronychocamptus nanus, Tachidius discipes, Canuella perplexa* and *Amphiascoides debilis* in some years. Important nematode species are *Oncholaimus oxyuris, Anoplostoma*

viviparum, *Theristus spp.*, *Leptolaimus limicolus*, *Sabatieria spec.*, *Metalinhomoeus filiformis* and others.

Of the harpacticoid copepods, only four species were common during the period of investigation. *Canuella perplexa* and *Paronychocamptus nanus* are mainly detritivores and show complicated dynamics with more than one peak yearly. *Halicyclops magniceps* and *Tachidius discipes* are mainly herbivorous and show simple dynamics with only one peak each year. In both these species-pairs there is segregation in the temporal dimension and the larger species of both pairs occurs later in the year. In all the species the number of generations occurring during a year is much smaller than what is possible according to their reproductive potential.

The dynamics of these populations were analysed by spectral analysis. All parameters which were examined (density and biomass of populations, density and diversity of the taxocene) have most of their variance explained by phenomena with low periodicities. This is a desirable property for parameters in monitoring especially on sea, as the number of samples necessary to characterize the phenomenon will be low (Heip, in press)

Summary

A summary of work on benthic communities in the Southern Bight of the North Sea and adjacent estuaries is presented. This work investigates patterns in species composition, in density and biomass which are stable enough, both in the temporal and spatial domain, to be used as baseline data in monitoring, and from which information on systems functioning can be obtained.

Acknowledgments

Much of the work reported here was assisted by biology students among whom André Goossens, Guy Janssens de Varebeke, Guido Rappé, Rudy Surkyn, Marleen Vaeremans and Els Van Steen have been particularly helpful. Technical assistance from Alex Braeckman, Rosette De Boever, Mark De Keere, Gerrit Lambert, Anita Van Bost and Dirk Van Gansbeke is gratefully acknowledged. We are also particularly grateful to all public instances that have always assisted us with great competence : the Management Team of the Mathematical Model North Sea (Ministry of Public Health, Belgium), the Sea Service of Antwerp (Ministry of Works, Belgium), the Rijkswaterstaat at Vlissingen (Flushing) (Ministry of Works, The Netherlands), the Delta Institute of Hydrobiological Research at Yerseke (The Netherlands) and the Biological Research Ems-Dollard Estuary Group at Groningen (The Netherlands).

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Dynamics of organic matter in three planktonic ecosystems of the southern North Sea

Report of the workgroup "Organic Matter", 1977-1978

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Introduction

For the last few years, we have attempted to describe and understand the ecometabolism of some biocenoses in the Southern North Sea. In this synecological approach, it was necessary to determine the main characteristics of the carbon and nitrogen cycles: biomasses and concentrations, fluxes and activities. A summary of the results of this team work has been published (Billen et al., 1976). In this paper, the authors gave a general picture of the ecometabolism of the visited ecosystems, and raised some new problems, mainly concerning the planktonic phase. The group "Organic Matter" took as a goal, in 1977, to try to solve these problems.

0.1.- CONSISTENCY OF THE RESULTS OF PRODUCTION AND CONSUMPTION

The construction of the carbon budget revealed an important contradiction : in the absence of any significant import of exogenous organic matter, the only source of organic carbon consists in primary production. However

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the results obtained in the Sluice-Dock of Ostend showed that the account was unbalanced, and that there was a contradiction between the amount of organic matter formed by gross primary production and the amount used by consumers; consumption was almost twice as high as production. In the Southern Bight of the North Sea, consumption is 10 to 20 times higher than production. This means that either the gross primary production had been underestimated, or the consumption overestimated (see Joiris, 1977 a,b).

In order to solve this contradiction, we had to verify the measurements of high planktonic respirations on the one hand, and gross primary production, on the other hand.

Within the values of respiration, we had to determine whether our supposition, that bacterioplankton indeed plays the main role, was correct. This means that we had to try to determine the real (i.e. *sensu stricto*) heterotrophic activity through the use of other independant methods.

In the case of primary production, two factors could lead to an underestimation: the production of soluble (excreted) organic matter with such a high turnover rate that it could be respired during the incubation, and/or a phytoplanktonic respiration with much higher values than earlier calculated.

0.2.- THE RECYCLING ROLE OF ZOO- AND BACTERIOPLANKTON

Another important remark to be drawn from the same results concerns the relative importance of zooplankton and heterotrophic microorganisms (mainly bacteria) in the utilization of the phytoplanktonic production. In contradiction to the classical scheme of a "complete" food web: producers - - herbivors - carnivors, the study of the coastal biocenoses of the Southern North Sea indicated that the bacterioplankton played a prominant role in the recycling of the produced organic matter. This aspect of the discussion was however obscured by the contradiction between production and consumption figures, and needed to be confirmed by new measurements.

0.3.- COMPARISON OF DIFFERENT BIOCENOSES

The description of ecological structure of the coastal biotopes in the Southern Bight can be completed with some results from other regions in the North Sea. All results can be framed in the following hypothesis: the Atlantic water coming into the North Sea through the region of the Shetlands

is characterized by a complete food chain: primary producers - zooplankton - fish - pelagic seabirds; bacteria only in very low amounts. In the central North Sea, on the contrary, one fimds a bacterial by-path to the normal food chain; seabirds are scarce, but bacteria are much more abundant (Joiris, 1978).

A confirmation of the role played by zooplankton in the northern Atlantic water was obtained in the Fladdenground (Flex 70): the variations of the phytoplankton standing-crop could be entirely explained by the measured values of primary production and the measured grazing of zooplankton on living phytoplankton (Daro, 1979).

We considered therefore it would be worthwhile in trying, not only to confirm the importance of bacterial recycling in North Sea waters, but

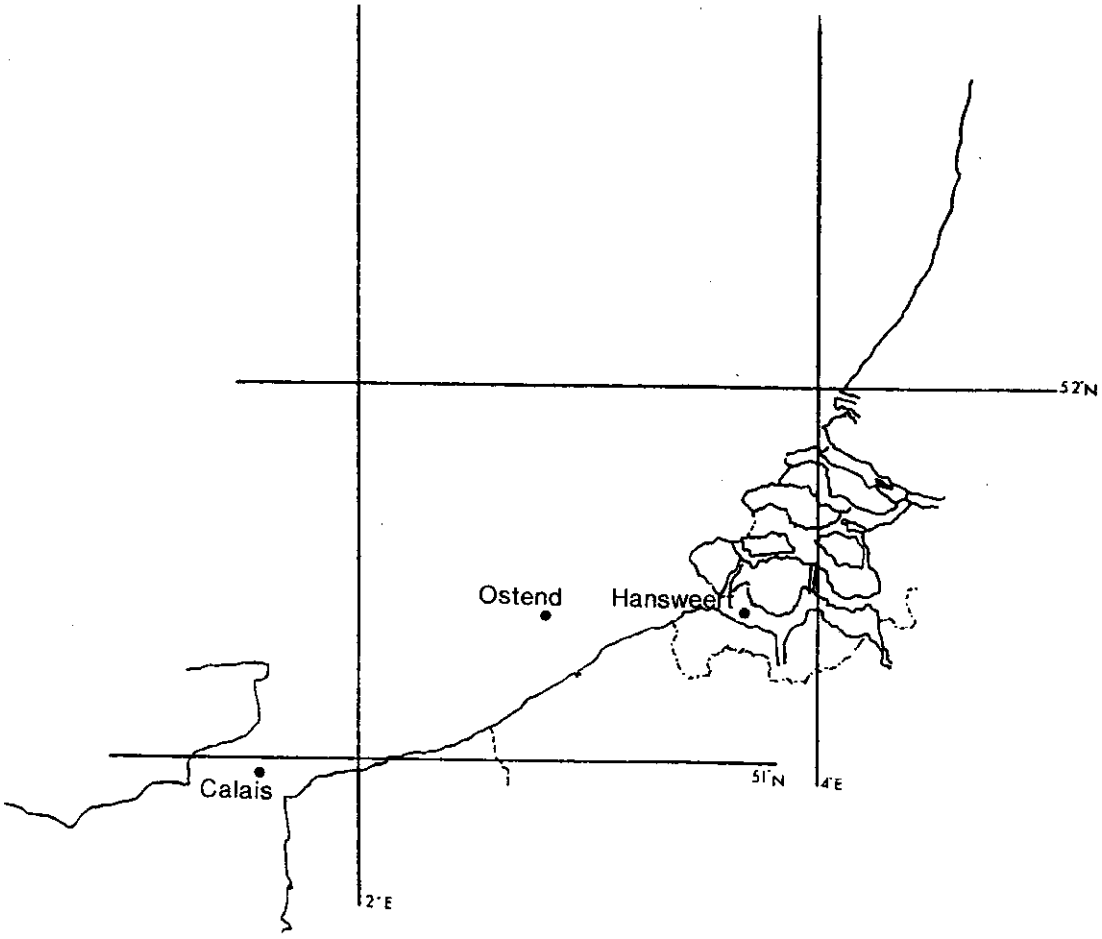

fig. 1.

Position of the sampling stations visited

also to use the same methods for evaluating the stocks and fluxes in Atlantic water. For practical reasons, such as the lack of adequate ship facilities, we were not able to reach the northern Atlantic water. As an alternative solution, we looked for a water mass with "Atlantic" characteristics in the English Channel.

Finally, a third biotope was added in the programm: the Scheldt estuary, since a completely different ecological structure was to be expected there. These three stations are representative of the main types of biocenoses in the North Sea: estuary, coastal sea, open sea.

The position of the three stations is as following (see fig. 1):

1. North Sea water : station "Ostend" 51°24'N, 2°48'E
2. "Atlantic" water: station "Calais" 50°57'30"N, 1°23'30"E
3. Scheldt estuary : station "Hansweert" : 35 km from the open sea.

The experimental work was done on board of the *RV Mechelen* (coordination : H. Picard) and, on two occasions, on board of the *RV Friedrich Heincke* : 7 - 10 October 1977 (coordination : P. Weigel) and 7 - 18 April 1978 (coordination : W. Hickel).

1.- Methodology

In the previous investigations, use was made of rather crude methods for the determination of fluxes, namely :

- measurement of $H^{14}CO_3^-$ incorporation for estimating particulate net primary production with the classical Steeman-Nielsen (1952) method;
- measurement of initial dark oxygen consumption for estimating total planktonic respiration;
- calculation of zooplankton ingestion from the biomass of each zooplankton species and development stage, and their "daily food requirement" compiled from the literature.

The results presented here are based on a refined methodology achieving a more detailed speciation both of the stocks of organic matter and of the fluxes they undergo. This methodology was developed in order to approach more closely the basic nature of the biological processes involved in the relationships:

1. phytoplankton - organic matter - bacteria
2. phytoplankton - zooplankton

1.1.- PHYTOPLANKTON — DISSOLVED ORGANIC MATTER — BACTERIA RELATIONSHIP

Among the huge diversity of organic substances produced by phytoplankton and constituting dissolved and particulate organic matter, only a small part can be directly taken up and used by microorganisms.

Dialysis or ultrafiltration of dissolved organic matter in seawater reveals indeed that it is mostly made of macromolecules with molecular weight higher than 500 (Ogura, 1974). Now, only low molecular weight organic molecules can be directly taken up by bacteria. Therefore, the pool of directly usable organic matter is constituted by the pool of low molecular weight organic molecules, which is alimented either by direct excretion by phytoplankton, or by exoenzymatic hydrolysis of macromolecules or particles.

These considerations have led us to focus the measurements on directly usable organic substrates, their production and consumption rates.

A method was developed for measuring dissolved primary production. It involves the kinetic measurement of labelled dissolved organic matter produced during incubation with $H^{14}CO_3^-$ in the light and simultaneously allows an estimation of the rate of microbiological consumption of the excretion products (Lancelot, submitted). Ultrafiltration of the excreted organic matter also allows a first speciation of the dissolved organic matter produced. The results indicate that about 30 - 50% of the excreted organic matter is made directly usable compounds (MW < 500) (Lancelot, submitted).

Apart from the determination of the overall organic matter concentration (TOC, BOD_5) numerous dissolved - directly usable - organic substrates in seawater were determined: individual free amino-acids, glucose, glycollate, lactate and acetate. From these measurements, a tentative estimation of the total pool of directly usable organic substrates was made (Billen et al., submitted).

The rate of utilization of these substrates was also determined by adding high specific activity ^{14}C labelled molecules and studying their uptake kinetics and their respiration (Billen et al., submitted).

A tentative estimation of *sensu stricto* heterotrophic activity (excluding intracellular phytoplanktonic utilization of their own photosynthetized substrates) was derived from these measurements.

1.2.- PHYTOPLANKTON – ZOOPLANKTON RELATIONSHIP

Zooplankton nutrition can occur either on living phytoplankton, on detritus and bacteria or on accumulated lipid reserves. These three modes of nutrition have of course quite different effects on the dynamics of the system.

Grazing on living phytoplankton was determined by incubating zooplankton with pre-labelled natural phytoplanktonic populations and counting the radioactivity ingested (Daro, 1978).

Speciation of particulate primary production was achieved through biochemical fractionation of the radioactivity incorporated during incubation with $H^{14}CO_3^-$. Comparison of these data with the biochemical composition of living phytoplankton and detritus provides indications on the relative utilization rates of the various particulate biochemical constituents (Lancelot, in prep.).

Biochemical composition of zooplankton was also determined, providing evidence of the constitution of lipidic reserves by these organisms (Hecq, and Gaspar, in prep.).

Zooplankton density was also determined species by species and development stage by development stage. When available analysis of time series of such data allows the determination of the population dynamics parameters of zooplankton (Bossicart and Mommaerts, in prep.).

2.- Results and discussion

A summary of the results to be used in the general discussion is presented in table 1 and in figures 2, 3 and 4. This constitutes the basic information for the discussion of the three problems presented in the introduction:

- coherence of production and consumption measurements
- relative roles of zooplankton and bacterioplankton
- comparison of three different biocenoses.

Table 1

Summary of the results obtained in the Belgian coastal zone (zone 1S) (1973-1975) and at the stations "Ostend", "Calais" and "Hansweert" (1977-1978)

	Method[a]	Units	Belgian coastal zone[b]	Station "Ostend"			
				mean	min	Max	(n)
Phytoplankton biomass	1	mgChl/m^3	7.93	7.35	2.77	21.50	(10)
Primary production							
net particulate	2	mgC/m^2day	293	362	251	474	(2)
net dissolved	2	"	(122)	98	30	172	(2)
net total	2	"	(415)	460	281	636	(2)
gross(30% respiration)	0	"	(593)	(658)			
(50% ")	0	"	(830)	(920)			
Zooplankton							
biomass	3	mgC/m^3		7.30	0.29	22	(5)
grazing	0	mgC/m^3day	19.4				
	2	%stock/day	-	5			
respiration	4	$mMO_2/m^3h.$	0.015	0.015			
Planktonic respiration	4	$mMO_2/m^3h.$	5.25	0.67	0.13	1.00	(3)
				3.20[c]			(21)
Heterotrophic activity	5	mgC/$m^3h.$	-	2.50	0.86	17.60	(22)
-respiration (2/3)	5	"	-	1.67			
-assimilation(1/3)	5	"	-	0.83			

	Units	"Calais"				"Hansweert"			
		mean	min	Max	(n)	mean	min	Max	(n)
Phytoplankton biomass	mgChl/m^3	1.02	.34	2.25	(6)	7.38	4.48	18.51	(7)
Primary production									
net particulate	mgC/m^2day	163	117	260	(3)	15			(1)
net dissolved	"	49	40	58	(2)	2			(1)
net total	"	212	157	318		17			(1)
gross(30% respir.)	"								
(50% respir.)	"	(424)				(34)			
Zooplankton									
biomass	mgC/m^3	2.50	.17	9.0	(5)	-			
grazing	mgC/m^3day	-				-			
	%stock/day	6				-			
respiration	$mMO_2/m^3h.$	0.02				-			
Planktonic resp.	$mMO_2/m^3h.$	0.37	0	2.55	(13)	1.13	1.10	1.15	(2)
Heterotrophic activity	mgC/$m^3h.$	0.33	0.04	1.88	(20)	8.45	4.28	14.50	(5)
-respiration	"	0.22				5.64			
-assimilation	"	0.11				2.81			

a. Methods : 0 = calculated; 1 = chlorophyll; 2 = ^{14}C-bicarbonate incorporation; 3 = counts; 4 = oxygen consumption rate; 5 = incorporation of labelled substrates.

b. From Billen et al., 1977.

c. Mean value from 21 determinations in the coastal zone (not only Ostend), 1977-1978.

(n) : Number of determinations.

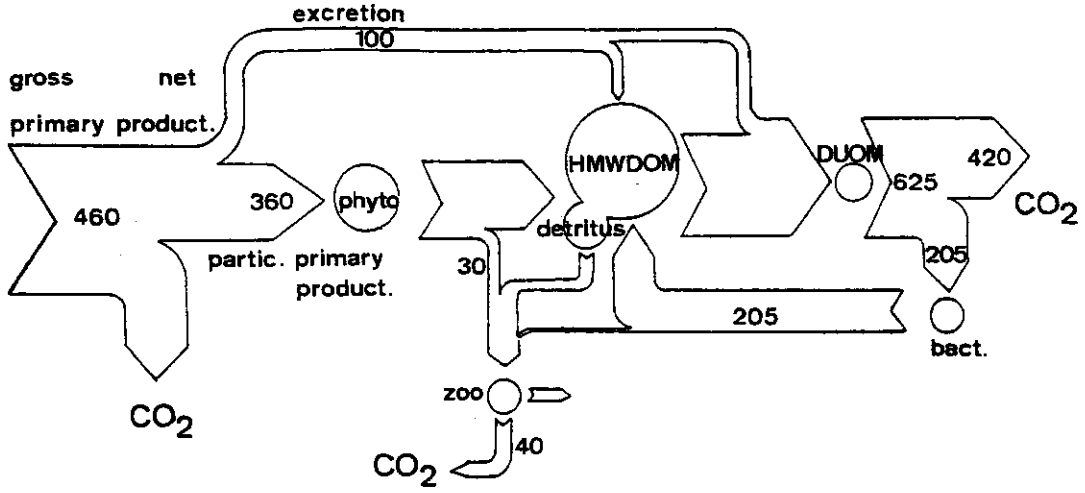

fig. 2.

Circulation of carbon between the first trophic levels at the station "Ostend".
(All fluxes in mg C/m^2 day.)
Abbreviation : HMWDOM : high molecular weight dissolved organic matter.
DUOM : directly usable organic matter.

2.1.- COHERENCE OF PRODUCTION AND CONSUMPTION MEASUREMENTS

Different approaches can be used, in order to solve the contradiction between the values of gross primary production and total consumption. This discussion concerns first of all the results obtained at the station "Ostend", and the results obtained earlier in the same zone ("zone 1 South") of the southern Bight.

2.1.1.-

A first remark to be made is that, generally speaking, the values obtained in 1977 and 1978 at "Ostend" can very well be integrate into the mean values obtained in the previous years for the zone 1s with much greater sampling. This allows us to consider that the new results are sufficiently representative of the real situation, even though the number of samples is rather low.

2.1.2.-

The estimation of the planktonic heterotrophic activity (*sensu stricto*) obtained by adding up the several specific utilization rates gives, of course, strictly minimal figures, since there is always a possibility that some substrates, which had not been measured, play a significant role.

At the station "Ostend", this flux of heterotrophic activity reaches a value (625 $mgC.m^{-2}day^{-1}$) comparable with the net primary production (460 $mgC.m^{-2}day^{-1}$). The respiratory fraction was measured as 2/3 of the heterotrophic uptake and reaches the same value (420 $mgC.m^{-2}day^{-1}$) as the primary production.

The comparison between heterotrophic activity and dissolved primary production clearly shows that the phytoplanktonic excretion (100 $mg\,C.m^{-2}.day^{-1}$) cannot be considered as the main source of organic matter for the heterotrophic microorganisms (the bacteria). Therefore, other mechanisms, such as phytoplanktonic mortality, must be considered since all the produced organic matter must be made available for the heterotrophic organisms.

2.1.3.-

In order to explain the contradiction between production and total consumption, the dissolved primary production must be very important and the produced substances had to show a very high turnover rate. The mean value for excretion is not very high, being about 25% of the particulate primary production; the linearity of the kinetics implies that there is not a high turnover rate for the excreted substances. However, it is worth noticing that, in a few cases, turnover rates up to 40% per hour were detected, indicating the possible existence of one or several substrates not yet detected by the methods presently used. If such results are confirmed later, it would be very important to identify and study these substances.

A special discussion must be devoted to glycollate: it is generally considered to be the main excretion product of marine phytoplankton and represent 9 to 38 % of the total excreted amount (Hellebust, 1965). This is confirmed by the fluxes we measured: from the measurements of heterotrophic utilization of glycollate, a flux of 36 $mgC.m^{-2}day^{-1}$ was measured at Ostend (29 at Calais), or 37 % of the dissolved primary production (59 % at Calais).

In terms of turnover rates, however, the utilization by bacteria is rather low: 0.27 % h^{-1} at Ostend, 0.06 % at Calais. Therefore glycollate cannot be the hypothetical excretion product utilized at a very high turnover rate that we are looking for.

2.1.4.-

We still need more measurements to confirm the results before a definitive conclusion can be drawn, but the general impression is that a series of values can be considered as being correct:

- the net particulate and dissolved primary productions,
- the planktonic heterotrophic activity (*sensu stricto*),
- the efficiency of the heterotrophic microorganisms (about 33 %).

It follows that all results, including those that are apparently inconsistent (production versus consumption), together fit well on the condition that the simple hypothesis proves to be correct, i.e. that the respiration of the autotrophic organisms (the phytoplankton) is much higher than estimated in the earlier calculations. Hence the gross primary production would be much higher than estimated earlier, and that the carbon cycle would be equilibrated.

The research program for the next years will give a priority to more direct methods for the assessment of phytoplanktonic respiration.

It must however be born in mind that another possibility cannot yet be totally excluded, even though we consider it highly improbable, i.e. the existence of an organic substance excreted by the primary producers and very rapidly utilized by the heterotrophic organisms.

2.2.- RELATIVE ROLE OF ZOOPLANKTON AND BACTERIOPLANKTON

As for the section 2.1, in this discussion we will make use mainly of the results obtained for the zone 1S (1973-1975) and at the station "Ostend" (1977-1978).

Two major pieces of information were added:

2.2.1.-

On the one hand, at the level of the heterotrophic activity (*sensu stricto*) : as discussed earlier, a minimal value has been given. It reaches at least the same order of magnitude as the net primary production.

2.2.2.-

On the other hand, at the level of the grazing of the zooplankton on living phytoplankton (Daro, 1978). The results obtained with this method, where zooplankton is taking up radioactive phytoplankton, and the daily food

requirement supply calculated on the basis of the weight of zooplankton are consistent and lead to the same kind of conclusion: the grazing by zooplankton concerns a low percentage of the phytoplankton biomass per day, even though the results may have been underestimated because most of the measurements were performed during day time.

These two pieces of information confirm earlier conclusions: the role of heterotrophic microorganisms is very important in the recycling of the produced organic matter, whereas the role of zooplankton is quantitatively much less important.

2.3.- COMPARISON BETWEEN THE THREE BIOCENOSES

In comparison with the ecological structure of the coastal marine system (station "Ostend") as it was discussed earlier, the following remark can be made about the two other stations (fig. 3 and 4).

2.3.1.-

Before discussing the quantitative differences, it has to be remembered that qualitative differences were noted.

The biochemical composition (proteins, carbohydrates and lipids) of the particulate organic matter, as well as of the phytoplankton and the primary production, is different in the three zones (Lancelot, in prep.).

At the level of zooplankton, such a difference was also noted, but it could be due to temporal variations linked with the development of the phytoplankton bloom (Hecq and Gaspar, in prep.) or to geographical variations.

2.3.2.- "Calais" (fig. 3)

2.3.2.1.-

The primary production measured at the station "Calais" is not significantly different from that of the station "Ostend". This conclusion is certainly not a definitive one, because of the small amount of measurements and because of the absence of any phytoplankton bloom at Calais during the sampling periods; it obviously needs to be confirmed during the following campaigns.

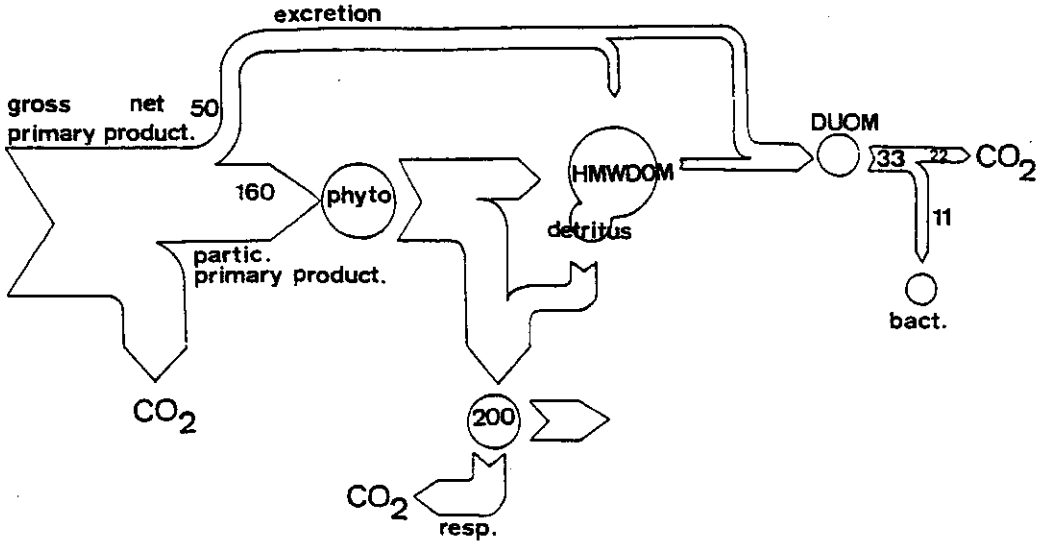

fig. 3.

Circulation of carbon between the first trophic levels at the station "Calais". (All fluxes in mg C/m^2 day.)

2.3.2.2.-

The heterotrophic activity (*sensu stricto*) is clearly lower than at Ostend, both in absolute value and in proportion to the primary production. This indicates that the bacteria here play only a minor role in the recycling of the produced organic matter.

2.3.2.3.-

The case of zooplankton is less clear. Zooplankton biomasses, expressed per m^2 are higher in Calais, but the measured grazing was very low: it seems even too low to allow the survival of the zooplankton present there. A possible interpretation is that the zooplankton preaccumulated fat reserves earlier in the season during a phytoplankton bloom, and was utilizing its own lipids during our sampling period (Hecq and Gaspar, in prep.).

A high value of zooplankton respiration could be used as a confirmation for this hypothesis.

New measurements are needed in order to confirm these observations and their interpretation.

2.3.2.4.-

The actual conclusion is that the recycling of organic matter is not made by heterotrophic organisms at Calais, as expected (see introduction). The complementary information on the importance of zooplankton

has however still to be completed, before its relative role in the utilization of the primary producers is proved. So that, all in all, the results fit the hypothetical scheme of a proeminent role of zooplankton and the higher trophic levels at Calais, but they do not yet prove it definitively.

2.3.3.- "Hansweert" (fig. 4)

At Hansweert, a typical estuarian structure is found, with a very low primary production and high heterotrophic and respiratory activities. The situation is of course completely different from that at the other ecosystems, the exogenous organic matter here playing an important role.

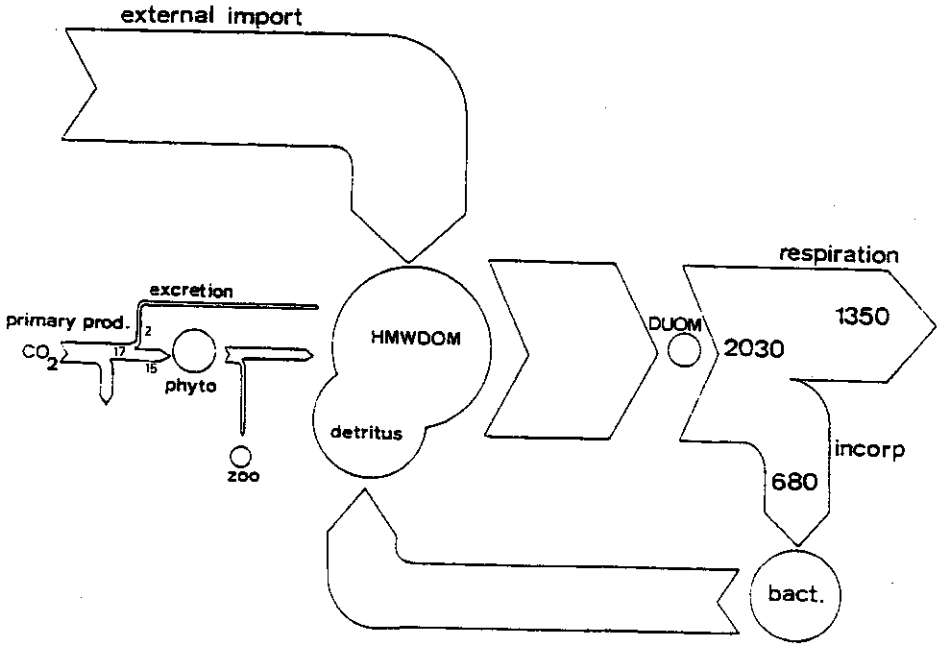

fig. 4.

Circulation of carbon between the first trophic levels at the station "Hansweert". (All fluxes in mg C/m^2 day.)

It is very interesting to note that, in those circumstances where phytoplankton activity is very low and can almost be neglected, the total respiration determined as oxygen consumption rate and the sensu stricto heterotrophic activity are not significantly different. This confirms that the measured heterotrophic activity is indeed the real one. No important element is missing and the differences noticed between total respiration and

heterotrophic activity in the other zones can be attributed to a phytoplankton metabolism, such as phytoplankton respiration, as discussed earlier.

2.3.4.- Regulation of the circulation of organic matter at the first trophic levels

A proper understanding of trophic web structure and of its differences between the three zones investigated requires that the factors determining the intensity of each flux be known. This is particularly important at the sites of branching in the trophic web.

Three main branching determine the overall phytoplankton - zooplankton-bacteria bifurcation (fig. 5):

- the branching particulate/dissolved primary production
- the branching phytoplankton/zooplankton/detritus
- the branching detritus/zooplankton/bacteria.

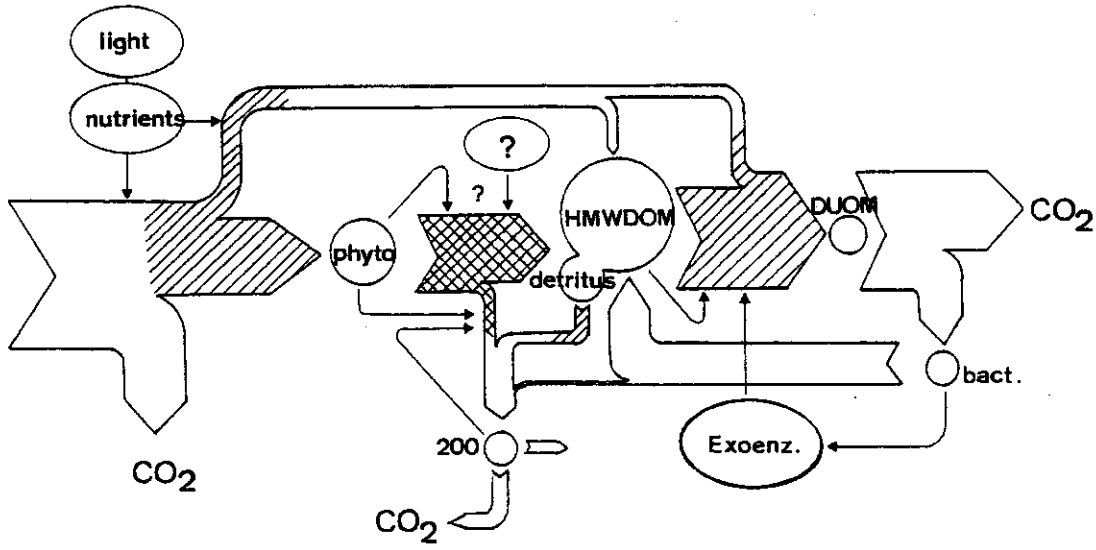

fig. 5.

Main regulation mechanisms of the carbon circulation between the first trophic levels in marine ecosystems.

2.3.4.1.- *The branching particulate/dissolved primary production*

According to the works of Anderson and Zeutschel (1970), Thomas (1971) and Berman & Holm-Hansen (1974) the phytoplankton excretion mainly results from an insufficient nutrient disponibility with the respect to photosynthetic carbon fixation. The relative value of dissolved versus particulate

production would therefore be under the combined influences of light intensity and nutrient concentration.

The data obtained from our own measurements (Lancelot, submitted; Bertels, thesis work) are generally coherent with this theory (see Table 2).

Table 2

Seasonal variations of the phytoplankton extracellular release

	Date	Chlorophyll	% extracellular release
Ostend	050478[1]	16.2	22 %
	160478[2]	2.8	19 %
	190478[2]	4.8	31 %
	190478[1]	5	44 %
	160578[1]	5.9	60 %
Calais	040478[1]	3	19 %
	170478[2]	1.15	24 %
	180478[1]	0.84	23 %
	170578[1]	3.4	54 %
Hansweert	070478[1]	7.2	70 %
	210478[1]	6.3	0 %
	190578[1]	7.2	12 %

1. Lancelot (1979b).
2. A. Bertels (Thesis work).

- dissolved primary production is generally lower at Hansweert than at the other less eutrophic stations
- at Ostend and Calais, excretion increases during the course of the phytoplankton bloom, in parallel with the exhaustion of nutrients.

2.3.4.2.- *The branching phytoplankton/zooplankton/detritus*

Phytoplankton cells either are grazed by zooplankton or die and form detritus and dissolved organic matter.

The process of spontaneous phytoplankton mortality has now been widely recognized (Jassby and Goldman, 1974; Lund et al., 1958; Daro, 1974; Mommaerts, 1977). Its determinism, however, remains to be defined.

Grazing on living phytoplankton, on the other hand has been more closely investigated. It is dependant both on the quantity and on the quality (size and biochemical composition) of the phytoplankton present (Samain et al., 1975; Mayzaud and Poulet, 1978).

For the two main zooplanktonic species occuring during the spring bloom, namely *Temora longicornis* and *Pseudocalanus elongatus*, the form of the dependance of grazing on phytoplanktonic concentration has been experimentally

put in evidence. The relationship is linear from 0 to 9-10 mg chlorophylla/ m^3. Above this value, grazing becomes independant of phytoplanktonic concentrations. This value being only very unfrequently reached, grazing is generally closely regulated by algal density.

On the other hand, the biochemical composition of phytoplankton and detritus (namely their relative content in proteins and carbohydrates) influences zooplankton grazing, growth and reproduction. Friedman & Sticker (1975) have demonstrated the existence of chemoreceptors allowing the copepods to select their food according to its nutritional quality.

Differences in this respect exist between the three biotopes we studied: phytoplankton cells synthetize relatively more proteins than carbohydrates in more eutrophic media (Ostend and Hansweert) than in oligotrophic ones (Calais).

Studies on the selectivity of grazing in relation to phytoplanktonic size and biochemical composition are in progress.

2.3.4.3.- *The branching detritus/zooplankton/bacteria*

As explained above, detritus and high molecular weigh dissolved organic matter (HMWDOM) can be ultimately degraded by bacteria only through the action of exoenzymes, hydrolyzing them into small organic polymers. These alone form the pool of directly usable organic matter (DUOM).

It may be surprising that, although the rate of heterotrophic bacterial activity differs by at least a factor of 10 between the three environments investigated (in the order Hansweert > Ostend > Calais), the size of this pool of DUOM is quite similar (table 3). It seems the overall rate of heterotrophic activity is not regulated by the pool size of its direct substrate.

This apparent paradoxe has been resolved by a simplified model developed by Billen et al. (submitted) showing that system formed by bacterial populations and their substrates produced at a rate P, rapidly reaches a stationnary state in which the size of the substrate only depends on the affinity of the bacteria for it, while only the size of the bacterial population and it total rate of activity depends on the production rate P.

The production of DUOM is the sum of direct excretion of small metabolites by phytoplankton and of exoenzymatic hydrolysis of detritus and HMWDOM. Very little is known about the kinetics of the action of free exoenzymes

Table 3

Concentration of small organic substrates determined at the at the three stations under study (in µmoles/ℓ)

	Ala	Asp	Lys	Glyc	Gluc	Acet	Lact
Hansweert							
mean	.049	.019	.013	3.6	0.07	1.1	0.2
max	.084	.033	.020	4.5	0.08	3.3	0.2
min	.020	.010	.010	2.0	0.05	0.2	0.2
Ostend							
mean	.029	.023	.020	2.6	0.03	1.0	1.7
max	.050	.030	.036	3.0	0.05	2.5	5
min	.010	.020	.010	1.8	0.02	0.2	0.2
Calais							
mean	.069	.037	.024	1.8	0.014	1.15	1.1
max	.176	.100	.034	2.3	0.040	4.0	1.6
min	.010	.010	.010	0.9	0.005	0.2	0.2

in natural waters, although their occurence has been demonstrated (Kim and Zobell, 1974; Reichardt et al., 1967).

Production of exoenzymes by bacteria has often been shown to be repressed by high concentration of monomeric organic substrates (Green and Colarusso, 1964; May and Elliot, 1968; Neumark and Citri, 1962; Hofsten, 1965). It is quite doubtfull, however, that such high concentration could ever occur in the water column, so that exoenzymes production is probably mostly dependant on bacterial density.

Khailov and Finenko (1970) have shown that the activity of exoenzymes is very dependant on the presence of particles on which macromolecules can adsorb.

Studies on the mechanisms of exoenzymatic degradation are in progress.

3.- Conclusion – Summary

All results actually available on the ecometabolism of the Southern Bight of the North Sea, i.e.:

- net primary production, particulate and dissolved;
- total planktonic respiration;
- heterotrophic activity (*sensu stricto*);
- grazing on living phytoplankton,

fit well together within the simple hypothesis that the respiration of the autotrophic organisms is much higher than estimated in the earlier calculations. The gross primary production would be much higher and the inconsistency between production and consumption would be solved in that way.

The comparison between the different biocenoses shows the existence of three different ecological structures:

- at Calais : an open sea situation. The phytoplanktonic production is not recycled mainly by heterotrophs (bacteria), but probably used by zooplankton and a complete food web;

- at Ostend : a typical marine coastal situation. The organic matter produced is mainly recycled by heterotrophic microorganisms (the bacterioplankton), after it has been made available to them by mortality and exoenzymatic hydrolysis. The role of zooplankton is much less important;

- at Hansweert : an estuarian situation. The high heterotrophic activity and total respiration are not dependant on a low primary production, but on important quantities of exogenous organic matter.

The research program for the next years will give a priority to more direct methods for the measurements of phytoplanktonic respiration and to the mechanisms of regulation of the branching from primary producers to zooplankton or to bacterioplankton.

Acknowledgment

We are especially grateful to our colleagus of the Biologische Anstalt Helgoländ : P. Weigel, W. Hickel, M. Treutner, P. Mangelsdorf, G. Gassman and P. Martens for their good hospitality on board of the *R.V. Friedrich Heicke* and access to a few un published results.

The skilled technical assistance of J. Nijs, R. Vanthomme and R. Swaelens is acknowledged.

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Culturing of marine microscopic algae

Progress report on the research activities of the laboratory for mariculture[1]

N. DE PAUW, L. DE LEENHEER, H. VERLET and M. DOCHY

Introduction

Any maricultural development is by definition dependent of an efficient energetic transfert between successive trophic levels.

Marine algae being the first link of the aquatic food chain, the first of our targets was to look at the optimal uptake of nutrients from the culturing medium and to the effect of light, temperature, pH and turbulence, as the major external parameters regulating algal growth (Soeder and Stengel, 1974).

Indoor experiments with artificial light as well as outdoor experiments under natural light conditions have been carried out in volumes ranging from 2 liter to 250 liter even up to 50 m^3 in one specific experiment. The final objective of our experimenting is to assess the feasibility of maintaining long-term semi-continuous or continuous cultures of marine planktonic algae in enriched seawater, either specific species (*Chlorella saccharophila* and *Dunaliella viridis*) or natural phytoplankton as life food organisms.

In view of a possible utilization of thermal effluents a comparison was made between algal growth in heated and unheated cultures.

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1. State University of Ghent (Belgium); dir.: Prof. Dr. G. Persoone.

Results and discussion

1.- NUTRIENTS AND pH

1.1.- Growth of marine algae on different nitrogen sources

Small scale batch culture experiments in 2 liter air-bubbled serum bottles (cf. Persoone and Sorgeloos, 1975) have been carried out to investigate the influence on the algal growth of the chemical nature under which nitrogen is provided as a nutrient (ratio of ammonium to nitrite and or nitrate) at different pH levels. The pH in the cultures was stabilized at a preselected value by mixing the air with an adjustable volume of carbon dioxide. The algal species selected for these experiments were *Chlorella saccharophila* (Krüger) Migula (a marine non-motile unicellular Chlorophyte) and *Dunaliella viridis* (a marine unicellular flagellated Chlorophyte). *Chlorella* was cultured in natural sea-water sampled from the Ostend Sluice-dock (± 29 ‰ salinity) ; *Dunaliella*, a halophilic species at 50 ‰ salinity in an artificial seawater made up with tap water and a commercial seasalt "Salins du Midi".

The increase in biomass of the algae has been determined by measuring the optical density (O.D.) at 678 nm. Furthermore for *Chlorella* dry weights (DW) have been determined ; for *Dunaliella* countings were made, since the DW technique is not applicable for this species due to plasmolyses. The experiments were performed at 26 ± 1°C. The nutrient uptake by the algae has been determined regularly during the growth period by nitrogen and phosphorus analysis. The basic culturing medium utilized was the Walne (1956) recipe of which only the major components were used. In this medium the nitrate concentration is 5000 mg N ℓ^{-1}. According to the nitrogen source desired, $NaNO_3$ was replaced by $NaNO_2$ or by NH_4HCO_3.

Different nitrogen salts have been tested out either alone (NH_4^+ , NO_2^- , NO_3^-) or in combination ratio 1:1 ($NH_4^+ + NO_2^-$, $NO_2^- + NO_3^-$, $NO_3^- + NH_4^+$) and ratio 1:2:1 ($NH_4^+ + NO_2^- + NO_3^-$) at different pH's : 6 , 7 and 8 .

The experiments were carried out at two different initial concentrations of nitrogen : 20 and 100 mg N ℓ^{-1}. Data on growth and nutrient uptake are given in De Pauw and De Leenheer (1977).

From the results it appears that the productions with ammonium as source of nitrogen are higher at pH 6 than at pH 8, when the ammonium concentration is 100 mg ℓ^{-1}. The most plausible explanation is that at

alkaline pH part of the ammonium is transformed into ammonia ($NH_4^+ \rightarrow NH_3$) which inhibits the algal growth.

At the higher nitrate concentration we find the reverse : the growth is better at pH 8 than at pH 6. At the lower N-concentrations there does not seem to be any significant effect of the pH's tested out on the growth with either ammonium or nitrate. With nitrite as sole source of nitrogen the two algal species react different. Even at the lower NO_2^- concentration (20 mg N ℓ^{-1}) the growth of *Chlorella* is seriously inhibited, whereas *Dunaliella* does not seem to be affected (yields of the same order as those obtained with NH_4^+) . At high nitrite concentration (100 mg N ℓ^{-1}) *Dunaliella* is intoxicated at pH 6 and 7, but at pH 8 growth is still normal. At pH 6, mixtures of nitrite with either ammonium or nitrate inhibit the growth of *Chlorella* completely when the NO_2^- level reaches 50 mg ℓ^{-1}. At pH 8 the algae are growing, but the productions are much lower than those obtained in the absence of nitrite. The best results were obtained with mixtures of ammonium and nitrate with no marked influence of the pH. According to Syrett and Morris (1963), ammonium is taken up preferentially by the algae with less energy expenditure for conversion to amino acids than is needed for the uptake of nitrate. Soeder (1976) also emphasized that ammonium is more suitable than nitrate since the utilization of the latter leads to a considerable increase of the pH of the cultures.

1.2.- Growth of *Dunaliella* on different commercial inorganic fertilizers

For large-scale algal cultures, the use of pure chemicals as nutrients cannot be considered in view of their relatively high cost.

Experiments carried out with cheaper sources of nitrogen and phosphor involved two potential groups of compounds :

1) commercial (agricultural) inorganic fertilizers
2) bio-degradable wastes, more specifically bio-industrial wastes including manures, which are known to be very rich in nitrogen and phosphor.

At the latter source of nutrients is analyzed extensively in our laboratory on its potential use for mass culturing of both freshwater and marine microscopic algae in a separate research program, we refer the reader to the reports and papers on this subject (De Pauw et al., 1978, De Pauw and De Leenheer, 1977, De Pauw et al., 1979).

The following commercial fertilizers have been selected on the basis of their price and their extensive utilization :

- Calciumnitrate : $Ca(NO_3)_2$
- Triple-superphosphate : a mixture of $Ca(H_2PO_4)_2$, $CaHPO_4$ and $Ca_3(PO_4)_2$
- Ammoniumsulphate : $(NH_4)_2 SO_4$

As source of phosphor we also utilized phosphoric acid (85% technical grade) : H_3PO_4.

The combinations which were tested out are :

- Calciumnitrate and triple-superphosphate
- Calciumnitrate and phosphoric acid
- Ammoniumsulphate and triple-superphosphate
- Ammoniumsulphate and phosphoric acid

The experimental set-up was the same as described above; the temperature in the cultures fluctuated around 25°C (± 2°C). The total content of inorganic nitrogen in the culturing medium at the start was 50 mg ℓ^{-1}, that of orthophosphate-phosphorus 10 mg ℓ^{-1}.

Two different sets of pH's were tested : 6,5 to 7,5 and 7,5 to 9. The pH was stabilized by addition of CO_2. The results of these experiments reveal that at lower pH's, triplesuperphosphate gives the highest yields, at higher pH's on the other hand, phosphoric acid is better. For both pH-ranges, ammoniumsulphate is the most convenient nitrogen-source.

From the economic point of view, ammoniumsulphate and phosphoric acid are the most interesting products and should eventually be preferred over calciumnitrate and triple-superphosphate respectively, since the use of the former, by their chemical nature, results in a lowering of the pH of the culture, which can mean a substantial saving of the (expensive) carbon dioxide as pH regulator.

1.3.- Uptake of nutients in outdoor cultures

The uptake of nitrogen and phosphor by *Chlorella saccharophila* in 250 liter cultures under open-air conditions was studied over a 6 month period. The culture medium in which the *Chlorella*'s were grown was a modification of the basic medium of Walne (1956) containing 1 g PO_4^{---}-P ℓ^{-1} 2.5 g NH_4^+-N ℓ^{-1}, 2.5 g NO_3^--N ℓ^{-1}. The make-up water was coastal seawater of about 29 ‰ salinity. The average agal dry weight yield for the uptake of 1 mg nitrogen (Y_N) varied between 8 and 13 mg, the average yield

for phosphorus (Y_P) between 57 and 100 mg. This means that the N:P ratio of the nutrients consumed varied between about 5 and 13. These values indicate that neither N nor P were probably limiting. Data obtained for the nutrient uptake in other cultures of natural phytoplankton populations, consisting mainly of diatoms, revealed a higher N:P ratio for the nutrients consumed indicating that the P consumption by diatoms is lower than the one taken up Chlorococcales such as *Chlorella*.

2.- INFLUENCE OF LIGHT ON ALGAL YIELDS

During nearly a complete year cycle, the influence of the irradiation on the algal yields was studied (De Pauw, Verlet and De Leenheer, 1979). Semi-continuous and continuous 250 liter cultures of *Chlorella saccharophila* on natural phytoplankton were set up in open-air conditions. Continuous mixing of the algae in the tank was done by air-lift pumps. The pH of the cultures was stabilized between 7.5 and 8 by addition of carbon dioxide. The algae were grown in seawater enriched with inorganic fertilizers (ammoniumsulphate and phosphoric acid 85%). Depending on the time of the year, the detention time of the cultures was changed and varied between 30 days during winter and 4 days during summer. This corresponds with harvest rates of 3% and 25% per day respectively. The daily yields were calculated from the increase in algal dry weight. The parameter for steering the culture and determining the moment of harvest was optical density. In order to study the influence of sunlight irradiation on the algal biomass production, the effect of temperature fluctuations was eliminated by heating the cultures to a constant temerature of 22 to 23°C. The experiment ran from August 1977 till April 1978.

The results revealed that almost independently of temperature, the mean algal dry weight production at our latitude (55.1°N) varied between 0 and 1 and 10 g $m^{-2}d^{-1}$ during the winter and the summerperiod respectively (De Pauw, et al., 1979). At irradiation values of 200 J $cm^{-2}d^{-1}$, algal growth is almost nil despite heating of the cultures. Light utilization as calculated from the dry weight figures, total irradiation and a caloric content of 5.5 Kcal g dry wt^{-1} (Komarek and Pribil, 1968) was in average 1.14% which corroborates with other data found in literature (Paelinck, 1978).

3.- INFLUENCE OF TEMPERATURE ON SPECIES COMPOSITION

The growth of natural phytoplankton populations was studied in enriched heated and unheated seawater in the same 250 liter culture device as described before. Observations were made within a temperature range of 1 to 26 °C. The cultures were run on a continuous bases i.e. continuous harvest at rates between 3% and 25% per day depending on the season.

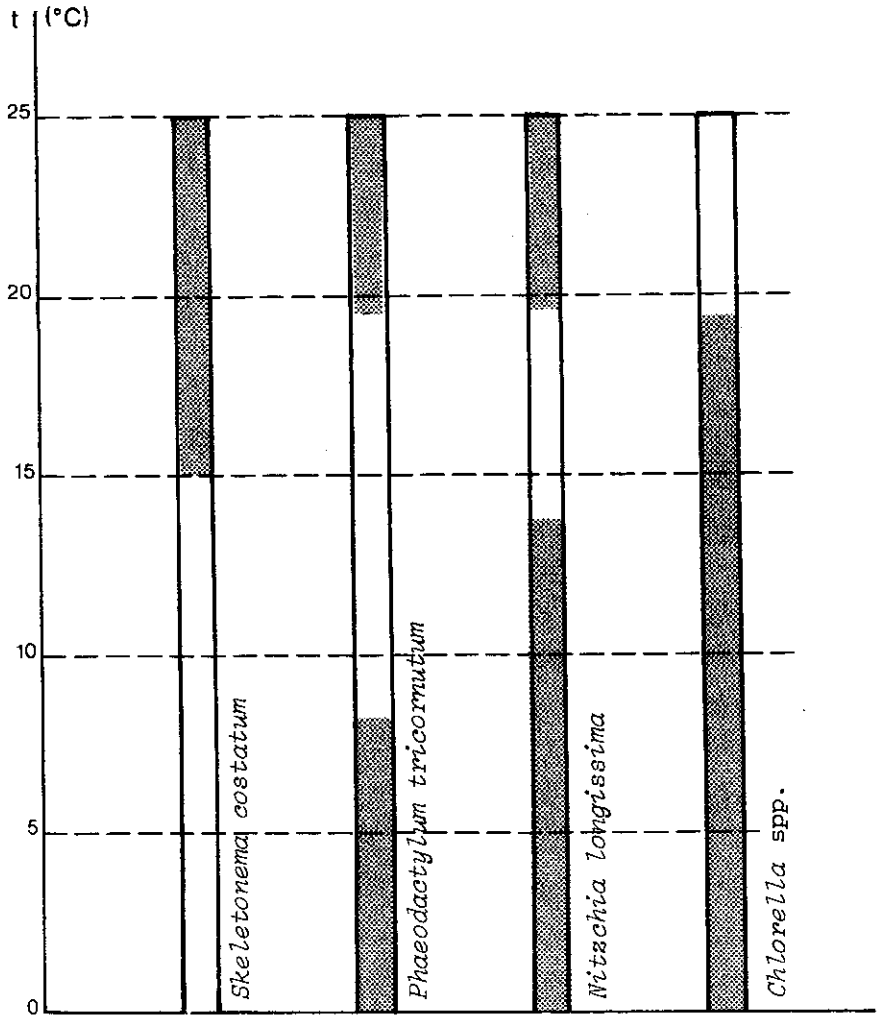

fig. 1.

Temperature range and dominance of phytoplankton species in sea water enriched cultures. Summary of observations for Ostend (Belgium) during 1977-1978.

▒▒▒ : regions of species instability where the species can remain dominant for a short period, but can also be quickly overtaken by other ones more adapted to the prevailing temperature regime.

Whereas increased temperatures may not have a clearly pronounced effect on the algal yields, temperature, as a prime ecological factor, certainly plays a crucial role in determining the species composition of natural phytoplankton populations in enriched seawater through temperature dependent interspecific competition (Goldman and Ryther, 1976; Goldman, 1977; De Pauw, Verlet and De Leenheer, 1979).

In figure 1 the species composition noted in a fluctuating temperature range of 0 to 26 °C is given.

In our cultures, persisting high temperatures of 20 to 23°C always resulted in a predominance of Chlorococcales (*Chlorella* spp). It should be mentioned that silicates were probably not a limiting nutrient in the experiments, since diatom blooms occured at all times in the unheated cultures. At lower temperatures between 0 and 15°C, small diatoms such as *Skeletonema* and *Phaeodactylum* dominated. *Nitzschia longissima* apparently prefered temperatures between 15 and 20°C, but this species never dominated the plankton completely. Our observations which corroborate the findings of several authors, indicate that *Skeletonema*, *Phaeodactylum* and *Chlorella* are clearly eurytherm, tolerating a large temperature range between 0 and 26°C.

For a more detailed discussion on this matter we refer to Goldman and Ryther, 1976 and De Pauw, Verlet and De Leenheer, 1979.

4.- TURBULENCE

The advantages of keeping the algal suspension in movement are numerous. The continuous mixing prevents sedimentation of the algal biomass (Stengel, 1970), it keeps the nutrients in active contant with the algal cell surface, leading to a stimulation of the nutrient uptake (Schumacher and Whitford, 1965, Ukeles, 1971), and induces a more effective utilization of incident light (Gates and Borchardt, 1963). Mixing of large-scale cultures is also essential to prevent thermal stratification, bottom anaerobiosis (Oswald, 1977) and to avoid photoinhibition (cf. Soeder and Stengel, 1974).

Within the framework of our research on suitable technologies for high density culturing of algae for mariculture purposes, we have been looking for alternative ways of agitating algal suspensions in relatively

shallow cultures which are characterized by a relatively large surface to depth ratio. By trial and error we found out that simple airlift-pumps well-known in aquariology, are very efficient in keeping algal suspensions in continuous movement throughout the watercolumn(Sorgeloos et al., 1977). From the economic point of view it is clear that mechanical energy provided to an algal culture, be it paddle-wheel movement, pumping, or circulation by compressed air (for ex. via air-water lifts) is a factor which contributes to a substantial percentage of the production costs. As such, it is also necessary to determine whether or not continuous circulation of the algal suspension is necessary or justified.

To explore this question, algal growth experiments in cultures mixed continuously or discontinuously versus non agitated (batch) cultures were carried out. The effect of mixing on pH stabilization has also been studied. Indoor small scale experiments with *Chlorella* in 100 liter tanks as well as outdoor large-scale experiments with natural phytoplankton in 70 m^3 tanks were set up. For a detailed description of the experiments, we refer to Persoone et al. (1979). The results clearly indicate that circulation of the algal suspension by airlift pumps increased the algal growth rate and thus the final yield in comparison to static cultures without any circulation. This was true for the small scale cultures of *Chlorella* as well as for the large scale cultures with natural phytoplankton populations in enriched seawater. The final yields in the mixed cultures were about 30% higher than in the non-mixed cultures.

The extrapolation of laboratory scale aeration and CO_2 bubbling to mass cultures indoors or outdoors, results however in a number of technological as well as economic problems, the importance of which is of course directly related to the scale of the operation. In many aquaculture operations no mechanical agitation nor CO_2 bubbling is applied in outdoor algal cultures when the volume of the units exceed a few m^3.

Bearing in mind the economic repercussion of agitation in large outdoor units, we have been wondering if a continuous circulation of the algal suspension is necessary. Our experiments revealed that a halftime circulation (30 minutes aeration - 30 minutes no aeration) gives a final yield only 4% less than a continuous agitation and still 27% more than a non treated culture.

It is clear that the minimum of mixing energy beyond which the productivity does not increase anymore must be determined, as recently emphasized by Oswald and Benemann (1977).

Another interesting finding of our experiments is that the pH evolution in the cultures can be regulated, at least to a certain extent, by the time of aeration or the mixing intensity. A 50% reduction for example in aeration intensity resulted only in a 20% decrease of the final algal output. A practical conclusion which can drawn from these preliminary experiments is that for each type of culturing unit, the most economic aeration regime for which the algal output is maximal, should be determined.

Future planning

Further attention will be paid to the effect of different parameters on the species composition of the cultures. Competition experiments with natural phytoplankton populations will be carried out in relation to nutrient load, pH, retention time and temperature. Efforts will be made to determine under which controlled steering conditions suited algal species for mariculture purposes can be cultured outdoors on a large scale.
Since algal cultures may be very susceptible to predation by ciliates and zooflagellates, especially in large, open cultures, experiments will be carried out to evaluate the possible curative and preventive effects of several types of chemicals.
Pilot-scale outdoor algal enclosures of 100 m^2 surface each, are now in construction and will be equipped with different types of agitation mechanisms, to contribute further to the cost-benefit analysis of the mass culturing of microscopic algae.

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Survey and culturing of edible molluscs at the Belgian coast

Progress report on the research activities of the laboratory for mariculture[1]

C. CLAUS, H. MAECKELBERGHE, L. VAN HOLDERBEKE and A. VAN DE VELDE

Introduction

During the course of the last three decades the aquaculture of bivalve molluscs has been given more and more attention in coastal countries all over the world. The continuous progresses in technology have lead to the development of bivalve culturing in all coastal and estuarine areas, provided with a suitable climate. New perspectives are opened at an increasing rate in developing countries with no experience in this field, but with unlimited solar energy that can be transformed through algal cultures into living biomass.

In Belgium, a country which is located between two major European producers of bivalves (France and Holland) the own production of mussels and oyster is practically nil.

Twenty years ago Belgian and Dutch mussel-farmers however considered the mussel population from the poles of the pier in Nieuwpoort as a most valuable stock of seed for the mussel industry in the Western and Eastern Scheldt. Moreover, at that time and even long before, Ostend was famous for its locally produced oysters, the "Ostendaises".

The pollution of some areas of the Belgian coast, and the desinterest of the oyster-producers to adopt the new developments in bivalve aquaculture,

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1. State University of Ghent (Belgium); dir.: Prof. Dr. G. Persoone.

had as result that the Belgian oyster industry is presently reduced to a wholesale business of imported oysters, which are stocked for maximum six months in the Sluice Dock of Ostend or Blankenberge.

Although there are not many suitable sites for oyster and mussel culture along the Belgian coast (which is only 65 km long), several sites (for ex. the Sluice Dock in Ostend and Blankenberge and the mud-flats in Nieuwpoort) are excellent biotopes for the fattening of oysters and clams and are presently under-exploited in this regard. As far as the nursery-culture of juvenile molluscs is concerned, this is theoretically everywere along our coast, in indoor as well as in outdoors conditions.

Contrary to the oysters and clams, the edible blue mussel, *Mytilus edulis* L. is a common inhabitant of the intertidal zone along our coast. Spawning occurs in the summer, and the natural spatfall is so abundant, that every exposed substrate is, after a while, completely covered with young seed mussels, even in areas 20 km offshore.

An adequate disposition of the appropriate type of seed collectors should yield substantial quantities of juvenile mussels which could either be grown out on the bottom of the Dutch Eastern Scheldt, or along the Belgian coast or artificial substrates.

In view of the foregoing, investigations have been started by our research team which shall hopefully lead in the future to commercial exploitation of natural and cultured populations of edible molluscs in Belgium.

Experiments and results

1.- THE GROWTH OF EDIBLE BIVALVES IN THE OPEN SEA

The growth of edible bivalves in the open sea and along the coast is presently monitored in four different ways :

1) A qualitative survey of the mussel population on the buoys moored for navigation purposes at different sites offshore the belgian coast. After a period of 20 months the buoys are completely covered with mussels and other fouling organisms and are replaced by new ones. Each time a buoy is brought back to the Ostend harbour, a random sample of ± 5 kg of

mussels is taken. Shell length, weight and dry weight of the meat are measured on a subsample of 100 mussels. The residue of heavy metals accumulated in the body is analyzed by courtesy of the Ministry of Agriculture, I.S.O. in Tervuren.

To date 5 buoys have been analyzed. One location gave significantly larger specimens. The mussels attached to the anchor-chain of the same buoy were 30% smaller.

In average a shell length of 36 mm was attained in a period of 20 months. This corresponds with a growth rate intermediate to that observed in the dutch Wadden Sea and on the french "bouchots" in Brittany. These results clearly illustrate that growth is essentially temperature-dependent.

In none of the mussel samples an alarming level of heavy metals has been detected. Hg, Cd and Pb concentrations were normal. The Cu level was slightly higher than normal, the Zn level highest (> 200 ppm). The antifouling treatment of the buoys prior to morring has not caused any important accumulation of heavy metals in the mussels.

2) The second type of analysis is a semi-controlled culture of the blue mussel on rope in open sea. Twenty ropes with each 10 kg of juvenile mussels were suspended from a seaffolding attached to a moored lightship. This technology, however, was very vulnerable to the heavy fall and winter storms in the North Sea. Although the device has resisted to the turbulent sea, a large part of the attached mussels were lost, and those who remained must have been too much perturbed to feed sufficiently. In consequence growth was practically nil during a period of 12 months. Length increased with only 20%, the dry weight of the meat with 50%.

Settlement of new spat however took place during the summer, and this spat tends to grow faster than the juveniles which were hung out at the start of the experiment. The results are in any case inferior to the mussel growth on the buoys.

3) In a third series of tests started mid June 1979, the growth of juvenile mussels, oysters and clams will be followed in a culturing module placed on the sea-bottom ± 500 m offshore Knokke-Het Zoute. This experiment is carried out in view of the construction of a special pier designed basically for the protection of the harbour of Zeebrugge, but conceived

as a unique maricultural structure for the mass-culture of bivalve molluscs, with an expected annual production of 5000 ton mussels.

4) The fourth series of tests consists of a qualitative and quantitative survey of the settlement and growth of mussel spat on sisal and nylon ropes in the Nieuwpoort estuary from May till October 1979.

2.- THE GROWTH POTENTIAL OF MOLLUSCS IN NATURAL AND ARTIFICIAL SEA-WATER PONDS

The growth potential of molluscs in natural and artificial sea-water ponds along the Belgian coast is evaluated by means of a series of growth experiments with mussels, clams and oysters.

Three biotopes are taken into consideration : the Sluice-dock of Ostend : a shallow water body of 86 ha, the mud-flats of the estuary in Nieuwpoort and a sea-water basin in concrete of 130 m^3 contenance located in Den Haan, a few km east of Ostend.

In all three biotopes different experiments are in progress, with analyses of the growth of bivalves in function of :

- the size of the specimens (length and live weigth)
- the stocking density (per surface and volume-unit)
- the seasonal variation of temperature, light intensity and food supply
- the technology and length of the experiment.

After one and a half year of experiments, we can conclude to date that all three of the test biotopes are valuable for the fattening of bivalves.

When the stocking density is not limiting, the growth of the bivalves is directly in correlation with the feeding regime, which is very similar in the three locations. As a rule the seawater tank in Den Haan gave slightly better results for oysters. Mussels and clams on the contrary, trived best in the Ostend Sluice Dock.

Growth rate is very different according to the various bivalve species. Starting from spat with similar dimensions, (a length of 6 mm), after 6 months (from end May until end September), *Crassostrea gigas* reached a mean length of 53 mm, *Ostrea edulis* of 40 mm, and *Venerupis semidecussata* of 14 mm. The growth rate of both oyster species can be

considered as very high. The results with the flat oyster *Ostrea edulis* exceed significantly the results obtained by Drinkwaard (1978) in the Eastern Scheldt and Lake Grevelingen.

The rapidly growing *Crassostrea gigas* seems to be fully adapted to the local environmental conditions. Growth in these locations is significantly higher than in the locations in the U.K. mentioned by Askew (1978).

During winter growth is zero and higher mortality rates are noted. For example, the 1978-1979 winter was fatal to almost all *Ostrea edulis* juveniles in all three exprimental sites. *Crassostrea gigas* is much more resitant and even continues to increase slightly in weight even at temperatures below 4°C.

The Manilla clam *Venerupis semidecussata* trives very well in the Sluice Dock of Ostend. In the seawater tank in Den Haan it suffered high mortality. The culturing of clams in suspended trays has not always been successfull thusfar ; one of the reasons may be that this artificial environment is very different from the natural habitat of the clam, which lives burried in a sandy sediment. A second series of tests has been set up very recently.

For a full analysis of the potential yields of oysters in the three locations taken into consideration, more data are needed. Especially variations in meat yield, either seasonally or between areas, needs further attention. From our results one can conclude that from the biological point of vue, there was no reason to cut down the belgian oyster industry. The rather limited areas of potential production are sufficiently rich in nutrients to support a profitable oyster on-growing over the entire size range to be handled. Similarly, the culture of the Manila clam *Venerupis semidecussata* looks promising although the culturing technology and growing schedules need to be improved.

The productivity of the Ostend Sluice Dock has also been monitored by a one year study of the growth of young mussels (*Mytilus edulis*) with the technique of hanging ropes. Mussel seed with a shell length of 15 mm was attached to nylon ropes which were suspended on two rafts in the Sluice Dock. Parameters such as shell length and weigth, total fresh weigth, freshweigth and dry weigth of the meat, were followed every month, together with a quantitative and qualitative analysis of the fouling. The growth rate of *Mytilus edulis* in the Sluice Dock equals the highest

growth rates recorded in the U.K. by Bayne et al. (1976), and those recorded on the french bouchots in Brittany. It is significantly higher than the growth rate of the dutch mussels parks in the Eastern Scheldt. In a review study Seed (1976) calculated that mussels should reach a shell length of 60-70 mm in 12 till 18 months in optimal conditions. In the Sluice Dock of Ostend this size was reached in 21 months, which in comparison to the results obtained in other European waters, is a very high growth rate. The condition index of the mussels from the Sluice Dock (the ratio shell weigth/dry weigth of the meat) was however not very satisfying : 92.5% of the total fresh weigth consists of unedible material, whereas in the mussel industry the current percentage is only 87.5 % . The mussels collected from the buoys showed condition indices which were 30 % higher in average.

For this reason, but also because of the fact that the very limited area (86 ha) and depth (1 - 1.5 m) of the Ostend Sluice Dock is insufficient to support a profitable grow out of mussels, we stopped the work with this species in this biotope and focused entirely on oysters and clams.

Nevertheless, the growth experiments with *Mytilus edulis* in the Ostend Sluice Dock have provided very interesting information, with regard to the growth of bivalve molluscs in artificial inland seawater ponds versus those obtained in the open sea. In addition, this test provided us with data about the accumulation rate of heavy metals in young bivalves. As far as this type of pollution is concerned, the levels determined in the mussels from the Sluice Dock are completely similar with the amounts found in mussels collected from breakwaters all along the Belgian coast.

3.- A BIVALVE NURSERY CULTURING SYSTEM

A bivalve nursery culturing system on pilot scale has been built in the laboratories of the Institute for Marine Scientific Research (IZWO) at the border of the Ostend Sluice Dock.

Unfiltered seawater is pumped through 20 culturing tanks with a capacity of 30 liters each. The retention time of the water in these tanks averages 1 hour. Water is heated during the winter at various temperatures.

In addition to the water circulation by pumping, an extra upward water flow is provided with the aid of a special culturing device, the 3-dimensional system (or 3-D system). The oyster spat is spread out on the sieve bottom of a culturing cilinder through wich water flows from the bottom to the top by the action of an external air-water lift.

Several experiments have already been carried out in this installation, especially with regard to the utilization of waste heat and recycling of biodegradable wastes, directly or indirectly through algal cultures. This research is part of a national R & D program concerned with the recycling of wastes. Data and details can be found in Persoone et al. (1978).

More basic experiments with *Mytilus edulis*, *Ostrea edulis*, *Crassostrea gigas* and *Venerupis semidecussata* have also been carried out and are still in progress. This tests are dealing with feedings rates, diets, water circulation, stocking densities, etc.

Special attention has been paid to the sapect of providing the juvenile bivalves with a continuous supply of live food of high quality (Persoone and Claus, 1978).

Research is also in progress on the feeding of mussels, oysters and clams spat with inert foods. Soya flour, spray dried *Spirulina* (blue alga) and micronized rice bran have been fed to *Mytilus edulis* and *Venerupis semidecussata*. The results obtained with *Venerupis semidecussata* fed with rice bran are particularly promising and could open new perspectives for the nursery rearing of bivalves on a year round basis, independently of the seasonal changes in primary productivity and subsequently the amount and quality of the algal food.

At this moment, a semi-industrial algal culture – bivalve nursery culture system is under construction. It consists of four algal tanks of 100 m^2 each and a bivalve nursery with 32 culturing cylinders each with a capacity of 7 500 oysters (Persoone et al., 1979; Jaspers et al., 1979).

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Research at the *Artemia* reference center

Progress report on the research activities of the laboratory for mariculture[1]

P. SORGELOOS[2], E. BOSSUYT, E. BRUGGEMAN, A. COOREMAN, J. DOBBELEIR, P. VANHAECKE and D. VERSICHELE

Introduction

Although we had postulated at the FAO Technical Conference on Aquaculture (Kyoto-Japan, May 26 - June 2, 1976) that the *Artemia* cyst-problem is artificial (Sorgeloos, 1976) we still were pessimistic in 1977 when we reported that "... the provision of *Artemia* cysts, which presently can already not meet the demands any more, will become more and more a bottle-neck" (Sorgeloos et al., 1977a).

However in 1978 the *Artemia* cyst's situation has finally improved: i.e. various new sources for cysts have been exploited (Sorgeloos, 1979a) and the approximate offer of 100 metric tons per year has greatly alleviated the critical shortages from the past. Furthermore the price of cysts with high hatching quality dropped to about 40 US dollars per kilogram and is expected to decrease further (Sorgeloos, 1979b).

As a consequence of this promising outlook for the future, the use of *Artemia* as a cheap and high quality source of animal protein can be re-evaluated. It is clear that now, more than ever, many aspects on the use of *Artemia* need to be studied in order to reach this goal. Our team, in collaboration with many laboratories and institutes from all over the world, is studying the following aspects:

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1. State University of Ghent (Belgium); dir.: Prof. Dr. G. Persoone.
2. "Aangesteld Navorser" at the Belgian National Foundation for Scientific Research (N.F.W.O.).

1.- The artificial inoculation of salt ponds with brine shrimp

The world distribution of *Artemia* in salinas is not continuous: in certain salt water bodies of the world brine shrimp are not present either due to lack of natural dispersion or by the (periodically occuring) unfavorable climatic conditions (cf. review in Persoone and Sorgeloos, 1979).

Clark and Bowen (1976) show evidence that in the past decades man, at repeated occasions, has seeded salt works with *Artemia* cysts in order to achieve better salt production (cf. review in Sorgeloos, 1979c).

Helfrich (1973) was the first to consider *Artemia* inoculation for aquaculture application; however his site selection at Christmas Island turned out not to be favorable for commercial application. Since 1977 successful inoculations have been achieved with our aid in Brasil, India, the Philippines and Thailand.

In April 1977 the nauplii hatched out of 250 g San Francisco Bay cysts were introduced in a limited number of evaporation ponds of a very extended salt work in Macau (Rio Grande do Norte, Brasil). The ecological conditions in the Macau-salinas (the intake water of which originates from a very rich mangrove area) turned out to be very favorable for *Artemia*-production: the brine shrimp population spread out over several thousands of hectares and within 1 year over 15 metric tons of cysts were harvested (hatching quality: 4 ± 1 g product for the production of 1 million nauplii; cf. Sorgeloos et al., 1978). To date the yields are expected to exceed 30 metric tons of cysts per year (Von Tilburg, Dijkema and Guimaraes, pers. comm.).

The technical feasibility of man-controlled *Artemia*-production in temporary salt ponds in SE-Asia has been demonstrated during the 1977-78 dry season in 2 salinas at Barotac Nuevo (Iloilo Province, Philippines; Anonymous, 1978; Sorgeloos, 1978; De los Santos et al., 1979) and was further confirmed by tests repeated during the 1978-79 dry season at various other places in the Philippines and in Thailand (Bernardino, respectively Vos, pers. comm.).

Studies are now underway at the SEAFDEC-Aquaculture Department in the Philippines (Primavera et al., 1979 and pers. comm.) and at the Department of Fisheries in Thailand (Hutasingh, Tumsutatanich and Vos, pers.

comm.) to evaluate a model system for integrated pond production of salt and *Artemia* during the dry season, and shrimp and/or fish during the rainy season.

Inoculation tests with various geographical strains will not only provide new information on geno- and phenotypical strain-characteristics (cf. cyst-sizes in Vanhaecke and Sorgeloos, 1979) but will also lead to strain selection in function of the production performances.

It is clear that application of this inoculation-principle (either a one time or a cyclic activity, depending on the local climate) will further alleviate the cyst provision problem, both at the national (e.g. SE-Asia) and at the international level.

Although cysts might be the first production goal, the exploitation of the adult biomass as a most valuable protein source for many aquaculture organisms and even for man (Sorgeloos, 1979b) will undoubtedly be considered in the next future.

2.- Optimisation of the use of brine shrimp cysts in aquaculture hatcheries

As reported in previous articles, more, better and cheaper *Artemia* nauplii can be hatched out of cysts by application of the latest progresses made in this field (Sorgeloos et al., 1977b, 1977c). In this regard our newest findings can be summarized as follows:

2.1.- DECAPSULATION OF CYSTS

Since our last paper on this subject (Bruggeman et al., 1979), we have worked on the following aspects :

- decapsulation technique using bleaching powder calciumhypochlorite instead of liquid bleach sodiumhypochlorite;
- prototype system for large scale decapsulation;
- desactivation methods for the chlorinated residues which affect the hatchability of the decapsulated cysts;
- beneficial effects of the decapsulation process on the hatching

efficiency and the energetic content of the hatched nauplii (at least for some geographical strains).

More details on these studies can be found in Bruggeman and Sorgeloos (1979);

2.2.-

Minimal illumination conditions for maximal hatching rate and efficiency in large scale hatching conditions (cf. Sorgeloos, 1979b);

2.3.-

Beneficial effect and practical application of low salinity and high pH-media on hatching rate, hatching efficiency and energetic content of the hatched nauplii (Sorgeloos, 1979b);

2.4.-

Influence of the cyst's storage conditions on their hatching characteristics.

3.- Controlled mass production of *Artemia* adults

3.1.-

The technique of batch production of *Artemia*-biomass in air-water-lift operated raceways on ground ricebran is now a routine-procedure : using a turbidimeter-controlled automatic food distribution, an average production of 2 kg *Artemia* adults per m^3 is attained after 10 days culturing at 28 °C (more details in Bossuyt and Sorgeloos, 1979; Sorgeloos et al., 1979).

Since various other agricultural wastes proved to be a suitable diet for brine shrimp and the maximum particle size which can be ingested by *Artemia* nauplii and adults has been determined (Dobbeleir et al., 1979) we shall now start an economic feasibility-study of the controlled mass production of brine shrimp on micronized wastes using thermal effluents as heat source.

The nutritional suitability of *Artemia* adults, grown on various (eventually mixtures of) inert diets will be tested in collaboration with various fish and crustacean hatcheries.

We hope to increase our present production figures by switching from plate separators to "cross-flow-sieve"-techniques for a more efficient removal of the suspended faeces from the culturing medium.

3.2.-

The flow-through culturing technique, developed jointly with the St. Croix (US Virgin Islands) Marine Station of the University of Texas Marine Science Institute, offers great potential for high density mass culturing of *Artemia*. As compared to the batch culturing methods, the production data per unit of tank volume can be over 10 times higher (Tobias et al., 1979a; Sorgeloos, 1979c).
From the St. Croix-experiments it appears that in artificial upwelling mariculture systems (f.ex. in the effluent of an OTEC-system, cf. Roels, 1979), the microalgae can be valorized much more efficiently with an *Artemia*-production unit than in a Mollusc-hatchery (Sorgeloos, 1979c).
In view of its possible application in geothermal and OTEC-projects, we are also investigating the potential of flow-through culturing of *Artemia* on micronized wastes. The following technical aspects are presently under study:

- various types of food distribution;
- maximal retention times of the culture medium for productions of more than 15,000 animals per liter;
- application of the "cross-flow-sieve"-technique for continuous and automatic harvesting of the offspring produced from the effluent of the culture tanks.

4.- Controlled mass-production of *Artemia* cysts

The technical feasibility of cyst production in batch conditions on inert diets (Versichele and Sorgeloos, 1979) or in flow-through systems on live algae (Tobias et al., 1979a) has been demonstrated.

We doubt if these cyst production techniques will ever be able to compete with natural cyst exploitation. However, their application, especially the flow-through culture method, might not only lead to a further unraveling of the cyst's characteristics and the diapauze-activation process (Versichele

and Sorgeloos, 1979), but also to the production of sufficient inoculation material from natural or laboratory produced strains.

5.- Comparative study of various geographical strains of brine shrimp, *Artemia* spp.

A thorough characterization and selection study of the numerous strains of *Artemia* for application in aquaculture is only possible on a multidisciplinary basis. This postulation has been achieved in 1978 through the joined efforts of 5 university laboratories from different countries: an integrated research programme for the collaborating parties of the so-called "International Study on *Artemia*" (ISA) was initiated and is coordinated by our *Artemia* Reference Center. The participants to this study and their specific research are:

- Department of Food Science and Technology, Nutrition and Dietetics, University of Rhode Island, USA (Coordinator: K.L. Simpson).
  Chemical and biochemical analysis of cysts, nauplii and adults: amino acids, fatty acids, lipids, carotenoids, chlorinated hydrocarbons and heavy metals;
- Department of Genetics, University College of Swansea, UK (Coordinator: J.A. Beardmore).
  Genotype characterization; inheritance of specific quantitative characteristics; temperature and salinity adaptation studies;
- Environmental Research Laboratory, Environmental Protection Agency at Narragansett-RI, USA (Coordinator: A.D. Beck).
  Biological effectiveness of brine shrimp for the fishes *Menidia menidia* and *Pseudopleuronectes americanus*, and the crustaceans *Mysidiopsis bahia* and *Rhithropanopeus harrisii*; naupliar swimming behavior;
- Center for Mariculture Research, Port Aransas Marine Laboratory of the University of Texas Marine Science Institute, USA (Coordinator: O.A. Roels).
  Biological effectiveness of brine shrimp for the fish *Cynoscion nebulosus* and the crustacean *Penaeus vanamei*;
- St. Croix Marine Station, University of Texas Marine Science Institute, US Virgin Islands (Coordinator: O.A. Roels).
  Production performances of *Artemia* in the local Artificial Upwelling Mariculture System; production of nauplii, cysts and/or adults as test-

material for the other participating laboratories;

- *Artemia* Reference Center, State University of Ghent, Belgium (Coordinator: P. Sorgeloos).

Biometrical analyses; hatching, growth and reproduction characteristics in function of different temperature-salinity combinations; crossing tests; preparation and standardization of research material for the participating laboratories.

The initial results of a detailed characterization study of 6 selected strains of *Artemia*, i.e. San Francisco Bay (CA-USA), San Pablo Bay (CA-USA), Great Salt Lake (UT-USA), Margaritha di Savoia (Italy), Shark Bay (W-Australia) and Macau (NE-Brazil) will be reported in Beck et al. (1979), Johns et al. (1979), Klein-MacPhee et al. (1979), Olney et al. (1979), Schauer et al. (1979), Seidel and Simpson (1979) and Soejima et al. (1979).

A wider range of strains was studied for their genetic similarities (Abreu-Grobois and Beardmore, 1979); their biometrical characteristics (Vanhaecke and Sorgeloos, 1979); their production performances on live algae in a flow-through system (Tobias et al., 1979b) and their naupliar locomotory rates, patterns and photoresponses (Miller et al., 1979).

These initial data already provide significant information for the selection and practical use of brine shrimp strains in aquaculture: e.g. with regard to the pesticide-contamination of the cysts, the size and energetic content of the freshly hatched nauplii, the difference in nutritional value of particular strains for specific predators, etc...

In the future, correlation analyses of the data obtained by the various contributing laboratories will allow to better distinguish between geno- and phenotypical characteristics and to select the most important characterization criteria for the evaluation of new strains. Production tests with specific strains (natural or after cross-breeding) in (semi-) controlled environments, e.g. in St. Croix or after inoculation in SE-Asian salt ponds, will contribute to the further unravelling of the above mentionned strain characteristics and will allow to start with strain improvement tests.

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Synthesis of research on nutrients in the Southern Bight of the North Sea[1]

J.P. MOMMAERTS[2], W. BAEYENS[2] and G. DECADT[3]

Introduction

When the "nutrients" group was set up in 1977, the problems had already been clearly set forth. Later on, they were regularly recalled, but progress is very slow. Such is the case of a fundamental question which concerns the dynamics of our coastal eco-system and which was raised for the first time six years ago (!) within the framework of the "Sea Project" : Is there a limiting element ? What is it ? How does it limit planktonic production ?

There is clearly a need here for some research which no-one has to date been disposed to fulfill.

It is however also in the biogeochemical cycle of an element such as nitrogen (rather than that of carbon) that the clear translocations between biological compartments are most apparent.

A major part of the problems is obviously due to the technical difficulties associated with measuring the uptake and excretion activities and the practical difficulties associated with measuring the inputs on the borders of the system.

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1. This paper is a part of the report "Synthesis of research on nutrients" OM/77-78/02 of the Belgian National Program, by the same authors.

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The research undertaken during the 1977-1978 period covered two main aspects :

1) *the regulation of phytoplanktonic activity* [based on work of A. Bertels, Excretie en primaire productiebepaling in de Noordzee, personal communication, 1978; J. Nijs et al., Bruto resultaten van de partikulaire en opgeloste primaire produktie voor Oostende - Calais - Hansweert, personal communication, 1978] with

a) examination of the seasonal curves observed in the three media in order to determine :
   1° the periods at which the concentrations of certain nutrients fall to a value such that one can reasonably estimate that they are limiting ("kinetic" limitation), G. Decadt et al., Seizoenvariatie en ruimtelijke verspreiding van de nutriënten in de Zuidelijke Noordzee, personal communication 1978.
   2° the periods at which the N/P ratio varies considerably from its mean value (~ 7 in weight) ("stoechiometric" limitation).
b) enrichment experiments (conducted at sea) to determine which nutrient (therefore limiting) can stimulate photosynthesis.
c) enrichment experiments conducted in a reactor to determine the nature of the limiting element and to define the nutrient-uptake speed relation.
d) dosages of nitrate-reductase in the phytoplankton to determine if a capacity for the use of NO_3^- exists, even in the presence of NH_4^+, M. Somville, Nitrification et dénitrification dans l'estuaire de l'Escaut, Dosage de la nitrate réductase en Mer du Nord et dans la partie aval de l'estuaire de l'Escaut, personal communication 1978.

2) *the search for coherence* (means of translocation)

If the direct (or calculated) measurements of the flows of consumption and regeneration by the biological compartments, plus the inputs and outputs at the borders of the system are correct, then the variations of nutrient concentrations observed in the medium must be coherent with the resulting flow. The following points are discussed :

a) method of analysis of nutrients,
b) seasonal variations (time and space) of nutrients in the Belgian coastal zone,
c) the flows implied by these variations.

Results

1.- REGULATION OF PHYTOPLANKTONIC ACTIVITY

1.1.- Recall of a few theoretical aspects

Just as light controls the intensity of primary production, the concentration of one or more nutritious elements (one generally thinks of NO_3^-, NH_4^+, PO_4^{---}, $Si(OH)_4$, but there may be others) influence the rate of biosynthesis and play a determinant role in the interspecific competition within the phytoplankton.

A mathematical model of the ecosystem must necessarily take into account the regulating effect which the limiting nutrient exercises on :

1°) the uptake speed U of this nutrient S : it is generally accepted that the relation has a hyperbolic form, described by Michaëlis and Menten :

$$U = U_{max} \times f(S)$$

with

$$f(S) = \frac{S}{K_s + S}$$

varying between 0 and 1 ;

2°) the uptake speed of other elements (nutrients or constitutive elements such as carbon) with two approaches :

a) *the simple approach* : the speeds are in the same ratio as the constituents of the living matter (phytoplankton) : 41 : 7.2 : 1 for C : N : P (in weight). The ratios C/N = 5.7 and its inverse

$$\frac{1}{\text{Yield}} = Q = 0.18$$

are particularly used.

b) *the complex approach* : several works indicate that a distinction should be made :

α) between the metabolism of *carbon* (photosynthesis, regulated primarily by light) and the *limiting nutrient* (uptake, regulated primarily by the ambient concentration);

β) between the *uptake* and *growth* mechanisms.

In actual fact, whatever Monod might have written, the equation which best describes the growth (cf. net particulate production) does not necessarily have the same Michaëlian form as that which describes the uptake : growth will be achieved rather by drawing from an internal reservoir which is constituted during a period of non-limitation. Droop (1973) proposed a new formula taking into account the very minute studies made in chemostats :

- uptake (e.g. in nitrogen) :

$$U = U_{max} \times \frac{S}{K_s + S}$$

- growth (e.g. in carbon) :

$$\mu = \mu_{max} \left(1 - \frac{Q_0}{Q}\right)$$

where $Q = \frac{S}{C}$ in the cell (quota)[1], with S is nitrogen for example and Q_0 is the minimum value of quota;

- evolution of intracellular quota :

$$\frac{dQ}{dt} = u - \mu Q$$

This formula, having been established for a system of constant light and based, as regard growth, on numbers of cells, cannot therefore be directly used in an ecosystem model.

Also taking into account the restriction referred to in § (α), Mommaerts (1978) proposed a model which incorporated these various elements in a logical manner :

- gross primary production (carbon) :

$$\frac{dC}{dt} \times \frac{1}{C} = U^C = U^C_{max} \times f_1(I) \times f(Q)$$

where U^C_{max} is the maximum speed of uptake of C (per unit of C), $f_1(I)$ is the function of light intensity, $f(Q)$ is the function of internal pool of nitrogen (ex.: $1 - \frac{Q_0}{Q}$) ;

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1. The form in which the nutrient reserve is stored is not specified. What is important here is that there is an approach per model which takes into account the biochemical composition of the phytoplankton, cf. Nijs et al., personal communication, loc. cit.

- uptake of nitrogen (if limiting) :

$$\frac{dN}{dt} \times \frac{1}{C} = U^N = U^N_{max} \times f(N) \times f_2(I)$$

where U^N_{max} is the maximum speed of uptake of N (per unit of C), $f(N)$ is the function of the external concentration of nitrogen, $f_2(I)$ is the function (to be specified) of light intensity (perhaps, function of stock of ATP available);

- evolution of the intracellular quota of N :

$$\frac{dQ}{dt} = U^N - (U^C - r)\,Q$$

where r is the rate of respiration.

Comment

Since Q can vary only within certain limits, the models provides for excretion (nitrogen or carbon, depending on the case) of the excess assimilated. In this, it is coherent with the observations of Fogg (1971) who writes that the excretion is much more important in an oligotrophic medium, or other more recent observations, regarding the photoreduction of O_2 (with release of glycollate) which can be taken as a means of absorbing an excess reducing power brought about by photosynthesis, cf. Bertels, personal communication 1978, loc.cit.

1.2.- Research into the limiting element

1.2.1.- *Theoretical considerations*

It may be useful to recall that there are two fundamental approaches to this problem :

1°) *the stoechiometric approach* : the study of the N/P ratio (for example) in water makes it possible to forecast the nature of the limiting element or at least that which would be the first limiting at the end consumption.

2°) *the kinetic approach* : below a certain concentration saturating value (in practice, less than 10 times K_s), the negative retroaction on the assimilation flow can effectively exist. Since the most commonly cited values of K_s (different phytoplanktonic species and different biotopes) are grouped around 1 µg at/ℓ of N(14 mg/m^3) or P(31 mg/m^3), one can

see that these two nutrients can occasionally be limiting, taking into account that the ranges observed in the North Sea vary between 3 and 30 µg at/ℓ for N and 1.4 to 3 µg at/ℓ for P (see also § 1.2.2.).

1.2.2.- *Seasonal variations of the main nutrients in the three zones*

Calais and Hansweert

The table 1 contains a few pieces of information (in µM/ℓ) extracted from the data of the Belgian team and also from the data issued by P. Mangelsdorf of the Biologisch Anstalt Helgoland, personal communication, 1978.

Table 1

	$NO_3^- + NO_2^-$	NH_4^+	PO_4^{---}	SiO_2	Source
Calais					
04.04.78	5.45	3.18	0.50	2.2	OM/1978 : 15
07.04.78	4.40	3.75	0.73	1.0	"
11.04.78	19.33	3.76	0.88	3.2	"
17.04.78	8.48	0.40	0.40	3.5	"
18.04.78	11.08	2.81	0.51	3.0	"
Hansweert					
05.05.77	215	61	-	-	OM/1978 : 21
07.04.78	261	28.17	-	-	"
21.04.78	191-249	18.0-36.3	-	-	"

Belgian coastal region

The seasonal variations in the different nutrients are made known to us by internal reports, cf. Mommaerts et al., personal communication, 1977, Decadt et al., personal communication, 1978. One can see that the ranges of concentration are roughly as given in table 2.

These results are discussed more particularly in § 2.3 and 2.4 as regards the precautions to be taken for their interpretation, the spatial and temporal variations and the flows they imply.

Discussion

The few results collected here are insufficient to establish a final comparison of the three biotopes : let us say that the presumption of a greater wealth in Ostend than in Calais is not invalidated. The even greater

Table 2

	1977	1978	
$NO_3^- + NO_2^-$	0 - 850	100 - 2000	in µg N/ℓ
	(0 - 60)	(7 - 143)	in µM/ℓ
NH_4^+	0 - 600	25 - 175	in µg N/ℓ
	(0 - 43)	(1.8 - 12.5)	in µM/ℓ
PO_4^{---}	40 - 300	25 - 300	in µg P/ℓ
	(1.3 - 9.7)	0.8 - 9.7)	in µM/ℓ
SiO_2	300 - 3000	250 - 1000	in µg Si/ℓ
	(10.7 - 107)	(8.9 - 35.7)	in µM/ℓ

wealth of the Scheldt cannot of course be questioned. As regards Ostend and Calais, one can see that the nitrogen and phosphorous are likely to fall to levels where they are kinetically limiting (if one acknowledges that the K_s of the phytoplanktonic organisms of the eutrophic waters in general exceed the unit). This would also be the case of the silica in Calais. In Ostend, and outside the main nitrogen peaks, the N/P ratio is always less than 7, which indicates that, in the case of prolonged consumption, the nitrogen would be exhausted in first place.

In conclusion, one cannot define the exact nature of *the most probable* limiting element without help of a more direct approach : enrichment experiments conducted at sea, enrichment experiments conducted in a reactor, taking into account all the "management parameters" who make the establishment of the exact relationship possible between *in vivo* and *in vitro* experiences (use of chemostat, controlled light, discarding effects of non limiting elements, etc.).

1.2.3.- *Enrichment experiments conducted at sea*

Stimulation effects on the primary production by adding NO_3^- (presumed to be limiting) have been studied during two cruises :

- in October 1977, positive stimulation effects have been observed at Ostend and at Hansweert (Nijs et al., 1978, loc. cit.);
- in April 1978, no stimulation effects have been observed at the three places under study (Ostend, Calais, Hansweert) [cf. Nijs et al., 1978, loc. cit.].

Discussion

One must first take into account the fact that this type of experience is not at all perfect in his conceptual formulation : on the contrary of the speed of *uptake* of the tested nutrient, the speed of *synthesis* of living matter is only indirectly related to the concentration of the limiting substrate (see also § 1.1.). Falkowski et al. (1975) have more particularly shown that the absence of stimulation can result from the competition between carbon dioxide and nitrate in the production scheme of ATP during the cyclical photophosphorylation processes. The absence of stimulation by nitrate, observed in the spring-time, near Ostend and near Calais, can also be a consequence of the limiting effect on the primary production due to other nutrients (PO_4^{---} for instance) :

Table 3

Concentrations in $\mu M/\ell$

	NH_4^+	NO_3^-	PO_4^{---}	SiO_2
Calais (4-4-78)	3.18	5.30	0.50	2.2
Ostend (5-4-78)	5.38	16.81	1.91	7.30

The stimulation effectively observed in autumn is not however understood since the concentrations of all nutrients were high. Furthermore, one observes that the curves observed are not at all of the Michaëlis-Menten type (see linear transformations in fig. 1).

These few results therefore leave us perplexed; it is to be regretted that these experiments were limited to a single type of nutrient.

1.2.4.- *Enrichment experience in a reactor*

This study which is currently under way and which forms the object of a research simultaneously conducted by the Analytical Department (V.U.B., Brussels) and the "Unité de Gestion des Modèles Mer et Escaut", sets out to determine the limiting element and establish kinetic curves which describe the overall substrate uptake regulation for natural populations in the North Sea. It is an experiment inspired in part by the experiment of Harrison and Davis (1977).

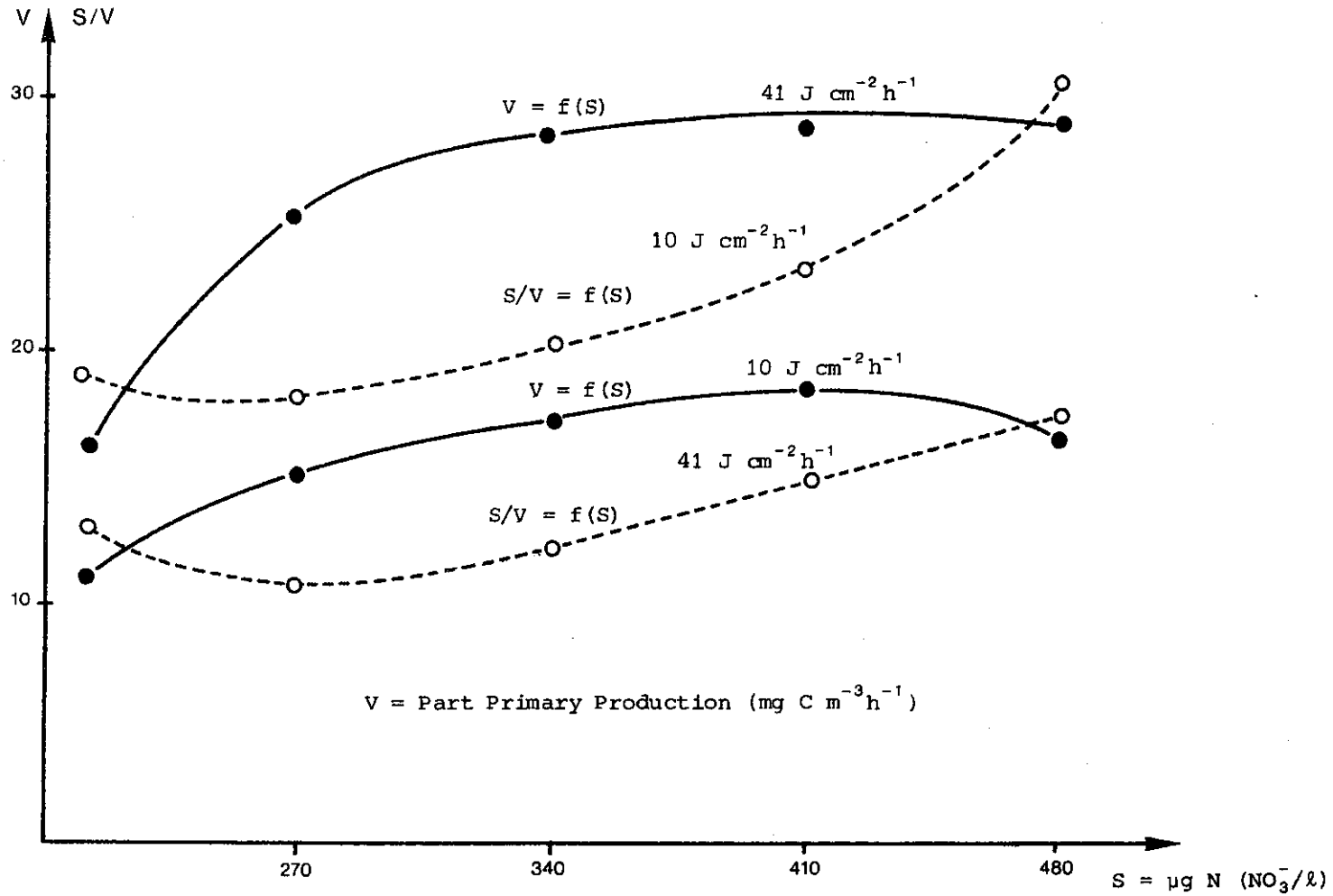

fig. 1.

Sampling point 33
(18-10-77)

1.3.- Ammonia-nitrate-reductase interaction

The phytoplankton can use the nitrate and ammonia as sources of nitrogen. This latter form would however be used preferentially since the cells thus dispense with a reduction.

To this must be added that, above a certain threshold of concentration (~ 1 µM NH_4^+/ℓ), the synthesis of the nitrate-reductase would be curbed. (e.g. Eppley et al., 1969). Since concentrations of NH_4^+ of more than 1 µM are currently observed, the assimilation of NO_3^- would in theory be virtually impossible in the three biotopes studied.

To check out this assumption, dosages of nitrate-reductase were regularly performed (Somville, personal communication, 1978, loc.cit.) by testing cellular extracts with a coenzyme in a reduced form (NADH in a non limiting concentration and in the presence of NO_3^-. The nitrite appearing in the extracts is a mesure of the degree of the enzymatic activity of the nitrate-reductase.

Results

In winter, the enzymatic activity cannot be determined except for a few offshore stations. This does indeed seem to be a question of detectability (very few phytoplankton) rather than a question of the presence or absence of enzyme.

In spring and in summer, nitrate-reductase is to be found virtually everywhere, particularly so the nearer one comes to the coast, whereas the NH_4^+ is generally present and sometimes very abundant (e.g. the greater enzymatic activities in the Scheldt).

In conclusion, the capacity for use of NO_3^-, even in the presence of NH_4^+ seems to have been established for our regions.

2.- THE SEARCH FOR COHERENCES

2.1.- Terms of the problem

By virtue of the principle of the conservation of matter, the net variations of concentrations of dissolved nutrients must be coherent with the direct measurements of the flows of consumption and regeneration (uptake by primary production and regeneration by microbiological processes

especially) as well as the input and output flows at the borders of the system.

As regards the latter, we have already seen for the South Bay of the North Sea (Nihoul et al., 1977) that the input and output flows are virtually equal (namely $\simeq 300.10^3$ tons N/year) and that the Scheldt and the coastal region contribute a quantity in the order of 10^4 tons N/year. Both this coastal input and the probable error on the "flows" balance sheet are small in the light of the circulation of matter exclusively due to biological processes. On the basis of a net primary production of some 200 g C/m^2 per annum, one calculates a consumption of some 200.10 tons N/year.

It is therefore very useful to compare the variations in biological activities with the variations in nutrients in the three zones (Calais, Ostend and Hansweert) studied by the "Organic Matter" group (cf. these proceedings).

Unfortunately, there are currently two problems being encountered :

a) with the exception of the Belgian coastal region which is regularly visited within the framework of the Monitoring national programme, the Channel and the Calais zone are known to us only through measurements fairly spaced out in time, and originating from various sources (problems of intercomparability, a.s.o., see § 1.2.2.). As regards the Scheldt, which though well followed up as regards nitrogen (Somville, personal communication, 1978, loc.cit.), the problems are obviously more complex because of the specific hydrodynamic mechanisms and the pelagic bacterial processes unknown at sea : nitrification and denitrification. The case of the Scheldt will therefore not be dealt with in this synthesis.

b) As regards the spatiotemporal variations in the concentrations of nutrients in the Belgian coastal zone, unexpected phenomena have been observed, phenomea never observed (or the significance of which was not realized) in the former network (1970-1975) which was also considerably more extensive, and as a result visited much less frequently. This double problem (significance of data originating from different sources, phenomena with no common measure with known biological mechanisms) has given rise to a great deal of thought and serious reconsideration.

The following paragraph in fact illustrates the need for great caution in the interpretation of nutrient analysis results when precise functional relations with biological compartments are studied.
It is therefore not so much the reliability of the analyses which is questioned, but rather the need for a dynamic interaction between biologists and analysts.

2.2.- Discussion of analytical methods

2.2.1.- *Brief reminder of the techniques generally studied*

2.2.1.1.- *Conservation and pre-treatment techniques*

In all cases, the parameters are determined on samples which are neither filtered nor dialysed and conserved in plastic containers at - 20 °C , except in the case of PO_4^{---} (glass containers, addition of chloroform and cold storage).

2.2.1.2.- *Analytic methods*

a) Phosphorous

The analysis only concerns orthophosphate (dissolved and particulate). One induces the formation of a phosphomolybdic complex with a well defined pH (H_2SO_4 0.6 N), so as to prevent interference from the silica. This complex is reduced with ascorbic acid to obtain a blue colouring which absorbs particularly at 830 nm .

b) Ammonia

With Na phenolate and Na hypochlorite, the ammonia forms a blue complex of indophenol, the absorption of which depends on the pH and is measured at 625 nm . The precipitation of Ca and Mg hydroxides is prevented by the addition of EDTA on the one hand, and a mixture of Na and K tartrate and Na citrate on the other. A sample of aged seawater is used for checking.

c) Nitrate + nitrite

There are in fact two measurements :

1°) direct measurement of the NO_2^- using a classical diazoreaction with the sulfanilamide, coupled with a reaction with the N-naphtylethylene-diamine so as to induce a purple stained complex, the absorption of which is measured at 540 nm.

2°) measurement, using the same method, of the total ($NO_3^- + NO_2^-$) following

reduction to NO_2^- by passage on a column of cupro-cadmium. The pH of the sample does not play an essential role whilst it ranges between 5 and 9 .

d) Silica

One induces the formation of a yellow molybdic complex with a pH of approximately 1.6 so that there is little interference from the phosphates (furthermore the addition of oxalic acid considerably reduces the staining due to phosphorous which becomes negligible up to 5 parts for 1 part of silicium). This complex is reduced by amino-1 naphtol-2 sulphonic-4 acid or ascorbic acid so as to obtain a blue staining which is measured either at 815 nm or 765 nm .

2.2.2.- *Outline of the main problems raised by these methods*

In order to ensure correct *interpretation* of the analytical results and especially of their significance from the point of view of functional relations with the biological compartments, the following problem should be discussed : *Is the information obtained precisely that which is sought ?* In actual fact, the analytic methods described above provide the *total* concentrations of certain forms of nutrients whereas a more detailed speciation would be preferred.

Ex :

- the total orthophosphates measured concern the dissolved and particulate phases (adsorbed or solid). Moreover, neither the polyphosphates nor organic forms are measured although it would be interesting to know more about them.
- as regards the ammonia, there is no doubt that the easily degradable forms (ex. urea, amines) play a major role in the nitrogen cycle. To what extent can these forms interfere in the consumption patterns of the actual measured forms (NH_4^+, NO_2^- + NO_3^-) ? To what extent should a prior UV irradiation stage, before analysis - as recently introduced e.a. by UK teams - improve our knowledge in uptake mechanisms ?
- as regards the silica, one is faced with a fairly particular problem : considering the values of Si dissolved in the medium, one always finds values lower than those expected from the thermodynamic balances between the various solid forms (quartz, amorphous silica, carapaces of diatoms, etc.) and silica in solution. This situation results

either from the absence of some solids or from the biological activities which prevent the balance being struck. Furthermore, one can ask oneself if current analytic methods do not influence this balance in such a way as to provide incorrect results. Inversely, could the dialysis - which was already sometimes used and which is based on a completely different principle of analysis - not provide more information on this problem ?

2.3.- Spatial and temporal variations in the concentrations of NO_3^- , NO_2^- , NH_4^+ , PO_4^{---}, SiO_2 in the Belgian coastal zone

The data are drawn out from internal reports (Mommaerts et al., personal communication 1977, loc.cit.; Decadt et al., personal communication 1978, loc.cit.). These data give some idea of the major variations which occurred in the Belgian coastal zone in 1974, 1977 and 1978.

One can synthesize the information as follows :

- during the periods of (May-June) and/or (August-September) there sometimes occur very important peaks in concentration as regards the (NO_3^- + NO_2^-) and the NH_4^+. These peaks do not correspond to the overall summer consumption-winter regeneration plan which can be observed for the other nutrients.
- the variations (both spatial and temporal) in (NO_3^- + NO_2^-) and NH_4^+ are more or less associated. This applies also to those of the PO_4^{---} and SiO_2. The behaviour of these two couples is however radically different.
- regionally, the greatest values are always observed near the mouth of the estuary (Sector III) outside the peak periods. The map with the sectors is given in figure 2. The general trend is one of a decreasing coastal-offshore gradient (see figure 3). Inversely, when there is a seasonal maximum (peak) the highest values are observed offshore and to the west (Sector II). There is no longer a coast-offshore gradient, but high concentration nuclei situated rather more offshore than on the coast or in the estuary (see figure 4).

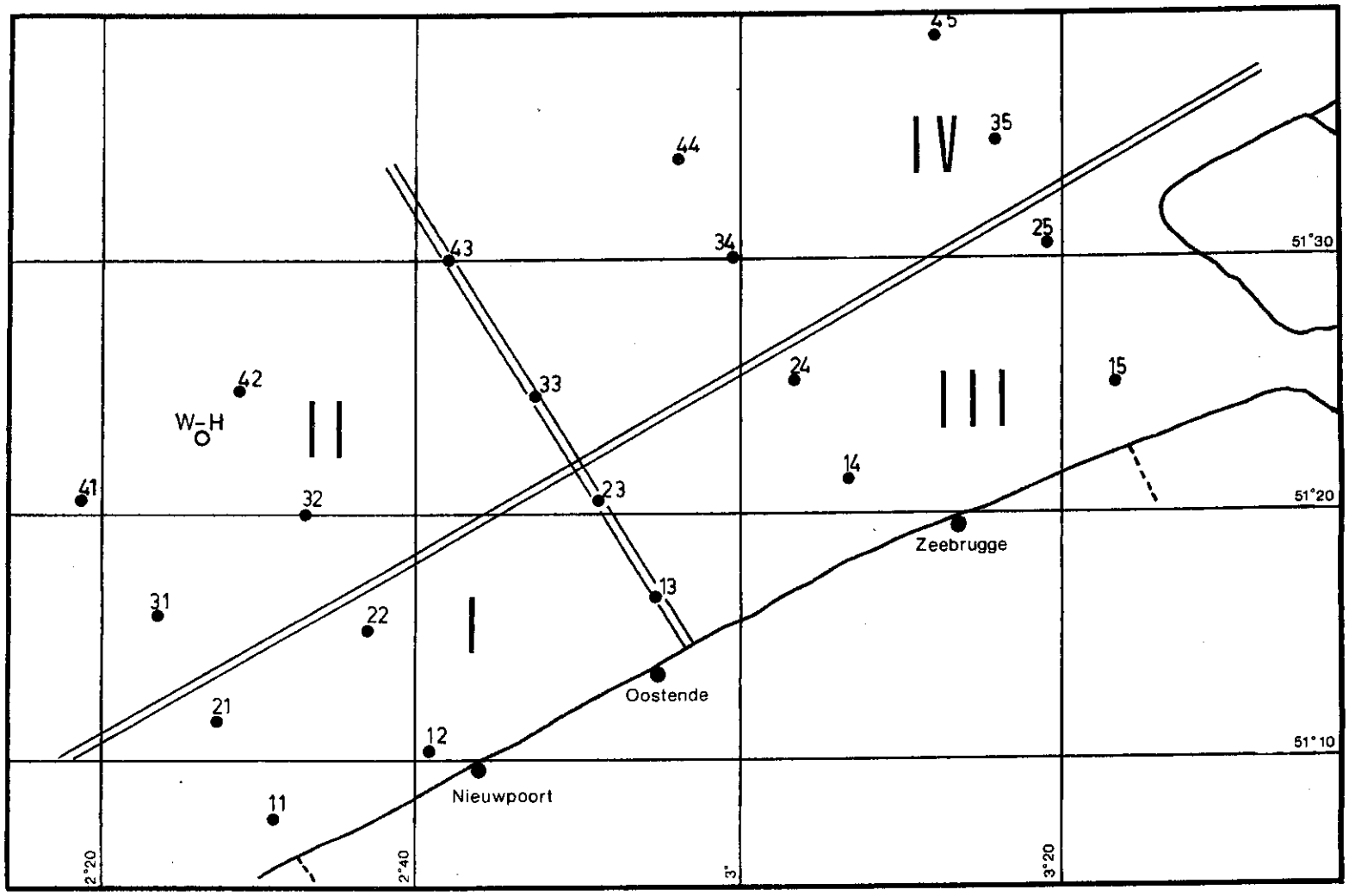

fig. 2.

Belgian coastal zone (sectors)

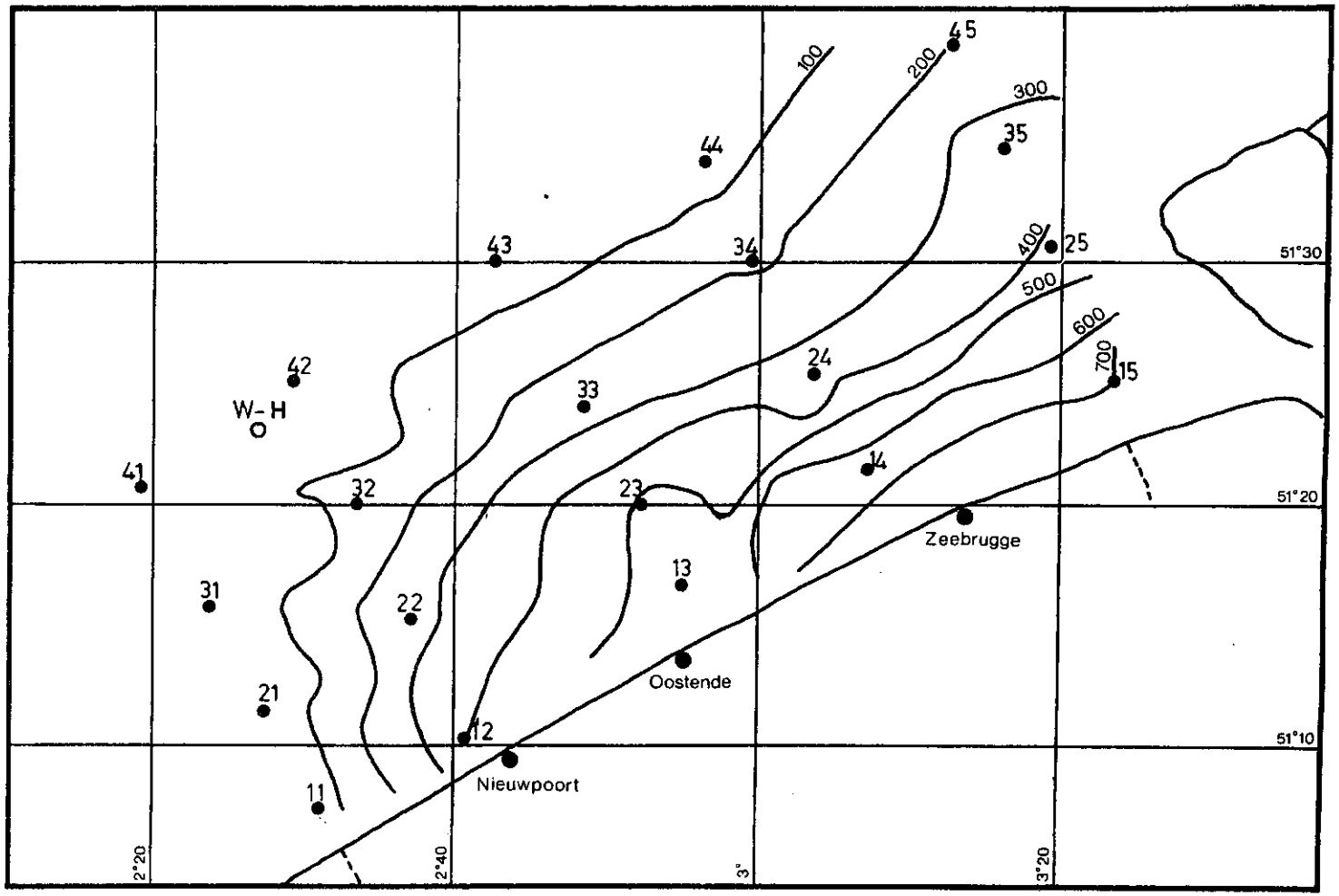

fig. 3.

Spatial distribution of NO_2^- + NO_3^- (µg N/ℓ)
(April 1978)

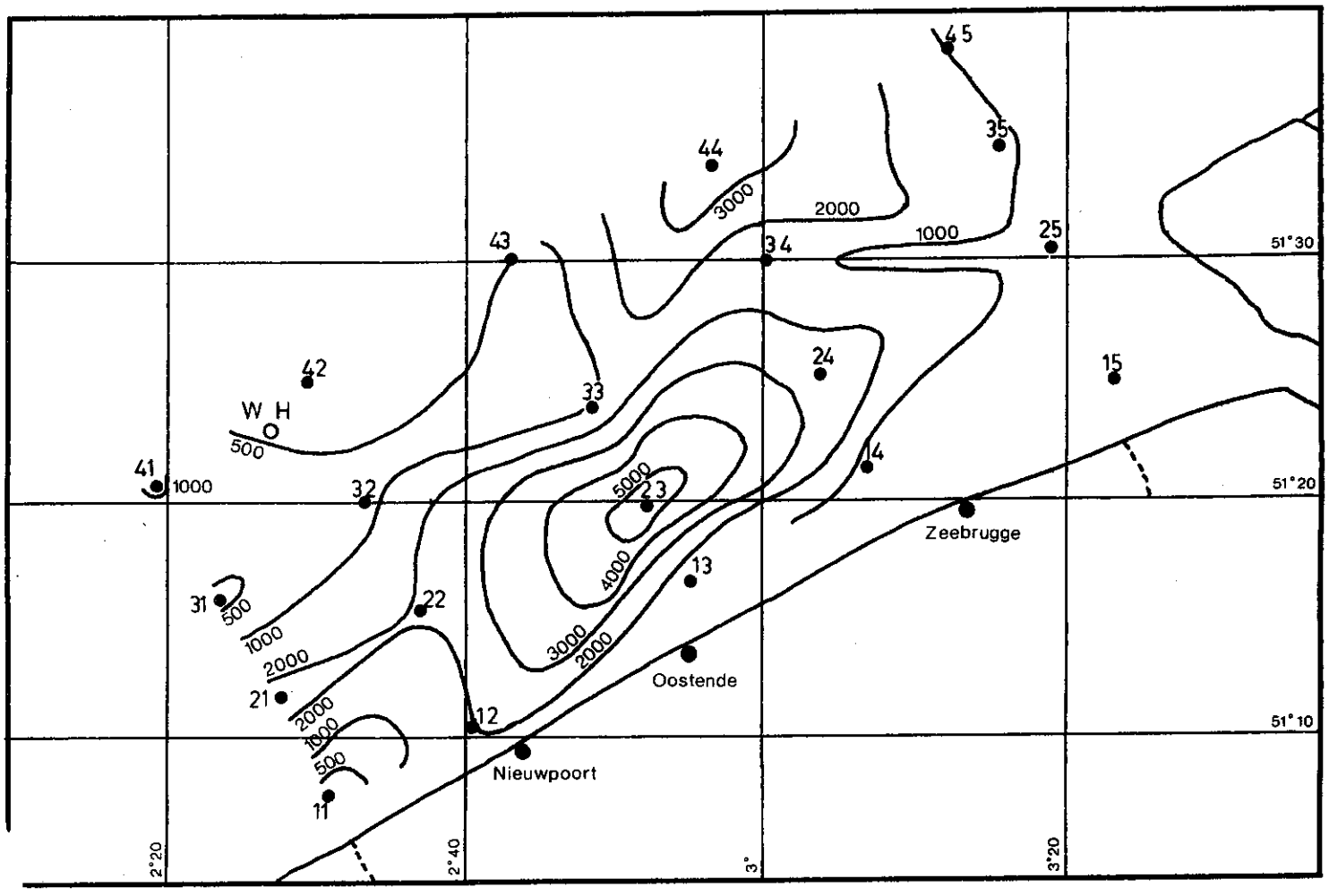

fig. 4.

Spatial distribution of NO_2^- + NO_3^- (µg N/ℓ)
(June 1978)

2.4.- Flows of net consumption and net regeneration implied by the concentration variations observed

The figure 5 obtained by calculating the first derived function of the concentration curves show that the net consumption and regeneration of nitrogen observed *outside the springtime period* largely exceed the minimal primary productions they imply (especially in 1977).

On the other hand, the flows of consumption of N , P and Si observed in the spring period of 1978 imply perfectly normal primary productions and are in the N : P : Si proportions typical of living matter.

During the important nitrogen peaks, one observes nothing in the water column (turbidity, abnormal bacterial activity, chlorophyll) which could cast light on this problem.

Moreover, there is no question of the Scheldt being such an important source of nitrogen at certain times of the year, if only because of the major dilution brought about by the mixture with North Sea waters.

2.5.- Conclusion

One could conclude this paragraph by bringing to mind certain recommendations (this list is by no means exhaustive) :

- from the analytic point of view, it would be useful if current methods were to have more specificity
- it would also be interesting to cross-check the results measured using other methods in the dissolved and particulate phases. This is particularly true for nitrogen (methods currently developed).
- from the point of view of sampling strategy, there should be a way of reducing the analysis time so as to be able to adapt the sampling frequencies whenever a special phenomenon is observed.

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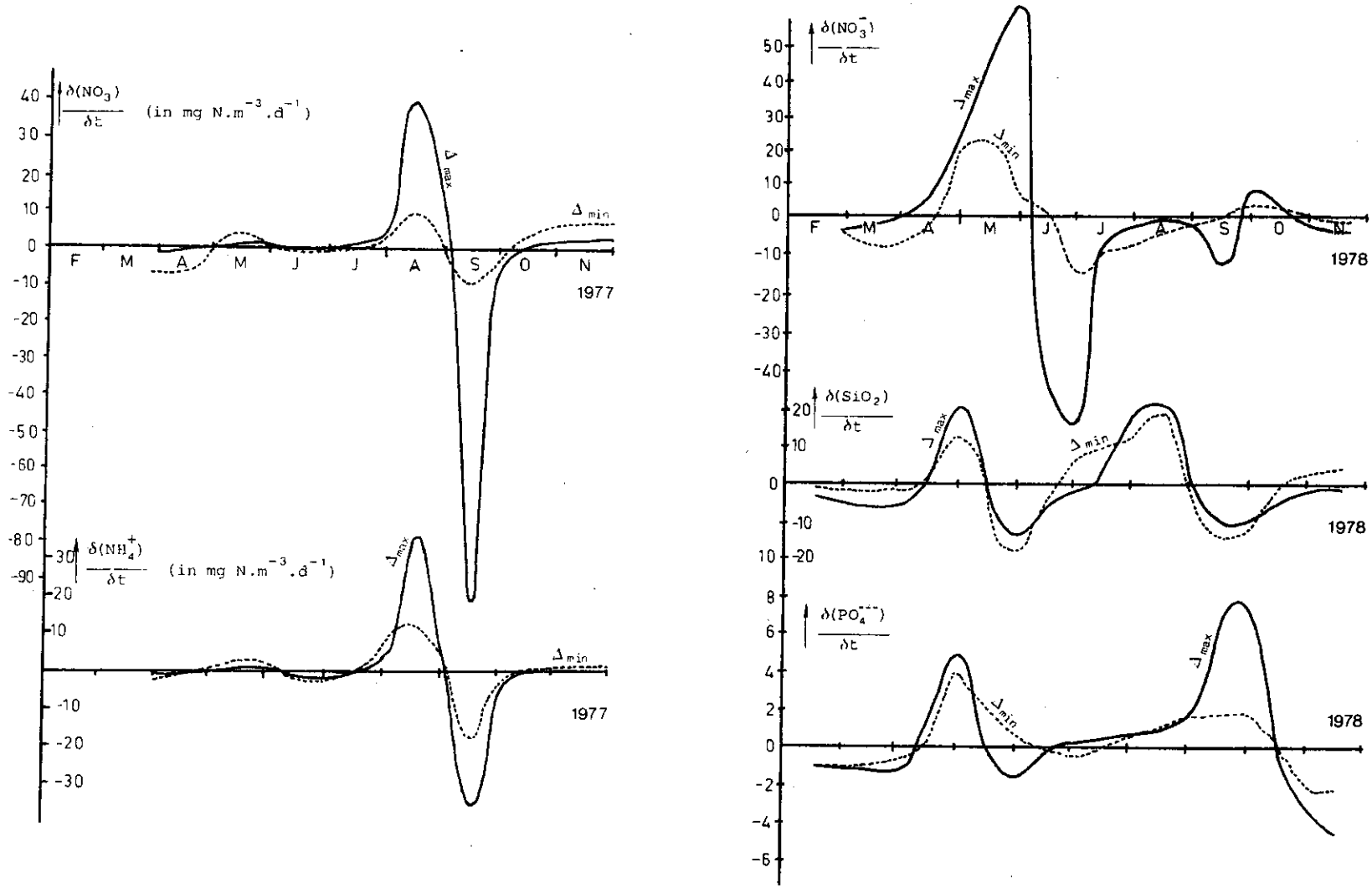

fig. 5.

Flows of net consumption and net regeneration of some nutrients

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Determination of dissolved, particulate and total mercury in the watercolumn of the Southern Bight of the North Sea, with adapted analytical procedures

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Introduction

Mercury is in the marine environment a constituent which asks for special attention because of its high toxicity. In the international Commissions - especially those of the Oslo, London and Paris Conventions - for the protection of the marine environment and for the reduction of the pollution, it was decided to give the first priority to the problems caused by mercury pollution. The final aim, namely the establishment of discharging norms, however, can only be realized if the coherence between the monitoring results of various origin is considerably improved. This implies that the different methodologies of sampling, storage and analysis, are examined and compared with the utmost attention. It is not very probable that a chain of manipulations, where different instruments and working methods are used, would give the same final result.

Intercalibration programs allow to compare statistically the accuracy of methods and instruments under the condition that the mercury component(s) and compartment(s) of the eco-system to be analysed, were unambiguously defined.

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Previous examinations (Baeyens et al., 1978 - Wollast, internal report, personal communication 1977 - Iparcom, 1977) lead to the conclusion that *dissolved* mercury concentrations in the marine environment are mostly very low and approach the sensibility of the analytical instrument. The reason of these low concentrations is a direct consequence of the adsorption kinetics and the large adsorptioncapacity of particulate suspended matter for several mercury components (Baeyens, 1977 - Decadt, personal communication 1977). In this view the determination of dissolved mercury requires a certain number of treatments - to avoid for example the adsorption on the wall of the container or loss to the atmosphere - from the moment of sampling to the final analysis, so that the result obtained would still be representative for the real *in situ* value.

If the determination of dissolved mercury caused problems in connection with sampling, filtration and storage aspects, the direct determination of the *total mercury content* in the watercolumn is even more difficult because the particulate mercury fraction is linked to, possibly incorporated in, the suspended solid matters. Depending on the digestion technic used, the total quantity of mercury present can be released or not and possibly even a part of the volatile components can be lost.

The applied digestion method plays also a very important part in analysing mercury in the sediments or centrifuged suspended matter. In order to release metals, not only a series of acid media ranging from ammonia-acetate till mixtures of concentrated hydrogenfluoride, nitric acid, perchloric acid (CNEXO, 1978) are available, but also a choice of the oxydator, temperature and the digestion time will influence the result.

This study concerns the establishment of a "tentative" relationship between the obtained results for total and particulate mercury in the water column and the applied analytical procedure. It is tried to find an explanation of the spatial mercury distribution in the water column of our coastal zone for some of the 1978 cruises. Finally it is examined whether or not a correlation could be derived from the observed values of mercury and some interacting parameters such as turbidity.

1.- Sampling problems

1.1.- DETERMINATION OF TOTAL MERCURY CONCENTRATION

During each consecutive treatment phase - sampling, storage and analysis - it is potentially possible to perturb the mercury concentration in the sample. This system can be improved considerably by excluding the storage phase and carrying out the analysis on board of the ship immediately after sampling. Since, because of practical reasons, this is very difficult to realize at present time, the finalizing of such a storage procedure becomes one of the main requirements in order to maintain the "original" distribution of the mercury in solution. Adsorption or desorption on the wall of the container, the loss to the atmosphere as a consequence of the volatility of various mercury compounds and the chemical transformations to forms of mercury with a larger adsorption - desorption capacity or volatility, are factors that can influence the reliability of the method. Several storage technics, in combination or not, can be used, such as : acidification, oxydation, storage at low temperature (in refrigerator or freezer), preconcentration, complexing, ...

For the cruises of the actual routine program organized in the North Sea by the "Unité de gestion du Modèle Mer et Estuaire, Belgium", it appears difficult to apply the extremely appropriate storage technics in use for the Scheldt-cruises, because of the very low levels to be determined, the heterogeneity of the samples and on the other hand, longer storage time needed. Different alternatives were available, but in view of a later speciation in the laboratory itself (determination of dissolved, particulate and total mercury in one and the same sample), a freezing method at -20°C was choosen, in analogy with the method used by Duyckaerts et al. (1977) for other heavy metals. The polyethylenecontainer was pretreated with dilute acid and was several times rinsed with deionized water. The results of the first cruises (Dec.77 - Feb.78) in respect of the examination of mercury were all situated at the detection limit (tables 1 and 2). After repeated treatment of the container with an acidified solution of pH = 1 or an unique treatment with a permanganate - acid solution[1], measurable quantities were released as a consequence of a

1. both mercury free solutions.

Table 1

Cruise December 1977

a) Working method

- Treatment prior to cleaning polyethylenebottles : Rinse with deionized water
- Precautions to assure the stability of the solution : Freeze at -40°C
- Treatment of the polyethylenebottles after sampling and prior to measurement :(1°)Thawing of samples → measurement;(2°)- add 20 mℓ/ℓ $KMnO_4$ (2%) in H_2SO_4 (50%); - leave 24 hours → measurement.
- Measuring method : (1°) - $KMnO_4/HNO_3/H_2SO_4$; (2°) - idem

b) Results :

Identification	Direct measurement µg/ℓ Hg	20 mℓ/ℓ $KMnO_4$ in H_2SO_4 µg/ℓ Hg
12.03.151277.1200	N.D.	0.43
42.03.151277.1400	N.D.	0.39
32.03.151277.1450	N.D.	0.08
13.03.121277.1055	N.D.	0.46
43.03.121277.1255	N.D.	0.40
33.03.121277.1350	N.D.	0.13
15.03.131377.1115	N.D.	0.29
45.03.131277.1345	N.D.	0.25
35.03.131277.1445	N.D.	0.85
11.03.141277.1045	N.D.	0.51
41.03.141277.1340	N.D.	0.27
31.03.141277.1445	N.D.	0.07

desorption of the metal from the wall. This indicates that a storage method which is completely efficient for certain metals, appears to be insufficient for others. After treatment of the samples in this way, we found for the first cruises 0.3 µg Hg/ℓ (total mercury) as mean concentration for the points located under the influence of the Scheldt plume (fig. 1; points 14, 15, 25 and 35). This value, however, is much too high, since concentrations in the Scheldtmouth itself, probably the main input of heavy metals in our coastal waters, fluctuate between 0.4 and 0.1 µg Hg/ℓ (Baeyens et al., 1978 - Wollast, 1977, personal communication - Iparcom, 1977).

Table 2

Cruise February 1978

a) Working method

- Treatment prior to cleaning polyethylenebottles : Rinse with deionized water
- Precautions to assure the stability of the solution : Freeze at -40°C
- Treatment of the polyethylenebottles after sampling and prior to measurement : (1°) Thawing of samples → measurement; (2°) add HNO_3 (1 : 2) until pH sample = 1; leave 24 hours → measurement; (3°) measurement of desorption of the wall of the polyethylenebottle.
- Measuring method : $KMnO_4/HNO_3/H_2SO_4$.

b) Results :

Identification	Direct measurement µg/ℓ Hg	pH=1 Hg µg/ℓ	Desorption Hg µg/ℓ
12.03.200278	0.05	0.30	0.16
11.03.200278	N.D.	0.14	0.01
13.03.200278	0.01	0.18	0.13
14.03.240278	0.40	0.56	0.01
15.03.240278	0.01	0.07	0.09
25.03.240278	0.03	0.10	0.01
32.03.210278	N.D.	0.28	N.D.
45.03.240278	N.D.	0.31	0.17
22.03.210278	N.D.	0.09	0.02
35.03.240278	N.D.	0.05	N.D.
21.03.210278	N.D.	0.05	N.D.

Thus after these first cruises it was decided to improve the pretreatment of the polyethylene bottles on one hand and the storage procedure on the other. Some specific tests showed that a pretreatment of the container with a solution of $KMnO_4$ (2%) in H_2SO_4 (50%) during 24 hours made the polyethylene bottle completely mercury-free[1]. As has been discussed above, a storage procedure can be efficient for one element and totally insufficient for another; furthermore the efficiency of mostly used storage procedure for mercury is not subject to an unanimous judgement. Topping et

1. excluding a possible influence on aging of the containers.

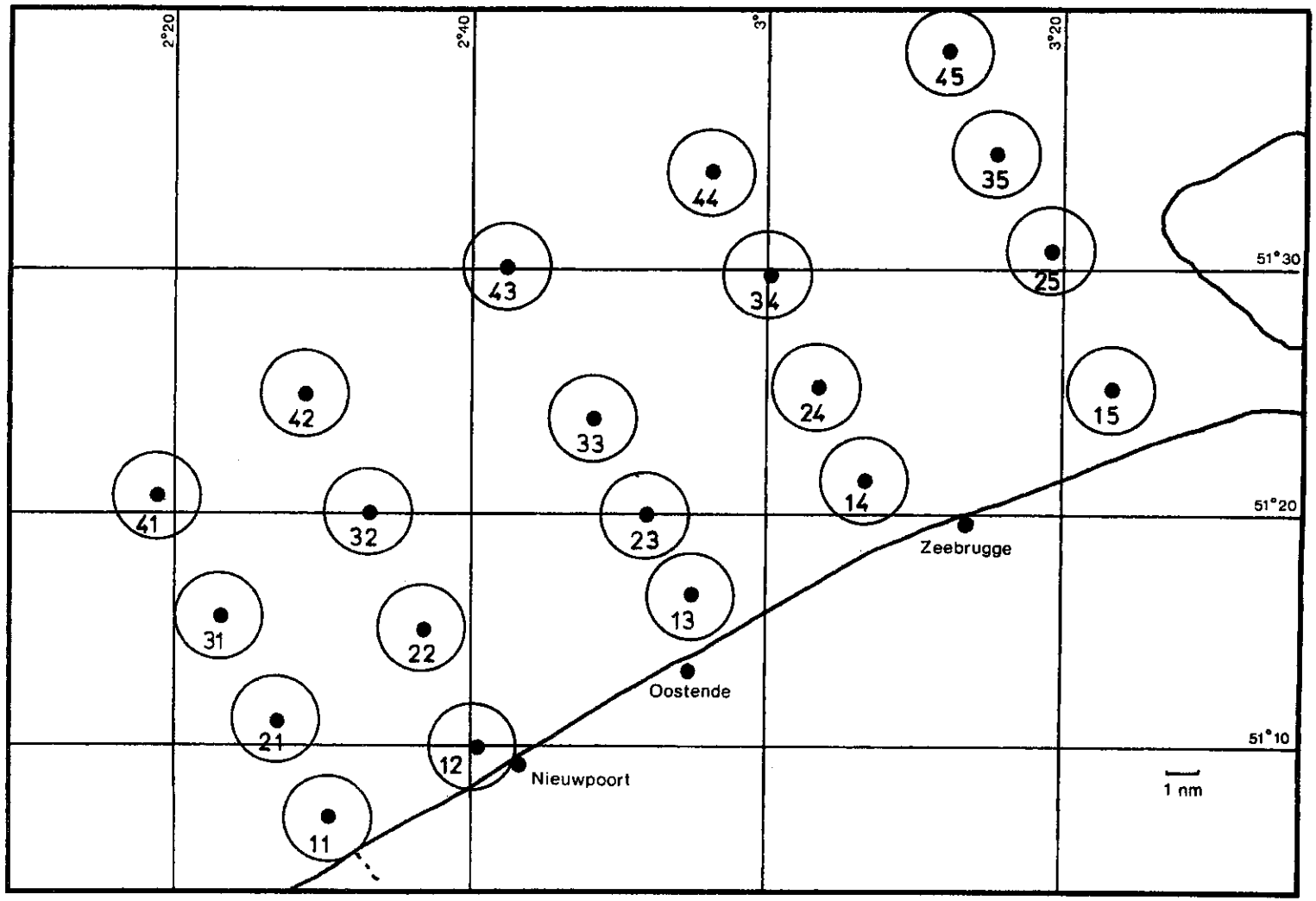

fig. 1.

Map of the Belgian coastal zone

al. (1972) and Carr et al. (1978) assert that adding 20 mℓ/ℓ of a $KMnO_4$ (2%)-solution in H_2SO_4 (50%) or the acidification with HNO_3 to pH = 1, stabilized the sample completely, while Feldman (1974) considers this working method to be insufficient. Feldman (1974) and Fitzgerald (1974) came to the conclusion that storage in pyrex- or teflonbottles instead of polyethylene containers, results in a notable improvement.

Finally we opted for a sample storage at -20°C in a polyethylene bottle after acidification to pH = 1 of the samples (determination of total mercury). The cruise of September 1978 was used, however, to compare the storage efficiency of pyrex- and polyethylene bottles. Because mercury concentrations in the North Sea often approach the detection limit, it is impossible to draw a conclusion already now. Supplementary experiments will be carried out for that purpose, with more sophisticated instruments in order to improve the detection limit.

1.2.- SUSPENDED MERCURY

The sample is immediately filtered on board of the vessel through a 0.45 µm poresize Milliporefilter for the determination of the particulate mercury concentration. The filtration system is shown schematically in figure 2. During 8 days the filters were submerged in a 0.01 M DTPA-solution (pH = 6), (Duyckaerts et al., 1977) to minimalize the content of heavy metals, and subsequently rinsed several times with double deionized water. Immediately after filtration, the filters are freezed at -40°C and stored at - 20 °C [1].

2.- Analytical methods

Although these methods must be considered as classical at this time, (Vanderstappen et al., 1975, personal communication), it will be helpful to recall *some aspects* of the procedures, taking into account that each

1. The next step in the improvement will be the use of a continual centrifugal separator, with teflon container (Kocken, Instituut voor Bodemvruchtbaarheid, The Netherlands, 1979, personal communication).

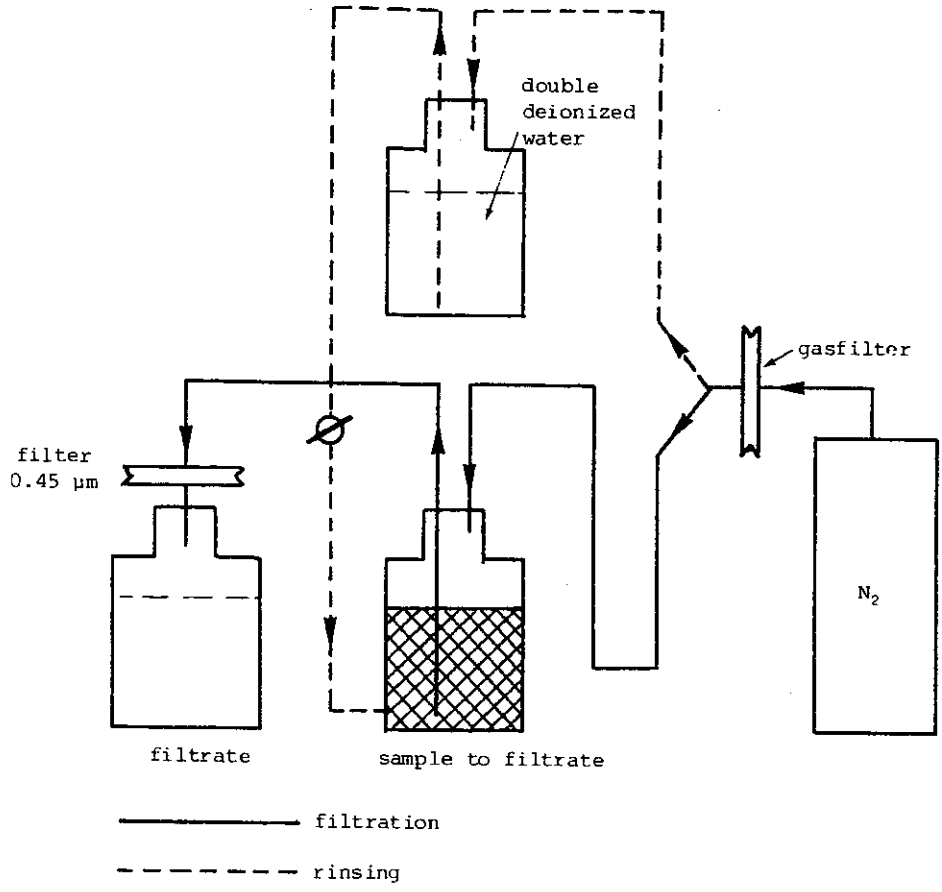

fig. 2.

Scheme of the filtration system

step in the determination is a possible source of misunderstanding in the interpretation of the results.

2.1.- TOTAL MERCURY CONTENT

The method is based on the complete conversion of all mercury components present to Hg(II), subsequently reduction of this form to Hg(0) and spectrophotometric determination after aeration of the solution. An important part of the mercury components is associated with the particulate matter and exists in the form of metallic or organic mercury, or is complexed with certain organic constituents. It is therefore important to choose an appropriate digestion method for the complete oxydation to Hg(II).

2.1.1.- $KMnO_4/HNO_3/H_2SO_4$ - method

Subsequently 5 mℓ HNO_3 (1 : 2), 5 mℓ H_2SO_4 (1 : 1) and 5 mℓ $KMnO_4$ (5 %) is added to 150 mℓ sample. The digestion carried out lasts 16 hours at 60 °C .

The excess $KMnO_4$ is reduced with 1 mℓ hydroxylamine (5 %). The volume in the BOD-bottle is brought to 180 mℓ . After adding 1 mℓ $NaBH_4$ (1 %), measuring witha MAS-50 is carried out.

Blanco : 150 mℓ double deionized water to which the same quantities of reagents are added.

2.1.2.- H_2O_2/H_2SO_4 - method

5 mℓ concentrated H_2SO_4 and 3 mℓ H_2O_2 (30%) are added to 100 mℓ sample. The sample is heated to 80°C under reflux during 24 hours. After refrigeration to roomtemperature the sample is quantitatively transferred into a BOD-bottle. $KMnO_4$ is added until a light pink colour appears. This slight excess is reduced with hydroxylamine (5%).

The volume in the BOD-bottle is brought to 180 mℓ and after addition of 1 mℓ $NaBH_4$ (1%) the measurement with the MAS-50 is carried out.

Blanco : 100 mℓ double deionized water to which the same reagents are added.

2.2.- PARTICULATE MERCURY CONTENT

Subsequently 5 mℓ concentrated H_2SO_4 and 15 mℓ $KMnO_4$ (5%) are added to the filter. The sample is heated to 60°C during 24 hours. The excess of $KMnO_4$ is reduced with hydroxylamine (5%). The volume in the BOD-bottle is brought to 180 mℓ. After addition of 1 mℓ $NaBH_4$ (1%), the measurement with the MAS-50 is carried out.

Blanco : the same quantities reagents are added to a blanco filter.

3.- Results and discussion

The results of the first cruises in respect of mercury examination were already discussed in paragraph 1.1. Consequently only measurements with *the improved analysis* procedure are here taken into account. The total

Table 3

Cruise September 1978

a) Working method

- Treatment prior to cleaning bottles : Fill with a soapsolution (extran, 50°C); rinse with deionized water; fill with solution of 20 mℓ/ℓ $KMnO_4$ (2%) in H_2SO_4 (50%); leave 24 hours; rinse with deionized water
- Precautions to assure the stability of the solution: add 20 mℓ/ℓ HNO_3 (1 : 2) (pH sample = 1 à2); freeze at -40°C.
- Treatment of the bottles after sampling and prior to measurement : thawing of samples → measurement.
- Measuring method : (1) $KMnO_4/HNO_3/H_2SO_4$; (2) H_2O_2/H_2SO_4 .

b) Results :

Identification	polyethylene bottles		pyrex bottles	Turbidity
	$KMnO_4$ - method µg/ℓ	H_2O_2 - method µg/ℓ	$KMnO_4$ - method µg/ℓ	mg/ℓ
41.03.180978.1141	0.03	-	0.01	21.6
31.03.180978.1245	0.01	N.D.	0.03	7.9
21.03.180978.1340	0.02	N.D.	0.01	6.1
11.03.180978.1430	N.D.	-	N.D.	14.2
12.03.180978.1535	0.01	N.D.	0.02	16.7
22.03.180978.1640	N.D.	0.01	0.03	14
13.03.190978.0845	0.01	0.02	0.02	23.8
23.03.190978.0940	0.10	0.06	0.02	10
33.03.190978.1035	0.07	0.04	N.D.	18
43.03.190978.1200	N.D.	N.D.	N.D.	15.2
42.03.190978.1320	0.05	0.02	N.D.	18
32.03.190978.1425	0.03	N.D.	N.D.	19.8
24.03.200978.1010	0.06	-	0.05	73
34.03.200978.1055	0.02	-	N.D.	21.6
44.03.200978.1150	0.04	-	N.D.	21.2
45.03.200978.1350	0.03	0.02	N.D.	12.6
35.03.200978.1430	0.06	0.04	N.D.	47.6
25.03.200978.1515	0.09	0.06	0.08	127.4
15.03.200978.1620	0.14	0.12	0.14	165
14.03.200978.1805	0.10	0.08	0.13	124.2

and particulate mercury concentrations determined in our coastal zone during several representative cruises (September, October and November 1978) are shown in the tables 3, 4 and 5, while the spatial distribution is represented

Table 4

Cruise October 1978

a) Working method

- Treatment prior to cleaning bottles : Fill with a soapsolution (extran, 50°C); rinse with deionized water; fill with solution of 20 mℓ/ℓ $KMnO_4$ (2%) in H_2SO_4 (50%); leave 24 hours; rinse with deionized water
- Precautions to assure the stability of the solution : add 20 mℓ/ℓ HNO_3 (1 : 2) (pH sample = 1 ă2); freeze at -40°C.
- Treatment of the bottles after sampling and prior to measurement : thawing of samples → measurement.
- Measuring method : $KMnO_4/HNO_3/H_2SO_4$

b) Results :

Identification	Hg µg/ℓ	Turbidity mg/ℓ
11.03.161078.1120	0.02	40.2
31.03.161078.1320	0.03	22.2
32.03.161078.1600	0.02	14.4
15.03.191078.1140	0.04	45
35.03.191078.1330	0.01	29
41.03.161078.1415	N.D.	17.2
22.03.161078.1645	N.D.	32.2
12.03.161078.1030	0.02	33.4
42.03.161078.1515	N.D.	21.4
25.03.191078.1245	0.07	82
21.03.161078.1225	N.D.	18.4
45.03.191078.1405	0.01	23.6
13.03.201078.0940	0.03	-
43.03.201078.1215	0.02	12.6
24.03.191078.1610	0.02	51.4
34.03.191078.1530	0.02	21.4
23.03.201078.1015	0.02	41.4
14.03.191078.1035	0.12	168
33.03.201078.1035	0.01	-

graphically by the figures 3 to 6. Although an unambiguous determination of the iso-concentration curves is impossible, - given the too limited number of points in the zones where relatively important concentration gradients are distinguished -, the following general characteristics, for the total

Table 5

Cruise November 1978

a) Working method

1) Hg total :

- Treatment prior to cleaning bottles : Fill with a soapsolution (extran, 50 °C); rinse with deionized water; fill with solution of 20 mℓ/ℓ $KMnO_4$ (2 %) in H_2SO_4 (50 %); leave 24 hours; rinse with deionized water.
- Precautions to assure the stability of the solution : add 20 mℓ/ℓ HNO_3 (1 : 2) (pH sample = 1 à 2); freeze at - 40 °C .
- Treatment of the bottles after sampling and prior to measurement : thawing of samples → measurement.
- Measuring method : $KMnO_4/HNO_3/H_2SO_4$.

2) Hg suspension :

- Treatment prior to cleaning the filters : wash in a 0.01 M DTPA - solution; rinse with tridistilled H_2O .
- Precautions to assure the stability : freeze at - 40 °C .
- Treatment of the filters after sampling and prior to measurement : wait until roomtemperature is reached; dissolve in 5 mℓ H_2SO_4 (conc.) + 30 mℓ H_2O + 15 mℓ $KMnO_4$ (5 %); let digest at 60 °C during 16 hours; measurement at total or at an aliquot.

b) Results

Identification	Hg-total µg/ℓ	Hg-suspension µg/ℓ	Turbidity mg/ℓ
11.03.221178.1550	N.D.	0.03	10.8
21.03.221178.1410	0.01	0.04	8.2
31.03.221178.1300	0.02	0.05	8.8
41.03.221178.1140	N.D.	0.03	8.6
12.03.221178.1700	N.D.	0.02	12.6
13.03.241178.0905	0.04	0.10	24.6
23.03.241178.0940	0.03	0.08	20.4
33.03.241178.1040	0.02	0.05	-
43.03.241178.1145	N.D.	0.03	10.6
14.03.231178.1750	0.06	0.12	58.2
24.03.231178.1635	0.04	0.08	27.4
34.03.231178.1610	0.01	0.05	17.6
44.03.231178.1515	0.03	0.06	11
15.03.231178.1015	0.05	0.10	52.8
25.03.231178.1130	0.08	0.15	105.6
35.03.231178.1220	0.04	0.08	22.2
45.03.231178.1335	0.03	0.06	19

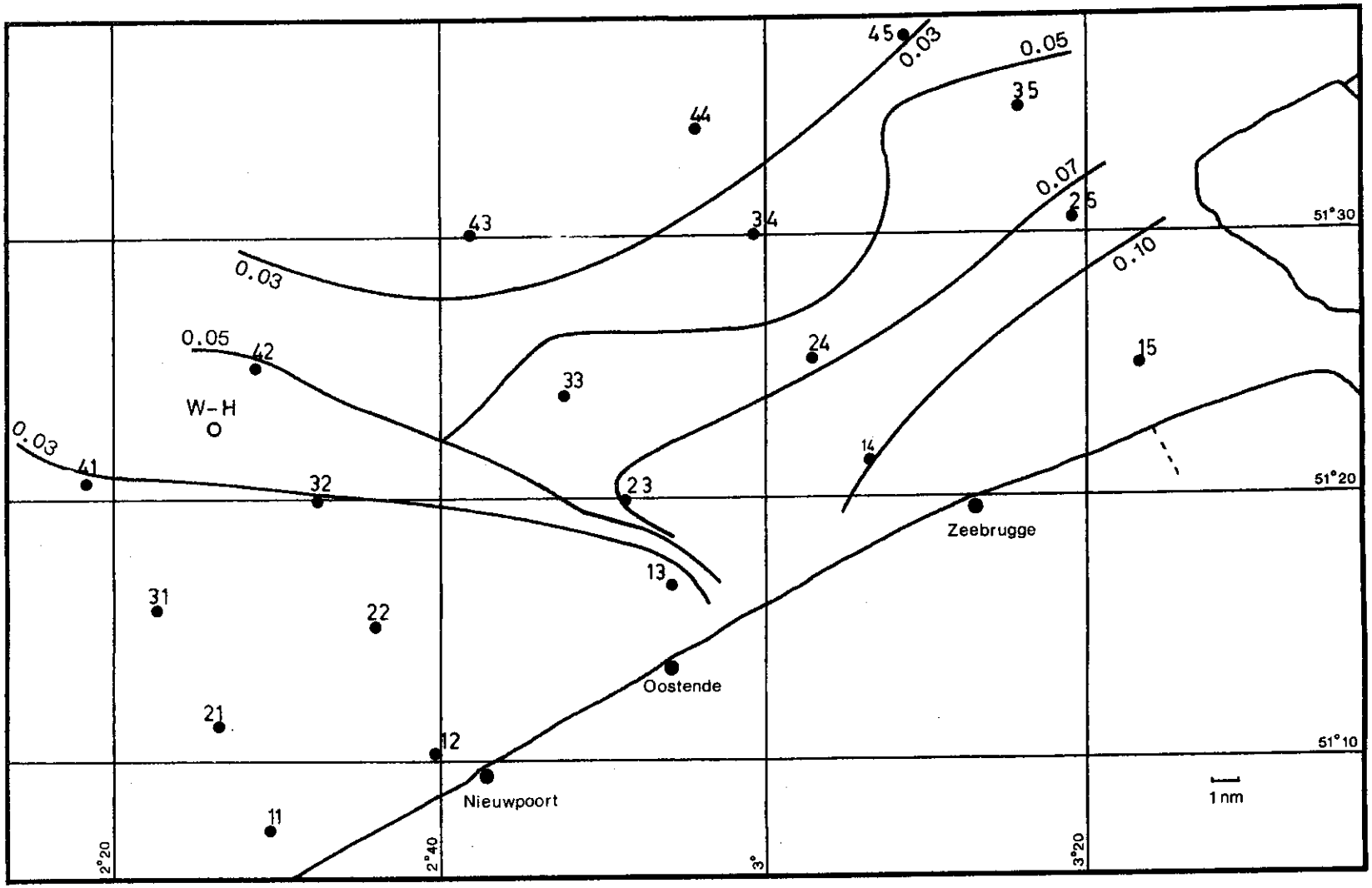

fig. 3.

Spatial distribution of total mercury (µg Hg/ℓ)
September 1978

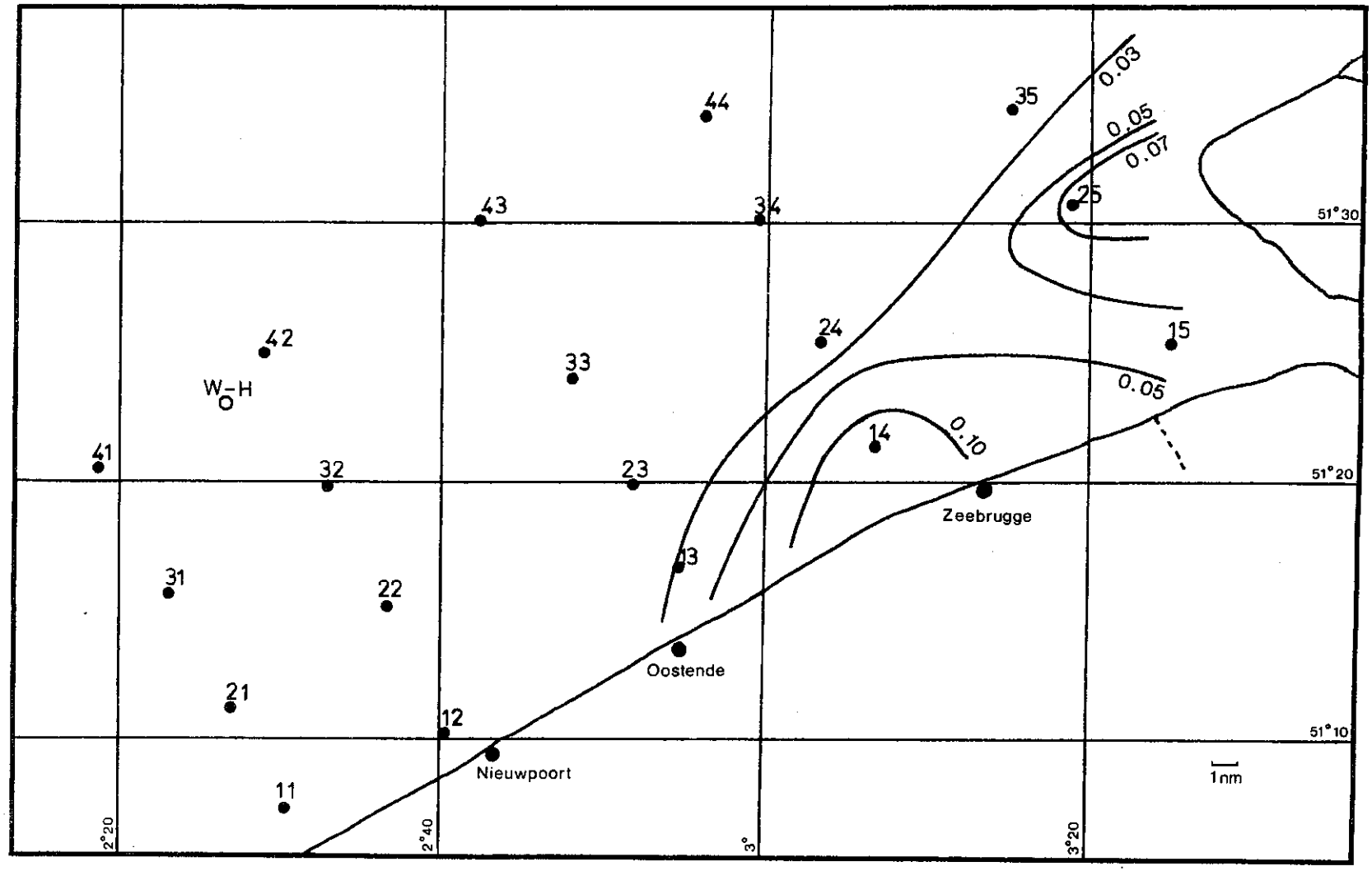

fig. 4.

Spatial distribution of total mercury (µg Hg/ℓ)
October 1978

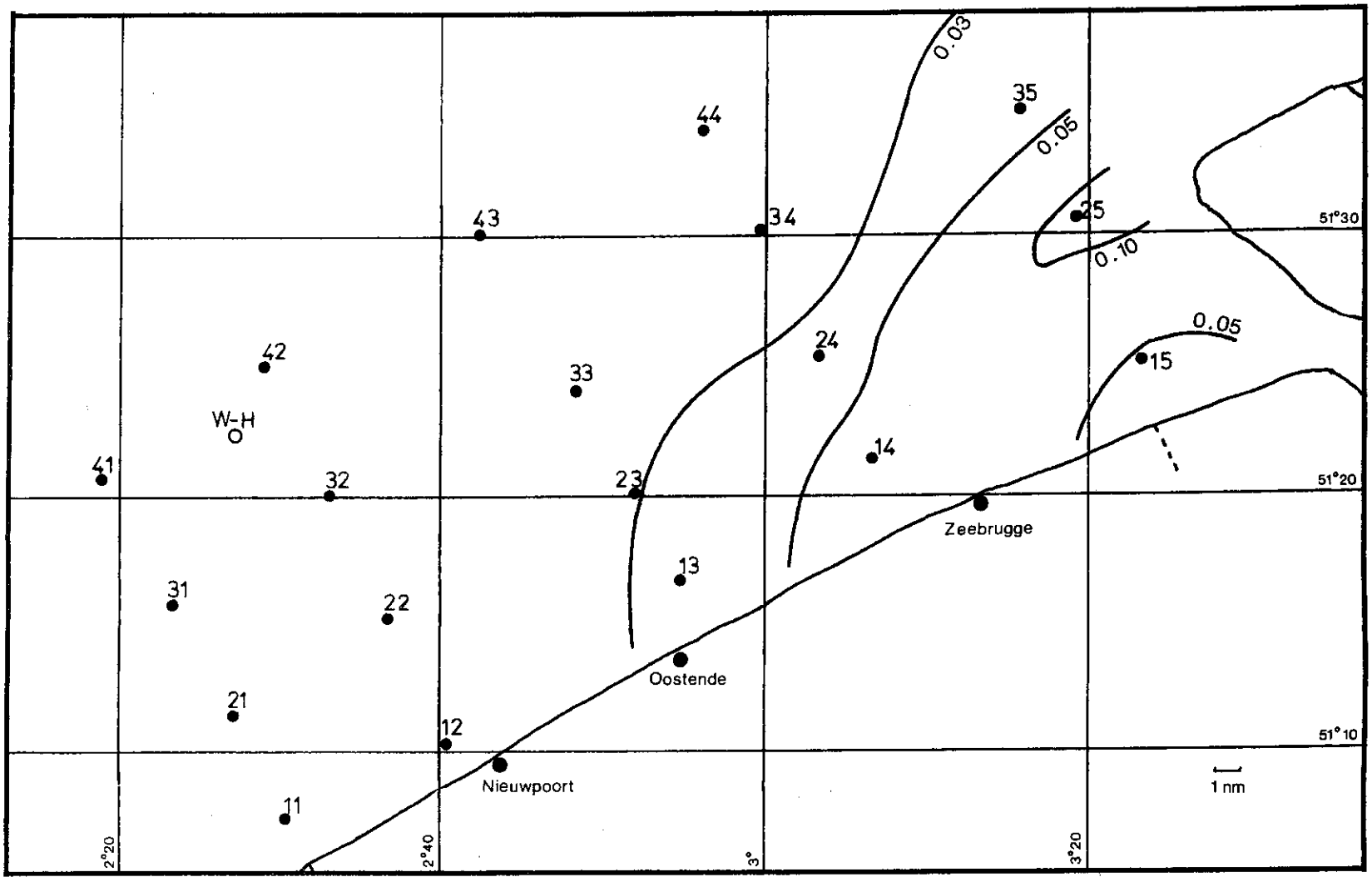

fig. 5.

Spatial distribution of total mercury (µg Hg/ℓ)
November 1978

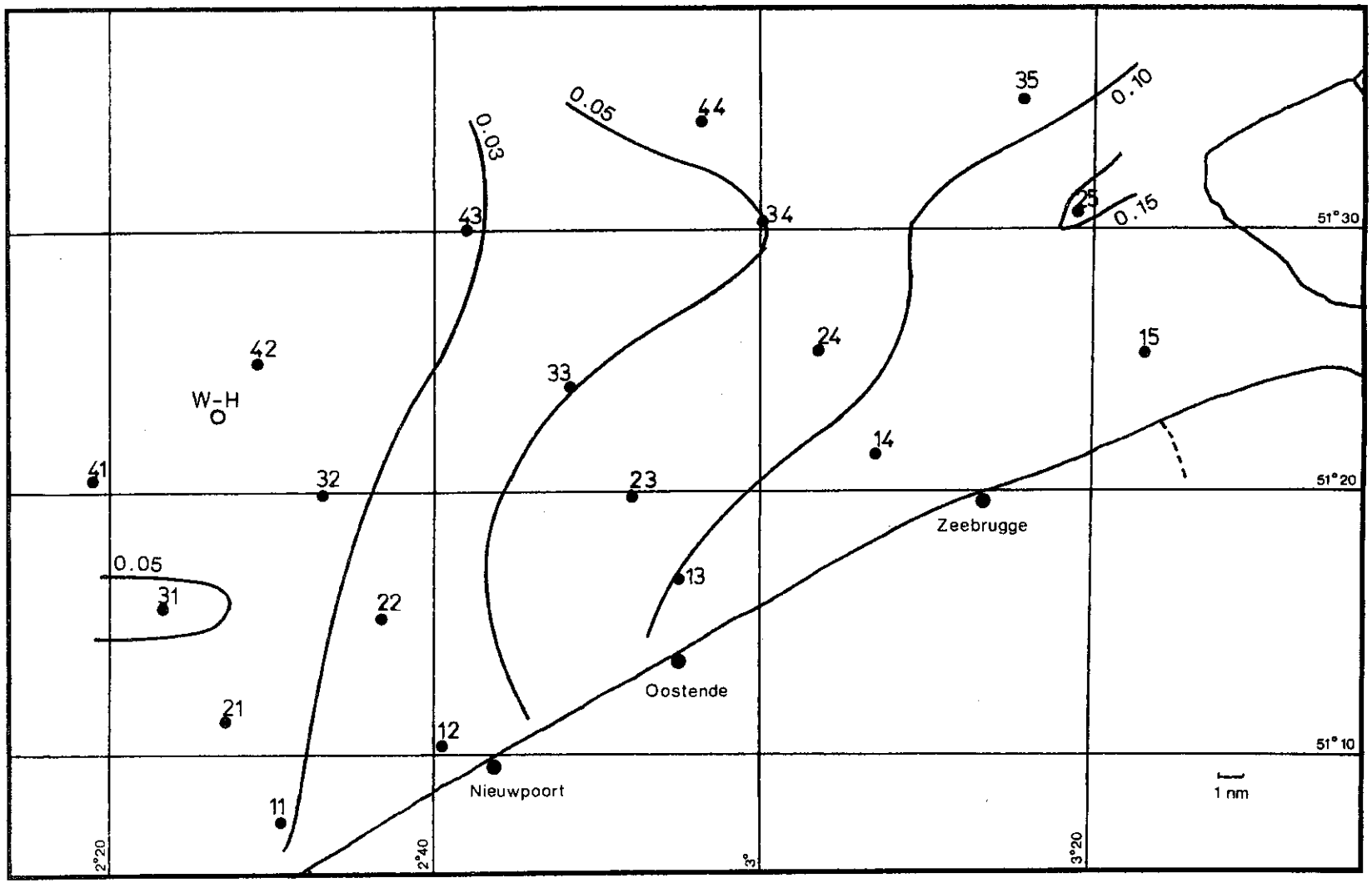

fig. 6.

Spatial distribution of particulate mercury (µg Hg/ℓ)
November 1978

as well for the particulate mercury content, may be drawn out :

- a zone with relatively high concentrations, situated near the Scheldt-estuary
- a progressive transfer to an open-sea zone, where concentrations become comparable with those of ocean water, namely 0.03 µg Hg/ℓ, according to the distance from the Scheldtmouth.

As previous studies (Baeyens et al., 1978 - Baeyens, 1977) show a strong interaction between several mercury components and the suspended matter, it was tried to derive *graphically* a relation between turbidity and mercury content. When more data would be available, more sophisticated statistical methods will be used.

For a first approach, both curves, total and particulate mercury content versus turbidity, are shown in figure 7.

- A first important fact that clearly appears from this figure is a difference in accuracy of the analytical procedures for the determination of particulate and total mercury. This is probably due to the fact that in the actual state of the sampling procedure, *the absolute quantities* involved in the case of the determination of the particulate mercury are more or less 6 times higher than in the case of the determination of the total mercury.
- *In general* the concentrations of total and particulate mercury are practically identical, since the dissolved mercury concentrations are mostly located on the detection limit. An adapted method (extraction and preconcentration on an exchange-column) for the determination of dissolved mercury is checked at present time, in order to obtain a more exact value of these "dissolved" concentrations.
- For the measurements at high turbidity , a constant factor is observed between the particulate Hg concentration and the total Hg concentration measured at the same turbidity and, both expressed in µg/ℓ. The constant difference can be due to incomplete release of the mercury from the suspended matter during the determination of the total mercury content, while when determining *directly* the particulate mercury after filtration, the release does take place completely, according the use of a highly

1. Although rather limited in number but still significant.

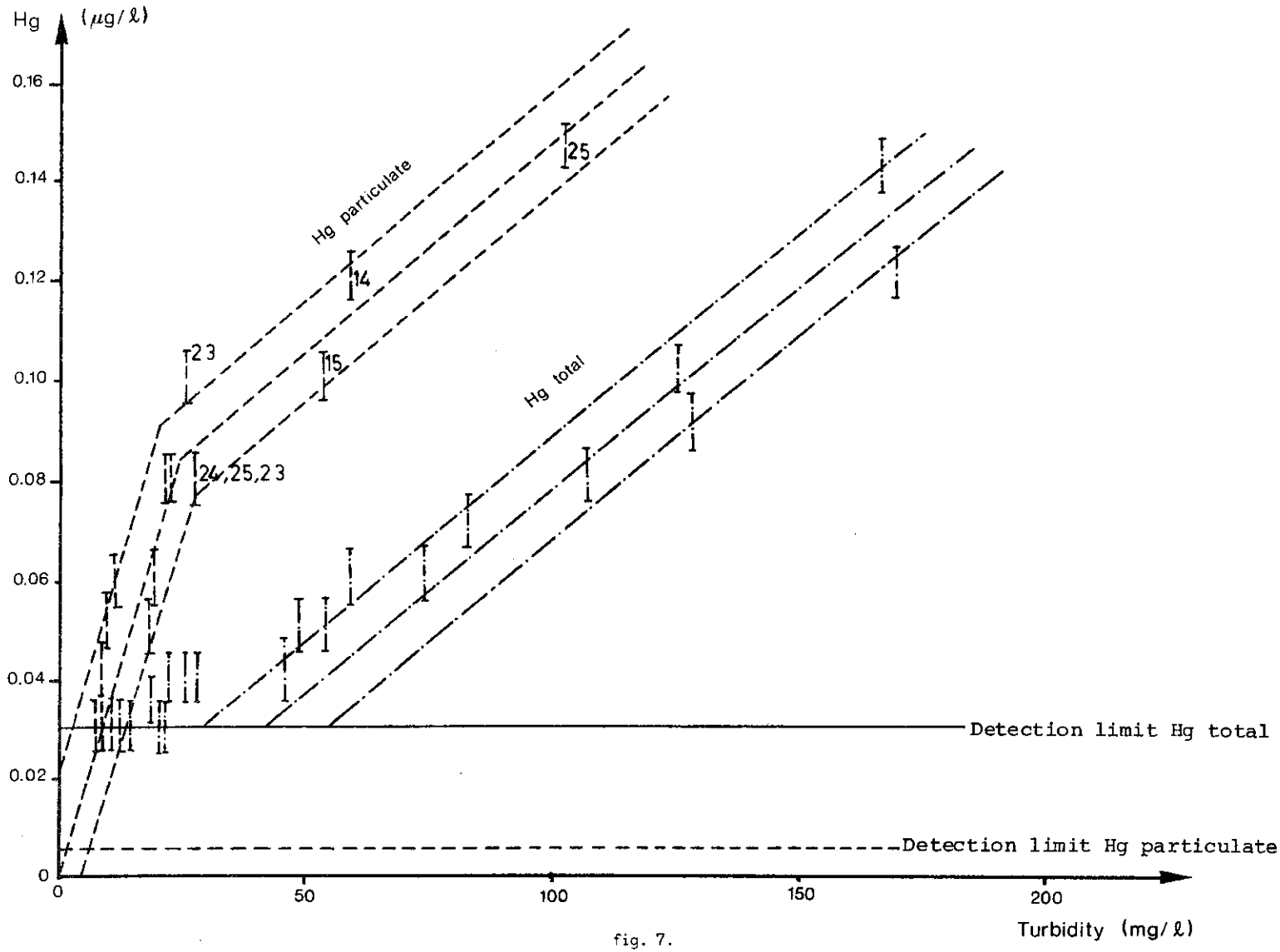

fig. 7.

Total and particulate mercury content versus turbidity

concentrated acid combined with a strong oxydator. Tests were carried out to check whether one of these methods : $KMnO_4$/acid or H_2O_2/acid would give the best results for the determination of the total mercury content. During the cruise of September 1978 (table 3) both methods were compared, but no systematic difference could be shown. On the other hand, the acidification to pH = 1, prior to the storage of the sample for the determination of total mercury, can perturb its original concentration. With such a pH, a desorption of particulate mercury takes place with forming of $HgCl_3^-$ and/or Hg(0). Simultaneously CO_2 is evolved, through which a fraction of the present mercury can diffuse to the atmosphere.

The curve (fig. 7) indicating the relation between the particulate mercury concentration and the turbidity, shows two discrete parts. More mercury is adsorbed per weight-unit of suspended matter at low than at high turbidity. The points of low turbidity are open-sea points and no mercury is discharged in this zone. Its origin must be sought in one or more of the following hypothesis :

- the fine matter transported by the Scheldt plume and containing most mercury, precipitates relatively slowly, while the more coarse material, containing little mercury, does not reach the open sea.
- there is a continuous remobilisation of dissolved mercury (through the decomposition of organic matter, through the Eh-pH circumstances in the sediments, etc.) with a reasonable rapid re-adsorption on smaller quantities of suspended matter.
- the Scheldt transports particulate as well as dissolved mercury. If the suspended marine matter has a higher adsorption capacity and/or follows another reaction kinetic scheme than for the particulate Scheldt-matter, it can contain more mercury per weight-unit of suspended matter.

4.- Conclusion

In the present approach, the storage and the analysis steps were *before all* studied thoroughly and improved, but the *sampling procedure* also will examined in more details in the future. Direct determination of the total mercury content, however, still causes problems. The dissolved mercury

concentrations will therefore also be measured, after an extraction or a preconcentration procedure. The particulate mercury concentrations obtained after filtration and centrifugation will be compared with each other. Finally, a certain number of supplementary studies will be carried out to explain the higher mercury content per weight unit of solid matter in the open sea zone. The kinetics of the adsorption of mercury on the particulate matter in the Scheldtmouth, the Scheldt plume and in the open sea zone will be established for that purpose. Parallel to this program, valuable information concerning the fate of the particulate matter transported by the Scheldt can be supplied by studies on sediment transport.

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Achevé d'imprimer le 10 septembre 1979
sur la presse offset
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D/1979/1191/7