A three layer vertical and microbiological processes model for shelf seas
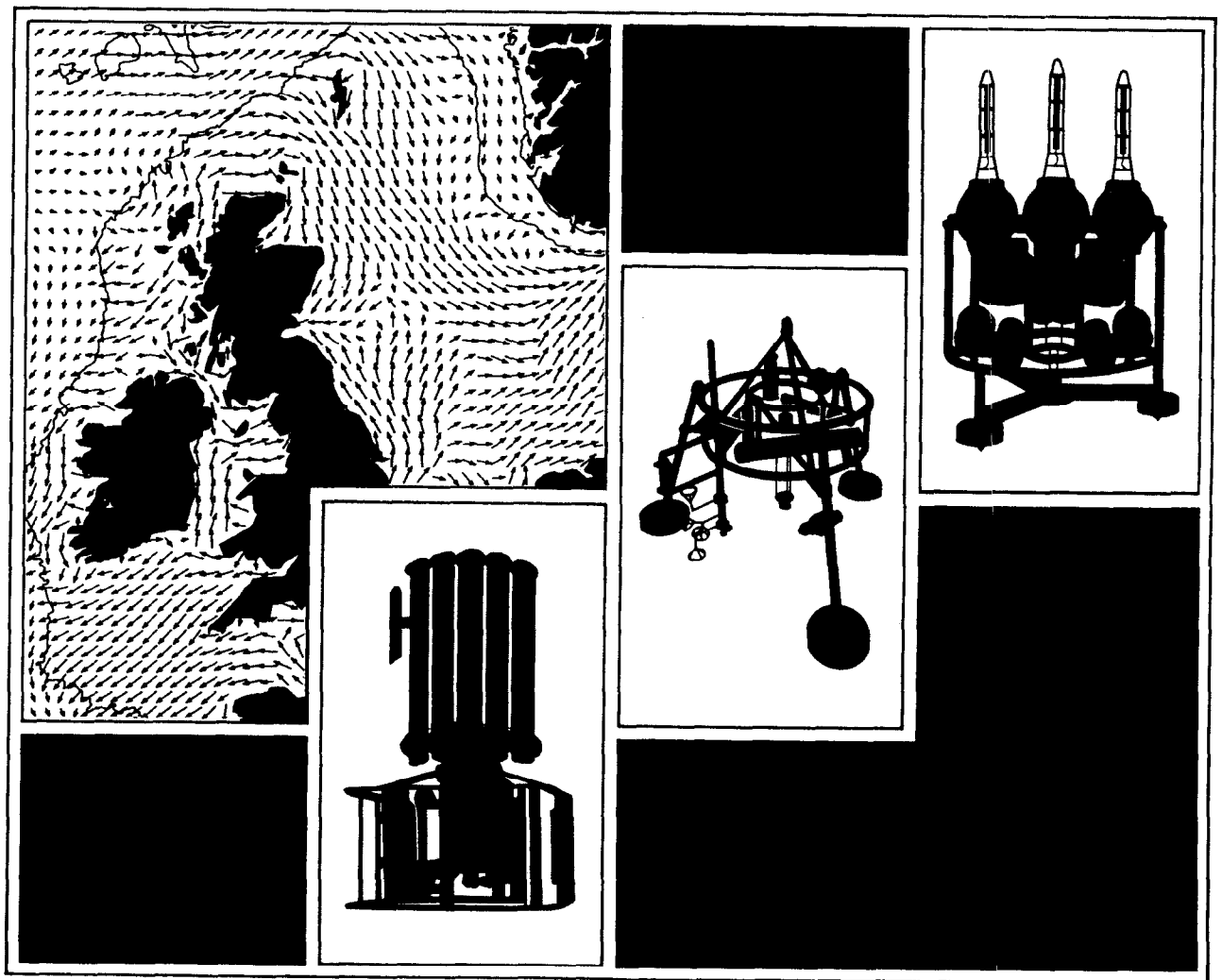
P Tett

Report No 14 1990

Tett, P. 1990. A three layer vertical and microbiological processes model for shelf seas. Proudman Oceanographic Laboratory, report 14.

Corrections (as at 5 Mar 91)

p.32:

right-hand side of (10.4) : an integral sign should be inserted before {
right-hand side of (10.5) : an integral sign should be inserted before {
$\qquad$ the penultimate term should be $(\sin(\text{omega}))^2$

p.45

```
FUNCTION WELLMIXED:BOOLEAN;
CONST MIN=0.000001;
BEGIN
   PHI:=0.0 (* can't be better than well mixed, so +ve not allowed *);
   H[1]:=D; H[3]:=D;
   T[1]:=TOTALHEAT/(D*RHO*C); T[3]:=T[1];
   IF (D-OLDH1)>MIN THEN BEGIN
      OVERTURN:=TRUE;
      E[1,3]:=D-OLDH1;
   END ELSE BEGIN
      OVERTURN:=FALSE;
      E[1,3]:=0.0;
   END;
   E[3,1]:=0.0;
   WELLMIXED:=FALSE;
END;
```

p.67

corrections to function/procedure heading:

```
FUNCTION GRAZING (DAY:INTEGER; VAR G:MON):REAL;

PROCEDURE MICROPLANKTON
(VAR B,H,I,N,NHS,NOS,O,TEMP,X,DB,DC,DM,DN,DNHS,DNOS,DOX:LYA;   VAR E:EXA;   G:REAL;
MIXED:BOOLEAN);
```

p.71

correction to procedure heading:

```
PROCEDURE WATER_COLUMN
(VAR C,H,M,NHS,NOS,O,TEMP,DC,DM,DNHS,DNOS,DOX:LYA;   VAR E:EXA; MIXED:BOOLEAN);
```

PROUDMAN OCEANOGRAPHIC LABORATORY

REPORT No. 14

A three layer vertical and microbiological
processes model for shelf seas

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ABSTRACT

L3VMF is a 3 layer vertical processes model which combines physical and microbiological processes in order to simulate seasonal cycles of phytoplankton, detritus, combined nitrogen and oxygen in a tidally stirred shelf sea. Advection is not included. The three layers are the surface- and bottom-mixed layers of the water-column, separated by the seasonal thermocline, and the superficial, oxic, layer of the sediment. A one-day averaging period is used.

The depth of the thermocline is predicted from wind and tidal stirring and superficial heat exchange using equations for heat and potential energy conservation. The deposition and resuspension of inorganic and organic sediment is predicted from tidal stirring and sediment sinking rate, using a description appropriate to cohesive sediments. The attenuation of photosynthetically effective light in the water-column is related to suspended sediment and phytoplankton. Air-sea gas exchange is a function of wind speed. Sediment-water exchange of dissolved substances is driven by a notional pore-water diffusivity. Phytoplankton and planktonic microheterotrophs are combined in a microplankton compartment, described by a cell-quota, threshold-limitation model in terms of alternative light or nitrogen control of growth. Detritus is produced by microplankton death or as a result of simulated zooplankton grazing; the decay of detritus in the water-column or sediment consumes oxygen and remineralizes nitrogen as ammonium, which is subsequently oxidized to nitrate.

The report discusses the choice of physical and biological structure for the model, and presents equations and standard parameter values for each process, in many cases on the basis of observations during the 1988/89 North Sea study. Extracts from a simulation program in Pascal are included. Results are presented from a simulation of seasonal cycles at a site in summer-stratified North Sea waters. Phytoplankton show Spring and Autumn peaks, as expected, but the present version of the model does not predict stable mid-winter nitrate levels.

This work was carried out for the North Sea Project under a commission via POL to UCNW.

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The Library, Proudman Oceanographic Laboratory.

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PART I : GENERAL

1. Introduction

A mathematical model is a theoretical description of a system by means of equations defining interrelationships amongst the components of the system. Such equations are sometimes solved by repeated calculation, and the word 'model' is also used to refer to a computer program for implementing such a solution as a numerical simulation. Finally, either type of model can be seen as a statement of a complex hypothesis in a form susceptible of refutation (see note).

This report deals with the first stage in the development of an integrated physical and biological model for productive and destructive microbiological processes in the tidally stirred waters of European shelf seas. Resuspension and aerobic remineralization in the underlying sediment are included. This version of the model, which contains no terms for horizontal exchange, is intended as a testbed for descriptions of microbiological processes which will later be included in the 2-D transport, layered, North Sea phytoplankton-nutrient-oxygen model now under development at the Proudman Oceanographic Laboratory.

The model described here is called L3VMP, for 'three-layer vertical microbiological processes'. The name refers to (a) the set of generalized equations that define the model, and (b) a Pascal program for the numerical solution of these equations. The success of the program, once complete, will be judged by its ability to simulate seasonal cycles of phytoplankton chlorophyll, and dissolved oxygen and nitrate, at a range of sites in the North Sea.

This report is written for two audiences. The first consists of professional numerical modellers with a mainly physical or mathematical background, the second of observational or experimental marine scientists with limited experience of numerical modelling. In the interests of the latter I give an account of the derivation of the program L3VMP from the set of differential equations which make up the theoretical model. The first audience will be well aware of limitations in the numerical solutions used in the program.

Either audience may find parts of the theoretical model too simple. This is a likely consequence of a first attempt to design a multidisciplinary model. Nevertheless, in my view, the interactions between physics and biology so strongly influence the microbiological processes fundamental to a

North Sea water quality model that it is essential to begin by constructing an simple integrated framework rather than building separate, detailed, chemical and biological modules to 'bolt onto' a physical model. This is not to argue that for actual simplicity in the real physical and microbiological systems that it describes, only that it is worth testing the hypothesis that a well-considered simple model can (a) make bulk predictions of some accuracy, and (b) contribute to an understanding of biophysical interactions.

Note

In popular usage, a 'model' is a miniature version of the real thing. According to the (shorter) Oxford English Dictionary, the technical definition of 'model' as "a simplified or idealized description of a system, situation or process, often in mathematical terms..., devised to facilitate calculations and predictions", dates only to 1949 and is thus contemporaneous with the first generation of electronic digital computers.

In an essay first published in 1948, Karl Popper (1972, appendix) argued that physicists from Descartes to Maxwell "tried to explain all newly discovered relations by means of <u>mechanical models</u>"; that is, they described them by analogy with the movement of billiard balls or the works of clocks. "Maxwell, too, first tried to develop his theory of the electromagnetic field in the form of a mechanical model of the ether; but in the end he gave up the attempt. With this, the mechanical model lost most of its significance: only the equations which were meant to describe the mechanical model of the ether remained .... With this transition from a mechanical to an <u>abstract theory</u> a stage is reached in the evolution of science at which in practice no more is required of explanatory theories than that they can be tested independently; we are ready to work with theories that can be intuitively repesented by diagrams ... if they are obtainable .. or else, .. with 'abstract' mathematical theories..".

The definition of 'mathematical model' used at the head of this section follows Giordano & Weir (1985), who emphasize the "modelling process as a closed system". In this system, models are formulated on the basis of "real-world data" and analysed to give "mathematical conclusions", which, however, "pertain only to the model". The conclusions may, nevertheless, be interpreted as "predictions/explanations" of the real world, to be tested against data from the latter, and rejected or improved in the case of a bad fit to such data. In this view, therefore, mathematical models are refutable hypotheses in the tradition of Popper's critical rationalism and evolutionary epistemology. Popper (e.g. 1972, chapter 2), however, takes a more subtle view of 'correspondence with reality'.

2. Physical structure: a layer model

As a result of forcing from the sea surface and the sea bed, many marine biologically important properties vary with depth. 'Vertical-process' biophysical models consider only this variation and ignore horizontal transports and gradients. One class of such models describes rates of change in chemical and biological properties as, in principle, continuous functions of depth and time, usually through the mediation of depth-varying turbulent diffusivity and irradiance (Radach & Maier-Reimer, 1975; Jamart et al., 1977; Tett, 1981). In practice, however, the use of finite-difference

approximations to solve model equations requires the division of the water column into a sequence of points, and thus effectively into layers. The adoption of the layer principle in L3VMP raises the question of how many layers are required adequately to represent the nonlinear interactions between depth-varying physical and biological process.

This is a complex issue, and the answer is likely to depend on the processes considered. Since the dominant biological processes in L3VMP are the formation and destruction of organic material, the question of layer number is best approached through considering the balance between phytoplankton photosynthesis and respiration (Tett, 1990). The mean net rate of formation of organic material in a layer in which the depth-averaged daily total irradiance is I' (microEinsteins m^{-2} d^{-1}), and X is the mean concentration of phytoplankton, measured as mg m^{-3} of the photosynthetic pigment chlorophyll, is:

$$p = (\alpha I' - r^X).X \qquad\qquad \text{mmol C } m^{-3} d^{-1} \qquad\qquad (2.1)$$

Here α is the 'efficiency' (mmol C (mg chl)$^{-1}$ (muE m^{-2})$^{-1}$) at which phytoplankton use light to synthesize organic material, and r^X is the relative rate (mmol C (mg chl)$^{-1}$ d^{-1}) of destruction of this material by their respiration.

Suppose the model layer for which the equation is solved extends from sea surface to bed, and is sufficiently deep that $\alpha I' < r^x$. Hence consumption exceeds production. In the case that the water column is in reality well-mixed, equation (2.1) correctly predicts no phytoplankton growth, as discussed by Sverdrup (1953). In the case of a stratified water column, however, the equation gives a false average if $\alpha I' > r^x$, allowing phytoplankton growth, in the layer above the pycnocline. Hence stratification can divide the water column into a region dominated by organic production and phytoplankton growth and a region dominated by the consumption of organic material produced elsewhere. A realistic model of microbiological processes in the water column must, at least, support such a dichotomy.

In some water columns another limiting factor comes into operation. Whereas lack of light may prevent phytoplankton growth below the pycnocline, shortage of mineral nutrients may restrict growth above the pycnocline. In such cases the optimum region for phytoplankton is within the pycnocline (Pingree et al., 1975). A three-layer model of the water column is the minimum for adequate description of such cases. Nevertheless, the occurrence of maximum phytoplankton

concentrations in the pycnocline does not fundamentally alter the nature of biological processes in the water column, and the contribution of these phytoplankton to production can be included in that of the surface mixed layer of a two-layer water-column model.

Considerations of this sort (and see note) lead to the layer structure adopted in L3VMP and illustrated in figure 1. Layer (0) is the air, an infinite source or sink for oxygen and heat. The 'bed layer' (4) is included in the model scheme in case concentrations here are required to regulate fluxes between the sea bed and the water column, and corresponds to the layer of bed-load transport or the viscous sublayer at the benthic boundary (Dyer, 1986).

L3VMP is called 'three-layer' in respect of the three layers in which microbiological processes are fully described. These are the water column layers (1) and (3) and the upper sediment layer (5). The 'surface-mixed' layer (1) represents the part of the water column that is mixed at least once a day by wind-generated and convective turbulence; it includes the 'diurnal thermocline' as well as the 'mixed layer' of Woods & Barkman (1986). The 'bottom-mixed' layer (3) corresponds to the 'bottom boundary layer' of Soulsby (1983); it is stirred by turbulent eddies resulting from friction between tidal currents and the sea-bed. Layers (1) and (3) are separated by the seasonal thermocline, and may merge during winter or when tidal stirring is strong. Because of the method used to predict the depth of the seasonal thermocline, the thermocline layer (2) is not represented in this version of the model.

Layer thicknesses are given by h. Since layer (2) is absent, and the thickness of layer (4) is nominal, water column depth d is given, for stratified conditions, by:

$$d = h_1 + h_3 \qquad \text{metres} \qquad (2.2)$$

and h_1 gives the depth of the seasonal thermocline. For the North Sea implementation of the model, d varies between 20 and 200 m, and h_1 between 0 m and d. Under mixed conditions the two layers become co-extensive and d can be equated with either h_1 or h_3.

The oxygenated layer was between 3 cm and 10 cm deep in sediment cores taken during the 1988-89 North Sea survey (A.Upton, Essex). Thus h_5 will be taken as 0.05 m. The layer is that in which bioturbation or tidal pumping is strong, or which is regularly resuspended by tidal or wind-wave turbulence. The exchange of dissolved substances between this layer and the overlying water is controlled by rates of physical mixing and bioturbation within the layer as well as the presence or

absence of an overlying viscous layer. The resuspension of layer (5) particulates, depends in L3VMP on the drag of tidal currents on the seabed.

Note

According to Russell (1961), the medieval philosopher William of Occam said "it is vain to do with more what can be done with fewer". Although the latter was not talking of model layers, the pruning of complications with 'Occam's razor' is a useful tactic in the development of a model.

3. Exchange velocities

A basic assumption of a stratified model is that each layer is internally well-mixed, allowing depth-varying processes to be averaged across the layer. Rate-limiting physical fluxes are deemed to take place only at the boundaries between the strata, generally in L3VMP as a product of an 'exchange velocity' E and a concentration difference. The following example predicts the flux of nitrate from layer (3) into layer (1):

$$<S>_{1,3} = E_{1,3}(S_1 - S_3) \qquad \text{mmol m}^{-2} \text{ day}^{-1} \qquad (3.1)$$

This treatment aims at separating the physical transport from the thing transported, and is a finite difference approximation to the advection-(Fickian)diffusion equation:

$$<S> = w.S - K_z dS/dz \qquad \text{mmol m}^{-2} \text{ day}^{-1} \qquad (3.2)$$

where S is nitrate concentration (mmol m^{-3}), w is a mean vertical velocity (m day^{-1}) and K_z is a vertical turbulent diffusivity (m^2 day^{-1}). The two equations are related by:

$$E_{1,3} = ((K_{z(1,3)}/\Delta z) - w_{1,3}) \qquad \text{m day}^{-1} \qquad (3.3)$$

where $K_{z(1,3)}$ is the limiting diffusivity within Δz, the distance between the centres of layer (1) and layer (3). In practice it is diffusion within the thermocline itself. Since L3VMP contains no advective terms, and the sinking of particulates is treated separately, $w_{1,3}$ refers only to the rate at which the thermocline deepens in the model. It is zero (but $w_{3,1}$ is positive) when the thermocline shallows.

In this example, the exchange velocity is the rate of movement of layer (3) water (and associated dissolved substances, heat, and neutrally buoyant particulates) into layer (1) through each square

metre of layer boundary, as a result of either one-way entrainment or two-way turbulent exchange, or both. In the case of entrainment alone, E is the rate of thermocline movement; in the case of turbulent diffusion alone it may be thought of as proportional to (but generally only a small fraction of) typical (root-mean-square) eddy velocities averaged over the distance between layer centres. In the case of sediment-water fluxes of particles, $E_{3,5}$ may be thought of as the rate of erosion of the sediment surface by tidal current drag. Finally, $E_{1,0}$, for gas flow between air and water, is a 'transfer velocity'.

4. Physical and biological components

L3VMP consists of a set of differential equations for each water-column and sediment layer. One such equation gives the rate of change of the 'state variable' phytoplankton biomass B (mmol C m^{-1}) in layer (1):

$$dB/dt = (1/h_1).(<B>_{1,3} + <<B>>_1) \qquad \text{mmol C m}^{-3}\text{ d}^{-1} \qquad (4.1)$$

This has been written so as to distinguish physical and biological-chemical components of the model. The physical transport of phytoplankton between layers is the flux:

$$<B>_{1,3} = E_{1,3}(B_3 - B_1) - {}^B w.B_1 \qquad \text{mmol C m}^{-2}\text{ d}^{-1} \qquad (4.2)$$

where ${}^B w$ is the sinking velocity (m d^{-1}, positive downwards) of phytoplankton. The net total of the biological production or destruction of phytoplankton within a layer is:

$$<<B>>_1 = h.(\mu - G).B_1 \qquad \text{mmol C m}^{-2}\text{ d}^{-1} \qquad (4.3)$$

where μ and G are the proportionate rates (d^{-1}) of, respectively, intrinsic phytoplankton growth and removal by zooplankton grazing. The main purpose of the physical components of L3VMP is to predict the E terms; the purpose of the biological components of the model is to predict $<<B>>$ and analogous terms. Note the conventions for fluxes. Those such as $<B>$, which cross a layer boundary and have subscripts indicating source and sink layers, are 'conservative': they do not change the total of the state variable in the simulated water column. Those such as $<<B>>$ refer to changes within the layer indicated by the single subscript; these changes may alter the water column total of the state variable.

Water column optical properties (which help to determine phytoplankton growth rate) are treated as part of the physical model, which for this purpose includes the resuspension of fine inorganic sediments, concentration A mg m^{-3}. The sinking of phytoplankton and other organic particulates is included within the biological model.

5. Biological model : autotrophic and heterotrophic processes

All living things described by L3VMP are small, mostly less than 0.1 mm in size, and behave as passive contaminants of water or sediment motion, except insofar as their excess weight or buoyancy (or that of the particles they are attached to) causes them to sink or float. 'Autotrophs' make the organic raw materials of life from carbon dioxide, water and mineral salts. Phytoplankton are the main autotrophs in the sea, and the only type represented in L3VMP. Their organic synthesis releases oxygen and is powered by solar radiation of wavelengths between 400 and 700 nm absorbed by the green pigment chlorophyll. The attenuation of this photosynthetically active radiation (PAR) by seawater imposes strong depth dependency on phytoplankton photosynthesis, and is thus one of the main cause of biological structure in the water column.

'Heterotrophs' consume organic material and, in most cases, oxygen; the process of organic degradation releases ("remineralizes") the inorganic salts of phosphorus, nitrogen and silicon originally taken up by photosynthesizing phytoplankton. These salts (most commonly in the form of ions of nitrate, nitrite, ammonium, phosphate and silicate) are loosely called 'nutrients'. Heterotrophs include large animals; from a functional viewpoint, however, the most important heterotrophs in the sea belong to the microbiota, and include bacteria and a variety of single-celled creatures, the Protozoa.

'Microplankton' is a convenient name for the community of planktonic algae, bacteria and protozoans whose members are characterized by small size and potential rapid growth and decay of population numbers, and which can be described by equations similar to those for dissolved substances or suspended particulates. The seabed also contains microbiota. Only heterotrophs are represented in the sediment layer of L3VMP, and, like the microplankton of the water column, they are described in terms of bulk properties by simple differential equations.

Larger creatures such as fish or benthic worms are less amenable to mathematical treatment as functions continuous with time. Their population growth is slower and it can be necessary to

distinguish periods of reproduction, when numbers increase, from periods when individuals increase in size but numbers decrease. Mathematical descriptions may behave "chaotically". In addition, large animals are able to respond actively to environmental changes, and so do not behave as passive contaminants of water or sediment motion. They are not explicitly described in L3VMP, although the model does take account of some consequences of their activities, for example of the effect of zooplankton grazing on phytoplankton dynamics and nutrient cycling.

L3VMP thus describes 'microbiological' and not 'macrobiological' processes. In the same way that the first question relating to the physical model was about number of layers, the fundamental issue for the biological model concerns the minimum number of biological and chemical compartments needed adequately to represent microbiological processes influencing water quality in shelf seas.

One answer is shown in figure 2. The compartment called "microplankton" represents the potential autotrophic activity of the water column microbiota under illuminated conditions. In this version of L3VMP it bulks together the planktonic free-living protozoa and bacteria as well as the diatoms, dinoflagellates and flagellates of the phytoplankton, and thus embodies the community properties of the microplankton as a whole (Tett *et al.*, 1988). Of its three defining variables, chlorophyll concentration X relates only to the phytoplankton and is the index of photosynthetic activity. B (biomass as particulate organic carbon concentration, mmol m^{-3}) and N (particulate organic nitrogen concentration mmol m^{-3}) relate to the microplankton as a whole. B is used as the index of respiratory activity, and r^B includes both phytoplankton and microheterotroph respiration.

"Detritus", the other component of the biological model, is characterized by purely destructive processes. It is described by two variables : C, particulate organic carbon concentration (mmol m^{-3}), and M, particulate organic nitrogen concentration (mmol m^{-3}). In weight it is dominated by nonliving organic material, formed from dead phytoplankton and the undigested material in zooplankton faecal pellets. Heterotrophic microorganisms, especially bacteria, are associated with this dead stuff and use it as a supply of energy and organic raw materials. They consume oxygen and release inorganic nitrogen. L3VMP converts sinking phytoplankton to detritus on contact with the seabed, and hence the exchange of biological particulates between sediment and water involves only detritus.

Oxygen (concentration O mmol m^{-3}) is produced in the water column by photosynthesis and consumed by the respiration of the microplankton and detrital microorganisms. The gradient that drives its diffusion into the sediment is maintained by detrital respiration in the sediment, which lacks

oxygen-producing processes.

In L3VMP, the action of microorganisms on detrital nitrogen releases ammonium, concentration ^{NH}S mmol m^{-3}, which is also the main form in which nitrogen is excreted by zooplankton. Water column ammonium, if not absorbed by phytoplankton, is rapidly oxidized to nitrate, concentration ^{NO}S mmol m^{-3}. Much sediment ammonium remains unoxidized because of low oxygen concentration in the sea bed, and the resulting concentration gradient drives its diffusion into the water column.

The links between the cycling of carbon, nitrogen and oxygen are important in a water quality model. L3VMP contains several variables and parameters defining these relationships. Nitrogen:carbon ratios, or nutrient quotas Q, help determine the rates of phytoplankton growth and detrital remineralization. The 'photosynthetic quotient' relates oxygen released to organic carbon assimilated in photosynthesis; it is often greater than 1.0 moles oxygen per mole carbon because the simultaneous photoassimilation of nitrate, and its reduction to organic nitrogen compounds, also releases oxygen. The 'respiratory quotient' is however always taken by L3VMP as 1.0 moles oxygen consumed per mole carbon mineralized. This is because detrital or zooplankton mineralization of organic nitrogen to ammonium are not themselves oxygen-consuming processes, and because microplankton respiration is assumed to mineralize only carbon, nitrogen being internally recycled. In L3VMP, the extra consumption of oxygen when ammonium is oxidized, and which corresponds to the extra production of oxygen when nitrate is photoassimilated, takes place as an independent process.

6. State variables, parameters and constants

In general terms, L3VMP consists of a set of differential equations in the model's 'state variables', plus other equations that expand rate terms in the differential equations. Tett & Droop (1988) distinguished "framework equations" defining the structure of a model, from subsidiary "rate equations", on the grounds that the latter could be derived piecemeal from laboratory experiments, whereas the former represented a particular dissection of ecosystem processes and could only be assessed as a whole. In general the aim in numerical simulations of a model is to evaluate the state variables as functions of time and depth, or, in L3VMP, layer number. Differences between simulations result from differences either in the time-series, or location-dependent, variables used to force the model or in the parameters embedded in the rate equations.

The main state variables of L3VMP, and the layers for which they are defined, are listed in Table 1. The symbols for these variables are given capital letters. Capital letters are also used for most of the important driving variables such as tidal current speed U or exchange velocity E. In contrast, subsidiary rate variables, parameters and constants are denoted by lower-case letters. The main exceptions to these rules are the lower case symbols d, h and t for water column depths, layer thicknesses, and time. (note a).

Heat content H and temperature T are not independent but are related by constants:

$$H = \rho.c.T \qquad\qquad \text{J m}^{-3} \qquad\qquad (6.1)$$

where ρ is seawater density and c is the specific heat of seawater.

Potential energy anomaly Φ and thermocline depth h_1 differ from other variables in being properties of the water column as a whole rather than of particular depths or layers. A column with warm surface water has less potential energy than a mixed column in which work has been done against gravity to lift cold, dense, water from near the sea-bed. In the case of a two-layer water column such as that of L3VMP, potential energy anomaly may be calculated from thermocline and seabed depths, and layer temperatures T_1 and T_3 :

$$\Phi = g.\rho.a.(T_1 - T_3).h_1.(h_1 - d)/2 \qquad\qquad \text{J m}^{-2} \qquad\qquad (6.2)$$

The constant g is the gravitational acceleration, and a is the coefficient of thermal expansion of seawater. The value of Φ is negative for a stratified water column and zero for a column that is completely mixed.

Although photosynthetically available radiation (PAR) I is the rate at which white-light photons pass downwards through unit area parallel to the sea surface, it is treated as a state variable because it varies with depth and time as a consequence of changes in other state variables as well as of temporal changes in the external driving variable $'I_o$, the all-wavelength solar irradiance falling on the sea surface. It is assumed that no light reaches the sediment.

All other state variables are concentrations. Living phytoplankton are assumed not to exist in the sediment; thus only detrital organic carbon C and nitrogen M and the dissolved species oxygen O,

ammonium ^{NH}S and nitrate ^{NO}S, are defined there. Concentrations of solubles relate to pore-water volume, of particulates to both phases of the sediment. The amount of light-attenuating inorganic sediment A is assumed to be constant in layer (5), and sediment temperature is equated with that in the overlying water. In addition to T (and H), and I, and the concentration variables A, C, M, O, and S, the three phytoplankton state variables (organic carbon biomass B, and particulate nitrogen N and chlorophyll X concentrations) are also defined in layers (1) and (3). As already mentioned, dissolved and particulate substances transfer between layers by entrainment or exchange of water, sinking at rates w (metres per day), or resuspension.

Finally, only oxygen concentration O and temperature T are defined (as, respectively, a concentration equal to seawater saturation, and a dewpoint temperature) for the air layer and hence only oxygen and heat flow between air and sea.

A 'parameter' is a symbol in an equation that can be replaced by a single value rather than by a further equation or a changing value. Unlike those of true constants, the values of parameters may be changed between numerical simulations. L3VMP treats some variables as constants when allowing them to vary would have insignificant effects on the calculations in which they are used. An example is the water-column average density of seawater ρ, set to 1025 kg m^{-3} despite typical geographical and seasonal variation from 1023 to 1027 kg m^{-3} in the North Sea. Such 'constants' are listed in Table 2. L3VMP contains a large number of parameters, and an important part of model development lies in providing standard values for them (note b).

Because of the variety of parameters and variables, a complex notation has been adopted for qualifying the symbols that identify these terms. The convention is $^1_2\$^3_4$, where $\$$ is any variable or parameter. The leading superscript 1 refers to chemical or biological species, for example to nitrate NO in ^{NO}S, and the following superscript 3 to standardization, for example to biomass B in microplankton respiration rate r^B. The following subscript 4 refers to parameterization of a state or rate variable (for example, as in μ_{max}, the maximum intrinsic rate of growth for phytoplankton), or to layer number; the leading subscript 2 is used for layer number when position 4 is already occupied.

Finally, { ... } encloses the subject of an operator. Thus $exp\{-G.t\}$ is equivalent to $e^{-G.t}$. The operator $L\{$ .. $\}$ is an instruction to select the parenthetical term with the lowest value. { ... } alone, encloses logical alternatives.

Note a

Difficulties arise in choosing symbols for a multidisciplinary model, since the usage of one discipline often conflicts with that of another. For example the bacteriologists who developed microbial growth theory employed s for the concentration of growth-limiting substrates in the media which physically and nutritionally supported their bacteria. Algologists extended the symbol to include concentrations of mineral nutrients, which were the analogous limiting agents for phytoplankton growth. Physicists use C for concentration: I have retained (but capitalized) S for nutrients and used C for detrital carbon.

Note b

There are some difficult numerical and philosophical problems in the estimation of parameter values for models (Lederman & Tett, 1981). For example, in linear regression the simple model $y = a + b.x$ is fitted to sets of observations of y and x by choosing values of the parameters a and b that minimize the sum of squares of differences between observed and model-predicted values of the dependent variable y. Parameter values for L3VMP might estimated in similar empirical fashion, although the task becomes complex when numerous parameters must be simultaneously determined. Since, however, the rate equations of L3VMP are theoretically-based, and the model itself is to be seen as a refutable hypothesis about shelf sea microbiology, it is proper that "standard" parameter values be obtained either from the literature or from North Sea measurements that are independent of observations used to test L3VMP. The sum of squares of differences between observed and model-predicted values of key state variables is then an index of model accuracy, not a model-fitting tool.

7. Time-scales and time-steps : problems of averaging and numerical approximation

The physical processes described by L3VMP vary on tidal, diel, fortnightly and seasonal time-scales. Under constant conditions, the characteristic time-scales of marine microbiological processes range from a few hours to a few days. The basic time interval in L3VMP is, however, 24 hours. This simplification avoids the need for explicit description of diel cycles of warming and photosynthesis, or tidal-cycle changes in stirring and resuspension. A day is the natural period for balancing inputs of thermal buoyancy against wind and tidal stirring, or of photosynthetic production against microplankton respiration, and is the shortest timescale on which the surface layer is always completely homogenized. Since the surface layer is treated as a unit by L3VMP, there are thus links between spatial and temporal averaging.

Two sorts of problem arise from the use of a 24-hour time-scale in L3VMP. A fundamental question concerns the way in which faster processes are averaged. Woods & Onken (1982) point to the difference, in the case of photosynthetic production, between (i) multiplying layer-mean

chlorophyll concentration and photosynthetic efficiency by layer- and time- mean irradiance, and (ii) averaging the 24-hour total of photosynthesis carried out by individual phytoplankton cells that have performed a random walk through the depth- and time- varying light field in the surface mixed layer. L3VMP tries to avoid difficulties by (i) careful choice of state and rate variables to provide appropriate averaging, and (ii) use of equations and numerical methods that tend to converge to stable steady-state solutions, so that initial undershoots or overshoots during numerical simulation are automatically corrected during calculations for subsequent days. An example of (i) is the use of "cell-quota theshold-limitation" theory (Droop, 1983, Tett & Droop, 1988) to describe phytoplankton growth in terms of processes whose natural time-scale is a day or longer.

The other type of problem arises during numerical solution of the equations of L3VMP. When exact analytical solutions are not available, it is necessary to use finite difference approximations. Significant errors due to these approximations may arise when a variable changes by a substantial amount during a 24-hour period. An example derives from the simplified equation for phytoplankton biomass:

$$dB/dt = (\mu - G).B \qquad \text{mmol m}^{-3} \text{ d}^{-1} \qquad (7.1)$$

where μ is phytoplankton specific growth rate (d^{-1}) and G is the proportional rate of removal of phytoplankton by zooplankton grazing (d^{-1}). The 'forward finite difference' approximation corresponding to (7.1) is :

$$\Delta B = (\mu - G).B_t \Delta t \qquad \text{mmol m}^{-3} \qquad (7.2)$$

where ΔB is the addition, during the time interval Δt, of biomass to the original concentration B_t. There is an exact solution to (7.1):

$$\Delta B = (exp\{(\mu - G).\Delta t\} - 1).B_t \qquad \text{mmol m}^{-3} \qquad (7.3)$$

which exceeds the approximate solution in the ratio:

$$1 + {}^B error = (exp\{\mu - G\}.\Delta t\} - 1)/((\mu - G).\Delta t) \qquad (7.4)$$

If Δt is 1 day, the relative error will be large if the value of $(\mu - G)$ is substantial. It is less than 0.1 when $(\mu - G).\Delta t < 0.2$. Thus, the error resulting from simple finite-difference approximation can be kept small by making Δt small, perhaps much less than 1 day. Note that this is purely a numerical device concerning the <u>time-step</u> and has no implications for the considerations used in defining the model's <u>time-scale</u>. Alternatively, an approximate analytical solution can be used: see section 20.

8. The program L3VMP

The program extracts included in this report are written in Apple Pascal 1.3, which is a version of UCSD Pascal. As far as possible they use only ISO Pascal. The source code given here should thus require only minor changes to compile and run on any computer supporting Pascal. The extracts have been run on an Apple IIc microcomputer in an expanded version of the program shown in Table 3. For convenience the physical and biological procedures were separately compiled to a library file and linked to the main program at run-time.

For those unfamiliar with Pascal, the assignment operator is ":=" and (* .... *) enclose comments. The language is 'block-structured', so that everything between a BEGIN and the corresponding END is treated as an entity. The program commences (following the external links) with definitions of data types and variables. Note especially the type LYA, which is defined as a 1-dimensional array of real variables with index values between 0 and 5, corresponding to the layers of the model. The variable B, for example, is of this type, so that B[1] is the variable corresponding to phytoplankton biomass in layer (1). The 'main program', which calls the previously or externally defined procedures and functions, comes at the end of the code. It begins with procedures to attach external data files (which may be disc-files) to program variables of type text. This allows data to be input to, or output from, the program.

The simulation part of the program is contained in two loops, which repeat all the procedure they contain each time the loop control variable DAY increases by one. The function STRATIFICATION is of major importance here. Supplied with information on sea-surface heat flux, wind and tidal amplitude, it updates thermocline depth h_1, potential energy anomaly Φ, and the temperature array, and calculates the exchange velocities $E_{1,3}$ and $E_{3,1}$, for each 24 hour period. The modified values of these variables are available to other procedures. The function is defined as BOOLEAN. NOT STRATIFICATION sets the simple BOOLEAN variable MIXED to TRUE if the value returned by STRATIFICATION itself is FALSE as a result of an excess of stirring over

buoyancy. In order to provide correct initial conditions for a simulation, STRATIFICATION is 'prerun' for several simulated years before any results are output or used by other procedures. Note that in the latter part of the main program, in the block within the DO loop from STARTDAY to ENDDAY, STRATIFICATION is computed before the biological procedures. In essence, the day's inputs of stirring and buoyancy are totalled, and used to adjust thermocline depth, at the beginning of the day. Biological calculations for the day then make use of the revised thermocline depth.

Suspended fine inorganic sediment is also changed at the beginning of the time-step, so that it is the new concentrations that help determine the optical properties of the water column. In all other cases, changes in state variables are not made until the end of the time-step. For example, removal of dissolved nitrate by phytoplankton uptake is calculated using phytoplankton biomass and nitrate concentration at the beginning of the time-step. The procedure MICROPLANKTON, which carries out the computation, preserves unchanged the initial values of nitrate in the array NOS, and carries changes in the array DNOS. Only when all nitrate fluxes have been calculated using the initial values in NOS does the procedure WATER_COLUMN add the changes in DNOS to NOS to give new values of nitrate concentration.

For the sake of simplicity in presentation, most model parameters are included as constants within the procedures in this version of L3VMP. When station-dependent, the parameter values are those for mooring site A of the 1988/89 North Sea survey, at 55° 30'N, 01° 00'E, in about 80 metres of water.

Table 1 : State, and driving, variables

STATE VARIABLES

Functions of time (t, days) and in some cases of depth (z, metres) or layer-number (subscript 0 to 5).

A : nominal concentration of irradiance-Attenuating sediment, g m^{-3};

B : phytoplankton organic carbon Biomass, mmol C m^{-3};

C : detrital particulate organic Carbon, mmol m^{-3};

H : Heat content, J m^{-3};

h : layer thickness, m; h_1 is depth of seasonal thermocline and h_3 is thickness of tide-mixed layer;

I : downwards diffuse PAR Irradiance, μE m^{-2} s^{-1}; PAR is "photosynthetically available radiation", 400 - 700 nm;

M : detrital particulate organic nitrogen, mmol m^{-3};

N : phytoplankton organic Nitrogen, mmol m^{-3};

O : dissolved Oxygen, mmol m^{-3};

Φ : water column Potential energy anomaly (relative to mixed column), J m^{-2};

Q : ratios in particulates. $^{N}Q^{B}$ is phytoplankton nitrogen Quota, the ratio N/B, mmol N (mmol C)$^{-1}$; $^{X}Q^{B}$ is phytoplankton chlorophyll:carbon ratio, mg chl (mmol C)$^{-1}$; $^{M}Q^{C}$ is detrital nitrogen:carbon ratio, mmol N (mmol C)$^{-1}$;

S : dissolved combined inorganic nitrogen as Substrate for phytoplankton growth, mmol N m^{-3}; with leading superscripts ^{NO} for nitrate, ^{NH} for ammonium;

T : Temperature, °C;

X : phytoplankton biomass as Chlorophyll, mg m^{-3};

DRIVING VARIABLES

Functions of (time and) position

A_5 : constant concentration of light-attenuating inorganic sediment in layer (5), g m^{-3};

$C_5(t{=}0)$: initial concentration of detrital carbon in layer (5), mmol m^{-3};

d : water column depth, m;

$G(t)$: proportional loss rate of phytoplankton by grazing, d^{-1};

h_5 : thickness of oxygenated sediment layer, m;

$^tI_0(t)$: daily mean, all-wavelength-total solar irradiance on the sea-surface, $J\ m^{-2}\ s^{-1}$;

$K_{z,2}$: (constant) diffusivity within thermocline, $m^2\ d^{-1}$;

$K_{z,5}$: (constant) sediment diffusivity, $m^2\ d^{-1}$;

$O_0(t)$: nominal air oxygen concentration, in fact saturation concentration of oxygen in seawater at the temperature of layer (1), $mmol\ m^{-3}$;

$M_5(t=0)$: initial concentration of detrital nitrogen in layer (5), $mmol\ m^{-3}$;

$T_o(t)$: (daily mean) dewpoint temperature of air close to sea-surface, °C;

$U(t)$: (tidal-and-column-mean) tidal speed, $m\ s^{-1}$;

$W(t)$: (daily-mean) wind speed close to sea surface, $m\ s^{-1}$;

Table 2 : Constants

a : coefficient of thermal expansion of seawater, $2.1\ x\ 10^{-4}\ °C^{-1}$;

c : specific heat of seawater, $3900\ J\ kg^{-1}\ °C^{-1}$;

g : gravitational acceleration, $9.81\ m\ s^{-2}$;

ρ : density of seawater, $1025\ kg\ m^{-3}$;

$^{air}\rho$: density of air, $1\ kg\ m^{-3}$;

Table 3 : The program L3VMP

```
PROGRAM L3VMPB;

(* Outline program in UCSD Pascal to show relationship between      *)
(* model procedures;  most parameters included as constants within  *)
(* procedures.          PT, 11 July 90.                             *)

USES TRANSCEND, {$U L3:GENERAL.LIB} GENERAL, {$U L3:PHYSICS.LIB} PHYSICS,
    {$U L3:BIOLOGY.LIB} BIOLOGY;

(* USES calls utilities and model procedures from library files.         *)
(* Model procedures are:                                                 *)
(*   (Physics) METEOROLOGY, HEATFLUX, TIDE, STRATIFICATION, REDISTRIBUTE, *)
(*   BENTHIC_EXCHANGE, AIR_SEA_EXCHANGE, OPTICS;                          *)
(*   (Biology)  GRAZING, MICROPLANKTON, SEDIMENT, WATER_COLUMN.           *)

CONST YEAR = 365;

(* TYPEs already declared in GENERAL unit :                       *)
(* LYA = ARRAY[0..5] OF REAL ( layers of model );                 *)
(* EXA = ARRAY[1..5,0..5] OF REAL ( exchanges between layers);    *)
(* MON = ARRAY[1..12] OF REAL ( monthly data );                   *)
(* STRING defined in UCSD Pascal as variable-length array of CHAR *)

VAR
    A,B,C,H,I,M,N,O,NHS,NOS,TEMP,X : LYA (* arrays for state variables  *);
    DB,DC,DM,DN,DOX,DNHS,DNOS,DX : LYA (* arrays for changes in st.vars.*);
    E : EXA (* exchange velocities *);
    G : MON (* zooplankton grazing pressure *);
    PHI : REAL;
    D,FD,ITOT,U_TIDE,W_WIND : REAL (* driving variables *);
    DAY,STARTDAY,ENDDAY,PREYEARS,RUNYEARS : INTEGER;
    MIXED, OVERTURN : BOOLEAN;
    STATION : STRING;
    INPD, PAR, RES : TEXT (* input data and results files *);

PROCEDURE OPEN_FILES (VAR I, P, R : TEXT);
VAR I_NAME, P_NAME, R_NAME : STRING (* external file names *);
BEGIN (* obtain I_NAME, P_NAME, R_NAME and link I, P, R with these files *)
END;

PROCEDURE OBTAIN_PARAMETERS(VAR P:TEXT; VAR PREYEARS,RUNYEARS:INTEGER;
VAR D:REAL; VAR DES:STRING; VAR G:MON);
BEGIN (* Input these parameter values from file P or from keyboard *)
END;

PROCEDURE INITIALIZATION (VAR INPD : TEXT; VAR
A,B,C,H,I,M,N,O,NHS,NOS,TEMP,X : LYA; VAR E : EXA; VAR PHI:REAL);
BEGIN (* initialize state variables from INPD, or from keyboard *)
END;

PROCEDURE STORE_RESULTS (VAR R : TEXT);
BEGIN (* write selected values to R, or to console *)
END;

PROCEDURE ZERO_DARRAYS (VAR DB,DC,DM,DN,DNHS,DNOS,DOX : LYA);
VAR L : 1..5;
BEGIN
    FOR L:=1 TO 5 DO BEGIN (* set values in D.. arrays to zero *) END;
END;

PROCEDURE TIDY_FINISH (VAR R : TEXT);
BEGIN (* close results file and generally bring program to a tidy end *)
END;
```

```
BEGIN (* main program *)

OPEN_FILES(INPD,PAR,RES);
OBTAIN_PARAMETERS(PAR,PREYEARS,RUNYEARS,D,STATION,G);
INITIALIZATION(INPD,A,B,C,H,I,M,N,O,NHS,NOS,TEMP,X,E,PHI);
STARTDAY:=PREYEARS*YEAR; ENDDAY:=(PREYEARS+RUNYEARS)*YEAR;
ZERO_DARRAYS(DB,DC,DM,DN,DNHS,DNOS,DOX);

(* constant tide in this version, hence need compute sea-bed *)
(* exchange only once                                        *)
U_TIDE:=TIDE(DAY);
BENTHIC_EXCHANGES(H,E,FD,U_TIDE);

FOR DAY:= 1 (* = March 1 *) TO STARTDAY-1 DO BEGIN
    METEOROLOGY(DAY,ITOT,TEMP,W_WIND);
        MIXED:=NOT
    STRATIFICATION(D,H,TEMP,E,PHI,OVERTURN,HEATFLUX(ITOT,TEMP,W_WIND),
    U_TIDE,W_WIND);
END (* pre-run to stable cycle of seasonal thermocline *);

FOR DAY:=STARTDAY TO ENDDAY DO BEGIN (* main simulation *)
    METEOROLOGY(DAY,ITOT,TEMP,W_WIND);
    MIXED:=NOT
    STRATIFICATION(D,H,TEMP,E,PHI,OVERTURN,HEATFLUX(ITOT,TEMP,W_WIND),
    U_TIDE,W_WIND);
    IF OVERTURN THEN RESDISTRIBUTE (A,B,C,M,N,NHS,NOS,O,X,E);
    E[1,0]:=AIR_SEA_EXCHANGE(O,TEMP,W_WIND);
    OPTICS(A,C,H,I,X,E,FD,ITOT,MIXED);
    MICROPLANKTON
  (B,H,I,N,NHS,NOS,O,TEMP,X,DB,DC,DM,DN,DNHS,DNOS,DOX,E,GRAZING(DAY,G),MIXED);
    SEDIMENT(C,H,M,NHS,NOS,O,TEMP,DC,DM,DNHS,DNOS,DOX,E,FD);
    WATER_COLUMN(C,H,M,NHS,NOS,O,TEMP,DC,DM,DNHS,DNOS,DOX,E,MIXED) ;
    ZERO_DARRAYS(DB,DC,DM,DN,DNHS,DNOS,DOX);
    STORE_RESULTS(RES);
END;

TIDY_FINISH(RES);
END.
```

Figure 1 : the physical structure of L3VMP.

E : exchange velocities, m d^{-1};

h : layer thickness, m;

I : day- and layer- mean photosynthetically effective irradiance, microEinsteins m^{-2} s^{-1}; $^tI_0$ is daily mean all-wavelength solar irradiance above the sea surface, W m^{-2};

q : air-sea heatflux due to temperature difference, W m^{-2};

T : layer mean temperature, °C; T_0 is dewpoint temperature;

w : particulate sinking rate, m d^{-1}.

Figure 2 : the biological and chemical structure of L3VMP.

Shown for a mixed water column. The symbol $\stackrel{\perp}{=}$ indicates a sink which does not conserve state variables.

PART II : PHYSICAL MODEL

9. Thermocline depth and exchange

The most important control on phytoplankton production is the mean illumination of the surface mixed layer, which is determined by time of year and the depth and transparency of the layer. In L3VMP the function STRATIFICATION (table 5) computes the existence of stratification and the thickness of the surface layer.

The model for the depth h_1 of the seasonal thermocline derives from Simpson & Bowers (1984). By changing the heat content and potential energy anomaly of the water column, wind and tidal stirring, and vertical heat flows, alter the thermocline depth. In the following equations U is tidal amplitude, and W wind speed (m^{-1}). Other terms are defined below or in Tables 1, 2 or 4.
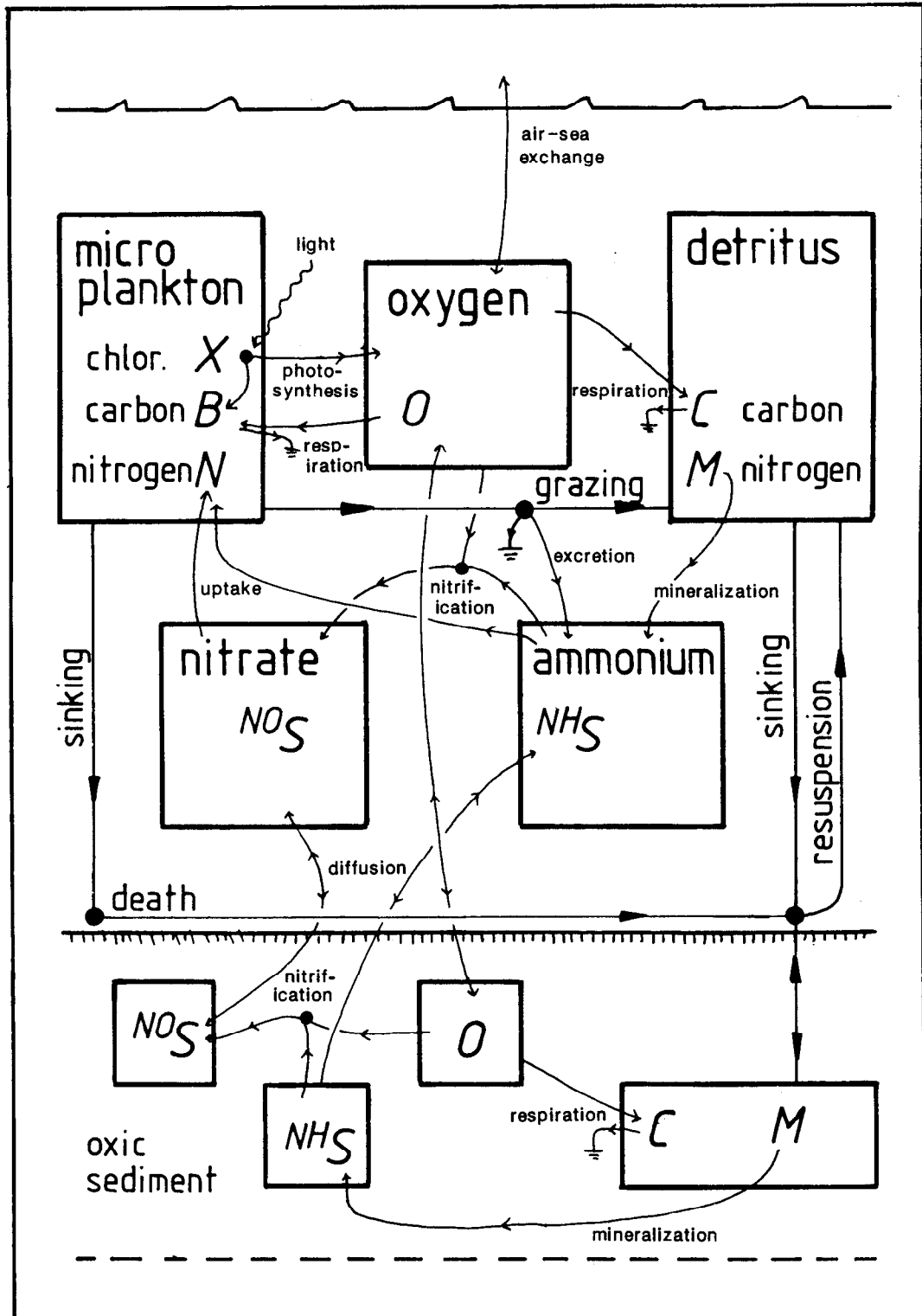
Rates of change (averaged over 24 hours) of layer heat content are given by

$$d(H_1.h_1)/dt = q(t) + E_{1,3}.\rho.c.(T_3 - T_1) \quad J\ m^{-2}\ s^{-1} \tag{9.1}$$

$$d(H_3.h_3)/dt = E_{1,3}.\rho.c.(T_1 - T_3) \quad J\ m^{-2}\ s^{-1} \tag{9.2}$$

and rate of change of potential energy anomaly by

$$d\Phi/dt = -q(t).d.g.a/(2.c) + W^3.{}^{air}\rho.f_o.k_o + \tag{9.3}$$

(thermal p.e.decrease) (wind t.k.e.input)

$$U^3.\rho.f_3.k_3.4/(3.\pi) + \rho.g.a.E_{1,2}.d.(T_1 - T_3)/2 \quad J\ m^{-2}\ s^{-1}$$

(tidal t.k.e.input)   (thermocline mixing p.e.increase)

"Thermal p.e.decrease" refers to the potential energy deficit due to the buoyancy that is added to the water column each day by surface warming. It is assumed that this buoyancy is input initially to the top metre of the water column. "t.k.e." refers to the turbulent kinetic energy input by tidal and wind-generated flows. A part of this is available to work against gravity by lifting colder, denser water towards the sea-surface. The resulting increase in potential energy offsets the deficit resulting from surface warming.

The exchange velocities are:

$$E_{1,3} = E_{1,2} + \{\Delta h_1 \ if \ +ve, \ else \ 0\} \quad m \ s^{-1} \tag{9.4}$$

$$E_{3,1} = E_{1,2} - \{\Delta h_1 \ if \ -ve, \ else \ 0\} \quad m \ s^{-1} \tag{9.5}$$

where $E_{1,2}$ is the exchange velocity resulting from internal mixing in the thermocline

$$E_{1,2} = K_{z2}/l_2 \quad m \ s^{-1} \tag{9.6}$$

where K_{z2} is a vertical turbulent diffusivity ($m^2 s^{-1}$) in, and l_2 a length scale for, the thermocline. This diffusion is assumed to operate symmetrically in both directions across the thermocline, so that $E_{1,2}$ = $E_{2,1}$ = $E_{3,2}$ = $E_{2,3}$. It is not included in Simpson & Bowers (1984), but could make a significant contribution to vertical mixing in some shelf seas, where K_{z2} might be of order 10^0 to $10^1 \ m^2 \ d^{-1}$ (Sandstrom & Elliott, 1984; Sherwin, 1988). An upper limit to $E_{1,2}$ is thus 1 m d^{-1}.

Net heat flux into the surface mixed layer is given by $q(t)$, which is a function of sea-surface solar irradiance ^tI_o (W m^{-2}), wind speed and air dewpoint temperature T_o:

$$q(t) = {}^tI_o + q^T.(T_o - T_1) \quad J \ m^{-2} \ s^{-1} \tag{9.7}$$

where q^T is an empirical thermal exchange coefficient accounting for all the processes by which heat is gained or lost at an air-sea boundary. It includes back-radiation, conduction and evaporation. The calculation for q^T in the procedure HEATFLUX (Table 5) is derived from Edinger et al. (1974, as cited by Clarke, 1986).

Clarke (1986) gives a numerical method for solving these equations for T_1, T_3, and h_1 as functions of time, and this is largely adopted in STRATIFICATION. The function is driven by daily values of W, T_o, ^tI_o and U. Initial values of T_1, T_3, and h_1 must also be supplied, but may be arbitrary, for after 3 simulated years the seasonal cycle of temperature and stratification should repeat to within 0.1 °C. Each new day's values are calculated from the old values by first considering the effect of surface heat flux and wind stirring on layer (1) temperature and thickness, and then the effect of bottom stirring on layer (3). It is assumed that all processes apply continuously during each 24 hour period, and no allowance is made for diel variations in heating or tidal-period cycles of bottom

stirring.

In L3VMP the additional effects of trans-thermocline mixing are computed after the surface and bottom effects described by Clarke, on the assumption that thermocline mixing exchanges warm layer (1) water with cold layer (3) water without altering the thermocline depth.

The following conventions have been adopted to avoid numerical problems during complete vertical mixing and at the start and end of stratification. When inputs of t.k.e. cause h_1 to equal or exceed d, h_1 and h_3 are both set equal to d, Φ is set to zero, and STRATIFICATION returns FALSE. State variables are thereafter computed for the most convenient layer of (1) or (3), and values copied to the other layer. When the daily decrease of p.e. due to surface warming again exceeds the t.k.e. input, and h_1 again becomes less than d, layer (3) is reinserted in the simulation with $h_3 = d - h_1$. This procedure ensures that initial values of state variables for both layers are those of the well-mixed water column immediately before stratification. On any day that STRATIFICATION, having been TRUE, first becomes FALSE, the BOOLEAN variable OVERTURN is set TRUE; at all other times it is FALSE. The procedure REDISTRIBUTE (Table 5) is effective only when OVERTURN is TRUE: that is, on the day that a stratified water column first becomes completely mixed.

10. Sediment resuspension.

An account of sediment resuspension is an important part of a model for shallow shelf seas. The mineralization of resuspended organic material may contribute substantially to water column oxygen demand, and the attenuation of light by seawater can be greatly increased by suspended inorganic sediments.

The exchange of particulates between water column and sediment is a complex and much-discussed process (Dyer, 1986; note a). The resuspension and transport of sand is normally modelled in terms of a reference concentration in a bedload layer, but this approach may not be applicable to the more cohesive sediments found in parts of the North Sea, and L3VMP thus uses a direct relationship between tidal drag and sediment erosion. Wind effects are not included at this stage. The aim of the resuspension submodel is to predict the concentrations in layer (3) of fine inorganic sediments (A) and organic detritus (C and M) from free-stream tidal amplitude U. The instantaneous drag of tidal currents on the sea-bed is proportional to the square of the instantaneous friction

velocity U_*, which is related to time-varying free-stream velocity by:

$$U_* = |sqrt(k_3).U(t)| \qquad\qquad m^2\ s^{-2} \qquad\qquad (10.1)$$

where k_3 is a bottom drag coefficient, with typical value about 2.5×10^{-3} (Bowden, 1983), as used also in the thermocline model. Bottom stress is $\rho.U_*^2$ N m^{-2}, where ρ is the density of seawater. (For present purposes the directions of U_* or bottom stress are unimportant.) U_{*m} is the friction velocity corresponding to the maximum value of $|U(t)|$ during the tidal cycle, that is, to the tidal amplitude symbolized here by U. Since U varies over the southern North Sea (and with the spring/neap cycle) between 0.25 and 1.5 m s^{-1}, U_{*m} ranges from 0.012 to 0.075 m s^{-1}, and maximum bottom stress from 0.15 to 6 N m^{-2} in this region.

The tidal cycle may be divided into three phases. During periods of high current $(U_*(t) > U_{*e})$, sediment is lifted from the sea-bed at a rate proportional to the excess of tidal over critical erosional shear stress. During periods of low current $(U_*(t) < U_{*d})$, suspended material accretes to the sea-bed at a rate depending on the extent that tidal shear is less than critical depositional stress. Settlement at zero flow takes place at the free-stream sinking rates $^A w$ or $^C w$. During periods of intermediate flow ($U_{*d} < U_*(t) < U_{*e}$) neither deposition nor erosion takes place. U_{*d} and U_{*e} are critical depositional and erosional friction velocities; for simplicity they will both be taken as 0.01 m s^{-1} in this version of L3VMP (note b).

On the assumption that the concentrations of particulates in layer (3) remain constant during a tidal cycle, the net flux of fine inorganic particulates into (3) from (5) is:

$$<A>_{3,5} = E_{3,5}.A_5 - {}^A w.f^d\{\ U_{*d}/U_{*m}\ \}.A_3 \qquad\qquad g\ m^{-2}\ d^{-1} \qquad\qquad (10.2)$$
$$\text{erosion} \qquad\qquad \text{deposition}$$

The exchange velocity is:

$$E_{3,5} = k_e(86400).U_{*m}^2.f^e\{\ U_{*e}/U_{*m}\ \} \qquad\qquad m\ d^{-1} \qquad\qquad (10.3)$$

where k_e is an erosion constant, estimated from North Sea survey data as of order 10^{-6} m^{-1} s (note c). Its value needs further investigation.

The nondimensional erosion function is:

$$f^e\{U_{*c}/U_{*m}\} = (1/\pi). \quad \{0 \ if \ sin(\omega) < U_{*c}/U_{*m}$$

$$else$$

$$(sin(\omega))^2 - (U_{*c}/U_{*m})^2)\}.d\omega \tag{10.4}$$

where the integral is taken between ω of 0 and π radians (that is, over one half of a symmetrical tidal cycle). Example values are:

U_{*c}/U_{*m}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$f^e\{..\}$	0.50	0.49	0.46	0.42	0.37	0.31	0.24	0.17	0.10	0.04	0.00

The depositional function, which describes the extent to which settlement is inhibited by near-bottom turbulent flow, is:

$$f^d\{ U_{*d}/U_{*m} \} = (U_{*m}/U_{*d})^2. \ (1/\pi). \quad \{ 0 \ if \ sin(\omega) > U_{*d}/U_{*m}$$

$$else$$

$$(U_{*d}/U_{*m})^2) - (sin(\omega))_2 \}.d\omega \tag{10.5}$$

It also is nondimensional, and example values are:

U_{*d}/U_{*m}	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.5	2.0
$f^d\{..\}$	0.00	0.09	0.18	0.27	0.37	0.50	0.65	0.78	0.88

The equations are derived from those given by Dyer (1986) in terms of shear stress. Equation [10.2] may be solved for the layer (3) concentration in the steady state and the absence of input to (3) from (1):

$$A_3 = E_{3,5}.A_5/(^Aw.f^d\{ U_{*d}/U_{*m} \}) \qquad g \ m^{-3} \tag{10.6}$$

Similar equations can be written for detrital organic carbon, with the addition of a term $<<C>>_3$ for the net total of microbiological processes. This leads to the steady state solution:

$$C_3 = (E_{3,5} \cdot C_5 + <<C>>_3)/(^Cw \cdot f^d\{ U_{*d}/U_{*m} \}) \qquad \text{mmol m}^{-3} \qquad (10.7)$$

which, again, assumes no input of detritus from layer (1).

The procedure BENTHIC_EXCHANGES (Table 5) computes the exchange velocity $E_{3,5}$ and the depositional function f^d for output to other procedures in the simulation program. Changes in A are computed by OPTICS and resuspension fluxes in C (and M) by SEDIMENT.

Note a

I am grateful to Alan Davies and Sarah Jones (UCNW) and Alison Weeks (Southampton) for helpful discussions of sediment processes. A reference concentration model was used in an earlier draft, but was rejected as providing a less good prediction of suspended sediment at weakly stirred sites.

Note b

Dyer (1986) summarizes criticial erosional shear stresses as between 1 and 10 dyne cm^{-2}, and gives a single example of a critical depositional stress of 0.6 dyne cm^{-2}. The latter corresponds to a friction velocity of 0.008 m s^{-1} and the former to 0.01 to 0.03 m s^{-1}. Wainright (1990) observed detectable resuspension at "shear velocities (u_*) or 0.95 to 1.35 cm s^{-1} in sediments ranging from fine to coarse sands." A value of 0.01 m s^{-1} thus seems appropriate as an initial choice for both U_{*d} and U_{*e}.

Note c

The resuspension constant k_e was estimated from North Sea survey data for winter mean suspended particulates at a strongly and a weakly stirred station, using the steady state equations (10:6) and (10:7) and U_{*m} from Pingree & Griffiths (1978) M_2 depth averaged tidal amplitude. C_5 was extrapolated from information supplied by A.Upton, Essex. $<<C>>_3$ was assumed to be 5 mmol m^{-2} d^{-1}, and the sinking rates ^Aw and ^Cw were both taken as 5 m d^{-1}. The station-related data are:

mooring station	$U*m$ m s^{-1}	A[3] g m^{-3}	C[3] mmol m^{-3}	C[5] kmol m^{-3}
A	0.014	0.2	7	1
E	0.043	3.7	21	0.2

The resulting estimate of k_e was 5×10^{-7} m^{-1} s, and A_5 was estimated as 51 kg m^{-3}, implying that fine inorganics make up between 2% and 3% of the sediment. The value of k_e is very low compared with that of 2×10^{-3} m^{-1} s which can be estimated from resuspension fluxes observed by Wainright (1990).

11. Exchanges of dissolved substances between water and sediment.

In principle, the exchange of dissolved oxygen, nitrate or ammonium between water and sediment may be retarded by slow transport in three regions. These are: the pore water in the sediment itself; a thin overlying viscous layer of smoothly changing flow; and, above this, a zone, metres thick, in which flow, and turbulence, increase with hieght above the sea bed.

A viscous layer arises as a result of steady flow over a smooth surface, conditions which preclude the entrainment of particles into the flow and which reduce the vertical flux of dissolved substances because of the absence of turbulence in the horizontal flow. Rahm & Svennson (1989) give an equation for oxygen flux through a viscous layer. The equation can be written:

$$<O>_{4,3} = k_4 U_* (O_3 - O_4) \qquad \text{mmol m}^{-2}\text{ s}^{-1} \qquad (11.1)$$

where O_3 is the free-water concentration of oxygen and O_4 that at the sediment surface. U_* is friction velocity (m s^{-1}) and k_4 a semi-empirical, dimensionless, constant of order 10^{-3}.

Generally, however, the roughness of the seabed in relation to tidal flows is such that the viscous layer does not exist in many parts of the North Sea. Indeed, particulate resuspension can only take place in conditions in which turbulence extends to the sediment surface, and hence compatability between the models for particulates and solubles prohibits the existence of a viscous layer in L3VMP. Instead, the oxygen flux to the sediment from the water column is in principle described by:

$$<O>_{4,3} = E_{4,3} (O_3 - O_4) \qquad \text{mmol m}^{-2}\text{ s}^{-1} \qquad (11.2)$$

The exchange velocity can be related to tidal drag on the assumption that vertical turbulent diffusivity is given by $\beta . \kappa U_* z$ where z is height above the sea bed, κ is Von Karman's constant (0.4) and β is a factor relating the turbulent diffusion of dissolved susbstances to that of momentum. Its

value is usually taken as 1.0 in the absence of density gradients. Assuming that the sediment roughness length z_o (of order 10^{-3} to 10^{-2} m) defines the lower limit of integration, exchange velocity (note a) is:

$$E_{4,3} = (\beta.\kappa.U_*)/(ln(h_3/(2.z_o))) \qquad m\ s^{-1} \tag{11.3}$$

In a steady state, the flux $<O>_{4,3}$ must equal that into the sediment pore water. The latter flux (note b) is:

$$<O>_{5,4} = E_{5,4}.(O_4 - O_5) \qquad mmol\ m^{-2}\ s^{-1} \tag{11.4}$$

where the exchange velocity depends on an empirical sediment turbulent diffusion coefficient, K_{z5}, to which molecular diffusion, bioturbation, tidal pumping and sediment movement may all contribute,

$$E_{5,4} = 3.K_{z5}/h_5 \qquad m\ s^{-1} \tag{11.5}$$

Combining (11:2) and (11:4) gives

$$<O>_{5,3} = 86400.(1/((1/E_{4,3}) + (1/E_{5,4}))).(O_3 - O_5) \quad mmol\ m^{-2}\ d^{-1} \tag{11.6}$$

Values of $E_{4,3}$ for the southern North Sea are of order 10^{-3} m s^{-1}. Observations on oxygen fluxes into sediment cores freshly taken from the North Sea during 1988-89 survey cruises (A.Upton, Essex) suggest that $E_{5,4}$ is of order 10^{-6} m s^{-1}. This is compatable with empirical estimates of diffusivities near the sediment surface by Rutgers van der Loeff (1980a, Wadden Sea) and Billen (1978, Southern Bight of the North Sea, as reported by Rutgers van der Loeff, 1980b). Clearly, transport of oxygen within the sediment is the dominant control on the flux of the gas, and hence L3VMP can use

$$<O>_{5,3} = E_{5,3}.(O_3 - O_5) \qquad mmol\ m^{-2}\ d^{-1} \tag{11.7}$$

where the exchange velocity is:

$$E_{5,3} = 259200.K_{z5}/h_5 \qquad m\ d^{-1} \tag{11.9}$$

and K_{z5} probably lies between molecular diffusion at 10^{-9} m^2 s^{-1} and at least 10 times this value. Thus

$E_{5,3}$ is between 10^{-2} and 10^{-1} m d^{-1} (note c). The exchange velocity $E_{5,3}$ applies equally to nitrate or ammonium:

$$<S>_{5,3} = E_{5,3}(S_3 - S_5) \qquad \text{mmol m}^{-2}\text{ d}^{-1} \qquad (11.9)$$

In the case of oxygen, the minimum value of O_5 is zero, and hence the maximum value of $<O>_{5,3}$ is $E_{5,3}O_3$. The fastest timescale for oxygen depletion of the water column by the seabed is thus $h_3/E_{5,3}$, of order 10^3 days. Conversely, the timescale for changes in the sediment due to exchanges with layer (3) is set by $h_5/E_{5,3}$, of order 1 day, and some care is required in computing these exchanges.

In the program L3VMP the components of (11:7) and (11:9) are computed in two places. The (physical) procedure BENTHIC_EXCHANGES (Table 5) outputs a value for $E_{5,3}$ for use in computing fluxes of oxygen and nutrients in the (biological) procedure SEDIMENT.

Note a

Given the Fickian equation for oxygen flux: $<O> = -K_z dO/dz$, and replacing K_z by $\beta.\kappa.U_*z$, the exchange velocity $E_{4,3}$ can be estimated by integrating $(1/z).dz = -(\beta.\kappa.U_*/<O>).dO$ between O_4 at z_0 and O_3 at $z = h_3/2$.

Note b

Assume that oxygen flux within the sediment can be described by a Fickian equation with constant diffusivity, and that the flux decreases linearly with depth due to a rate of oxygen consumption that is constant within the oxygenated layer. Let z here refer to distance into the sediment, from $z = 0$ at the surface where the flux is $<O>_{5,4}$, to $z = h_5$ at the bottom of the oxygenated layer where the flux is zero. Thus:
$$-K_{z5}dO/dz = <O>_{5,4} - k.z \qquad \text{mmol m}^{-2}\text{ s}^{-1}$$
Integration and solving for oxygen concentration gives:
$$O(z) = O_4 - (<O>_{5,4}z - k.z^2/2)/K_{z5} \qquad \text{mmol m}^{-3}$$
The mean oxygen concentration between $z = 0$ and $z = h_5$ is
$$O_5 = (1/h_5) \int O(z).dz \qquad \text{mmol m}^{-3}$$
and hence
$$<O>_{5,4} = (3.K_{z5}/h_5).(O_4 - O_5) \qquad \text{mmol m}^{-2}\text{ s}^{-1}$$

Note c

$E_{5,3}$ may also be seen as the sum of five components. The first is $3.p.K/h_5$, where K is molecular diffusion and p is sediment porosity, about 0.4 according to Rutgers van der Loeff (1980b). The term is thus about 2×10^{-3} m d^{-1}. The next three terms are transfer velocities due to tidal, wave and biotic pumping of sediment pore water. The last is $E_{3,5}$, due to the erosion and redeposition of superficial sediment during a tidal cycle, and varying between 10^{-6} and 10^{-4} m d^{-1}. Since estimates of $E_{5,3}$ from experimental and field data are 10^{-2} m d^{-1}, or greater the pumping terms would seem to dominate, and it is thus unfortunate that tidal and wind-wave pumping are excluded during ship-board measurements of fluxes using sediment cores. The rough agreement between the North Sea survey measurements, obtained from cores, and the observations of Rutgers van der Loeff (1980a) on changes in nutrient profiles of in situ sediments in the Wadden Sea, suggest however that bioturbation may dominate in both regions.

12. Air-sea oxygen exchange.

The flux of gas between air and sea can be described as the product of a 'transfer' or 'piston' velocity and a concentration difference across the interface. Thus, in the case of oxygen:

$$<O>_{1,0} = E_{1,0}(O_0{}'(T) - O_1) \quad \text{mmol m}^{-2} \text{ d}^{-1} \tag{12.1}$$

where $O_0{}'(T)$ is the actual air concentration modified by the (temperature-dependent) ratio of the equilibrium air and water concentrations of oxygen. It is related to temperature:

$$1/O_0{}'(T) = 1.37 + 0.039.T_1 \quad \text{mmol m}^{-3} \tag{12.2}$$

on the basis of oxygen solubility values in Carpenter (1966) and a typical chlorinity of 19 ppth in the southern North Sea. The term $(O_0{}'(T) - O_1)$ is in fact the difference between the atmospheric equilibrium and the actual concentrations of oxygen in surface sea water, assuming 760 mm atmospheric pressure. The concentration stored in O[0] in L3VMP is thus the saturation concentration of oxygen in sea water at the temperature of layer (1), and not the air concentration itself.

Much work has taken place on the relationship between the transfer velocity and wind speed, and there has been considerable discussion of the shape of the relationship as well as of parameter values and their dependence on the gas involved (Liss 1988). The following simple function approximates the three-part relationship summarized by Liss:

$$E_{1,0} = 86400.k_w.W^2 \quad \text{m d}^{-1} \tag{12.3}$$

where the coefficient k_w is about 5×10^{-7} m^{-1} s.

13. Illumination.

The basic equation for the penetration of light in the sea is :

$$dI/dz = \lambda.I \qquad \mu E\ m^{-3}\ s^{-1} \qquad (13.1)$$

where I is downwelling irradiance and λ is an appropriate diffuse attenuation coefficient. λ is a function of wavelength and of radiance distribution (Kirk, 1983) and so of depth, since downwelling light becomes progresively more vertical and monochromatic as it penetrates further into the sea. This version of L3VMP follows Tett (1990) by treating subsurface light as monochromatic, and correcting surface illumination to allow for the greater attenuation near the sea-surface of wavelengths and paths of light which penetrate the water less well. Future versions might partition PAR into several, independently-attenuated, wavelengths, and might allow for diurnal, weather-related, and seasonal changes in radiance distribution at the sea surface and as a function of scattering by suspended sediments. In this version I refers to PAR averaged over 24 hours, and the optical parameters to mean conditions in respect of sun angle and cloudiness.

I_o refers to PAR irradiance immediately beneath the sea-surface. It is related to total solar irradiance $'I_o$ in W m^{-2}:

$$I_o = m_0.m_1.m_2{'}I_0 \qquad \mu E\ m^{-2}\ s^{-1} \qquad (13.2)$$

where m_0 of 1.91 μE J^{-1} converts all-wavelength solar energy in Joules to PAR photons, m_1 of 0.95 allows for PAR losses at the sea-surface, and m_2 of 0.37 allows for additional subsurface losses of polychromatic light (Tett, 1990). The use of m_2 results in an underestimation of light immediately beneath the surface, but simplifies the calculation of layer-mean illuminations and is especially appropriate when a linear photosynthesis-light relationship is used in the prediction of phytoplankton growth.

Mean illumination in the surface-mixed layer is:

$$I_1 = I_0(1 - exp\{ -\lambda_1.h_1 \})/(\lambda_1.h_1) \qquad \mu E\ m^{-2}\ s^{-1} \qquad (13.3)$$

In most cases, the layer is "optically deep" and the exponential term is small and can be neglected. In the bottom layer the illumination is:

$$I_3 = I_0 exp\{ -\lambda_1.h_1 \}.(1 - exp\{ -\lambda_3.h_3 \})/(\lambda_3.h_3) \quad \mu E \ m^{-2} \ s^{-1} \qquad (13.4)$$

and the second exponential term can often be neglected.

The task of the OPTICS procedure (table 5) in L3VMP is to compute and output the mean illuminations. Prior to this, however, it must calculate the attenuation coefficients for each layer. These are made up of contributions from seawater ($^{SW}\lambda$, taken as 0.10 m^{-1}, note a), suspended fine inorganic sediment, and phytoplankton chlorophyll:

$$\lambda = {}^{SW}\lambda + {}^{A}\epsilon.A + {}^{X}\epsilon.X \qquad m^{-1} \qquad (13.5)$$

where the ϵ are 'absorption cross-sections' for fine inorganic sediment and chlorophyll. North Sea survey data suggest that $^{A}\epsilon$ should be about 0.1 m^2 g^{-1} (note b), and a suitable value for $^{X}\epsilon$ in moderately clear coastal water is 0.02 m^2 mg^{-1} (Tett, 1990). $^{X}\epsilon$ is dependent on water optical type, and a value of 0.01 m^2 mg^{-1} would be more appropriate for very turbid water. Equation (13:5) could be improved by adding terms for light attenuation by detritus and for salinity-related absorption by 'yellow-substance' in freshwater.

Since the only role of fine inorganic sediment in L3VMP is to attenuate light, values of A are calculated by OPTICS and not in a separate procedure. In this version the steady-state equation (10:7) is used to predict A_3. When MIXED is false, changes in layer (1) concentration are given by:

$$dA_1/dt = (E_{1,3}(A_3 - A_1) - (^{A}w/h_1).A_1)/h_1 \qquad g \ m^{-3} \ d^{-1} \qquad (13.6)$$

Note a

Jerlov (1968) gives a minimum attenuation of 0.12 m^{-1} for 'type 1' coastal water, but observations (note b) in the northern part of the 1988/89 North Sea survey area included estimates of minimum attenuation (that some distance below the surface at stations low in suspended solids) of 0.09 to 0.10 m^{-1}.

Note b

The CTD system used from Challenger during North Sea survey cruises included a downwards irradiance sensor, which could be used to estimate diffuse PAR attenuation λ by profiling during daylight, and a transmissometer, which could be used to estimate red beam attenuation c. For Challenger cruise 57 (July 1989), and excluding stations with abundant phytoplankton, the two attenuations were related:

$$\lambda = -0.05 + (0.28).c \qquad \qquad \text{m}^{-1}$$

Sarah Jones (UCNW) calibrated a similar transmissometer against gravimetrically determined total suspended sediment at North Sea station BJ, and obtained:

$$c = 0.57 + (0.34).(A+B+C) \qquad \qquad \text{m}^{-1}$$

Combining the two equations gives

$$\lambda = 0.11 + (0.095).(A+B+C) \qquad \qquad \text{m}^{-1}$$

supplying 0.11 as an estimate of $^{SW}\lambda + {}^{X}\lambda.X$, and 0.095 $\text{m}^2\,\text{g}^{-1}$ as an estimate of the absorption cross-section for total seston.

14. Forcing terms for the physical model.

The physical model is forced by eight terms. The meteorological variables wind speed W, air dewpoint temperature T_0 and total solar irradiance $^tI_0$ are time-dependent and drive the seasonal cycle of stratification and PAR illumination. It would not be unrealistic to treat them as constant, for a given day, over a region such as the Southern Bight of the North Sea. Water-column depth d and tidal amplitude U are strongly dependent on location, and are sufficient on their own to predict frontal transitions from mixed to thermally stratified waters (Simpson & Hunter, 1974). The other terms are the thickness h_S of the oxygenated sediment layer, the concentration A_S of fine inorganics therein, and thermocline mixing $E_{1,2}$. Although these are likely to be station and time-dependent, they are treated as station-independent, time-constant parameters in this version of L3VMP.

In this version daily values of the meterological variables W, T_0 and $^tI_0$ are computed in the procedure METEOROLOGY (table 5) from sine functions such as:

$$W(t) = {}^Wa_1 + {}^Wa_2 sin(\omega t + {}^Wa_3) \qquad \text{m s}^{-1} \qquad\qquad (14.1)$$

where $^W a_1$ is the annual mean wind speed (m s^{-1}), $^W a_3$ the (mean to peak) amplitude (m s^{-1}) of a sine wave whose period is one year and whose phase (in radians relative to March 1) is determined by $^W a_3$. The term ω.t gives time in radians; hence ω is $2\pi/365$ radians day^{-1} for t in days. Clarke (1986) provides gridded values of the parameters for wind speed and dewpoint temperature for the continental shelf of NW Europe, and gives the irradiance parameters as functions of latitude between 62 and 45 °N (note).

Such smoothed inputs imitate general features of the climatic seasonal cycle. Instead, real meterological data could be input from a table holding values for each day of a given year. Alternatively, the statistical effects of 'weather' might be simulated by peturbing the climatically-determined values of W and $^t I_0$ for a particular day according to the value of a 'weather-state' variable determined from a sum which is randomly incremented, within presecribed limits, each simulated day. The second and third options are not implemented in this version of L3VMP.

Simpson & Bowers (1981) found that frontal positions changed little during the spring-neap cycle. Following Clarke (1986), this version of L3VMP uses time-invariant but location-dependent values of U, equal to the amplitude of the depth-averaged M_2 tidal velocity and taken from Pingree & Griffith's (1978) tidal model of the NW European Shelf. Spring-neap variation could be investigated in a general way by using:

$$U = U_{M2}(1 + b.cos(\omega t)) \quad \text{m s}^{-1} \tag{14.2}$$

(Simpson, 1981) where $b = 0.3$ gives a ratio of springs to neaps typical of the north-eastern North Sea, and a value of 0.1 would be characteristic of the inner German Bight (Lee & Ramster, eds., 1981). ω is $2\pi/14.5$ radians d^{-1} for t in days. This improvement could be combined with the use of a stratification-dependent mixing efficiency in the model for the seasonal thermocline (Simpson & Bowers, 1981).

Note

In the case of simulations for the site of North Sea mooring A, at 55°30'N, the constants given by Clarke (1986) for Mylnefield, 56°27'N, have been adjusted by inspection of Meteorological Office data (Anon, 1980) for Mylnefield, giving : $^l a_1$ of 112 (105) and $^l a_2$ of 96 (98) W m^{-2}. The values cited by Clarke are given in parenthesis. The small differences are important in winter; predicted midwinter irradiance is now 16 (7) W m^{-2}.

Table 4: Parameters for the physical model

(see also Table 1 for variables and 2 for constants)

(standard values given where appropriate)

a_1 : annual mean of sine wave for daily mean of wind speed (superscript ^{W}, units m s^{-1}), dewpoint temperature (^{T}, °C) or solar irradiance (^{I}, J m^{-2} s^{-1});

a_2 : amplitude (mean to peak) of sine wave for wind speed, dewpoint temperature or solar irradiance;

a_3 : phase (in radians, relative to 1 March) of annual sine wave function for wind speed, dewpoint temperature, or solar irradiance;

b : ratio, to mean tidal amplitude, of half the difference between the amplitudes of spring and neap tides;

β : ratio of turbulent diffusion of dissolved substance to that of momentum, 1.0;

d : water column depth, m;

$^A\epsilon$: (diffuse) PAR attenuation cross-section (attenuation per unit) of suspended inorganic sediment, 0.1 m^2 g^{-1};

$^X\epsilon$: (diffuse) PAR attenuation cross-section (attenuation per unit) of phytoplankton chlorophyll, 0.02 m^2 (mg chl)$^{-1}$;

f_0 : efficiency of wind mixing, 0.0029;

f_3 : efficiency of tidal mixing, 0.004;

f^d : depositional function/parameter in resuspension model;

f^e : erosional function/parameter in resuspension model;

$^I I_0$: (24-hr mean) total solar irradiance above sea surface, W m^{-2};

I_0 : (24-hr mean) downwards PAR immediately beneath the sea surface (corrected for surface reflectance only), μE m^{-2} s^{-1};

k_0 : sea-surface (wind) drag coefficient, 0.0013;

k_3 : sea-bed (tidal current) drag coefficient, 0.0025;

k_4 : parameter in Rahm & Svenson viscous layer oxygen flux model, 10^{-3};

k_e : erosion parameter in resuspension model, 10^{-6} m^{-1} s;

$K_{z,2}$: vertical turbulent diffusivity in the thermocline, $m^2\ s^{-1}$;

$K_{z,5}$: notional diffusivity in the sediment, $m^2\ s^{-1}$;

k_w : coefficient relating wind, and air-sea gas transfer, velocities, $5 \times 10^{-7}\ m^{-1}\ s$;

K : Von Karman's constant, 0.4;

λ : (diffuse) PAR attenuation coefficient, m^{-1};

$^{sw}\lambda$: (diffuse) PAR attenuation coefficient for coastal sea-water free of particulates, 0.10 m^{-1};

l_2 : thermocline length-scale, m;

m_0 : 1.91 μE PAR photons per J all-wavelength solar irradiance;

m_1 : proportion of PAR penetrating sea-surface, 0.95;

m_2 : proportion of PAR at penetrating wavelengths, 0.37;

ω : time-dependent phase term in wave functions, radians d^{-1};

p : sediment porosity, 0.4;

q^T : coefficient (function of wind speed and temperature) for air-sea heat exchange, $J\ m^{-2}\ s^{-1}\ {}^{\circ}C^{-1}$;

U_{*d} : critical depositional friction velocity, $0.01\ m\ s^{-1}$;

U_{*e} : critical erosional friction velocity, $0.01\ m\ s^{-1}$;

U_{*m} : friction velocity corresponding to tidal amplitude, $m\ s^{-1}$;

w : sinking rates of particulates (superscripted ^{A} for fine inorganics or ^{C} for detritus both), $5\ m\ d^{-1}$;

z_0 : sediment roughness length, m;

Table 5: Program extracts: procedures for physical model

```
PROCEDURE METEOROLOGY (DAY:INTEGER; VAR ITOT:REAL; VAR T:LYA; VAR W:REAL);
(* Evaluates surface irradiance, ITOT, air dewpoint temperature T[0] *)
(* and wind speed W as sine functions of DAY. DAY 1 = March 1.       *)
(* In this version, values of the sine function parameters for North *)
(* Sea mooring A at 55 30 N, 01 00 E, are supplied as constants.     *)


CONST
   CUBECORR=1.18 (* from Clarke, 1986, to give accurate cube mean wind *);
(* wind *) WA1=7.5 (* mean m/s *); WA2=2.4 (* amplitude, m/s *);
          WA3=2.5 (* phase, rad. *);
(* dewpoint *) TA1=6.6 (* deg C *); TA2=4.8 (* deg C *); TA3=-1.25 (* rad *);
(* irrad, from Anon 1980 *) IA1=112 (* W/m**2 *);
          IA2=96 (* W/m**2 *); IA3=-0.33 (* rad *);
          OMEGA=0.017214 (* 2pi/365 *);

BEGIN
   W:=WA1 + WA2*SIN(OMEGA*DAY + WA3); W:=W*CUBECORR;
   T[0]:=TA1 + TA2*SIN(OMEGA*DAY + TA3);
   ITOT:=IA1 + IA2*SIN(OMEGA*DAY + IA3);
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - *)


FUNCTION HEATFLUX (ITOT:REAL; VAR T:LYA; W:REAL):REAL;
(* Computes 24-hr mean air-sea thermal exchange, in W/sq m, including *)
(* direct and back-radiation, conduction and evaporation.            *)
(* Equations from Edinger et al 1974, via Clarke 1986.               *)

CONST Q1=4.5; Q2=0.03; Q3=0.82; Q4=0.015; Q5=0.012;
VAR QT,TMEAN:REAL;

FUNCTION WIND(W:REAL):REAL;
CONST FB=11.2; FW=2.85; (* Clarke, 1986, p 3.4 *)
BEGIN WIND:=FB + FW*W; END;

BEGIN
   TMEAN:=(T[0] + T[1])/2;
   QT:=Q1 + Q2*T[1] + WIND(W)*(Q3 + Q4*TMEAN + Q5*TMEAN*TMEAN);
   HEATFLUX:=ITOT+QT*(T[0]-T[1]);
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - - - *)

FUNCTION TIDE (DAY:INTEGER):REAL;
CONST M2=0.28 (* depth-meaned amplitude for mooring A, m/s *);
BEGIN TIDE:=M2; END;
```

```
(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - *)
FUNCTION STRATIFICATION
(D:REAL;  VAR H,T:LYA;  VAR E  :  EXA;  VAR PHI:REAL;  VAR OVERTURN:BOOLEAN,
HEATFLUX,U,W:REAL):BOOLEAN;)
(* Computes changes in layer temperatures T and thicknesses H        *)
(* due to surface heating/cooling HEATFLUX, wind and tidal stirring  *)
(* (derived from wind speed W and tidal amplitude U), and            *)
(* thermocline exchange.  Inputs averaged over 24 hours;             *)
(* calculation timestep = 1 day.  PHI is potential energy anomaly,   *)
(* joules/sq metre : negative values indicate stratification. The    *)
(* function returns 'false' when PHI=0, and the value of OVERTURN    *)
(* is 'true' on (and only on) the day that PHI becomes 0.            *)
(* Algorithms partly after Clarke, 1986.                            *)
(*   D =  watercolumn depth                                          *)
(*   E = exchange velocity array; E[1,3] and E[3,1] are required     *)
(*        output from procedure; E[1,2] = E[3,2] supply             *)
(*        thermocline mixing velocity                               *)

CONST PI=3.14159;
     DAYLENGTH = 86400.0 (* seconds *);
     AEXP=2.1E-4 (* seawater expansion per deg C *);
     C=3900 (* specific heat seawater, J/kg/deg C *);
     G=9.81 (* gravitational acceleration, m/s**2 *);
     RHO=1025.0; AIRRHO=1.0; (* seawater and air densities, kg/m**3 *)
     F0=0.0029 (* efficiency of wind mixing - Clarke, 1986   *);
     F3=0.004 (* efficiency of tidal mixing - Clarke, 1986   *);
     K0=0.0013 (* sea-surface (wind) drag coefficient - Clarke, 1986 *);
     K3=0.0025 (* sea-bed (tidal) drag coefficient - Clarke, 1986 *);

VAR OLDH1,OLDH3,DT,TOTALHEAT,DPHI,H1DT,H3DT,TFLUX:REAL;

FUNCTION WELLMIXED:BOOLEAN;
BEGIN
     PHI:=0 (* can't be better than well mixed, so +ve not allowed *);
     H[1]:=D; H[3]:=D;
     T[1]:=TOTALHEAT/(D*RHO*C); T[3]:=T[1];
     E[3,1] IF D>OLDH1 THEN BEGIN:=0;
     OVERTURN:=TRUE;
     E[1,3]:=D-OLDH1;
     END ELSE BEGIN
     OVERTURN:=FALSE;
     E[1,3]:=0.0;
     END;
     WELLMIXED:=FALSE;
END;

BEGIN (* main function *)

OLDH1:=H[1]; OLDH3:=H[3];
DT:=T[1]-T[3]; TOTALHEAT:=RHO*C*(T[3]*D + DT*H[1]);

(* surface effects *)
TOTALHEAT:=TOTALHEAT + HEATFLUX*DAYLENGTH;
DPHI:=-AEXP*G*HEATFLUX*D/(2*C) (* heating *);
DPHI:=DPHI + F0*K0*AIRRHO*W*W*W (* wind stirring *);
PHI:=PHI + DPHI*DAYLENGTH;
IF PHI > 0 THEN STRATIFICATION:=WELLMIXED
(* and no need for tidal effects *)
ELSE BEGIN
     H1DT:=(TOTALHEAT/(RHO*C)) - D*T[3];
     H[1]:=D + 2*PHI/(RHO*G*AEXP*H1DT);
     T[1]:=T[3] + H1DT/H[1];      (* bottom effects *)
     DPHI:=(4/(3*PI))*RHO*F3*K3*U*U*U; PHI:=PHI+DPHI*DAYLENGTH;
     IF PHI > 0 THEN STRATIFICATION:=WELLMIXED
          (* and no need to mix at thermocline *)
     ELSE BEGIN
        H3DT:=(T[1]-T[3])*(H[1]-D);
```

```
          H[1]:=2*PHI/(RHO*G*AEXP*H3DT);
          H[3]:=D-H[1]; T[3]:=T[1] + H3DT/(H[3]);

          (* thermocline mixing *)
          TFLUX:=E[1,2]*(T[1]-T[3]);
          T[1]:=T[1] - TFLUX/H[1]; T[3]:=T[3] + TFLUX/H[3];
          PHI:=PHI + TFLUX*RHO*G*AEXP*D/2;
          IF PHI > 0 THEN STRATIFICATION:=WELLMIXED
          ELSE BEGIN
              IF H[1] > OLDH1 THEN BEGIN
                  E[1,3]:=E[1,2] + (H[1] - OLDH1); E[3,1]:=E[1,2]; END
              ELSE BEGIN
                  E[3,1]:=E[1,2] + (OLDH1 - H[1]); E[1,3]:=E[1,2]; END;
              STRATIFICATION:=TRUE;
      END;
  END;
END;


T[5]:=T[3];
END (* of function stratification *);

PROCEDURE REDISTRIBUTE (* (VAR A,B,C,H,M,N, NHS,NOS,O,X : LYA; VAR E : EXA) *);
(* Redistributes tracers following overturn; E[1,3] gives thickness of    *)
(* layer (3) before overturn, and H[1]=D under mixed conditions.          *)

FUNCTION JOIN(VAR P:LYA):REAL;
BEGIN
    JOIN:=(P[1]*(H[1]-E[1,3]) + P[3]*E[1,3])/H[1];
END;

BEGIN
    A[1]:=JOIN(A); A[3]:=A[1];
    B[1]:=JOIN(B); B[3]:=B[1];
    C[1]:=JOIN(C); C[3]:=C[1];
    M[1]:=JOIN(M); M[3]:=M[1];
    N[1]:=JOIN(N); N[3]:=N[1];
    NHS[1]:=JOIN(NHS); NHS[3]:=NHS[1];
    NOS[1]:=JOIN(NOS); NOS[3]:=NOS[1];
    O[1]:=JOIN(O); O[3]:=O[1];
    X[1]:=JOIN(X); X[3]:=X[1];
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - *)

PROCEDURE BENTHIC EXCHANGES (VAR H:LYA; VAR E:EXA; VAR FD:REAL; U:REAL);
(* Computes velocities for exchange of particulates and dissolved *)
(* substances between water-column and sediment.                  *)
CONST EROSION=TRUE; DEPOSITION=FALSE;
      DAYLENGTH=86400.0 (* seconds *);
      K3SQRT=0.05 (* sqr root tidal drag coefficient of 0.0025 *);
      KE=1E-6 (* erosion constant, m-1 s *);
      KZ5=2E-4 (* benthic diffusivity, m2 d-1 *);
      USTARE=0.01 (* critical erosional friction velocity, m s-1 *);
      USTARD=0.01 (* critical depositional friction vel., m s-1 *);
VAR USTARM:REAL (* maximum friction velocity *);

FUNCTION TIDAL(ERODE:BOOLEAN;UR:REAL):REAL;
(* tidal function for erosion and deposition: *)
(* if ERODE=true, UR = U*e/U*m; if ERODE=false, UR=U*d/U*m  *)
CONST PI=3.14159; N=40;
VAR I:1..N; DOMEGA,S,ST:REAL;
BEGIN
    DOMEGA:=PI/N;S:=0.0;
    FOR I:=1 TO N DO BEGIN
        ST:=SIN(DOMEGA*I);
        IF ERODE THEN
            IF ST < UR THEN (* do nothing *) ELSE S:=S+(ST*ST-UR*UR)*DOMEGA
```

```
        ELSE (* depositional function *)
            IF ST > UR THEN (* do nothing *) ELSE S:=S+(UR*UR-ST*ST)*DOMEGA;
        END;
    IF ERODE THEN TIDAL:=S/PI ELSE TIDAL:=S/(PI*UR*UR);
END;


BEGIN
    (* particulate resuspension and desposition *)
    USTARM:=K3SQRT*U;
    E[3,5]:=KE*DAYLENGTH*USTARM*USTARM*TIDAL(EROSION,USTARE/USTARM);
    FD:=TIDAL(DEPOSITION,USTARD/USTARM);
    (* exchange of solubles *)
    E[5,3]:=3*KZ5/H[5];
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - *)


FUNCTION AIR_SEA_EXCHANGE (VAR O,T:LYA; W : REAL):REAL;
(* Computes temperature-dependent seawater oxygen saturation,        *)
(* and returns value of air-sea transfer velocity.                   *)
(* Function for saturation based on data in Carpenter (1960);        *)
(* for transfer velocity, based on data in Liss (1988).              *)
CONST ASAT=1.37E-3 (* m3 mmol-1 *); BSAT=0.039E-3 (* degC m3 mmol-1 *);
      DAYLENGTH=86400.0 (* seconds *); KW=5E-7 (* m-1 s *);
BEGIN
    O[0]:=1/(ASAT + BSAT*T[1]);
    AIR_SEA_EXCHANGE:=DAYLENGTH*KW*W*W;
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - *)


PROCEDURE OPTICS (VAR A,C,H,I,X : LYA; VAR E:EXA; FD,ITOT:REAL;
MIXED:BOOLEAN);
(* Outputs mean illumination in each layer, using contributions *)
(* to attenuation from inorganic sediments and chlorophyll.     *)
CONST M0=1.91 (* muE PAR per J total solar irradiance *);
      M1=0.95 (* allows for surface losses *);
      M2=0.37 (* allows for near-surface losses polychromatic light *);
      AW=5 (* sinking rate fine inorganic sediment, m d-1 *);
      SWLAMBDA=0.10 (* attenuation clean coastal seawater, m-1 *);
      AEPSILON=0.10 (* abs. x-section, susp. inorg,sed., m2 g-1 *);
      XEPSILON=0.02 (* abs. x-section phyto, m2 mg chl-1 *);
VAR LAMBDA : LYA;


BEGIN
    (* calculate suspended inorganic sediment, *)
    (* using steady-state eqn for layer [3].   *)
    A[3]:=E[3,5]*A[5]/(AW*FD);
    IF MIXED THEN A[1]:=A[3] ELSE
        A[1]:=A[1] + (E[1,3]*(A[3] - A[1]) - AW*A[1])/H[1];
    (* calculate attenuations for each layer *)
    LAMBDA[3]:=SWLAMBDA + AEPSILON*A[3] + XEPSILON*X[3];
    IF MIXED THEN LAMBDA[1]:=LAMBDA[3] ELSE
        LAMBDA[1]:=SWLAMBDA + AEPSILON*A[1] + XEPSILON*X[1];
    (* calculate 24-hr mean PAR irradiances, after Tett (1990) *)
    I[0]:=M0*M1*M2*ITOT;
    I[1]:=I[0]/(LAMBDA[1]*H[1]);
    IF MIXED THEN I[3]:=I[1] ELSE
        I[3]:=I[0]*EXP(-LAMBDA[1]*H[1])/(LAMBDA[3]*H[3]);
END;
```

PART III : BIOLOGICAL MODEL

15. Grazing.

There is no zooplankton state variable in L3VMP; instead the effects of these planktonic animals are dealt with by means of time-varying grazing pressure $G(t)$ day^{-1}, the instaneous rate of removal of phytoplankton as a proportion of phytoplankton concentration. If phytoplankton concentration B does not change for any other reason, the plant material consumed in a day's grazing is $B.exp\{-G\}$ mmol C m^{-3}. Of this a fraction γ is digested and assimilated by the animals, so that $(1-\gamma).B.exp\{-G\}$ mmol C m^{-3} d^{-1} is defaecated and becomes detritus. A similar fraction of phytoplankton nitrogen is also converted to detritus. A fraction e of the nitrogen assimilated by the zooplankton is deemed to be immediately metabolized and excreted as ammonium, which thus potentially increases by $e.\gamma.N.exp\{-G\}$ mmol N m^{-3} d^{-1}. The remaining fraction of nitrogen is lost to L3VMP, and thus the ecosystem described by the model is 'open' at the second trophic level. Its simulated production will 'run down' unless the lost nitrogen is replaced (note a).

Grazing pressure can be estimated from observed zooplankton abundance $Z(t)$ (animals m^{-3}) and imputed 'volume clearance' f^z, the rate at which seawater is stripped of phytoplankton by individual animals:

$$G(t) = f^z.Z(t) \qquad\qquad \text{d}^{-1} \qquad\qquad (15.1)$$

The following estimates are based on copepod concentrations (note b) in the vicinity of North Sea mooring A during the 1988-89 survey. Abundances are given for large adult female copepods of the genus *Calanus*, for which f^z is assumed to be 5×10^{-4} m^3 animal^{-1} d^{-1} (Paffenhöfer, 1971) and adult females of smaller species, for which f^z is assumed to be 1.25×10^{-4} m^3 animal^{-1} d^{-1} (Paffenhöfer & Harris, 1976) (note c). The value of the product $f^z.Z(t)$ was summed over the two groups, and doubled to allow for grazing by adult males and by young of each group.

Month	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug
Year	88	88	88	88	88	89	89	89	89	89	89	89	89
animals/m^3													
Calanus	22	6	9	8	6	4	14	9	8	5	28	34	27
small copepod	174	116	107	215	49	13	30	15	69	37	128	51	101
$G(t)$ d^{-1}	.07	.04	.04	.06	.02	.01	.02	.01	.03	.01*	.06	.05	.05

* May value of 0.05 used in simulations.

A maximum grazing rate of 0.07 d^{-1} implies that copepod grazing will have a relatively small impact on phytoplankton near mooring A. In continental coastal waters, however, small copepods sometimes exceeded 10^3 m^{-3}, implying grazing pressures of at least 0.25 d^{-1}. Protozoan grazers might have a greater impact on populations of smaller phytoplankton: Burkill *et al.* (1987) estimated microzooplankton grazing impacts of 0.15 to 1.0 d^{-1} in Carmarthen Bay and the Celtic Sea, and Smetacek (1981) concluded that "protozooplankton" were the dominant grazers in Kiel Bight in spring and autumn. In this version of L3VMP, however, the effects of protozoan grazing are included as increased respiration within the microplankton compartment : see section 17.

Note a

The problem of 'ecosystem closure' as discussed by Steele (1976).

Note b

Copepods are the characteristic animals of the plankton; in temperate seas many species are about 1 mm in length as adults, although *Calanus* grows up to 4 mm. An adult female *Calanus* contains about 80 μ-g of carbon, whereas adults of the smaller species contain of order 10 μ-g carbon. When phytoplanktonic food is plentiful, the life cycle of *Calanus* takes about 60 days, and that of the smaller copepods 20 - 30 days. The abundance data were provided by Swier Oosterhuis and colleagues at NIOZ, and are based on vertical hauls of a net of mesh size 300 μm at 1 to 4 North Sea survey stations within 50 km of mooring A. The smaller species belong to the genera *Temora, Acartia, Pseudocalanus* and *Centropages*. I am grateful to Martien Baars and Bouwe Kuipers (NIOZ) for discussions of zooplankton distribution and grazing.

Note c

The copepod 'volume clearance rates' reported by Paffenhöfer are up to 10 times greater than those published by other workers, perhaps because of the former's improvements in techniques. The Paffenhöfer rates may be accepted as realistic because, unlike the lower estimates, they imply that copepods can obtain adequate food at naturally occurring concentrations of phytoplankton.

16. The microplankton : phytoplankton equations.

The microplankton model is in most respects that developed by Tett (1981) and Tett *et al.* (1986) for summer phytoplankton, and used to simulate the seasonal cycle of phytoplankton on the Malin shelf by E.Woods (UCNW, thesis in prep.). Woods combined the phytoplankton model with the stratification model of Clarke (1986), and this combination is also used in the simulation program TBP, written in VAX Pascal, for teaching phytoplankton seasonal cycle dynamics at UCNW. The main changes for L3VMP are those that take account of the explicit inclusion of bacterial and protozoan consumers in this compartment, but there are also some improvements in the description of photosynthesis. In this section the model is discussed in relation to phytoplankton only, and consideration of modifications required for inclusion of microheterotrophs in the microplankton compartment is postponed to the next section.

Phytoplankton growth depends on the supply of organic carbon provided by photosynthesis, and the supply of mineral nutrients of which nitrogen is the most important. The model is thus best stated in terms of the framework equations for phytoplankton carbon B and nitrogen N, given here for layer (1) under conditions of stratification:

$$dB_1/dt = \mu.B_1 - G.B_1 - {}^B w.B_1/h_1 + E_{1,3}.(B_3 - B_1)/h_1 \quad \text{mmol C m}^{-3}\text{ d}^{-1} \qquad (16.1)$$

$$\;\; (1) \quad\;\; (2) \quad\;\;\; (3) \qquad\;\; (4)$$

$$dN_1/dt = u.B_1 - G.N_1 - {}^B w.N_1/h_1 + E_{1,3}.(N_3 - N_1)/h_1 \quad \text{mmol N m}^{-3}\text{ d}^{-1} \qquad (16.2)$$

where terms (1) refer to internal processes resulting in an increase in the state variable, (2) are grazing losses, (3) are sinking losses and (4) are gains or losses by exchange of water. The 'specific growth rate' μ of the phytoplankton is defined as $(dB/dt).(1/B)$ d^{-1} in the absence of other gains or losses. Nutrient uptake u is also relative to biomass, having units of millimole nitrogen taken up per millimole of phytoplankton organic carbon per day. ${}^B w$ is sinking rate, of order 1 m d^{-1} for healthy populations (Bienfang, 1982; Riebesell, 1989).

Growth rate is a 'threshold-limitation' function (Droop, 1983; Tett & Droop, 1988) of internal nutrient supply and photosynthesis net of respiratory losses:

$$\mu = L\{ \mu'_{max} f(T).(1 - Q_{min}/Q), \ (\alpha.I.^X Q^B - r^B) \} \qquad d^{-1} \qquad (16.3)$$

$$\text{nutrient control} \qquad \text{light control}$$

where the operator $L\{..\}$ is an instruction to select the least of the enclosed terms: the threshold-limitation hypothesis states that only one potentially-limiting factor controls growth at any given time. Q is the 'cell quota' of nutrient, defined as N/B mmol N (mmol C)$^{-1}$, and with a typical minimum value Q_{min} of 0.05 mmol N (mmol C)$^{-1}$ for most types of phytoplankton (Tett & Droop, 1988). Despite uncertainities discussed by Tett & Droop, maximum nutrient-limited growth rate is treated as a function of temperature:

$$f(T) = exp\{(0.07).(T - 20)\} \qquad d^{-1} \qquad (16.4)$$

assuming a doubling of growth rate for every 10°C increase in temperature. This temperature coefficient is a little greater than the factor of 1.88 per 10°C reported by Eppley (1972). The usual temperature for experimental studies of algal growth is 20°C, and hence this is the reference temperature. μ'_{max} is taken as 2.0 day^{-1} at this temperature.

Theory relating to 'photosynthetic efficiency' α is reviewed by Tett (1990). The term is the product of photosynthetic quantum yield and photosynthetic pigment absorption cross-section. A suitable value for quantum yield, when light controls growth, is 40 nanomoles of carbon converted to organic material for each microEinstein of PAR absorbed by the chlorophyll of phytoplankton consisting of a mixture of species and physiological states. Absorption cross-section quantifies the efficiency of light-absorption by chlorophyll and associated pigments, and, as a first approximation (note a), is the same as the attenuation cross-section parameter $^X\epsilon$ of the optical model. The value depends on the spectral quality of submarine light, and $^X\epsilon = 0.02$ m^2 mg chl^{-1} will be used for the North Sea. Thus α is 0.07 mmol C (mg chl)$^{-1}$ d^{-1} (μE m^{-2} s^{-1})$^{-1}$.

The ratio of chlorophyll to phytoplankton carbon is made a function of nutrient quota in L3VMP:

$$^X Q^B = {}^X Q^N_{max}(Q - Q_{min}) + {}^X Q^N_{min}.Q_{min} \qquad \text{mg chl (mmol C)}^{-1} \qquad (16.5)$$

Approximate values for the chlorophyll:nitrogen ratio parameters are 3 mg chl (mmol N)$^{-1}$ for $^X Q^N_{max}$ and 1 mg chl (mmol N)$^{-1}$ for $^X Q^N_{min}$ (note b).

Phytoplankton respiration rate r^B (mmol C (mmol C)$^{-1}$(day)$^{-1}$ has basal and growth-rate-related components:

$$r^B = r^B_0 + r.\mu(I) \qquad \text{d}^{-1} \qquad (16.6)$$

where $\mu(I)$ refers to light-limited growth. Respiratory losses are not relevant in simulating nutrient-controlled growth since under these latter conditions it is the shortage of cellular organic nitrogen, rather than photosynthetically-fixed organic carbon, which limits. There is little convincing evidence for the direct effect of temperature on respiration. The review by Tett & Droop (1988) gives 0.03 - 0.04 d^{-1} for r^B_0 for low-light- adapted phytoplankton and 0.2 to 0.7 for r.

Nitrogen uptake by phytoplankton is expressed relative to phytoplankton biomass and is the sum of uptake of ammonium and nitrate. In the case of ammonium:

$$^{NH}u = {}^{NH}u_{max}(1 - Q/Q_{max}).^{NH}S/(^{NH}S_{1/2} + {}^{NH}S) \quad \text{mmol N (mmol C)}^{-1}\text{ d}^{-1} \qquad (16.7)$$

A similar equation describes nitrate uptake:

$$^{NO}u = {}^{NO}u_{max}(1 - Q/Q_{max}).^{NO}S/(^{NO}S_{1/2} + {}^{NO}S) \quad \text{mmol N (mmol C)}^{-1}\text{ d}^{-1} \qquad (16.8)$$

The term $(1 - Q/Q_{max})$ approximates a more complex relationship and ensures a reduction in nutrient uptake as phytoplankton approach their maximum nitrogen holding capacity Q_{max}, taken as 0.25 mmol N (mmol C)$^{-1}$ (Tett & Droop, 1988). Otherwise, each equation is a saturation function of the seawater concentration of the nutrient. $^{NH}S_{1/2}$ and $^{NO}S_{1/2}$ are nutrient concentrations at which uptake is half-maximal; values are 0.24 mmol ammonium m^{-3} and 0.32 mmol nitrate m^{-3}. No account is taken of inhibition of nitrate uptake by the simultaneous uptake of ammonium; instead, the maximum uptake rate $^{NH}u_{max}$ of ammonium is made 1.6 mmol N (mmol C)$^{-1}$ d^{-1}, and that for nitrate, 0.6 mmol N (mmol c)$^{-1}$ d^{-1} so that ammonium uptake precedes faster than nitrate uptake. The uptake parameters are derived from data presented by Caperon & Meyer (1972b) for several species of laboratory-grown phytoplankton.

Note a

Equating absorption and attenuation cross-sections implies that phytoplankton scatter very little light. This is true for many types of planktonic algae (Bricaud *et al.*, 1983), but there are some exceptions: for example, coccolithophorids, small flagellates bearing calcarous scales.

Note b

The ratio of chlorophyll to carbon is widely agreed to be one of the more critical parameters in determining phytoplankton growth, and yet there is no agreed theory for its variation under natural conditions. (But see Laws & Bannister, 1980). Equation (16.5) and the related parameter values are derived from considering data in Caperon & Meyer (1972a). In effect the function states that the nitrogen that makes up the minimum phytoplankton cell content is associated with relatively little chlorophyll, whereas nitrogen in excess of this minimum is associated with greater amounts of chlorophyll.

17. Including microheterotrophs in the microplankton compartment.

Section 16 describes a 'bulk' model of phytoplankton, that is, one which treats the phytoplankton as an entity with properties averaging a mixture of algal species. The present version of L3VMP adds properties associated with planktonic microheterotrophs to the microplankton compartment. The bacteria that are nourished by dissolved organic compounds derived from the products of phytoplankton photosynthesis, and the protozoans that graze these bacteria and the smaller phytoplankton, grow at rates which depend on phytoplankton production and which are similar to those of the phytoplankton. Phytoplankton nitrogen grazed by microheterotrophs and returned to the water as ammonium is likely to be immediately re-assimilated by growing phytoplankton. Thus L3VMP couples the carbon and nitrogen biomass of these microheterotrophs to that of the phytoplankton, with the effects of enhancing the relative respiration rate and decreasing the relative chlorophyll content of the compound microplankton.

To describe the properties of this microplankton, I assume that growth-rate-related algal plus microheterotroph respiration consumes a constant amount of any phytoplankton photosynthesis which is in excess of that needed to balance basal algal respiration. The equation for light limited growth then becomes:

$$\mu(I) = (\alpha.I.^X Q^B - r^B{}_0)/(1 + r) \qquad d^{-1} \qquad (17.1)$$

where r is increased to 0.7, to allow for microheterotroph respiration, at PAR above the

compensation illumination (note a). Microheterotroph activity is assumed insignificant when I is less than the compensation illumination, and hence r^B_0 has its algal value of 0.04 day^{-1}. To allow for dilution of chlorophyll in relation to carbon because some microplankton nitrogen is in microheterotrophs, the value of $^XQ^N_{max}$ in equation (16.5) is reduced to 2.0 mg chl (mmol N)$^{-1}$, but $^XQ^N_{min}$ is left unchanged at 1 mg chl (mmol N)$^{-1}$ to avoid predicting excessively low values of $^XQ^B$. Under nutrient-limited conditions the rate of increase of the microplankton should be the same as that of the phytoplankton alone (note b), unless there are differences between the nitrogen:carbon ratios of heterotrophs and autotrophs. Since heterotrophs may be unable to store excess nitrogen to the same extent as as algae, Q_{max} is reduced to 0.2 mmol N (mmol C)$^{-1}$. Maximum uptake rates should be reduced in relation to the dilution of algal by microheterotroph biomass; thus $^{NH}u_{max}$ becomes 1 mmol N (mmol C)$^{-1}$ d^{-1}, and $^{NO}u_{max}$ becomes 0.4 mmol N (mmol C)$^{-1}$ d^{-1}. Finally, it is assumed that simulated zooplankton grazing impacts equally on all parts of the microplankton.

These changes are rough and ready. The alternative is to split the microplankton compartment; a minimum realistic division of North Sea microplankton might require four types each of phytoplankton and microheterotroph (note c). Nevertheless, Occam's razor defends the simpler model at this stage, for the imprecisions involved in parameterizing such an increase in complexity might be at least as great as those associated with the approximation of a single microplankton compartment.

Note a

The compensation illumination I_c is that at which 24-hr photosynthesis and respiration are in balance. Thus, for phytoplankton alone, $\alpha.I_c{}^XQ^B = r^B_0$. The use of r of 0.7 implies that, above the compensation illumination, microheterotrophs immediately consume about 40% of phytoplankton photosynthesis in excess of basal respiration. The value is derived from futher analysis of observations reported by Tett *et al.*, (1988).

Note b

The argument that the presence of microheterotrophs does not alter the nutrient-limited growth rate of the microplankton is at first sight surprising. Nevertheless, given a steady state and complete recycling of nitrogen within the microplankton, all internal gains and losses of nitrogen are in balance with the exception of uptake from non-microplankton sources. Ignoring grazing and physical losses:

$$dN/dt = (^au.^aB - {}^hG.^aN + {}^hr.^hN) + (^hG.^aN - {}^hr.^hN)$$

phytoplankton   heterotrophs

$$= {}^au.^aB$$

where the superscripts a and h refer, respectively, to autrotrophs and (micro)heterotrophs, ^hG is microheterotroph grazing pressure on the autrotrophs, and ^hr is microheterotroph excretion rate. An absence of superscript implies the microplankton as a whole. Making use of the steady-state relationship $\mu = u.Q$, and writing b for the ratio $^hB/^aB$:

$$dB/dt = (^au.B)/(^aQ.(1+b))$$

Thus if ^aQ is the same as Q, the nutrient-limited growth rate of the microplankton is affected by the presence of microheterotrophs only to the extent that ^au must be reduced by the ratio $1/(1+b)$.

Note c

The four types of phytoplankton are: diatoms, requiring silicon as well as nitrogen; large photosynthetic dinoflagellates, which can migrate vertically; small photosynthetic flagellates; and the colonial phase of the flagellate *Phaeocystis*. The four types of microheterotroph (Fenchel, 1988) are: bacteria, exploiting dissolved organic material produced by other microplankton processes; small zoo-flagellates, feeding on bacteria; ciliates, eating small plant and animal flagellates; and heterotrophic dinoflagellates, eating diatoms as well as other algae (Jacobson & Anderson, 1986). Tett (1987) explores some aspects of modelling microplankton diversity in this way; Fasham (1985) describes a food web model with microbiological components specified taxonomically.

18. Detritus

Detritus is mostly non-living, but plankton-derived, organic material. Associated with it are micro-organisms responsible for its mineralization. What distinguishes the activity of these bacteria and protozoans from those forming part of the microplankton is the time-scale of mineralization, which is long compared with that of microplankton growth and decline. The active part of the detrital compartment is thus those microheterotrophs that are not in a steady state with phytoplankton, even though they consume material originally produced by phytoplankton. Despite the mixed contents, the activity of the detrital compartment is treated as a whole, and mineralization processes in the water column and sediment described as functions of the bulk properties of suspended detritus or sediment organic matter. These properties are the concentrations (mmol m^{-3}) of organic carbon C and nitrogen M, and the detrital nitrogen quota $^MQ^C$, the ratio of M to C.

Newell *et al.* (1988) concluded that "the flux of nitrogen through the microheterotrophic community of bacteria and protozoa is dependent to a large extent on the C:N ratio of the natural substrates available for utilization ...." (note a). In their account of nitrogen cycling in coastal waters, Billen & Lancelot (1988) stressed the role of the sediments in regenerating water column mineral nutrients on a time-scale longer than that of most water column remineralization processes. Lancelot

& Billen (1985) distinguish two types of biodegradable organic nitrogen: a labile fraction with a representative relative breakdown rate at 20°C of 0.05 d^{-1} and a more refractory component with rates of order 10^{-2} to 10^{-3} d^{-1}. L3VMP makes remineralization a function of the detrital nitrogen quota: simulated 'fresh' detritus, with a high nitrogen quota, breaks down quickly, whereas older detritus, which has lost more nitrogen than carbon, decays more slowly. The following equations for remineralization rates are tentative, and are the simplest that can be devised with the required properties.

$$^{C}r = f(T).(f(O).^{C}r_{max}(1 - {}^{M}Q^{C}{}_{min}/^{M}Q^{C})^2 + f(O).^{C}r_0) \qquad d^{-1} \qquad (18.1)$$

$$^{M}r = f(T).^{M}r_{max}(1 - {}^{M}Q^{C}{}_{min}/^{M}Q^{C})^2 \qquad\qquad d^{-1} \qquad (18.2)$$

The equations, which give the rate relative to the detrital mass of the element, assume that microheterotroph biomass is in equilibrium with the detrital mass, and that rates of nitrogen and carbon turnover are linked to microheterotroph growth rate and efficiency, which in turn depend on the bulk N:C ratio of the detritus. The square function of $^{M}Q^{C}$ is needed to ensure a sufficient reduction in the remineralization rate of 'refractory' relative to 'fresh' detritus (note b). For the latter to decay into a more refractory form, the maximum rate of ammonium production, relative to detrital nitrogen, should exceed the maximum rate of carbon mineralization relative to detrital carbon, and hence if $^{M}r_{max}$ is 0.07 d^{-1}, a suitable value of $^{C}r_{max}$ would be 0.05 d^{-1} (note c). According to Lancelot & Billen (1985) bacterial production of ammonium ceases when the atomic C:N ratio of the organic substrate exceeds 17 (note d), and thus $^{M}Q^{C}{}_{min}$ is taken as 0.06 mmol N (mmol C)$^{-1}$. $^{C}r_0$ sets the long-term minimum rate of ammonium release, since consumption of detrital carbon at $^{M}Q^{C}{}_{min}$ increases the N:C ratio and hence renews nitrogen mineralization. A value of 0.00005 d^{-1} was used for $^{C}r_0$ at 20°C.

Many biological rates double for each 10°C increase in temperature, and thus

$$f(T) = exp\{ (0.07).(T-20) \} \qquad (18.3)$$

where the maximum rates used in (18.1) and (18.2) apply at 20°C. Since the aerobic mineralization of carbon by definition requires oxygen, carbon respiration is also a function of ambient oxygen concentration, and:

$$f(O) = (O/(O_{1/2} + O))$$ (18.4)

where $O_{1/2}$, the concentration of oxygen at which carbon respiration is half its maximum value for that temperature and detrital N:C ratio, is taken as 10 mmol m^{-3} for the function regulating $^{C}r_{max}$ and 1 mmol m^{-3} for the function regulating $^{C}r_0$ (note e). It is assumed that the release of ammonium from detritus is independent of oxygen concentration.

Other processes affecting detritus have already been described. They are: its production as a result of zooplankton grazing or the sinking and death of phytoplankton; and its sinking, resuspension and vertical exchange. The framework equations for detrital carbon, assuming the existence of stratification, are:

$$dC_1/dt = (1-\gamma).G.B_1 - {}^{C}r.C_1 + (E_{1,3}.(C_3 - C_1) - {}^{C}w.C_1)/h_1 \quad \text{mmol C m}^{-3} \text{ d}^{-1}$$ (18.5)
$$ \text{grazing respiration} \quad \text{exchange} \quad \text{sinking}$$

$$dC_3/dt = (1-\gamma).G.B_3 + {}^{B}w.B^3 - {}^{C}r.C_3$$
$$ \text{phyto.sinking}$$
$$+ (E_{3,1}.(C_1 - C_3) + {}^{C}w.C_1 + E_{3,5}.C_5 - {}^{C}w.f^d.C_3)/h \quad \text{mmol C m}^{-3} \text{ d}^{-1}$$ (18.6)
$$\phantom{+ (E_{3,1}.(C_1 - C_3) + {}^{C}w.C_1 + E_{3,5}.C_5)} \text{sediment exchange}$$

$$dC_5/dt = - {}^{C}r.C_5 + ({}^{C}w.f^d.C_3 - E_{3,5}.C_5)/h_5 \quad \text{mmol C m}^{-3} \text{ d}^{-1}$$ (18.7)

The nitrogen equations are similar. Thus, for layer (3) in a stratified water column:

$$dM_3/dt = (1-\gamma).G.N_3 + {}^{B}w.N_3 - {}^{M}r.M_3$$
$$+ (E_{3,1}.(M_1 - M_3) + {}^{C}w.M_1 + E_{3,5}.M_5 - {}^{C}w.f^d.M_3)/h_3 \quad \text{mmol N m}^{-3} \text{ d}^{-1}$$ (18.8)

Note a

Newell *et al.* go on to compare detritus-dominated systems, where the C:N ratio is generally high and the external nitrogen pool small, with phytoplankton-based systems where C:N is close to the Redfield ratio of 7:1. They argue that microheterotrophs are major regenerators of nitrogen in the latter but not in the former. In the case of detritus, " ... nitrogen is limiting, and large fluxes of carbon may be associated with efficient conservation of nitrogen and little nutrient regeneration." I reverse this argument in L3VMP, on the grounds that the microheterotroph/phytoplankton microplankton compartment efficiently cycles nitrogen internally, whereas although the slowly decaying detritus compartment may release nitrogen relatively slowly, its greater mass and persistence makes it an effective long-term regenerator of nutrient.

Note b

The square function of detrital N:C ratio may be justified by the argument that both relative detrital content of microorganisms, and the metabolic rate of these organisms, depend on detrital nitrogen content.

Note c

These values of maximum remineralization rate were chosen so that at $^M Q^R = 0.14$ (the Redfield ratio), $^M r$ at 20°C is 0.02 d^{-1}, within the range of values given by Lancelot & Billen (1985).

Note d

Bacteria presented with nitrogen-poor substrates may take up ammonium if the external concentration is sufficiently high. But not in this version of L3VMP.

Note e

According to Henriksen & Kemp (1988) the half-saturation constant for the respiration of aerobic bacteria is less than 1 mmol m/3. The lower ("Pasteur", Ruttner, 1971) limit for oxygenic respiration is however often given as about 1% of present atmospheric concentration. I have therefore taken the half-saturation constant for $^C r_{max}$ as 10 mmol oxygen m^{-3} and that for $^C r_0$ as 1 mmol oxygen m^{-3}. In the program L3VMP oxygen consumption is halted when the concentration falls below 0.1 mmol oxygen m^{-3}, and this in effect defines the lower oxygen limit for aerobic conditions.

In the absence of oxygen, organic carbon can be oxidised by nitrate (which is itself reduced to ammonium or to molecular nitrogen), in the absence of nitrate by sulphate (reduced to hydrogen sulphide), and in the absence of sulphate, carbon dioxide (reduced to methane). These anaerobic processes are not described in L3VMP, since they would require the addition of extra sediment layers to the model.

19. Dissolved nutrients and oxygen.

Dissolved nitrate ^{NO}S, ammonium ^{NH}S and oxygen O are the remaining components of L3VMP. Their concentrations are given in mmol m^{-3}; in the case of the sediment the volume is that of the pore fluids only, a fraction p of total volume. All three state variables are subject to water-column and sediment exchange, and oxygen to exchange with the air. Biological fluxes of oxygen and nitrate are reciprocally related, since ammonium oxidation produces nitrate but consumes oxygen, and microplankton growth produces oxygen and, in general, consumes nitrate. Although changing organic nitrogen to ammonium does not consume oxygen, the uptake of ammonium by nutrient-limited microplankton allows growth, fixation of organic carbon, and hence oxygen evolution. However, the organic carbon resulting from ammonium uptake must eventually decompose, using oxygen, and so an overall balance is maintained. In a stratified water-column, however, the balance in the surface

waters is tilted in favour of oxygen production and nutrient depletion, although the extra oxygen produced by photosynthesis may be lost to the air. In the bottom waters, and most markedly in the sediment layer, the balance is tilted towards consumption; oxygen concentrations are reduced and ammonium and nitrate concentrations increased, by the mineralization of detritus.

The equation for rate of change of nitrate in layer (3) of a stratified water-column is typical:

$$d^{NO}S_3/dt = -^{NO}u.B_3 + ^{NH}r.^{NH}S_3$$

$$\phantom{d^{NO}S_3/dt =} \text{uptake} \quad \text{nitrification}$$

$$+ (E_{3,1}.(^{NO}S_1 - {}^{NO}S_3) - E_{5,3}.(^{NO}S_3 - {}^{NO}S_5))/h_3 \qquad \text{mmol m}^{-3} \text{ d}^{-1} \tag{19.1}$$

$$\text{-------- exchange --------------------}$$

The kinetics of nutrient uptake, u, are discussed in section 16. 'Nitrification', or the oxidation of ammonium to nitrate, is assumed to be mediated by nitrifying bacteria, whose abundance however is never limiting. Thus:

$$^{NH}r = f(T).^{NH}r_{max}O/(O_{1/2,nit} + O) \qquad \text{d}^{-1} \tag{19.2}$$

where $f(T)$ is the temperature function of equation (18.3). The half-saturation constant $O_{1/2,nit}$ is 30 mmol oxygen m^{-3} (note a). Nitrification is thought to proceed rapidly in the sea, and hence the maximum rate at 20°C is taken as 1.0 d^{-1}.

The corresponding equation for layer (3) ammonium has additional terms because of inputs of the nutrient from grazing and detrital decay:

$$d^{NH}S_3/dt = -^{NH}u.B_3 - {}^{NH}r.^{NH}S_3 + e.\gamma.G.N_3 + {}^{M}r.M_3$$

$$\phantom{d^{NH}S_3/dt =} \text{uptake} \quad \text{nitrification} \quad \text{grazing} \quad \text{remin.}$$

$$+ (E_{3,1}.(^{NH}S_1 - {}^{NH}S_3) - E_{5,3}.(^{NH}S_3 - {}^{NH}S_5)/h_3 \qquad \text{mmol m}^{-3} \text{ d}^{-1} \tag{19.4}$$

$$\text{------------------ exchange ----------}$$

where e is the proportion of phytoplankton nitrogen that is grazed, digested, metabolized and immediately excreted as ammonium by zooplankton. Grazing is discussed in section 15, nitrate uptake in section 16, and detrital remineralization in section 18.

The equation for dissolved oxygen in layer (1) of a stratified water column is:

$$dO_1/dt = (^Oq^B.\mu + {}^Oq^{NO}.^{NO}u).B_3 - {}^Oq^{NH}.^{NH}r.^{NH}S_3 - {}^Oq^C.^Cr.C_3$$

$\qquad$ growth and uptake $\qquad$ nitrification $\qquad$ detrital resp.

$$+ (E_{0,1}.(O_0\text{-}O_1) - E_{1,3}.(O_3\text{-}O_1))/h_1 \qquad \text{mmol m}^{-3}\text{ d}^{-1} \tag{19.4}$$

$\qquad$ air-sea exchange $\quad$ water-col. exch.

where the q parameters are photosynthetic and respiratory quotients. In the present version those for microplankton carbon growth $^Oq^B$ and detrital carbon respiration $^Oq^C$ are taken as 1.0 mmol oxygen (mmol C)$^{-1}$; those for nitrification $^Oq^{NH}$ and for microplankton nitrate uptake $^Pq^{NO}$ are taken as 2.0 mmol oxygen (mmol C)$^{-1}$ (note b).

Reactions linking particulate and dissolved substances in the sediment must be corrected in the case of the dissolved substances for porosity p. Thus, in the case of oxygen:

$$dO_5/dt = - {}^Oq^{NH}.^{NH}r.^{NH}S_3 - {}^Oq^C.^Cr.C_3/p + E_{5,3}.(O_3\text{-}O_5)/h_5 \quad \text{mmol m}^{-3}\text{ d}^{-1} \tag{19.5}$$

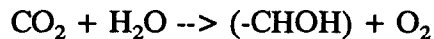$\qquad$ nitrification $\qquad$ detrital resp. $\qquad$ water-col. exch.

Rutgers van der Loeff (1980b) used a porosity of 0.4 for the Southern Bight of the North Sea.
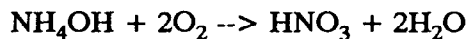
Note a

Nitrification is a two-step process. Each step supplies energy to the bacterium responsible. *Nitromonas* oxidizes ammonium to nitrite, with a half-saturation constant of 16 mmol oxygen m^{-3}. *Nitrobacter* then oxidises nitrite to nitrate, with a half-saturation constant of 62 mmol oxygen m^3 (Henriksen & Kemp, 1988). Nitrite is omitted from the present version of L3VMP, which treats nitrification as a single process with a half-saturation oxygen concentration more similar to the more restricting nitrite, than to the nitrate, half-saturation parameter.

Note b

The simplest chemical equation for the photosynthesis of organic carbon is

$$CO_2 + H_2O \text{ --> } (\text{-CHOH}) + O_2$$

and so $^Oq^B$ is taken as 1 mmol oxygen released per 1 mmol carbon incorporated into organic material. Carbon respiration is the reverse process. The nitrification of ammonium is most simply described by

$$NH_4OH + 2O_2 \text{ --> } HNO_3 + 2H_2O$$

and so $^Oq^{NH}$ is taken as 2 mmol oxygen consumed per 1 mmol nitrate formed. Nitrate uptake by

phytoplankton is assumed to result in a commensurate production of oxygen as the nitrate is reduced to ammonium by the algae. See Raine (1983) for a discussion of these ratios.

20. Biological procedures in the program L3VMP.

The main biological procedures, MICROPLANKTON, SEDIMENT and WATER_COLUMN, are listed in Table 7. In this version of L3VMP the procedures are as far as possible made self-contained and self-explanatory by including most parameters as internal constants. 'Change' arrays such as DOX are used to transfer fluxes between procedures. The short function GRAZING merely supplies a daily grazing pressure from the table of monthly values input to the array G by the procedure OBTAIN_PARAMETERS (Table 3).

As anticipated in section 7, there were difficulties in translating the equations for phytoplankton and dissolved substances into algorithms for numerical simulation. These difficulties did not arise with detritus, since the rate terms in equations for C and M are small when related to detrital mass, and hence numerical integration could be safely carried out using forward finite difference approximations and a timestep of 1 day.

In some circumstances, water-column nutrients can be rapidly depleted by phytoplankton. Depletion rates can be evaluated with a simplified equation for rate of change of nutrient concentration:

$$dS/dt = -u.B + e.G.N \qquad \text{mmol m}^{-3} \text{ d}^{-1} \qquad (20.1)$$

where u is the rate of uptake per unit phytoplankton biomass (mmol N (mmol C)$^{-1}$ d^{-1}), given by

$$u = u_{max}S/(S_{1,2} + S) \qquad \text{mmol N (mmol phyto.C)}^{-1} \text{ d}^{-1} \qquad (20.2)$$

When S is less than the half-saturation parameter $S_{1/2}$ (mmol N m^{-3}), equation (20.2) can be approximated by $(u_{max}/S_{1/2}).S$. This allows the formation of a simple equation for the time-scale of nutrient depletion:

$$t_u = 1/((u_m.B/S_{1/2}) - (e.G.Q.B/S)) \qquad \text{day} \qquad (20.3)$$

which is of order 10^{-1} d for $S = S_{1/2}$, $B = 10$ mmol m^{-3}, and typical values of the other parameters.

The time-scale is dominated under these conditions by the uptake term. Thus a 24-hour time-step with the simple finite-difference approximation:

$$\Delta S = (-u.B + e.G.N).\Delta t \qquad \text{mmol m}^{-3} \qquad (20.4)$$

might give sufficient nutrient uptake sufficient to drive sea-water nutrient below zero. An approximate analytical solution that avoids this problem can be found if B is replaced by an exponential function of time and it is assumed that changes in B are independent of changes in S. Assuming the resupply terms to be negligible, the solution is:

$$S(t+\Delta t) = S(t).exp\{(-u_{max}/S_{1/2}).(B(t)/(\mu-G)).(exp\{(\mu-G).\Delta t\} - 1)\} \quad \text{mmol m}^{-3} \qquad (20.5)$$

which shows that S will, in general, decrease asymptotically to zero (as expected in the absence of any resupply terms). The following modified finite difference approximation retains the essential property of (20.5) by ensuring that S cannot be driven below zero:

$$\Delta S = \{ -u.B.\Delta t \ \text{if} \ \Delta S < S(t) \ else \ - S(t) \} \qquad \text{mmol m}^{-3} \qquad (20.6)$$

Such 'zero-stop' or similar algorithms are commonly used in L3VMP.

Several problems afflict the numerical integration of equations for phytoplankton biomass B and nitrogen N. Both variables can change rapidly during a day. Simple finite difference approximations might thus substantially underestimate biomass increase or the amount of material transferred to detritus by grazing. Conversely, they might overestimate 24-hour biomass loss and hence drive B below zero. A 'zero stop' as used for nutrient concentrations is inappropriate for phytoplankton biomass, since $B = 0$ prevents all further propulation growth as well as giving rise to 'divide by zero' computing errors during the calculation of $Q = N/B$. The solution adopted in MICROPLANKTON is to use an approximate analytical solution to microplankton growth equations such (16.1), giving:

$$\Delta B = B(t).(exp\{ b'.\Delta t \} - 1) \qquad \text{mmol C m}^{-3} \qquad (20.7)$$

where $B(t)$ is biomass at the start of the time-step and:

$$b' = \mu - G - {}^{B}w/h + E.(\Delta B(t,z))/(h.B(t)) \qquad \text{d}^{-1} \qquad (20.8)$$

The solution assumes that the rate terms remain unaltered during the 24-hour time-step. This includes the standardized vertical exchange term $E.(\Delta B(t,z))/(h.B(t))$, where $\Delta B(t,z)$ refers to the initial biomass difference between two layers; it must be assumed that the relative difference $\Delta B(z)/B$ does not change during the day.

Equation (20.7) predicts biomass change during the time-step, and avoids biomass going zero or negative during periods of microplankton decrease. In order to calculate, for example, grazing transfer, it is also necessary to predict mean biomass over the time-step. This is

$$B' = B(t).(exp\{ b'.\Delta t \} - 1)/(b'.\Delta t) \qquad \text{mmol C m}^{-3} \qquad (20.9)$$

and the transfer of grazed phytoplankton to detritus is then:

$$<<B>>_G = (1-\gamma).G.B'.\Delta t \qquad \text{mmol C m}^{-3} \qquad (20.10)$$

The timestep Δt does not appear explicitly in the program, except when it is less than 1 day.

The most severe numerical problems arise during the computation of sediment oxygen changes. Although the exchange velocity $E_{5,3}$ is small (between 10^{-3} and 10^{-2} m d^{-1}), it applies to a thin layer (h_5 is 0.05 m), and, under conditions of sediment oxygen depletion, to a large concentration difference. In the simplified equation:

$$(dO_5/dt).(1/O_5) = E_{5,3}.(O_3-O_5)/(h_5.O_5) + {}^O q^C.{}^C r.C_5/(p.O_5) \qquad \text{d}^{-1} \qquad (20.11)$$

both the relative flux $E_{5,3}.(O_3-O_5)/(h_5.O_5)$ and the oxygen-relative detrital respiration ${}^O q^C.{}^C r.C_5/(p.O_5)$ can very substantially exceed 1 for oxygen concentrations of the same order (10 mmol m^{-3}) as the half-saturation parameter. The net flux of oxygen is thus very sensitive to small changes in the absolute concentration of oxygen at levels typically found in the sediment. Several approximate analytical solutions were investigated, but it was found that sufficient numerical stability and accuracy could only be obtained by reducing the time-step to 10^{-1} day or less.

The procedure SEDIMENT is thus constructed about an inner loop which computes changes in sediment oxygen, ammonium and nitrate concentrations 10 or more times during the 24-hr main time-step used to evoke the procedure. The procedure has been written to minimize the number of

calculations that take place within the loop.

Such precautions are unnecessary in the case of water-column oxygen, since depletion fluxes are smaller and are applied to oxygen concentrations near the typical saturation value of 600 mmol m^3. The structure of the procedure WATER_COLUMN is thus simpler than that of SEDIMENT and MICROPLANKTON.

The comments embedded in the procedures further explain the numerical methods used.

Table 6: Parameters and rate variables for the biological model

(see also Table 1 for state variables)

(standard values given where appropriate)

α	:	phytoplankton photosynthetic efficiency, 0.07 mmol C $(\text{mg chl})^{-1}$ d^{-1} $(\mu E\ m^{-2}\ s^{-1})^{-1}$;
e	:	excreted fraction of grazed and assimilated phytoplankton nitrogen;
x_ϵ	:	phytoplankton absorption cross-section, 0.20 m^2 $(\text{mg chl})^{-1}$;
f^d	:	depositional fraction of sinking particles - those that cohere to sediment;
f^Z	:	zooplankton volume clearance rate, m^3 animal^{-1} d^{-1};
G	:	grazing pressure on phytoplankton, day^{-1};
γ	:	fraction of grazed phytoplankton that is assimilated by zooplankton;
μ	:	phytoplankton/microplankton specific growth rate, d^{-1};
μ'_{max}	:	maximum phyto/microplankton specific growth rate, 2.0 d^{-1} at 20°C;
p	:	sediment porosity, 0.4;
$O_{1/2}$	:	oxygen half-saturation constant for detrital carbon respiration, 10 mmol m^{-3} for maximum, nitrogen quota-dependent respiration, 1 mmol m^{-3} for minimum respiration;
$O_{1/2,nit}$	:	oxygen half-saturation constant for ammonium nitrification, 30 mmol m^{-3}
Q	:	phytoplankton/microplankton nitrogen quota, mmol N $(\text{mmol C})^{-1}$;
Q_{max}	:	maximum (phyto/)microplankton nitrogen quota, (0.25) 0.20 mmol N $(\text{mmol C})^{-1}$;
Q_{min}	:	minimum phyto/microplankton nitrogen quota, 0.05 mmol N $(\text{mmol C})^{-1}$;
x_Q^B	:	phytoplankton/microplankton pigment content, mg chl $(\text{mmol C})^{-1}$;
$x_{Q^N_{max}}$	:	maximum (phyto/)microplankton chlorophyll yield from nitrogen, (3) 2 mg chl $(\text{mmol N})^{-1}$;
$x_{Q^N_{min}}$	:	minimum (phyto/)microplankton chlorophyll yield from nitrogen, 1 mg chl $(\text{mmol N})^{-1}$;
$^M Q^C$	:	detrital nitrogen content, mmol N $(\text{mmol C})^{-1}$;
$^M Q^C_{min}$	:	minimum detrital nitrogen content, 0.06 mmol N $(\text{mmol C})^{-1}$;

$^O q$: photosynthetic and respiratory quotients, with trailing supercripts ^{B} or ^{C} for microplankton or detrital carbon, both 1 mmol oxygen (mmol C)$^{-1}$, ^{NH} or ^{NO} for ammonium nitrification or microplankton nitrate uptake, both 2 mmol oxygen (mmol N)$^{-1}$;

r : proportion of phytoplankton photosynthesis (in excess of requirement for basal respiration) used in microplankton respiration, 0.7; alternatively, slope of graph of phytoplankton respiration against specific growth rate;

r^B : biomass related phytoplankton/microplankton respiration rate, d^{-1};

r^B_0 : basal phytoplankton respiration rate, 0.04 d^{-1};

$^C r$: detrital carbon respiration rate, d^{-1};

$^C r_{max}$: maximum detrital carbon respiration rate, 0.5 d^{-1} at 20°C;

$^C r_0$: minimum detrital carbon respiration rate, 0.00005 d^{-1} at 20°C;

$^M r$: detrital nitrogen remineralization rate, d^{-1};

$^M r_{max}$: maximum detrital remineralization rate, 0.07 d^{-1} at 20°C;

$^{NH} r$: ammonium nitrification rate, d^{-1};

$^{NH} r_{max}$: maximum ammonium nitrification rate, 1.0 d^{-1} at 20°C;

$S_{1/2}$: half-saturation constants for uptake of nutrient by (phyto/)microplankton, with superscript ^{NH} for ammonium, 0.24, or ^{NO} for nitrate, 0.32 mmol m^{-3};

u : phytoplankton/microplankton nutrient uptake rate, with superscript ^{NH} for ammonium or ^{NO} for nitrate, mmol N (mmol C)$^{-1}$ d^{-1};

$^{NH} u_{max}$: maximum (phyto/)microplankton ammonium uptake rate, (1.6) 1.0 mmol N (mmol C)$^{-1}$ d^{-1};

$^{NO} u_{max}$: maximum (phyto/)microplankton nitrate uptake rate, (0.6) 0.4 mmol N (mmol C)$^{-1}$ d^{-1};

w : particulate sinking rate, with superscript ^{B} for (phyto/)microplankton, 1 m d^{-1}, or ^{C} for detritus, 5 m d^{-1};

Z : zooplankton abundance, animals m^{-3}

Table 7: Program extracts : procedures for biological model

```
FUNCTION GRAZING (DAY:INTEGER; VAR G:MON);
CONST YEAR=365;MONTH=30.42;
VAR M:1..12;
BEGIN
    WHILE DAY>YEAR DO DAY:=DAY-YEAR;
    M:=1 + TRUNC(DAY/MONTH); GRAZING:=G[M];
END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - *)


PROCEDURE MICROPLANKTON
(VAR B,H,I,N,NHS,NOS,O,TEMP,X,DB,DC,DM,DN,DOX,DNHS,DNOS,:LYA; VAR E:EXA;
G:REAL; MIXED:BOOLEAN);
(* TYPE LYA=ARRAY[0..5] OF REAL, corresponding to model layers      *)
(* State variables and corresponding 'change' arrays are :          *)
(* B (DB) : microplankton biomass, mmol C/m3                        *)
(*    (DC) : (change in) detrital concentration, mmol C/m3          *)
(* H       : layer thickness, m                                     *)
(* I       : layer 24-hr- and depth- mean PAR irradiance, muE/m2/s  *)
(*    (DM) : (change in) detrital nitrogen, mmol N/m3               *)
(* N (DN) : microplankton nitrogen, mmol N/m3                       *)
(* O (DOX): dissolved oxygen, mmol/m3                               *)
(* NHS (DNHS) : ammonium, mmol/m3                                   *)
(* NOS (DNOS) : nitrate, mmol/m3                                    *)
(* TEMP    : temperature, deg C                                     *)
(* X       : chlorophyll, mg/m3                                     *)
(* E is ARRAY[1..5,0..5] of exchange velocities, m/d                *)
(* G is grazing pressure, per day                                   *)
(* The procedure has an implicit 24-hr time step                    *)
CONST ALPHA=0.07
        (* mmol C/mg chl/day/(muE/m2/s) = 0.8 nmol C/mg chl/(muE/m2) *)
        (* based on quantum yield of 40 nmol C/muE and Xepsilon = 0.02 m2/mg *);
        BW=1.0 (* sinking rate, m/day *);
        EXCR=0.5 (* excreted part of grazed nitrogen *);
        GAMMA=0.8 (* assimilated proportion of food eaten by zooplankton *);
        MUMAX20=2.0 (* maximum specific growth rate at 20 C, per day *);
        BPQ=1.0 (* photosynthetic quota for carbohydrate, mmol O/mmol C *);
        NOPQ=2.0 (* photosynthetic quota for nitrate uptake, mmol O/mmol N *);
        QMIN=0.05 (* minimum cell nutrient, mmol N/mmol C *);
        QMAX=0.20 (* maximum cell nutrient, mmol N/mmol C *);
        XQNMAX=2.0 (* maximum ratio, mg chl/mmol N *);
        XQNMIN=1.0 (* minimum ratio, mg chl/mmol N *);
        RB0=0.04 (* minimum respiration rate, mmol C/mmol C/day *);
        R=0.7 (* fraction of excess photosynthesis consumed by microplankton *);
        NHSHALF=0.24 (* half-sat constant for ammonium uptake, mmol/m3 *);
        NOSHALF=0.32 (* half-sat constant for nitrate uptake, mmol/m3 *);
        NHUMAX=1.0 (* maximum uptake rate for ammonium, mmol N/mmol C/day *);
        NOUMAX=0.4 (* maximum uptake rate for nitrate, mmol N/mmol C/day *);

VAR BMEAN,BRATE,NMEAN,NRATE,MU,U,NHU,NOU,Q,XQB : LYA; L:1..3;

FUNCTION DAYMEAN(RATE:REAL):REAL;
BEGIN
    IF ABS(RATE) < 0.01 THEN DAYMEAN:=1.0
    ELSE DAYMEAN:=(EXP(RATE) - 1)/RATE;
END;

FUNCTION MUMAX(MM20,T:REAL):REAL;
CONST REFTEMPT=20.0; FAC=0.07;
BEGIN
```

```
        MUMAX:=MM20*EXP(FAC*(T-REFTEMPT));
END;


PROCEDURE RATES;
VAR CF,NETPHOT,NUTGROW,URATE:REAL;
BEGIN
    FOR L:=1 TO 3 DO IF NOT ((L=2) OR ((L=3) AND MIXED)) THEN BEGIN
        (* initial ratios *)
        Q[L]:=N[L]/B[L]; XQB[L]:=X[L]/B[L];
        (* threshold-limitation growth rate *)
        (* photosynthesis less respiration can be negative  *)
        NETPHOT:=ALPHA*I[L]*XQB[L] - RB0;
        IF NETPHOT > 0.0 THEN NETPHOT:=NETPHOT/(1 + R);
        (* nutrient-controlled growth, cannot be less than zero *)
        NUTGROW:=MUMAX(MUMAX20,TEMP[L])*(1 - QMIN/Q[L]);
        IF NUTGROW<0 THEN NUTGROW:=0.0;
        (* select lowest rate *)
        IF NETPHOT<NUTGROW THEN MU[L]:=NETPHOT ELSE MU[L]:=NUTGROW;
        (* provisional nutrient uptake rate *)
        IF (Q[L]>QMAX) (* as a result of respiration of carbon *) THEN BEGIN
            NHU[L]:=0.0;(* excrete nitrate *) NOU[L]:=QMAX-Q[L]; END
        ELSE BEGIN
            IF NHS[L] <= 0.0 THEN NHU[L]:=0 ELSE
            NHU[L]:=NHUMAX*(1 - Q[L]/QMAX)*NHS[L]/(NHSHALF + NHS[L]);
            IF NOS[L] <= 0.0 THEN NOU[L]:=0 ELSE BEGIN
            (* computation to avoid overshooting Qmax by rapid nitrate uptake *)
                URATE:=(NOUMAX/QMAX)*NOS[L]/(NOSHALF+NOS[L]);
                CF:=DAYMEAN(-URATE);
                NOU[L]:=URATE*(QMAX - Q[L])*CF + MU[L]*Q[L]*(1 - CF);
                END;
            END;
        END;
    END (* of rates *);

PROCEDURE TRANSFERS;
BEGIN
    (* detritus results from defaecation                  *)
    (* and from death of sinking phytoplankton            *)
    DC[1]:=DC[1]+(1-GAMMA)*G*BMEAN[1];
    IF MIXED THEN BEGIN DC[1]:=DC[1]+BW*BMEAN[1]/H[1]; DC[3]:=DC[1]; END ELSE
        DC[3]:=DC[3]+((1-GAMMA)*G + (BW/H[3]))*BMEAN[3];
    DM[1]:=DM[1]+(1-GAMMA)*G*NMEAN[1];
    IF MIXED THEN BEGIN DM[1]:=DM[1]+BW*NMEAN[1]/H[1]; DM[3]:=DM[1]; END ELSE
        DM[3]:=DM[3]+((1-GAMMA)*G + (BW/H[3]))*NMEAN[3];
    (* nutrients and oxygen *)
    FOR L:=1 TO 3 DO IF NOT ((L=2) OR ((L=3) AND MIXED)) THEN BEGIN
    DNHS[L]:=DNHS[L] - NHU[L]*BMEAN[L] + EXCR*GAMMA*G*NMEAN[L];
    DNOS[L]:=DNOS[L] - NOU[L]*BMEAN[L];
    DOX[L]:=DOX[L] + DB[L]*BPQ + NOU[L]*BMEAN[L]*NOPQ;
        END;
    IF MIXED THEN BEGIN DNHS[3]:=DNHS[1]; DNOS[3]:=DNOS[1]; DOX[3]:=DOX[1];
END;
END (* of transfers *);

BEGIN (* main part of microplankton *)

    RATES;

    (* microplankton biomass, using approx. analytical solution *)
    BRATE[1]:=MU[1] - G - BW/H[1];
    IF NOT MIXED THEN BRATE[1]:=BRATE[1] + E[1,3]*(B[3]-B[1])/(B[1]*H[1]);
    DB[1]:=DB[1] + B[1]*(EXP(BRATE[1]) - 1);
    BMEAN[1]:=B[1]*DAYMEAN(BRATE[1]);
    IF NOT MIXED THEN BEGIN
        BRATE[3]:=MU[3] - G + (BW+E[3,1])*(B[1]-B[3])/(B[3]*H[3]);
        DB[3]:=DB[3] + B[3]*(EXP(BRATE[3]) - 1);
        BMEAN[3]:=B[3]*DAYMEAN(BRATE[3]);
```

```
END;
(* check uptake to avoid driving S negative *)
FOR L:=1 TO 3 DO IF NOT ((L=2) OR ((L=3) AND MIXED)) THEN BEGIN
    IF NHU[L]*BMEAN[L]>NHS[L] THEN NHU[L]:=NHS[L]/BMEAN[L];
    IF NOU[L]*BMEAN[L]>NOS[L] THEN NOU[L]:=NOS[L]/BMEAN[L];
    U[L]:=NHU[L]+NOU[L];
    END;
(* microplankton nutrient - nitrogen must be conserved, so *)
(* use finite difference arithmetic to obtain overall change *)
NRATE[1]:=U[1]/Q[1] - G - BW/H[1];
IF NOT MIXED THEN NRATE[1]:=NRATE[1] + E[1,3]*(N[3]-N[1])/(N[1]*H[1]);
NMEAN[1]:=N[1]*DAYMEAN(NRATE[1]);
DN[1]:=DN[1] + U[1]*BMEAN[1] - NMEAN[1]*(G + BW/H[1]);
IF NOT MIXED THEN BEGIN
    NRATE[3]:=U[3]/Q[3] - G + (BW+E[3,1])*(N[1]-N[3])/(N[3]*H[3]);
    NMEAN[3]:=N[3]*DAYMEAN(NRATE[3]);
    DN[1]:=DN[1] + E[1,3]*(NMEAN[3] - NMEAN[1])/H[1];
    DN[3]:=DN[3] + U[3]*BMEAN[3] - G*NMEAN[3]
                + (BW+E[3,1])*(NMEAN[1]-NMEAN[3])/H[3];
    END;

TRANSFERS;

(* calculate new values of state variables *)
FOR L:=1 TO 3 DO IF NOT ((L=2) OR ((L=3) AND MIXED)) THEN BEGIN
    B[L]:=B[L] + DB[L]; N[L]:=N[L] + DN[L]; Q[L]:=N[L]/B[L];
    XQB[L]:=XQNMAX*(Q[L] - QMIN) + XQNMIN*QMIN;
    X[L]:=B[L]*XQB[L];
    END;
IF MIXED THEN BEGIN B[3]:=B[1]; N[3]:=N[1]; X[3]:=X[1]; END;
END (* of microplankton *);


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - *)

FUNCTION TCHANGE(T:REAL):REAL;
CONST FAC=0.07; REFTEMP=20.0;
BEGIN
    TCHANGE:=EXP(FAC*(T-REFTEMP));
END;

FUNCTION QF2(Q:REAL):REAL;
CONST DETQMIN=0.06 (* mininum detrital mmol N/mmol c *);
VAR QF:REAL;
BEGIN
    IF Q < DETQMIN THEN QF2:=0.0 ELSE BEGIN
        QF:=1 - (DETQMIN/Q); QF2:=QF*QF; END;
    END;

FUNCTION CR(O,Q,T:REAL):REAL;
(* relative respiration rate of detrital carbon *)
CONST MAXOHALFSAT=10.0 (* detrital resp. half-sat. constant, mmol oxy/m3 *);
      MINOHALFSAT=1.0 (* min. detr. resp. half-sat. constant, mmol oxy/m3 *);
      CRMAX20=0.2 (* maximum detrital C respiration at 20 C, per day *);
      CRMIN20=1E-4 (* minimum detrital respiration at 20 C, per day *);
      OMIN=0.1 (* minimum (micro)aerobic oxygen, mmol/m3 *);
VAR QF:REAL;
BEGIN
    IF (O< OMIN) THEN CR:=0.0 ELSE
        CR:=TCHANGE(T)*O*
            (CRMAX20*QF2(Q)/(MAXOHALFSAT + O) + CRMIN20/(MINOHALFSAT + O));
    END;

FUNCTION MR(Q,T:REAL):REAL;
(* relative remineralization rate of detrital nitrogen *)
CONST MRMAX20=0.3 (* maximum detrital N respiration at 20 C, per day *);
BEGIN
    MR:=TCHANGE(T)*MRMAX20*QF2(Q);
```

```
      END;

FUNCTION NHR(O,T:REAL):REAL;
(* relative nitrification rate of ammonium *)
CONST NITMAX20=1.0 (* maximum nitrification rate, rel. to ammonium, d-1 *);
      OHALFNIT=30 (* oxygen half-sat. const. for nitrification, mmol m/3 *);
      OMIN=0.1 (* minimum (micro)aerobic oxygen, mmol/m3 *);
BEGIN
   IF O < OMIN THEN NHR:=0.0 ELSE
   NHR:=TCHANGE(T)*NITMAX20*O/(OHALFNIT + O);
   END;


(* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - - *)


PROCEDURE SEDIMENT
(VAR C,H,M,NHS,NOS,O,TEMP,DC,DM,DNHS,DNOS,DOX :LYA; VAR E:EXA; FD:REAL);
(* Computes changes in sediment variables during 24 hrs;         *)
(* potential changes in oxygen and DIN large, so smaller         *)
(* time-step used for solubles.                                  *)

CONST DAY=1.0;
      DMAX=10 (* maximum number of time-steps in day *);
      CRQ=1.0 (* mmol oxygen consumed per mmol C respired *);
      NORQ=2.0 (* mmol oxygen consumed per mmol ammonium nitrified *);
      CRMAX20=0.1 (* maximum detrital C respiration at 20 C, per day *);
      CRMIN20=1E-4 (* minimum detrital C respiration at 20 C, per day *);
      NITMAX20=1.0 (* maximum nitrification rate at 20 C, per day *);
      CW=5.0 (* sinking rate of detritus, m/d *);
      OMIN=0.1 (* minimum aerobic oxygen, mmol/m3 *);
      POR=0.4 (* sediment porosity *);

VAR CFLUX,CRFLUX,CRMAXC,CRMINC,CRQPOR,DT,EF,EFD,EXCFLUX,EXMFLUX,EXNHFLUX,
    EXNOFLUX,EXOFLUX,MQC,MRFLUX,NHFLUX,NITMAXN,NITNHFLUX,NOFLUX,
    OFLUX : REAL;
    D : 1..DMAX;

FUNCTION CRD(MAX,MIN,O:REAL):REAL;
(* simplified detrital respiration *)
CONST MAXOHALFSAT=10.0 (* detrital resp. half-sat. constant, mmol oxy/m3 *);
      MINOHALFSAT=1.0 (* min. detr. resp. half-sat. constant, mmol oxy/m3 *);
BEGIN
   CRD:=O*((MAX/(MAXOHALFSAT + O)) + (MIN/(MINOHALFSAT + O)));
   END;

FUNCTION NHRD(MAX,O:REAL):REAL;
(* simplified nitrification *)
CONST OHALFNIT=30.0 (* half-sat. const. for nitrification, mmol oxy/m3 *);
BEGIN NHRD:=MAX*O/(OHALFNIT + O); END;

BEGIN (* sediment *)

    (* calculate values that remain constant during day *)
    DT:=DAY/DMAX; EF:=E[5,3]/H[5]; EFD:=EF*DT;
    MQC:=M[5]/C[5]; CRQPOR:=CRQ/POR;
    CRMAXC:=TCHANGE(TEMP[5])*QF2(MQC)*CRMAX20*C[5]*DT;
    CRMINC:=TCHANGE(TEMP[5])*CRMIN20*C[5]*DT;
    MRFLUX:=MR(MQC,TEMP[5])*M[5]*DT/POR;
    NITMAXN:=TCHANGE(TEMP[5])*NITMAX20*NHS[5]*DT;
    (* zero local accumulation variables *)
    NHFLUX:=0.0; NOFLUX:=0.0; OFLUX:=0.0; CFLUX:=0.0;

    FOR D:=1 TO DMAX DO BEGIN (* solubles loop with time-step DT *)
        (* detrital respiration *)
        CRFLUX:=CRD(CRMAXC,CRMINC,O[5]);
        (* nitrification *)
        NITNHFLUX:=NHRD(NITMAXN,O[5]);
        (* exchanges with water column *)
```

```
        EXNHFLUX:=EFD*(NHS[3]-NHS[5]); NHFLUX:=NHFLUX+EXNHFLUX;
        EXNOFLUX:=EFD*(NOS[3]-NOS[5]); NOFLUX:=NOFLUX+EXNOFLUX;
        EXOFLUX:=EFD*(O[3]-O[5]); OFLUX:=OFLUX+EXOFLUX;
        (* update state variables; do not let O become less than OMIN *)
        NHS[5]:=NHS[5] + EXNHFLUX + MRFLUX - NITNHFLUX;
        NOS[5]:=NOS[5] + EXNOFLUX + NITNHFLUX;
        DOX[5]:=EXOFLUX - CRQPOR*CRFLUX - NORQ*NITNHFLUX;
        IF (O[5] + DOX[5]) < OMIN THEN BEGIN
            CRFLUX:=CRFLUX - (OMIN - DOX[5] - O[5])/CRQ;
            O[5]:=OMIN; END ELSE O[5]:=O[5] + DOX[5];
        CFLUX:=CFLUX+CRFLUX;
        END;


     (* apply day-total fluxes to layer 3 using 'change' arrays *)
     DNHS[3]:=DNHS[3] - NHFLUX*H[5]/H[3];
     DNOS[3]:=DNOS[3] - NOFLUX*H[5]/H[3];
     DOX[3]:=DOX[3] - OFLUX*H[5]/H[3];


     (* calculate changes in particulates using 1 day time-step *)
     EXCFLUX:=E[3,5]*C[5] - CW*FD*C[3]; DC[3]:=DC[3] + EXCFLUX/H[3];
     C[5]:=C[5] - EXCFLUX/H[5] - CFLUX;
     EXMFLUX:=E[3,5]*M[5] - CW*FD*M[3]; DM[3]:=DM[3] + EXMFLUX/H[3];
     M[5]:=M[5] - EXMFLUX/H[5] - MRFLUX*POR/DT;


  END (* of sediment *);


  (* - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - *)


  PROCEDURE WATER_COLUMN
  (VAR C,H,M,O,NHS,NOS,TEMP,DC,DM,DOX,DNHS,DNOS:LYA; VAR E:EXA; MIXED:BOOLEAN);
  (* Computes changes in water-column detritus, dissolved oxygen and *)
  (* DIN for 24-hr time step.                                        *)

  CONST CRQ=1.0 (* respiratory quotient for detritus, mmol oxy/mmol C *);
        NORQ=2.0 (* mmol oxygen req. per mmol ammonium oxidized to nitrate *);
        CW=5.0 (* detrital sinking rate, m/d *);

  VAR MQC,CRFLUX,MRFLUX,NITNHFLUX :LYA; L:1..3;

  BEGIN
     FOR L:=1 TO 3 DO IF NOT (((L=1) AND MIXED) OR (L=2)) THEN BEGIN
        MQC[L]:=M[L]/C[L];
        CRFLUX[L]:=CR(O[L],MQC[L],TEMP[L])*C[L];
        MRFLUX[L]:=MR(MQC[L],TEMP[L])*M[L];
        NITNHFLUX[L]:=NHR(O[L],TEMP[L])*NHS[L];
        (* DC and DM already include effects of defaecation,      *)
        (* microplankton death by sinking,  and sediment exchange *)
        DC[L]:=DC[L] - CRFLUX[L]; DM[L]:=DM[L] - MRFLUX[L];
        (* DOX, DNHS and DNOS already include effects of          *)
        (* microplankton production/respiration, nutrient uptake, *)
        (* grazing regeneration, and sediment exchange            *)
        DOX[L]:=DOX[L] - CRQ*CRFLUX[L] - NORQ*NITNHFLUX[L];
        DNHS[L]:=DNHS[L] + MRFLUX[L] - NITNHFLUX[L];
        DNOS[L]:=DNOS[L] + NITNHFLUX[L];
     END;
     IF MIXED THEN (* air-sea exchange directly with layer 3 *)
         DOX[3]:=DOX[3] + E[1,0]*(O[0]-O[3])/H[3]
     ELSE (* stratified *) BEGIN
        DC[1]:=DC[1] + (-CW*C[1] + E[1,3]*(C[3]-C[1]))/H[1];
        DC[3]:=DC[3] + (CW*C[1] + E[3,1]*(C[1]-C[3]))/H[3];
        DM[1]:=DM[1] + (-CW*M[1] + E[1,3]*(M[3]-M[1]))/H[1];
        DM[3]:=DM[3] + (CW*M[1] + E[3,1]*(M[1]-M[3]))/H[3];
        DOX[1]:=DOX[1] + (E[1,3]*(O[3]-O[1]) + E[1,0]*(O[0]-O[1]))/H[1];
        DOX[3]:=DOX[3] + E[3,1]*(O[1]-O[3])/H[3];
        DNHS[1]:=DNHS[1] + E[1,3]*(NHS[3]-NHS[1])/H[1];
        DNHS[3]:=DNHS[3] + E[3,1]*(NHS[1]-NHS[3])/H[3];
        DNOS[1]:=DNOS[1] + E[1,3]*(NOS[3]-NOS[1])/H[1];
```

```
        DNOS[3]:=DNOS[3] + E[3,1]*(NOS[1]-NOS[3])/H[3];
   END;

   (* update state variables *)
   FOR L:=1 TO 3 DO IF NOT (((L=1) AND MIXED) OR (L=2)) THEN BEGIN
        C[L]:=C[L]+DC[L]; M[L]:=M[L]+DM[L];
        O[L]:=O[L]+DOX[L];
        NHS[L]:=NHS[L]+DNHS[L]; NOS[L]:=NOS[L]+DNOS[L];
   END;
   IF MIXED THEN BEGIN
        C[1]:=C[3]; M[1]:=M[3]; O[1]:=O[3];
        NHS[1]:=NHS[3]; NOS[1]:=NOS[3];
   END;

END (* of water-column *);
```

PART IV : CONCLUSION

21 Results.

Figure 3 shows results from a simulation of seasonal cycles at North Sea Survey Station CS (or Mooring A, 55°30'N, 01°00'E). Parameter values were those in the program excerpts; other details are summarized in the Figure legend. The simulation predicts stratification between mid-April and late October, with a Spring phytoplankton bloom reaching a peak in early May following the formation of the seasonal thermocline. An Autumn bloom, peaking in October, results from nutrient entrained into layer (1) as the thermocline deepens. Each bloom is associated with a peak in detritus in deep water, augmenting a background due to sediment resuspension. Water-column oxygen concentrations mainly show the influence of water temperature, with some depletion in deep water beneath the thermocline in summer. Sediment oxygen becomes almost completely depleted in mid-Autumn. This is caused by the enhancement of respiration by sea-bed warming, following the Autumn overturn of stratification, and by detrital sedimentation, after the Autumn plankton bloom. Sediment ammonium concentration peaks at this time.

Many of these results correspond qualitatively to seasonal cycles observed at station CS, although there are differences in quantity and timing.

22. Discussion and Conclusions.

The main aims of this report have been to describe the structure of the model L3VMP and to review the arguments which led to that structure. The program L3VMP has been tested to the extent of simulating seasonal cycles at a summer-stratified station without obvious numerical problems; the results appear realistic. The next stage should be to test the robustness of the model and program by simulating cycles at a range of North Sea sites. This will best be done after transferring the program to a mainframe or faster microcomputer, and will no doubt force numerical improvements in the algorithms used in the program.

Beyond such immediate developments, there are several ways in which L3VMP might be used.

(1) Predictions may be tested against observations made during the 1988/89 North Sea survey. A proper test requires the model to be driven by 'real' values of the meteorological variables.

(2) The model may be used to interpolate between insufficiently intense observations in the North Sea, for example to predict the detailed timing and amplitude of the Spring phytoplankton bloom at stations visited only at monthly intervals.

(3) The model may be improved piecemeal by criticism of particular components, perhaps as a result of circulation of this report.

(4) Validated components could be included in North Sea circulation models, to investigate the effects of horizontal exchange and, in the long run, to make predictions of water quality.

It is already clear that the present version of L3VMP is lacking in several respects. These include the cycling of nitrogen and the effects of wind on the seabed.

Studies during the North Sea project (note) have shown that wind stirring can greatly increase sediment resuspension, both in deep water in winter and in shallow water at all times of year. This resuspension, and later redeposition, may have significant effects on the structure of the upper layers of the sediment, and the resulting turbidity may significantly diminish light-limited phytoplankton growth. Conversely, wind-wave pumping may augment benthic exchange, and hence favour phytoplankton growth as a result of additional release of nutrients from the seabed. It seems desirable to include some of these effects in a future version of L3VMP.

Denitrification in anoxic sediments is thought to be an important loss of combined nitrogen, and hence this process should be added to the model. Its description will need a second sediment layer. Other improvements might be sought in the aerobic remineralization model, perhaps by relating sediment-water exchange to sediment properties or water temperature, which may influence bioturbation. If the production of the ecosystem simulated by L3VMP is not to run down because of nitrogen loss, however, further thought must be given not only to recycling nitrogen through higher trophic levels but also to resupplying the real losses of this element to fisheries, sea-birds and denitrification. An adequate balance of the nitrogen budget might be achieved only within a North Sea circulation model. In the short run, however, it should be possible to use known transports and nutrient gradients to estimate the external input of nitrate to any location where the seasonal cycle is to be simulated by a vertical-processes model.

In the longer run a bulk microplankton model may not be adequate for predicting water quality. Diatom and *Phaeocystis* blooms, for example, have different environmental consequences. It thus seems desirable to divide the microplankton into several types of phytoplankton and microherotrophs. This will require the addition of state variables for dissolved and particulate silicon, because of the importance of this nutrient in controlling diatom growth, and the introduction of an explicit thermocline layer, to provide a niche for exploitation by simulated vertically-migrating dinoflagellates.

Note

General acknowledgements

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Figure 3 : Results of numerical simulation for 55°30'N, 01°00'E, mooring site A of North Sea Survey.

Physical model pre-run for 1 simulated year. Illustrations show results from the second simulated year of the full model, averaged over 10-day periods. Plotted by D. Mills.

Parameters as in program excerpts, Tables 5 and 7. Conditions at start of first simulated year of full model: A_5 = 50 kg m^{-3} (constant); B_1 = B_3 = 1 mmol C m^{-3}; C_1 = C_3 = 1 mmol C m^{-3}; C_5 = 10^6 mmol C m^{-3}; M_1 = M_3 = 0.1 mmol N m^{-3}; M_5 = 0.062 x 10^6 mmol N m^{-3}; N_1 = N_3 = 0.2 mmol C m^{-3}; O_1 = O_3 = O_5 = 600 mmol m^{-3}; $^{NH}S_1$ = $^{NH}S_3$ = 0.0 mmol m^{-3}; $^{NH}S_5$ = 10 mmol m^{-3}; $^{NO}S_1$ = $^{NO}S_3$ = 4 mmol m^{-3}; $^{NO}S_5$ = 10 mmol m^{-3}.

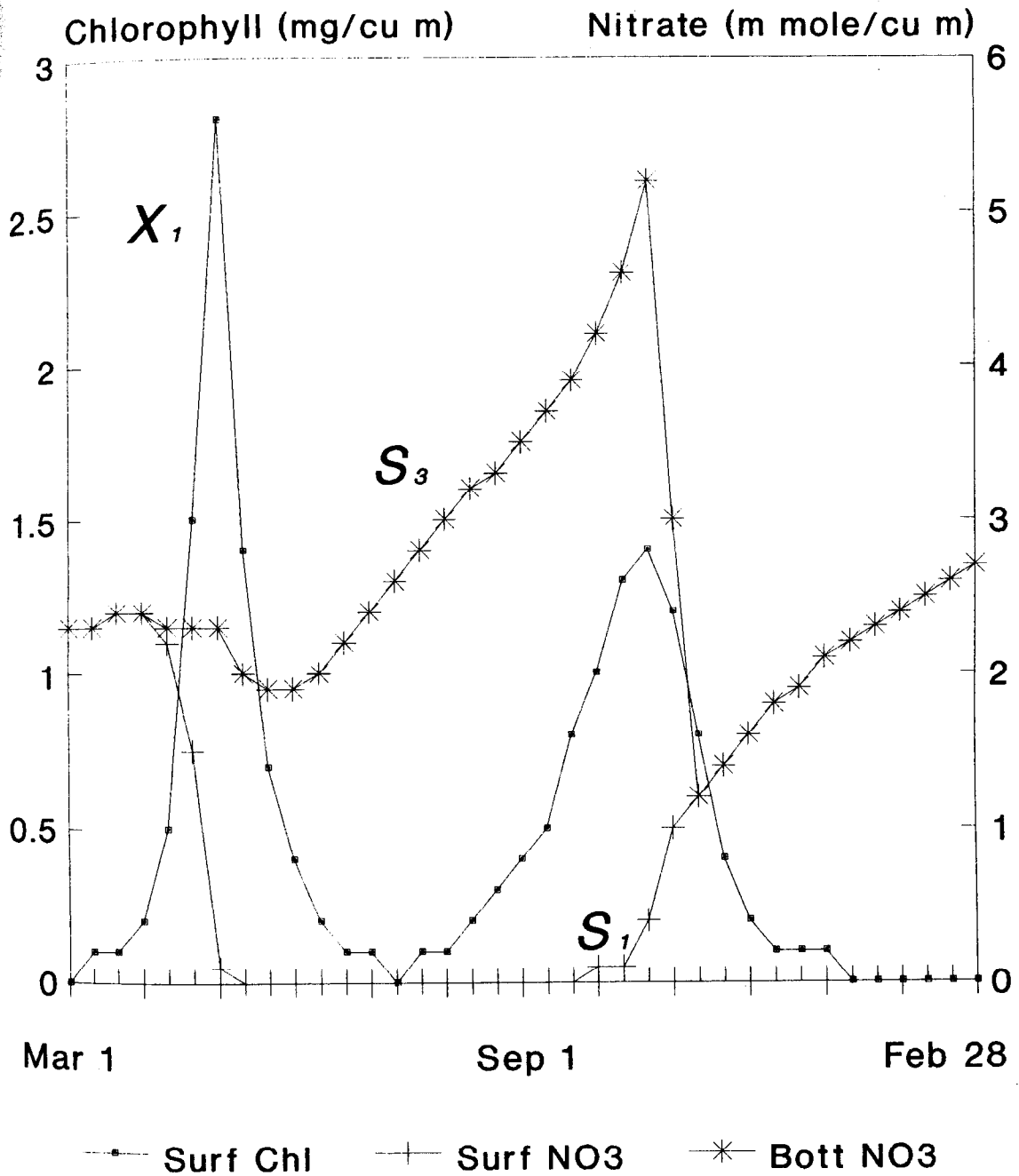**a: physical variables:** h_1, thermocline depth, m; I_1, 24-hr-mean irradiance in surface mixed layer, microEinsteins m^{-2} s^{-1}; T_1 and T_3, temperatures in surface and bottom layers, °C.

b: phytoplankton and water-column nutrients: X_1, surface layer phytoplankton, mg chl m^{-3}; $^{NO}S_1$ and $^{NO}S_3$, nitrate concentrations in surface and bottom layers, mmol N m^{-3}.

c: phytoplankton and detritus: X_1, surface layer phytoplankton, mg chl m^{-3}; C_1, bottom layer detritus, mmol C m^{-3}.

d: sediment chemistry: O_3 and O_5, oxygen concentrations in bottom layer and sediment pore water, mmol m^{-3}; $^{NH}S_5$, ammonium concentration in sediment pore water, mmol N m^{-3}.
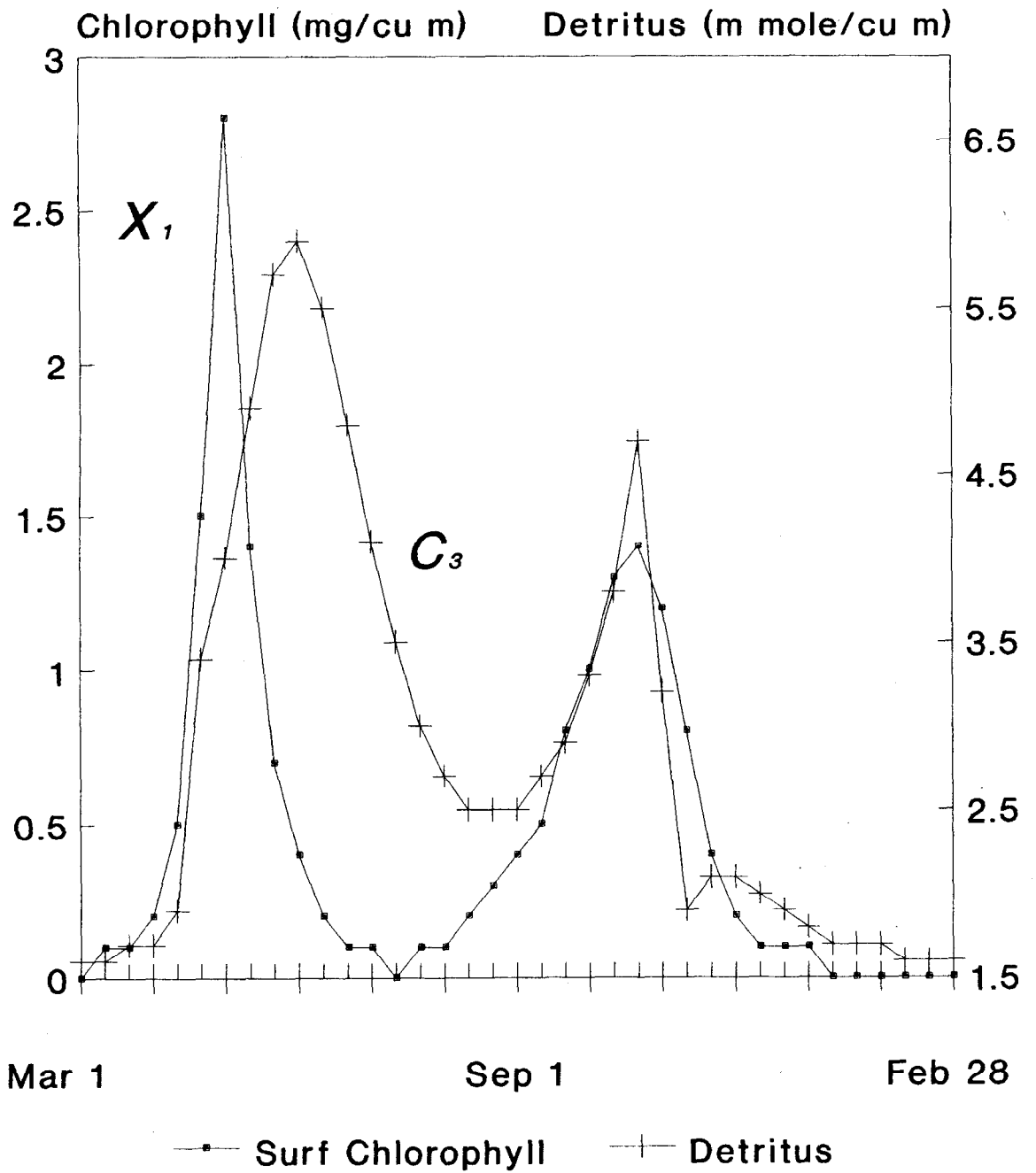
a: physical variables: h_1, thermocline depth, m; I_1, 24-hr-mean irradiance in surface mixed layer, microEinsteins $m^{-2} s^{-1}$; T_1 and T_3, temperatures in surface and bottom layers, °C.
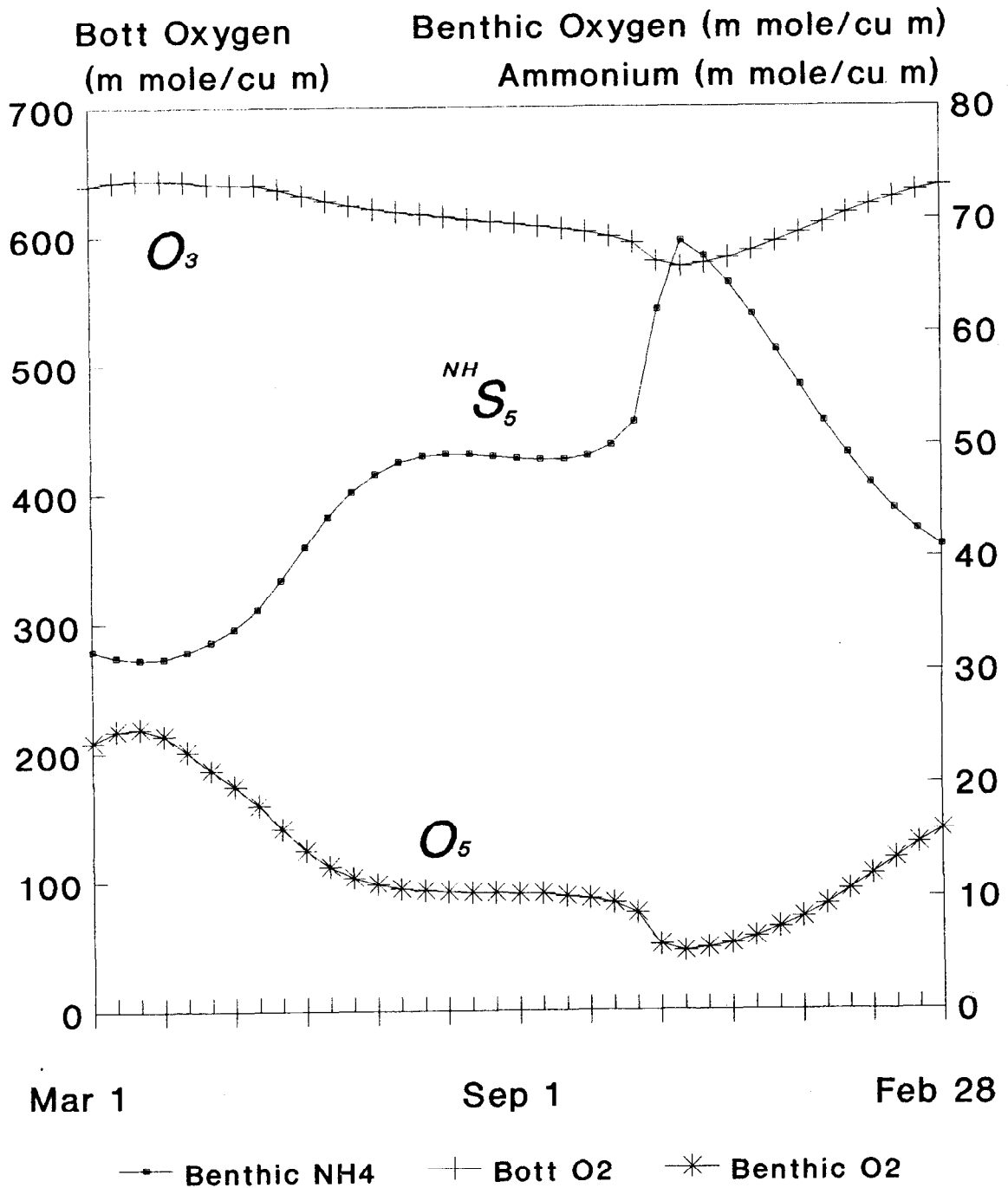
b: **phytoplankton and water-column nutrients:** X_1, surface layer phytoplankton, mg chl m^{-3}; $^{NO}S_1$ and $^{NO}S_3$, nitrate concentrations in surface and bottom layers, mmol N m^{-3}.

c: phytoplankton and detritus: X_1, surface layer phytoplankton, mg chl m^{-3}; C_1, bottom layer detritus, mmol C m^{-3}.

d: sediment chemistry: O_3 and O_5, oxygen concentrations in bottom layer and sediment pore water, mmol m^{-3}; $^{NH}S_5$, ammonium concentration in sediment pore water, mmol N m^{-3}.