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Simulation of Regional Variability and Seasonal Fluctuations in Phytoplankton Biomass and Productivity in the Black Sea Ecosystem: Results from a Baseline Experiment

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Consider the following idealizations in the model:

(1) a nitrogen-based ecosystem involving 2 groups of phytoplankton, 2 groups of zooplankton, particulate organic matter, ammonium, nitrate,

(2) 3-layer representation of the upper layer biochemical structure for plankton productivity and nitrogen cycling

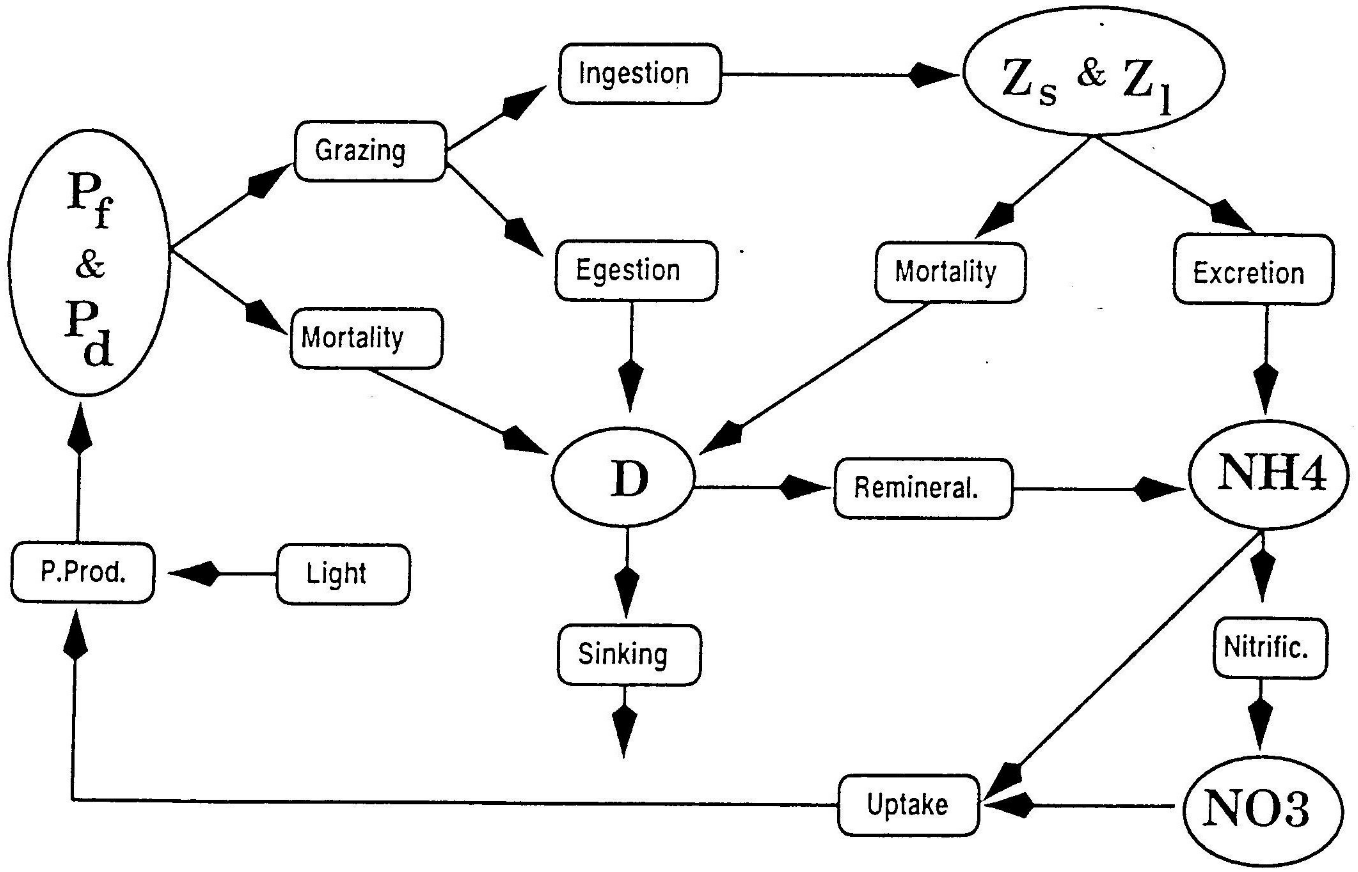
(3) time-invariant circulation field ,

(4) externally-specified density contrast at the base of the mixed layer,

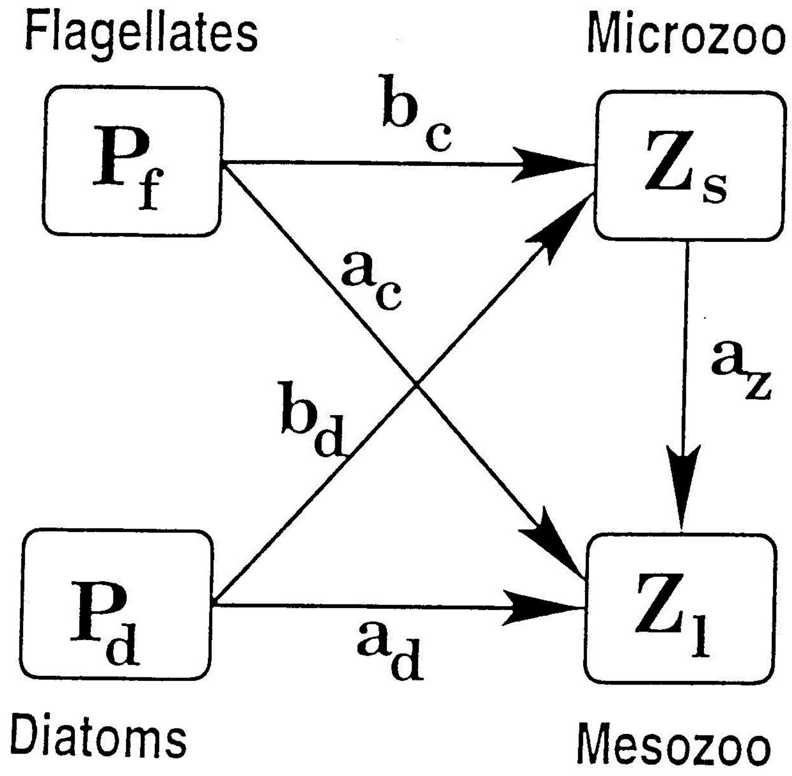
(5) horizontally-uniform wind stress, heat flux, salt flux and PAR forcing over the basin,

(6) biological processes do not depend on the temperature,

The schematic diagram of the ecosystem model showing biochemical processes and pathways of nitrogen exchange between the model compartments



Trophic interactions between different plankton groups and coefficients of food preferences



The Biological Model

Let F_i be the concentration of any biological variable at layer i. Then, the local temporal variations of all biological variables are expressed by transport equations of the general form

$$\frac{\partial F_i}{\partial t} + \mathrm{v_i} \cdot \nabla F_i = K_b \nabla^2 F_i + \Re_i + \frac{Q_i}{H_i}$$

where $\mathrm{v_i}$ is the horizontal velocity fields, $\Re_i$ and Q_i are the biological source-sink and vertical flux terms, respectively, K_b is the horizontal mixing coefficient. In the presence of finite the fossil layer, interfacial transports are

$$Q_1 = (F_2 - F_1)\left[w_e + \nu_{21}\right], \quad Q_3 = -(F_3 - F_2)\,\nu_{32}, \quad Q_2 = -(Q_3 + Q_1)$$

In the case of vanishing H_2 (i.e. no fossil layer, and the mixed layer comprises the entire euphotic zone), the model reduces to a two layer case in which the interfacial transports are

$$Q_1 = -Q_3 = (F_3 - F_1)\left[w_e + \nu_{31}\right]$$

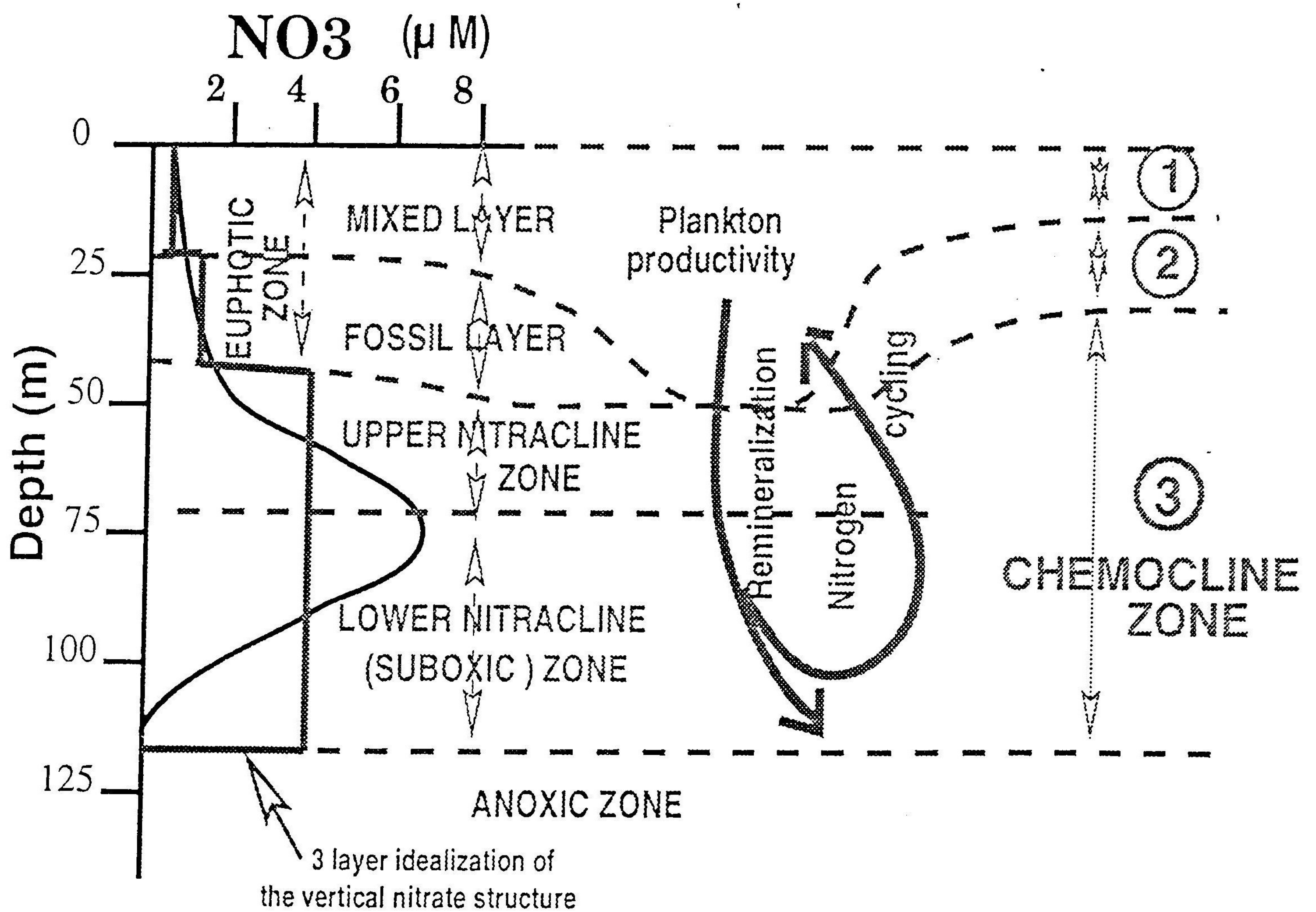
The terms proportional to w_e and ν_{ij} parameterize the transports across the layer interfaces due to entrainment process and bacground vertical mixing. We note that there is no entrainment flux across the interface between the second and third layers.

a nitrogen-based ecosystem involving 2 groups of phytoplankton, 2 groups of zooplankton, particulate organic matter, ammonium, nitrate

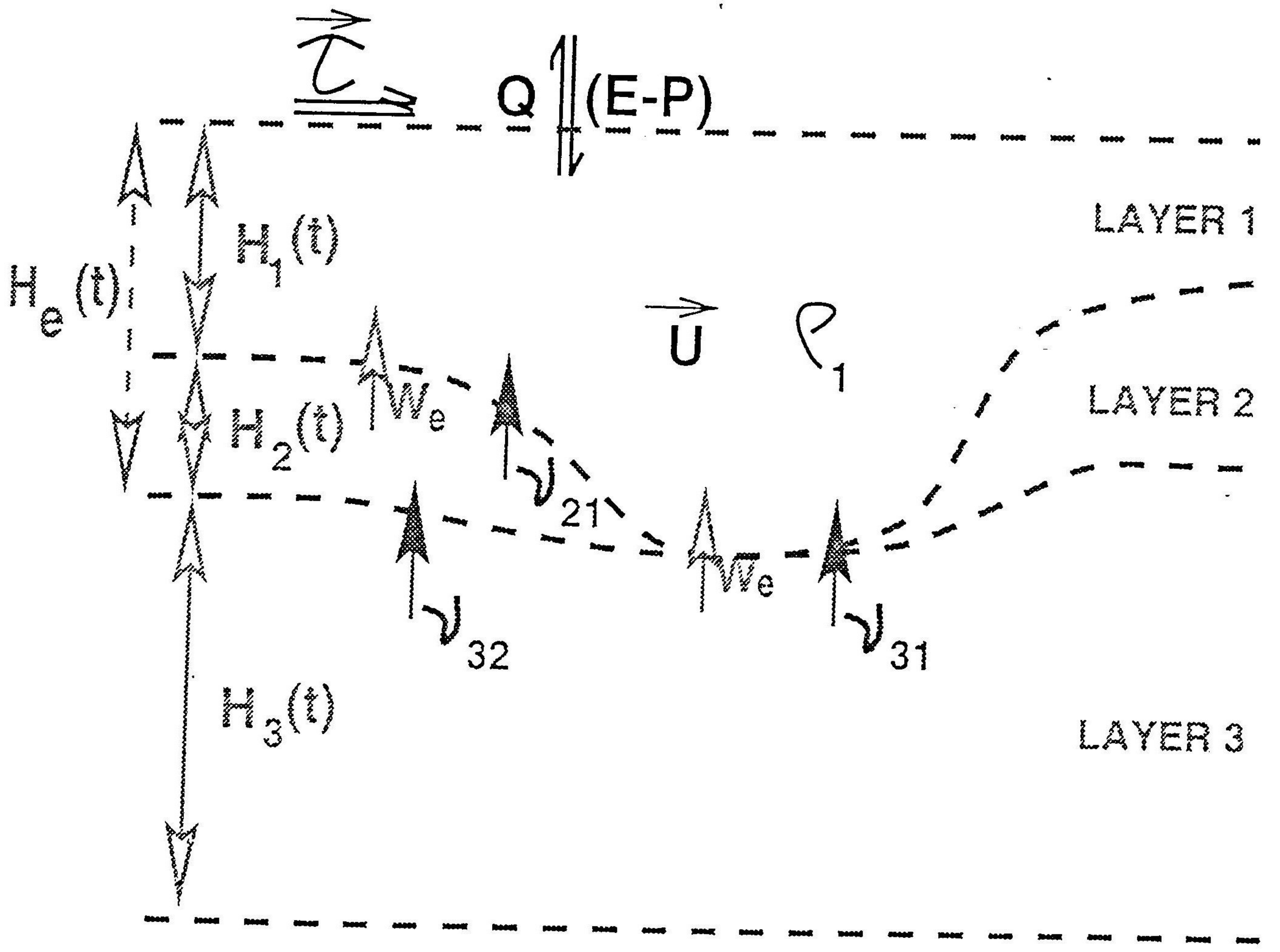
Biological Source-Sink Terms

Flagellates	P_f	$\Re_{Pf} = \sigma_f \Phi P_f - G_s(P_f) Z_s - G_l(P_f) Z_l - m_f P_f$
Diatoms	P_d	$\Re_{Pd} = \sigma_d \Phi P_d - G_s(P_d) Z_s - G_l(P_d) Z_l - m_d P_d$
Microzoo	Z_s	$\Re_{Zs} = \gamma_s G_s(P_f) Z_s + \gamma_s G_s(P_d) Z_s - G_l(Z_s) Z_l - \mu_s Z_s - \lambda_s{}^2 Z_s$
Mesozoo	Z_l	$\Re_{Zl} = \gamma_l G_l(P_f) Z_l + \gamma_l G_l(P_d) Z_l + \gamma_l G_l(Z_s) Z_l - \mu_l Z_l - \lambda_l{}^2 Z_l$
Detritus	D	$\Re_D = (1-\gamma_s)[G_s(P_f) + G_s(P_d)] Z_s$ $+ (1-\gamma_l)[G_l(P_f) + G_l(P_d) + G_l(Z_s)] Z_l$ $+ m_f P_f + m_d P_d + \lambda_s{}^2 Z_s + \lambda_l{}^2 Z_l - \epsilon D$
Ammonium	NH_4	$\Re_{NH4} = -\Phi\left(\frac{\beta_a}{\beta_t}\right)(\sigma_f P_f + \sigma_d P_d) - \Omega_a(z)\, NH_4$ $+ \epsilon D + \mu_s Z_s + \mu_l Z_l$
Nitrate	NO_3	$\Re_{NO3} = -\Phi\left(\frac{\beta_n}{\beta_t}\right)(\sigma_f P_f + \sigma_d P_d) + \Omega_a(z)\, NH_4$

3-layer idealization of the upper layer biogeochemical structure in the Black Sea



A schematic representation of the 3-layer model structure



Mixed Layer - Entrainment Model (1)

The **mixed layer thickness**, $\mathbf{H_m}$, is determined from the continuity equation

$$\frac{\partial H_m}{\partial t} + \nabla \cdot (H_m \mathbf{u}) = w_e$$

where

$\mathbf{u}$ = Current velocity

$\mathrm{w_e}$ = Entrainment/Detrainment velocity; positive upwards

The thickness of the **fossil layer** is

$$H_2 = H_e - H_m$$

The depth of the **euphotic zone**, H_e, is obtained by the 1 % light level for given values of the exctinction coefficients.

The mixed layer **entrains** ($w_e > 0$) or **detrains** ($w_e < 0$) water as in the Kraus-Turner (1967) model, in which vertical mixing is maintained by turbulence generated at the surface by wind stirring and cooling. The fossil layer, which is the layer comprising the rest of the euphotic zone below the seasonal thermocline, can be engulfed completely into the mixed layer during the case of strong turbulence generated by intense winter cooling. Under these conditions, we set

$$H_m = H_e \qquad \textit{and} \qquad H_2 = 0$$

Mixed Layer - Entrainment Model (2)

When the mixed layer deepens; i.e., ($P > 0$), the entrainment rate is defined by

$$w_e = \frac{P}{[1/2 g H_m \Delta\rho/\rho_0]}$$

where

$\Delta\rho$ = Density contrast at the base of the mixed layer

P = The turbulent kinetic energy production in the mixed layer

$$P = m u_*^3 - \frac{1}{2} g H_m \left[\frac{\alpha Q_s}{\rho_0 C_p} + \lambda S_0 (E - P) \right] (1 - \gamma) \qquad (5)$$

where

$\mathbf{u}_*^2 = |\tau|/\rho_0$ = Friction velocity

m = Wind stirring coefficient

γ = A fraction of TKE loss due to background dissipation

α, λ = Coefficients of thermal and salinity expansions

$\mathbf{Q_s}$ = Net surface heat flux

$\mathbf{S_0 (E - P)}$ = Surface fresh water flux

Mixed Layer - Entrainment Model (3)

When the mixed layer shalows, i.e., $(P \leq 0)$, the detrainment rate is defined by

$$w_e = \frac{(H_m^* - H_m^-)}{\Delta t}$$

where

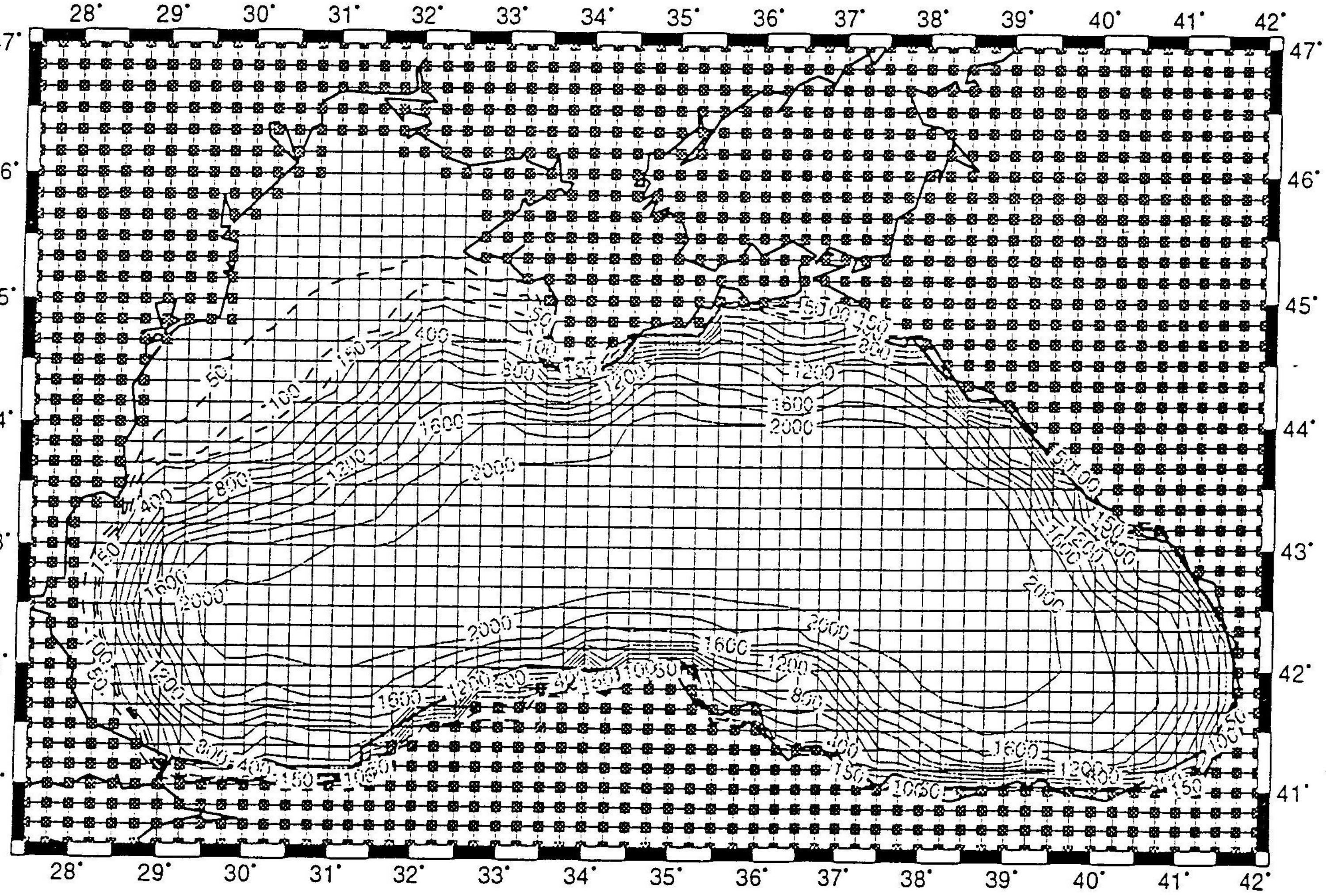
Δt = Time step of the integration

H_m^- = The mixed layer depth computed at the previous time step

H_m^* = The Monin-Obukhov depth obtained by setting $P = 0$ as

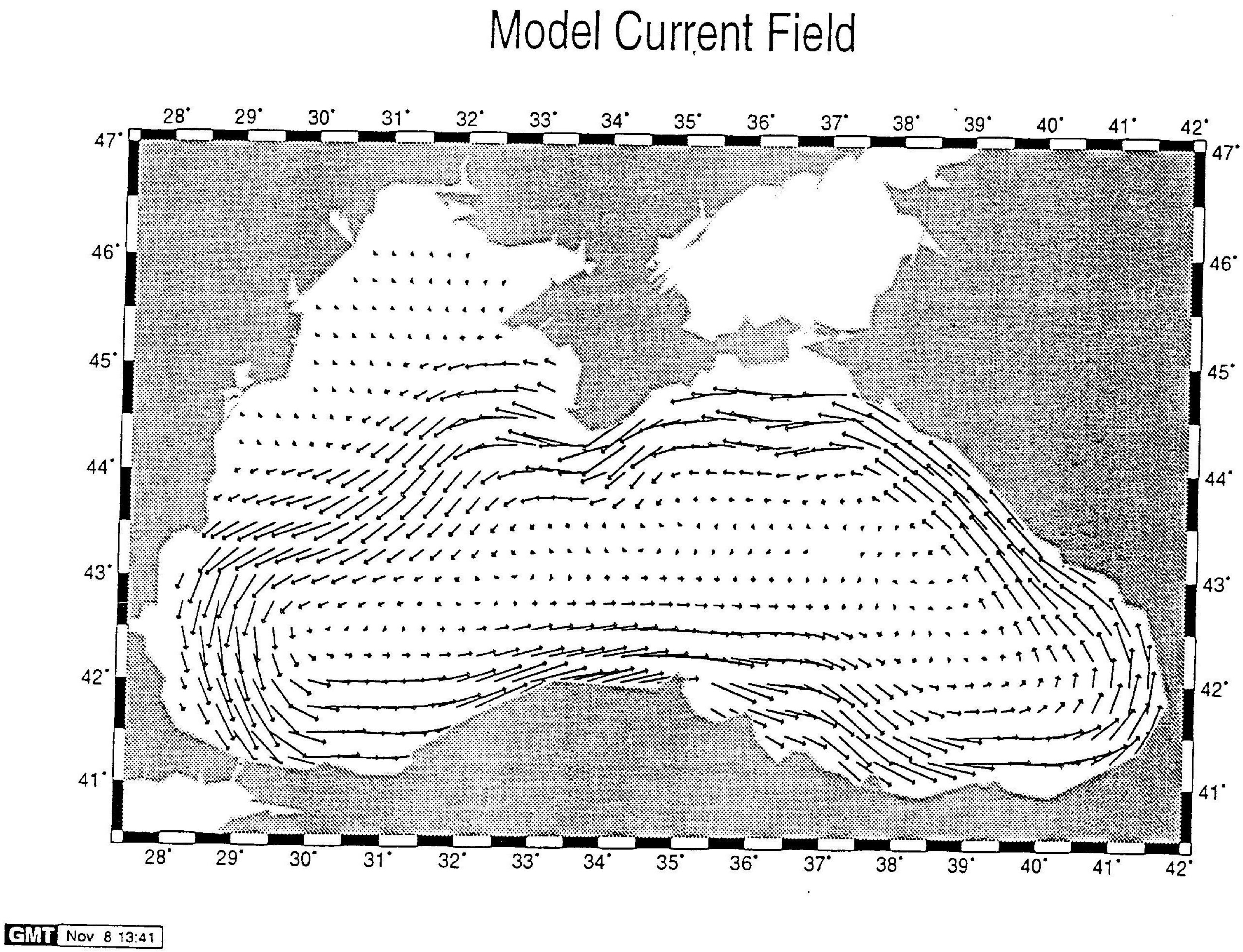
$$H_m^* = \frac{m u_*^3}{[1/2 g \Delta\rho/\rho_0]}$$

Model Grid & Topography

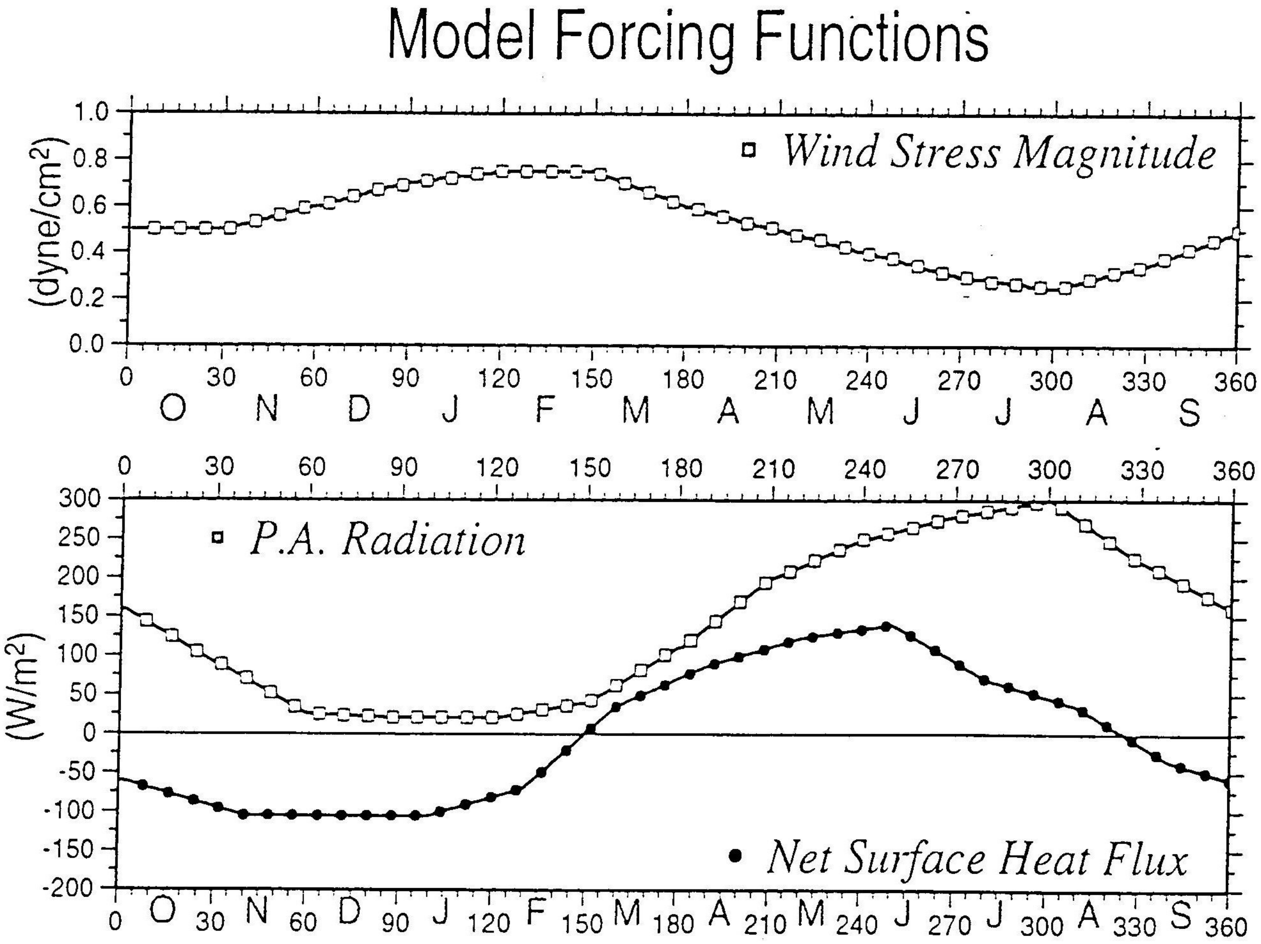


DX=19.5 km
DY=18.5 km

A time-invariant current field is specified.



horizontally-uniform wind stress, heat flux, salt flux and PAR forcing over the basin



TOTAL PHYTOPLANKTON BIOMASS (mmol/m3)

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