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THE NORWEGIAN ECOLOGICAL MODEL SYSTEM

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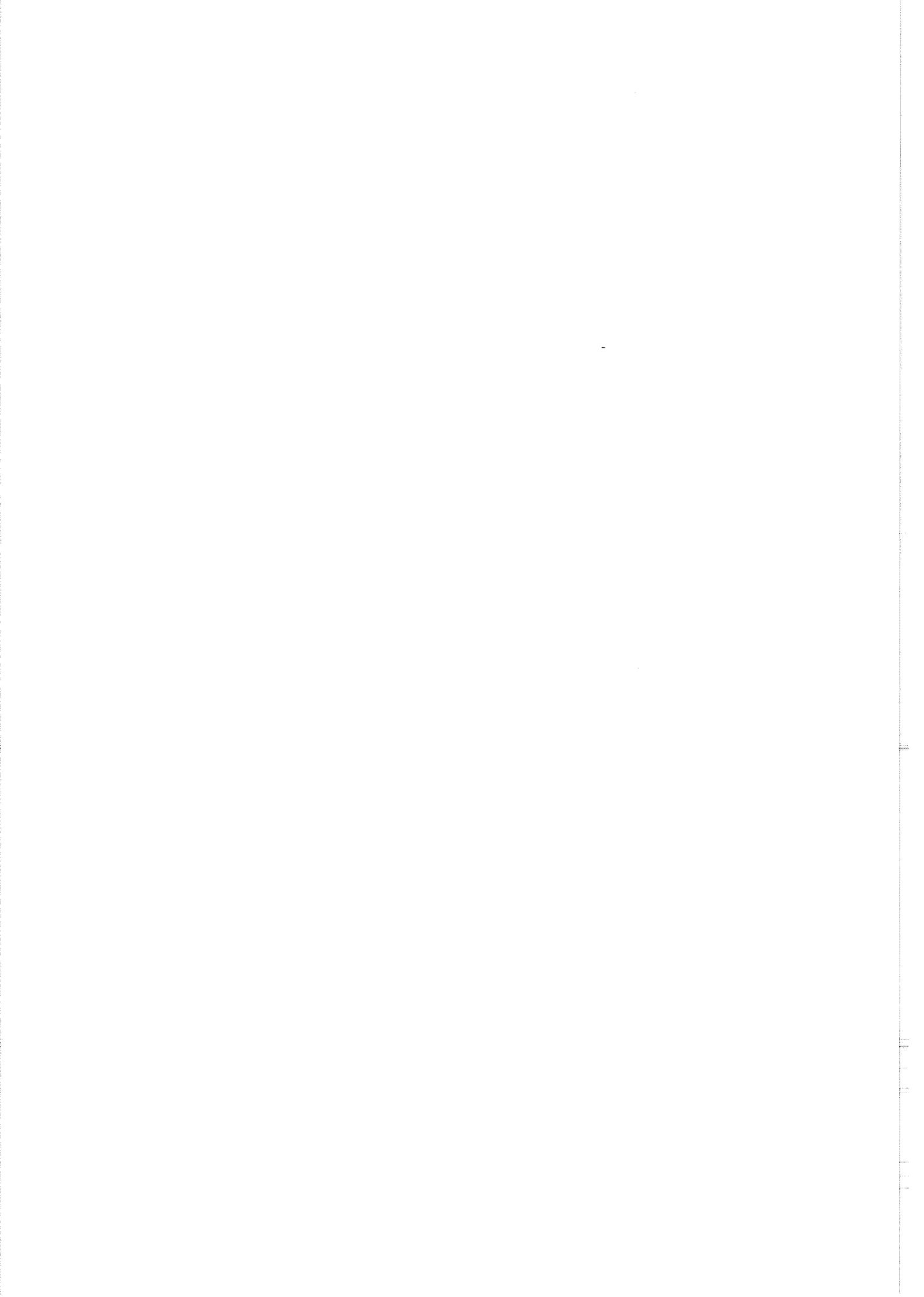Emneord - norsk:
1. Numerisk modell
2. Bruker manual

Emneord - engelsk:
1. Numerical model
2. User's guide

Prosjektleder

Seksjonsleder

A User's guide to

NORWECOM v2.0

The NORWegian ECOlogical Model system

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Foreword

A coupled 3 dimensional Physical-Chemical-Biological model system, NORWECOM, has been developed through cooperation between several Norwegian institutions. The physical module is based on the Princeton Ocean Model already well documented in several reports. This guide is an attempt to give an introduction to the Chemical-Biological module, and will hopefully help new users to understand the flow between and processes inside the various subroutines. The guide will concentrate on how the chemical-biological dynamics is formulated in the module. Why these formulation is preferred to others, is not a part of such a guide.

Contents

Chapter 1

Introduction

NORWECOM, the NORWegian ECOlogical Model system, is a coupled three dimensional physical, chemical and biological model system applied to study primary production and dispersion of particles (fish larvae, pollution). The model is the result of a cooperation between several Norwegian institutions. The coupled physical-chemical-biological modeling activity of the whole North Sea started in 1990-91 through close cooperation between the Institute of Marine Research (IMR) in Bergen, the Department of Fisheries and Marine Biology (IFM) at the University of Bergen, and The Norwegian Meteorological Institute (DNMI) in Oslo. Later, also Department of Mathematics at the University of Bergen has taken part in the development of NORWECOM.

The physical module is based on the well known Princeton Ocean Model (POM) by Blumberg & Mellor (1987). This model has been applied successfully in many regions after its first version was presented in 1977 (Blumberg & Mellor, 1980). The model also performed favorably in a Norwegian model evaluation project, MOMOP (Martinsen et al., 1990; Slørdal et al., 1991). It is a clear strength that the chemical-biological module is run coupled to a well known physical model, instead of using more or less realistic dispersion techniques.

The chemical-biological module is based on a paper by Aksnes & Lie (1990) who used it in a land-locked fjord, Lindåspollene, in western Norway. After this the model has been further developed and studied, and implemented on a model area covering an extended North Sea. This implementation was used by Aksnes et al. (1995) for simulating the *Chrysochromulina polylepis* bloom in Skagerrak in 1988. In the same paper the nutrients and phytoplankton development in six enclosures were simulated in order to do a verification of the validity of the set of parameters proposed by Andersen & Nival (1989). Skogen et al. (1995) used NORWECOM for simulating the time variability of both nutrient distributions and primary production in 1985 in the whole North Sea. In the same paper they also studied the possible effects of reducing the anthropogenic riverine loads and atmospheric nutrient deposition, and the transport of nutrients to the Skagerrak.

The main weakness of 3-D modeling activities claiming to simulate nature is the lack of comparison with adequate real data. Using the extensive SKAGEX dataset (Danielssen et al., 1991, 1997; Ostrowski, 1994) the model has been validated (Dee, 1994) in Svendsen

1

et al. (1996a); Skogen *et al.* (1997c). Additional model validation through comparison with field data can also be found in Aksnes *et al.* (1994); Berntsen *et al.* (1996); Svendsen *et al.* (1995c); Søiland & Skogen (1998). The model has been used to investigate long-term residual transports in the North Sea together with two other models (Smith *et al.*, 1996), and taken part in several model to model intercomparison studies (Røed *et al.*, 1989; Gustafsson & Jönsson, 1995; Proctor *et al.*, 1997; OSPAR, 1998).

In recent years, the model has been used in new ares and for a wide range of applications. In Laane *et al.* (1996); Skogen *et al.* (1997b, 1998); Skogen & Moll (1998); Skogen (1998b); Svendsen *et al.* (1995a,b); Søiland *et al.* (1996) the model has been used for estimation of transports and primary production, and investigation of eutrophication in the North Sea and Skagerrak. In Iversen *et al.* (1998); Skogen *et al.* (1997a); Svendsen *et al.* (1995c, 1996b); Sætre *et al.* (1998); Walsh *et al.* (1996) the model, coupled with a Lagrangian transport model, has been used in studies of fish recruitment and assessment, and in Skogen (1998a) a version of NORWECOM has been implemented for the Benguela upwelling system.

The model is described in parts in several of the above mentioned references. The first thorough presentation of the model, including data flow and the subroutines, was given in *A Users guide to NORWECOM* (Skogen, 1993). The present report is an updated version of that user's guide, including the extensions and changes that has been done based on the experiences the last years. This guide will only discuss how things are done within the model, to answer questions like why one formulation is preferred to another, is not a part. This report can be downloaded in postscript format from the NORWECOM home page `http://www.ii.uib.no/~morten/norwecom.html`

1.1   What's new ?

The main change from NORWECOM version 1.0 to NORWECOM version 2.0 is the inclusion of oxygen as a prognostic variable, and the inclusion of a sedimentation and resuspension module. A major limitation of the previous version was also the lack of regeneration of silicate, due to this the model could only be run one year at a time. In this version a new prognostic variable, biogenic silica (diatom frustules), is included, and the model can therefore be run for more than one year, without reinitialization.

In addition there has been a change in a few parameters, and several updates in the physical formulation and forcing.

The content of this guide is very similar to the previous one (Skogen, 1993). However, two extensions are done. A tabular showing the value of all constants given in Section 3.4, and one extra chapter is included to show some examples and validation results from several different model runs.

Chapter 2

The Physical Model

The circulation model is based on approximations from the three-dimensional, primitive equation, time-dependent, wind and density driven Princeton Ocean Model (POM). The model is fully described in Blumberg & Mellor (1987); Mellor (1996); O'Connor (1991). Therefore only a short review of the main physical processes is presented here. For a more thorough study of the physical processes, see the references above, or find more information at the POM homepage at : http://www.aos.Princeton.EDU/WWWPUBLIC/htdocs.pom/

2.1   The main processes

The prognostic variables of the Princeton Ocean Model are :

- three components of the velocity fields
- temperature
- salinity
- turbulent kinetic energy
- turbulent macroscale
- water level

The governing equations of the model are the horizontal momentum equations, the hydrostatic approximation, the continuity equation, conservation equations for temperature and salinity and a turbulence closure model for calculating the two turbulence variables (Mellor & Yamada, 1982). The equations and boundary conditions are approximated by finite difference techniques. In the vertical a sigma-coordinate representation is used, and the horizontal grid uses cartesian coordinates in a staggered *Arakawa C grid* (Mesinger & Arakawa, 1976).

The physical forcing factors are atmospheric wind and pressure, tides, freshwater runoff, surface heat fluxes and in- and out-flows at the open boundaries. The freshwater runoff is handled by routines developed by Berntsen and Ådlandsvik. Here, the water level is increased in the grid point nearest to the river outlet, and the salinity updated assuming a homogeneous upper layer of 3 meter. Special routines for the exchange between external

basins (e.g. the Baltic) and the model area are included and based on techniques due to Stigebrandt (1980). In the lack of data on the surface heat fluxes, a "relaxation towards climatology" method is used (Cox & Bryan, 1984). During calm wind conditions, the surface temperature field will adjust to the climatological values after about 10 days (Oey & Chen, 1992). The net evaporation precipitation flux is set to zero.

Around the open boundary a *Flow Relaxation Scheme* (FRS-zone) is used (Martinsen & Engedahl, 1987). Each prognostic variable, ϕ, in the zone is simply updated by the translation $\phi = (1 - \beta)\ \phi_{int} + \beta\ \phi_{ext}$, where ϕ_{int} contains the time integrated, unrelaxed values calculated in the entire model domain, i.e. also in the areas covered by the FRS-zone, and ϕ_{ext} is the specified external solution in the zone. ϕ is the new value and β a relaxation parameter which varies from 0, at the end of the zone facing the interior model domain, to 1, at the outer end of the zone. This simple FRS zone technique effectively absorbs inconsistencies between forced boundary conditions and model results.

For modeling in the North Sea and Norwegian Sea areas, the model is using six-hourly hindcast atmospheric pressure fields provided by the Norwegian Meteorological Institute (DNMI) (Eide *et al.*, 1985), 6-hourly wind stress (translated from the pressure fields by assuming neutral air-sea stability) and four tidal constituents (M2,S2,K1,O1). Initial values for velocities, water elevation, temperature and salinity are taken from monthly climatologies (Martinsen *et al.*, 1992). Interpolation between these monthly fields are also used at all open boundaries.

In the POM-model the horizontal time differencing is explicit whereas the vertical differencing is implicit. The latter eliminates time constraints for the vertical coordinates and permits the use of fine vertical resolution in the surface and bottom boundary layers. The model has a free surface and a split time step. The external mode portion of the model is two-dimensional and uses a short time step based on the CFL (Courant Friedrichs Levy) requirement related to the *external* wave speed (the fastest wave), while the internal mode is three dimensional and uses a much longer time step based on the same CFL requirement, but now related to the *internal* wave speed.

There are many different constants to be initialized in the physical module. Two of them need special attention, since the physical results are highly dependent on their values (Berntsen *et al.*, 1996). .

UMOL (m^2/s), the minimum allowed value for the vertical eddy viscosity/diffusion coefficient (which are calculated in connection with the turbulence closure model), causes vertical gradients to be smoothed, and should therefore be kept at a minimum. Unfortunately, too small values may cause instabilities. To avoid this, three different UMOLs are introduced in NORWECOM. One is related to the vertical gradients in horizontal velocity, one for the vertical temperature and salinity gradients and one for the chemical/biological gradients. The first one is given the default value set in POM of $2 \cdot 10^{-5}$, while the two others are set to 10^{-7}.

By comparing with data there are clear indications that using the default value of $2 \cdot 10^{-5}$ is smoothing the vertical salinity gradients too much in strongly stratified waters. Using 10^{-7} for the minimum temperature and salinity vertical diffusion coefficient, seems to give much more realistic results. However, to avoid instability problems which occurred

in the most shallow and stratified waters with this value, a simple filtering and surface boundary condition procedure has been added.

HORCON is a dimensionless horizontal diffusion constant used in connection with the Smagorinsky diffusivity for horizontal diffusion (Smagorinsky, 1963),

$$A_M = HORCON \cdot \Delta x \, \Delta y \, \frac{1}{2}[(\frac{\partial u}{\partial x})^2 + \frac{1}{2} \, (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})^2 + (\frac{\partial v}{\partial y})^2]^{\frac{1}{2}} \, .$$

The technique is used for eliminating small scale ($2\Delta x$) velocity-and density structures being produced in the model (and in nature) but not being resolved. A large value for HORCON increases the horizontal diffusion. If the grid spacing is small enough, HORCON can be null. In the model a value of 0.20 is used for the velocities and the chemical/biological variables, while 0.03 is used for temperature and salinity.

Chapter 3

The Chemical-Biological Model

The first version of the biological-chemical module was first described Aksnes & Lie (1990). For further applications and model description see also Aksnes *et al.* (1995); Skogen *et al.* (1995).

This chapter describes the main processes, the differential equations, the different subroutines and a list of the chemical and the biological variables and constants as used in NORWECOM v2.0.

3.1   The main processes

The biological model is coupled to the physical model through the subsurface light, the hydrography and the horizontal and the vertical flow and mixing of the water masses. NORWECOM differs between two groups of phytoplankton, diatoms (DIA) and flagellates (FLA), and their growth is affected by the nutrient concentration, light intensity and temperature. The nutrients are represented by inorganic nitrogen (NIT) such as nitrate and ammonia, inorganic phosphorus (PHO) (phosphate) and inorganic silicon (SIL) (silicate). The main difference between diatoms and flagellates, is that silicate is not rate limiting for the production of flagellates. The nutrients are added to the system through the river runoff and from the atmosphere, further nitrogen and phosphorus are regenerated from the dead algae, detritus (DET), and silicate from biogenic silica (SIS) at a constant rate. Oxygen (OXY) is released during primary production (growth) and it is consumed in respiration and when detrital matter is regenerated. Oxygen is assumed to be saturated at the surface.

For both the dead and living algae a sinking rate which may depend on the nutrient concentrations, is included. There are no zooplankton eating the algae. Instead a constant death rate, that also should include grazing, is included. Thus in this context, also zooplankton is included as a forcing variable. The particles (DIA, FLA, DET and SIS) may settle at the bottom, and can either be buried in the sediments or resuspended. The sedimentation and resuspension is a function of the bottom stress, which in the model is the sum of the stress due to surface waves, and the bottom currents, including tides. Algae that settle at the bottom is transformed immediately to detritus. Detritus mineralize in

the sediment at the same rate as in the pelagic, but a constant fraction of the remineralized nitrogen is lost due to denitrification. Processes like aggregation and flocullation affect the sedimentation and resuspension rates, but are not included. A limitation is also the lack of realistic light attenuation due to riverine inputs of yellow substance etc..

There is a total of ten prognostic variables in the chemical-biological part. In addition to the eight already mentioned, NIT, PHO, SIL, DET, SIS, FLA, DIA and OXY, also light in the water column, RAD, and an inorganic suspended particulate matter variable ISPM, are included. The sinking speed used for ISPM is tuned towards small particles ($< 50 \ \mu m$). All variables are defined at the modeled temperature and salinity, (S,T), points of the Arakawa-C grid. All chemical-biological concentrations in the model are given in (mg/m^3)s, except ISPM which is given as (g/l). A schematical overview of the different processes is given in Figure 3.1.

3.1.1   Incident irradiation

The incident irradiation is modeled using a climatological light formulation (Skartveit & Olseth, 1986, 1987), that have been updated to include real light measurements (Ulvestad, pers.comm). In this section, first the climatological formulation will be presented, and than the updated real-light algorithm will be given.

The original formulation gives a *mean* irradiation as a function of latitude and season. This mean climatological irradiance, varies according to a presumed sinusoidal variation, and all constants, $a_x - f_x$, should be specific for the area to be modeled. The irradiance is split into a diffuse ($x = dif$) and a direct ($x = dir$), (or beam) component

$$H_x(h, n) = I_0(n) \cdot Tr_{0x}(n) \cdot F_x(h). \qquad (3.1)$$

Here $H_x(h, n)$ is either direct or diffuse irradiance at the surface, $I_0(n)$ the solar irradiance at normal incidence just outside the atmosphere, $Tr_{0x}(n)$ the transmittance and $F_x(h)$ the solar elevation function. Further h is the solar elevation and n the day number. The transmittance at overhead zenith sun is given by :

$$Tr_{0x}(n) = a_x(1 + b_x \cos \frac{n - c_x}{365} 2\pi). \qquad (3.2)$$

The solar elevation function, $F_x(h)$, expresses the effect of varying solar elevation, which is estimated in every internal time step, and is given by :

$$F_x(h) = d_x + e_x \sin h - f_x(\sin h)^{1/2}. \qquad (3.3)$$

The formulas are valid when the solar elevation is above 5 degrees, nevertheless they are used for all solar elevations.

In case of large day to day variability in the incoming light, such a climatological approach is not good enough if one wants to initiate or simulate special blooms. Therefore an interpolation technique for the parameters $a_x - f_x$, in the case when real light measurements are available, has been proposed.
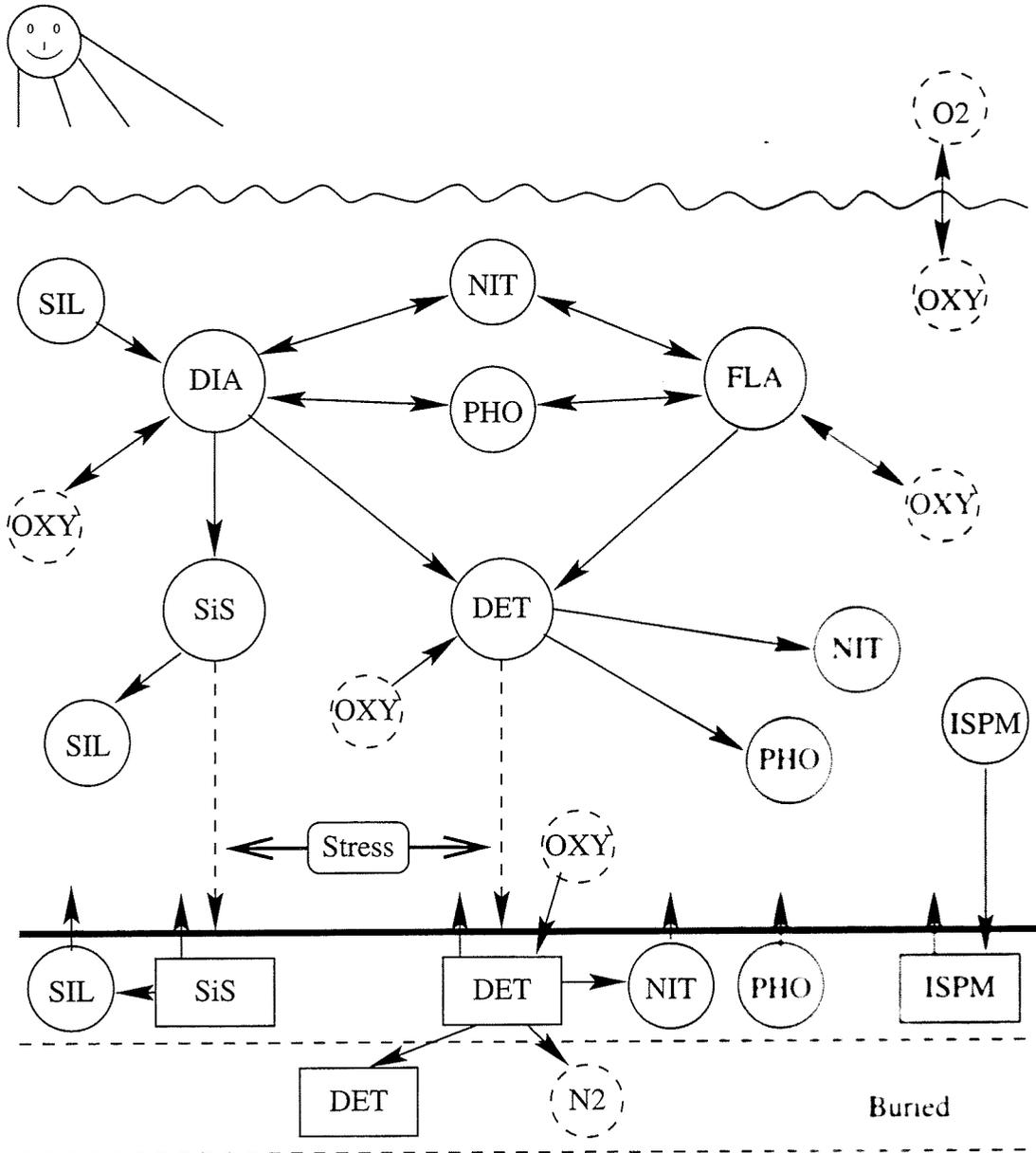
Figure 3.1: Schematical overview of the chemical-biological module

As input the global irradiance per day is needed for one or several distinct points in the model domain. One must also define the (sub)domains where these time series are assumed valid. The constants $a_x \dots f_x$ in (3.2) and (3.3) depends on the light intensity, thus in their papers Skartveit & Olseth differ between clear sky and all days average constants. Given these values for global, diffuse and direct light, the new algorithm interpolates and incorporates the parameters $a_x \dots f_x$ in the following way.

Given one point, a domain and a time series of global daily irradiance :

main loop

$\vdots$

C
C For each day find the transmittance (3.2)
C
    if (newday)
        meanglo = global irradiance (daynr,average constants)
        maxglo = global irradiance (daynr,clear sky constants)
        read (irrad_file), **global** = global irradiance (daynr)
        if (global < meanglo)
            lowirrad = .true.
        else if (global > maxglo)
            compute transmittance from clear-sky-constants
        else
            interpolate new constants from average and clear sky
            compute transmittance using interpolated constants
        end if
    end if
C
C At every time step find direct and diffuse irradiance (3.1)
C
    find sun height (longit,latit,daynr,time)
    if (lowirrad)
        direct = 0.
        diffuse = global(sunheight,daynr,aver_const.)
    else if (global > maxglo)
        compute the irradiances from clear-sky-constants and sun height
    else
        interpolate new constants from average and clear sky
        compute the irradiances using interpolated constants and sun height
    end if
C

$\vdots$

C
    continue (main loop)
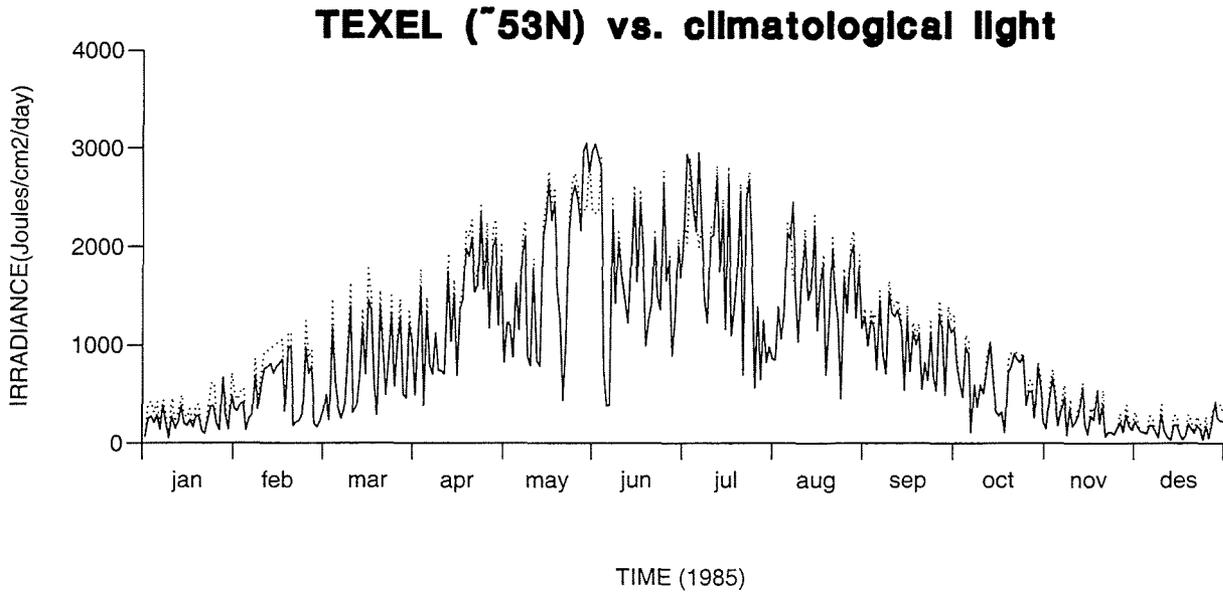
TEXEL (¨53N) vs. climatological light

Figure 3.2: Modeled global irradiance (dotted line) vs. real measurements at Texel (53 °N) in 1985

As seen it is now differed between three cases. In the first one with high global irradiance, the *clear-sky* constants are used, and in the second one with medium light, a set of *interpolated* constants are defined. In the third one with low irradiance, the *average* constants are used, but the light formulations are changed (see Equation (8) in Skartveit & Olseth (1986)) such that the direct irradiance is set equal to zero and the diffuse irradiance is set equal to a global hourly irradiance function, which for hour j and day n is given as :

$$\bar{H}_x(h_j, n) = \bar{H}_x(n) \cdot \frac{F_x(h_j)}{\sum_i F_x(h_i)}, \tag{3.4}$$

where $\bar{H}_x(n)$ is the given global irradiance for the actual day, and $F_x(h)$ is the solar elevation function.

This new real-light formulation enables the mapping of the day to day variations in the global irradiance in a very precise way. In Figure 3.2 a comparison between the modeled and measured light at Texel (53 °N) in 1985 is given.

3.1.2 Light in the water column

The diffuse light is calculated from

$$I_{dif}(x, y, z, t) = PAR \cdot R_{dif}(x, y, t) \, e^{-\frac{\kappa(x,y,z,t)}{\mu}}, \tag{3.5}$$

where $R_{dif}(x,y,t) = H_{dif}(h,n)$, the diffuse component of the surface irradiance, and PAR, photosynthetic available radiance, a constant which converts from incident diffuse irradiation to photosynthetic active irradiation. μ is the mean cosine of the diffuse light (Platt & Jassby, 1976), and κ the attenuation coefficient which is kept as a function of the concentration of chlorophyll and "other substances".

$$\kappa = b_2\, z + \frac{\nu}{N2Chla} \int_0^z (DIA(x,y,z,t) + FLA(x,y,z,t))dz. \tag{3.6}$$

Here ν is the chlorophyll-a light extinction coefficient, $N2Chla$ the fraction of nitrate and chlorophyll_a in a cell, and b_2 extinction due to water and other substances.

A similar formulation to (3.5) is given for the direct light, $I_{dir}(x,y,z,t)$, by substituting R_{dif} with R_{dir} and μ with $\cos\phi$, where ϕ is the zenith angle of the direct light in the water column computed from Snells formula, $n_1 \cos h = n_2 \sin\phi$, where n_1 and n_2 are the refraction coefficients for air and water.

3.1.3   Primary production

The concentration of chlorophyll in the system is affected by the production of the algae, their death rate and respiration. Since zooplankton is not included in the model, the death rate of algae also includes possible grazing.

The relationship between phytoplankton production and light intensity, and the relationship between phytoplankton production and nutrient uptake is represented by an affinity formulation, see Aksnes *et al.* (1995). The combined effects of nutrient and light limitation are multiplicative and given by :

$$\mu_{dia}(x,y,z,t) = \mu_{max} \cdot V_1 \cdot N_{lim} \cdot Dia(x,y,z,t), \quad N_{lim} = \min_{2 \leq i \leq 4} V_i, \tag{3.7}$$

where

$$V_i = \frac{S_i}{S_i + \frac{\mu_{max}(T)}{\alpha_i}}, \quad i = 1, \ldots, 4 \tag{3.8}$$

is a modified Michaelis-Menten limitation for substance S_i. In the equations $i = 1$ corresponds to irradiance, $i = 2$ to nitrate, $i = 3$ to phosphate and $i = 4$ to silicate. In this formulation the constant half saturation parameters, K_s, are avoided. Instead they are made temperature dependent through the affinity parameter, α_i, defined as :

$$\alpha_i = \frac{\mu_{max}(T_0)}{K\_Dia_i}, \tag{3.9}$$

where K_Dia_i is the conventional half saturation constant for diatoms for substance number i at temperature T_0. μ_{max} is the specific growth rate of the population under optimum light and nutrient conditions and is made temperature dependent as suggested in Eppley (1972). The relation

$$\mu_{max}(x,y,z,t) = a_1 e^{a_2\, T(x,y,z,t)}, \tag{3.10}$$

is chosen, where a_1 is the diatom production maximum at $0\,°C$ (s^{-1}), and a_2 is the production rate temperature dependence $(°C^{-1})$ for diatoms.

The respiration is assumed to be related to the temperature according to the equation

$$R_{dia}(x, y, z, t) = a_5\, Dia(x, y, z, t)\, e^{a_6\, T(x,y,z,t)}, \tag{3.11}$$

with a_5 and a_6 the repiration rate at $0\,°C$ (s^{-1}) and the respiration rate temperature dependence $(°C^{-1})$ respectively.

The death rate of the algae (in the whole water column) is assumed to be constant as long as the chlorophyll concentration of the algae at the surface is above a minimum level, and zero if it is below. This is because the biological model is light limited in winter, and in order to prevent the algae in the model to extinct, further death when their concentration becomes too small, must be prevented.

All these expressions refers to the diatoms. Analogous formulations are used for the production of flagellates. The only difference is that silicate is not rate-limiting for the flagellates.

3.1.4 Nutrients

The primary production is limited by three different nutrients, NIT, PHO and SIL [1], which are transported together with the water masses, and are added to the system through river input, atmospheric deposition and by regeneration of NIT and PHO from dead organic matter (DET) and SIL from the biogenic silica (SIS). Inside the algae, both dead and alive, PHO and SIL are expressed as NIT-equivalences, i.e. the uptake of PHO and SIL through the photosynthesis is expressed as a constant times the uptake of NIT. The Redfield ratios are used for these cellular ratios. For more details on the uptake and regeneration see the differential equations in Section 3.2.

3.1.5 Oxygen

The oxygen concentration is affected by the primary production, respiration and remineralization of detrital matter. The amount of oxygen released by primary production is proportional to the amount of inorganic nitrogen consumed, and is given by constant (Redfield ratio). The same ratio for oxygen consumption is used for the respiration and remineralization process. The ratio is based on the assumption that inorganic nitrogen is converted from nitrate to organic matter and vice versa. For the fraction of nitrogen that is denitrified in the sediments a somewhat smaller consumption takes place.

3.1.6 Sedimentation and resuspension

Particulate matter (ISPM) has a sinking speed relative to the ambient water and thus may reach the bottom. However laboratory measurements, and also field experience, show

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[1]Flagellate production is not limited by SIL

that if the bottom stress is above a threshold value it does not settle on the bottom, but remains suspended. If the stress is below a certain value, particles settle on the bottom. The opposite process of resuspension is also dependent on the bottom stress, such that resuspension occurs if the stress is above a certain limit. The value at which resuspension occurs is higher than the maximum stress value for sedimentation to occur, such that there is a small window at which neither sedimentation nor resuspension takes place. These limits are in general a function of the properties of the particles (sinking speed), and also of the time since sedimentation occurred (armouring). Since the values are variable, quite a scatter of values for these limits are occur in the literature, but we have chosen values used in other North Sea models (Pohlmann & Puls, 1994; Mayer, 1995). The sedimentation and resuspension are controlled by the following relationships :

$$
\begin{aligned}
\tau &< \tau_1, && \Rightarrow sedimentation \\
\tau_1 < \tau &< \tau_2, && \\
\tau_2 < \tau && \Rightarrow resuspension,
\end{aligned}
\tag{3.12}
$$

where $\tau_1 = 0.064\ Pa$ and $\tau_2 = 0.78\ Pa$. In a shallow area such as the North Sea the bottom stress is due to both the current and surface waves. In NORWECOM the total bottom stress, τ_B, is calculated as the sum of these two components.

$$
\tau_B = \tau_{wave} + \tau_{current} \, .
\tag{3.13}
$$

The magnitude of the wave stress is given by :

$$
\tau_{wave} = \frac{1}{2}\, \rho \cdot f_w \cdot U_w^2,
$$

where f_w is the wave friction factor and U_w is the wave orbital velocity close to the bottom, while the bottom current stress, τ_c, is taken from the physical model. The stress due to surface waves is based on wave data from the WINCH wave model (SWAMP-Group, 1985; Reistad *et al.*, 1988).

The resuspension rate is proportional to the bottom stress and is given by :

$$
\epsilon = M\,(\tau_B - \tau_2), \qquad M = 10^{-4} m^{-1}.
\tag{3.14}
$$

There are several forms of particulate matter in the sediment, and if resuspension occurs they are resuspended in the fraction of the total that they occur.

The algae that sediment out to the bottom is immediately transferred to the detrital pools (DET and SIS (only DIA)). Since algae is transferred to these detrital pools there are only two forms of detrital matter (DET and SIS) and the inorganic particulate matter variable (ISPM) present in the sediment. Here the detrital matter is mineralized back to inorganic nutrients using the same rate constants as in the pelagic. Oxygen is not a variable in the sediments so the oxygen consumed in this process is drawn from the water just above the sediments (lowest sigma layer). A constant fraction of the nitrogen

that is remineralized in the sediments may also be transformed to nitrogen gas through denitrification Lohse *et al.* (1996).

Another potential sink term for nutrients in the sediments is the part that is buried. Burying is formulated as a rate term for the amount of detrital matter above a given value. This is a slow process (seasonal) and it does not prevent the high concentrations of detrital matter in the sediments giving rise to unrealistic high fluxes of nutrients from the sediments. To keep the remineralization at a reasonable level a max value for this release based on published values is assumed (Gehlen *et al.*, 1995; Lohse *et al.*, 1995).

3.2 The differential equations

The concentrations of the nine prognostic chemical-biological variables, NIT, PHO, SIL, DET, FLA, DIA, SIS, OXY and ISPM, and the different processes they take part in, can be described using the following set of differential equations :

$$\frac{\partial N}{\partial t} + adv(N) = diff(N) + R_{Dia} + R_{Fla} + cc_4\,Det - (P_{Dia} + P_{Fla}) + \phi(N)$$

$$\frac{\partial P}{\partial t} + adv(P) = diff(P) + cc_1(R_{Dia} + R_{Fla} + cc_4\,Det - (P_{Dia} + P_{Fla})) + \phi(P)$$

$$\frac{\partial Si}{\partial t} + adv(Si) = diff(Si) - cc_2\,P_{Dia} + scc_4\,Sis + \phi(Si)$$

$$\frac{\partial Det}{\partial t} + adv(Det) = diff(Det) + cc_3\,(Dia + Fla) - cc_4\,Det + \phi(Det)$$

$$\frac{\partial Sis}{\partial t} + adv(Sis) = diff(Sis) + cc_2\,(R_{Dia} + cc_3\,Dia) - scc_4\,Sis + \phi(Sis)$$

$$\frac{\partial Dia}{\partial t} + adv(Dia) = diff(Dia) + P_{Dia} - R_{Dia} - cc_3\,Dia + \phi(Dia)$$

$$\frac{\partial Fla}{\partial t} + adv(Fla) = diff(Fla) + P_{Fla} - R_{Fla} - cc_3\,Fla + \phi(Fla)$$

$$\frac{\partial Oxy}{\partial t} + adv(Oxy) = diff(Oxy) + scc_1\,(P_{Dia} + P_{Fla} - R_{Fla} - R_{Fla} - cc_4\,Det) + \phi(Oxy)$$

$$\frac{\partial Ispm}{\partial t} + adv(Ispm) = diff(Ispm) + \phi(Ispm)$$

Here *adv* are the terms due to advection, *diff* the terms due to diffusion, *P* production terms, *R* respiration terms, ϕ river and atmospheric deposition (fluxes), or sink and source terms due to sedimentation and resuspension, cc_1 intercellular P/N relationship, cc_2 intercellular Si/N relationship, cc_3 phytoplankton death rate, cc_4 regeneration rate of detritus, scc_1 fraction of oxygen and nitrate for each cell produced, and scc_4 the remineralization rate of biogenic silica.

In more details the operators (after a transformation to the σ-coordinate system) can be written as :

$$adv_\sigma(F) = \frac{\partial}{\partial x}(FUD) + \frac{\partial}{\partial y}(FVD) + \frac{\partial}{\partial \sigma}(F\omega) \tag{3.15}$$

$$diff_\sigma(F) \;=\; \frac{\partial}{\partial \sigma}\left(\frac{K_H}{D}\frac{\partial F}{\partial \sigma}\right) + \frac{\partial}{\partial x}\left(DA_H\frac{\partial F}{\partial x}\right) + \frac{\partial}{\partial y}\left(DA_H\frac{\partial F}{\partial y}\right), \qquad (3.16)$$

where F is the substance to be integrated, U and V the horizontal velocities in x and y-direction respectively, ω the vertical velocity in the sigma coordinate system, $D \equiv H + \eta$ (bottom depth + water elevation), $A_H(m^2 s^{-1})$ the horizontal diffusivity and $K_H(m^2 s^{-1})$ the vertical diffusivity. In addition the sinking rates of the particulate variables (DIA, FLA, DET, SiS and ISPM) are applied after the above updates.

3.3   The subroutines

The main chemical-biological module is coupled to the physical module through the call to one biology routine, BIOLOGY.F90. In this routine all chemical-biological dynamics is handled in 25 different subroutines. These subroutines can be divided into three groups (light, biochemical and transport) in a natural way. Each of these subroutines will be described shortly in the following subsections. For a more detailed description of the various parameters, see also Section 3.4 and the prologue inside each subroutine. A flowchart is given in Figure 3.3, to illustrate the division, the dependencies between the different subroutines, and the order they are called in. To ease the data flow, two include files (BIOCOM.H and SEDCOM.H) are used. The include files are given in Appendices A and B respectively.

Before BIOLOGY is called, the hydrodynamic forcings should be updated. This includes new computations of the velocity field, the water elevation and fields for horizontal diffusion and vertical eddy viscosity. In addition the bottom stress due to the waves and bottom currents, are calculated before BIOLOGY is called.

3.3.1   Light routines

The biological module starts with calculation of the light conditions. There are two entries to this part, either through the routine DAYNUMB (that are called once every day), or through the routine BIOSUN (see Figure 3.3). All together there are 10 light routines. Five of these (**daynumb, declin, comprad, trans, lowlight**) are only called through the daynumb entry once a day. The main light routine is RADIATION which calculates the radiation (direct and diffuse) in the whole water column as a function of the direct and the diffuse irradiance at the surface and the *water quality*. The other nine subroutines estimate these dependencies (Equation (3.1) and b_2 in Equation (3.6)). Data for the global daily irradiance is also read here, once every day.

biosun(daynr,theta,longit,latit,sunti,sunhei)   Computes the sun height, h, used in (3.3). Sunhei is input to **irrsur** and **snell**.

comprad(iflag,daynr,theta,clirad,dti)   Computes the total climatologically integrated global surface irradiance at daynumber using either mean or clear sky constants from Skartveit & Olseth (1986, 1987). The irradiances are used as input to **trans**.

daynumb(daynr,ndate) Determines the day number given the date.

declin(daynr,theta) Computes the declination of the sun, θ, as a function of the daynr. The declination is the elevation of the sun measured over the north pole given in degrees. θ is used as input to the subroutine **biosun.**

irrsur(beamtr,difftr,daynr,diffus,direct,global,low,maxglo,meanglo, sumdf, sunhei, ...) Computes the $I_0(n)$ part of Equation 3.1, and the solar elevation function (3.3), including the interpolation to find the new constants d_x and e_x. Finally the multiplication giving the diffuse and direct components of the surface irradiance (3.1) is done. The irradiances, **diffus** and **direct** are input to **radiation** .

lowlight(daynr,latit,longit,maxglo,meanglo,sumdf,theta,fsm,dti) Determines the irradiance when the total diurnal integrated irradiance (from data) is lower than the value using the mean sky constants (3.4). This irradiance is input to **irrsur.**

radiation(direct,diffus,i,j,kappa,phi,dt,dz) The main light routine. Computes both the diffuse (3.5) and the direct components of the radiation, RAD, in a water column determined by (i,j). It also computes the self shading (integral part of (3.6)), and estimates the attenuation coefficient, κ. The radiation is used as input to the biochemical routine, **phyto_growth.**

snell(sunhei) Computes the zenith angel of direct light, ϕ, in the water column using Snells formula. ϕ is input to **radiation.**

trans(daynr,beamtr,difftr,global,low,maxglo,meanglo) Determines the beam and diffuse transmittance (3.2), through the interpolation procedure determining the constants $a_x, \ldots, c_x$, and the logical variable *low*. The transmittances is input to **irrsur,** and *low* determines if the routine **lowlight** should be called.

wqual(kappa,s,fsm) Computes the extinction coefficient, b_2 in (3.6), in the water as a function of water type. κ is input to **radiation.**

3.3.2 Biochemical routines

There are eight biochemical routines with **phyto_growth,** where the respiration (3.11) and primary production (3.7) are calculated, as the main one. The light that was computed in **radiation** is input to **phyto_growth.** These routines can logically be divided into two, where one group (**atmnit, biosource, botsource, oxysat**) computes different source terms used by the transport routine **vertbio.**

affin(aa,kndia,knfla,kpdia,kpfla,ksdia,krdia,krfla) Finds the affinity parameters, α_i, in Equation (3.9), when the half saturation constants and T_0 are given, and initiates the constants, a_i, used in Equations (3.10) and (3.11). Affin is only called once.

atmnit(.....)　Updating NIT in the surface layer, according to data for atmospheric deposition. Must be called after the transport routine **fctf**. Used as input to **vertbio**.

biosource(icode,source,pdia,pfla,rdia,rfla,ddia,dfla)　Give the source terms, i.e. the values for production, death rate and respiration rate in the differential equations, for all chemical and biological variables. The source term is input to **vertbio**.

botsource(icode,source,fsm,dz,dt,dti)　Computes the source terms for all chemical and biological variables in the sediment layer, and an additional source term in the next to bottom layer, due to leakage (NIT, PHO, SIL) from the sediment. Input to **vertbio**.

detritus(fsm,death_dia,death_fla)　Computes the phytoplankton death rate as a function of the chlorophyll concentration in the surface layer (see end of Section 3.1.3). The death rates are used as input to **biosource**.

oxysat(oxysurf,rho,s,t,fsm)　Calculate the concentration of oxygen in the surface layer assuming saturation in contact with one normal atmosphere. Should be called after the transport routine **fctf**. Used as input to **vertbio**.

phyto_growth(i,j,t,proddia,prodfla,reddia,redfla)　The main biochemical routine. Computes the phytoplankton growth (3.7), the production maximum (3.10) and the respiration (3.11) at temperature t, for both diatoms and flagellates. The **prod** and **red** terms are input to **biosource**.

slim(alpha,pmax,s)　Computes the modified Michaelis-Menten limitation, $V_i \in [0 \ldots 1)$, for substance S in Equation (3.8). **Slim** is a local function called by **phyto_growth**.

3.3.3　Transport routines

The last seven routines are mainly dealing with the horizontal and vertical distribution (through advection and diffusion) in the water masses of the chemical-biological variables, according to the updates (in time) given by the differential equations in Section 3.2. Based on the old (last time step) concentrations and the new updates of the physical variables, the advection and horizontal diffusion is first updated in **fctf**. Then all source terms from the biochemical routines are included before vertical diffusion is applied in **vertbio**. Finally there are updates due to sinking and the boundary conditions.

biobound(icode,ndate,fsm)　Relax the solution of the advection and diffusion equation (and possible sinking, sedimentation and resuspension) in the FRS-zone according to the external specified open boundary condition. Zero the fields in land point.

deadbot(dia,fla,det,sis)　Boundary conditions for algae in the sediment layer. Called after applying the boundary conditions in **biobound**. Tranfer all diatoms and flagellates at the bottom to detritus, and diatoms to also from biogenic silica.
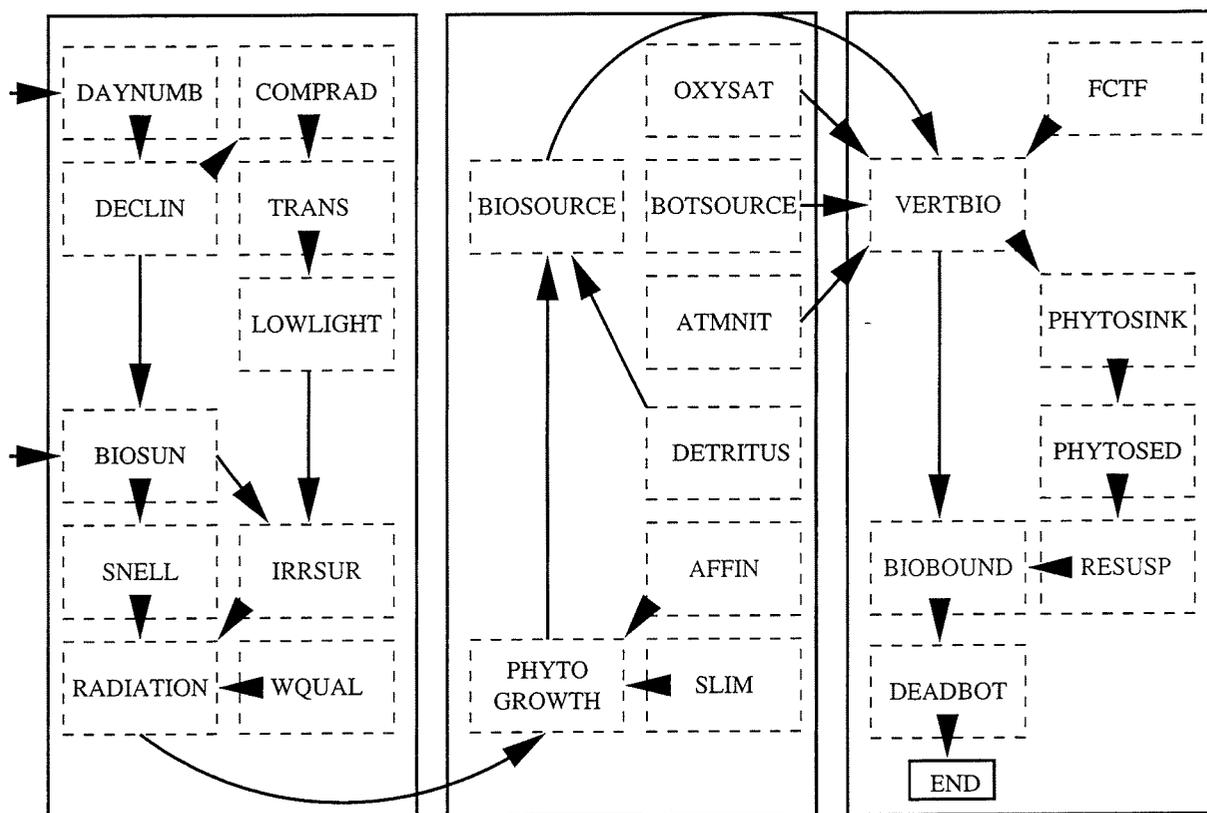
Figure 3.3: Flowchart for the main biology routine, BIOLOGY.F90. Light routines (left), biochemical routines (middle) and transport routines (right)

fctf(....) Advects the scalar fields, Equation 3.15, and adds the horizontal part of the diffusion, i.e. the second and third term of (3.16), using the flux-corrected transport algorithm. This method is chosen because of the absolute requirement of having positive definite chemical/biological fields. The horizontal diffusivity, A_H, should be computed by the physical module. After calling **fctf**, a routine for adding vertical diffusion and for including the surface boundary conditions and source terms must be called, i.e. **vertbio.** .

phytosink(icode,tmp,d,dz,dzz,dti) Performs the sinking of the particulate matters (DIA, FLA, DET, SIS and ISPM). The sinking of all matters are done **after** the updates from vertical diffusion in **vertbio.**

phytosed(icode,tmp,d,dz,dzz,dti) Performs sedimentation of dead and living algae from the next to bottom layer to the bottom. Called after **phytosink.**

resusp(icode,tmp,d,dz,dzz,dti) Performs resuspension of particles from the bottom. Called after **phytosed.**

vertbio(....) Adds the contribution from the vertical diffusion term when advecting scalar fields. The vertical diffusivity, K_H, should be taken from the physical module. A call to **vertbio** must be preceded by a call to a routine, **fctf**, for advecting horizontally taking into account all terms of the advection equation except the vertical diffusion term. The vertical integration is implicit from time step n to time step $n+1$. The **source** terms from several biochemical routines are included in the fields before the integration.

3.3.4 Include files

The include-file for the chemical-biological variables is named **biocom.h.** It contains the fields for the seven prognostic variables NIT, PHO, SIL, DET, FLA, DIA and RAD, together with some important constants. See Appendix A for a further description and for an example of this include file.

A second include file, **sedcom.h,** is used for OXY, SIS, ISPM, and all parameters controlling the sedimentation and resuspension. An example of this file can be found in Appendix B.

3.4 The Chemical-Biological variables

In this section the complete list of all chemical-biological constants, and variables that goes in and out of the subroutines, are given.

GLOBAL PHYSICAL CONSTANTS :

> **im:** Maximum number of points in x-direction
>
> **jm:** Maximum number of points in y-direction
>
> **kb:** Maximum number of points in z-direction

REAL CONSTANTS :

> **AA(6):** Consists of several constants used for phytoplankton production and respiration. All constants are initiated in AFFIN.F.
>
> > **aa(1):** Diatom production maximum at $0\,^{\circ}C$ (s^{-1})
> >
> > **aa(2):** Temperature dependent PMAX for diatoms, $(^{\circ}C^{-1})$)
> >
> > **aa(3):** Flagellate production maximum at $0\,^{\circ}C$ (s^{-1})
> >
> > **aa(4):** Temperature dependent PMAX for flagellates, $(^{\circ}C^{-1})$)
> >
> > **aa(5):** Respiration rate at $0\,^{\circ}C$ (s^{-1})
> >
> > **aa(6):** Respiration rate temperature dependence, $(^{\circ}C^{-1})$)
>
> **b2:** Extinction due to water and non chlorophyll materials (m^{-1}). Initiated in BIOCOM.H

CC(4): More phytoplankton constants. Initiated in the include file BIOCOM.H.

    cc(1): Fraction of phosphate and nitrate in a cell (mgP/mgN)

    cc(2): Fraction of silicate and nitrate in a cell $(mgSi/mgN)$

    cc(3): Phytoplankton death rate, (s^{-1})

    cc(4): Decomposition rate detritus, (s^{-1})

CCAR: Atomic weight carbon. Initiated in SEDCOM.H

COXY: Atomic weight oxygen. Initiated in SEDCOM.H

COXY2: Atomic weight oxygen gas. Initiated in SEDCOM.H

CNIT: Atomic weight nitrate. Initiated in BIOCOM.H

CPHO: Atomic weight phosphate. Initiated in BIOCOM.H

CSIL: Atomic weight silicate. Initiated in BIOCOM.H

DENITFR: Fraction of nitrogen in detritus in the sediment that denitrifies. Initiated in SEDCOM.H

DETBUL: Max amount of DET before burying occurs. Initiated in SEDCOM.H

DETMAX: Amount detritus that corresponds to max inorganic nitrogen flux from sediment. Initiated in SEDCOM.H

DETW: Molecule weight DET. Used in connection with TOTSED calculations. Initiated in SEDCOM.H

DIAMIN: Minimum concentration (mgN/m^3) of diatoms. Initiated in BIOCOM.H. Used in order to prevent the algae in the model to extinct

FLAMIN: Minimum concentration (mgN/m^3) of flagellates. Initiated in BIOCOM.H. Used in order to prevent the algae in the model to extinct.

KN_DIA: Affinity nitrogen, diatoms $(\mu MN)^{-1} s^{-1}$. Initiated in AFFIN.F.

KN_FLA: Affinity nitrogen, flagellates $(\mu MN)^{-1} s^{-1}$. Initiated in AFFIN.F.

KP_DIA: Affinity phosphate, diatoms $(\mu MP)^{-1} s^{-1}$. Initiated in AFFIN.F.

KP_FLA: Affinity phosphate, flagellates $(\mu MP)^{-1} s^{-1}$. Initiated in AFFIN.F.

KR_DIA: Affinity radiation, diatoms $m^2 (\mu Einstein)^{-1}$. Initiated in AFFIN.F.

KR_FLA: Affinity radiation, flagellates $m^2 (\mu Einstein)^{-1}$. Initiated in AFFIN.F.

KS_DIA: Affinity silicate, diatoms $(\mu MSi)^{-1} s^{-1}$. Initiated in AFFIN.F.

MY: Cosine of the mean zenith angle of the diffuse light. Initiated in BIOCOM.H.

N2CHLA: Fraction of nitrate and chlorophyll_a in a cell $(mgN/mgCHL\_A)$. Initiated in BIOCOM.H.

NIW: Molecule weight of N in DET. Used in connection with TOTSED calculations. Initiated in SEDCOM.H

NY: Chlorophyll light extinction coefficient $(m \; mgChl\_a)^{-1}$. Initiated in BIO-COM.H.

PAR: Photosynthetic active irradiance (%). Initiated in BIOCOM.H.

SCC(7): Several constants for oxygen and sedimentation-resuspension. Values set in SEDCOM.H.

   scc(1): Fraction of oxygen and nitrate for each cell produced (mgO/mgN)

   scc(2): Fraction of carbon and nitrate in a cell (mgC/mgN)

   scc(3): Fraction Oxygen/Nitrogen for the denitrification

   scc(4): decomposition rate biogenic silica (s^{-1})

   scc(5): Minimum rate of leakage of nutrients from sediments (s^{-1})

   scc(6): Maximum rate of leakage of nutrients from sediments (s^{-1})

   scc(7): Burial rate DET and SIS in sediments (s^{-1})

SIB: Concentration of SIL (μM) when max sinking speed of DIA occurs. Initiated in SEDCOM.H

SISBUL: Max amount of SIS before burying occurs. Initiated in SEDCOM.H

SISMAX: Amount biogenic silica that corresponds to max inorganic silicate flux from sediment. Initiated in SEDCOM.H

SISW: Molecule weight SIS. Used in connection with TOTSED calculations. Initiated in SEDCOM.H

SIW: Atomic weight silicon. Used in connection with TOTSED calculations. Initiated in SEDCOM.H

SRDET: Sinking rate DET (ms^{-1}), set in SEDCOM.H

SRDIAMAX: Minimum sinking rate DIA (ms^{-1}), set in SEDCOM.H

SRDIAMIN: Maximum sinking rate DIA (ms^{-1}), set in SEDCOM.H

SRFLA: Sinking rate FLA (ms^{-1}), set in SEDCOM.H

SRSED: Sinking rate ISPM (ms^{-1}), set in SEDCOM.H

SRSIS: Sinking rate SIS (ms^{-1}), set in SEDCOM.H

T0: Temperature for which the half saturation constants are given, see (3.9). Used and initiated in AFFIN.F.

LOGICAL VARIABLES :

BIO: Set true if biology module should be called

LOW: Set true if GLOBAL $\leq$ MEANGLO

SEDIMENT: Set true if sedimentation should be included

WAVES: Set true if waves should be included

REAL VARIABLES :

BEAMTR: Beam transmittance ($\mu Einstein/m^2/s$)

DAYNR: The day number (1-365, not including February 29)

DIFFTR: Diffuse transmittance ($\mu Einstein/m^2/s$)

GLOBAL: Total global irradiance from data

MAXGLO: Global irradiance using clear sky constants

MEANGLO: Global irradiance using mean sky constants

PHI: Zenith angle in water of the direct light

THETA: The declination of the sun

TTIME: Time of day

2-DIMENSIONAL REAL ARRAYS :

DEATH_DIA(IM,JM): Actual death-rates diatoms (s^{-1}) in each water column. Equals 0 if the concentration of diatoms in the surface cell < DIAMIN

DEATH_FLA(IM,JM): Same purpose as DEATH_DIA

DENIT(IM,JM): Accumulated amount of nitrogen denitrified in sediments

DETBU(IM,JM): Accumulated amount of detritus buried in sediments

DIFFUS(IM,JM): Diffuse surface irradiance ($\mu Einstein/m^2/s$).

DIRECT(IM,JM): Direct surface irradiance ($\mu Einstein/m^2/s$).

KAPPA(IM,JM): Coefficient of light extinction depending on the water quality (except for self-shading)

LATIT(IM,JM): Latitude

LONGIT(IM,JM): Longitude

SISBU(IM,JM): Accumulated amount of biogenic silica buried in sediments

SUMDF(IM,JM): Sum (daily) of the diffuse irradiance functions when GLOBAL $\leq$ MEANGLO

SUNHEI(IM,JM): Sun height

SUNTI(IM,JM): Sun time

TOTSED(IM,JM): Total mass of the accumulated sediment in each gridpoint. Used in the calculation of the resuspension from Equation 3.14.

TTAU(IM,JM): The total bottom stress

3-DIMENSIONAL REAL ARRAYS :

DET(IM,JM,KB): Detritus concentration (mgN/m^3)

DIA(IM,JM,KB): Diatom concentration (mgN/m^3)

FLA(IM,JM,KB): Flagellate concentration (mgN/m^3)

ISPM(IM,JM,KB): Inorganic suspended particulate matter variable concentration (mg/m^3)

NIT(IM,JM,KB): Nitrate concentration (mgN/m^3)

OXY(IM,JM,KB): Oxygen concentration (mgO/m^3)

PHO(IM,JM,KB): Phosphate concentration (mgP/m^3)

PROD_DIA(IM,JM,KB): Production of diatoms ($mgN/m^3/s$)

PROD_FLA(IM,JM,KB): Production of flagellates ($mgN/m^3/s$)

RAD(IM,JM,KB): Irradiance in the water column ($\mu Einstein/m^2/s$).

RED_DIA(IM,JM,KB): Respiration of diatoms ($mgN/m^3/s$)

RED_FLA(IM,JM,KB): Respiration of flagellates ($mgN/m^3/s$)

SIL(IM,JM,KB): Silicate concentration ($mgSi/m^3$)

SIS(IM,JM,KB): Biogenic silica concentration ($mgSi/m^3$)

SOURCE(IM,JM,KB): Source terms for an actual chemical or biological constituent (mg/m^3)

3.5   User supplied input/initialization

The user must support initial fields for the prognostic variables NIT, PHO, SIL, DET, FLA, DIA, OXY, ISPM and SIS, and fields for the inflow of these variables on the open boundaries should also be supplied. These initial and boundary conditions can either be given in separate user supplied routines, or together with the initial and boundary conditions for the physical part of the model. The user must also supply nutrient input from rivers and the atmosphere together with the river fluxes and temperature.

The chemical-biological model depends on a number of constants, and the output from the model will reflect the way these are initialized. The constants are set in the routines **biocom, sedcom** and **affin.** The routine **fctf** uses values for horizontal diffusivities, and **vertbio** a vertical diffusion coefficient. These values are related to similar physical constants, and should be supplied by the physical model. The biological module also needs fields for bottom stress to be used in the sedimentation and resuspension routines. For these computations wave fields should be included.

Vertbio needs a field for surface fluxes or values. In the model these are all set to zero, except for the oxygen concentration, where saturation in contact with one normal atmosphere is assumed.

The light routines could be substituted by real light if that is available. Several constants (see Eqs. (3.2) and (3.3), and subroutines are used for the computations (Skartveit

& Olseth, 1986, 1987). These can be varied to give a more sunny/cloudy weather, dependent of the geographical area to be modeled. The constants set in the model at present are for Bergen(3.2), and the average of Bergen and Montreal (3.3).

Parameter	Explanation	Value
$a(1)$	diatom production maximum at $0\,°C$	1.53E-5 (s^{-1})
$a(2)$	diatom temperature dependent P_{max}	0.063 $(°C^{-1})$
$a(3)$	flagellate production maximum at $0\,°C$	1.02E-5 (s^{-1})
$a(4)$	flagellate temperature dependent P_{max}	0.063 $(°C^{-1})$
$a(5)$	metabolic loss rate at $0\,°C$	8.05E-7 (s^{-1})
$a(6)$	metabolic loss rate temp. dependence	0.07 $(°C^{-1})$
$\alpha_{d.1}$	growth affinity for irradiance (diatoms)	3.6E-7 $m^2\ \mu Einstein^{-1}$
$\alpha_{d.2}$	growth affinity for nitrate (diatoms)	1.7E-5 $s^{-1}\ \mu M^{-1}$
$\alpha_{d.3}$	growth affinity for phosphate (diatoms)	2.7E-4 $s^{-1}\ \mu M^{-1}$
$\alpha_{d.4}$	growth affinity for silicate (diatoms)	2.5E-5 $s^{-1}\ \mu M^{-1}$
$\alpha_{d.1}$	growth affinity for irradiance (flagellates)	1.1E-7 $m^2\ \mu Einstein^{-1}$
$\alpha_{d.2}$	growth affinity for nitrate (flagellates)	1.5E-5 $s^{-1}\ \mu M^{-1}$
$\alpha_{d.3}$	growth affinity for phosphate (flagellates)	2.5E-4 $s^{-1}\ \mu M^{-1}$
b2	Extinction due to water and non chlorophyll	0.07 (m^{-1})
$cc(1)$	intercellular P/N relationship	0.138 $(mgP\,mgN^{-1})$
$cc(2)$	intercellular Si/N relationship	1.75 $(mgSi\,mgN^{-1})$
$cc(3)$	death rate (0.1)	1.6E-6 (s^{-1})
$cc(4)$	rate of decomposition detritus (0.013)	1.52E-7 (s^{-1})
DENITFR	fraction of nitrogen in sediment that denitrifies	0.3
DETBUL	limit of burying of DET	630 $(mg\ m^{-3})$
DETMAX	corresp. conc. to max flux of NIT from sediment	630 $(mg\ m^{-3})$
DETW	molecule weight DET	3555
DIAMIN	Minimum value DIA concentration	0.1 $(mgNm^{-3})$
FLAMIN	Minimum value FLA concentration	0.1 $(mgNm^{-3})$
μ	mean cosine of diffuse light zenith angle	0.83
N2CHLA	cellular fraction of nitrate and Chl_a	11.0 $(mgN\,mgChl\_a^{-1})$
NIW	molecule weight of N in DET	224
ν	Chl_a light extinction coefficient	1.38E-2 $(m\,mgChl\_a^{-1})$
PAR	photosynthetic active irradiance	40 %

SISBUL	limit of burying of SIS	6720 (mgm^{-2})
SISMAX	corresp. conc. to max flux of SIL from sediment	6720 (mgm^{-2})
SISW	molecule weight SIS	60
SIW	atomic weight silicon	28
SRDET	Sinking rate DET	3.0 (md^{-1})
SRDIA$_{min}$	Minimum sinking rate DIA	0.3 (md^{-1})
SRDIA$_{max}$	Maximum sinking rate DIA	3.0 (md^{-1})
SRFLA	Sinking rate FLA	0.25 (md^{-1})
SRSED	Sinking rate ISPM	1.0 (md^{-1})
SRSIS	Sinking rate SIS	3.0 (md^{-1})
SIB	Conc. of SIL when max sinking speed DIA	1.0 (μM)
scc(1)	Fraction of OXY and NIT for each cell produced	19.71 (mgO/mgN)
scc(2)	Fraction of C and NIT in a cell	5.68 (mgC/mgN)
scc(3)	Fraction OXY/NIT for the denitrification	3.42
scc(4)	Decomposition rate biogenic silica	1.45E-8 (s^{-1})
scc(5)	Min. leakage rate of nutrients from sediments	1.157E-6 (s^{-1})
scc(6)	Max. leakage rate of nutrients from sediments	4.63E-6 (s^{-1})
scc(7)	Burial rate (120 days)	9.65E-8 (s^{-1})

Table 3.1: ...(continue)... Parameter values

Chapter 4

Some model results and examples

In this chapter a few example figures are given, to show some of the application that the model has been used for. The results are not properly discussed, for that purpose the papers and reports referred should be consulted.

For most purposes NORWECOM has been used in an area covering an extended North Sea with a horizontal resolution of 20 × 20 kilometers. This resolution is too coarse to proper model processes within the Skagerrak, and for that purposes a nested version of the model is used. In the nested model, boundary values from the coarse North Sea model is used as input to a fine grid (4 × 4 kilometer) model for the Skagerrak and Kattegat. These boundaries are updated every hour, to resolve tides. In both models 12 σ-layers have been used, with a relative finer resolution in the surface layers to better resolve the biological and chemical processes that are most important here. The two bottom topographies are shown in Figure 4.1.

Using the physical module of NORWECOM the North Sea circulation, and it's long term variability, has been modeled (e.g. Smith *et al.* (1996); Iversen *et al.* (1998)). In Figure 4.2 the modeled mean (1976-1996) winter circulation at 10 meters depth in the North Sea is shown, while in Figure 4.3 the variability in the modeled inflow through a section from the Orkneys to Norway (along 59.17 °N) is given.

In Skogen *et al.* (1995) the model was for the first time used to model a whole annual cycle of the North Sea primary production. Results for individual ICES boxes were reported, and compared with measurements. In addition a scenario where the anthrophogenic inputs of inorganic nitrogen and phosphorus were reduced with 50 %, to measure the effect of such reduction in accordance with agreements from the International conference on the protection of the North Sea (London 1987). The results, annual integrated primary production ($gC/m^2/year$) and percentage reduction are given in Figure 4.4.

To study the dispersion and dilution of different water masses, it is possible to label these in the model. This is done by including an extra prognostic variable, in the model, and treat it as a passive tracer by the modeled circulation and diffusion. This algorithm was used in Skogen *et al.* (1997b), where the transport of water with origin in the German Bight were labeled, to investigate this transport to Skagerrak. In this work the nested model system (North Sea → Skagerrak) was used, and the model was run several years to
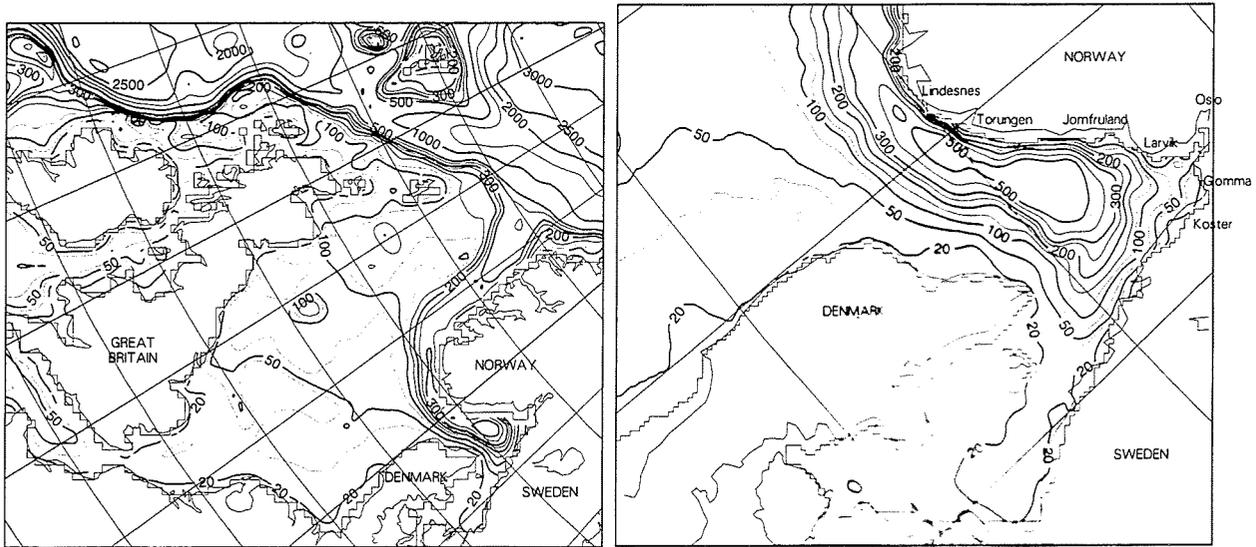
27

Figure 4.1: Bottom topography, North Sea 20×20 km. left, and Skagerrak 4×4 km. right

look into variability between different years. In Figure 4.5 the interannual variability of
water from the German Bight through a section (Tyborøn) on the Danish west coast are
shown.

Another eutrophication issue is the concern about oxygen depletion. In Skogen (1998b)
different nutrient reduction strategies was investigated in the light of change in minimum
bottom oxygen values in the German Bight. The change in this minimum was discussed,
as freshwater nutrients were reduced from either the Rhine or the German rivers (Elbe,
Ems and Weser) - or both. In Figure 4.6 oxygen in the bottom layer for a reference run is
given.

One validation process that the model has been through. is a comparison with clima-
tological nutrient fields in the North Sea (Søiland & Skogen. 1998) Using a costfunction
(Berntsen *et al.*, 1996), where the absolute difference between model and data are normal-
ized using the standard deviation, quantitative measures on the model performance can
be established. In Figure 4.7 such an example is given. Both the modeled phosphate field,
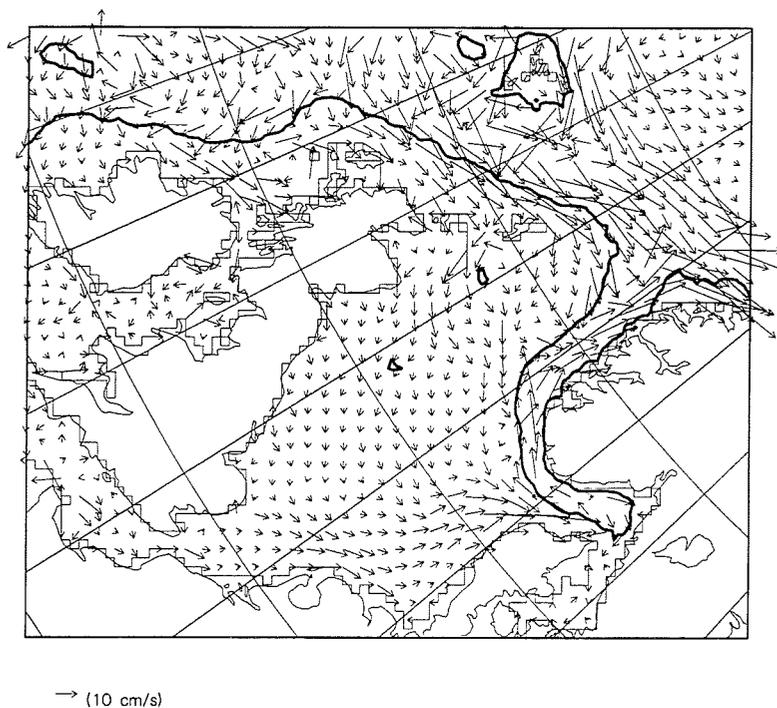and the costfunction for this field is shown.

Figure 4.2: Modeled mean (1976-1996) flow field for January, February and March at 10 meters depth. The solid line is the 200 meters depth contour
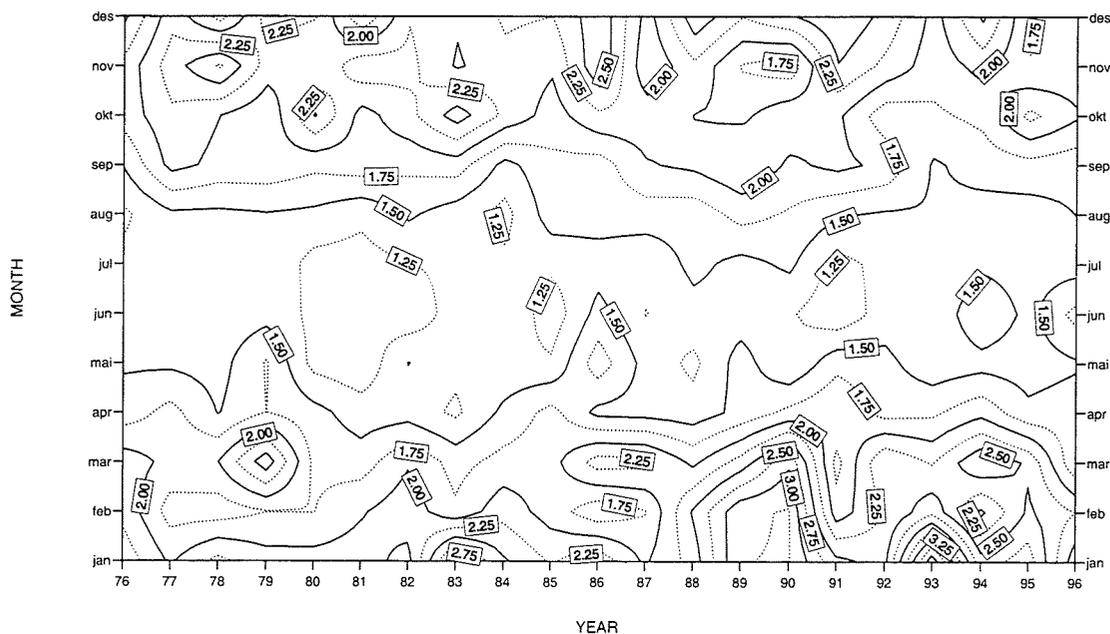

Figure 4.3: Modeled transports (in Sverdrup) southwards through section Orkney - Norway (Utsira) for the period 1976-1996
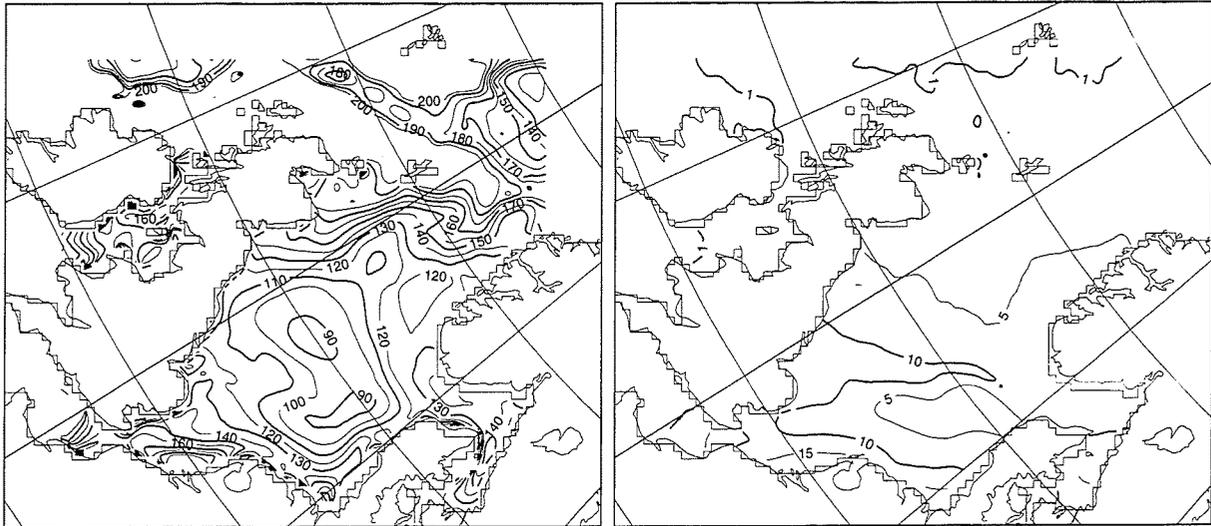
Figure 4.4: Annual depth integrated primary production ($gC/m^2/year$) for 1985 (left), and reduction (in percentage) with a 50 % reduction of anthrophogenic inputs (right)
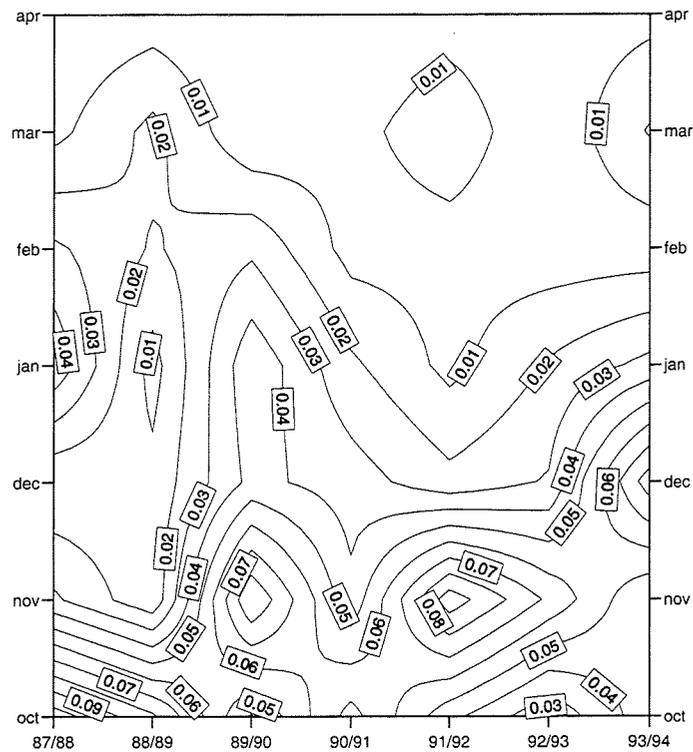

Figure 4.5: Monthly mean transport in Sverdrup of GBW through the Tyborøn section
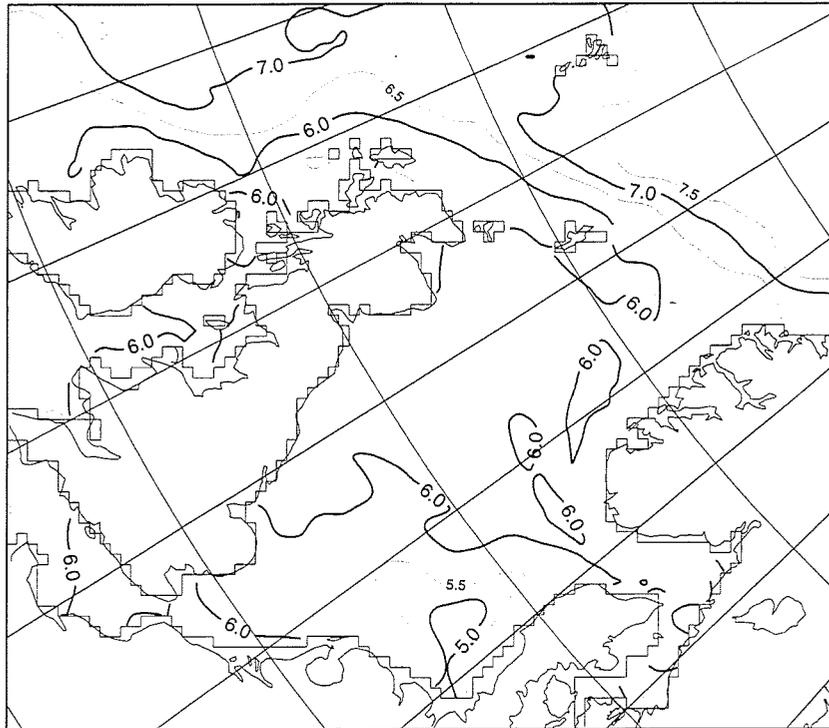
Figure 4.6: Oxygen (ml/l) in the bottom layer (2.5 % of total depth above bottom) at July 1 in the reference run
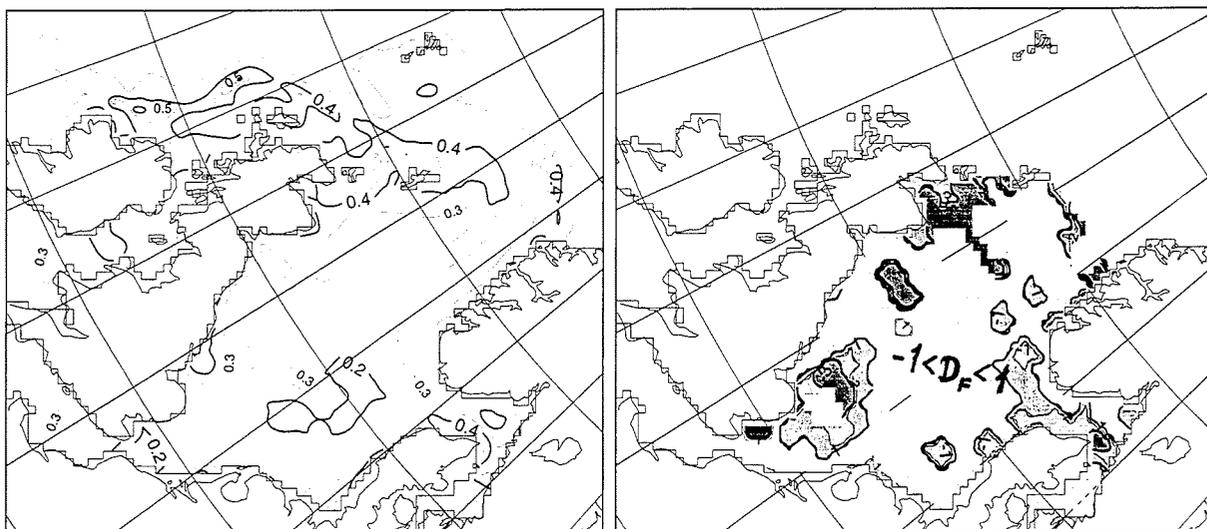

Figure 4.7: Mean (1980-89) model (left) and costfunction (right) field for phosphate. The results are for May-June-July in the upper 20 meters. The nutrient fields are in (μM), while the isolines in the costfunction field are -3, -2, -1, +1, +2 and +3

Appendix A

The include file BIOCOM

This appendix gives an example of an include file, BIOCOM.H, used together with the chemical-biological part of NORWECOM. The include file consists of common blocks defining the seven prognostic variables (NIT, PHO, SIL, DET, FLA, DIA and RAD) together with some important constants.

```
C
C Atomic weights
C
C   CNIT = nitrate
C   CPHO = phosphate
C   CSIL = silicate
C
      REAL CNIT,CPHO,CSIL
      DATA CNIT/14.01/,CPHO/30.97/,CSIL/28.09/
C
C   CC(1) : Fraction of phosphate and nitrate in a cell (mgP/mgN)
C   CC(2) : Fraction of silicate and nitrate in a cell (mgSi/mgN)
C   CC(3) : Phytoplankton death rate (s⁻¹)
C   CC(4) : Decomposition rate detritus (s⁻¹)
C
      REAL CC(4)
      DATA CC(1)/0.138/,CC(2)/1.75/,CC(3)/1.6E-6/,CC(4)/1.52E-7/
C
C Minimum values of phytoplankton concentrations (mgN/m³)
C
      REAL DIAMIN,FLAMIN
      PARAMETER(DIAMIN=0.1,FLAMIN=0.1)
C
C   N2CHLA : Fraction of nitrate and Chl_A in a cell. (mgN/mgChl_A)
C   MY : Cosine of the mean zenith angle of the diffuse light.
C   NY : Chlorophyll light extinction coefficient (m mgChl_A)⁻¹.
C   PAR : Photosynthetic active radiance (%)
```

- $CC(1)$: Fraction of phosphate and nitrate in a cell (mgP/mgN)
- $CC(2)$: Fraction of silicate and nitrate in a cell $(mgSi/mgN)$
- $CC(3)$: Phytoplankton death rate (s^{-1})
- $CC(4)$: Decomposition rate detritus (s^{-1})
- Minimum values of phytoplankton concentrations (mgN/m^3)
- N2CHLA : Fraction of nitrate and Chl_A in a cell. $(mgN/mgChl\_A)$
- NY : Chlorophyll light extinction coefficient $(m\ mgChl\_A)^{-1}$.

```
C    B2 : Extinction due to water (m⁻¹)
C    RC1 : Refraction coefficient air
C    RC1 : Refraction coefficient water
C
     REAL MY,NY,PAR,N2CHLA,B2,RC1,RC2
     PARAMETER (MY=0.83,NY=1.38E-2,PAR=0.40,N2CHLA=11.0,
   + B2=0.07,RC1=1.0,RC2=1.34)
C
C Nutrients common declarations
C
     REAL NIT(IM,JM,KB),PHO(IM,JM,KB),SIL(IM,JM,KB)
     COMMON /NUTCOM/NIT,PHO,SIL
C
C Biological common declarations
C
     REAL DET(IM,JM,KB),FLA(IM,JM,KB),DIA(IM,JM,KB)
     COMMON /BIOCOM/DET,FLA,DIA
C
C Light common declaration
C
     REAL RAD(KB)
     COMMON /LIGHT/RAD
```

Appendix B

The include file SEDCOM

This appendix gives an example of an include file, SEDCOM.H, used together with the chemical-biological part of NORWECOM. The include file consists of common blocks defining the three new prognostic variables from version 1.0 (SIS, OXY, ISPM), together with constants used in the sedimentation-resuspension routines.

```
C
C Sediment common declarations
C
      REAL TTAU(IM,JM)
      LOGICAL WAVES,SEDIMENT
      COMMON/COMSED/TTAU
      COMMON/COMLOG/WAVES,SEDIMENT
C
      REAL SIS(IM,JM,KB),OXY(IM,JM,KB),ISPM(IM,JM,KB)
      COMMON /BIOSED/SIS,OXY,ISPM
C
      REAL TOTSED(IM,JM)
      REAL DETBU(IM,JM),DENIT(IM,JM),SISBU(IM,JM)
      COMMON/BOTW/TOTSED
      COMMON/BOTPRO/DETBU,DENIT,SISBU
C
C Atomic weights and molecule weights
C
      REAL DETW,SISW,NIW,SIW
      PARAMETER (DETW=3555., SISW=60., NIW=224., SIW=28.)
C
C   COXY = oxygen
C   COXY2 = oxygen gas (O₂)
C   CCAR = carbon
C
      REAL COXY,COXY2,CCAR
      DATA COXY/16.00/,COXY2/32.00/,CCAR/12.01/
```

```
C
C    SCC(1) : Fraction of oxygen and nitrate for each cell produced (mgO/mgN)
C    SCC(2) : Fraction of carbon and nitrate in a cell (mgC/mgN)
C    SCC(3) : Fraction Oxygen/Nitrogen for the denitrification
C    SCC(4) : Decomposition rate biogenic silica-180 days (s^{-1})
C    SCC(5) : Minimum rate of leakage of nutrients from sediments - 10 days (s^{-1})
C    SCC(6) : Maximum rate of leakage of nutrients from sediments - 6 hours (s^{-1})
C    SCC(7) : Burial rate - 120 days (s^{-1})
C
      REAL SCC(6)
      DATA SCC(1)/19.71/,SCC(2)/5.68/,SCC(3)/3.42/,SCC(4)/1.45E-8/
      DATA SCC(5)/1.157E-6/,SCC(6)/4.63E-5/,SCC(7)/9.65E-8/
      REAL DETMAX,DETBUL,DENITFR,SISBUL,SISMAX
      DATA DENITFR/0.3/,DETMAX/630./,DETBUL/630./
      DATA SISMAX/6720./,SISBUL/6720./
C
C Sinking speeds
C
      INTEGER DAY
      REAL SRDET,SRFLA,SRDIAMAX,SRDIAMIN,SRSIS,SIB,SRSED
      PARAMETER(DAY=86400,SIB=1.0,SRDET=3.,SRFLA=0.25)
      PARAMETER(SRSED=1.0,SRDIAMAX=3.0,SRDIAMIN=0.3,SRSIS=3.0)
```

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