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A new radiation model for Baltic Sea ecosystem modelling

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ABSTRACT

Photosynthetically available radiation (PAR) is one of the key requirements for primary production in the ocean. The ambient PAR is determined by incoming solar radiation and optical properties of sea water and the optically active water constituents along the radiation pathway. Especially in coastal waters, the optical properties are affected by terrigenous constituents like yellow substances as well as high primary production.

Numerical models for marine ecosystems account for the optical attenuation process in different ways and details. For the consideration of coloured dissolved organic matter (CDOM) and shading effects of phytoplankton particles, we propose a dynamic parametrization for the Baltic Sea. Furthermore, products from biological turnover processes are implemented. Besides PAR and its attenuation coefficient, the model calculates the Secchi disk depth, a simple measurable parameter describing the transparency of the water column and a water quality parameter in the European Water Framework Directive.

The components of the proposed optical model are partly implemented from other publications respectively derived from our own measurements for the area of investigation. The model allows a better representation of PAR with a more realistic spatial and temporal variability compared to former parametrizations. The effect is that regional changes of primary production, especially in the northern part of the Baltic Sea, show reduced productivity due to higher CDOM concentrations.

The model estimates for Secchi disk depth are much more realistic now. In the northern Baltic Sea, simulated oxygen concentrations in deep water have improved considerably.

1. Introduction

A basic requirement for photosynthesis in the sea is the incident solar radiation measured as photosynthetically available radiation (PAR). The light penetration determines, beside the availability of nutrients, the primary production. PAR is the photon flux density (photons per second per square meter) within the visible spectral range (usually 400 to 700 nm). It indicates the total energy available to plants for photosynthesis, and is thus a key parameter for biological and ecological studies. Therefore, a most realistic vertical light penetration is of central importance for coupled hydrodynamic-biogeochemical models. Depending on the considered spectral range, the light penetration depth has an effect on primary production (at least in the photosynthetically available radiation range) or on the heat fluxes. The depth at which PAR is 1% of the surface PAR is defined as the euphotic depth, in which production and respiration is equivalent.

The vertical distribution of PAR follows an exponential function:

$$PAR(z) = PAR(0)\exp(-K_{PAR}\,z), \quad (1)$$

where $PAR(0)$ $[\mu E\, m^{-2} s^{-1}]$ is the surface irradiance, $PAR(z)$ is the irradiance at depth z $[m]$, and K_{PAR} $[m^{-1}]$ is the diffuse vertical attenuation coefficient (Kirk, 1994). The attenuation coefficient K_{PAR} and the vertical transport of radiation is determined by the absorption and scattering properties of seawater itself, and the dissolved and suspended optically active water constituents. K_{PAR} is the sum of the contributions of water and constituents produced by different biogeochemical processes and/or transported by rivers into the sea:

$$K_{PAR} = K_w + K_{PH} + K_{CDOM} + K_{SPM}, \quad (2)$$

where K_w is the contribution by water, K_{PH} by phytoplankton, K_{CDOM} by coloured dissolved organic substances and K_{SPM} by suspended matter (Kirk, 1994).

In most regional ecosystem models (e.g. (Eilola et al., 2009)), the implementation of radiative transfer started with simple approaches calculating K_{PAR} from known chlorophyll concentrations Chl:

$$K_{PAR} = k_w + k_c\, Chl, \quad (3)$$

where k_w is a constant background attenuation of PAR including effects of pure water and background concentrations of coloured dissolved organic and suspended matter and k_c is the chlorophyll-specific PAR

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attenuation. In his Baltic Sea box model, Savchuk (2002) used different k_w for each box mimicking local CDOM concentrations. A similar approach but using salinity as a proxy for CDOM was applied by Maar et al. (2011). Edman (2006) described and evaluated a light attenuation model for the Baltic Sea considering plankton and yellow substances (CDOM), and therefore, provides a highly mechanistic formulation. Yellow substances are parametrized by organic nitrogen riverine loads. Edman (2006) concluded that the more mechanistic model improves the simulated optical properties but also indicates a premature spring bloom. Stramska and Zuzewicz (2013) compared different optical models and their influence on the sea surface temperature.

The aim of this study is the improvement of the radiative transfer model in the ecosystem model ERGOM (Leibniz-Institute for Baltic Sea Research, 2015) for the Baltic Sea. The ERGOM Baltic Sea Ecosystem Model (Neumann, 2000) uses in Eq. (3) the numerical values $k_w = 0.18\ \mathrm{m}^{-1}$ and $k_c = 0.03\ \mathrm{m}^2(\mathrm{mmol\ N})^{-1}$, which corresponds to $0.02\ \mathrm{m}^2(\mathrm{mg\ Chl})^{-1}$ according to Fasham et al. (1990)) and considers the sum of phytoplankton and detritus.

The new optical model shall consider most of the optically active water constituents in the total attenuation coefficient, which are only partly calculated in ERGOM. Contributions of chlorophyll-containing particles (K_{Chl}) and detritus (K_{DET}) will be implemented separately.

The coloured dissolved organic matter (CDOM, yellow substance), which absorbs light in the water, can be produced in the water column during metabolism (K_{DON}) or transported by rivers into the Baltic (K_{CDOM}). The major portion of CDOM in the Baltic Sea comes from swamp and permafrost areas in the catchment area of the northern Baltic Sea and the Baltic states, and is discharged via rivers into the sea. The absorption of yellow substances is characterized by an exponential increase towards shorter wavelength and therefore has a strong influence on the blue spectral range, where chlorophyll has its absorption maximum (Siegel et al., 2005). Consequently, K_{PAR} consists of six main contributions:

$$K_{PAR} = K_w + K_{Chl} + K_{DET} + K_{DON} + K_{CDOM} + K_{SPM} \tag{4}$$

Actually, it is difficult to implement inorganic suspended solids K_{SPM}, but phytoplankton and detritus are dominating suspended matter in the open Baltic Sea. As the first attempt, we exclude the inorganic suspended matter.

The single contributions will be calculated using a material-specific coefficient and the concentration:

$$K_{PAR} = k_w + k_c\,Chl + k_{det}\,DET + k_{don}\,DON + K_{CDOM}(S), \tag{5}$$

where k_w $[m^{-1}]$ is the attenuation coefficient of water, k_c, k_{det}, and k_{don} $[(mg\ N)^{-1}m^2]$ are the nitrogen-specific attenuation coefficients of chlorophyllouse particles, detritus, and dissolved organic matter. Chl, DET, and DON $[mg\,N\,m^{-3}]$ are the concentrations of phytoplankton biomass, detritus, and dissolved organic matter due to metabolism and degradation processes. K_{CDOM} $[m^{-1}]$ is the attenuation coefficient of dissolved organic substance transported by rivers with fresh water into the estuary and S is salinity. Owing to a missing model component for CDOM, we parametrized CDOM concentration by salinity (see Section 2).

Furthermore, the model shall calculate the Secchi disk depth. Secchi disk depth is a simple measurable parameter describing the transparency of the water column. In recent years, this parameter became an across the Baltic Sea accepted water quality parameter implemented in the European Water Framework Directive.

2. Methods

2.1. Measurements of optical properties

Particularly for the implementation of CDOM and the Secchi disk depth, our own measurements were evaluated to verify the possibility of deriving relationships between absorption of CDOM and salinity as well as between the Secchi disk depth and K_{PAR} for the Baltic Sea and the transition area to the North Sea. This corresponds to an adaptation of the model to the conditions of the Baltic Sea. The area of investigation covers a wide range of optical water masses (Siegel et al., 2005). According to the optical classification of Jerlov (1976), the North Sea water represents Ocean Water Type III, the central Baltic Sea Coastal Water Type 1–3 and during phytoplankton blooms to Type 5, and water from river discharge and the northern Baltic Sea Types 5–9 or even higher (Siegel et al., 2005).

For the determination of spectral absorption of dissolved organic substances (CDOM, yellow substances) seawater was filtered under low vacuum through Whatman GF/F glass fibre filters (pore size approximately 0.7 μm). The filtered water was measured in a 10 cm cuvette using a dual-beam Perkin Elmer Lambda 2 or Lambda 35 instrument in the wavelength range between 300 and 750 nm with increments of 1 nm. Milli-Q water was the reference. Comparisons between utilisation of Whatman GF/F and membrane filters with a pore size of 0.2 μm did not deliver significant differences for the area of investigation. The spectral absorption coefficients $a_y(\lambda)$ were calculated according to (Kirk, 1994):

$$a_y(\lambda) = 2.3026\left(A(\lambda) - \frac{A(720nm)}{l}\right), \tag{6}$$

where $A(\lambda)$ is the spectrophotometer absorbance at wavelength λ, l is the optical path length (length of the cuvette), and $A(720nm)$ is the baseline correction. The absorbance $A(720nm)$ was selected because the influence of temperature and salinity is rather small. The spectral dependence of CDOM absorption is characterized by an exponential increase to shorter wavelength with a maximum in the UV spectral range and can be described according to Jerlov (1976), and Kirk (1994) by the following equation:

$$a_y(\lambda) = a_y(\lambda_0)\exp(-s(\lambda - \lambda_0)), \tag{7}$$

where $a_y(\lambda)$ is the absorption coefficient at the wavelength λ, λ_0 is the reference wavelength and s the spectral slope for the exponential dependence. The absorption coefficient at 440 nm is used for comparison between CDOM and salinity. Salinity was measured using a Sea Bird CTD. Measurements of CDOM absorption and salinity from the Bothnian Bay through the entire Baltic Sea, the Kattegat and Skagerrak to the entrance of the North Sea are compiled in Fig. 1(a).

The Secchi disk is a plain white circular disk (30 cm), which is mounted at a rope and slowly lowered in the water. The Secchi disk depth (SD) is reached when the disk disappears from the view of the observer, providing an indication about the transparency of the water and is related to water turbidity.

PAR was determined from measurements of vertical profiles of downward irradiance $Ed(z, \lambda)$ using a free-falling Satlantic Profiler SPMR (SeaWiFs Profiling Multi channel Radiometer) with 13 channels between 400 nm and 700 nm. The data were processed using the software Prosoft provided with the instrument. PAR was estimated using the following equation:

$$PAR(Z) = \int_{400nm}^{700nm} \frac{\lambda}{hc} E_d(z,\lambda)d\lambda, \tag{8}$$