Supplementary material

Description of models coupled to physical systems discussed in this paper.

HadOCC

The **Had**ley Centre **O**cean **C**arbon **C**ycle Model (HadOCC) is a NPZD class model, where NPZD stands for nutrient, phytoplankton, zooplankton and detritus. Dissolved inorganic carbon and alkalinity are included and hence a complete representation of the marine carbon cycle.[1] HadOCC uses nitrogen as basic currency, that is NPZD variables are modelled in terms of their nitrogen content. The main nutrient component is nitrate, yet ammonium is also calculated. Conversion between nitrogen and carbon is based on fixed Redfield ratios. The model uses a variable carbon to chlorophyll ratio.[2] Phytoplankton growth rates can optionally increase with temperature through the use of a Q_{10} parameter.[1,3] Furthermore, there is an option to use a multi-spectral light penetration model.[4] The full HadOCC model equations are given in [5].

ERSEM

The **E**uropean **R**egional **S**eas **E**cosystem **M**odel (ERSEM) is implemented in FOAM-ERSEM as described in [6], with a detailed description of the biogeochemical model given in.[7] The pelagic component of ERSEM models eight plankton functional types: four phytoplankton, three zooplankton and one bacterial. There is also a fully coupled benthic component. The base currency of ERSEM is carbon, but the cycling of nitrogen, silicon, phosphorus and oxygen is included, with variable stoichiometry between the carbon, nutrient and chlorophyll components of various model compartments. A coupled 3D sediment model [8] is used in the light attenuation calculations, along with contributions from seawater and various biological components. The version of ERSEM implemented with FOAM does not include a fully coupled carbon cycle, although other versions of ERSEM do include this.[9]

NORWECOM

The **NORW**egian **ECO**system **M**odel (NORWECOM)[10] was originally developed for the North Sea and has since been used in the Nordic Seas and Arctic.[11,12] The model includes three types of nutrients; nitrate, phosphate and silicate and two types of phytoplankton; diatoms and flagellates. Two size classes of zooplankton (micro- and mesozooplankton) components were added to the model during 2011. The model differentiates between biogenic silica, nitrogen and phosphorous detritus, but uses constant internal stoichiometric ratios in phytoplankton and zooplankton. In the model microzooplankton graze on flagellates, diatoms and detritus, while mesozooplankton preferentially graze on diatoms, and ingest detritus and prey on microzooplankton with equal preference. The grazing formulation used is from the ECOHAM4 model.[13,14,15] Excretion by zooplankton is added to the nitrate pool, while the fecal pellet production is added to the detritus pool. With grazers present, the background phytoplankton mortality was adjusted down to a low constant rate of 3.5% per day. Sinking is parameterized with a constant sinking speed for flagellates and detritus and as a function of silicate concentration for diatoms, so that when the silicate concentration is low, the diatoms will sink fast. This version of NORWCOM is coupled to HYCOM as described in[16] and run operationally for the Arctic region.

PISCES

The PISCES[17] (**P**elagic **I**nteraction **S**cheme for **C**arbon and **E**cosystem **S**tudies) model simulates biogeochemical cycles of oxygen, carbon and major nutrients controlling phytoplankton growth (nitrate, ammonium, phosphate, iron, silicic acid). The model has 24 state variables. The model distinguishes between two size classes of phytoplankton (diatoms and nanophytoplankton) and zooplankton (micro- and mesozooplankton). Phytoplankton growth depends on light, temperature and the external availability of nutrients. Prognostic variables of phytoplankton are total biomass in C, Fe, Si (for diatoms) and chlorophyll and hence the internal Fe/C, Chl/C, and Si/C ratios. For zooplankton, all these ratios are supposed constant and the total biomass in carbon is the only prognostic variable. The bacterial pool is not modelled explicitly. The PISCES standard version distinguishes three non-living organic carbon compartments: semi-labile dissolved organic carbon with timescales of several weeks to several years, two size classes of particulate organic carbon (small and big particles). While the C/N/P composition of dissolved and particulate matter is tied to Redfield stoichiometry, the iron, silicon and carbonate contents of the particles are computed prognostically. Next to the three organic detrital pools, carbonate and biogenic siliceous particles are modelled. The description of particle fluxes distinguishes two size classes: "small" with a constant sinking speed of 3m/d and "large" with a sinking speed increasing with depth. PISCES simulates dissolved inorganic carbon and total alkalinity (carbonate alkalinity + borate + water). The CO_2 chemistry is computed following the OCMIP protocols (http://www.ipsl.jussieu.fr/OCMIP). Cycles of phosphorus and nitrogen are decoupled by nitrogen fixation and denitrification. Boundary fluxes account for nutrient supply from three different sources: atmospheric dust deposition of Fe, Si and P, rivers for macronutrients, dissolved carbon, and alkalinity[18,19] and inputs of Fe from marine sediments.[20,21]

BFM

The biogeochemical component of OPATM-BFM is an adapted version of the **B**iogeochemical **F**lux **M**odel[22,23,24], an open-source code that builds on ERSEM[25] (European Regional Seas Ecosystem Model). The BFM model describes the biogeochemical cycles of carbon, nitrogen, phosphorus and silicon through dissolved and particulate inorganic compartments and biota. The latter is represented by 4 autotrophic (diatoms, flagellates, picophytoplankton and dinoflagellates) and 5 heterotrophic PFTs plus three non-living organic compartments. Every organic compartment is described by a flexible C:N:P:Si ratio, which depends also on the intracellular abundance of the macronutrients. The OPATM-BFM model is coupled to a carbon cycle model.[26] Nutrient uptake follows PFT-dependent modified Droop kinetics which allows for multi-nutrient limitation and variable internally-regulated nutrient ratios. Primary production is simulated by a modified version of.[27] It accounts for N and P co-limitation and relates phytoplankton growth rate, Chla:C, and N:C ratios to irradiance, temperature, as well as nitrogen and phosphate availability. The internal chlorophyll to carbon ratio is a prognostic variable. Carbon fixed during photosynthesis is rooted to the dissolved or particulate organic carbon pools according to the internal nutrient quota. Dissolved organic matter is represented by three compartments (labile, semi-labile and refractory) with flexible C:N:P.

Nutrient remineralization and DOC respiration by bacteria is controlled by the carbon to nutrient stoichiometry, which in turn also regulates the competition between bacteria and phytoplankton for dissolved inorganic nutrients. Beside bacteria, the heterotrophic PFTs include carnivorous and omnivorous mesozooplankton, heterotrophic nanoflagellates and microzooplankton. These heterotrophs provide a closure to primary producers and bacteria and control size-dependent predation of the autotrophic stocks.

GSBM

The **G**ulf of **S**t. Lawrence **B**iogeochemical **M**odel (GSBM) simulates biogeochemical cycles of oxygen, carbon and nitrogen, and the biological components that determine the dynamics of the planktonic ecosystem. The model has 10 state variables. The NPZD model is based on[28,29] and includes both simplified herbivorous and microbial food chains typical of bloom and post-bloom conditions. The export of biogenic matter at depth is mediated by the herbivorous food web (nitrate, large phytoplankton (diatoms), mesozooplankton, particulate organic matter), while the microbial food web (ammonium, small phytoplankton, microzooplankton, dissolved organic matter) is mainly responsible for nutrient recycling in the euphotic zone. Nitrate is also supplied by rivers. The tight coupling between small phytoplankton growth and microzooplankton grazing, autochtonous nitrogen release and DON remineralization to NH_4 is used to represent the dynamic of the microbial food chain. Biological transfer functions are derived from bulk formulations using mean parameters found in the literature. Biological variables are calculated in nitrogen units and algal biomass and production converted to Chl a and carbon units using fixed stoichiometric ratios. Detrital PON sinks toward the bottom at a constant rate. Sinking particles are gradually degraded into dissolved organic nitrogen via a fragmentation rate (0.1 d^{-1}) in the upper 100 m. Below 100 m, the fragmentation rate decreases following a quadratic function.[30] The phytoplankton growth rate is a function of light and nutrient availability.[28] The available light for phytoplankton growth is a function of sea-ice cover, Chl a and colored dissolved organic matter (CDOM).[29]

The impacts of biological processes on oxygen in the water column are integrated to the ecosystem model following[31] through constant Redfield stoichiometry. GSBM simulates dissolved inorganic carbon, total alkalinity, pH and calcium carbonate saturation.[32,33] The atmospheric pCO_2 time series used to force the model is based on a least squares fit to the 15 years (1978–1993) of *pCO2* observations in Cold Bay (Alaska). A linear regression of observed TA versus salinity is used to derive the model TA from the simulated salinity.

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