Modelling in the Baltic Sea

by the group at DMI (Danish Meteorological Institute), Denmark

Contents

Data Provider

DMI provides meteorological, oceanographic and related services for the community within the large geographical area of the Kingdom of Denmark (Denmark, the Faroe Islands and Greenland), including surrounding waters and airspace. The modelling group is led by Dr Jun She.

Regional summary

The Baltic is a semi-enclosed, brackish water sea. The Danish Straits connect the Baltic with the North Sea. The Baltic area size is ca. 410,000 square kilometers and the average depth is ca. 55 meters. The salinity varies from the average salinity in the North Sea to 2-3 PSU in the northern Bothnian Bay.

Hydrodynamic and biological characteristics

The annual freshwater supply to the basins was estimated ca. 2400 km3, and the annual water exchange between the Baltic and the North Sea was ca. 1800 km3. The average residence time for the water is about 30 years. The Baltic proper is strongly stratified by salinity. The halocline with a varying depth 50-70 m separates the upper layer of brackish water and the lower layer of salty water. The upper layer of water is subject to seasonal dynamics of atmospheric forcings and river loadings. The lower layer of water is much less turbulent, which is only subject to the intrusion events which are related to the North Atlantic Oscillation. The lower water in the Baltic proper is predominantly in redox conditions.

The Baltic has been suffering eutrophication since 1950s. The eutrophication started to deteriorate in 1980s and started to be relieved recently due to the implementation of the nutrient reduction policy. The persistent eutrophication for decades led to serious oxygen depletion, which caused the release of the inner phosphorus in the sediments. The surplus of phosphorus relative to nitrogen needs during spring blooms stimulate the nitrogen fixation. The primary production community is dominated by three functional groups: diatoms, flagellates and cyanobacteria. Diatoms have a maximum growth rate independent of temperature. Flagellates have a competitive threshold of nutrients uptake. Cyanonacteria has featured with the capability to utilize atmospheric nitrogen for photosynthesis, thus they are an extra nitrogen source to the Baltic ecosystem.

Justification of model selection

The circulation model selected for implementing in this project is HBM (Berg and Poulsen, 2012) and the biogeochemical model is ERGOM (Neumann, 2000). Both of them were selected as the operational models by the members of the Baltic Framework of MyOcean project. HBM has a well-documented development history and features a two-way nesting technique, the OpenMP and MPI hybrid parallel programming, the compressed-dry-points state variables which save on restoration resources substantially. ERGOM also has a long development history. The I application of ERGOM coupling to HBM is also well documented (Maar et al., 2011; Wan et al., 2011; Wan et al., 2012)

Hydrodynamic model

The hydrodynamic model used here is the Danish Meteorological Institute (DMI) operational model HBM (Berg and Poulsen, 2012). The core of the physical model – the circulation model – is based on the primitive geophysical fluid dynamics equations for the conservations of volume, momentum, salinity and heat. The operational products are open-accessible http://ocean.dmi.dk/anim/index.uk.php .

The model grid ranges from 48°33’N to 65°51’N and from 4°05’W to 30°15’E with a horizontal resolution of 6’ along latitude and 10’ along longitude, while a nested fine grid with one sixth of the coarse resolution covers the Danish Strait, in order to resolve the water exchange through the narrow sills between the North Sea and the Baltic Sea. The coarse grid has 50 vertical layers, with thicknesses of 8m (surface layer, to avoid drying at low tides), 2m (36 subsurface layers) and 4m (1), 8m (2), 25m (2) and 50m (8) increased gradually. The fine grid has 52 vertical layers, with thicknesses of 2m (surface), 1m (36) and 2m (all rest). The model domain includes both the Baltic Sea and the North Sea, in order to supply a sufficient transition to counteract the impacts from open boundaries.

Lower Trophic level model

The original ecosystem model ERGOM has 9 state variables, including the dissolved inorganic nutrients: ammonium, nitrate (DIN) and phosphate (DIP); three primary production functional groups: diatoms, flagellates and cyanobacteria; a bulk zooplankton community; a detritus pool; and the dissolved oxygen (DO). The model is a full mathematical description of the dynamics of 9 state variables and the related biogeochemical processes: photosynthesis, nutrient uptake, growth, grazing, digestion, respiration, excretion, mortality, mineralization, nitrogen fixation, nitrification, denitrification. This model is nitrogen-based, and phosphorus is coupled to nitrogen via the Redfield ratio. Hydrogen sulfate is included in the model as negative oxygen concentration. The model is featured with quadratic half-saturation expressions, like those for nutrient limitation to phytoplankton uptake, oxygen limitation to nitrification, and temperature dependence to flagellate growth and to detritus mineralization. Diatom growth independent of temperature is a further featore of the model. A detailed model description and a list of biogeochemical parameterization coefficients can be found in Neumann (2000) and Neumann et al. (2002). The development to ERGOM is highlighted below. The operational products are open-accessible http://ocean.dmi.dk/marine_ecology/index.baltic.uk.php .

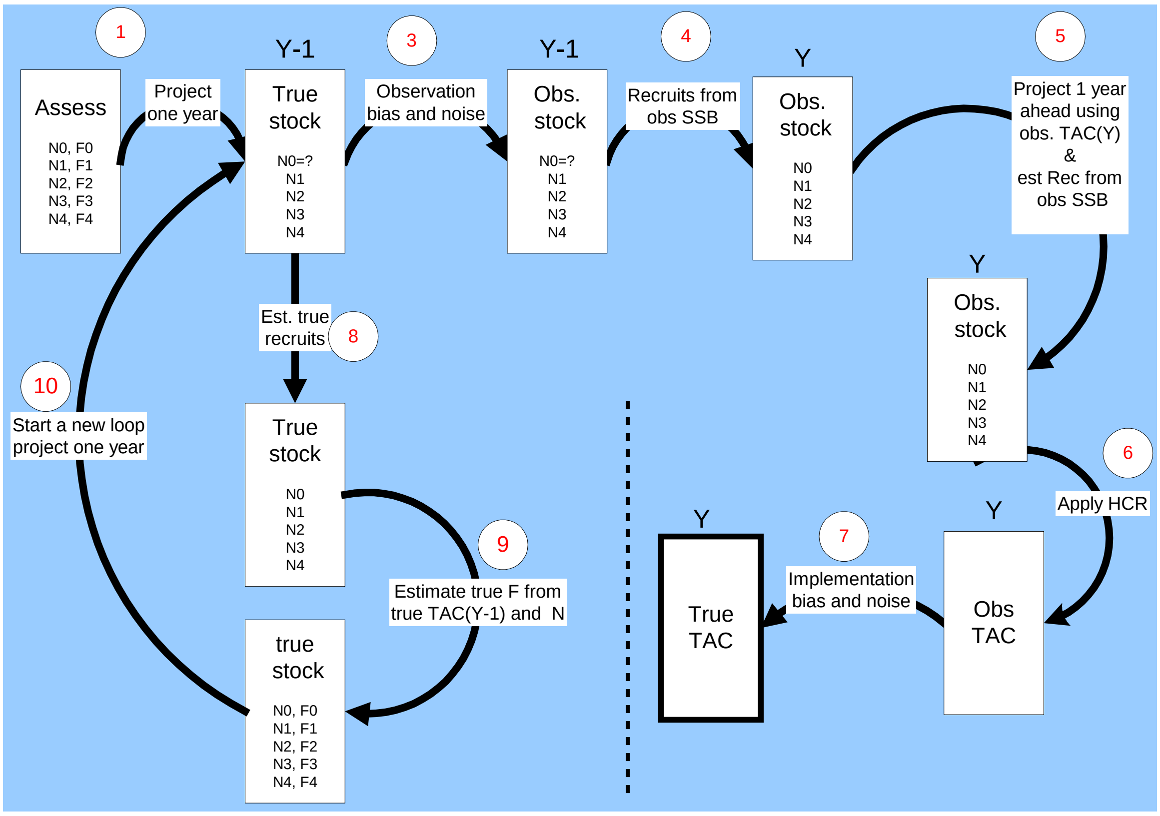
Higher trophic level models

The SMS model is a stochastic multispecies model describing stock dynamics of interacting stocks linked together by predation. It operates on annual or seasonal time steps. The model consists of sub-models of survival, fishing mortality, predation mortality, survey catchability and stock-recruitment. SMS uses maximum likelihood to estimate parameters and the total likelihood function consists of four terms related to observations of international catch at age, survey catch per unit effort (cpue), stomach contents observation, and a stock-recruitment (penalty) function. Uncertainties of parameters and biological key parameters (biomass and average fishing mortality) are estimated from the inverse Hessian matrix, or alternatively using the Marco Chain Monte Carlo (MCMC) methodology (*e.g.* Gilks *et al*., 1996)

The model developed is a mixture of age and size structured models. The catch model has been chosen to be age-structured while the food preference model is size based because preference depends on size rather than age. This also applies to the fishery mortality model as well, but catch data by size classes are not available for the North Sea. The mixed age-size structure implies that data by age groups are transformed to sizes using age-length keys.

SMS can be used as assessment model, where parameters and the historical stock dynamic are estimated. As forecast model, SMS uses the parameter estimates and terminal stock sizes to forecast stock dynamic in short or long term, given harvest control rules for the individual stocks.

Full model description available from http://marine-opec.eu/downloads/OPEC_D2.4.pdf



Overview of the SMS method for management plan evaluation. Numbers in circles refer to the text below.

Step 1:

Make an assessment with terminal year Y-2 to estimate "true" stock numbers

Step 2:

Project the true stock forward one year using F (fishing mortality) and M (mortality) for year Y-2. This will produce the true stock for year Y-1.

Step 3

Step 3 simulates the assessment done. The "observed" or perceived stock which makes the basis for the TAC is made on the basis of the true stock and an observation noise and bias:

$$N(a)_{obs} = N(a)_{true} * Bias * e^{(std*NORM(0,1))} * e^{(-(std^2/2))}$$

The bias factor (default=1) and the standard deviation (std) are given as input. The same random number drawn from NORM(0,1) are used for all ages, giving a correlation of one between the observed stock numbers. Alternatively random number drawn from NORM(0,1) can be drawn for each age, producing uncorrelated noise.

Step 4

Recruitment for the observed stock is estimated as a point estimate from the specified stock recruitment relation. The result is observed stock numbers for all ages.

Step 5

The observed N (numbers) at age is projected one year ahead using the observed TAC value for the year. This TAC is given as input for the first two years of simulations or calculated from a previous iteration in step 7. The observed recruitment in the TAC year (Y) is estimated as a point estimate from the stock recruitment relation. Step 5 results in observed stock numbers in the start of the TAC year, such that observed SSB in year Y can be calculated on the basis of the HCR.

Step 6

Apply the HCR (harvest control rule) to estimate the observed TAC(Y)

Step 7

Step 7 estimates the true TAC(Y) by adding implementation noise and bias to the observed TAC(Y). in a similar way as done for N in step 3.

Step 8

Step 8 estimates recruits for the true stock (N(Y-1)) using the stock recruitment relation and the noise function.

Recruitment (referred to as N0 in the figure) is estimated from a specified stock recruitment relationship (f(x)) and a log normal distributed noise term with standard deviation, std.

$$R_{obs} = f(x) * e^{(std * NORM(0,1))} * e^{(-(std^2/2))}$$

Step 9

Step 9 projects the true stock one year ahead by using the true stock (N(Y-1)), true TAC(Y-1), exploitation pattern and mean weight at age in the catch W(a).

Step 10

The result of step 10 is the true stock number, which goes into a new simulation loop.

Coupling of physical and lower trophic levels to higher trophic levels

Whereas the HBM/ERGOM models are completely integrated within the same code framework, the SMS model address different spatio-temporal scales, has a very different mathematical foundation and is implemented in another programming language, therefore the coupling between HBM/ERGOM and SMS is far from trivial, both on a conceptual and implementation level.

The *direct* bottom-up control, represented by HBM/ERGOM, occurs via different mechanisms at different life stages of a fish. Here we refer to the pathways of bottom-up control as link processes. For early life stages, the link processes are hatching success, pelagic transport and growth; for adult life stages the link processes are fecundity and growth. Previously bottom-up control was ignored in the SMS model, and the reproduction of the cod and sprat stocks for forecast runs was estimated assuming a relationship between spawning stock biomass and recruitment at age 0. This relationship is a stochastic distribution (with spawning stock biomass as parameter) with a relative large variance that expresses variance in unaccounted link processes. The next logical step is to parameterize link processes in relation to key indices describing critical spatio-temporal variability in physics and biogeochemistry. Coupling must generally be based on indices since spatial and temporal scales addressed by fish population models are much longer than scales represented by HBM/ERGOM; examples of these indices are regional averaged seasonal temperature and perceived habitat volumes. This was initially pursued in MEECE (EU FP7 Project) and the work consolidated in OPEC; two examples of data and inferred statistical relations are given below for sprat (Figure 2) and cod (Figure 3). Figure 2 show the sprat recruitment model, based on previous ECOSMO data is shown together with the parameter estimates in figure 2. Temperature was highly significant. The model fit for cod recruitment is shown in figure 3. The cod reproductive volume has no significant effect in the model; however, including reproductive volume enables to mimic decreasing recruitment at very high spawning stock biomass, when environmental conditions are bad. Therefore, the model was chosen for the SMS time slice predictions. The effect of cod reproductive volume can certainly be investigated further to improve the fit to observed data of recruitment, but for this purpose the coupling appeared sufficient.

Data Assimilation

The purpose of data assimilation is to seek the best model estimate given a dynamical model and measurements. To demonstrate the usage of satellite chlorophyl data in improving the ecosystem prediction, an Ensemble Optimal Interpolation (EnOI) will be used for the Baltic Sea. The EnOI is a simplified version of the EnKF by only integrating one model in time. It maintains the mult-variate property of the EnKF while the computational cost is reduced to 1/N of the EnKF if N is the ensemble size. The ensemble-based background covariance reveals anisotropic features corresponding well with local velocity fields. This is especially useful for the assimilations in coastal zones (Fu et al, 2011). For the higher trophic levels, the SMS model in hindcast mode performs full data assimilation by maximum likelihood estimation, as described above.

Forcing and Boundary Conditions

The wind, air pressure, air temperature, humidity, evaporation - precipitation and cloud cover are taken into account in the parameterization of surface boundary conditions. The tides and the monthly climatologically fields of temperature and salinity are imposed as the outer lateral conditions, and the river runoffs as the inner lateral condition. The reflection and absorption of shortwave radiation by the seabed in shallow zones is another model feature describing the thermodynamic bottom boundary.

The model is forced by hourly meteorological forcing (10 m winds, 2 m air temperature, mean sea level pressure, surface humidity and cloud cover) based on DMI's version of the operational weather model HIRLAM (High Resolution Limited Area Model). The weather model has a horizontal resolution of about 15 km. River runoff is set with the daily averaged data derived from river measurements for 5 German rivers, operational outputs for 43 Baltic catchments by a hydrological model HBV run in Swedish Meteorological Hydrological Institute (SMHI) (Bergström, 1976 and 1992) and climatology for the remaining rivers. Atmospheric nutrient deposition values are set based on Langner et al. (2009) and Eilola et al. (2009).

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