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Abstract

The overall objective of the project is to develop, test and demonstrate a pilot system for monitoring and prediction of the Norwegian marine coastal environment. Particular focus is on dominant physical and coupled physicalbiogeochemical interactive processes within the Norwegian Coastal Current and along its open boundaries. The tools to understand and model the Norwegian coastal zones including the Norwegian Coastal Current have gradually improved through advances in numerical simulation and high performance computing. Despite these developments there are still major deficiencies in our ability to understand and describe the variability of the Norwegian Coastal Current and its influence on the marine environment and ecology. It is therefore a need to fully integrate and validate an adequate set of numerical ocean models.

The three participants in the MONCOZE project each have their own numerical ocean model system which is well known within each institution. The Norwegian Meteorological Institute uses MI-POM, the Nansen Environmental and Remote Sensing Center uses their version of HYCOM and the Institute of Marine Research runs NORWECOM. In this report an overview of the three model systems is given. Technical details concerning model characteristics and coupled model systems are presented together with model products.

Keywords

Physical Oceanography, Numerical Modeling, Mesoscale

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1. Introduction

The primary objective of the project MOnitoring the Norwegian COstal Zone Environment (MONCOZE) is to develop, test and demonstrate a pilot system for the prediction of Norwegian marine coastal environment. The pilot system, named POMS (Pilot Ocean Monitoring System), focuses on the dominant physical, chemical and biological processes and their interactions within the Norwegian Coastal Current from its birth in the Skagerrak and north to 62^oN (cf. the web site: http://moncoze.met.no/most_recent.html).

A modern ocean monitoring system consists of three main components. These are:

- high accuracy in-situ, sub-surface observations,
- satellite observations for wide area quantitative information of the sea surface state and
- numerical prediction models.

Since observations are sparse both in space and time, models are the only tool available to provide a three-dimensional (3D) picture of the oceanic state. In addition by employing modern assimilation techniques, numerical ocean models effectively increase the value of satellite and field observations, and provide easily available and useful products to the end-user. In hindcast mode numerical models provide information on transport of pollutants and contaminant exposure time, while in forecast mode the models provide predictions for the development of the ocean state. The predictive capabilities are of great value in connection with toxic algae blooms, acute pollution episodes e.g. oil spills, warnings of extreme and potentially harmful events in water properties (e.g. cold water outbreaks impacting aquaculture) and extreme current conditions that may be hazardous to shipping.

Three models are available to the project, namely the two terrain following coordinate ocean models MI-POM and NORWECOM, and the hybrid coordinate ocean model HYCOM. A short overview is given of the three models. While MI-POM is run by the modeling group at the Norwegian Meteorological Institute (met.no), HYCOM is run by the Nansen Environmental and Remote Sensing Center (NERSC), and NORWECOM by the Institute of Marine Research (IMR). As is well known a numerical ocean model is forced not only by fluxes of momentum, heat and freshwater (precipitation) from the atmosphere at the ocean surface, but also by lateral conditions (rivers, and flow across open ocean boundaries or estuaries). Thus following this introductory section is a section describing the requirements and importances of the various forcing data used in MONCOZE.

2. Forcing data in MONCOZE

The numerical ocean model is at the core of any modern ocean prediction system, and performs the integration in time of the mathematical equations developed based on conservation principles of momentum, energy and mass and includes mathematical formulations of the governing physical, chemical and biological processes. These equations are partial differential equations that in their discretized forms are solved as an initial value problem. The solution to these equations is determined not only by the internal processes, but also by the specified boundary conditions. Thus high quality boundary conditions are of vital importance to obtain good solutions, i.e., predictions of the evolution in space and time of the physical and biochemical ocean state. The boundary conditions are also sometimes referred to as the forcing data for the models.

At the sea surface, the ocean is subject to meteorological forcing, and to obtain realistic solutions high quality meteorological forcing are necessary. River runoff and loads of chemical substances are also considered as important driving forces for ocean prediction models. This is particularly true for coastal ocean models where the freshwater input discharged by rivers supplies buoyancy to the ocean that affects the stratification and thereby the frontogenesis and cyclogenesis which in turn is of crucial importance for the transport and dispersion of dissolved tracers and particular matter *Røed and Fossum* (2004).

In limited area models there are in addition a boundary at lateral boundaries where the integration area has an interface bordering on the open ocean where water may freely be advected in and out of the area of interest *Røed and Cooper* (1987). Such boundaries are not natural and should be avoided if possible. However, to make it numerical feasible to do high resolution studies of an ocean area of special interest, that is, to be able to resolve the frontogenesis and cyclogenesis, the finite capacity of todays computers still limits the geographical area that can be covered to localized areas of the world oceans.

Finally it should be mentioned that satellite data and *in-situ* data that are assimilated and gently forces the model to be in line with the observed ocean state, also constitutes a forcing.

2.1. Meteorological forcing

In the real world the ocean and atmosphere are two spheres that interacts. Ideally an ocean model should therefore be coupled to an atmosphere model to make the fluxes from the atmosphere toward the ocean change in response to changes in the ocean surface properties. However, since the time scales of the atmospheric and oceanic processes are vastly different, and also for practical reasons, the atmospheric fluxes are treated as being independent of the evolving ocean state. Thus the needed atmospheric values are simply specified in time (or extracted from a numerical weather prediction model), and then used to compute the energy fluxes, e.g., momentum, heat and freshwater fluxes, needed to drive the ocean model of the numerical ocean weather prediction system.

The momentum flux is computed via the (wind) stress or traction at the ocean surface and via the (horizontal) gradients in the mean sea level pressure (MSLP). This wind stress (or vertical momentum flux) at the ocean surface directly gives rise to a time rate of change in the ocean currents via the vertical mixing term in the momentum equation. Likewise the MSLP gives rise to a time rate of change in the currents through its horizontal gradient. In addition the wind is also used to compute turbulent energy. As is common the three ocean models in MONCOZE require the wind velocities at a standard height above the surface (10m) (Figure 1) to compute the wind stress.

Both the long wave radiative exchange and the incoming short wave radiation are important factors in the ocean's heat budget. A fraction, S_w^r, of the downward short wave radiative flux, S_w^i, is reflected back into the atmosphere, and depends on the ocean surface roughness and albedo (ice/no ice). Moreover, the sun height and the distribution of direct and diffuse radiation affect the fraction reflected at the ocean surface. The data needed are not standard output from atmospheric models, so most ocean models are equipped with radiation and heat flux models. This also ensures that the heat fluxes are consistent. Most models calculate the radiative fluxes based on cloud cover data, commonly the cloud fraction CC, the 2m temperature, T_2, and the humidity in terms of the dew point temperature, T_{D2}, 2m above the ocean surface, supplied by a numerical weather prediction model or by a model (re)analysis (e.g., *Røed and Debernard* (2004)). The same is true for the other thermodynamic exchanges across the ocean surface. Furthermore, calculations of the sensible, F_s, and latent, F_l, heat fluxes are based on wind speed, differences between sea and air temperatures, and humidity (Figure 1). The contribution in the heat budget from the long wave radiation is divided into two parts, incoming L_w^i and outgoing L_w^o radiation. The incoming long wave radiation is often parameterized using CC and T_2 from the atmosphere model, while the outgoing long wave radiation is derived from the sea surface temperature T_{surf}. As a result, the net heat flux $F_{surf}^T = F_{net}^T$ is used in the ocean model as the surface boundary condition for heat flux, that is, as the sea surface boundary condition in the thermal energy equation.

Precipitation, P, and evaporation, E, influence the salinity in the upper layers. Evaporation may be calculated from air and sea surface temperature and humidity, or may be directly supplied by the meteorological model. On the other hand, precipitation is always supplied directly by the meteorological model, and a sea surface salinity flux, F_{surf}^S), is then derived from these two components (Figure 1).

2.2. Nesting and open boundary conditions

Limited area ocean models are commonly connected to the ocean circulation outside of the model domain through lateral open boundaries. At these boundaries the values of the variables must be provided to the limited area ocean models. Commonly this is made through the application of open boundary conditions *Røed and Cooper* (1987); *Martinsen and Engedahl* (1987). The values used are either seasonally varying climatological values or, preferably, input from a (geographically) larger scale model. To provide information on a fine enough grid it is not uncommon to employ nesting of the fine mesh model into a coarser grid model covering a larger geographic domain. Thus the coarse mesh model provides the values of the variables at the open boundaries of the finest mesh. The coarser mesh model may in turn be nested into en even coarser grid model covering an even larger domain, and so on. In MONCOZE a triply nested system is used in which the basin wide model is the HYCOM version used in the TOPAZ system (Figure 2 upper panel), see http://topaz.nersc.no for further details. Only HYCOM is used for this task, and it provides sea surface elevation, and horizontal currents and hydrography (temperature and salinity) at selected depths at the lateral boundaries of the three regional MONCOZE models. The regional models employs 20km (MI-POM and NORWECOM) and 7km mesh sizes (HYCOM), respectively. Furthermore, even finer mesh model versions of 4 km grid size is nested into the regional models. An example of the latter is shown in the lower panel of Figure 2 outlining the regional and fine mesh domains of MI-POM.

Various open boundary conditions are applied. The condition used in MI-POM and NOR-

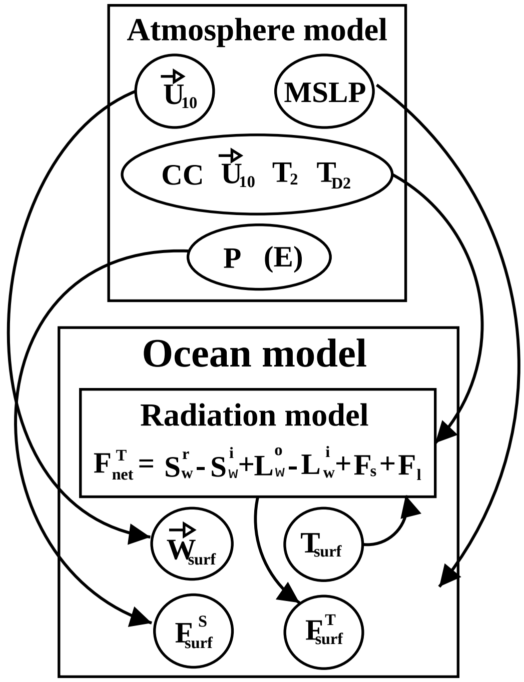

Figure 1: Schematic figure showing how data from atmosphere models often are used in ocean models. The wind stress, $\mathbf{W}_{surf}$, at the ocean surface is calculated using 10m winds, $\mathbf{U}_{10}$, from the atmosphere model. The radiation model, which calculates the ocean surface heat flux, F^T_{net}, is often included in the ocean model. Here S^r_w, S^i_w respectively denotes the reflected and incoming (downward) shortwave solar radiation, L^o_w, L^i_w respectively the outgoing and incoming long-wave radiation, and F_s, F_l respectively the sensible and latent heat fluxes. Precipitation (P) and evaporation (E) rates can be used to determine the sea surface salinity flux F^S_{surf}. T_{surf} is the sea surface temperature and is used in the radiation model to compute the fluxes together with the cloud fraction, CC, the 2m atmospheric temperature, T_2, and the atmospheric 2m dew point temperature, T_{D2}. F^T_{surf} is the net heat flux supplied to the ocean model and is equal to F^T_{net}.

WECOM is the Flow Relaxation Scheme of *Martinsen and Engedahl* (1987), while HYCOM uses an open boundary condition developed at NERSC (Section 3.2.4).

2.3. River data

In coastal regions, the distribution of salinity and nutrients are strongly influenced by the fresh-water and nutrient loads supplied by the river runoff. Technically, the freshwater may be supplied as a source or as a boundary inflow of freshwater. The freshwater supplies may be based on a hydrological model or observed transport, and nutrient concentration. In the MONCOZE hindcast studies observed river fluxes and nutrient concentrations from the rivers entering the North Sea will be used. Figure 3 shows the most important sources of freshwater within the MONCOZE area, while at the same time showing the fine mesh area (4 km grid size) of HYCOM.

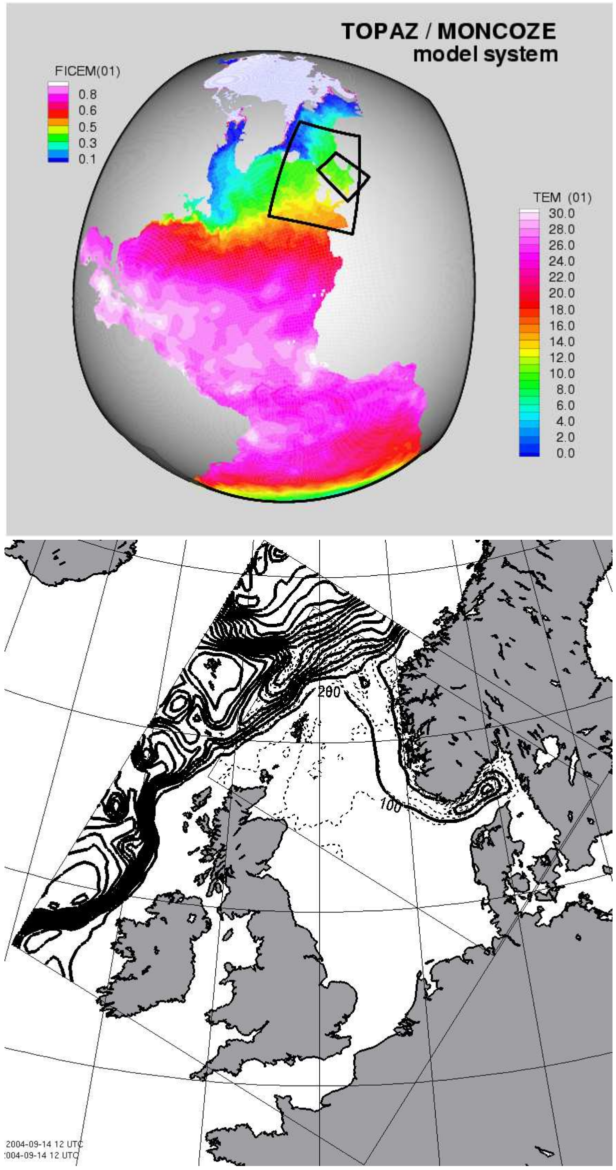

Figure 2: Examples of the triply nested model systems employed in MONCOZE. Upper panel shows the Atlantic basin wide coarse mesh model domain (colors indicate sea surface temperature), with the outline of the regional and fine mesh version of HYCOM (7 km and 4 km mesh sizes, respectively) inset (see also Figure 8). The coarse mesh version of HYCOM provides the lateral boundary values to be used at the open boundaries of the regional domains of all of the three MONCOZE models. Lower panel shows the regional and fine mesh domains of MI-POM. Solid heavy black lines outlines the topography contours of the regional domain with 200 m contour interval. The dotted finer line shows the bottom topography with contour interval 100 m.

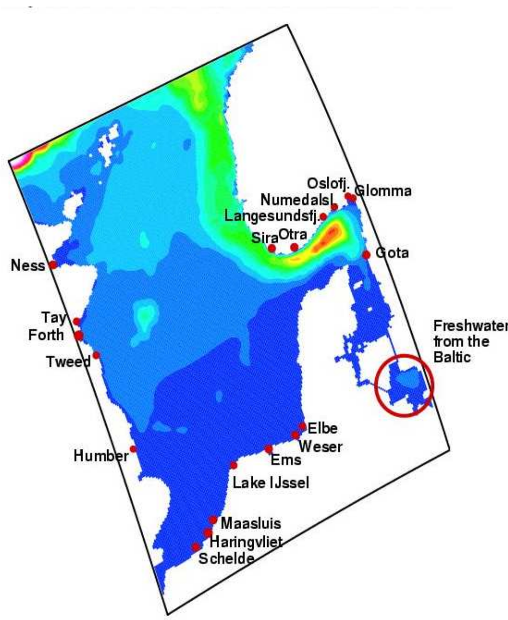

Figure 3: The key sources of freshwater river outflow in Skagerrak and the North Sea (the colors show bottom topography). The outflow from the Baltic Sea is often represented as a flux of brackish water with salinities between 8 and 18 psu.

3. Models

Only a short description of each of the three models is given. For details the reader is referred to the references given. All models are earlier used in research projects and to deliver products to industry and authorities. A selection of previously employed model domains along with some model products are also presented. More specific features and some remarks about the advantages and disadvantages of the models are given in Appendices A-D.

3.1. MI-POM

MI-POM is a fully barotropic/baroclinic, three-dimensional hydrodynamic, primitive equation, ocean model. Its prognostic variables are the sea surface elevation, the two horizontal current components, salinity and temperature, while the vertical velocity component, pressure, and density are computed diagnostically. The governing equations are conservation equations for mass (continuity), momentum and thermal energy together with a conservation equation for salinity and an equation of state.

MI-POM is met.no's version of the widely used Princeton Ocean Model (POM) developed at the Princeton University in the late 1970's *Blumberg and Mellor* (1987). It was implemented at met.no in the late 1980's and early 1990's, and has since 1993 been met.no's principle model for forecasting of water level (tides and storm surges), currents, and hydrography in Norwegian waters. Throughout the years the original code implemented at met.no has undergone numerous upgradings, improvements, and changes and thus is given its own name, namely MI-POM, which is short for Meteorological Institutes version of POM. Besides being met.no's chief model for research studies and assignments for authorities and oil companies engaged in offshore activity in Norwegian waters, e.g., *Hackett and Engedahl* (2000), MI-POM has also recently been employed in climate studies *Debernard et al.* (2002). A detailed description of an earlier version is found in *Engedahl* (1995), while a description of recent upgrades and improvements is found in *Engedahl et al.* (2001), and to some extent also in *Røed and Fossum* (2004).

The model has a free surface, and a time splitting procedure is used, in which the two-dimensional part of the dynamics (sea surface elevation and depth integrated currents) is calculated separately with a short time step, while the three-dimensional part containing the vertical distribution of currents, salinity and temperature, is computed with a much longer time step (usually 30-80 times longer).

Some other major features in MI-POM are:

- advanced computation of turbulent mixing by applying a 2.5-order turbulent closure - sub-model
- terrain following vertical coordinate (sigma-coordinate)
- orthogonal curvilinear staggered horizontal grid (Arakawa C)
- implicit scheme for time integration which allows for high vertical resolution

(see also *Engedahl* (2001).

3.1.1. Numerical and technical advances of MI-POM

The model code is modified to be able to run on massively parallel platforms. Also the Flow Relaxation Scheme (FRS) as the lateral open boundary condition *Martinsen and Engedahl* (1987); *Engedahl* (1995a) for all dynamic variables is implemented. To better conserve properties when advected the leapfrog advection scheme an may optionally be replaced by the Multidimensional Positive Definite Advection Transport Algorithm (MPDATA) *Smolarkiewicz* (1983) for salinity and temperature. In the same vein also an isoneutral diffusion scheme (Redi diffusion) and an eddy-induced tracer transport scheme (Gent-McWilliams scheme) can also be used to better conserve water masses (i.e. salinity and temperature) in climate change simulations (*Griffies* (2004); *Røed* (2001)).

Other modifications include:

- Implementation of more efficient computation of the vertical diffusion of the turbulent kinetic energy in the turbulence closure sub-model.
- Modification of the turbulent kinetic energy dissipation in the turbulence closure sub-model. This is provided by introducing a cut-off for the dissipation for a "critical" Richardson number in the case of stable stratification.

- A new version of the calculation of the bottom stress for 2-D simulations.
- Introduction of tidal forcing at the open boundaries.
- Introduction of fresh and brackish run-off from rivers and/or estuaries.

Important technical advances are:

- Adaptation to operational forecasting: all time variables are initiated according to the time for which the atmospheric forcing (mean sea level pressure and surface winds for MI-POM) is valid.
- Relaxation (optional) of the thermodynamic properties, i.e., salinity and temperature, both in deep layers and at the surface.
- One way nested simulations (by means of FRS) in which results from a coarse mesh run are used as boundary values for a fine mesh simulation.
- Implementation of a hot start (restart) procedure.
- General routines for interpolation between different types of curvilinear horizontal grids.
- Simple routines for assimilation of sea surface elevation, surface currents, sea surface temperature and sea ice concentration.
- Modification (optional) of the date-time counting variables in order to fit climate change simulations, e.g. 30 days climatological months.

The model system is fully portable, i.e., no geographical information, such as grid orientation, size and location of computational domain, is hard-coded in the model. All such information is given as input data together with the chosen model domain and topography.

3.1.2. Coupling to bio-geochemical modules

As part of a collaboration with the Institute of Marine Research, a coupled model system, in which a bio-geochemical module is invoked in the ocean model, is run operationally. The bio-geochemical module is identical to that implemented in NORWECOM (Section 3.3.2). This model system provides 168 hours forecasts of eutrofication and algae bloom in the North Sea and Skagerrak/Kattegat areas. These forecasts may be viewed on the web site http://moncoze.met.no.

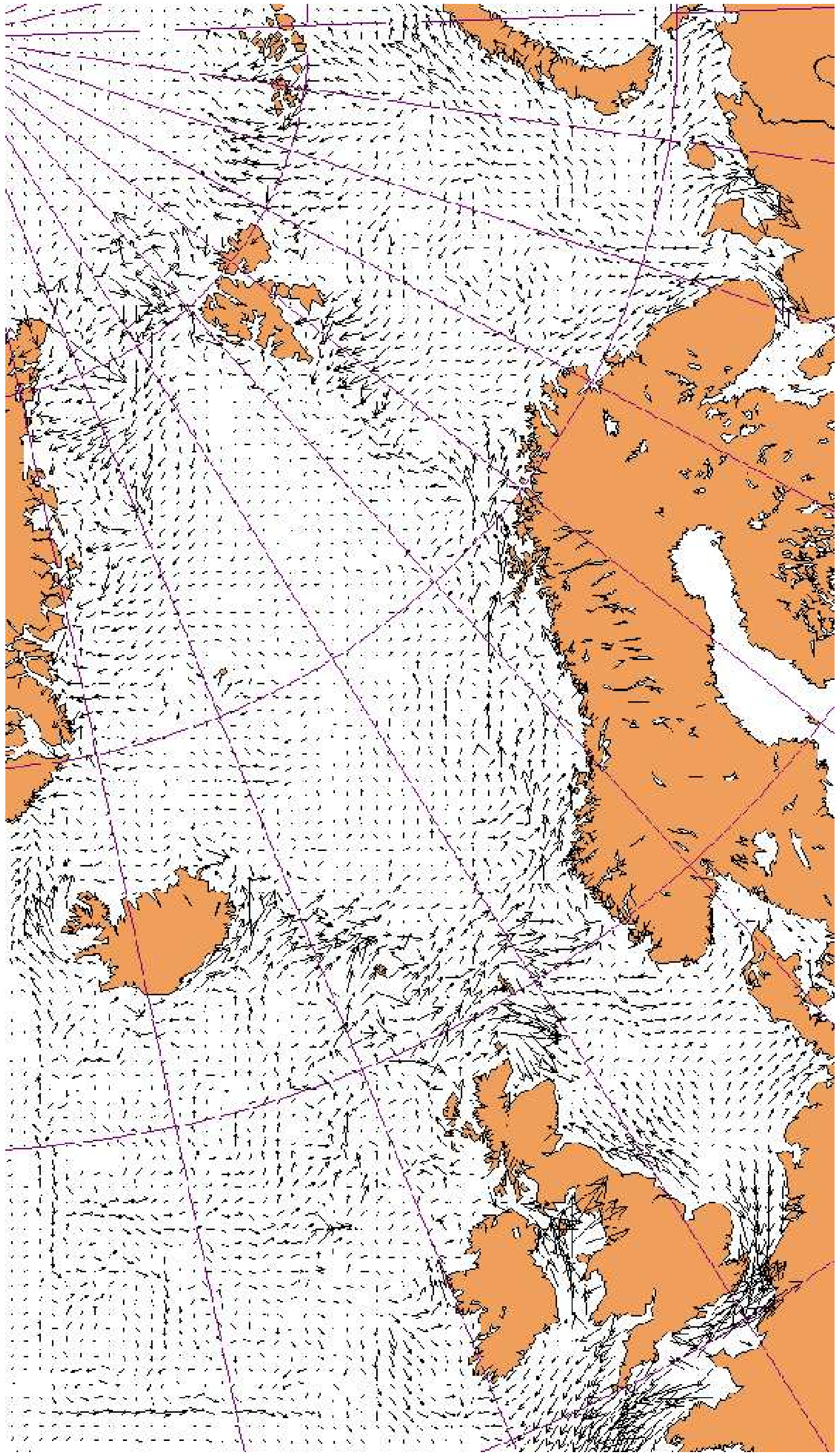

Figure 4: The operational MI-POM 20 km resolution domain. Instantaneous currents (every 2nd arrow or 40 km) at 10m depth are shown.

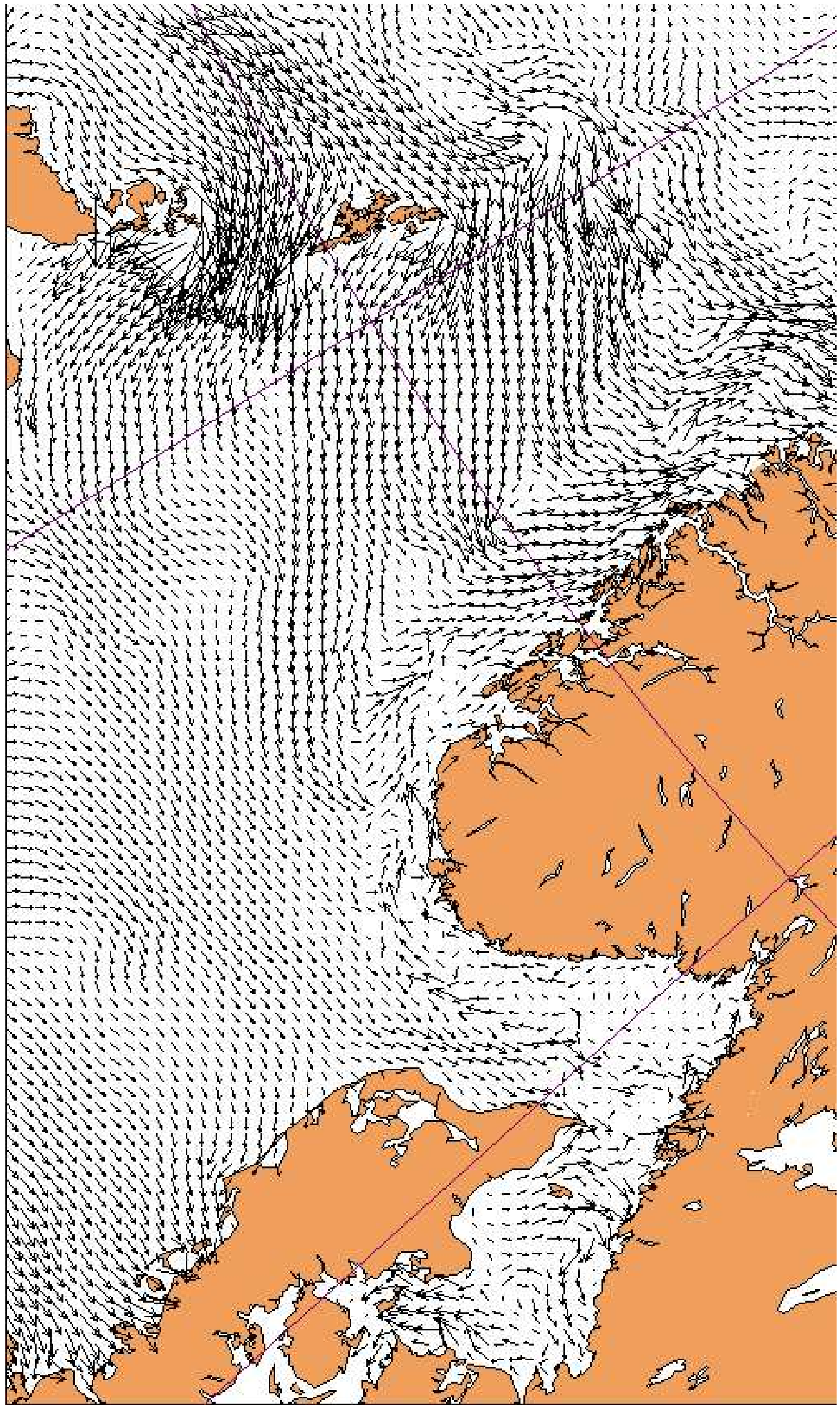

Figure 5: The operational MI-POM 4 km resolution nested area covering Skagerrak and the northern North Sea. Instantaneous currents (every 3rd arrow or 12 km) at 10m depth are shown.

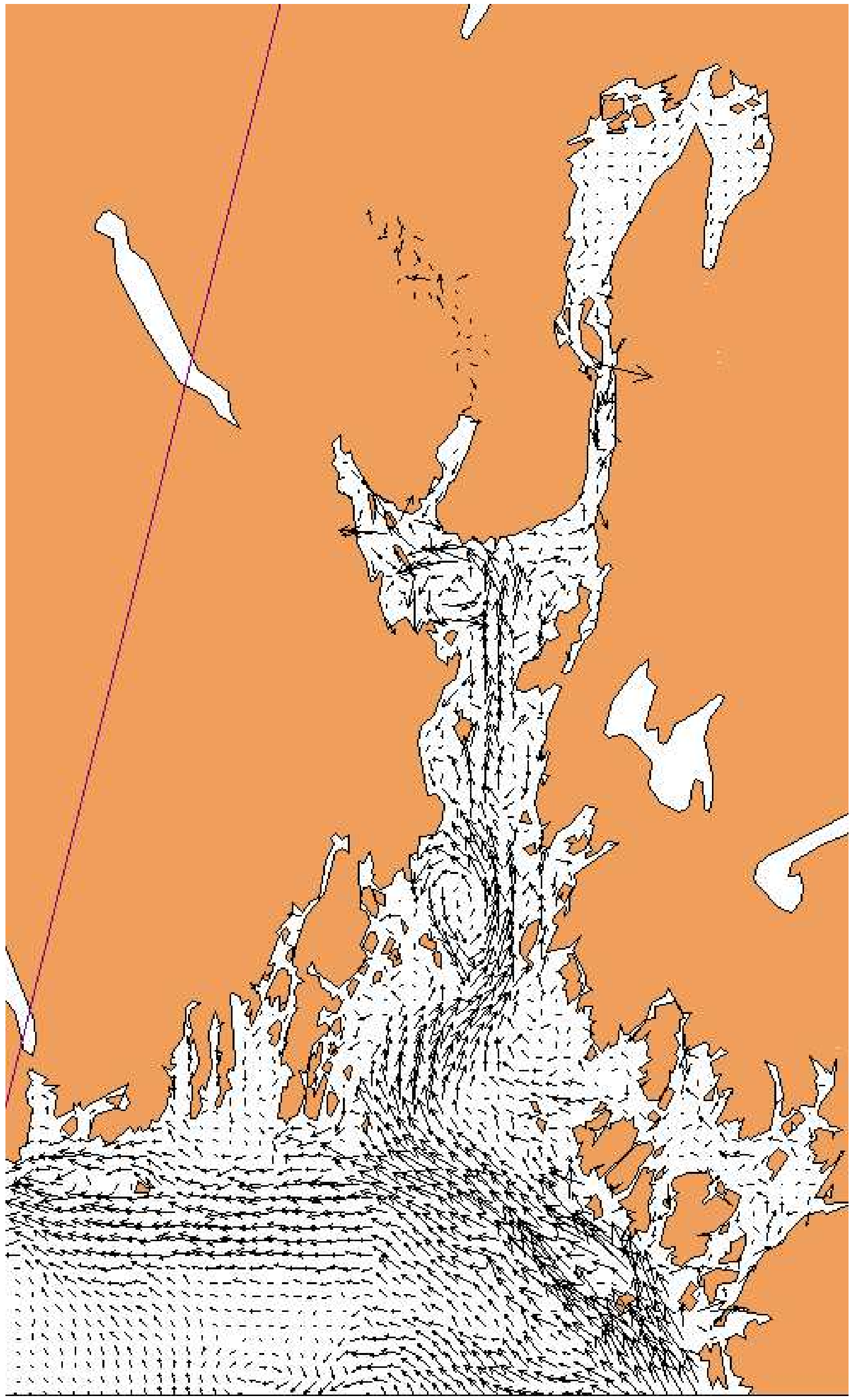

Figure 6: The operational MI-POM 300 m resolution nested area covering the Oslofjord. Instantaneous currents (every 4th arrow or 1.2 km) at 10m depth are shown.

3.1.3. Coupled ice-ocean version of MI-POM

Another model system has been developed where the ocean model is coupled with the three layer, two-dimensional sea-ice model, MI-IM (Meteorological Institute's Ice Model) (e.g. *Røed and Debernard* (2004)). MI-IM also features an module that calculates all the fluxes between the atmosphere and ocean, among them a radiation model. At present this coupled ice-ocean model produces a 10 day forecast once a day, but is not yet implemented in the operational routine at met.no. It is however this version which is used in MONCOZE and also other studies of the Nordic and Arctic Seas of climatological nature.

The most important component of this coupling in MONCOZE is the heat flux calculation in MI-IM. The net heat flux between the atmosphere and the ocean, Q_{ao}, is given by

$$Q_{ao} = -(1-\alpha_o)S_W - \varepsilon_o L_W + Q_{so} + Q_{lo} + \varepsilon_o \sigma T_o^4, \qquad (1)$$

where α_o is the albedo of open water, S_W is the incoming solar radiation, ε_o is the emissivity of open water, L_W is the incoming long wave radiation from the atmosphere, Q_{so} is the sensible heat flux, Q_{lo} is the latent heat flux, σ is Stefan-Boltzmann constant and T_o is the sea surface temperature. The last term in (1) expresses the outgoing long wave radiation from the ocean.

The short wave radiation is parameterized using the solar zenith angle and the total cloud cover. The incoming long wave radiation from the atmosphere is calculated from 2m atmospheric temperature and the total cloud cover. The sensible and latent heat fluxes are proportional to the differences in temperature and specific humidity, respectively, between the atmosphere and the ocean surface.

A skin-to-bulk parameterization reduces the net heat flux at the surface to be valid some distance down into the sea, where the upper temperature grid point in the ocean model is situated. The prescribed heat flux is then used as the surface boundary condition for temperature in the equation expressing the vertical diffusion. The short wave radiation absorbed within the first few meters (above the upper temperature grid point) is added to the surface boundary condition, while the remainder is attenuated according to a tabulated function *Jerlov* (1976). A parameterized sea surface salinity flux can also be used in the specifications of the boundary condition for salinity in MI-POM.

3.1.4. Model products

Examples of the presently Numerical Ocean Weather Prediction (NOWP) model system run daily at met.no is shown in Figures 4 - 6. They show respectively the large scale (mesh size 20 km) model (Figure 4) into which is nested the eddy resolving models (4 km mesh) covering the Skagerrak/northern North Sea (Figure 5). Finally, Figure 6 shows the Oslofjord model (300 m mesh size) nested into the Skagerrak/northern North Sea model.

3.2. HYCOM

Ocean general circulation models have traditionally been categorized based on their vertical representation. This involves, among others, the discretization in *z*-level coordinates, the terrain-following σ-coordinates, and isopycnal models using density as the vertical coordinate. The various choices of coordinates have advantages and disadvantages depending on their application, and a "hybrid" model combining the best parts from all of these, may be the model for the future.

The hybrid coordinate used here is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to a z-level coordinate in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. In doing so, the model combines the advantages of the different types of coordinates to optimally simulate both coastal and open-ocean circulation features.

The Hybrid Coordinate Ocean Model (HYCOM) is such a model. The recent developments (*Bleck* (2002) and other publications) are based on the previous Miami Isopycnal Coordinate Ocean Model (MICOM) by *Bleck et al.* (1992).

3.2.1. Model characteristics

HYCOM is a primitive equation model containing five prognostic equations - two for the horizontal velocity components, a mass continuity or layer thickness tendency equation, and two conservation equations for a pair of thermodynamic variables, such as salt and temperature or temperature and density. The prognostic equations are time-integrated using the split-explicit treatment of barotropic and baroclinic modes developed by *Bleck and Smith* (1990).

3.2.2. Vertical coordinate system

Vertical movement of water masses can be divided into a Lagrangian movement, where a coordinate surface is moving with the water in the vertical, and the movement of water through the coordinate surface as is done in all models with a fixed vertical coordinate system, e.g. z-level models and σ-coordinate models. HYCOM includes both representations of vertical movement of water masses. This allows for a combination of material coordinate surfaces as in MICOM with fixed surfaces as in z-level models and σ-coordinate models. The current algorithm exploits that all layers have an assigned reference density. However, whenever a layer thickness becomes sufficiently small, because this light water does not exist in the particular vertical column, this layer is used as a vertical level coordinate within the mixed layer. Further, this level coordinate is located in depth according to a predefined rule. The algorithm results in a stack of levels located from the surface and downwards with a specified resolution. Thus, the model allows for arbitrary high vertical resolution near the surface by adding a sufficient number of light (and therefore always massless) layers to the model. An example is given in Figure 7, where a vertical section from Torungen, at the Norwegian south coast, to Hirtshals, at the northern tip of Denmark, is taken, showing how the isopycnal layers are reverting to level coordinates in the upper part of the ocean, and to σ-coordinate in shallow water areas.

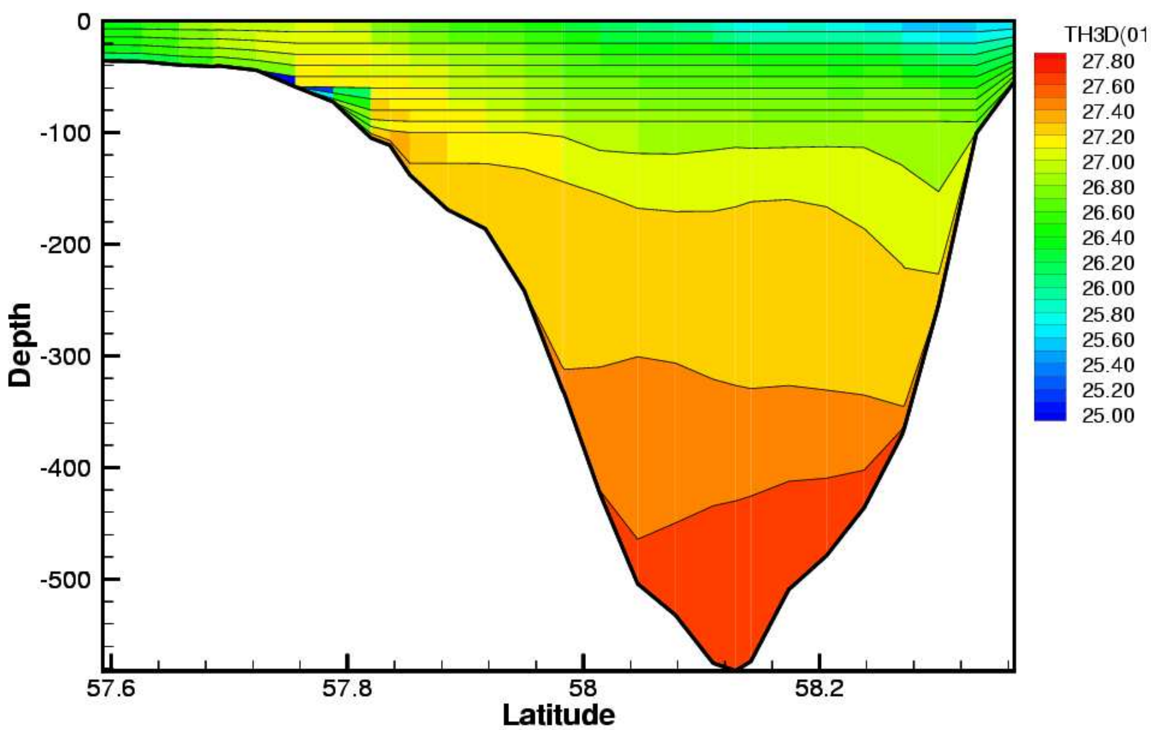

Figure 7: HYCOM vertical section from Torungen at the Norwegian south coast to Hirtshals at the northern tip of Denmark. The black lines represents the vertical coordinate. The colors show the potential density σ_θ in units of kg/m^3.

3.2.3. Vertical mixing processes

Vertical mixing in HYCOM is a combination of cabbeling and restoration processes and the explicitly prescribed mixing. Normally, the prescribed mixing exceeds other mixing processes by several orders of magnitude.

The horizontal advection of layer thicknesses, tracers and momentum in the original HYCOM code is computed using the same algorithms as in MICOM. But, as in most OGCM's, these numerical schemes are of second order and do not properly solve the dynamics of the scales smaller than a few grid steps. Because of this, it is implemented a fourth order numerical scheme (QUICK scheme) for the calculation of the advective terms in the momentum equation.

The advection of layer thicknesses in the continuity equation will introduce a vertical movement of the layer interfaces, also among the level coordinates near the surface. Further, horizontal diffusion of temperature and salinity in an isopycnic layer may lead to a deviation from the reference density. Thus, a hybrid coordinate generator algorithm is used every time step to restore the correct location of the coordinate surfaces. Among the isopycnal layers in the deep ocean, there is a restoration toward reference densities, an effect called cabbeling, where a slight amount of water is mixed between adjacent layers to restore the reference densities. This is normally a correction needed for a small deviation in density resulting from the diffusion of temperature and salinity in a layer (the non-linearity of the equation of state implies that the mixing of two water masses with different T-S properties, but with the same density, may result in a new water mass with a different density). For the level coordinates near the surface, water is moved/mixed between layers to restore the layer interfaces to their predefined locations in depth. Thus, vertical advection in the level coordinates is parameterized by a horizontal advection of tracers in a layer, and the layer thickness, followed by the restoration of the level coordinates. This process is designed to conserve temperature, salinity and momentum when water is moved between layers.

For the prescribed vertical mixing, HYCOM has several optional mixed layer models implemented. The one used in this model setup is the K-Profile Parameterization (KPP) vertical turbulence closure scheme, developed by *Large et al.* (1994). The scheme computes the vertical mixing coefficient over a vertical column in the model and takes into account the mixed layer turbulence induced by wind mixing and additional mixing parameterization for processes, such as, internal wave breaking, vertical current shear (from the Richardson number), salt fingering and double diffusion. A background vertical mixing coefficient ensures the presence of a low diapycnal diffusion in the deep ocean. The scheme uses an algorithm to compute the vertical diffusivity in a water column, and thereafter a one-dimensional diffusion equation is solved for temperature, salinity and momentum. Every time the vertical mixing has been applied, the hybrid generator is called to restore all layers/levels to their reference densities, if possible.

3.2.4. Nesting of regional models

Open boundary conditions and nesting in ocean circulation models are considered more as an art than real science. The main problem is that for a model with open boundaries, the number of boundary conditions depends on the structure of the flow field across the boundary. There are actually four cases which must be considered. The circumstances which must be considered, are inflow and outflow, and, for each of these, one may have supersonic and subsonic velocities. To avoid dealing with the problem of exactly specifying the boundary conditions in a "proper" nesting scheme, most approaches use some kind of boundary relaxation toward the outer model solution. This results in, what one normally would call, the one way nesting schemes, where the boundary conditions of the regional model are relaxed toward the output from a coarser large scale model. For the slowly varying variables, i.e., baroclinic velocities, temperature, salinity and layer interfaces, this is a fully appropriate way to specify the boundary conditions. For the fast propagating barotropic variables, the relaxation approach requires careful tuning to avoid reflection of waves at the open model boundaries.

In HYCOM, the barotropic model is a hyperbolic wave equation for pressure and vertically integrated velocities. Following an approach outlined by *Browning and Kreiss* (1982, 1986), it is possible to compute the barotropic boundary conditions exactly while taking into consideration both the waves propagating into the regional model from the external solution and the waves propagating out through the boundary of the regional model. The scheme has been tested extensively and has shown no problematic behavior yet. In addition, it also makes it fairly simple to include the tidal forcing on the barotropic mode.

3.2.5. MPI version of HYCOM

Version 2.0 of the HYCOM code is an MPI implementation, i.e., it is programmed particularly for parallel computers with distributed memory. This version of the code has been successfully installed and tested at the national computing center in Paris, where it takes advantage of the parallel computing architecture of the IBM SP3 and IBM Power4 systems.

3.2.6. Model setup

Figure 8 shows the two-level nested model system used in the MONCOZE project. The regional model system is part of the DIADEM/TOPAZ[1] model system, which again is coupled to a sea-ice model, biochemical models and a data assimilation module.

The large scale grid used in TOPAZ is based on a mapping of the North and South poles to locations near the Equator in the Pacific Ocean. This provides a grid with more uniform resolution in the Atlantic and Arctic (20-30 km) than what is obtained in traditional model grids. The intermediate regional model has a horizontal grid resolution of about 7 km, while the regional coastal model will have grid resolution down to 2-4 km. Figure 8 shows SST and ice thickness. As expected, the SST is high in the tropics, and it is evident that the water is much warmer in the North East Atlantic compared to the western part of the ocean at the same latitude. The Arctic is ice covered.

The model system is forced by wind fields (at 10m height), air and dew point temperatures (at 2m height), mean sea level pressure and cloud fraction cover (between 0 and 1). From these variables, the momentum and radiation fluxes are computed by the model. More details can be

[1]The DIADEM project includes a Development of Advanced Data Assimilation Systems for Operational Monitoring and Forecasting of the North Atlantic and Nordic Seas. TOPAZ is an acronym for Towards an Operational Prediction system for the North Atlantic and European coastal Zones.

found in *Simonsen and Drange* (1996) and *Drange and Simonsen* (1996). The model setup also include freshwater run-off from rivers.

3.2.7. Model products

As alluded to HYCOM is the numerical ocean model used in the TOPAZ system, which is now running in real time. HYCOM has also been used in several other project for the offshore industry, where the model has been tested and validated. Examples of application is the NWAG project, which includes validation of a circulation model for the North Western Approaches, and the WANE project, which is a hindcast simulation experiment for the West African Coast.

3.3. NORWECOM

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical and biological ocean model system *Aksnes et al.* (1995); *Skogen and Søiland* (1998), and is traditionally applied to study primary production, nutrient budgets and dispersion of particles (fish larvae and pollution) in the ocean.

3.3.1. The physical model

As MI-POM the physical part of NORWECOM is based on the POM model *Blumberg and Mellor* (1987). The forcing variables are six-hourly atmospheric pressure fields, wind, cloud cover, 2 m air temperature and humidity, short wave radiation, four tidal constituents at the lateral boundaries and freshwater run-off. The atmospheric variables are provided by the Norwegian Meteorological Institute from the operational model at the ECMWF (European Centre for Medium-Range Weather Forecasts). The radiative, sensible and latent heat fluxes are calculated based on the sea surface temperature in NORWECOM, and cloud cover, air temperature and humidity from a meteorological model. If these forcing data are not available, a relaxation method toward climatology for salinity and temperature is used for the surface layer *Cox and Bryan* (1984). During calm wind conditions, the surface field will adjust to the climatological values after about 10 days.

3.3.2. The chemical-biological model

Important input from the physical model to the chemical-biological part of NORWECOM is the sub-surface light, the hydrography and the horizontal and the vertical movement of the water masses. The prognostic variables are dissolved inorganic nitrogen (DIN), phosphorous (PHO) and silicate (SI), two different types of phytoplankton (diatoms and flagellates), detritus (dead organic matter), diatom skeletals (biogenic silica), inorganic suspended particulate matter (ISPM), oxygen and light. The incident irradiation is modeled using a formulation based on *Skartveit and Olseth* (1986, 1987). Short wave irradiance data from the ECMWF model is preferably used, but if these data are not available, daily irradiance data from the year 1990 is taken from a station at Taastrup (Denmark) and used globally. Nutrients (inorganic nitrogen, phosphorous and

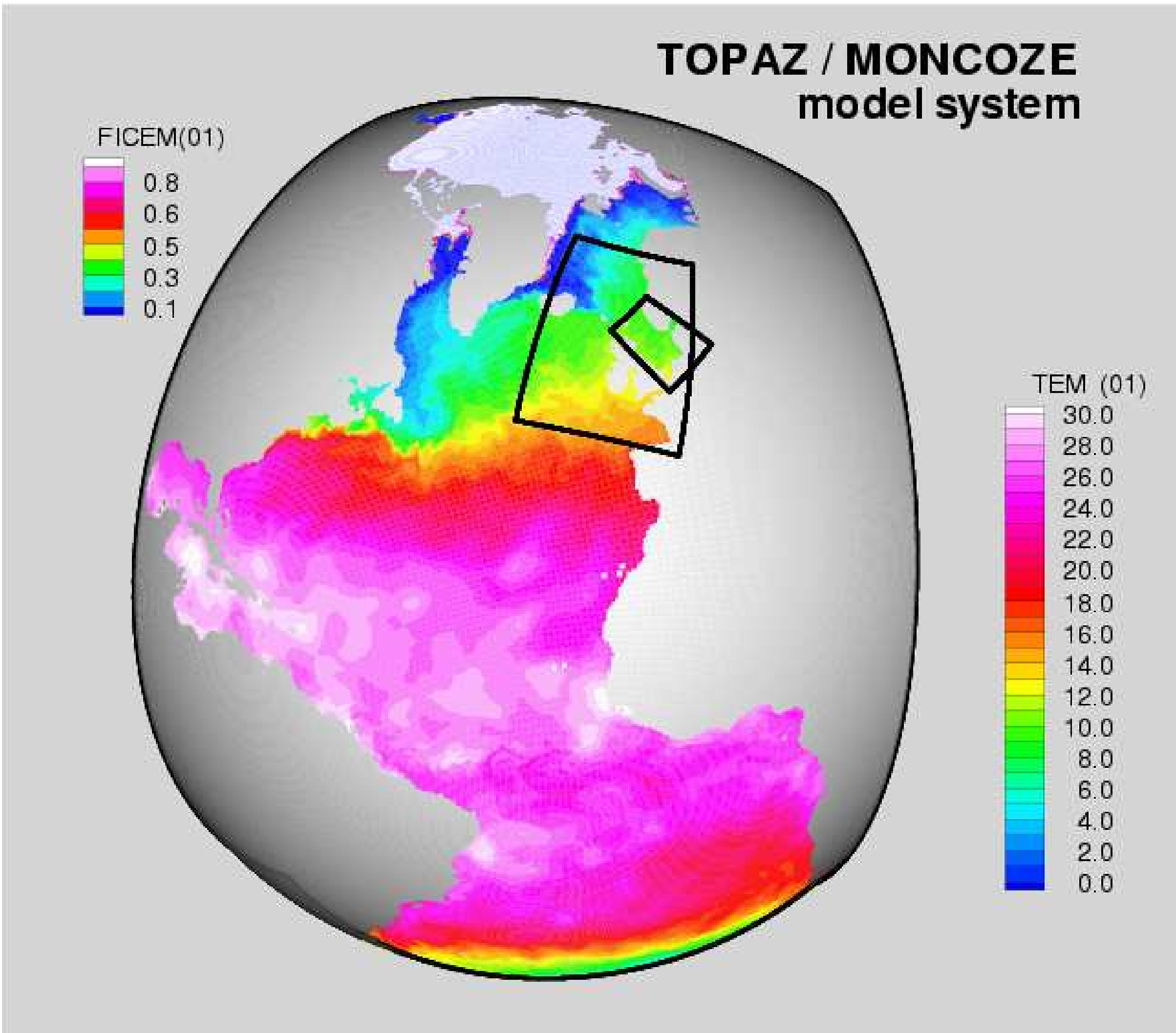

Figure 8: The model domain for the TOPAZ and MONCOZE projects. Nested high resolution areas indicated by rectangles. The colors show sea surface temperature.

silicate) are added to the system from the rivers, from the atmosphere (only inorganic nitrogen) and from the open boundary. Particulate matter has a sinking speed relative to the water and may accumulate on the bottom if the bottom stress is below a certain threshold value, and likewise, resuspension takes place if the bottom stress is above a limit. Regeneration of organic particulate matter takes place both in the water column and in the sediments. The bottom stress is due to both currents (including tides) and surface waves.

Initial values for velocities, water elevation, temperature and salinity in the coarse model are taken from monthly climatologies *Martinsen et al.* (1992). Interpolation between monthly fields are used at all open boundaries, except at the inflow from the Baltic, where the volume fluxes have been calculated from the modeled water elevation in the Kattegat and the climatological mean fresh water run-off to the Baltic, using an algorithm from *Stigebrandt* (1980). To absorb inconsistencies between the forced boundary conditions and the model results, a seven grid cell Flow Relaxation Scheme (FRS) zone *Martinsen and Engedahl* (1987) is used around the open boundaries. To calculate the wave component of the bottom stress, data from met.no's operational wave model, WINCH *SWAMP* (1985); *Reistad et al.* (1988), is used. The initial nutrient fields are derived from data obtained from ICES together with some small initial amounts of algae.

In the first version of NORWECOM *Skogen* (1993), no interactions with the sediments were included, i.e., all particulate matter remained in the pelagic zone. In the new version, particulate matter may settle on the bottom. Organic matter may remineralise, become permanently buried in the sediments, or be subject to resuspension. Both the sedimentation process and resuspension are dependent on the bottom stress. The bottom stress is caused by the bottom currents, including the tides, and in shallow seas such as the North Sea, surface gravity waves contribute significantly to the bottom stress. Actually, in shallow areas the wave action dominate the bottom stress during strong storms with high waves. In the bottom boundary layer, there is a complicated interaction of the oscillatory wave motion and the currents, and this affects the magnitude and direction of the stress. This interaction has been included in a simple form in NORWECOM. Sedimentation takes place if the total bottom stress is below a certain value (typically 0.064 N/m^2), and resuspension occurs if the bottom stress is above a certain threshold value (typically 0.78 N/m^2), and the rate is proportional to the square of the stress.

A technical description of NORWECOM including the new features is given in a report by *Skogen and Søiland* (1998). With the earlier version of NORWECOM, the model was initialized with winter conditions, and the model was run for one production season. The new developments have made it possible to make multi year runs with NORWECOM.

3.3.3. Model products

NORWECOM has been extensively used in multi-year studies of the primary production in the North Sea and the Skagerrak/Kattegat, and operationally in connection with harmful algae blooms in the area. It has also been used in the Benguela upwelling system on the south west coast of Africa. The monthly mean currents and salinities at 5 m depth for April 2000 in the Skagerrak/northern North Sea are shown in the upper panel of Figure 9. As is often the case there is a strong cyclonic circulation in Skagerrak, and low salinity water from the Baltic flows along the Swedish west coast and further along the south-east coast of Norway. On the south-west coast of Norway, off the Boknafjord, the coastal current makes an offshore turn, and this is a well documented feature of the mean flow in the area. The monthly mean depth integrated primary production for the same period is shown in the lower panel of Figure 9. Along the Norwegian coast, there is a band of high production due to an ongoing diatom bloom. High production also take place in the continental coastal water off the west coast of Denmark, and in parts of the Kattegat. The results shown are from runs performed with the 4 km resolution model, nested into the 20 km model covering the North Sea, with realistic meteorological forcing, river run-off and nutrient loads.

4. Procedures for comparing observed and modeled fields

Berntsen and Svendsen (1999) proposed to quantify the discrepancies between models and sections from measurements using a cost function. This is done by normalizing the difference between the modeled sections and the measured sections. However, it will also be valuable to look at the actual difference. The modeled fields can be a) instantaneously sampled on the same day as the data, b) daily average of the same day as the data, or c) extracted along the section at the same time as individual stations are taken (alt. b can be used for simplicity, but alt. c is more correct). With salinity (S) as an example variable, the following fields/sections can be produced:

$$\Delta S = S_{model} - S_{data}. \tag{2}$$

An example of the difference between a modeled and a measured section is given in fig. 10. The data are measured between Torungen and Hirtshals in the Skagerrak sea by the research vessel “G.M. Dannevig” around 13th of March 1998. The model data are 25 hour means retrieved from a hindcast run with MI-POM. The modeled fields are interpolated to the same grid as the measurements.

Since ΔS near the surface normally will be much higher than near the bottom, this difference can be normalized with the standard deviation $\sigma_{S_{data}}$ taken from many years of observations during the same months, as

$$\Delta_{norm} S = \frac{S_{model} - S_{data}}{\sigma_{S_{data}}}.$$

Similar sections can be produced for the other state variables. A limitation of that procedure is that it is often a problem of getting realistic standard deviations taken from measurements. For model inter-comparison, the standard deviations taken from one model can be applied for the other estimates of Δ_{norm}'s.

If the models are run for many years, it is possible to evaluate the variability of the models by looking at the anomaly correlation (AC). The AC does not indicate anything about the absolute model error, but it is a measure of the model's ability to simulate the variability of the observed data. The AC can be written

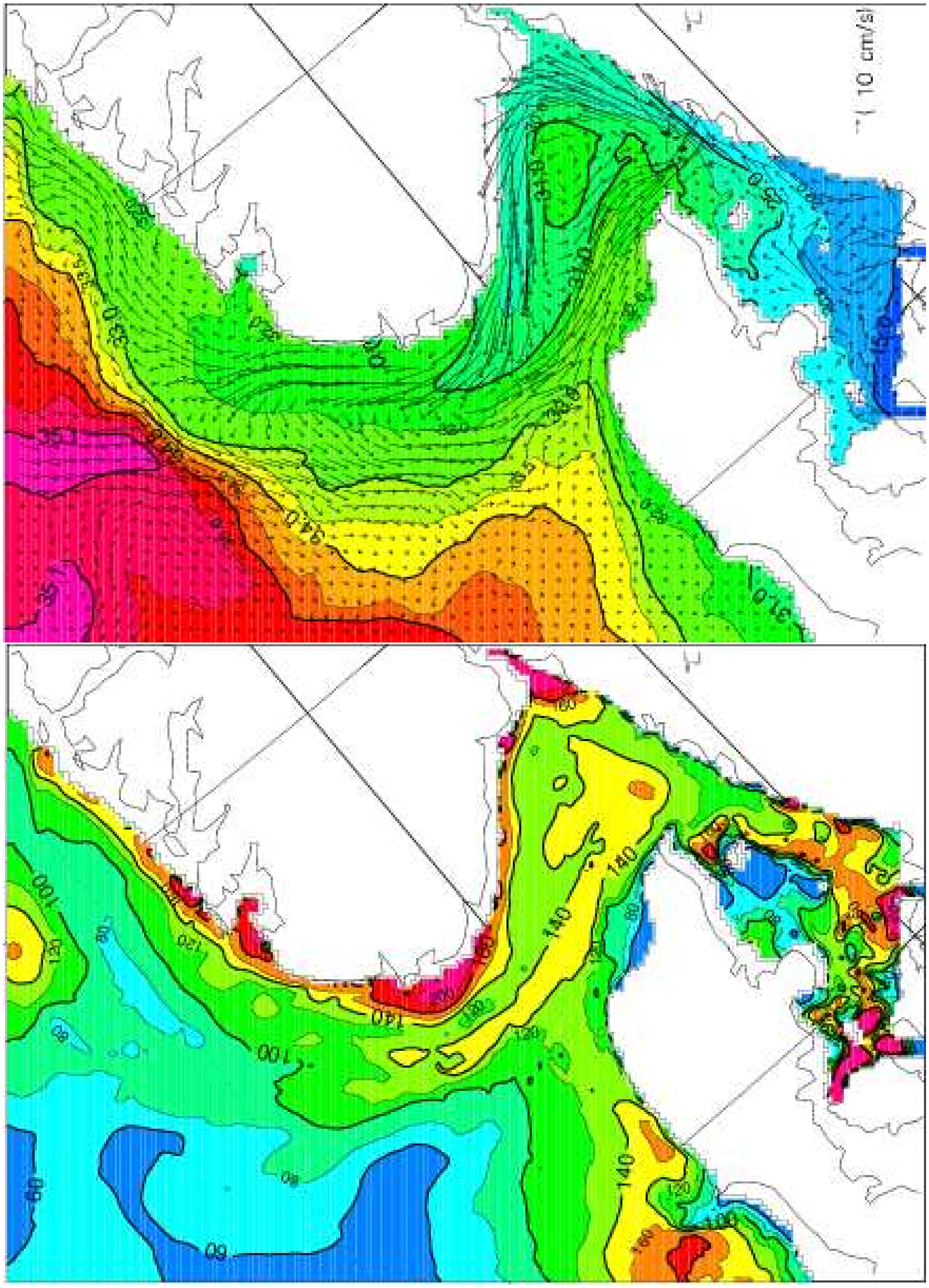

Figure 9: Upper panel shows the monthly mean currents and salinities (in *psu*) at 5 m depth, while lower panel shows the vertically integrated primary production (mgC/m^2) for April 2000, in the 4 km nested NORWECOM domain.

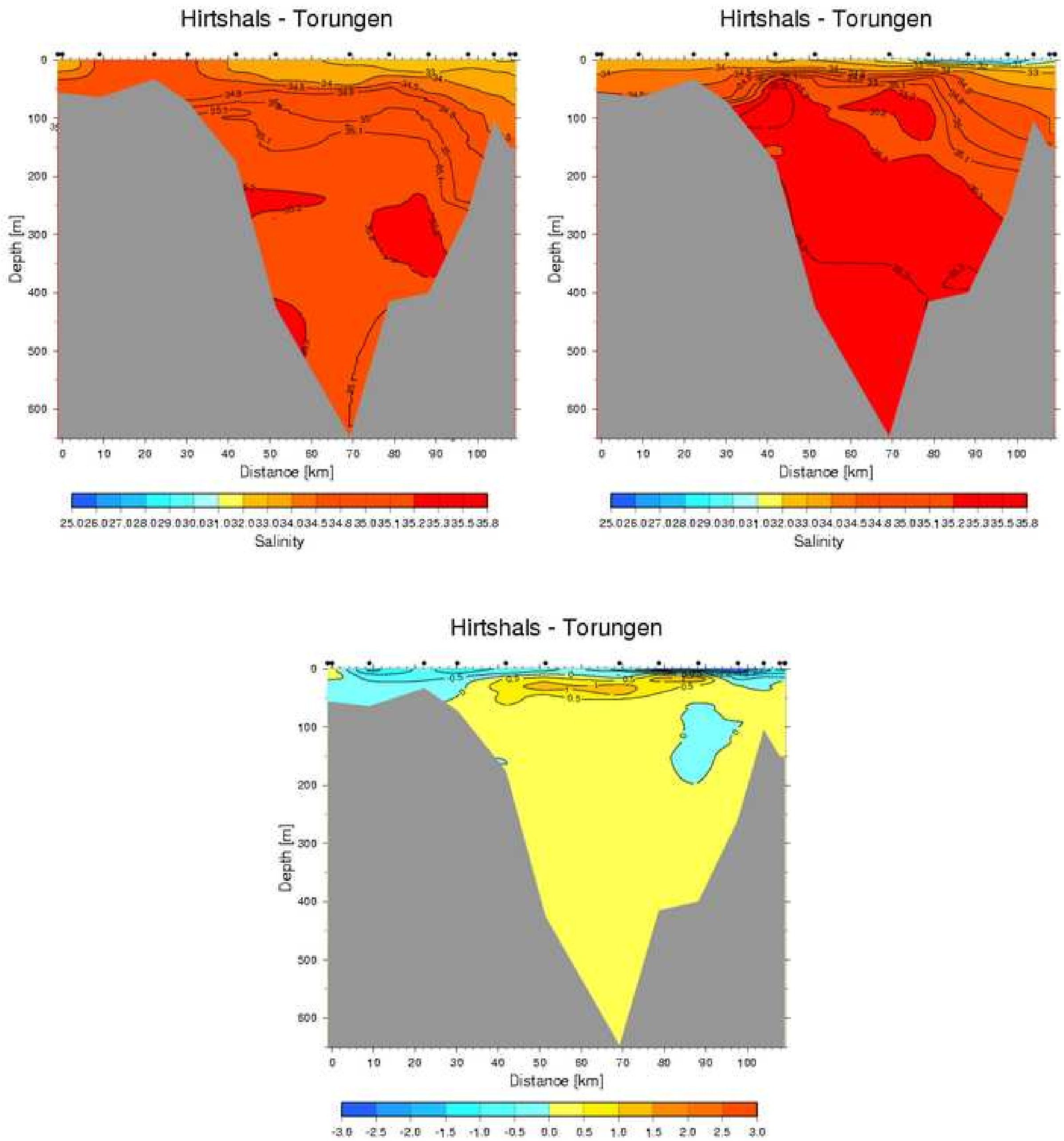

Figure 10: Salinity data valid around 8th of April 1998 along the Hirtshals - Torungen cross section. The upper left panel shows measured values, the upper right panel shows modeled values (25 hour means from a MI-POM hindcast run) and their difference (ΔS) is seen in the lower panel.

$$AC = \frac{Cov(S_{model}, S_{data})}{\sigma_{S_{model}} \sigma_{S_{data}}}. \quad (3)$$

The term, $Cov(S_{model}, S_{data})$, is simply the covariance between the modeled and observed data.

5. Summary

The physical parts of the three models, MI-POM, HYCOM and NORWECOM, have many similarities, but whereas MI-POM and NORWECOM are sigma coordinate models, HYCOM use density layers in the deep part and *z*-layers in the mixed layer. Another major difference is the vertical mixing schemes. MI-POM and NORWECOM use the 2.5 order turbulent closure scheme as described by *Mellor and Yamada* (1982). HYCOM has different optional mixed layer models implemented, and the K-Profile Parameterization (KPP) vertical turbulence closure scheme is used in the current model setup.

The bio-geochemical coupling is important within the MONCOZE project. The bio-geochemical module invoked in MI-POM and NORWECOM, used to provide forecasts of eutrophication and algae blooms (see http://moncoze.met.no), is described in Section 3.3.2. The bio-geochemical module coupled to HYCOM is based on the chemical model by *Peng et al.* (1987), the seven component ecosystem by *Fasham et al.* (1990) and *Fasham* (1993), and the three-dimensional extensions done by *Sarmiento et al.* (1993). Phytoplankton, zoo-plankton, bacteria, nitrate, ammonium, dissolved organic nitrogen, dissolved organic carbon, detritus (PON and POC), dissolved inorganic carbon and total alkalinity are all explicitly modeled. Recently, a new model version called Carbon:Nitrogen Regulated Ecosystem Model (CN-REcoM) has been implemented. This model maintains carbon, nitrogen and chlorophyll as individual state variables with a moderate degree of complexity, and the total number of state variables is then nine.

The three models will be extensively validated in MONCOZE, using in situ observations and satellite remote sensing data. The results from the validation experiments will be used to evaluate the three models, and compare how they perform.

Table 1: Overview of the various output variables and formulations used in the three MONCOZE models.

Model type	**Vertical coord.**	**Vertical mixing**	**Physical output**	**Chemical-Biological output**
MI-POM	Sigma	Turbulence closure M+Y	Sea surface height, velocity, salinity, temperature.	Diatoms, flagellates, nitrate, phosphate, silicate, detritus, (N+P,SI), oxygen, ISPM
HYCOM	Hybrid	Turbulence closure KPP	Sea surface hight, velocity, salinity, temperature, density.	Phytopl., zoo-pl., bacteria, nitrate, ammonium, nitrogen, carbon, total alkalinity.
NORWECOM	Sigma	Turbulence closure M+Y	Sea surface height, velocity, salinity, temperature.	Diatoms, flagellates, nitrate, phosphate, silicate, detritus, (N+P,SI), oxygen, ISPM

Appendix: Variables and formulations, pros and cons of the three MONCOZE models

Table 1 gives an overview of the various output variables, type and vertical mixing formulation used, and hence provides a quick comparison of the three MONCOZE models. The three tables Table 2, Table 3, and Table 4 gives the advantages and disadvantages of MI-POM, HYCOM, and NORWECOM, respectively.

Table 2: PROS & CONS for MI-POM. SST = Sea surface temperature, SSH = Sea surface height, SSS = Sea surface salinity

Item	Description	Pros	Cons
Atmospheric forcing data	MSLP and surface winds (10m) from HIRLAM50 for the 60 hours forecast, and from the operational atmospheric model at ECMWF for the extended forecast. ECMWF ERA and operational analysis used for hindcasts.	Flexible access to HIRLAM50, HIRLAM20, HIRLAM10, HIRLAM5 and ECMWF data.	
Oceanic forcing data	Relaxation of SST, SSS and temperature and salinity in the deeper layers and along the open boundaries toward climatology.	met.no/IMR climatology better than Levitus. Surface fluxes can be prescribed from MI-IM in a coupled model system.	Nesting to global model would be better.
Rivers	Climatological monthly values from met.no's standard river dataset.	Monthly better than annual climatology.	Near real time discharge data would be better.
Spatial resolution	*Horizontal*: From 300m resolution in the Oslofjord domain and up to 20km in the Nordic Sea domain.	Curvilinear grids may be used.	
	Vertical: Terrain fitted sigma layers.	Pressure gradient coordinates.	Error when steep topography.
Preferred validation data	Hydrography and currents. The model is validated against SSH observations and currents.		
Availability/ Portability	SSH distributed on the Internet, but model results are public available.	Fully portable. Easy to change from low to high resolution, exchange bottom topography matrices. Parallelized using MPI.	Difficult to access ocean forecast data from outside met.no
Operationality	Operated in real time, once or twice each day.	Long-time experience.	
Other	Implemented/tested assimilation schemes: assimilation heat flux nudging, OI of surface currents, MSC/OI of SSH.		No data in any of the *operational* models

Table 3: As Table 2, but for HYCOM

Item	Description	Pros	Cons
Forcing data	Atmospheric: ECMWF (forecast and hindcast) Oceanic: Levitus - SST and partly SSS surface relaxation Rivers: Mixing of freshwater, monthly climatology	High-quality re-analysis used in hindcast modeling	Rivers as bogus surface precipitation, no volume flux
Spatial reso-lution	Horizontal: Atlantic model with 15-20 km resolution, intermediate 7 km, coastal model down to 2 km resolution Vertical: Hybrid, i.e. isopycnal, terrain following coordinates in shallow regions and z-level coordinates in mixed layer.	Regular use of nested models allow very fine spatial resolution in local and limited areas. Curvilinear grids used. A state-of-the-art model system - the hybrid nature of the model makes it suitable for most applications.	Vertical scheme not developed for fresh water
Preferred validation data	Current data, XBT data.		Data availability limited.
Avail-ability/ Port-ability			
Operation-ality	TOPAZ system operated in real time.	Data assimilation module included	

Table 4: As Table 2, but for NORWECOM

Item	Description	Pros	Cons
Atmospheric forcing data	MSLP and surface winds (10m) from met.no, hindcast archive or ECMWF. Surface solar radiation and surface heat flux from ECMWF data.	Routines for latitude light differences and solar height in relation to diffuse and direct radiation.	
Oceanic forcing data	Relaxation of SST, SSS and temperature and salinity in the deeper layers and along the open boundaries toward climatology.	met.no/IMR climatology better than Levitus.	Nesting to global model would be better.
Spatial resolution	*Horizontal*: From 500m-1000m resolution in fjords and up to 20km in the open ocean.	Curvilinear grids may be used. Fine scale models may be set up everywhere and nested with coarse model.	
	Vertical: Terrain fitted sigma layers.	Pressure gradient coordinates.	Error when steep topography.
Preferred validation data	All state variables, chlorophyll and primary production estimates. Process formulations and parameterizations taken from scientific literature. Extensive validation using IMR database and SKAGEX dataset.		Availability of integrated quantities such as transports and primary production.
Availability/ Portability	Results published in peer-reviewed journals. Model implemented in Benguela and Mozambique channel.	Easy to change domain from low to high resolution. Model can be exported due to generic process formulations and parameterizations.	
Operationality	Old version operated in forecast mode at met.no. Put in operational forecast mode during Chatonella blooms 1998, 2000 and 2001.		Dependent on real-time atmospheric forcing from met.no or others.
Other		Data availability for validation and multidisciplinary competence at IMR.	No data assimilation.

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