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HIROMB, AN OPERATIONAL EDDY-RESOLVING MODEL FOR THE BALTIC SEA

Abstract

HIROMB is a 3-dimensional baroclinic model of the North Sea and the Baltic Sea, designed for daily operational use. The model is mainly developed by Eckhard Kleine at the German Federal Maritime and Hydrographic Agency (BSH) in Hamburg, Germany, and is based on a similar model, running in operational mode at that institution. The operational forecasts at SMHI started already in 1995 with a daily 24-hour forecast and were later extended to 48 hours. The model is forced by SMHI's operational atmospheric model (HIRLAM), but also by river runoff from an operational hydrological model and wave radiation stress from a wind wave model. The present version of the model is set up on a nested grid, where a 12 nautical mile (nm) grid covers the whole area, while Skagerrak, Kattegat, the Belt Sea and the Baltic Sea are covered with a 1 nm grid. A parallelized version of the model has been developed and runs on a distributed memory parallel computer.

1. Introduction

The HIROMB project, which the model is part of, started as a fruitful co-operation between the Swedish Meteorological and Hydrological Institute (SMHI) and the German Federal Maritime and Hydrographic Agency (BSH) with the aim of a common operational system for the North Sea and Baltic Sea region. The main objectives of the HIROMB co-operation are:

i) *The model should constitute the basis for a common operational system for all states surrounding the Baltic Sea.*

ii) *All states with a border to the Baltic Sea should be invited to the HIROMB project, and the member institute of each state should be appointed by the relevant ministry.*

iii) *The model should be run at one place where access to a supercomputer could be granted.*

iv) *The output from the operational run should be distributed to all members of the project.*

v) *Each participating state should contribute equally to the maintenance and development of the system.*

The first pre-operational runs started in summer 1995. At that time, the model was run on a vector-computer, producing a daily 24-hour forecast. In 1997, the model was transferred to a CRAY C90 parallel shared memory vector computer at the National Supercomputer Centre in Sweden. This made it possible to increase the forecast length to 48 hours, but still with only one simulation a day. During 1997-99, the model code has successively been parallelized [16] and a special method of partitioning the computational domain has been developed [12]. At present (2001), the 1 nm model runs on a distributed memory parallel CRAY T3E computer in parallel with a backup version on a SGI3800 computer.

The model output is archived and all members of the HIROMB project have access to the complete database via an ftp-server. A web site has been set up for real-time presentation of forecasts together with validation.

2. Grid configuration

Basically, there are two factors that determine the model area. Firstly, each project member has their own interest area and though the main region of interest is the Baltic Sea, countries like Sweden, Denmark and Germany also have interest in the Kattegat, Skagerrak and the North Sea. Secondly, the model area has an open boundary to the Atlantic and there is no ultimate choice of its location. Both physical and computational aspects have to be taken into consideration, and this has led to the following configuration:

1. A storm surge model for the NE Atlantic. This model only supplies that part of the water level at the boundary between the Atlantic and the North Sea that is driven by solely the meteological forcing. The tidal motion is added as an open boundary condition, treated in a similar manner as salinity and temperature (see section 3.2).

2. A nested set of HIROMB modules with a resolution ranging from a relatively coarse level for the North Sea down to 1 nm for the Skagerrak, Kattegat and the Baltic Sea. The 1 nm grid (see Fig. 1) covers the entire Baltic Sea. Boundary values at the open western border at 10°E are provided by a coarser 3 nm grid. This grid (see Fig. 2) covers the waters east of 6°E.

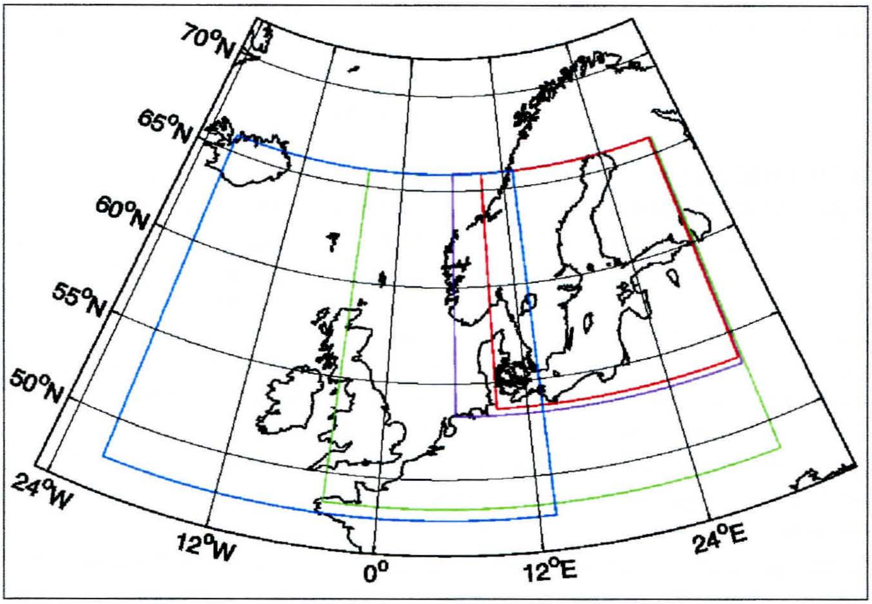

Fig. 1. 12, 3 and 1 nm grids for the 3D model encapsulated by the 24 nm grid for the North-East Atlantic storm surge model

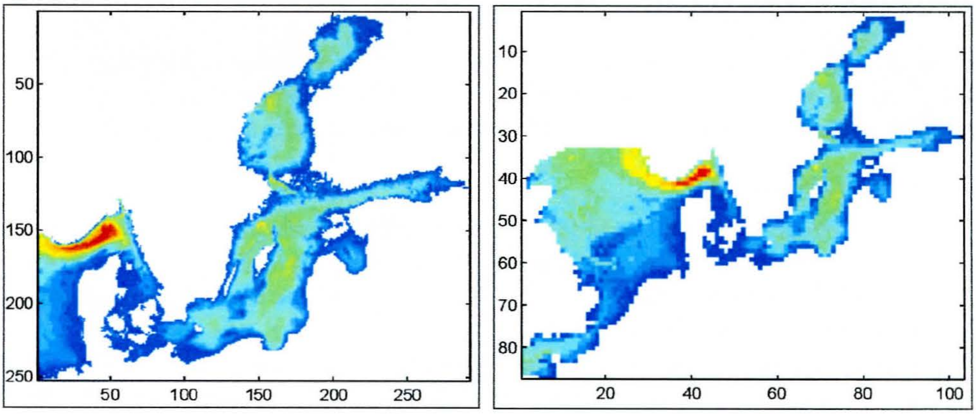

Fig. 2. The 3 nm grid, to the left has 154,894 active grid points of which 19,073 are surface points. The 12 nm grid, to the right, also covers the North Sea and has 9240 active grid points of which 2,171 are surface points

Table 1. Horizontal configuration of the HIROMB grids

Grid	No of points in W-E	No of points in S-N	Increment in longitude	Increment in latitude
NE Atlantic	52	46	40’	24’
HIROMB 12 nm	105	88	20’	12’
HIROMB 3 nm	294	253	5’	3’
HIROMB 1 nm	752	735	1’40”	1’

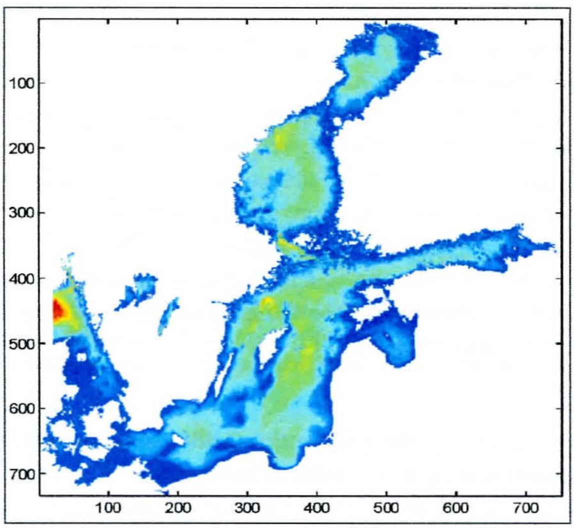

Fig. 3. The grid with 1 nm resolution covers the area from Skagerrak to the Baltic Sea. There are 1,126,607 active grid points of which 144,449 are surface points. The maximum depth is 710 m in Skagerrak and 460 m in the Baltic Sea.

3. Forcing

HIROMB requires input from both an atmospheric and a hydrological model as well as from an ocean wave model. This dependence on results from other models makes HIROMB sensitive to the security of the whole forecast production environment at SMHI.

3.1. Atmospheric forcing

The atmospheric model HIRLAM [8] provides HIROMB with sea level pressure, wind at 10 m above surface, air temperature and specific humidity at 2 m above surface and total cloudiness. These parameters fully control the momentum and the thermodynamic balance between the sea surface and the atmosphere.

Note that the thermodynamic forcing terms are dependent on the SST. Therefore, the atmospheric heat flux cannot be computed in advance, but is determined while HIROMB works. Those basic atmospheric parameters that one-way drive the thermodynamics of HIROMB are air temperature, humidity and cloud cover.

3.2. Open boundary forcing

HIROMB has an open boundary to the North Atlantic. One part of this boundary line runs through the British Channel, the other makes a straight line between northern Scotland and southwest Norway. Along all that line, water level, salinity and temperature are prescribed at each time step. As described earlier, boundary values of water level come from two sources. They are superposed by the results of a storm surge model for the North Atlantic, which is void of tides, and a setup of 17 tidal constituents, specified for each individual boundary cell.

To supply HIROMB with inflow data of salinity and temperature at its open boundary, we so far only have climatological fields, month by month. In order to relax their influence on the operational simulation, we have placed a sponge layer along the boundary line. Its purpose is to act as a buffer between the inner model domain and a "climatological reservoir" outside. We imagine the sponge layer to be a filter literally located in between interior and exterior. It is flushed by the normal flow component as computed for the next location to the boundary line. That flow either brings a climatological signal or outflow from the interior into the sponge. When flow direction is reversed from outward to inward, it returns what it was filled with, until, in sustained flow, its capacity is exhausted, and it passes more and more of the reservoir. Conversely, for outward flow, the sponge empties into the reservoir, which is thought to be of infinite capacity, i.e. does not respond to that input. The performance of the sponge is a matter if its capacity. This capacity should be sufficiently large not to let the reservoir be felt in tidal reversions, but sufficiently small to give an input effect for sustained inflow.

3.3. River runoff

A river runoff model [5] covering the entire Baltic drainage basin, Skagerrak and Kattegat runs on an operational basis at SMHI. The hydrological model produces as output, daily river runoff for 43 sub-basins of which 8 represents the Skagerrak-Kattegat area (see Fig. 4). A further division of the runoff for each sub-basin is made between the major rivers ending up at a total of 82 rivers. Climatological monthly means of river runoff are used as backup if the hydrological model has been out of operation for a week period or longer.

Fig. 4. Catchment area for the Baltic Sea, Skagerrak and Kattegat and the distribution of separate drainage basins (red lines) for which the river runoff forecast model is run. Also shown with thick black lines are the sub-basins for a chemical model. Major rivers are marked with blue lines

3.4. Wind wave forcing

Unlike entirely irregular turbulent fluctuations, waves are much more accessible to modelling. In our context, we employ a phase-averaged model, which describes the comparatively slow evolution of wave energy quantities. To account for the effect of waves, the following 6 parameters are extracted from the operational wave model:

1. Wind wave energy

2. Peak frequency of wind waves
3. Dominant direction of wind waves
4. Swell energy
5. Peak frequency of swell
6. Dominant direction of swell

The wave amplitude and orbital velocities may be treated as fluctuations from the mean and we may calculate the wave contribution for the Reynolds stress terms in the momentum equations by substituting for the fluctuating quantities.

By vertical integration of the momentum equations, it is also possible to calculate the influence of wind waves on the large-scale volume fluxes. In similar manner, we may integrate for the wind wave terms in the continuity equation. This net volume flux corresponds to the Stoke's drift.

4. Basic equations

A full description of the model equations may be found in Kleine [9] and here only a brief outline is presented.

4.1. Momentum balance and continuity

The momentum equations expressed in spherical coordinates are easily found in standard textbooks (see e.g. [3]). The model uses the standard approximations like the hydrostatic approximation and the Boussinesq approximation.

4.2. Reynolds averaging

The flow in the ocean is more or less turbulent and cannot be calculated exactly due to resolution problems connected to limitations in computer capacity. The time scales of the motion that are of interest for an ocean model are far beyond that of the turbulent velocity fluctuations. However, to include the turbulence in the conservations equations above, it is convenient to regard them as applied to a type of mean flow and to treat the fluctuating component in the same manner as the viscous shear stress. Following the statistical approach by Reynolds [13], we separate the instantaneous values of the velocity components and pressure into a mean and a fluctuating quantity, $u = \bar{u} + u'$, $v = \bar{v} + v'$ and $p = \bar{p} + p'$, where the mean of the fluctuating components is zero by definition and the mean is defined as the integrated mean over a specified period.

The averaging period has to be greater than the fluctuating time scale but is more or less artificial as there is hardly any such separation of scales to be found in nature. Averaging the momentum equations and ignoring density fluctuations in the acceleration terms result in a set of equations usually referred to as the Reynolds equations for the mean flow containing terms like: $\rho\overline{u'u'}$, $\rho\overline{v'u'}$, $\rho\overline{w'u'}$ etc.

The new terms, called the Reynolds stresses, represent the non-resolved scales of motion, i.e. what we here regard as turbulence. However, as the new set of equations is not closed, we have to express the Reynolds stress terms in the mean quantities. The normal approach to this closure problem is to make use of the analogy with molecular viscosity concepts as was first outlined by Stokes [15] and Boussinesq [2]. This means that the stress components are expressed as proportional to an eddy viscosity times the strain-rate of the mean flow.

4.3. Salinity and temperature equations

In deriving the equations for salinity and temperature we have ignored molecular viscosity and applied the continuity equation and the Boussinesq approximation. Then we have applied the same method of Reynolds averaging as for the momentum equations. Temperature and salinity are coupled to the momentum equations by the equation of state using the standard UNESCO formula.

4.4. Horizontal and vertical mixing

Depending on the large difference in scales between the horizontal and vertical motion in the ocean, the eddy viscosity for horizontal motion is several orders of magnitude greater than the vertical one. In the horizontal, we use the approach by Smagorinsky [14].

In its newly updated version of HIROMB, the vertical eddy viscosity is computed using a two-equation model (k-eps), i.e. one equation each for the turbulent kinetic energy and its dissipation. The turbulence model is based on the GOTM [4] model and contains option for a one-equation model [1] and different stability functions.

5. Dynamics of sea ice

The ice model consists of two main components: thermodynamics, i.e. growth and melting, and dynamics, i.e. drift. As for any other large-scale sea ice model, the ice drift model is based on continuum mechanics. The ice mechanics model computes forces and deformation. Thus, its components are an equation of motion (momentum budget) and a constitutive equation, which gives the response of the ice to deformation. To close the system, there are also evolution equations for the remaining budget quantities. For a more complete description of the ice model, see Hibler [7] and Kleine and Sklyar [10].

6. Thermodynamics of sea ice

Growth and melting of sea ice is controlled by the heat budget of the ice cover. In the model, the ice is considered as a plane slab. Its bulk heat budget is given by

$$Q + Q^o = \rho c_p h \frac{d\overline{T}}{dt} - \rho L \frac{dh}{dt}$$

where Q is the atmospheric heat flux at ice surface, Q^o the oceanic heat flux at ice bottom, ρ ice density, c_p specific heat capacity of ice, h ice thickness and $\overline{T}$ mean ice temperature. Both (external) heat fluxes are taken positive if directed into the ice. On the left-hand side of the above equation, there is the heat input into the ice while the contributions to r.h.s. come from heating/cooling and phase change by growing/melting.

As with surface temperature in modelling atmospheric heat flux over open ocean, the ice temperature is part of the problem, i.e. to be determined. We have to obtain both temperature and thickness from this equation. How this is done in detail, the reader is referred to Kleine and Sklyar [10].

7. Parallelization

Before the breakthrough of modern supercomputers with distributed memory and a large number of processors working in parallel, ocean model codes were often written in

Fortran 77. However, to really utilise the efficiency of both shared memory vector computers and distributed memory parallel computers, it has been necessary to at least rewrite some of the code in Fortran 90.

Unlike atmospheric models, where all the grid points in the model are active, ocean models contain a large number of land points. The computational domain therefore has to be partitioned into blocks containing a minimum of inactive points.

Accordingly, the task of parallelization the original HIROMB code has been divided into two main parts; rewriting of the code to take advantage of the Fortran 90 features and dividing the model area into blocks with a minimum of inactive points. A further part is the exchange of numerical algorithms especially designed for distributed memory parallel computers.

For more details concerning the parallelization, the reader is referred to the papers by Wilhelmsson, Schüle and Rantakokko.

7.1. Modification of the code

To minimize the coding work, most of the original Fortran 77 code has been kept intact except where new numerics has been added. The modification of the code has mainly consisted of using pointers to switch between the blocks and different grids. The Message Passing Interface (MPI) library has been used for communication between processors.

One of the most time-consuming parts in the code comes from the implicit solver that is used for both the barotropic part and the ice module. Therefore the old serial solver has been exchanged with a new distributed multi-frontal solver written by Herndon [6].

7.2. Decomposition into blocks

In the computational domain that covers the whole 1 nm grid, only 26% of the surface points and less than 10% of the volume points are active points. Thus the main task of the decomposition is to cut off as much as possible of the non-active grid points. This is achieved by decomposing the domain into blocks that contain as less as possible of the land points. At the same time, there has to be a limit on the number of blocks, because the more blocks the more work is spent on overhead from switching block context and updating block boundaries. A careful examination of how the performance rate depends on the distribution and number of blocks is therefore necessary to arrive at the optimum block decomposition. Because of the implicit treatment of the vertical diffusion it is an advantage if the decomposition is done only in the horizontal. Then a further reduction is possible by eliminating non-active deeper layers.

7.3. Decomposition of ice coverage

Even with the introduction of the new distributed solver for the implicit solution of the ice equations, the ice module still accounts for a large part of the total execution time as soon as the ice coverage reaches normal values. The dynamic nature of the ice coverage requires a time-dependent decomposition, which is different from the one for the water part. Special care also has to be taken to areas where ice will form as the computation of the forecast proceeds. To manage this, the area occupied with ice has been extended to include areas with a sea surface temperature below a given value. Fig. 5 shows an example of two decompositions of the same 1 nm grid, one for water and one for ice. Experiments with equal and different number of blocks for the water and ice part have shown that the best performance is achieved by using fewer blocks for the ice part compared to the water part.

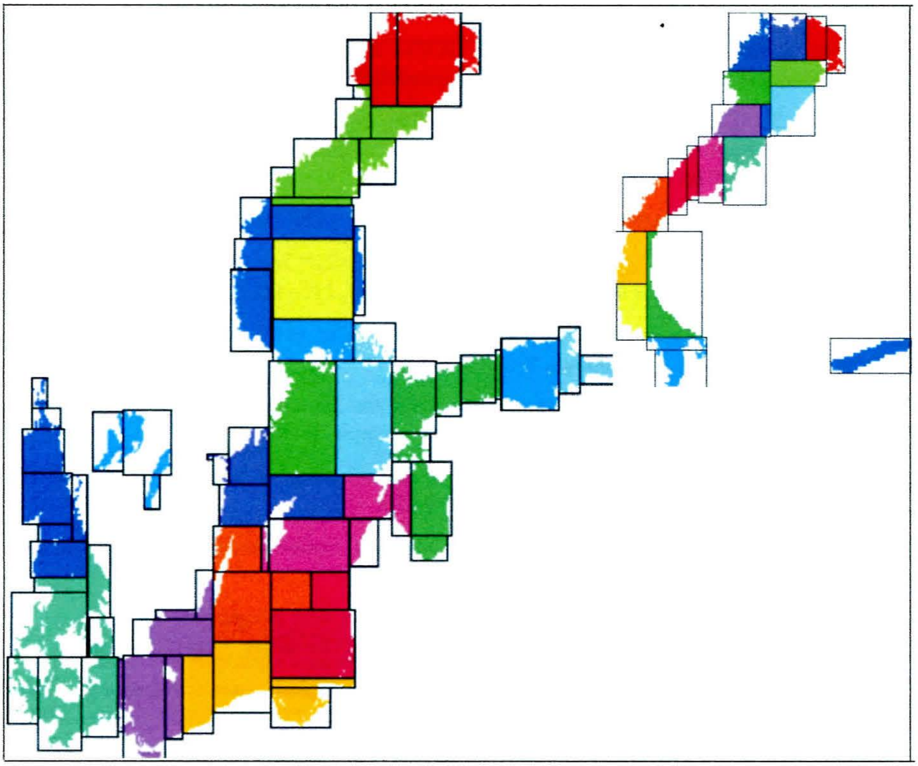

Fig. 5. Two decompositions of the 1 nm grid for water on the left and for ice on the right. The initial ice decomposition consists of 20 blocks on 16 processors [16]

7.4. Data handling

A master processor takes care of the assembling, packing, and writing data and is to some extent overlapping computations done by the working processors. This is a very important point in achieving parallel efficiency. The Herndon's solver [6] requires the working processors to be a power of two, implying that with the master processor included, $2^n + 1$ processors are used in the simulations. The master processor is also responsible for updating and distributing external boundaries to the working processors.

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