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The BSH New Operational Circulation Model Using General Vertical Co-ordinates

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At the Federal Maritime and Hydrographic Agency (Bundesamt fur Seeschiffahrt und Hydrographie) (BSH), a new model version of a circulation model is under development which will use not only an improved grid resolution but also a novel formulation of the vertical co-ordinate. The three-dimensional baroclinic circulation model (BSHcmod) is an important component of the operational model system, which has been running at the BSH for more than 20 years now. Important applications of the model system are the support of the BSH's water level prediction service, forecasting of oil drift paths and pollutant dispersion, as well as water quality studies.

The circulation model simulates tidal, wind and density driven motion in the entire North Sea and the Baltic Sea region. Two nested and interactively coupled grids are used for the German Bight and the western Baltic Sea. The horizontal grid spacing of the new version is 900 m in the nested areas, and approx. 5 km in the other parts of the North Sea and the Baltic. The vertical grid resolution has been improved as well. In addition, a new type of vertical co-ordinate representation has been implemented which allows layer thicknesses to be varied in time and space.

With regard to the performance of general circulation models in a more general context, the new formulation provides a dynamic co-moving description of stratification and its maintenance. Internal dynamics are captured using weakly inclined flexible co-ordinate surfaces. The formulation is of the evolution type, and all common forms of vertical representation are recovered as special examples.

Key words: *circulation model, grid, prediction service, vertical co-ordinate*

1. Introduction

An operational numerical model system supporting various maritime services has been in use at the BSH for many years now (Dick and Soetje, 1990, Dick et al., 2001). The model system is an in-house development of the BSH. Its main components are hydrodynamical models computing currents, water levels, temperatures, salinities, and ice cover in the North Sea and the Baltic (BSH circulation model, BSHcmod) and dispersion models to compute the drift and dispersion of substances (Lagrangian and Eulerian dispersion models, BSHdmod.L and BSHdmod.E). The other components of the model system are a surge model (BSHsmod) and local models for German estuaries, which were developed in order to provide medium-range surge predictions to the BSH's water level prediction service. A new version (v4) of the model system is currently being developed which incorporates several improvements over its predecessor, version 3. The most important alterations are an enhanced horizontal and vertical grid resolution, the introduction of a new vertical co-ordinate to the circulation models, and the implementation of a coupled circulation and wave model with a 3 nm grid spacing in the North Sea and the Baltic. (Fig. 1)

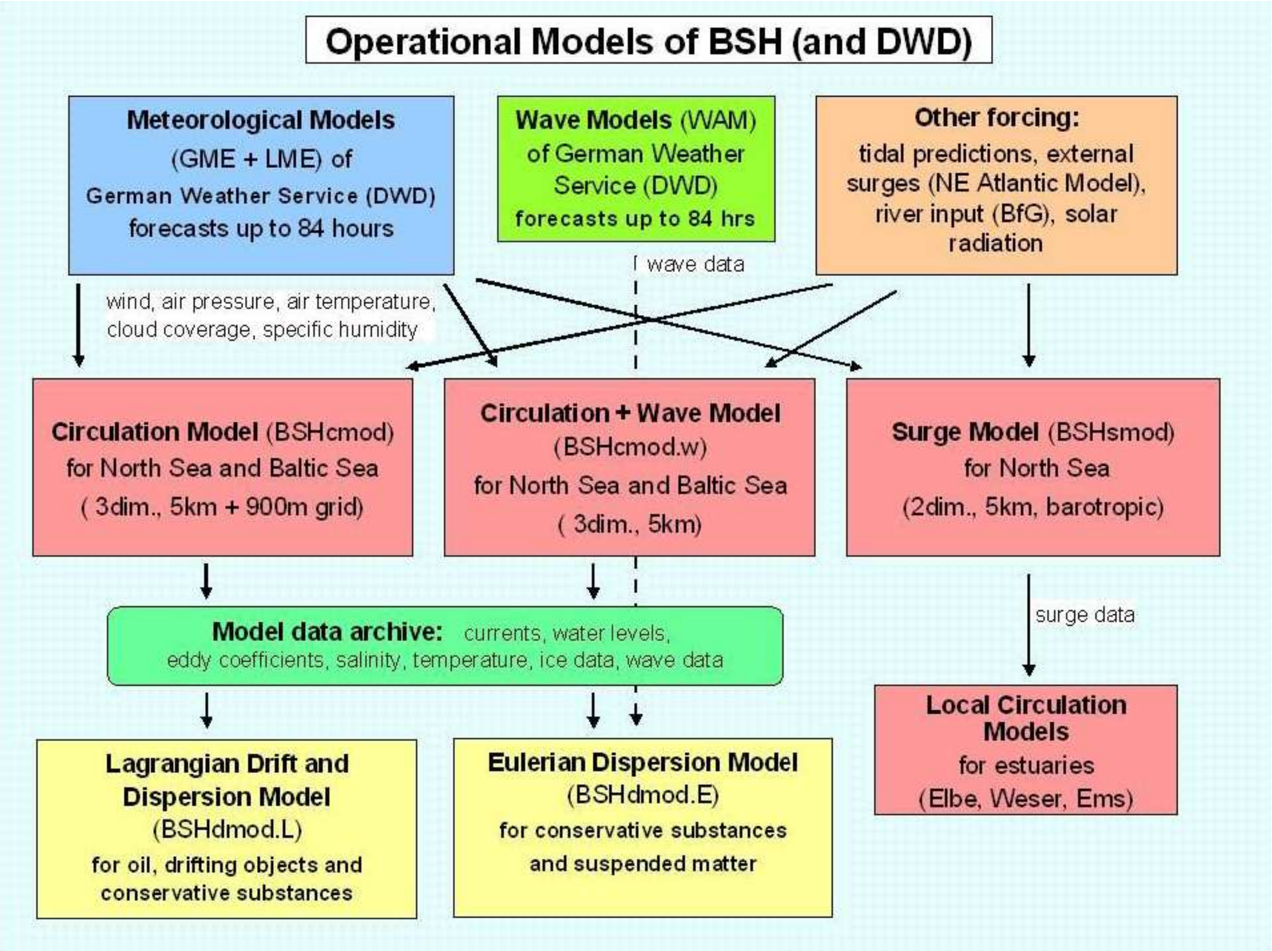

Fig. 1. The BSH's model system driven by models of the German Weather Service (DWD)

2. The Circulation Model

The circulation models of the North Sea and the Baltic are three-dimensional and take into account meteorological conditions, tides, and external surges entering the North Sea from the Atlantic as well as river runoff from the major rivers. Predictions for up to 84 hours are computed in daily routine runs, using meteorological and wave forecasts supplied by the German Weather Service (DWD). Tidal forcing is calculated from the harmonic constants of 14 tidal constituents. External surges entering the North Sea are computed by a model of the Northeast Atlantic and are superimposed on tidal forcing. The new version of the two-dimensional NE Atlantic model has a grid spacing of about 10 km and is also forced by meteorological data provided by DWD.

The circulation model simulates density driven (baroclinic) currents, which are of major importance in the Baltic Sea. Current freshwater input data of the most important rivers are provided by the Swedish Meteorological and Hydrological Institute (SMHI) and the Federal Institute of Hydrology (BfG) in Germany. Heat exchange between the air and water is computed by means of bulk formulae using DWD forecast data. To simulate temperature and salinity advection, the model uses a conservative, shape-preserving numerical scheme of low numerical diffusion (Kleine, 1993). As hydrodynamics is also influenced by ice conditions in the North Sea and the Baltic, an ice model has been integrated to simulate the formation, melting, and drift of sea ice.

In the BSH's North Sea and the Baltic Sea model, the hydrodynamic parameters are computed on two nested and interactively coupled grid nets. Grid spacing in the new model version 4 has been reduced to approx. 900 m in the German Bight and the western Baltic Sea, and approx. 5 km in the other areas of the North Sea and the Baltic Sea. Even bigger changes have been made to the vertical grid structure as compared to the former version. Version 4 not only has a larger number of layers and a higher vertical resolution but also incorporates a new co-ordinate system with weakly inclined flexible co-ordinate surfaces. A detailed description of the improved model will be provided in the following sections.

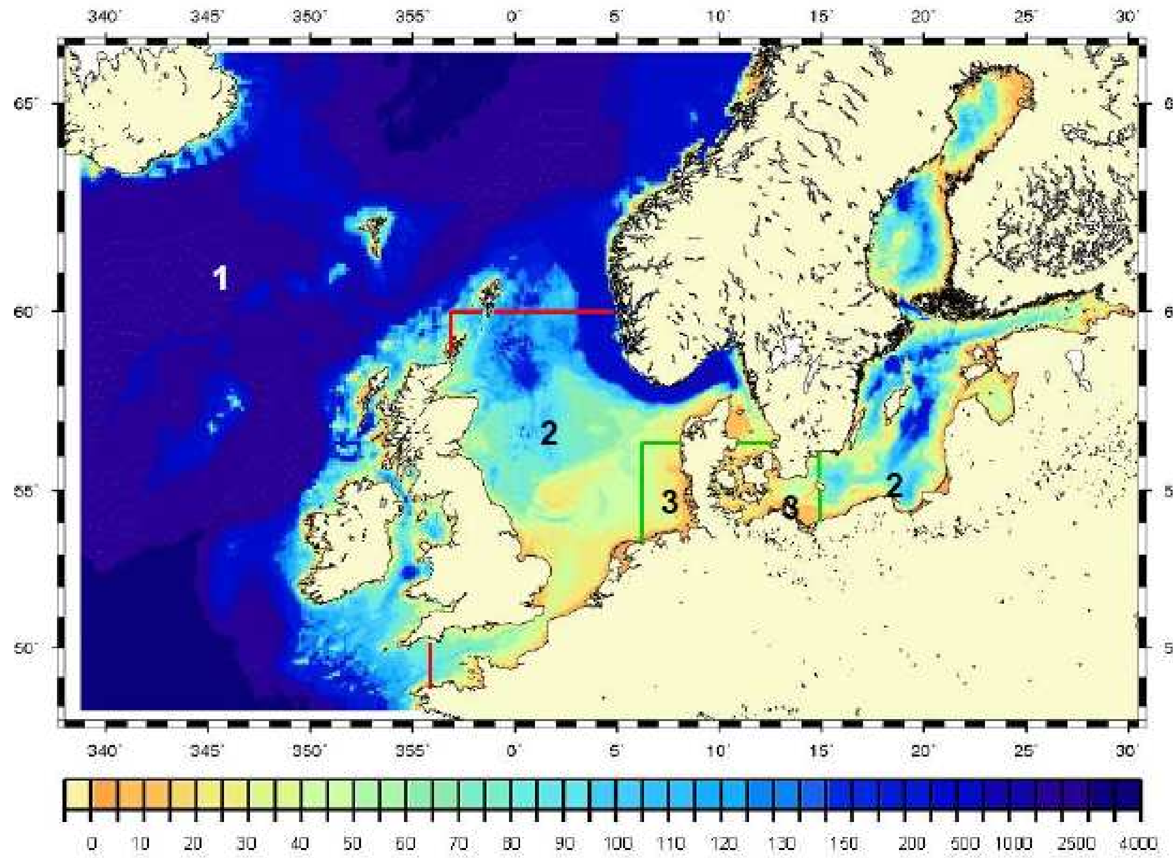

Fig. 2. *Model bathymetry and nesting of grid nets: 1: NE Atlantic (10 km), 2: North Sea + Baltic (5 km), 3: German Bight + western Baltic (900 m)*

3. Novel Design of the Vertical Coordinate

The new version of the BSH's circulation model is based on a special co-ordinate representation as the basic building block. It has been developed in order to improve the model's effective numerical performance.

A recurrent experience is that the effective resolution, used to capture flow features, is much lower than the resolution of the numerical grid. Common-type circulation models are prone to numerical diffusion. The worst effects occur in artificial vertical mixing, where the model's stratification is systematically eroded or even ruined. Expectations are often disappointed, and the model's value often has been greatly reduced. The trouble remains (to a considerable extent) even when a so-called high-resolution scheme is used to calculate transport. This type of scheme has its own effective resolution and at best allows the degradation to be partly compensated. Besides, additional expenses are incurred due to its considerable computational requirements, which are of limited efficiency though.

A different strategy to cope with the problem is addressed here which is at a level closer to its roots. We will deal with the co-ordinate representation and will try to find a physically appropriate description suitable for capturing water masses. To keep numerical diffusion due to vertical transport modelling as low as possible, we will try to find a layer description which follows the vertical motion of water masses as closely as reasonable. However, the co-motion has to be limited in order to keep the description of water masses from degenerating, an effect typically observed in isopycnal models. The method is briefly described in the following. A more thorough explanation has been provided by Kleine (2003).

In order to gain sufficient flexibility, we will use the calculus of a co-ordinate system with arbitrary representation of the vertical. The pertinent framework is found in Kasahara (1974), Johnson (1980), Burger & Riphagen (1990).

A one-dimensional transformation is applied to replace the vertical (height), z , by another variable, s , whose relation to height is required to be invertible, i.e. $\delta s/\delta z$ be non-zero, say $\delta s/\delta z > 0$. This transformation may vary over the horizontal, so that surfaces on which the new vertical co-ordinate is constant need not be horizontal. Partial derivatives with respect to a horizontal dimension should be understood to relate to such a non-horizontal surface. Therefore, it is not just the vertical which is affected by the transformation, but the entire co-ordinate system. Besides, the co-ordinate transformation may vary with time.

The transformed vertical co-ordinate is known as a "generalised vertical co-ordinate", as long as no other condition except invertibility is assumed to hold. The transformed system has the spatial co-ordinates x , y , and s (as vertical co-ordinate). Now, compared to the above, consider z from the opposite point of view, i.e. *from the perspective of the general vertical co-ordinate system*. Height z then is a function of (x, y, s, t) , where time t enters as another independent variable. Furthermore, let $\vec{v}$, w be conventional horizontal and vertical components of velocity, respectively. Let us look at the vertical velocity as *represented in the* (x, y, s, t) *system*.

It reads

$$w = \frac{Dz}{Dt} = \frac{\partial z}{\partial t} + \vec{v}\nabla_s z + \dot{s}\frac{\partial z}{\partial s} \qquad (1)$$

where

∇_s - denotes the horizontal *nabla* operator applied on a surface of constant s .

Interpreting this relation, we recognize the components of vertical motion of an object as *seen from the viewpoint of a general frame of non-horizontal vertically moving surfaces*. These are, firstly, the apparent motion of the object due to the up-and-down motion of the reference level, secondly, the vertical motion due to horizontal motion of the object and inclination of the reference level and, thirdly, the relative motion due to motion along the vertical with respect to the rising or falling reference level. The latter component of vertical velocity, across the moving s surface, is called *pseudo-vertical velocity*.

The above equation (1) provides a basic relation between the listed velocity components, and it holds true for any system with a generalised vertical co-ordinate. To characterise any special system, one more relation is required. Here, no algebraic equation will be introduced but another relation between pseudo-vertical velocity and up-and-down velocity, cf. (Kleine, 2003)

$$\dot{s}\frac{\partial z}{\partial s} = \gamma\frac{\partial z}{\partial t} + \frac{\partial}{\partial s}\left(\frac{\mu}{\partial z/\partial s}\right) - \nabla_s\left(\upsilon\nabla_s z\right) \qquad (2)$$

This equation is to specify the flow-driven co-ordinate surface motion. Non-negatively valued adjustable parameters (γ, μ, v) were chosen for the equation. As regards dimensions, γ is nondimensional while μ and v are diffusion coefficients [m^2/s]. The terms associated with μ and v are used to regularise the co-ordinate surface dynamics as they work to relax the configuration, balancing the distortion caused by co-motion with the flow. In the suggested equation, the pseudo-vertical velocity is related to the up-and-down velocity of the co-ordinate surface, a vertical redistribution process, and horizontal diffusion-like smoothing.

Equation (1) is a statement of a physical fact while equation (2) is a specifying ansatz – construction, essentially a model. In conjunction, they constitute a system of equations for the *evolution* of the vertical representation which may be solved for the up-and-down velocity and the pseudo-vertical velocity.

It is easily demonstrated that the suggested layer model comprises all common forms of vertical representation which are, firstly, height, secondly, sigma, eta (re-scaled height), and thirdly, material (isopycnal) surfaces, which are all covered as special limit cases. For the proof see Kleine (2003). Our implemented setting is intermediate in order to achieve a reasonable compromise between co-motion and regularity.

To focus on $\delta z/\delta s$ and its evolution, consider the equation of continuity (for an incompressible fluid). In the context of a general vertical co-ordinate, it takes the form of

$$\frac{\partial}{\partial s}\left(w - \vec{v}\nabla_s z\right) + \nabla_s\left(\vec{v}\frac{\partial z}{\partial s}\right) = 0$$

As a prognostic equation for differential layer thickness $\delta z/\delta s$ in flux form, it reads

$$\frac{\partial}{\partial t}\left(\frac{\partial z}{\partial s}\right) + \frac{\partial}{\partial s}\left(\dot{s}\frac{\partial z}{\partial s}\right) + \nabla_s\left(\vec{v}\frac{\partial z}{\partial s}\right) = 0 \qquad (3)$$

Plug Eq.(2) into the continuity equation (3). The result is an evolution equation for differential layer thickness, controlled by horizontal flow, vertical rectification, and horizontal smoothing.

$$(1+\gamma)\frac{\partial}{\partial t}\left(\frac{\partial z}{\partial s}\right) + \frac{\partial}{\partial s}\left(\frac{\partial}{\partial s}\left(\frac{\mu}{\partial z/\partial s}\right)\right) + \nabla_s\left(\vec{v}\frac{\partial z}{\partial s} - \upsilon\nabla_s\left(\frac{\partial z}{\partial s}\right)\right) = 0 \qquad (4)$$

To completely specify the evolution of $\delta z/\delta s$ (as a spatially distributed and time-varying scalar quantity), an initial-boundary value problem should be formulated. For a budget equation in flux form, it is natural to prescribe normal flux, i.e. the flow component normal to the boundary. In our special setting, the boundary conditions (for the co-ordinate evolution problem) are as of the eta (re-scaled height) model, i.e., firstly, vanishing pseudo-vertical velocity $\dot{s}\,\partial z/\partial s = 0$ at the surface and bottom and, secondly, fixed height $\delta z/\delta t = 0$ at the bottom.

4. Model Setup and First Results

In the horizontal, the model equations of BSHcmod are defined for a computational grid of spherical co-ordinates. Grid spacing in the German Bight and the western Baltic Sea is approx. 900 m (Δλ= 50''; Δφ= 30''), and in the other parts of the North Sea and the Baltic approx. 5 km (Δλ = 5 '; Δφ = 3').

The entire model, of which the equation of continuity is only one component, is formulated in the (x,y,s) system. Layer thickness varies in space and time, controlled by the transformation from (x,y,s) to (x,y,z). The vertical discretization is cast in terms of finite s (vertical integer index). Layering (number of stacked cells) in the water columns may be defined separately for each individual water column.

The finite counterpart of continuity equation (4) provides the vehicle which controls cell volume

dynamics. In the currently running implementation, the widely variable and flexible setting has been specified to remain close to Mesinger's "step-mountain" coordinate, which amounts to γ low, μ relatively high, and ν as large as required. The quantity μ may be viewed as a diffusion coefficient. With the mixing-length concept in mind, it assigns both length and velocity scales to each water parcel (mass element) in the (*x*, *y*, *s*) system. In each water column, the velocity scale is introduced as a normalising constant while the length scale is allowed to vary (as a function of *s*). When the flow diminishes, the vertical coupling term in (4) gives the model a tendency to relax to an equilibrium configuration. We will refer to this distribution of thickness as the reference configuration. This configuration may differ in different parts of the model domain but should reflect the prevailing hydrodynamic conditions as stratification or current shear. In its present version, the BSH model uses a maximum of 30 layers. In areas with more intensive tidal mixing, bigger reference layer thicknesses have been defined than in areas with low tidal influence. In the Baltic, the reference layer thickness of the first 10 layers is 2 m each, increasing gradually toward the bottom.

Another equilibrating term used is horizontal smoothing. The exchange coefficient ν is composed of another scaling velocity and grid spacing length as the "mixing length", in particular $(\nu_\lambda, \nu_\varphi) = (v^* R \cos\varphi\, \Delta\lambda,\ v^* R\, \Delta\varphi)$ where v^* denotes the scaling velocity referred to and *R* stands for the earth's radius.

The new version of BSHcmod has been tested in several sensitivity studies. Different simulations have been carried out - and are still going on - in order to adjust the quantities (*γ*, *μ*, *ν*). Finding suitable combinations of the quantities is a lengthy procedure which will have be continued in the near future. At the moment, we can only present preliminary results of a special version using the parameter setting described above. In this configuration, variations of layer thicknesses are due mostly to water level changes. This test version has been running in pre-operational mode since February 2006.

Figs. 3 and 4 show first computation results for salinities and currents in the western part of the Baltic Sea, predicted for 30 March, 2006, 00:00 CET and 13 April, 2006, 00:00 CET, respectively. Although the model layers in this version have a considerably reduced ability to follow the deformation of water masses, baroclinic structures in the form of meandering frontal structures, stratification, and eddy formation are reproduced much better than with the preceding (z-level) version. However, more sensitivity studies will have to be carried out during the next few months in order to find suitable values for *γ*, *μ and ν*. In our view, the suggested method has considerable potential which should be fully utilized

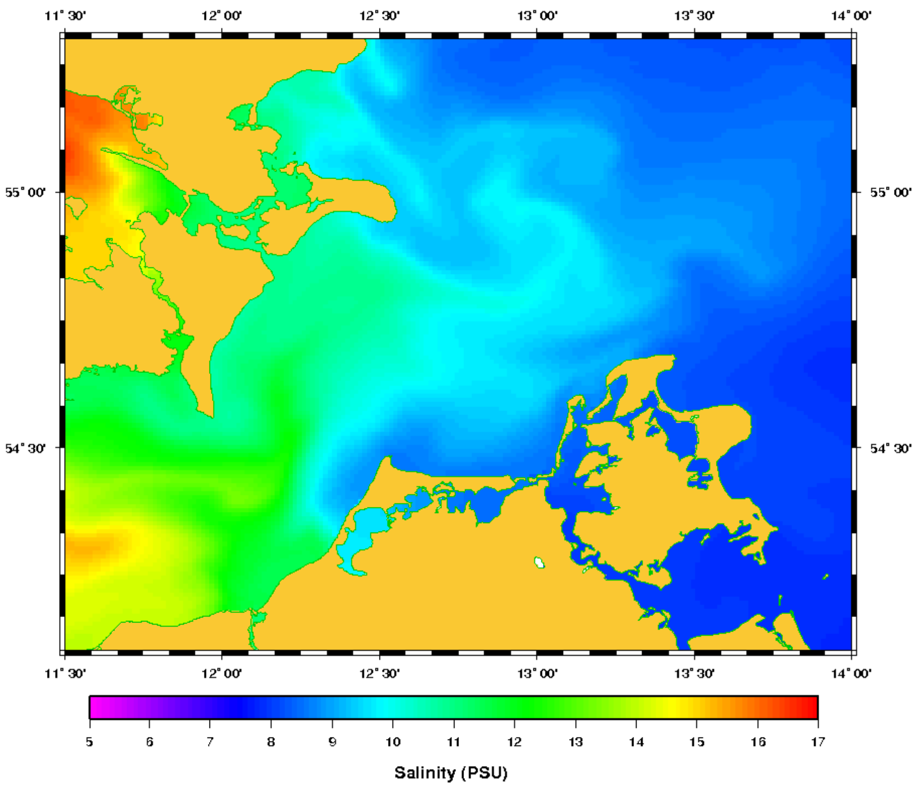

Fig. 3. Computed surface salinities in the western Baltic Sea on 30.03.2006, 00:00 CET

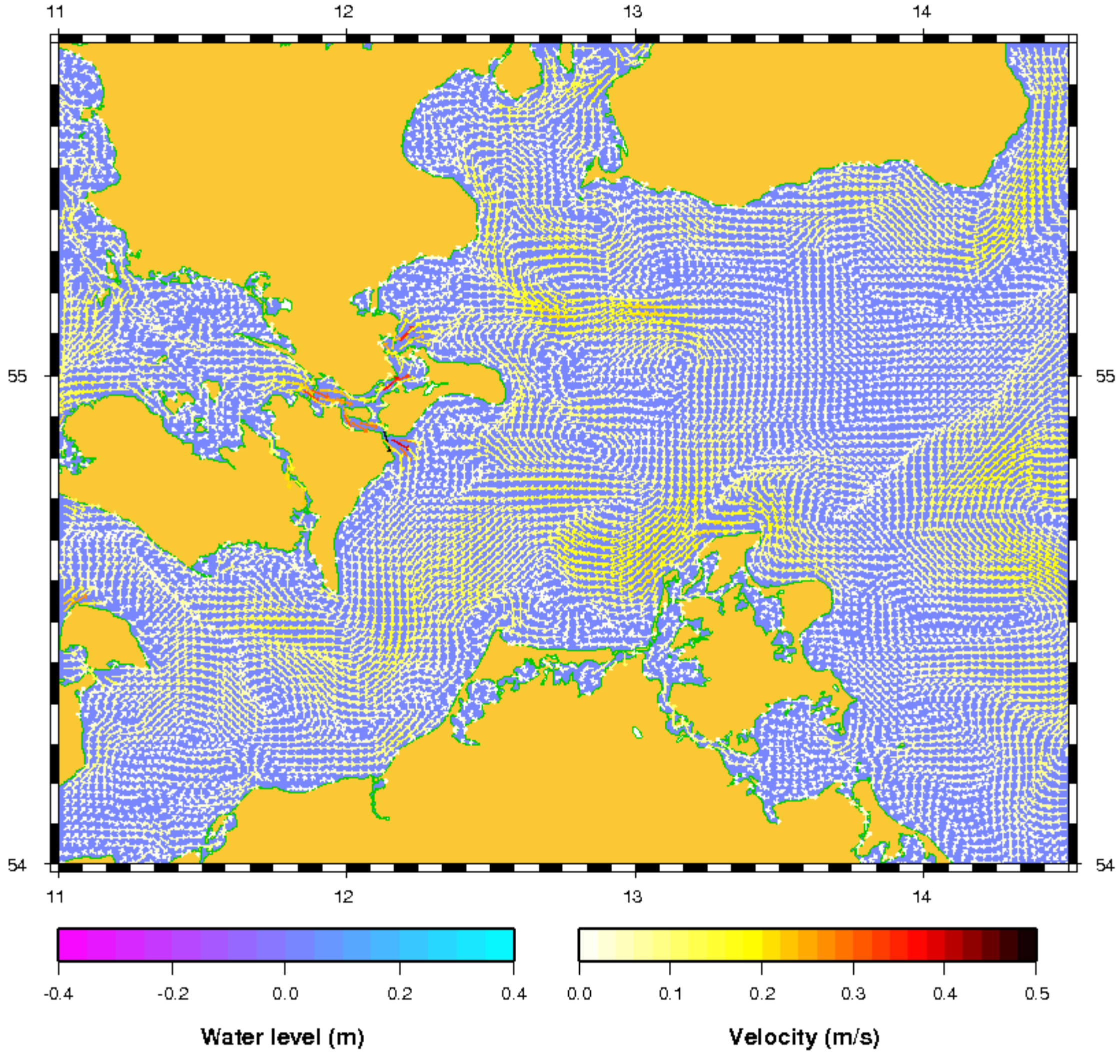

Fig. 4. Computed surface currents in the western Baltic Sea on 13.04.2006, 00:00 CET

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Operatyvinio hidrodinaminio modelio BSH naujoji versija integruojant vertikaliąsias koordinates

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Šiame straipsnyje aprašyta skaitmeninio modelio BSH nauja versija. Tai operatyvinis hidrodinaminis modelis, aprašantis Šiaurės ir Baltijos jūrų vandens lygių svyravimus ir tėkmių struktūras. Taip pat jį galima naudoti vandens kokybės studijose. Šiame modelyje naudojama naujoji vertikaliosiomis koordinatėmis paremta sistema. Pasirinkta modelio gardelių sistema (10 km, 5 km ir 900 m) leidžia detaliai prognozuoti jūrų hidrodinaminio režimo pokyčius. Sukurta 4-oji šio modelio versija padidina skaičiavimų efektyvumą.