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An operational model for Lithuania’s coastal zone

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Abstract The results of testing (hindcast) an operational hydrodynamic model HIROMB_LT for Lithuania’s coastal zone are presented and analysed in this paper. A model is developed using the program code of an operational hydrodynamic model of the Baltic Sea HIROMB (Swedish Meteorological and Hydrological Institute). The model grid (horizontal resolution 300m, vertical resolution 25 layers) covers the Baltic Sea coastal area until the Gdansk Bay in the West and Latvian border in the North and the Curonian Lagoon. The model simulated water levels, surface water temperature surface water salinity and ice cover variables were tested against measurements for the year 2009. The model shows satisfactory performance on water level and temperature and rather weak performance on salinity at stations where good reproduction of the mixing of fresh and saline water is critical (Juodkrantė and Klaipėda seaside stations). The model performance on ice thickness is still problematic because of too coarse spatial resolution of westerly winds. Despite of these shortcomings, the model can be used for operational forecasts already; however, data assimilation may be necessary for salinity and ice thickness.

Keywords *• Operational model • Validation • Baltic Sea • Coastal area • Lithuania*

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INTRODUCTION

The coastal zone is the place of the highest ecosystem goods and services (Costanza *et al.* 1997). Coastal zones are under threat from both natural and anthropogenic forcing which limit the capacity of these ecosystems to support the coastal goods and services. There is an urgent need for a better understanding of natural and human induced processes to develop decision-making in the coastal zones. It is necessary to monitor and forecast processes and changes in the ocean. This is the goal of rapidly emerging field of operational oceanography. Integration of *in situ* data and observation from space together with advanced modelling should serve as input to a decision support system that can be used to fulfil the duties with regard to navigational safety, Search & Rescue and environmental protection purposes.

The Baltic Sea (Fig. 1) is a young semi-enclosed intra-continental shallow sea that is ecological unique and highly sensitive to environmental threats due to its special geographical, climatological and oceanographic characteristics. Today the Baltic Sea faces major environmental problems. The human impact has increased the nutrient load and has led to eutrophication. The impact of climate change is an additional potential threat on a centennial timescale (Rodhe, Winsor 2002; Stigebrandt, Gustafsson 2002; Bates *et al.* 2008; Neumann *et al.* 2012). The coastal zones play a specific role in the Baltic Sea, because their extent is relatively large compared with the entire area of the sea. A very important component of Lithuanian Baltic Sea coastal area is the Curonian Lagoon that is in tight interaction with the coastal seawaters. The Curonian Lagoon is a shallow and semi-enclosed sub-basin of the Baltic Sea. The Curonian Lagoon is the largest coastal shallow lagoon in the Baltic Sea and Europe (Fig. 1). Total area of the Lagoon is approximately 1584 km^2, volume is 6.3 km^3, length 93 km, width 46 km, mean

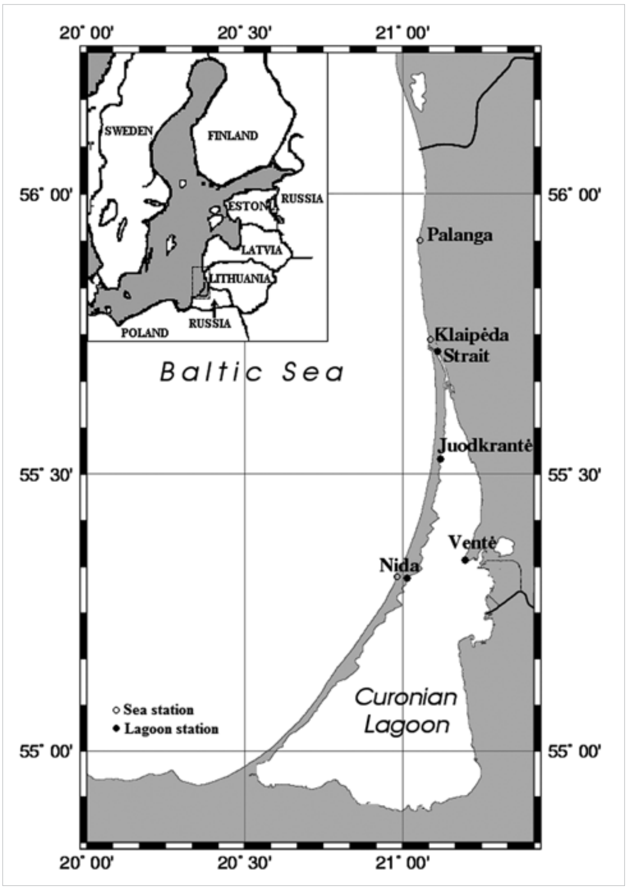

Fig. 1 Lithuania Baltic Sea coastal area, the Curonian Lagoon and coastal monitoring stations. Compiled by I. Dailidienė and P. Zemlys.

depth is approximately 3.8 m, the maximum 5.8 m (Žaromskis 1996). The lagoon is an invaluable component of the nature and ecosystem and together with sea coastal waters gives comfortable possibilities for the surrounding inhabitants to develop fishery, tourism and recreation. The Northern part of the lagoon is also used as a seaport. Being an important economical and nature resource the Lithuanian coastal area requires permanent monitoring of its current state and tools for the forecast the state in future.

According to HELCOM Recommendation 12/6 1991 regarding development of an oil drift, the Federal Maritime and *Hydrographic* Agency (BSH, Germany) and Swedish Meteorological and Hydrological Institute (SMHI, Sweden) have developed an operational hydrodynamic Baltic Sea model, HIROMB, with a capacity, as routine, to provide the Baltic Sea states with data necessary to fulfil their national duties with regard to navigational safety, Search & Rescue and environmental protection purposes. Using model HIROMB (High Resolution Operational Model for the Baltic Sea) (Funkquist, Kleine 2007) the Swedish Meteorological and Hydrological Institute makes daily weather and hydrological forecasts and warnings for Sweden and the Baltic Sea. The model gives daily forecasts of currents, salinity and temperature at different depths as well as surface elevation, ice coverage and ice thickness. The finest available model grid horizontal resolution for the Baltic Sea in HIROMB is one nautical mile.

HIROMB hydrodynamic forecasts being valuable by themselves are also used as driving forces for oil-spill drift forecasting system Seatrack Web (Ambjörn, Mattson 2006) that covers the Baltic Sea and the eastern part of the North Sea. The drift model calculates the three-dimensional movements of substances or objects at sea, including sinking, stranding and turbulent dispersion. The system has been developed in co-operation by several institutes around the Baltic Sea with the active participation of HIROMB Cooperative Society.

However, even if HIROMB forecasts are very useful for the whole Baltic Sea, 1nm mile horizontal resolution is too coarse for many coastal areas with more complex morphological properties. Therefore for many of such areas so called local models are developed. Some of them are based on the same code as HIROMB for the whole Baltic Sea (global model) some on different code but all of them are using global HIROMB forecasts for boundary conditions. Local models are developed or are under development for Gulf of Finland at Russian State Hydrometeorological University, for the Gulf of Riga at Marine Systems Institute of Tallinn University of Technology, for the Gulf of Gdansk at Maritime Institute in Gdansk, for Brofjorden fjord at SMHI.

The Lithuanian costal area (including the Curonian Lagoon) is covered by global HIROMB 1nm grid. The Klaipėda Strait, however, being nearly 300 m wide is too small to be adequately resolved by 1nm resolution, therefore the need of local model with finer resolution is obvious for this area. The aim of this study was to develop and to test the local model for Lithuania coastal area including the Curonian Lagoon to be suitable for the operational forecast of water levels, salinity, and temperature and ice cover.

No operational models are developed for this area yet. All applications of hydrodynamic models to the Curonian Lagoon until now were focussed on investigations of horizontal water circulation patterns (Raudsepp, Kouts 2002; Davulienė, Trinkūnas 2004; Chubarenko, Chubarenko 1995; Ferrarin *et al.* 2008). The recent application of 3-D model to the Curonian Lagoon and coastal area of the Baltic Sea was done by Zemlys *et al.* (2013). To make local operational model easier to couple with the operational model HIROMB for the whole Baltic Sea in the sense of data exchange and to be to run as part of the operational service, the code of HIROMB was chosen for local model development.

MATERIAL AND METHODS

The model HIROMB was used in this study. HIROMB (Funkquist, Kleine 2008) is a hydrodynamic 3-dimensional baroclinic model of the North Sea and the Baltic Sea, designed for a daily operational use for water level, water currents, and salinity, temperature and ice forecasts. The operational forecasts started in 1995 with a daily 24-hour forecast and were later extended to 48 hours. The model is mainly forced by SMHI's operational atmospheric model (HIRLAM), but also by river runoff from an operational hydrological 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 one nm grid. A parallelization of the model has been developed and runs on a distributed memory parallel computer (Wilhelmsson 2002).

The ice model in HIROMB 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 and uses modified Hibler formulation (Hibler 1979; Kleine, Sklyar 1995).

The model uses the so-called C-grid (Arakawa, Lamb 1977) for horizontal resolution. In the vertical, a z-coordinate system is used with fixed levels in a non-uniform distribution and the thickness of the bottom layer depends on the local depth. The variables are arranged so that vertical velocity is defined at the top and bottom of a grid cell while density is defined in the middle of the cell. Generally, for space discretization the central difference approximation of derivatives and averages wherever required are used.

The general scheme for time discretisation is a two-level time-stepping scheme. Horizontal advection of momentum, salinity and temperature as well as ice and the horizontal turbulent fluxes are treated explicitly. A shock capturing advection scheme is used for salinity and temperature. Implicit components are barotropic gravity terms in the momentum and continuity equations and vertical exchange of momentum, salinity and temperature. An iterative procedure with a sequence of linearizations is used for ice dynamics, interaction of momentum balance and constitutive equations.

The local model HIROMB_LT for the Lithuania coastal area was developed with a horizontal resolution 300 m and 25 vertical layers. The numerical computation has been carried out on a spatial domain that represents the Curonian Lagoon and coastal area of the Baltic Sea until the 70 m depth contour through a finite difference grid (Fig. 2). The grid contains 178 cells West-East and 492 cells in the South-North direction. The water column is discretized into maximum 25 vertical levels with progressively increasing thickness varying from 1 m for the first six layers, 2 m for the next 7 layers and 4 m for the deepest layers of the outer continental shelf.

The open boundaries are the rivers and edges of the Baltic Sea area (Fig. 2). Daily river discharges were provided by the Lithuania hydro-meteorological service. Open sea boundary water temperature, salinity and water levels were obtained by spatial interpolation of 1 nautical mile spatial resolution forecasts by the global operational hydrodynamic model HIROMB provided by the Swedish Meteorological and Hydrological Institute. The initial fields were also spatially interpolated from data of global HIROMB. Meteorological forcing fields were obtained by forecasts of the operational meteorological model HIRLAM (www.hirlam.org) provided by the Lithuania Hydro-meteorological Service.

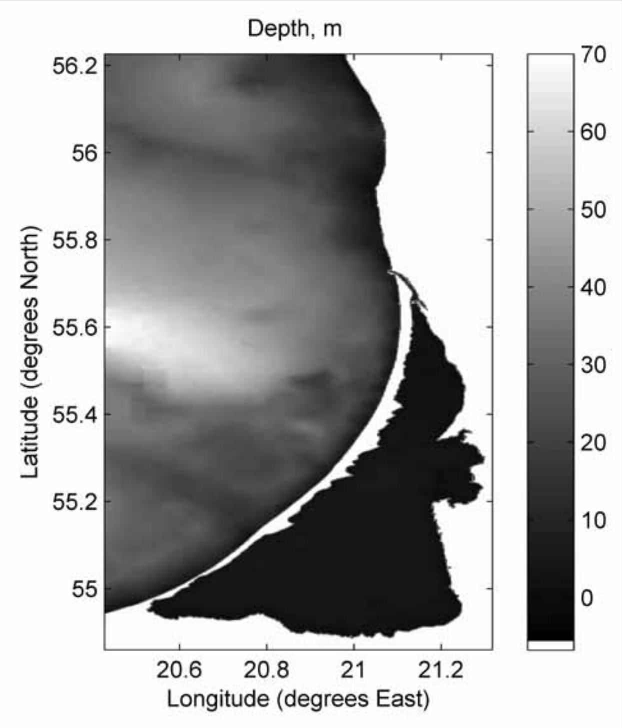

Fig. 2 Computational area for the local model HIROMB_LT. Compiled by P. Zemlys.

The model performance was tested using water levels, surface temperature surface salinity and ice thickness of Lithuania State Monitoring provided by Marine Research Department of the Lithuania Environmental Agency. The locations of monitoring stations are given in Fig. 1. The simulations have been carried out with a time step of 30 s for the time between 1 January and 31 December of the year 2009 with default model parameter values.

RESULTS

Time-series of observed and modelled water levels in different stations are shown in Fig. 3. The model reproduces water levels satisfactory. The correlation coefficient between observed and modelled water levels is higher than 0.95 for all stations except Juodkrantė where it is equal to 0.872.

Time-series of observed and modelled surface water temperature is shown in Fig. 4 and Fig. 5. The model reproduces the seasonal trend of temperature quite well, however modelled temperature has lower oscillation peaks than measured (Fig. 4). This effect is more expressed for the stations in the Curonian Lagoon for temperatures higher than 10 °C and much less for the Baltic Sea and Klaipėda Strait stations.

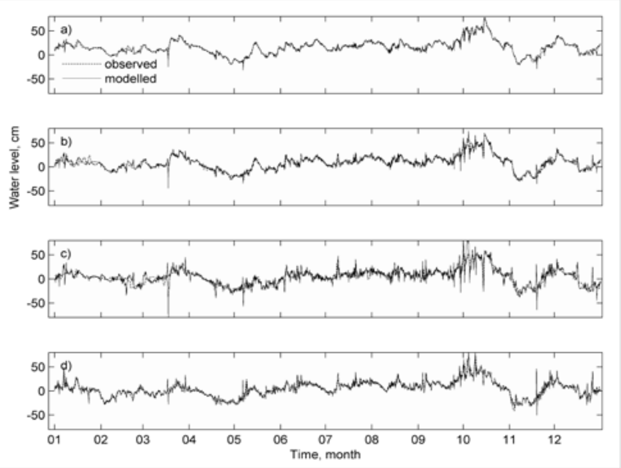

Fig. 3 Time-series of observed and modelled water levels: a) Nida lagoon side station (R=0.981, RMSE=2.895), b) Ventė station (R=0.957, RMSE=4.441), c) Juodkrantė station (R=0.872, RMSE=8.275), d) Klaipėda harbour station (R=0.961, RMSE=4.475). Compiled by P. Zemlys.

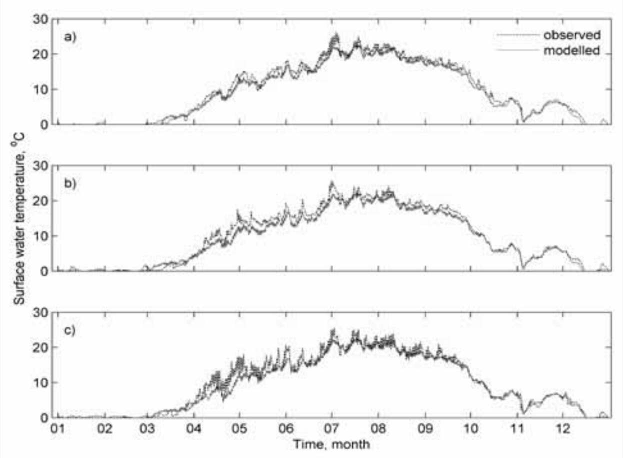

Fig. 4 Time-series of observed and modelled surface water temperature: a) Juodkrantė station (R=0.995, RMSE=1.16, b) Nida lagoon side station (R=0.993, RMSE=1.355), c) Ventė station (R=0.987, RMSE=1.509). Compiled by P. Zemlys.

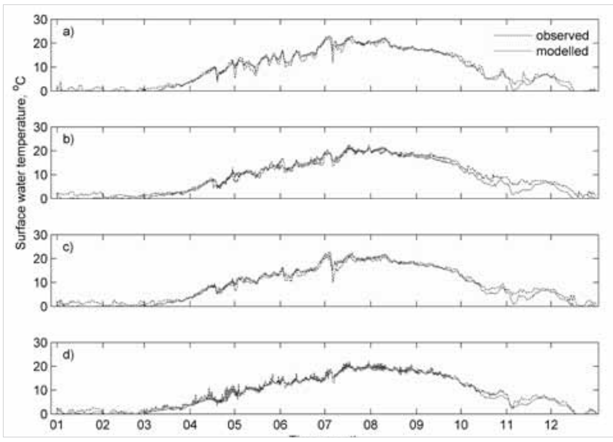

Fig. 5 Time-series of observed and modelled surface water temperature: a) Klaipėda harbour station (R=0.989, RMSE=1.203), b) Klaipėda sea side station (R=0.982 RMSE=1.627), c) Palanga station (R=0.987 RMSE=1.444), d) Nida sea side station (R=0.99 RMSE=1.116). Compiled by P. Zemlys..

Time-series of observed and modelled surface salinity is shown in Fig. 6 and Fig. 7. Stations Vente and Nida located in the Curonian Lagoon (Fig. 6a, Fig. 6b) are quite far from the Sea entrance where fresh water is observed almost the whole year. The model reproduces this situation quite well (Fig. 6a, Fig. 6b). Station Juodkrantė that is located much closer to the Sea entrance is affected by saline water intrusions quite often, but as one can conclude comparing measurements in Juodkrantė and station in Klaipėda Strait (Fig. 6c and Fig. 7a) not all intrusions reach this station. Though the majority of intrusions are correctly reproduced by the model in Klaipėda Strait (R=0.821, RMSE=1.494) (Fig. 7a), the majority of salinity peaks in Juodkrantė reproduced by the model are to low in comparison with observations and model performance for this station should be treated as poor (R=0.41 RMSE=1.656). The weakest performance for the sea stations can be found in Klaipėda where residual mean square error is equal to 1.9 ‰ while in other sea side stations the residual mean square error is less than 1 ‰.

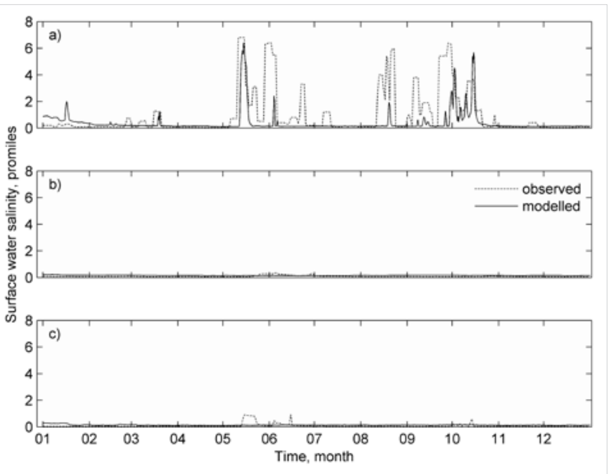

Fig. 6 Time-series of observed and modelled surface water salinity: a) Juodkrantė station (R=0.41 RMSE=1.656), b) Nida lagoon side station (RMSE=0.097), c) Ventė station (RMSE=0.153). Compiled by P. Zemlys.

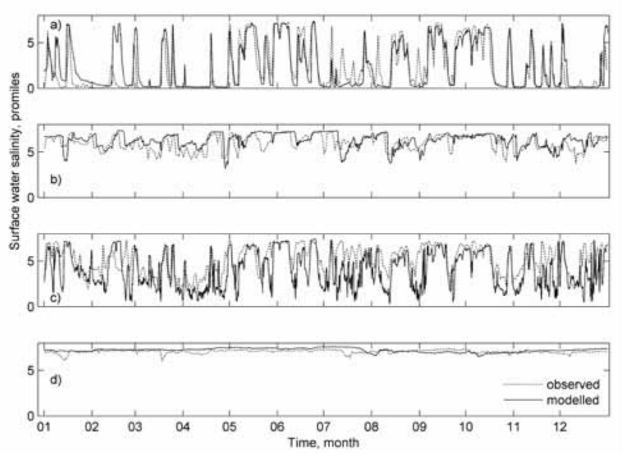

Fig. 7 Time-series of observed and modelled surface water salinity: a) Klaipėda harbour station (R=0.821, RMSE=1.494), b) Palanga station (R=0.446, RMSE=0.907), c) Klaipėda sea side station (R=0.615, RMSE=1.924), d) Nida sea side station (RMSE=0.316). Compiled by P. Zemlys.

Time-series of observed and modelled ice thickness is shown in Fig. 8. In all three stations, we observe underestimation of ice thickness. Also, as one can see from observed ice thickness data (Fig. 8) the ice cover was permanent in all stations except during a short period in Juodkrantė where after formation of ice cover in January it disappeared (was broken) after one week until the beginning of February. However, the model does not reproduce this situation correctly. As one can see from modelled ice thickness graphs (Fig. 8) presence and absence of ice change too frequently in comparison with observations.

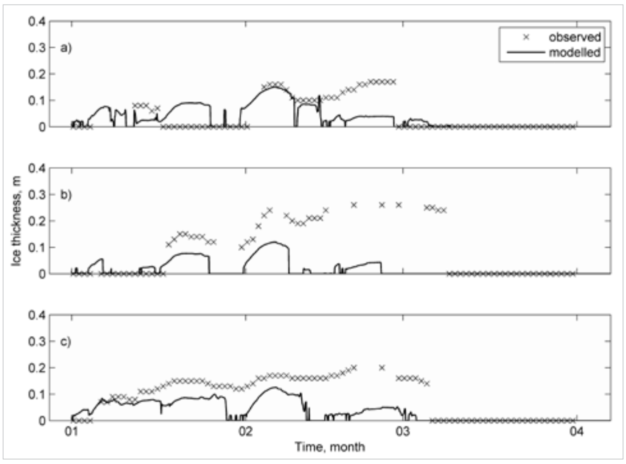

Fig. 8 Time-series of observed and modelled ice tickness: a) Juodkrantė station (R=0.502, RMSE=0.057), b) Nida lagoon side station (R=0.379, RMSE=0.112), c) Ventė station (R=0.625, RMSE=0.077). Compiled by P. Zemlys.

DISCUSSION

The model performance on water levels in general is satisfactory. The exact reasons of poorer model performance on water levels in Juodkrantė station are unknown. One of possible reasons may be the lower quality of measurements also shown by the periods of registered constant water level (see Fig. 3a).

The model performance on temperature is rather good. The only explanation could be given for lower temperature oscillation peaks than observed ones is that temperature is measured very close to the coast in the points with shallow depth where water can be heated by the sun more than in the places with higher depth, while modelled temperatures represent the average temperature of a cell with the depth 1 m and side length 300 m. Since in the seawater mixing is more intensive due to waves, we observe this effect here to a less extent than in the Lagoon stations (se Fig. 5).

It is not an easy task to reproduce salinity for the system where water exchange takes place through such a narrow (narrowest place a little bit less than 300 m) strait as Klaipėda Strait is. The global HIROMB resolution of 1nm does not give any possibility to reproduce exchange of fresh and saline water adequate to this area. As one can see from the local model results, the local model reproduces realistic salinity values. The model reproduces not all salinity peaks and their magnitude correctly but in most cases model gives satisfactory results. A too coarse local model resolution of 300 m still might be one of the possible reasons of quite poor model performance in Juodkrantė and Klaipėda seaside stations. However increasing the spatial resolution would increase computational time. The run time of the 24 hours forecast on 16 processors with 300m spatial resolution is about half an hour. Increasing the spatial resolution twice will increase the number of cells and accordingly the calculation time four times what is not very acceptable for the operational model. To use the model in operational mode with current resolution data assimilation might be necessary for the salinity.

The model performance on ice is rather poor but much more realistic than performance of global HIROMB. Analysis of global HIROMB forecasts for year 2009 showed that presence of ice was reproduced for very short periods (hours) only, and the majority of time reproducing no ice condition. The local model performs much better though still is not able to reproduce ice thickness satisfactory. One of the reasons of poor model performance on ice might be a too coarse resolution of the wind. The meteorological forcing in this study was reproduced from HIRLAM predictions with 8 km spatial resolution. In this case, the influence of the Curonian Spit (width 1–2 km) on to the speed of westerly winds is not taken into account. The comparison of HIRLAM wind speed with the wind speed observed in Nida meteorological station located on the lagoon side of the Curonian Spit shows that modelled westerly strong wind speed is almost twice as high than observed ones (Fig. 9). Too high wind speed in the model results in ice breaking by wind and its removal by currents. It can be expected that increasing the resolution of meteorological forcing will improve model performance on ice in some extent. With current wind field resolution data assimilation for ice might be necessary.

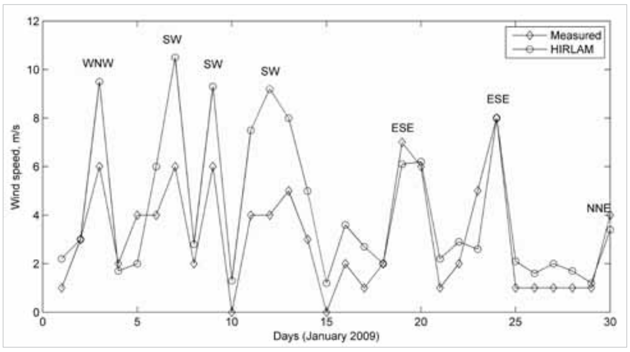

Fig. 9 Comparison of 8 km spatial resolution HIRLAM model wind speed with observations in Nida station. Compiled by P. Zemlys.

CONCLUSIONS

In this paper, an operational hydrodynamic local model of the Lithuanian Baltic Sea coastal area has been presented. A one-year simulation with real meteorological and hydrological forcing was carried out in order to test the model against water level, water salinity, temperature and ice thickness measurements (hindcast). Testing results let us draw the following conclusions:

The local model performs better than the global HIROMB model for the whole Baltic Sea. Therefore, development and use of the local model is reasonable.

The model shows satisfactory performance on water levels and temperature.

The model performance on salinity is satisfactory in the majority of stations and rather weak in Juodkrantė and Klaipėda seaside stations. It seems that the model spatial resolution of 300 m is too coarse to resolve water exchange between the Klaipėda Strait and Baltic Sea and between the Klaipėda Strait and the Curonian Lagoon adequately. The increase of spatial resolution, however, may increase the forecast computing time and may require more computer resources in order to make it usable for operational forecasts.

The model performance on ice thickness is rather weak. One of the possible solutions to increase model performance would be to increase the spatial resolution of wind forcing in order to resolve the impact of the Curonian Spit on the westerly winds.

The model can be used for operational forecasts; data assimilation for salinity and ice thickness might be necessary.

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