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VALIDATION OF HYDRODYNAMIC MODELS OF THE BALTIC SEA IN POLISH WATERS - HIROMB AS AN EXAMPLE

Abstract

Proper description of thermo-hydrodynamic processes in seas is important for scientific and for many practical purposes. Among mathematical models, deterministic models, basing on the set of conservation equations, and calculating the response of the modelled system on the external forcing, are now being most intensively used by researchers. Reliable forecast of thermo-hydrodynamic processes is one of the most important applications of the geophysical fluid dynamics. In this paper, we concentrate on problems of validation of the particular deterministic operational model for the Baltic Sea, the HIROMB model. Possibilities of observations and measurements useful for the model validation in the Polish zone of the Baltic Sea are discussed.

1. Introduction

The need to describe properly thermo-hydrodynamic processes in the ocean and seas is obvious not only for hydrophysicists themselves. The ocean plays a very important role in global heat transport, moderating temperature variations between equator and poles and in that way forming the global climate. Smaller ocean areas, like the Baltic Sea, contribute mostly in a local heat and mass transport, for example, causing sometimes the local atmospheric cyclogenesis over the sea area.

Thermo-hydrodynamic processes in the ocean and seas are significant for marine chemistry and biology. For example, the main source of transport of any substances and of many organisms, living in sea water, is the sea water motion. The sea water carries nutrients important to fisheries, pollutants (among them also nutrients), toxic substances like pesticides and heavy metals, radioactive wastes etc. Among parameters, important for biologists and chemists, there are also water temperature, salinity, transparency, surface and internal waves and others.

There are many specific fields of human activity which can benefit from the knowledge of sea hydrodynamics. For many activities, reliable marine forecast is the most important element of products, which can be provided by geophysical fluid dynamics. The main activity is, obviously, safety of navigation and navigation as a whole. This is also fisheries, oil and gas extracting industry, harbour management, shore protection etc. During the summer period, forecast of water temperature close to the coast in recreation zones shall be welcomed by many people.

Forecasts of meteorological parameters over the sea area (wind, precipitation, air temperature, humidity, visibility etc.) and thermo-hydrodynamic parameters of sea water (wind waves, currents, water temperature, salinity, density, water level) can play an essential role for search and rescue actions, searching for shipwrecked persons, vessels or their appliances, and for lost cargo, especially dangerous, in containers etc.

The Maritime Institute in Gdańsk, being designated by the Ministry of Transport and Maritime Economy to develop a computer system for aiding oil and chemical spill combating activities, is deeply interested in operational marine forecasting. The present state and the forecast of wind, air temperature and humidity, water waves and currents, water temperature, salinity in the Polish Exclusive Economic Zone (EEZ) of the Baltic Sea constitute, apart of the necessary data of the spill itself, the input data for the model of oil drift CAROCS, developed the Maritime Institute. The Baltic Sea and its Polish EEZ have its known specific features, which should be reflected by any model.

The Polish EEZ of the Baltic Sea is rather shallow in its western part, the Pomeranian Bay. Vertical mixing, due to wind action is strong here and vertical stratification is, as a rule, very weak, except the influence of Odra river water, which can be seen in salinity, temperature, density and transparency distribution. The Słupsk Channel, connecting the Bornholm Deep with the Gdańsk and Gotland deeps is the way which heavy and salt water from the North Sea penetrates to the east. Because of a special bottom relief (embranchment) in the eastern part of the Channel, the salt water, depending on external forcing (mainly wind conditions), flows into the Gdańsk Deep or Gotland Deep or to both deeps together. Both deeps are vertically stratified with a seasonal thermocline and, deeper, one or more haloclines. Horizontal stratification in these deeps is relatively low, the water is here well mixed horizontally, except in the vicinity of the mouth of one of the largest Baltic Sea rivers - the Vistula river and in the vicinity of the entrance to the large and shallow Vistula Lagoon. The bottom relief, together with the highly variable wind conditions, is the main factor, deciding on the speed and direction of sea currents. For example, the Hel Peninsula, entering far into the deep part of the Gulf of Gdańsk, plays a significant role in the distribution of currents in this area. A three-dimensional model, taking into account water stratification, shall properly simulate the mentioned above peculiarities.

Among different mathematical models, the deterministic models, which base on the set of equations of thermo-hydrodynamics, are now being most widely used. The so-called numerical scheme is an approximation of the original differential equations together with the appropriate initial and boundary conditions using, particularly, the finite difference technique. The numerical scheme creates large systems of algebraic equations, which can be solved by the use of computers. Such a method is also common in meteorology.

Since wind action is the main driving force in the ocean and seas, reliable forecast of parameters of the sea is impossible without a reliable forecast from the model of the atmosphere. During the last decade, large-scale and, sometimes, mesoscale wind forecasts over many seas have become satisfactory for oceanographic purposes. In several centres around the world, mainly in the USA, scientists develop operational models for the ocean or seas.

The model, called HIROMB (High Resolution Operational Model for the Batic Sea) has been developed in Germany in at BSH (Bundesamt für Seeschiffahrt und Hydrographie), Hamburg. Later, the model was improved together by the BSH and SMHI (Sveriges meteorologiska och hydrologiska institutet), Norrköping, Sweden, under the agreement, also called HIROMB. Now the HIROMB model is run pre-operationally in Sweden. The horizontal resolution of the model is now approximately 3 nautical miles, and vertically it is divided into 26 layers, with the finest resolution of 4 m in the upper subsurface layer. The model calculates water level in each node of the horizontal grid, and water temperature, salinity, current speed and direction in each node of the three-dimensional grid for 24 hours ahead. The model contains also an ice module, which is very important in the northern part of the Baltic. It is planned to run the model with better resolution, of 1 Nm in horizontal plane, and with 52 layers. More layers shall be added in the upper sea layers.

In the Polish EEZ of the Baltic Sea, because of its limited depths, the model has now 14 layers from the surface to the bottom in the deepest parts of the Gdańsk Deep. Poland is also entering the HIROMB Agreement, after Sweden, Germany, Denmark, and together with Finland. It is expected that all the Baltic states shall join this agreement, because no one state is able to provide its own hydro-meteorological service for the whole Baltic Sea area.

2. Validation of different thermo-hydrodynamic parameters of the sea

Validation of any model of the sea dynamics is difficult, because all direct measurements in situ are very expensive. Coastal measurements, as usual, are much cheaper. Aerial photography is used for some special purposes and is also expensive, but a large area taken even by a single photograph is a big advantage comparing to a contact measurement. Satellite images in different bands of the spectrum can provide very interesting information from very large areas of the sea surface, not only on water temperature, but also, indirectly, on the surface currents, different chemical and biological indicators. Wind waves, water level and wind can be also interpreted from the space photographs.

It is planned to start in 1999 continuous measurements of different hydrophysical parameters from the Polish oil rig "BETA", located in the open sea (55°29'N, 18°11'E). Till present, there is no such station in the Polish Baltic Sea area.

Since 1996, every year in the Gulf of Gdańsk measuring campaigns, aimed on the validation of hydrodynamic models, are organised. Most of Polish oceanographic institutes and representatives of the Polish maritime economy, administration and Navy take part in these campaigns. Since 1997, the Institute of Oceanology, the Atlantic Branch (Russian Academy of Sciences) from Kaliningrad joined the campaigns. The campaigns include CTD and ADCP profiles, fixed stations with CTD, ADCP and pressure measurements. Satellite images and aerial photographs, if available, are also analysed. Very important, from the point of view of combating oil and chemical spills, experiments with drifters and/or tracers are also conducted. Because every year rhodamine is used as a tracer, all these campaigns are called POLRODEX.

Each measured value of any parameter at any position in space and time can be compared with the value, obtained from the forecast. The approximate "modelled" value can be calculated from the values in several surrounding nodes. In the case of HIROMB, it means that the approximate value is calculated basing on the grid 3 Nm x 3 Nm in horizontal plane and with a time step of 6 hours, since the output from HIROMB was available every 6 hours. The difference between the measured and such approximated value from the model can be calculated for any single measurement. Next, statistical analysis of all the measurements can be carried out. In a case of quasi-synchronic measurements it is possible to create two-dimensional (in vertical plane) transects, sometimes it allows us to create quasi-synchronic horizontal fields of the chosen parameter.

Referring to wind waves, the wave model is now run in Sweden independent on the HIROMB model, and during the previous POLRODEX campaigns no special measurements of wave characteristics were made. However, wind waves are very important for scientific and practical purposes, and the interaction between both models in SMHI will be soon added.

2.1. Sea level

The net of tide gauges along the Polish coast is owned by the Institute of Meteorology and Water Management, Maritime Branch in Gdynia. The Weather Office of IMWM in Gdynia receives water level data from the stations at Świnoujście, Ustka, Hel, Gdynia and Gdańsk in the operational mode. Information from other Polish gauges is available later.

During POLRODEX activities in 1997 and 1998, water pressure measurements were made at some open sea stations at different depths. Extracting the pressure of the water column above the sensors (water temperature and salinity over the sensors were also measured) and taking into account temporal changes of the atmospheric pressure, it is possible to obtain the time series of water level changes. To obtain the absolute height values of water level is now also technically possible, but even time changes of the water level in the open sea are very valuable for the model validation.

Satellite altimetry allows now for more or less precise description of water level over a large area of the sea. It would be helpful in any hydrodynamic model validation.

In 1999, continuous measurements of water pressure at two levels shall be initiated from the oil rig "BETA". The data will be distributed in operational mode.

It means that together with the coastal stations, there will be a very important station for sea level validation in the open sea.

2.2. Water temperature

Sea water temperature, measured from the coast, very often is not representative for the open sea waters. During POLRODEX experiments, many measurements of temperature have been mode along vertical profiles. It was possible to construct quasi-synchronic vertical transects of temperature distribution and horizontal maps of water temperature. Then, subtracting the modelled approximate values from the measured values, it was possible to construct fields of differences between the measured values and data from the model.

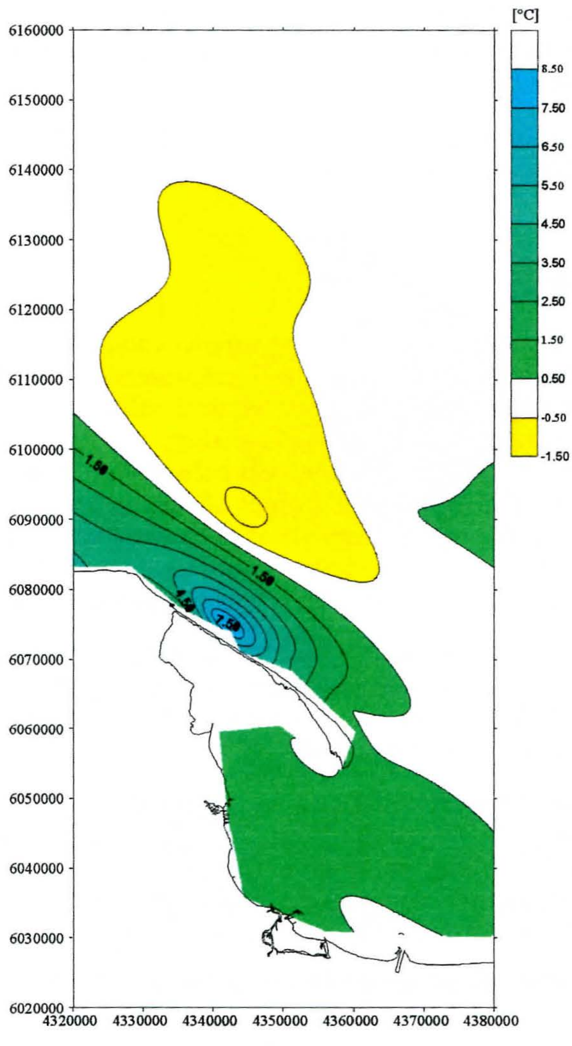

Fig. 1. Differences between modelled and measured surface water temperature, after [1]

In Fig. 1, an example of such field in the vicinity of the Hel Peninsula is shown. Large differences close to the coast occurred due to an intensive upwelling, which was also obtained in the model, but with a much smaller temperature difference and with its centre shifted in time and space. Outside the upwelling area, the temperature difference is not large. In general, it can be said that, for spill combat purposes, out of intensive upwelling areas the model describes water temperature satisfactorily.

Vertical distributions of modelled and measured water temperature show that the model gives smoothed profiles of temperature in the thermocline area. To a high degree, it is dependent on the vertical resolution of the model, which in the present HIROMB version is not satisfactory.

Basing on materials, collected during the POLRODEX'96, sea surface temperature from the satellite images and from the HIROMB has been analysed [2]. It was shown that the model reproduces well the large scale features of the surface temperature field. Mesoscale structures, with their scale of the order of the grid space, are not reflected in the model results.

In 1999, continuous measurements from the oil rig "BETA" of water temperature at two levels shall also be initiated. Also these data will be distributed in operational mode.

2.3. Water salinity

As in the case of water temperature, also salinity values measured from the coast, very often are not representative for the open sea waters. POLRODEX experiments enabled us to construct quasi-synchronic vertical salinity distribution charts and fields of horizontal salinity distribution. In analogy with the water temperature, it was possible to construct fields of differences between the measured and calculated values of salinity. Calculated vertical profiles of salinity are also smoothed out and do not reflect the halocline in the deep water of the Gulf of Gdańsk. As the vertical grid step at greater depths is rather large, proper description of the halocline in the model is more difficult than the question of thermocline description.

In Fig. 2, an example of the salinity difference distribution in the same area as for the temperature is shown. The largest differences are found in the vicinity of the Vistula river mouth. In general, only great rivers are a source of larger differences between the measured and modelled water salinity.

It is worth to add that the HIROMB model is run with the multi-annual mean river inflow into the Baltic Sea. Now in the SMHI, the operational hydrological model for the Baltic Sea basin is being connected to the model of the atmosphere. It means prospects of the operational river discharge input to the HIROMB. Dispersion of river water in the Baltic Sea will then be better quantitatively described.

In 1999, continuous measurements from the oil rig "BETA" of water salinity at two levels shall also be initiated. Also these data will be distributed in operational mode.

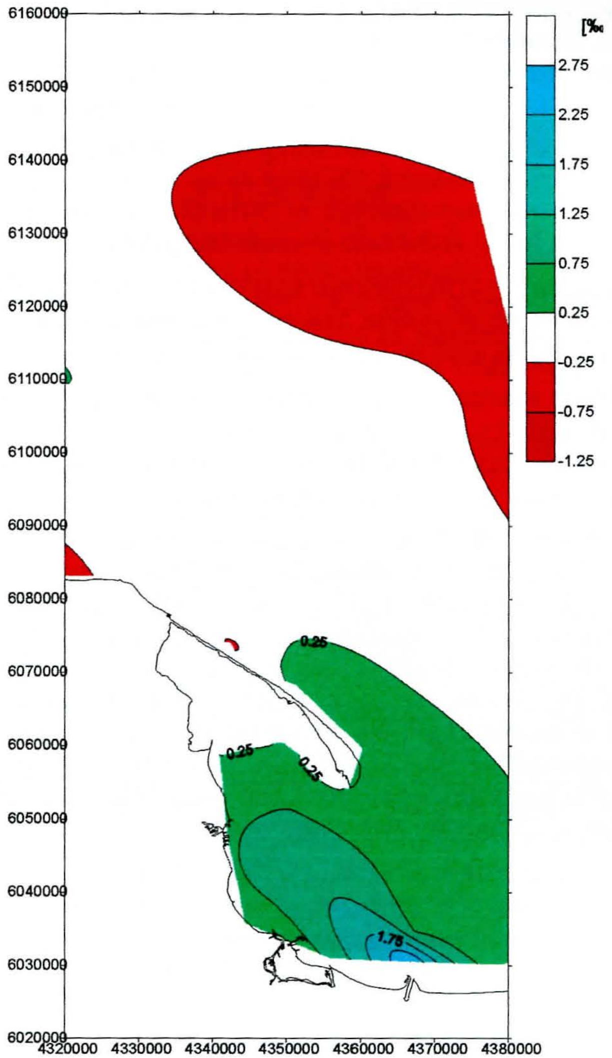

Fig. 2. Differences between modelled and measured surface water salinity, after [3]

2.4. Sea currents

Comparing to water temperature and salinity, sea currents are much more variable in time and space. Since the Baltic Sea is a shallow sea, currents are mainly wind-driven and the high wind variability explains current variability. It concerns all scales of currents - large and mesoscale. Mesoscale vortices are often generated in the Baltic Sea and they often transport more energy than the large scale currents. It means that proper description of vorticity in the model is crucial, apart from the grid resolution.

Because of the large spatial variability, there is a danger of misinterpretation of the current measurement data. Mesoscale and small scale perturbations in the current field can have an amplitude larger than the large scale current. Hence, any current measurements should be thoroughly filtered before they are compared with the results of calculations. In addition, atmospheric forcing has also its small scale fluctuations and they are not reproduced in the model of atmosphere. Obviously, when the real current field is smooth, preliminary filtration of measurements is not needed.

Measurements of currents, made using different methods during POLRODEX campaigns, although not filtered, for most cases showed good agreement between the measured and modelled direction of currents. As a rule, the magnitude of the currents was much lower in the case of modelled currents.

Acoustic diagnostics of the dynamic state of the water body enables us to measure currents in the entire water column. Since 1999, continuous ADCP measurements of currents in many layers shall be initiated from the oil rig "BETA".

It is possible to interpret satellite imagery to obtain surface current fields. Such an attempt was made by Krężel et al. [2]. Again, as it was mentioned above with regard to sea surface temperature, the model represents well the macroscale features of the surface currents and does not - mesoscale features.

Very important experiments, regarding modelling of drift and spreading of spills, have been realised every year during POLRODEX experiments. The rhodamine plume tracing is, however, also an important tool in the validation of a hydrodynamic model. Spreading rhodamine soon covers an area comparable with the grid cell area. Movement of the plume represents then the water current in a particular cell of the numerical grid. Fig. 3 shows positions of the centre of the rhodamine plume, released in the vicinity of the Hel Peninsula in August 1996, and the shape of the modelled plum. The drift model used the field of currents, predicted by HIROMB. The results of drift and spreading modelling are good. Results of other POLRODEX experiments with rhodamine drift modelling were also good.

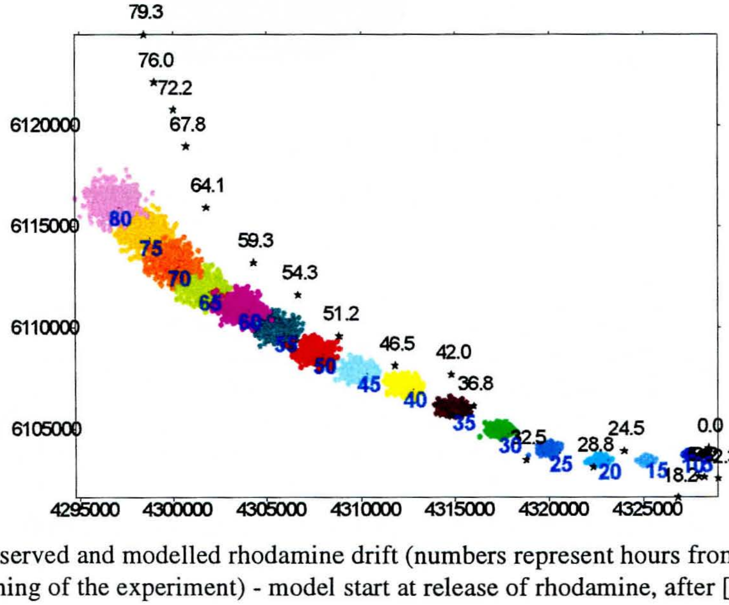

Fig. 3. Observed and modelled rhodamine drift (numbers represent hours from the beginning of the experiment) - model start at release of rhodamine, after [3]

Other methods of measurements of currents can also give a valuable material for model validation. It is possible, using Doppler effect, to measure surface currents from the coast. Total flow across the underwater electric cable can be evaluated on the basis of the electric induction.

3. Conclusions

Validation of hydrodynamic models is a difficult task because of very high costs of in situ measurements. That is why intensive measurements, simultaneously from many research vessels, are possible only for a short time. Such campaigns need relatively good weather conditions and thus can be planned mostly for the summer period. This is a loss of data during interesting events when wind is strong, waves are high or there is an ice cover.

Satellite images are extremely helpful when information from the sea surface is needed - but not much information can be deduced on deeper structures. Another limitation of remote sensing is its dependence on cloudiness. A cloud free sky does not often happen over the Baltic Sea, especially during interesting events.

One of the best ways, but also expensive, is to establish permanent mooring stations which can give us, independent on weather conditions, continuous information on the local state of environment in operational mode. This is the way chosen by Denmark, Germany and Sweden in the area of sounds. Of course, it does not mean that this is the only method of measurements used here by these countries. Due to the permanent mooring stations it is now possible to record water exchange with the North Sea, including inflow of salt water into the Baltic Sea. But large areas of the Baltic proper still lack such permanent stations. The first Polish station on the oil platform shall give very valuable information on the sea state in the south-eastern part of the Baltic. Real-time transfer of measured values is very important for continuous validation of the operational models, but it also enables research workers to introduce data assimilation algorithms into the model. In meteorology, data assimilation methods can highly improve the quality of forecasts.

It is obvious that a reliable hydrodynamic forecast has to be preceded by a reliable meteorological forecast. The HIROMB receives meteorological data from the HIRLAM (High Resolution Limited Area Model), precisely its version HIRLAM 44, being run operationally in Sweden, with horizontal resolution of 44 km. It means that the smallest atmosphere structures in this model can have a size of a hundred km. For a good description of a local Baltic cyclogenesis it is too large a value, since the mean width of the Baltic Sea is not much larger. Now, in the pre-operational mode, a mesoscale model including the whole Baltic Sea, with a grid step less than 17 km, is run in the Interdisciplinary Centre for Mathematical and Computational Modelling, Warsaw University (ICM). There are also active versions of HIRLAM on finer grid. Another defect of atmospheric and hydrodynamic models is that they smooth frontal gradients. Unsatisfactory front description in models of the atmosphere is often the main cause of smoothed calculated water level changes in hydrodynamic models, so the extreme values are sometimes far from the recorded ones. Also such local effects like breeze can influence sea currents and push the spill in another direction than that resulting from the larger scale atmospheric model. There is no such local model running operationally for the Baltic Sea yet. The ICM plans to run a local nonhydrostatic model during the BRIDGE experiment, in the frame work of the BALTEX project.

References

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