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On-demand coastal modelling with two-way nesting

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Abstract
The development and tuning of oceanographic models for coastal regions can be a time-consuming process. However, there are many situations in which an easily producible, user-friendly and still reliable tool is desirable for unresolved coastal regions, or planning modifications of coastal infrastructure, wind farms, assist in search and rescue operations, etc. This paper develops a prototype of an on-demand, relocatable modelling tool enabling to create the coastal setup easily by simply attaching higher resolution domain(s) to the base setup of open seas. The prototype runs on internal system at Danish Meteorological Institute (DMI), that is designed for further public use in a later stage in EU Digital Twin Ocean. To accomplish this, we apply the oceanographic circulation model HIROMB BOOS Model (HBM) which implements a two-way nesting technique to ensure a seamless transition from open seas to coastal waters. This tool is based on publicly available resources: bathymetry, oceanographic software, weather forcing, boundary forcing, etc., so that, it can be accessible by public community. The base bathymetry of the model at resolution of 2 arc seconds is derived from EMODnet bathymetry with coastal correction by using OpenStreetMap coastline. Lower resolution bathymetries in discrete resolutions are derived from the base bathymetry and processed beforehand, ensuring that users can apply them directly. To ensure close connections (strait, fjord, large river, channel, etc.) between water bodies, a vector layer of waterways is used for each low-resolution bathymetry. In the same way, narrow land forms (dam, narrow-long island or peninsula, road, etc.) are ensured by vector layer of dams. The on-demand tool is specifically designed for the North Sea-Baltic Sea region and is based on a tuned setup for open seas with properly-resolved Danish straits. As the on-demand tool will not use data assimilation, salinity inflow in the Baltic Sea is enhanced by slight smoothing of the bathymetry from Danish straits to Baltic proper. When comparing the results of base setup with existing reanalysis products in the North Sea - Baltic Sea, sea level of the HBM base setup shows favourable results. On-demand high resolution downscaling simulations have been tested for some major storm surge cases, showing benefits of using high resolution in storm surge modelling. The stability and quality of the resulting two-way nested coastal setups can be enhanced by implementing a cascade of two-way nestings. In summary, the paper demonstrates that creation of on-demand coastal oceanographic applications by attaching highly resolved coastal domains to existing base setups for open seas is achievable task.

Keywords On-demand modelling · HBM · Seamless oceanographic modelling · Relocatable modelling

1 Introduction

Existing coastal scale oceanographic software is rather complex for end user applications or has limited connectivity to the open ocean. On the other hand, the need for higher resolution applications in oceanography is increasing, e.g. coastal protection, port management, search and rescue operations, marine accidents, wind farms, aquafarms, marine infrastructure objects. Currently, experienced modellers need to spend several months or years to set up and tune a coastal oceanographic model for operational use. Ideally, the on-demand coastal modelling tool should be developed based on an operational, seamless and computationally light and efficient model. The “operational use” ensures model’s robustness and quality as its results have to be constantly evaluated by users. “seamless” means that the model can resolve synoptic to climate scales and river-to-sea scales which requires

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both flexible gids and flooding-drying facility. The computational efficiency and portability of the model should also be high. Furthermore, downscaled model domain needs to be dynamically two-way interacted with coarse resolution model domain instead of one-way interaction. The latter provides a quick and easy solution, but has drawbacks as inflow and outflow currents are slightly suppressed. The wind-driven inflow/outflow to the coastal system can be increased by increasing the sea level variation at the boundaries, as in [6], but this still results in lower salinity transport to the coastal system than the fully nested approach. Transport to and from the coastal system to the open ocean can be addressed by two-way nesting when using structured grids or using a regional scale unstructured grid model.

Today, there are several oceanographic software packages that are capable of solving coastal features and can be used for on-demand coastal modelling. These can be divided into two main classes, structured grids and unstructured grids. The unstructured grid has a natural way to connect the open sea with the coastal estuaries (MetOceanView 2018; Zhang and et la. 2016; Zhang et al. 2016). There are still some drawbacks to unstructured meshes in that they are computationally heavier and more difficult to parallelize and automate, which is an important factor for on-demand modelling.

Two-way nesting can be used also with unstructured grids (Ding et al. 2021; Qi et al. 2018), but this is less common. Some structured grid models such as ROMS (Combes and Matano 2014; Debreu et al. 2012), NEMO (Pandey et al. 2015), MARS3D (Petton et al. 2022) use the AGRIF two-way nesting framework (Herzfeld et al. 2019). AGRIF has strong functionality including dynamic nesting for tropical cyclones for example, but it requires additional computational resources. In comparison, the two-way nesting integrated in HBM (HIROMB-BOOS Model) is a lighter tool (Murawski et al. 2021, 2022; Frishfelds et al. 2022). Here, the low-resolution domain of the open sea is computed simultaneously with the high-resolution coastal domain as a single solution. This approach leads to better performance for sea level, currents and salinity transport than using one-way nesting (Murawski et al. 2021; Frishfelds et al. 2021; Jorge Urrego-Blanco and Dupont 2016). The two-way nested HBM has been used as an operational tool since early 1990 s in its earlier version HIROMB and BSHcmod (Klein and Dick 1999; She et al. 2007), and recently a seamless tool for Danish climate service (Thejll 2023) and river-to-sea modelling (Frishfelds et al. 2022). The model code had gone through significant code modernization and optimization for high performance computing (Poulsen et al. 2015). The existing developments of HBM provide an ideal basis for being further evolved into an on-demand modelling system.

There are a number of tools that can be used for on-demand coastal modelling. One of this is web platform (Oliveira 2020) based on SCHISM oceanographic model. As it is based on unstructured grid, then it still requires some experience of an on-demand user to build the grid and specify the boundary conditions. The use of one-way nesting in provided examples (Oliveira 2020) may not lead to a significant improvement in sea level statistics. Another methodology capable of on-demand coastal modelling uses MOHID environmental modelling system (Mendonça et al. 2023). The simulation management system there is constructed using Python scripting tools to automate the generation of coastal forecasts. However, the system has only been tested in two geographical locations and the authors pointed out that further development is necessary to be used as a robust and reliable on-demand modelling tool for any coastal area.

This paper investigates possibility of on-demand ocean modelling with a two-way nested approach using HIROMB BOOS Model (HBM) oceanographic software (Murawski et al. 2021; Frishfelds et al. 2022). It is one of the coastal ocean models applied for the EU Digital Twin Ocean. HBM is based on a structured grid that connects different resolutions by two-way nesting. A prototype of on-demand tool is currently tested as DMI's internal system, before transferring it to a public server. The proposed approach would require considerably less user effort to set up a coastal oceanographic model and ensuring quality of the result at the same time. The on-demand modelling tool is designed for North Sea - Baltic Sea with resolution varying from 3 nm (nautical miles) up to 1/30 nm.

In practice, there exist several challenges when developing an on-demand modelling tool, such as automatic construction of model bathymetry, model stability and quality, open source input data. A major difficulty in on-demand modelling is the automated construction of coastal bathymetry. There are now a number of Python tools that can be used to help construct coastal bathymetry. Connectivity of the straits and narrows is major concern of the creation of bathymetry. In Ye (2023), a Python-based tool for automatic meshing of river mouths is being developed, which will allow obtaining well-expressed river arcs along the river thalweg. We will apply an analogous strategy of automated bathymetry correction along the narrow passages.

The desired resolutions of open seas and coastal waters can be hundreds of times different. This could lead to instabilities due to high nesting ratios. In addition, high nesting ratios create artefacts at the nesting boundary. Therefore, the model should allow for several levels of nesting. For example, the Latvian operational setup with HBM includes 6 levels of nesting when moving from the resolution of the Baltic Sea to the port of Riga (Sennikovs et al. 2021). This provides an almost seamless transition from open sea to coastal scales and this will be available for on-demanded setups.

The quality of an oceanographic model in a high resolved coastal area depends largely on the quality of the open sea part in the two-way nested setup. It is therefore advisable that the basic open sea model is thoroughly tested and that the user can attach a coastal system to the primary open sea model setup. This will greatly reduce the problems for on-demand models, as open boundaries, major straits and freshwater inputs will be correctly represented in the base model for open seas. It is advisable to derive the base setup from an existing operational setups of the North Sea - Baltic Sea, as they have been thoroughly tested and tuned over decades. We have chosen the former HBM-based Baltic Monitoring Forecasting Centre (BAL MFC) setup, which was used as the Baltic Sea model in the Copernicus Marine and Environment Monitoring Service (CMEMS) in 2009-2020, before it was switched to NEMO (Cmems 2023). The advantage of this setup is that it properly resolves the Danish Straits, which is a critical issue in other operational setups for the North Sea - Baltic Sea (She et al. 2007), see Fig. 1.

The public on-demand ocean modelling application is planned to be available to community users of the EDITO Model Lab platform. It requires that the application uses only non-commercial data resources and software. Therefore, open source data is preferred. Several software tools and data sources are required for model development: oceanographic software, bathymetry, weather forcing, boundary conditions, river inflow, geospatial software, pre-processing scripts, graphical user interface (GUI), etc.

Most of today's oceanographic circulation software is non-commercial. However, each of them requires a lot of knowledge and it takes years to learn all its features. HBM is an open-source oceanographic software that is well suited for seamless applications from the open ocean to the coast. Currently, the HBM source code is still maintained in institutional servers. It will be put on a public server before the public launch of the on-demand tool. HBM can handle the shallow coastal systems well because it has high vertical resolution and it can handle wetting and drying. However, HBM lacks comprehensive documentation compared to other oceanographic software such as NEMO (Madec 2023). However, this need is minimised by using on-demand modelling, as the end user does not need to know the underlying software.

Bathymetry is a key component of oceanographic models. Meteorological institutes typically work with proprietary sources of bathymetry from national providers, but on-demand modelling requires the use of European-wide, harmonised and freely available bathymetry data for the end user. There, the EMODnet bathymetry (Emodnetdigitalbathymetry 2020) is a natural choice with a resolution of up to 115 m. This resolution may not be sufficient for some coastal ports and canals. Therefore, OpenStreetMap (OpenStreetMapcontributors year) features are also used to refine the bathymetry at the finest scale for coastlines.

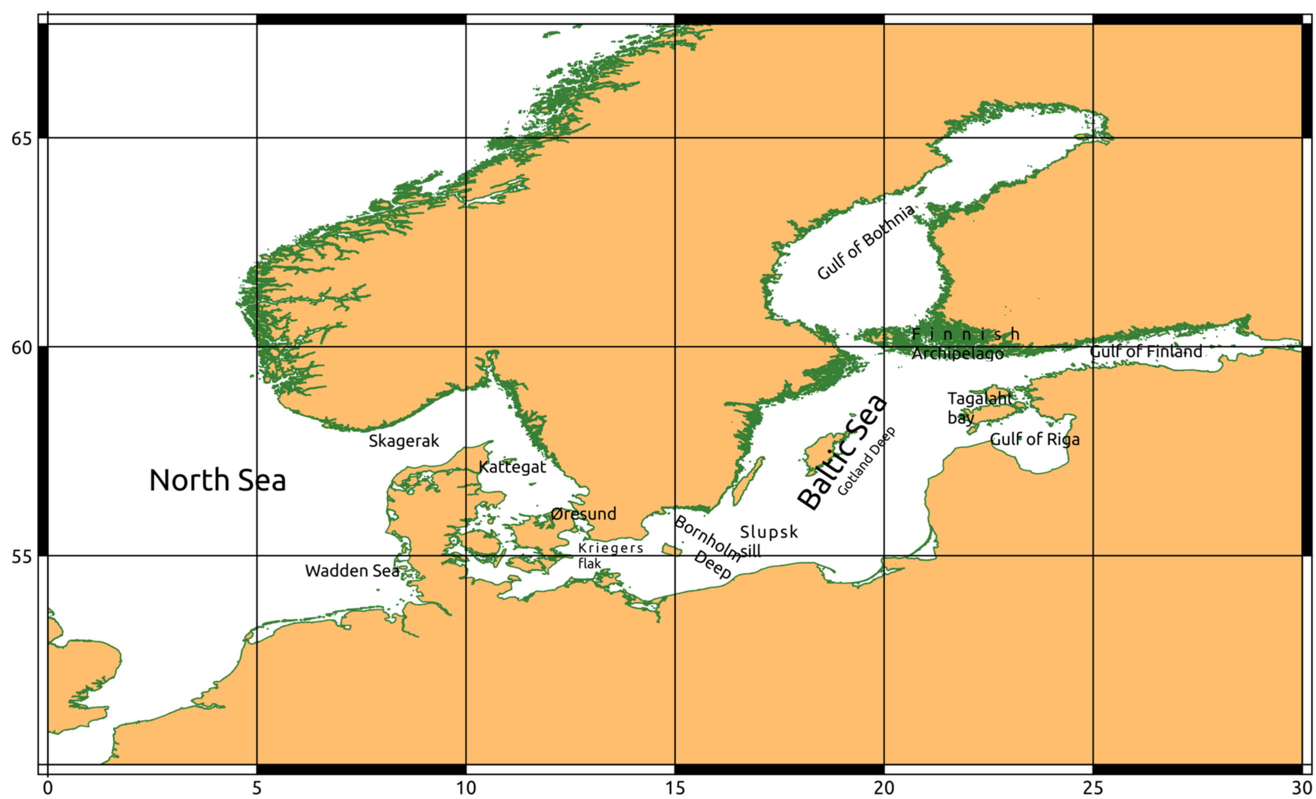

Fig. 1 Map of North Sea - Baltic Sea

Basin scale bathymetry may not be useful for coastal areas such as ports where higher resolution data isrequired. Local authorities may have detailed harbour bathymetry maps resulting from recent surveys that are much better than that of EmodNet. Therefore, the user should have the possibility to add coastal bathymetry to the base bathymetry. This was the case for the Latvian Operational setups for ports (Sennikovs et al. 2021), where the high resolution bathymetry data of ports were added. For this reason, the user will need the ability to add complementary coastal bathymetry to the base bathymetry. This is achieved by interpolating local user-defined bathymetry data onto the base grid, i.e. the finest grid that serves as the basis for other resolutions in on-demand modelling.

Weather forcing is a key element when it comes to ocean dynamics and storm forecasting. It must be thoroughly tested as an existing operational weather forcing model of the national meteorological agency. In the on-demand tool, weather data are currently predefined so that users do not need to know how to process the atmospheric model outputs.

The presented on-demand system does not cover the global ocean, but just the regional seas. Therefore, the boundary conditions have to come from other models. Principal importance have the tides, wind driven surge, water temperature and salinity at the wet boundary. These conditions have to be given to the on-demand modelling system.

Freshwater input is a key element in the salinity balance of the Baltic Sea. There are two options, either to use climatological river discharge or to use a hydrological model for the European area. The latter choice is crucial if salinity is a key parameter for the user case.

The on-demand tool must have a graphical interface as it is more intuitive for the user. Python has good compatibility between different systems, therefore the TKinter module is used to build a graphical interface. The interface is designed for two-way nested models with HBM oceanographic software. The sub-scripts of the on-demand tool must also be open source, and are created using Fortran, Python and GDAL GIS programming resources.

The on-demand coastal modelling tool requires the development of all of the above. Currently, the on-demand tool is still in the development phase and being tested in DMI's internal sytem, with the actual focus on the pre-processing and execution phase. Nevertheless, tests with different domain settings already show a good potential for the user initiated on-demand approach.

2 Methods

There are a number of interesting coastal applications possible for the North Sea - Baltic Sea area. Therefore, we want to develop a GUI application for this area allowing users to set up their subdomains and execute model runs. The oceanographic circulation will be modelled by HBM oceanographic software with better resolution used in the Danish Straits.

2.1 Generating basis bathymetry for North Sea–Baltic Sea

EMODnet Bathymetry provides harmonised digital bathymetry for the European maritime regions. It is therefore the natural choice for the North Sea - Baltic Sea region where harmonisation of national bathymetric data sources is the a key requirement. Bathymetric version of 2020 (Emodnetdigitalbathymetry 2020) has the resolution of 1/16 arc minute. However, the source data of the EMODnet bathymetry may have a lower resolution. Thus, the EMODnet bathymetry does not necessarily include details at such a resolution, e.g. it is rather smoothed in the Finnish archipelago. It also has some problems, for example the Oder delta and other places. Besides, the latest national data, e.g. for Denmark, provide much better details. The coastline in EMODnet bathymetry is aligned with the OpenStreetMap (OpenStreetMapcontributors year) data for the year 2020. More recent updates of the OpenStreetMap coastline may not be reflected in the EmodNET bathymetry.

Users may require resolutions better than 1/16 arc minute for coastal areas. As the EMODnet bathymetry is aligned with OpenStreetMap vector data, we can use OpenStreetMap to improve the bathymetry at the sub 1/16 resolution. This cannot improve open sea areas, but it definitely improves a rather finely structured coastline.

There are certain limitations on how high a resolution the oceanographic model can handle and what is the finest resolution that makes sense for an oceanographic model. The operational oceanographic setup for Latvian ports (Sennikovs et al. 2020) has a resolution of 37 m and still provides a stable solution with seamless connection to the open sea. Therefore, we have chosen 2 arc seconds as the finest resolution for on-demand coastal applications.

Some coastal locations are considered wet points in the current version of OpenStreetMap, but not in the EmodNET bathymetry. Therefore a nearest neighbour approximation is used to get the depth as the nearest wet point in the EmodNet bathymetry. This solves a number of fjords and channels where the EmodNet bathymetry has no value, while OpenStreetMap treats it as a wet point. This provides a reasonable quality base bathymetry from which lower resolution bathymetries can be derived, see Fig. 2.

Bottom currents in ocean circulation models are highly dependent on bottom roughness. A very rough ocean floor results in weaker near-bottom circulation. Weaker near-bottom circulation is also common in oceanographic simulations, especially when the ocean circulation model does not have the capacity to include bottom following currents. The

Fig. 2 Left: EmodNET bathymetry (raster) and OpenStreetMap (line) of Thurø island. Right: Interpolated bathymetry at the basis resolution when adding OpenStreetMap coastline information

resulting bottom circulation in the HBM may thus be limited, affecting deep water salinity transport and mixing. Therefore, the base bathymetry is smoothed for depths greater than 30 m and at least 10 km from the nearest coast to 3 nm in the Baltic Sea.

2.2 Bathymetry at low resolutions

It is expected that the highest resolution base bathymetry will only be used directly for small coastal areas, as it would require large computational resources for the open sea. Most of the North Sea - Baltic Sea will be modelled at lower resolutions. As the nesting in HBM can only handle integer nesting ratios, low resolution bathymetries will be constructed for integer multipliers of the base resolution. Therefore, possible resolutions will be 1, 2, 3,... times lower than the base resolution. The lowest possible resolution is chosen to be 3 nm, which still works relatively well in the open sea, but only the Great Belt of the Danish Straits would remain open. The advantage of discrete resolutions is that these resolution variants are pre-calculated and the end user can directly use already produced and tested low resolution bathymetry.

Each cell in the low resolution version may contain both wet and dry points of the base bathymetry. The question then arises as to whether the coarse grid cell should be threatened as a dry or wet point. We can choose a certain threshold in percentage of the wet area. A good value was found to be 2/3 area of the base grid is covered by the wet points when the low resolution cell is treated as a wet point. However, it overestimates transport through the Finnish Archipelago Sea or through narrow landforms, e.g., the salinity in the middle archipelago from around 4 PSU in Miettunen et al. (2020) to 5 PSU with a low (1 nm) resolution model. Therefore, we have chosen cell transparency criteria for transport in zonal and meridional directions, i.e. on the percentage of obstacle-free zonal and meridional lines in the base grid contained in the course resolution cell. If there are more than 22 % of these lines, then the cell is considered to be a wet point in the low resolution grid. However, it is still not sufficient to consider Finish Archipelago Sea in low resolution and much finer grids have to be used there Tuomi et al. (2018).

Coastal areas may include narrow straits and channels that may be disconnected if treated at a lower resolution. This could lead to the separation of water bodies. HBM does not include transport between diagonally placed cells. In order to preserve the important channels and straits, these locations must be explicitly considered when creating the low resolution bathymetry. The solution should work at any resolution. Therefore, a vector layer of main waterways (a common name for river thalweges, straits, narrows or channels) is created in the North Sea - Baltic Sea. It contains about 1000 predefined waterways. Each waterway has 2 main characteristics: nominal width and minimum depth. The nominal width represents the characteristic width of the waterway, possibly at the narrowest point. If lower resolution is used as the nominal width of the selected waterway, its connectivity is disregarded. If the resolution is higher than the nominal width of the selected waterway, then this waterway is checked to ensure connectivity along it. But, usually, the waterway is already well established in higher resolutions requiring no corrections. The minimum depth parameter ensures that the depth along the line segment is at least the specified value. This approach ensures the connectivity problem at any selected low resolution bathymetry, if a critical waterway has to be included for the given resolution, see example in Fig. 3 left.

There are also cases where narrow landforms with holes may appear when treated at lower resolution. At very high resolution, the narrow landforms could also be artificial dams in harbours preventing direct water exchange between water bodies. The narrow landforms should be preserved at all resolutions. For this reason, we have created a vector layer of line segments representing the main narrow landforms (called dams) in the North Sea - Baltic Sea. The landforms do not require any attributes other than location. In order to ensure that defined dams have no transport through them, we apply the HBM feature of dams either in zonal or meridional directions, see example in Fig. 3 right. It may happen that at low

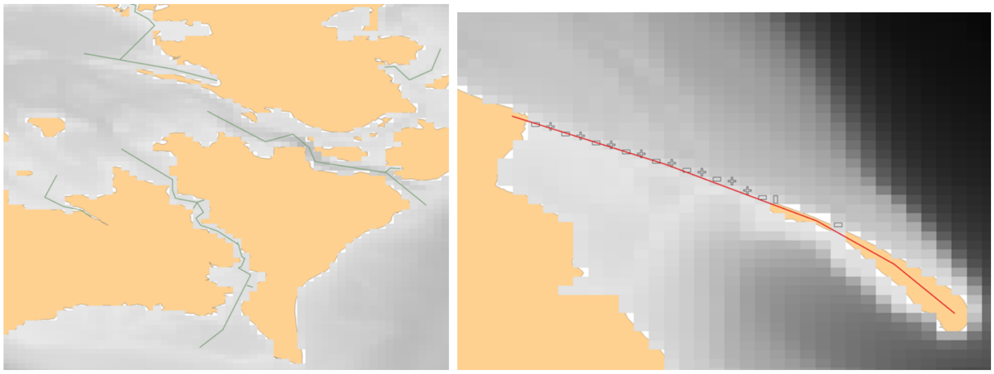

Fig. 3 Left: vector layer of waterways, ensuring connection between basins. Right: vector layer of dams to ensure no transport through narrow landforms

resolution the waterway is placed at the same point as the dam line in a course resolution bathymetry. In this case, the waterway will have a higher priority. Therefore, these two vector layers of waterways and dams correct the behaviour of coastal features at lower resolutions.

Water level stations are used in HBM for more frequent outputs of modelled sea level data. Water level stations are located at the nearest wet point in the current resolution. During low water events, a shallow location could become dry. Therefore, only wet points with a certain minimum depth are considered. The same water level station can be placed on several nesting levels. In this case, only the finest grid will be used for this water level station.

River discharge points can be placed at dry locations in low resolution bathymetry. These locations can be moved to nearest wet points in the same way as water level stations. However, if there is a waterway closer to the river discharge point, the nearest wet point will be found along that waterway. This ensures the correct location of the inflow of the corresponding freshwater source.

The end user of on-demand modelling should not have to worry about generating bathymetries at every resolution. Therefore, this finite number of user-defined resolution bathymetries with information on sea level stations, dams and river positions is pre-processed with a Python script. It is not necessary to generate all the different resolutions, as the user would typically select some of the most traditional resolutions such as 1 nm, 0.5 nm, 0.1 nm, etc.

2.3 Domains and domain features

HBM uses regular latitude and longitude grids in staggered Arakawa C-grid representation to model ocean circulation. Each grid in the setup is called a domain. The setup can contain up to 99 domains in the current version of HBM. The domains have different extents, resolutions and other properties. These domains interact when they are nested. The first domain interacts with the open boundary and usually has the coarsest resolution. Each domain has four coordinates that determine its extent: west, north, east and south coordinates. Domains are key elements in HBM that build an oceanographic model.

Each domain has its latitude and longitude spacing properties. For a nested domain, these spatial steps cannot be arbitrary because the spatial step ratios between nested domains should be an integer number. Therefore, only discrete spatial step sizes are allowed for the on-demand service. As the application of the described on-demand tool will be applied at mid-latitudes, the aspect ratio of latitude to longitude spatial steps will be kept close to 3/5, resulting in almost square cells in units of length. Therefore only one resolution parameter is required. The resolution of each domain is specified as a multiplicative factor of the base resolution of 2 arc seconds.

Vertical levels in HBM must be consistent between nested domains. Finer domains may have additional vertical levels. Typical vertical resolution used is around 1 or 2 ms in the top 100 ms of the ocean, depending on the application. HBM handles multiple vertical discretisation layers very well using parallel computing. The first layer for the North Sea domain needs to be 4-8 ms thicker due to the strong tides, while the top layer in the Baltic Sea is kept at 2 ms.

Each domain can have a different time step. Finer grids require smaller time steps. The time steps of nested domains can differ by a factor of 2^i, where i is an integer. Therefore, we only need to specify the absolute time step for the first domain and the time step ratios of the nested domains.

When nesting, the parent grid area partially overlaps the fine grid area. If several nesting levels are used, there may be several grids covering the same area. Internal calculations in HBM are performed in all domains, but only the results of the finest grid are copied to the domain results. In addition, unconnected water bodies may appear on a fine grid, which is of no benefit. It is therefore useful to exclude parts of the domains to improve performance, stability and post-processing. The excluded parts are given as latitude-longitude boxes within the extension of the domain.

The bottom friction coefficient is a less determinable quantity and has a strong influence on bottom currents. If the ocean circulation model does not have a bottom following feature, then bottom currents may be slightly underestimated and a smaller bottom friction factor must be chosen in the model. In HBM, the user can add bottom friction maps for each domain. Bottom friction has an effect on sea level and circulation, especially at shallower locations. Therefore, bottom friction maps are used to tune the sea level performance by changing the bottom friction coefficient in some areas.

The idea with on-demand modelling is that the open sea part of the North Sea and Baltic Sea is tuned and validated beforehand, and the user simply adds higher resolution coastal domains and nests them with the existing domains. This gives the user good quality results from the start. Therefore, the first three domains of North Sea - Baltic Sea will presumably remain fixed. These are the North Sea domain, the Baltic Sea domain and the domain representing the Danish Straits in better resolution. It is particularly important to keep the first North Sea domain unchanged, because then we can keep the same boundary conditions for tides, waves, temperature and salinity for all model variants.

2.4 Nesting

The HBM oceanographic model has a nesting capability that connects the coarse latitude-longitude grid domain with the finer domain. All grids are calculated simultaneously. The transfer of data from the coarse grid to the finer grid is via the nesting boundary. Within the finer grid domain, the data from the finer grid results are copied to the coarse grid. This ensures that the two domains are two-way nested.

HBM only accepts integer nesting ratios for latitude and longitude directions. As on-demand modelling uses fixed discrete resolutions, it automatically ensures correct nesting ratios. The resolution parameter in on-demand modelling is an integer multiplier of the base resolution. It is therefore only necessary that the resolution parameter of the coarse grid is divisible by the coarse grid. For example, for high resolution studies for the Copenhagen area, we used the following resolution parameters 150 (North Sea), 50 (Baltic Sea), 25 (Danish Straits), 5 (Øresund) and 1 (Copenhagen). Nesting ratios should be kept low, around 2-6. Too high nesting ratios lead to stability problems and numerical artefacts at the nesting boundaries. Therefore, it is better to use several nesting levels instead of a single one. Validation tests have shown that multi-level nesting significantly improves the results.

Nesting boundaries are sensitive to stability issues. This is particularly the case when high nesting ratios are used and for higher resolution domains. Stability is greatly improved if the bathymetry at the nesting boundaries is smoothed on both grids. Therefore, for the finer grid, the bathymetry is smoothed to a few cells away from the nesting boundary. The same is done for the coarse grid, but only one grid cell away from the nesting boundary.

2.5 Forcing, boundary conditions, tides, fresh water inflow

On-demand tool requires set of forcing data of oceanographic model. It relates to atmosphere, boundary conditions, tides and fresh water inflow. The users will not need to care about underlying forcing data and just apply the predefined input data sources. The forcing data applied to the prototype of on-demand tool are presented in this sub-section and tested in Results section.

We need to select such atmospheric model which has the weather data freely available, has sufficient resolution for highly resolved coastal domains and that has been thoroughly tested as a weather forcing for the ocean model. DMI's Harmonie (Technicalreport10-20 2010) and Hirlam models have been used for decades as weather forcing for DMI's HBM operational oceanographic model. Another reason to use DMI's meteorological data is its high resolution in the Baltic-North Sea (2.5 km grid) and that other reanalysis products based on HBM in Results section (see Subsection 3.1.1) uses the same weather forcing. NEMO reanalysis there is based on ERA5 atmospheric forcing with lower resolution and less good performance as compared to DMI's Hirlam or Harmonie based products (Technicalreport21-31 2021). The DMI's weather forecasts are freely available to the end user (Dmiopendata 2024). It is planed that the user of the on-demand tool will not have to worry of historical weather data from 2010 as the DMI historical data will be supplied to the super-computing system. The resolution of the Harmonie weather model is approximately 2.5 km. The Harmonie model data starts in 2017. Before 2017, the atmospheric model HIRLAM was used with a resolution about 4 times lower. These two models will cover the period of more than a decade for on-demand applications.

Winds over the Atlantic influence the sea level at the outer boundary of the North Sea. The corresponding surge at the boundary is estimated by the NOAMOD two-dimensional North Atlantic surge model. These historical boundary surge data produced at DMI will be supplied for the on-demand tool. It uses ECMWF global weather forcing and the NOAMOD model is run operationally at DMI.

The North Sea experiences significant tides. Fifteen tidal components are included in the HBM at the boundaries of the North Sea domain. Wind-driven waves and sea level variations due to tides are considered as additive quantities. The tidal amplitudes and phases are derived from the AVISO FES-

2014 global model (Lyard 2021), calculated on a 1/16 degree grid.

We use the climatological monthly values of temperature and salinity as boundary conditions for the North Sea. The climatological monthly profile values are derived from the global model of the World Ocean Atlas version 2023 (Reagan 2024) with a resolution of 1/4 degree and a statistical averaging period of 1991-2020.

The salinity balance of the Baltic Sea depends critically on the freshwater input from the rivers. The simplest option is to use climatological values for the discharge. However, river discharge into the Baltic Sea has a strong seasonal signal and large variations from year to year. As precipitation is increasing due to global warming, it is best to use a hydrological model to estimate river discharge into the North Sea - Baltic Sea. E-HYPE hydrological model produced by SMHI (Donnelly 2016) is well designed for European rivers and provides good estimates of the daily discharge for each of the sub-basins. However, the runoff peaks are somewhat smoothed by the hydrological model and rivers with hydropower plants may have different runoff scenarios than in the model. Nevertheless, the E-Hype hydrological model is still a good choice overall and they are used in model validation. However, only the freely available part of the E-hype data can be used for on-demand modelling, that is up to year 2011. Therefore, it is planned to use climatological disharge data summarised from E-hype model.

Tidal forcing applies not only to the boundaries but also to the waters within the model area. These can be taken into account using tidal potential. For example, in the eastern Gulf of Finland, sea level oscillations of up to 5 cm can occur due to tidal potential. The tidal potential is calculated from the positions of the Moon and the Sun. Hourly data on their positions are obtained from NASA databases.

2.6 Base setup

A base setup needs to be selected that will act as a collarbone for on-demand coastal applications. As a base setup we choose a four-domain configuration as in the former BAL MFC setup based on HBM for CMEMS dissemination before it was replaced with NEMO (Cmems 2023). It is designed to resolve the Danish Strait relatively well. It has 3 critical domains: North Sea with 3 nm resolution, Baltic Sea with 1 nm resolution and Danish waters with 0.5 nm resolution. Due to the interest in sea level variations in the Wadden Sea, the Wadden Sea domain with a resolution of 1 nm is included in the BAL MFC setup, see Fig. 4. The vertical resolution

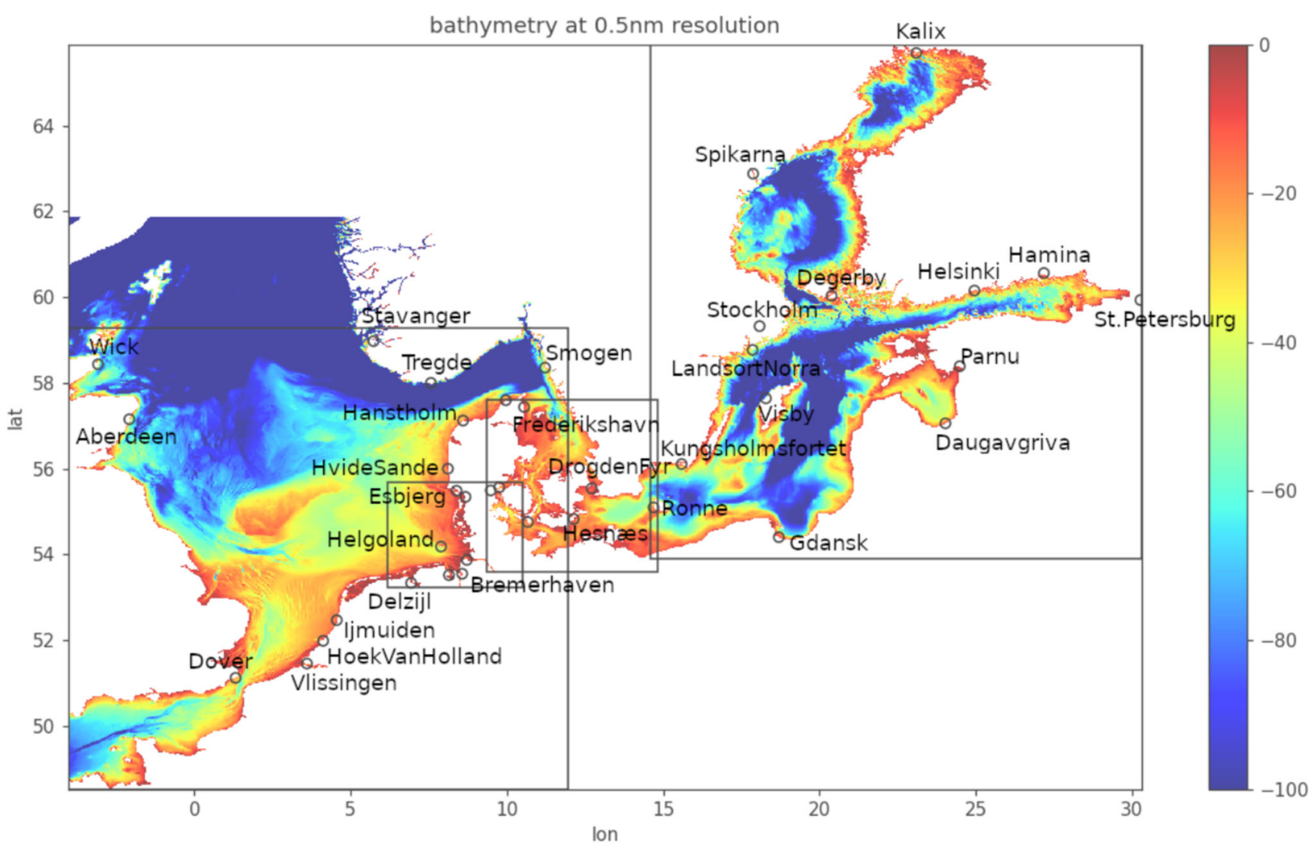

Fig. 4 Configuration of the base setup with 4 domains: North Sea (3 nm), Baltic Sea (1 nm), Danish waters (0.5 nm) and Wadden Sea (1 nm). Most sea level stations considered for validation are also displayed

between depths of 2 and 100 m is chosen to be 1 m in order to resolve the seasonal stratification in the Baltic Sea. Upper layer in North Sea and Wadden Sea domains is chosen to be 8 m, in order to avoid plunged first layer due to strong low tides. This four-domain configuration is chosen as the basis for the on-demand modelling as it has been extensively tested as both a reanalysis and operational model at DMI.

Bathymetry of domains, boundary conditions, river positions, sea level stations, etc. are derived by on-demand tools as described in previous subsections, which are different from the previous BAL MFC setup. Therefore, this provides an opportunity to compare the oceanographic setup based on open source bathymetry and resources with the tuned operational and reanalysis setup.

Parallelisation is an essential requirement for modern oceanographic software, as operational forecasts are run on large supercomputers. Two types of parallelization are simultaneously enabled for the HBM oceanographic model: OpenMP and MPI (Berg and Poulsen 2012). Automatic MPI decomposition is used for user-defined domains. MPI tasks as well as input and output must be organised. For this reason, HBM usually adds a separate input/output node for jobs with heavy calculations. Execution time of base setup on a modern supercomputer using 6 nodes and 36 cores per node is about half a year per computational day, thanks to the parallel processing.

3 Results

Creating a well-tuned and stable setup for on-demand oceanographic applications on the fly is almost impossible.

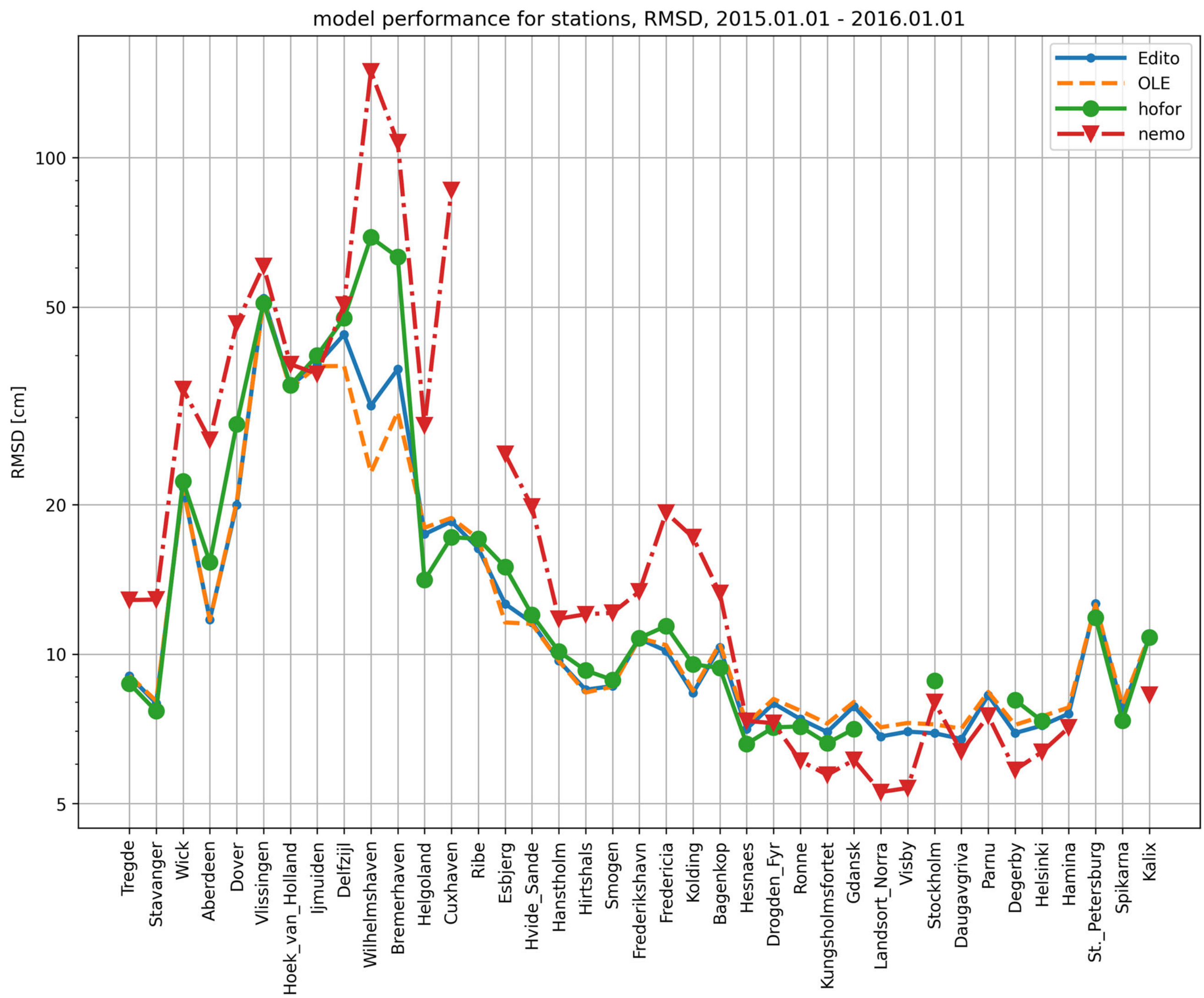

Fig. 5 Centered Root Mean Squared Deviation (RMSD) results "Edito" (blue) at North Sea and Baltic Sea stations for the year 2015 compared to two other reanalysis products: 9-domain high resolution on-demand setup "OLE" in Sect. 3.2 (dashed orange), "hofor" by HBM with dedicated bathymetry and tuning (solid green) and Nemo Reanalysis (dot-dashed red)

Therefore, it is assumed that the user will choose a base setup of open seas and add desired high resolution coastal areas. Therefore, it is necessary to tune and validate the base setup for the North Sea - Baltic Sea area. After that, the example setups with added coastal domains will be considered.

3.1 Tuning of base setup for North Sea–Baltic Sea

The validation period of the base setup is chosen to start in October 2013. The period encompasses the Xaver (named Bodil in Denmark) storm in December 4-7, 2013 and the major Baltic inflow during January-February of 2015 Rak 2016. In order to test the salinity balance in the Baltic Sea, several years have to be considered. A period of 3 years 2013-2016 is chosen for the validation runs.

3.1.1 Sea level validation

The results of the base setup should be compared with existing reanalysis products. The former reanalysis product (up to December 2020) BAL MFC produced by HBM is one of them, marked as “hofor” in Figs. 5 and 6. The other is the current CMEMS multi-year product produced by the NEMO oceanographic model (Cmems 2021), i.e., “nemo” in Figs. 5 and 6. The NEMO reanalysis product uses data assimilation with PDAF scheme for salinity and temperature profiles

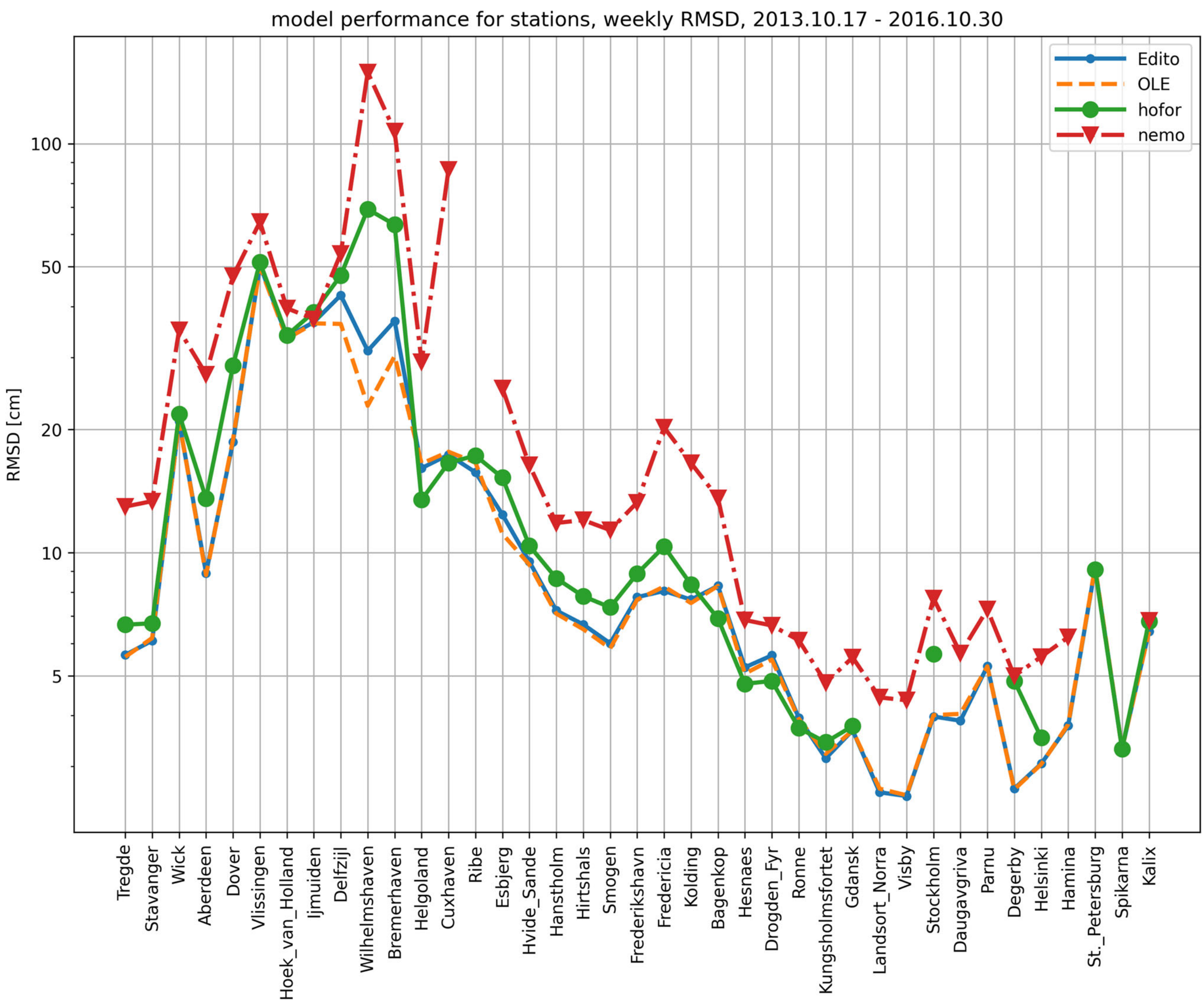

Fig. 6 Weekly mean Centered Root Mean Squared Deviation sea level results “Edito” (blue) at North Sea and Baltic Sea stations for a 3-year period compared with three other reanalysis data: 9-domain high resolution on-demand setup “OLE” in Sect. 3.2 (dashed orange), “hofor” by HBM with dedicated bathymetry and tuning (solid green) and Nemo Reanalysis “nemo” (dot-dashed red)

and SST satellite observations. On the other hand, the former BAL MFC setup based on HBM does not use any data assimilation scheme. Therefore, the resulting salinity in the Baltic Sea is more than 1 PSU lower than it should be after a multi-year simulation. These two reference models are primarily designed for the Baltic Sea, but their extent in the North Sea is the same as in the base setup.

The main sea level stations in the North Sea and Baltic Sea were selected for sea level validation, see Fig. 4. A higher number of Danish stations were included because they have a 10 min observation interval and it was necessary to test the parameters in the transitional waters of the Danish straits. Comparing to “hofor” and Nemo runs, the on-demand modelling results “Edito” are better for the North Sea but slightly worse for the Baltic Sea, see Fig. 5. Earlier reanalysis product “hofor” by HBM has the same resolutions of domains but created without using on-demand automated tools and bathymetry. The “hofor” and Edito runs use the same weather forcing, which is 6 hly forecasts. However, NEMO use ERA5 reanalysis which has much coarser resolution of about 35 km. NEMO performs well in the Baltic Sea, but falls behind in Danish waters because its setup cannot properly resolve the Danish straits with a structured grid without nesting. The performance in the North Sea is mainly related to the accuracy of the amplitude and especially the phase of the tidal oscillations. By using a newer version of the AVISO product (Lyard 2021) the performance for tidal oscillations is slightly improved. The former BAL MFC reanalysis product “hofor” from HBM performs very well in the southern Baltic Sea. However, this is achieved by using the slightly higher resistance of the Danish Straits at the expense of a lower salinity inflow into the Baltic Sea.

In sea level prediction, the vertical reference level for each station is adjusted to the latest available observations using recursive methods. This is because there is no strict vertical reference level in the HBM setup and the sea level bias varies slowly. Therefore, instead of calculating the Centered RMSD for the whole 3-year period, an alternative is to consider the weekly RMSD and average it over all weeks in the 3-year period. On-demand modelling “Edito” is clearly better using this validation metric, see Fig. 6, both in the North Sea and in the Baltic Sea.

3.1.2 Salinity exchange with Baltic Sea

The dynamics of bottom salinity and temperature depend on several factors: saline inflow from the North Sea, freshwater inflow, stratification, atmospheric and tidal forcing, precipitation/evaporation, etc. It is difficult to get the salinity balance

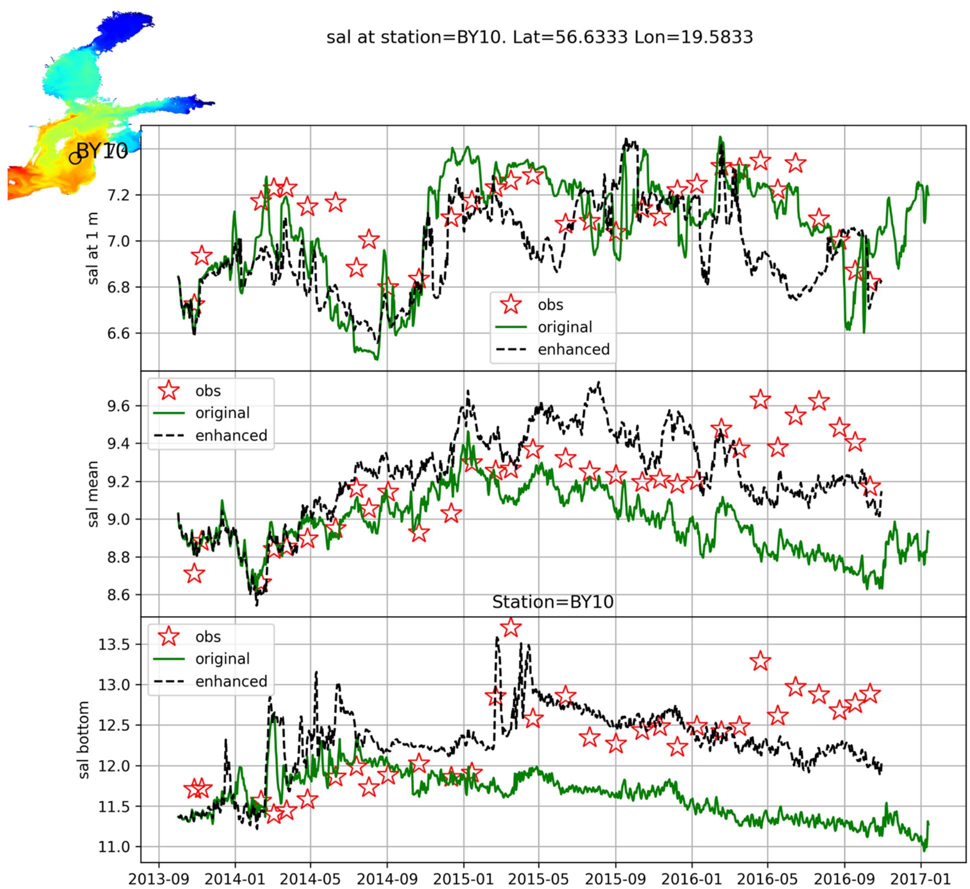

Fig. 7 Salinity at HELCOM BY10 station in Eastern Gotland basin. Plot at the top represents near surface values, middle - profile average, and bottom - bottom value at 134 m depth. Stars denote observations, green line is simulation result with original EMODnet bathymetry, black line - result with enhanced passage from Danish straits to Baltic proper

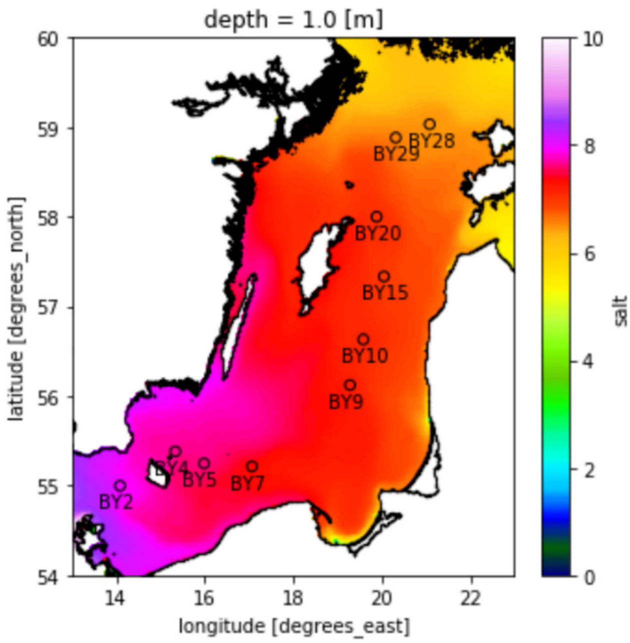

Fig. 8 CTD profile locations in Baltic Sea for salinity validation. Mean surface salinity in 2015 is shown as background

right after several years of simulation without data assimilation.

Usually, numerical oceanographic models underestimate the bottom transport, which leads to less saline inflow from the Danish Straits into the Baltic Sea. This is also the case for HBM, where the effect of the large Baltic inflow in early 2015 is too small and too short, see Fig. 7 at station BY15 of the HELCOM monitoring stations. The bottom temperature of the eastern Gotland Basin is also almost one degree lower, with insufficient inflow of denser and warmer water.

To overcome this problem, the bathymetry of the Baltic Sea is smoothed in places deeper than 30 m and at least 10 km from the coast to reduce bottom friction. In addition, the bathymetry is slightly increased in the passage from the Danish Straits to the Arkona Basin, then to the Bornholm Deep and then to the Slupsk Sill (Krek 2021) and into the Eastern Gotland Basin, but only by up to 1-5 ms in the deepest places. This results in a slightly enhanced salinity inflow into the Baltic Sea, see Fig. 7, which fits better with the profile average and bottom observed salinity levels. It does not necessarily improve surface salinity dynamics for the first years.

In the case of enhanced saline inflow, the values of salinity and temperature are mostly improved near the bottom, see Fig. 8 and Tables 1, 2, 3, 4. The locations represent a part of the HELCOM monitoring stations in the Baltic Sea. The improvement occurs mainly at stations located in the eastern Gotland Basin. Near-bottom salinity is also improved at stations east of Bornholm. The statistics for near-bottom temperature are similar for stations near Bornholm.

The inflow of saline water into the Baltic Sea can be greatly improved by improving transport through the Danish Straits. However, this has a strong impact on the sea level performance, especially during storms. Therefore, a compromise is found that fits the stand parameters quite well. For this reason, a slight increase in depth is used only on the Baltic Sea side of the Danish Strait, and by less than 1 m. A greater increase in depth is used around the Slupsk sill, up to 5 m, which does not significantly worsen the sea level dynamics.

3.2 Examples with added coastal domains

The number of wind farms is increasing today and they affect sea conditions by changing winds, waves, mixing and ocean circulation (Rennau et al. 2012). There are also more and more aquafarms (Maar 2023), which influence the ocean mixing and currents (Michelsen et al. 2019). For this reason, three high resolution areas have been added to the North Sea - Baltic Sea with a resolution of 1/10 nm: the area around Helgoland in the Wadden Sea, Kriegers Flak with the Øresund Strait and Tagalaht Bay on Saaremaa Island in Estonian waters. Another reason to create high resolution domains

Table 1 Bias of salinity of stations showed in Fig. 8 in period 2013.10.01 - 2016.11.01. "org." denotes original EMODnet bathymetry and "enh." with slightly improved passage from Danish straits to Baltic proper. "top" means surface values, "mean" - profile mean, and "floor" - value at the bottom

Station level	count	bias (org.) top	bias (org.) mean	bias (org.) floor	bias (enh.) top	bias (enh.) mean	bias (enh.) floor
BY2	34	−0.198	−0.480	−2.970	−0.220	0.628	0.324
BY4	33	−0.054	−1.819	−2.914	−0.097	−1.075	−1.512
BY5	32	−0.176	−0.594	−1.572	−0.207	−0.175	−0.392
BY7	7	−0.143	−0.190	−1.946	−0.327	0.195	−0.009
BY9	10	−0.076	0.029	−0.754	−0.118	0.178	−0.003
BY10	32	−0.547	−0.213	−0.658	−0.143	0.042	−0.024
BY15	32	0.006	−0.216	−0.651	−0.029	0.201	0.131
BY20	31	0.081	−0.181	−0.327	0.252	0.177	0.281
BY29	20	−0.030	−0.196	−0.311	−0.104	0.249	0.234
BY28	8	−0.181	−0.277	−0.236	−0.230	0.157	0.430

Table 2 RMSD of salinity of stations showed in Fig. 8 in period 2013.10.01 - 2016.11.01. "org." denotes original EMODnet bathymetry and "enh." with slightly improved passage from Danish straits to Baltic proper. "top" means surface values, "mean" - profile mean, and "floor" - value at the bottom

Station level	count	RMSD (org.) top	mean	floor	RMSD (enh.) top	mean	floor
BY2	34	0.434	0.867	2.387	0.458	0.910	2.607
BY4	33	0.223	0.999	2.020	0.246	0.926	1.734
BY5	32	0.257	0.786	1.501	0.280	0.682	1.679
BY7	7	0.222	1.181	2.239	0.183	0.862	1.527
BY9	10	0.127	0.144	0.570	0.167	0.206	0.633
BY10	32	0.177	0.285	0.781	0.189	0.229	0.567
BY15	32	0.191	0.395	0.665	0.221	0.277	0.505
BY20	31	0.216	0.325	0.458	0.205	0.221	0.292
BY29	20	0.225	0.314	0.441	0.287	0.177	0.213
BY28	8	0.221	0.225	0.277	0.249	0.189	0.124

is necessity to parameterize wind turbines and sea grass at arbitrary resolution. In order to avoid high nesting ratios, two domains with an intermediate resolution of 0.5 nm were added in the Wadden Sea and the Vainameri Sea (the sea between Estonian biggest two islands and Estonian mainland). The time step of the highest resolution domains is set four times smaller than in the parent domains. Therefore, this setup runs several times slower than the base setup. However, if the size of the additional domain is set to a small value, the speed is almost the same as in the base setup, see Frishfelds et al. (2022).

These additional coastal domains improve the sea level considerably, especially in places with more complicated coastlines as in the Wadden Sea, see Fig. 6, e.g. in stations Wilhelmshaven and Bremerhaven. The improvement occurs also in stations near Øresund, benefiting from higher resolved strait.

Another example is the use of an even higher resolution domain of Copenhagen with a resolution of 2 arc seconds. This domain is nested within the Øresund domain with a resolution of 1/10 nm, see Fig. 9. The simulation period was chosen to include the storm of 1872, which is the largest storm surge recorded in the southwestern Baltic Sea, with a recorded sea level of more than 3 m at Travemünde. Weather forcing was reconstructed from known historical pressure values (Andrée 2023). A relatively high sea level gradient exists in the Copenhagen Channel during the storm with a sea level variation of almost half a metre. The HBM nested setup was stable despite strong local currents during the storm. However, it was necessary to set a time step twice as low for the Copenhagen area as for the Øresund area. The most vulnerable parts are in the narrowest parts of the Copenhagen Canal. In general, a small deepening there leads to more stable solutions as the critical velocities are reduced. Two-way nesting is essential for the Copenhagen domain as it gives correct inflows and outflows through both ends of the channel in the same way as for Limfjord, see Murawski et al. (2021).

4 Discussion

When building an on-demand oceanographic model, it is important to tune the base setup so that it has good stability and performance. For sea level, the basin wide open sea variations usually play the dominant role. Therefore, if

Table 3 Bias of temperature of stations showed in Fig. 8 in period 2013.10.01 - 2016.11.01. "org." denotes original EMODnet bathymetry and "enh." with slightly improved passage from Danish straits to Baltic proper. "top" means surface values, "mean" - profile mean, and "floor" - value at the bottom

Station level	count	bias (org.) top	mean	floor	bias (enh.) top	mean	floor
BY2	34	−0.678	−0.897	−0.741	−0.683	−0.589	−0.748
BY4	33	−0.521	−0.998	−0.285	−0.535	−0.466	0.576
BY5	32	−0.586	−1.078	−0.677	−0.593	−0.803	0.188
BY7	7	−1.151	−0.994	−1.006	−1.153	−0.693	−0.174
BY9	10	−0.565	−0.689	−0.898	−0.607	−0.459	−0.338
BY10	32	−0.743	−0.667	−0.340	−0.588	−0.366	−0.176
BY15	32	−0.570	−0.446	−0.408	−0.486	−0.297	−0.393
BY20	31	−0.491	−0.357	−0.353	−0.316	−0.195	−0.107
BY29	20	−0.644	−0.442	−0.398	−0.941	−0.406	−0.168
BY28	8	−0.933	−0.451	−0.403	−1.130	−0.544	−0.030

Table 4 RMSD of temperature of stations showed in Fig. 8 in period 2013.10.01 - 2016.11.01. "org." denotes original EMODnet bathymetry and "enh." with slightly improved passage from Danish straits to Baltic proper. "top" means surface values, "mean" - profile mean, and "floor" - value at the bottom

Station level	count	RMSD (org.)			RMSD (enh.)		
		top	mean	floor	top	mean	floor
BY2	34	0.628	1.048	1.178	0.661	0.925	1.228
BY4	33	0.892	1.009	1.948	0.943	0.856	2.289
BY5	32	0.650	0.918	1.641	0.718	0.974	2.025
BY7	7	0.418	1.059	1.620	0.390	0.833	1.347
BY9	10	0.611	0.274	0.752	0.644	0.367	0.632
BY10	32	0.565	0.439	0.737	0.495	0.332	0.605
BY15	32	0.637	0.405	0.601	0.659	0.314	0.591
BY20	31	0.641	0.346	0.482	0.701	0.268	0.301
BY29	20	0.746	0.920	0.406	0.360	0.291	0.264
BY28	8	0.533	0.315	0.320	0.499	0.339	0.152

the basin scale model performs well, then the derived model setups should also work. Centered RMSD results show that the basin-scale model of the on-demand tool has comparable sea level performance in the Danish Straits, better in the North Sea, and slightly worse in the Baltic Sea compared to existing reanalysis products.

The base model of the on-demand tool performs much better for weekly averaged RMSD sea level, which means that seasonal and low-frequency variation in the Baltic Sea is not well resolved by the Edito runs. This metric is more specific to operational forecasting when one can continuously adjust the vertically reference of sea level forecasts to the latest observations.

In general, the sea level performance of highly resolved nested domains is better than of standalone coastal setups, see Murawski et al. (2021); Frishfelds et al. (2021, 2022), where the same two-way nesting technique is applied with HBM oceanographic model. The improvement of sea level performance in stations in Wadden sea (see Figs. 5-6) demonstrates the benefit of adding higher resolution sub-domains. The improvement of currents is also significant in highly resolved domains (Frishfelds et al. 2022) as well. High resolution plays a significant role in long, isolated coastal areas like Limfjord, Roskilde fjord.

There is still room for improvement in the next model updates, for example in the northern Bothnian Bay with present ice conditions. The North Sea stations can also be improved considerably. The case with the added Helgoland domain and better coastline shows that increasing the coastal resolution there is a huge improvement. For the Kattegat and the southwestern Baltic Sea, the adjustment of the Danish straits is essential. Higher bottom friction in the Øresund is used to improve the sea level metrics. The Little Belt area requires a resolution higher than 0.5 nm. Test runs with additional 1/10 nm resolution area resulted in considerable improvement of sea level in nearby stations: Kolding, Haderslev, Assens, Faaborg, Fredercia. Comparisons of on-demand setup with existing forecast products reveal similar conclusions and the results will be presented on a special issue for Barbet storm in October, 2023.

Creating a data assimilation scheme for an on-demand modelling approach is rather challenging. Therefore, the model should be of reasonable quality even without data assimilation. The most sensitive parameters for long-term deviations are bottom salinity and temperature. Bottom transport needs to be improved in numerical models to achieve reasonable long-term performance in salinity. The inflow in the Baltic Sea is quite critical. The transport through the Danish Straits, Arkona Basin, Bornholm Deep, Slupsk Sill into the Baltic Proper needs to be improved. Smoothing of the bathymetry will remove obstacles to transport of water close to the bottom. Minor deepening of shallower sills is also necessary.

Because the long term bottom salinity transport is insufficient with HBM, then transport to local sub-basins of the Baltic Sea also needs to be enhanced as well. These include the Gulf of Riga, the Gulf of North Bothnia, the Curonian Lagoon, etc. A slight increase in depth of up to 5 m in the corresponding straits improved salinity transport by 5 % in the Gulf of Bothnia and the Gulf of Riga.

Adding domains in on-demand modelling needs to be as simple as possible, as users may come from a variety of backgrounds. Therefore, as a minimum, only the domain

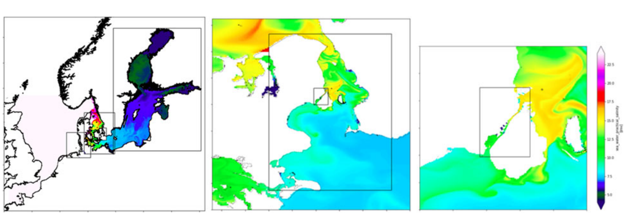

Fig. 9 Setup with high resolution domain of Copenhagen area in storm of November, 1872. Color represents simulated surface salinity at the peak of the storm

location and resolution need to be added. There is no guarantee that this will work for every choice made by the user. Also, the improvements are only expected if the addition of new domain(s) is done properly. Therefore, some examples with high resolution domains added will be provided as additional templates to learn how to make successful setups with EDITO Model Lab.

What about if the model becomes unstable after adding new domains? This happens rarely. One may try to improve the stability by smoothing the nesting boundary. It usually works if the nesting levels are not too high. Therefore, it is better to add intermediate levels of nesting by adding subdomains with intermediate resolution. It may be necessary to reduce the time step if the new high resolution domain is in the location of strong currents. Regarding to the highest resolution domains allowed in on-demand modelling at 2 arc seconds, they do not usually work on the fly as they may require some additional local considerations to improve stability. There are also issues with the stability of ice drift and wetting and drying in very high resolution domains. These issues will need to be addressed in future upgrades of the on-demand tool. Nevertheless, the current version of the on-demand tool is useful for less demanding applications and works reasonably well for resolutions down to 0.1 nm.

The on-demand modelling tool can also be used for operational setups. This requires excellent stability of the model in all weather conditions. The operational setup of Latvian ports (Sennikovs et al. 2020) uses the same two-way nesting approach with HBM, with a resolution of 37 m for 4 Latvian ports. This operational setup has been running for 3 years with a 7-day forecast 4 times a day without any stability problems. This suggests that the current methodology can achieve stable on-demand coastal oceanographic models with a resolution of up to 1-2 arc seconds.

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