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6	Norwegian Meteorological Institute, Norwegian Ice Service	Met.no	NO
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SUMMARY

The present work aims to describe the sea ice forecast system for the Barents and Kara Seas that is under development at Nansen Environmental and Remote Sensing Center.

Offshore activities in the Barents and Kara Seas have increased during the last years following new oil and gas exploration in the area. Fishery in Barents Sea is economically important both for Norway and Russia and increased offshore activities may have impact on the ecologically sensitive system in the area.

The present forecast system distinguishes between the sea ice rheology in the consolidated ice pack and in the marginal ice zone. An elastic-viscous-plastic (EVP) formulation is used in the pack ice while a rheology based on statistics of random collisions between solid ice floes is used in the marginal ice zone. A newly developed wave-in-ice model (WIM) propagates surface waves into the ice and may break large pieces of sea ice into smaller floes. The waves at the boundary of the ice edge are taken from forecasts given by a surface wave model. A floe size based criterion then determines the transition from pack ice rheology to marginal ice zone rheology. The assimilated TOPAZ system, covering the North Atlantic and the Arctic Ocean, is used to produce nested lateral boundary conditions for the regional Barents and Kara Sea model. The regional ocean and sea ice forecast model include tidal forcing at open boundaries, atmospheric forcing from ECMWF regional forecast, and river input based on a climatologically forced hydrodynamic model. Forecast surface wave data from the Norwegian Meteorological Institute are used in the wave-in-ice model. These data are interpolated to the model grid using a nearest grid point approach.

The daily forecast is published on a webpage that also include validation to SIW-TAC sea ice concentrations. Work is ongoing to validate the model performance as well as forecast products.

1 Objectives

This report D7.1 is the first deliverable within work package 7, reporting on the work done within Task 7.1 “Implement a sea ice forecast model of the Barents and Kara Seas”. The purpose of this report is to describe the implemented forecast system. Evaluation of model performance as well as forecast products will be undertaken during next period and described in deliverable D7.2.

The report includes a description of the regional high resolution (4km) model over the Barents and Kara Seas, the nesting to the operational TOPAZ assimilation system covering north Atlantic and the Arctic Ocean, the sea ice model with new development of the marginal ice zone model, and the structure of the automatic daily forecast system including a updated webpage.

2 Background

Oil and gas production is under development both in the Norwegian and the Russian sector of the Barents Sea. Several exploration wells as well as production licences have been awarded in the Norwegian sector of the Barents Sea since 1980 (see for instance www.Barentswatch.no or the .Barentsportal.com).

The ecosystem in the Barents Sea are directly related to the oceanographic conditions, where the Polar front in the central part of Barents Sea separate the Arctic water masses in the north from the Atlantic water masses in the south. Variability in the ecosystem is also related to the seasonal and interannual variations in the oceanographic conditions, such as sea ice extent and inflow of Atlantic water. Fishery in Barents Sea is economically important both for Norway and Russia and increased offshore activities may have impact on the ecologically sensitive system in the area.

In the last years we have seen a highly decreased sea ice extent in the Arctic Ocean. This may in the future open up for commercial transportation along the North East Passage, connecting the north Atlantic with the north Pacific. This may lead to a further increase in ship activities in the Barents and Kara Seas.

The increase in offshore activities and related transportation lead to a demand for a higher preparation for oil-spill recovery operations. In case of an oil-spill, oil-spill models are used to track the oil in the ocean and plan for oil recovery. Few of today's oil-spill models include a state of the art sea ice model as well as a representation of oil captured in the ice.

For any kind of operations in the Barents and Kara Seas, good forecasts of weather, ocean, wave, and sea ice conditions are essential. The present work focus on the capability to model and forecast the sea ice conditions with focus on the development of the MIZ model. The conditions in the MIZ are highly variable, and may change rapidly in time scales of hours. High amplitude surface waves may travel over a large distance before they reach the ice edge and suddenly break up the ice over several kilometres. The ability to model the MIZ will be important for the local conditions, though it may also improve the modelling of sea ice and air-sea interaction over longer temporal and spatial scales.

The Barents and the Kara Seas are Arctic shelf seas located north of Norway and the western part of Russia. Even though geographically partly restricted, the Barents and Kara Seas play important roles in the climate system. A major part of the heat exchange between the Arctic Ocean and lower latitudes is taking place in the Fram Strait and the Barents and Kara Sea regions, this both in the ocean and in the atmosphere. The local conditions in the Barents and Kara Seas strongly influence the north-south heat exchange and influence the water mass formation in the Arctic Ocean as well as large-scale atmospheric dynamics. The production, melting, and transport of sea ice in the Barents and Kara Seas set the condition for the vertical heat exchange between the atmosphere and the ocean.

There are some clear differences between the Barents Sea and the Kara Sea. While Barents Sea is directly connected to the Nordic Seas and receives warm and saline Atlantic water, Kara Sea is shield off from direct influence by Atlantic water. There is a large inflow of fresh water into the Kara Sea from two of the Arctic's major rivers, Ob and Yenisey. Together these factors have strong influence on the local ice condition. The sealed off and less salty Kara Sea has a relatively constant ice cover during the winter season, while there are strong inter annual as well as seasonal sea ice variability in the Barents Sea. (Sorteberg and Kvingedal 2006, Keghouche et al. 2010)

The most influential atmospheric conditions during winter seasons are low-pressure system formed in the North Atlantic, travelling northeast into Barents Sea. These cyclones bring warm and humid air masses into high latitudes and have a strong impact on the water masses and the ice condition in the Barents and Kara Seas.

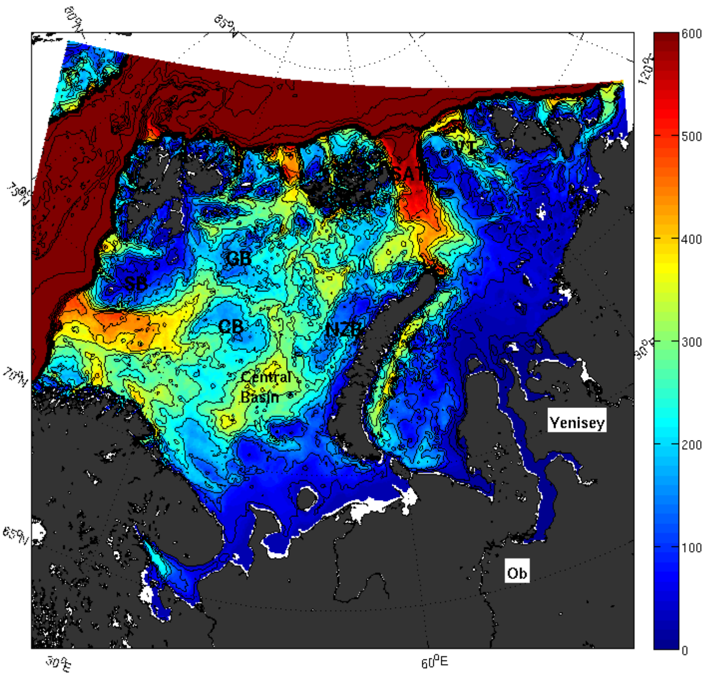

Figure 1. Bathymetry used in the Barents and Kara Sea model, with the larges rivers, Ob and Yenisey, indicated as well as the Central Basin, Central Bank (CB), Great Bank (GB), Svalbard Bank (SB), Novaya Zemlya Bank (NZB), St. Anna Trough (ST), and Veronin Trough (VT). The colour scale is limited down to 600 m depth to highlight the bathymetry on the shelf. Non-coloured areas are outside the model domain and indicate the open boundaries in the north and the west.

Barents Sea has an opening to the North Atlantic in the west, from mainland Norway up to the Svalbard Islands, and a restricted connection to the Arctic Ocean in the north, between Svalbard and the shallow areas around Franz Josefs Land, see Fig. 1. Barents Sea has an average depth of less than 230 m, with the deepest parts in the south, Central Basin deeper than 300 m, and the most shallow areas south-east of Svalbard, the Central Bank and the Great Bank less than 200 m. The north to south stretched out island Novaya Zemlya separate Barents Sea from Kara Sea in the east. The connection between the two seas, is restricted to a narrow and shallow passage south of the island and a wider and partly deeper area north of the island, see Figure 1.

The Kara Sea is relatively shallow with a large part less than 100 m deep. Though, a deep narrow channel along the east coast of Novaya Zemlya 200-400 m and two deep troughs in the north, St

Anna Trough around 500 m and Veronin Trough around 400 m, result in an average depth of 111 m (Volkov et al. 2002). The central and eastern parts are the shallowest areas with the river mouths of the Ob and the Yenisey rivers, less than 30 m, and several islands. The two deeper troughs in the north connect Kara Sea to the much deeper Nansen Basin in the Arctic Ocean, see Figure 1.

3 Ocean and sea ice model

3.1 TOPAZ

The TOPAZ model and data assimilation system developed at NERSC (TP4) is the main monitoring forecasting system for the Arctic region within the MyOcean project. The TOPAZ ice-ocean data and model system is the combination of the Hybrid Coordinate Ocean Model (HYCOM, Bleck 2002, and the Ensemble Kalman Filter (EnKF, Evensen, 2009) and covers the Nordic and Arctic Seas at a horizontal resolution of about 12-16 km (Bertino and Lisæter, 2008, Sakov et al. 2012, see ://topaz.nersc.no). The models use 28 hybrid z-isopycnal layers in the vertical. The TOPAZ system is today operational at the Norwegian Meteorological Institute (.no) and daily forecast and download of data are available within the MYOCEAN platform (.met.no/ARC-MFC). NERSC has preceded a 20-year re-analysis of the TOPAZ system, which assimilates altimetry data, SST, ice concentration, and hydrographic profiles (Sakov et al. 2012). In the HYCOM model at NERSC, the prescribed vertical mixing is solved using the GISS vertical turbulence closure scheme developed by Canuto et al. (2002). The GISS is a Reynolds stress-based model, calculating vertical diffusivities for momentum, heat, and salt in terms of the density ratio, the Brunt-Väisälä frequency, the Richardsson number, and the dissipation rate of kinetic energy.

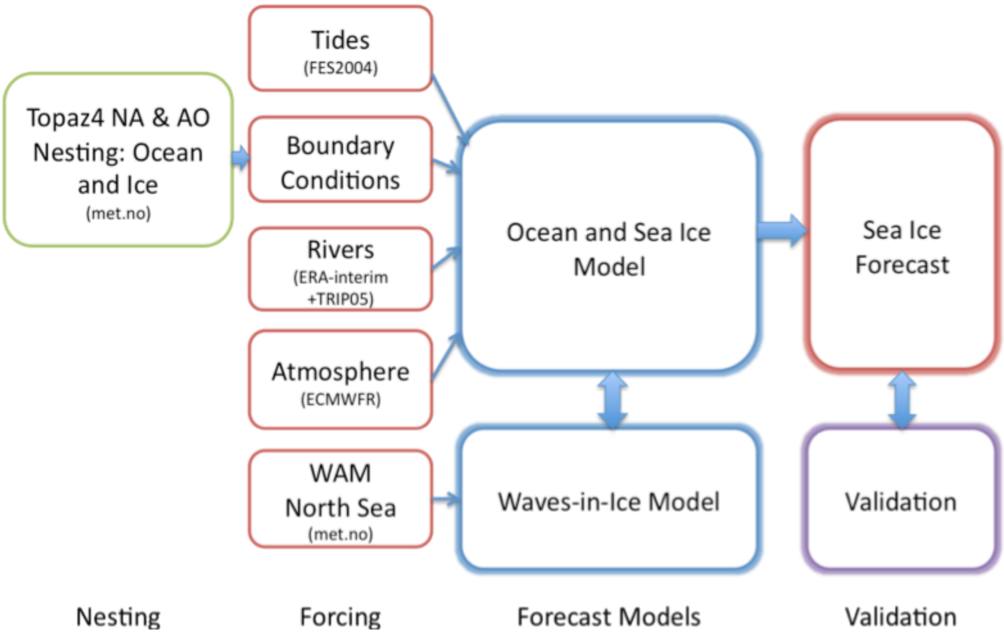

Figure 2. Schematics of forcing, models, the nested forecast system for Barents and Kara Seas.

The regional model over the Barents and Kara Seas (BS1) covers the area of the Barents Sea and the Kara Sea as well as a some parts of the areas in the Fram Strait, Nordic Seas, and Arctic Ocean, see Figure 1. The regional model uses the NERSC HYCOM specifications as described for TP4 above. A high-resolution 510x450 grid is applied, that gives approximately a 5 km horizontal resolution. For a stable nesting from the TP4 model, 28 vertical levels are used also in the regional model. Tidal forcing is applied at open boundaries based on a global hydrodynamic tidal model (FES2004, Lyard et al. 2006). Atmospheric forcing is taken from ECMWF regional forecast. River runoff is modelled with a hydrological model, Total Runoff Integrating Pathways (TRIP, Oki and Sud 1998). Today the TRIP model use climatologically values from ERA-I. In the present set up no assimilation is done in the regional model. A similar model set up has earlier been used in Keghouche et al. 2009 and 2010.

3.2 Sea ice model

Strong winds and surface waves reach and brake up the ice edge into smaller flows that more easily moves with surface currents, tidal motions, and winds. The physical properties of the ice in the marginal ice zone (MIZ) are very different from the physical properties in a more consolidated ice pack. The applied sea ice model in the NERSC HYCOM model system distinguishes between the rheology in the sea ice in the consolidated ice pack and the sea ice in the marginal ice zone, see Figure 3. A one thickness ice category sea ice model is used in the present setup.

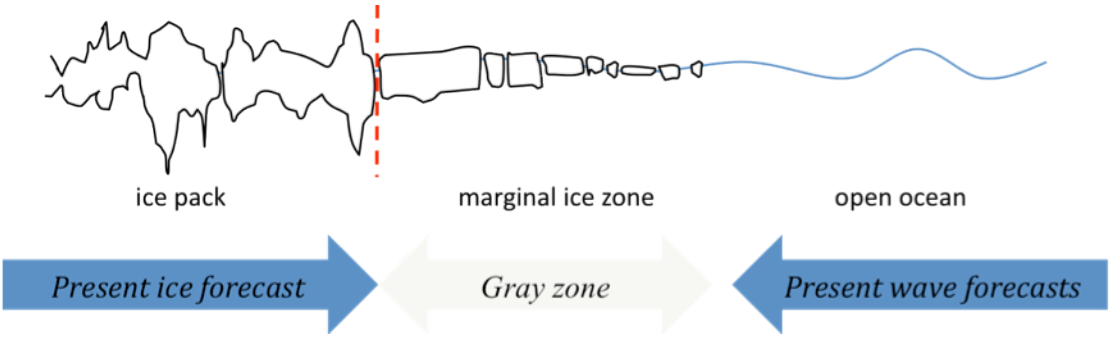

Figure 3. Describe the transition from open ocean, via the marginal ice zone, to the consolidated ice pack. The red line indicate the MIZ criteria.

The rheology used today in the consolidated ice pack is an elastic-viscous-plastic (EVP) model based on Hunke and Dukowicz 1997. In this model the strain rate is separated into the sum of plastic and elastic contribution where the Young's modulus (E) control the level of strain rate when a transition towards the viscous-plastic (VP) regime take place and large values of shear viscosity transform the rheology towards a elastic regime. A new MIZ rheology has been implemented into the NERSC HYCOM model system (Shen et al, 1987), where internal stresses are based on statistics of chaotic collisions between circular floes of a given size. The rheology has been further developed to include the mechanical breaking of ice floes using the mechanical parameters of sea ice (Dumont et al, 2011). Today work is ongoing to develop and validate a wave-in-ice model (WIM), where surface waves are propagated into ice-covered areas and break up the ice into smaller flows (Williams et al, 2012a). Surface waves characteristics are taken from a surface wave forecast model. The WIM model propagates these waves into the ice and keeps wave characteristics in the model memory. Surface waves impose strain in the ice and may break up the ice into smaller floes. The waves dissipate energy travelling into the ice, due to internal ice resistance and wave reflection, and will at some position be too weak to break up the ice. With the WIM model we are able to define a new criteria for the MIZ based on the flow size, in the present setup a flow size of 250 m define the upper bound.

The thermodynamical part of the sea ice model as well as air-sea fluxes are described in Drange and Simonsen 1996. The surface albedo will depend on snow cover, surface temperature, melt ponds, and ice thickness. Some corrections to the snow and albedo schemes have been done following the evaluation done by Vionnet 2009.

4 Forecast system

4.1 Nesting

In the regional Barents and Kara Sea forecast system the TOPAZ forecast for the North Atlantic and the Arctic Ocean (TP4) is used as an outer model in the nested system, see Figure 2. Initial conditions are taken from the assimilated TOPAZ system operated by the Norwegian Meteorological Institute (met.no). Locally the TP4 model runs once a week for an 11 days period, with 9 days forecast, and produce boundary conditions for the regional model of the Barents and Kara Sea (BS1). The BS1 model runs on a daily basis producing 3 days forecast of sea ice and ocean conditions. The nesting cycle and the forecast procedure are described in Figure 4. The figure shows the weekly forecast cycle starting at a Tuesday, here described as Day0. After one week on the next Tuesday, here Day+7, the cycle repeats itself.

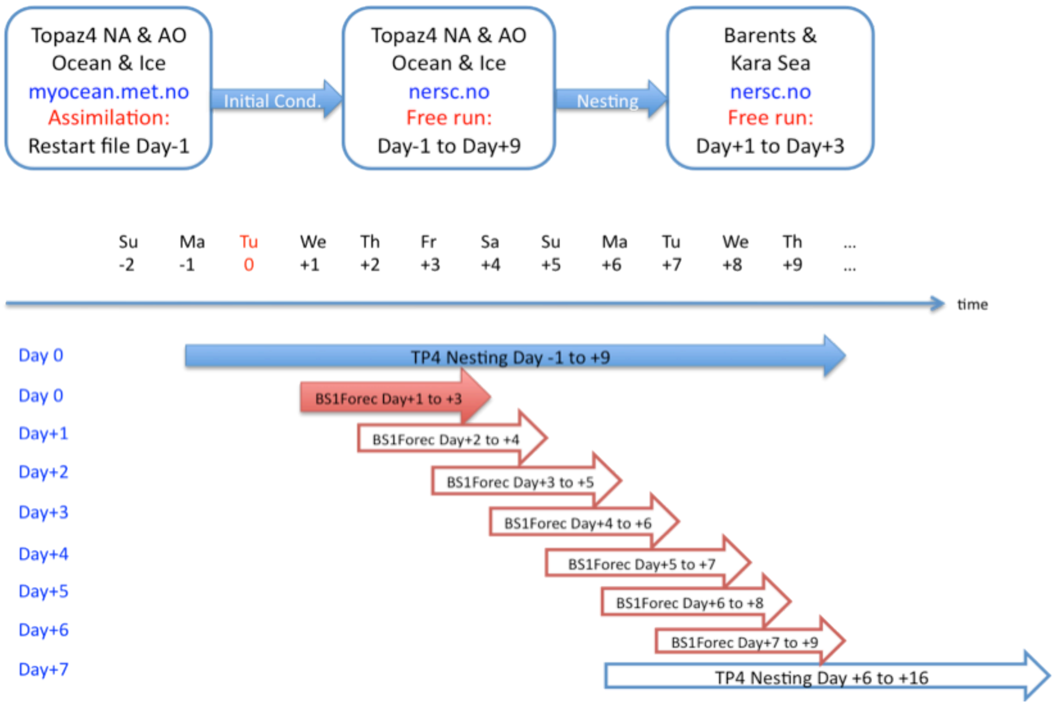

Figure 4. The cycle of the nested Barents and Kara Seas sea ice and ocean forecast system.

4.2 Wave data

In the present setup wave data is taken from the 10 km WAM North Sea forecast model (10km WAMNSEA) operated by the Meteorology Institute in Norway. This is the highest resolution wave forecast available in the area, though this product does not cover the eastern and upper north-western parts of the BS1 model domain. The wave model runs four times a day with HIRLAM atmospheric forcing to give a 60 h forecast. Wave characteristics as significant wave height, peak wave period, and mean wave direction are read into the NERSC HYCOM model and used in the WIM model. When both the wave data and the ice-ocean model are on rotated spherical grids, a nearest point solution is applied to convert the wave characteristics onto the model grid. The domains of the BS1 model and the WAM North Sea model (WAMNSEA) are presented in Figure 5 together with the calculated geographical distances between converted data points. The maximum distance between converted data points in the present model are calculated to be 7813 m.

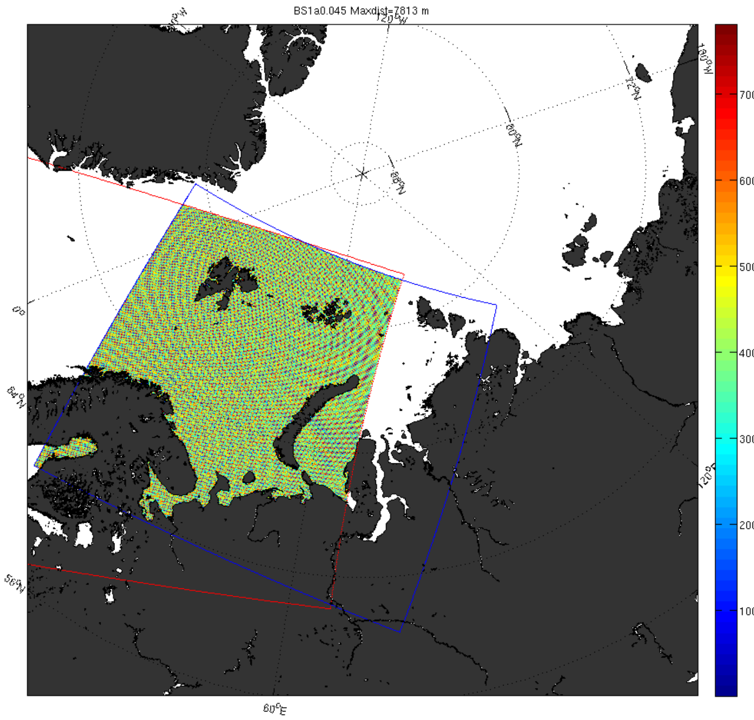

Figure 5. Distance between grid points in the BS1 model and the related nearest grid point in the WAMNSEA model, the model domain for the Barents and Kara Sea model (blue) and the 10 km WAMNSEA wave model (red) are indicated.

4.3 Webpage

A webpage is constructed and maintained where the daily sea ice forecasts are presented, see ://topaz.nersc.no/Knut/IceForecast/Barents. An automatic system is setup that downloads forcing fields, validation data, run the TP4 and the BS1 model, produce figures, and update the webpage. The webpage also include a Validation section where earlier forecast are compared with OSI-SAF sea ice concentration fields. Earlier forecast are found in the Archive section. A short System Description and Updates are also included. Today the forecast presented at the webpage only include the EVP + MIZ sea ice rheologies and not the wave-in-ice model WIM, see Section 3.2. During a period of development and evaluation of the WIM model, a parallel webpage, ://topaz.nersc.no/Knut/IceForecast/Barents2, is used to present the forecast with the EVP + MIZ + WIM models.

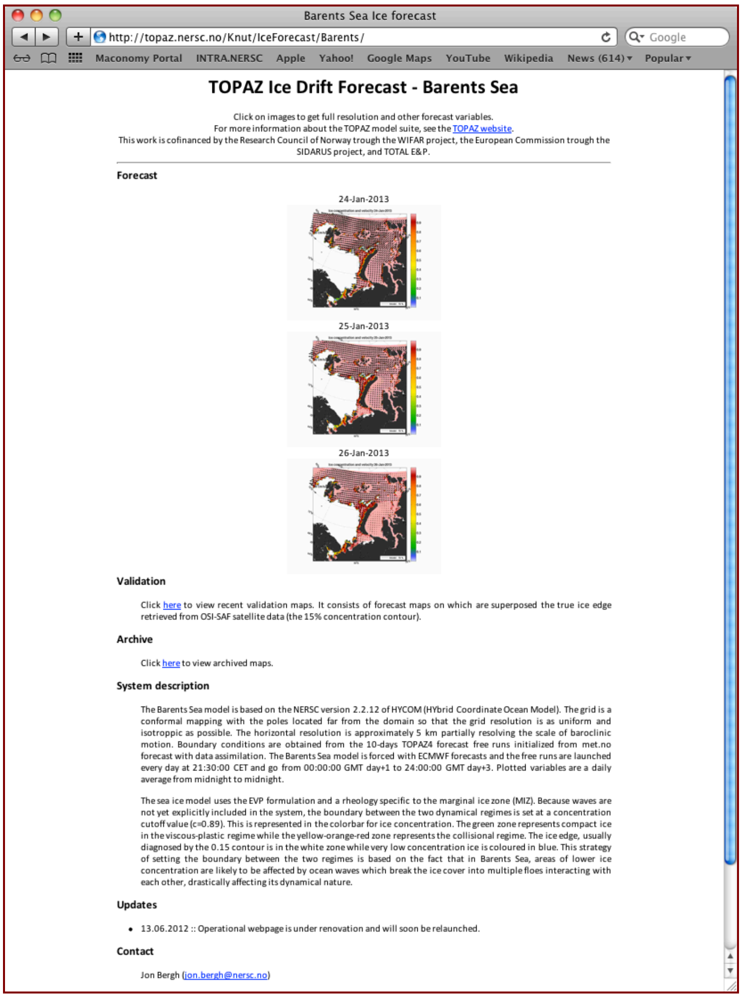

Figure 6. A webpage is constructed and maintained where daily sea ice forecasts are presented together with validation and a short system description.

4.4 Products

Today only few possible products are presented on the webpage, the sea ice concentration overlapped with sea ice velocity vectors, see Figure 7, sea ice thickness, and sea ice absolute velocities. On the webpage are also the sea ice concentration validated against 15% OSI-SAF sea ice concentration, based on passive microwave data from SSM/I. In Figure 8 is the sea ice concentration from the forecast compared to the concentration from OSI-SAF data, with the 15% OSI-SAF sea ice concentration indicated. The complete concentration field from the OSI-SAF data is plotted in Figure 9. There are other possible products available from the forecast model, for instance snow thickness and the related surface albedo, see Figure 12 and 13.

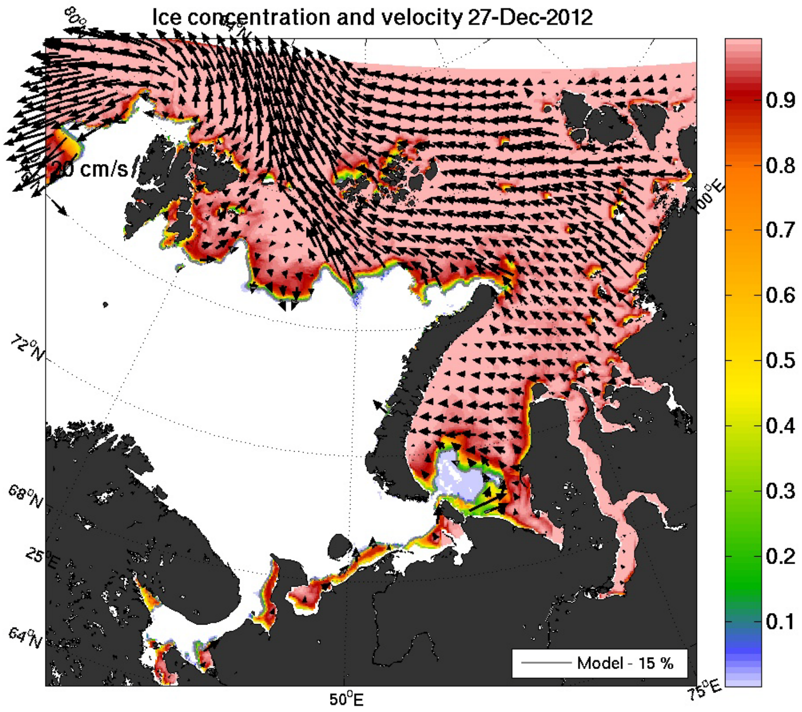

Figure 7. Example of data presented at webpage from 2012-12-27: Model sea ice concentration (colorbar) and velocities indicated by arrows, model 15% sea ice concentration indicated (gray line).

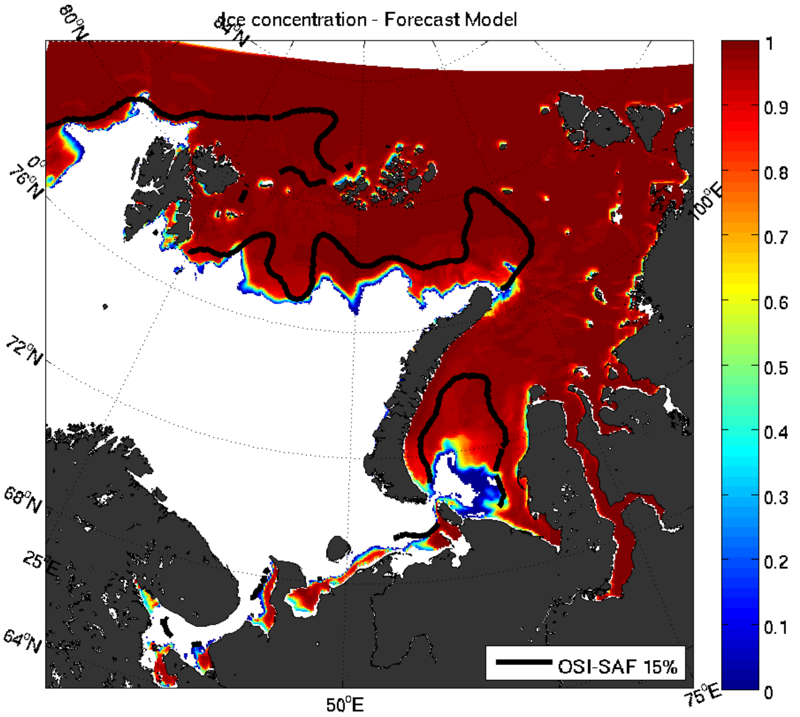

Figure 8. Date 2012-12-27: Sea ice concentration from model, 15% OSI-SAF sea ice concentration indicated (black line).

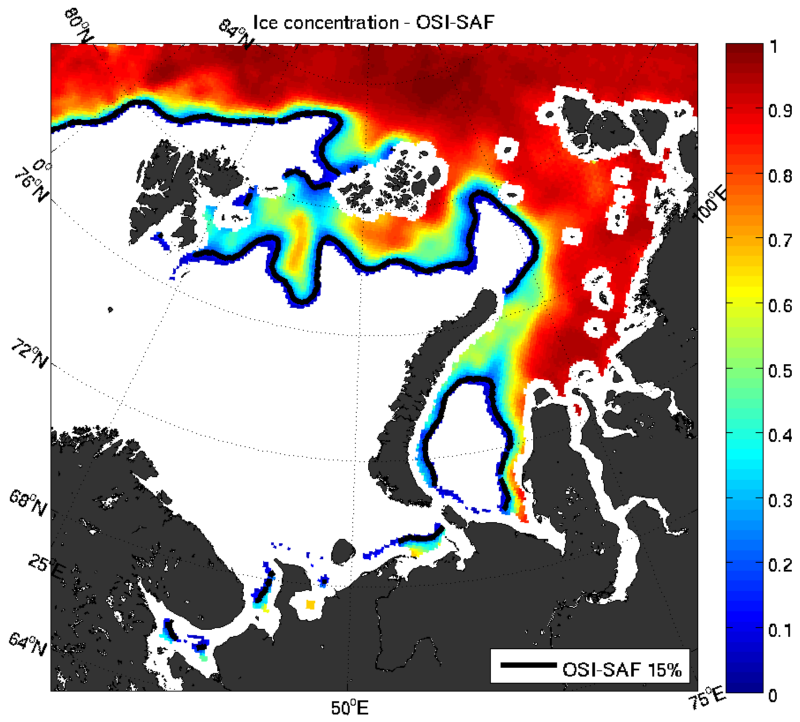

Figure 9. Date 2012-12-27: Sea ice concentration from OSI-SAF data with 15% concentration indicated (black line).

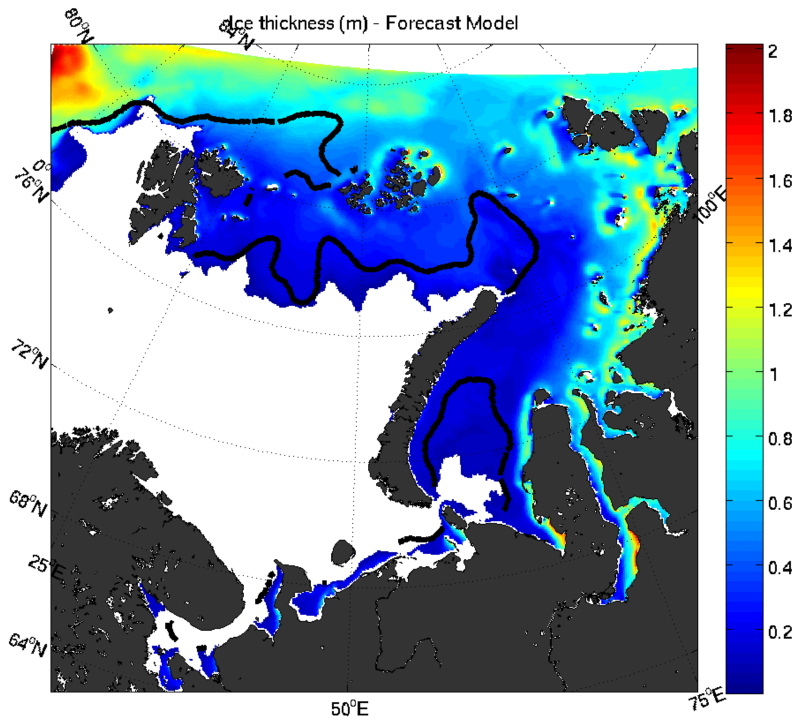

Figure 10. Date 2012-12-27: Sea ice thickness from model (m), 15% OSI-SAF sea ice concentration indicated (black line).

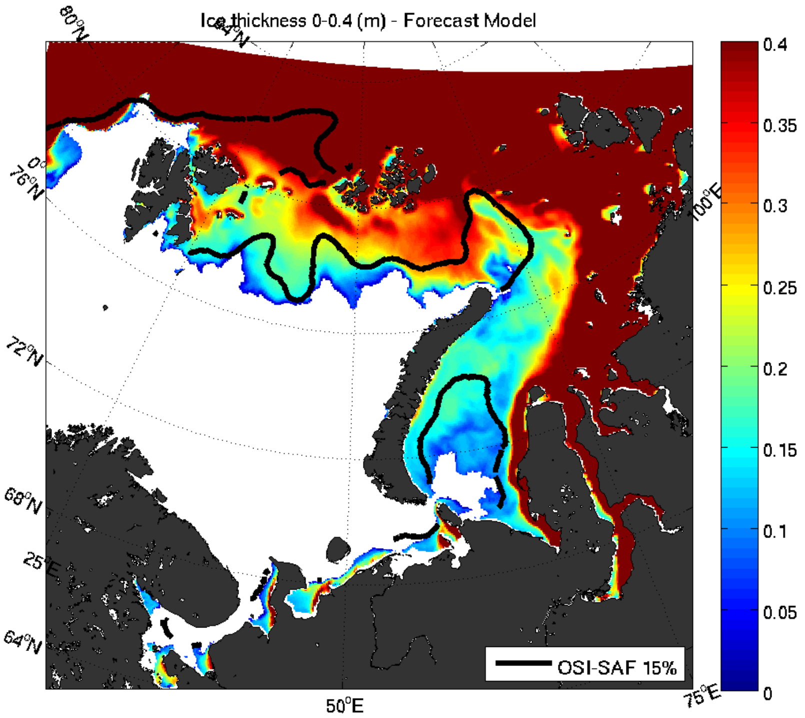

Figure 11. Date 2012-12-27: Sea ice thickness from model (m) with 0-0.4 m colorbar, OSI-SAF 15% sea ice concentration indicated (black line).

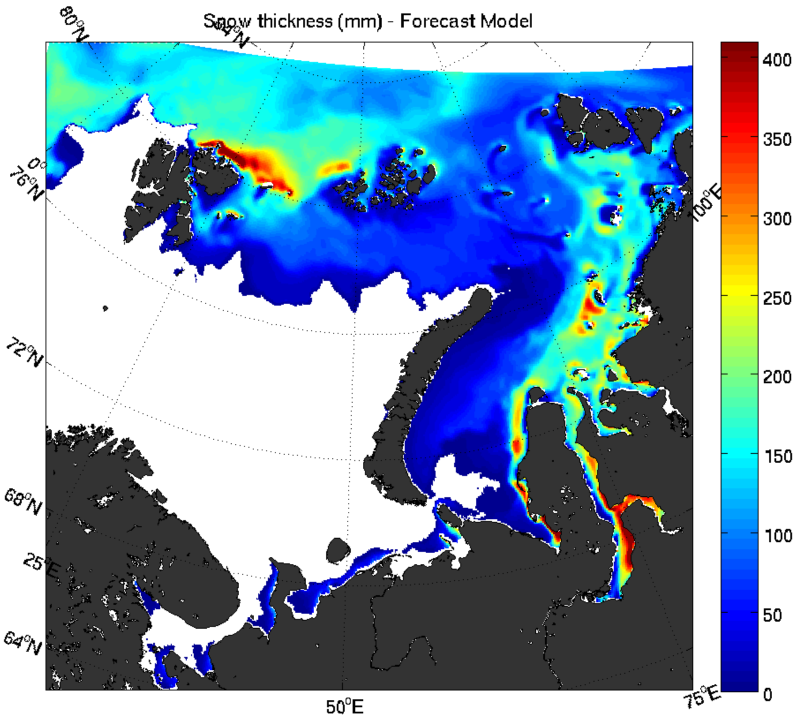

Figure 12. Date 2012-12-27: Snow thickness from model (mm).

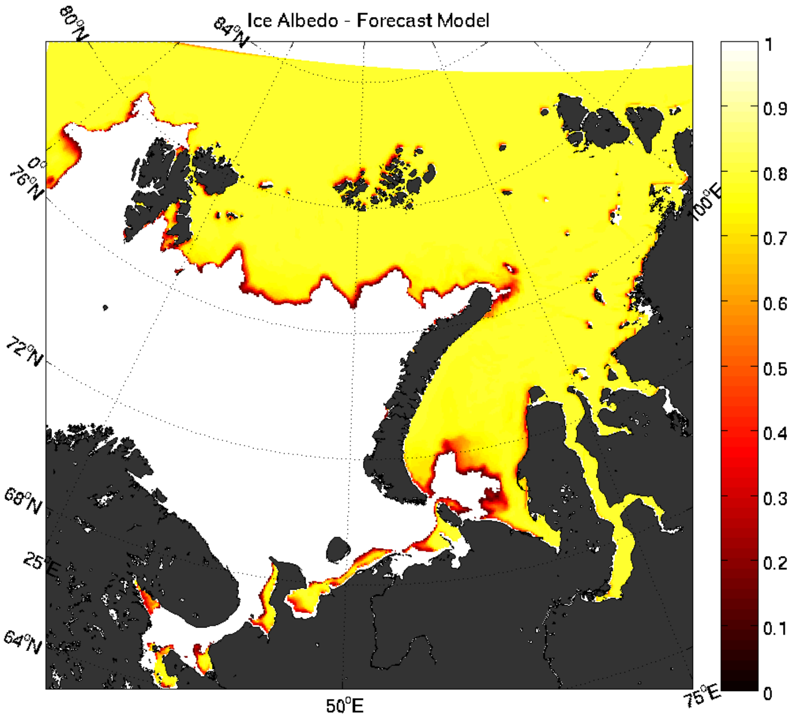

Figure 13. Date 2012-12-27: Sea ice surface albedo from model.

5 Discussion

Even though this report do not contain a proper validation, some comments about the model and the forecast products may be useful for further validation.

The sea ice forecast for 2012-12-27 presented in Figure 7-13 is chosen to show the differences between the sea ice concentrations in the forecast compared to OSI-SAF data. Studying Figure 11, where the 15% OSI-SAF concentration line is plotted on top of sea ice thickness in the model with an adjusted color scale, a clear pattern is seen. In areas with thin sea ice, the differences in the sea ice concentration between model and OSI-SAF data are the largest. The extracted values from the model are daily mean values, and how these values compare to the OSI-SAF data need to be studied.

In the near future, new satellite observations of thin ice thickness will become available for example from the SMOSIce project (U. Hamburg) as well as sea ice albedo observations from the Uni. Bremen. Both will be critically important to understand respectively the propagation of waves in sea ice – being very sensitive to ice thickness – and the thermodynamics of the ice surface. These comparisons can be added to the webpage as soon as the satellite data become available in near real-time.

The results presented in the archive on the webpage are only using EVP+MIZ sea ice rheology. To validate the newly implemented WIM model, longer time series are needed. A long run using the regional Barents and Kara Seas model is planned, where the different sea ice configurations, only EVP, EVP+MIZ, and EVP+MIZ+WIM, will be compared. After a validation period, the plan is to merge the forecasts, and the web pages, into one that use the WIM model.

Comparing the sea ice concentration in the model and the OSI-SAF data, Figure 8 and 9, its clear that the transition from low to high concentration is much sharper in the model. There are several possible reasons for this. In the present setup a one-thickness category sea ice model is applied, resulting in a grid dependent gradient. Further, in the EVP+MIZ model the criteria to define the transition between EVP and MIZ rheology is based on sea ice concentration. Implementing the new wave-in-ice model WIM, surface waves may break up large pieces of ice into smaller floes, and with a rheology criteria based on floe size (rather than concentration) large areas of MIZ may be formed during a short time period. The sea ice in the MIZ is more dynamic with a more rapid response to wind and currents. This should result in a sharper gradient in the concentration, small MIZ area, in periods of surface drift towards the ice edge and less sharp gradient in the ice concentration, large MIZ area, in periods of surface drift away from the ice edge.

There are some known possible sources of error in the WIM model that has not been studied. Since there are no floe size defined in the outer TOPAZ model in the nested system, a default or calculated floe size value has to be applied to the sea ice advected into the regional model through the open boundaries. The wave data taken from the 10km WAMNSEA forecast model do not include the north east part of the BS1 model domain. There is an internal propagation and memory of waves within the WIM model, though the WIM models capability to propagate waves in open ocean for longer periods are not studied.

There is no specific sea ice thermodynamics applied within the MIZ. There are several open questions related to this, for instance lateral melting of floes, refreezing, frazil ice formation, that would be different from the thermodynamics in the ice pack.

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