D6.10 – A report in METOC models and uncertainty estimates

Project no.	636329
Project acronym:	EfficienSea2 EFFICIENSEA2 – efficient, safe and sustainable traffic at sea
Funding scheme:	Innovation Action (IA)
Start date of project:	1 May 2015
End date of project:	30 April 2018
Duration:	36 months
Due date of deliverable:	30.1.2018
Actual submission date:	31.1.2018
Organisations in charge of deliverable:	Danish Meteorological Institute, CLS and the Danish Technical University

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Document Status

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Document History

Version	Date	Initials	Description
1	31.1.2018	TAR	First version. Input gathered from multiple authors

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1 Introduction

The bulk of work in this document has been made as work package 6.5 for the EfficienSea2 project funded by the European Commission. The document itself represents D6.10.

1.1 Purpose of the Document

The purpose of this document is to provide an overview of the developments made within Efficiensea 2 in WP 6.5. Two main contributions are provided:

- Space weather developed by CLS and the Danish Technical University (DTU)
- Operational weather, ocean and sea ice services implemented in WP 4.3 and 4.7 by the Danish Meteorological Institute (DMI).

The two contributions started from different initial states of developments. The space weather service is a new innovative service that provides a forecast of when space weather may interfere with the instrumentation on board a ship.

The developments of the meteorological and oceanographic (METOC) services are provided in WP 4 of Efficiensea 2. The impact of WP 6.5 is improved services without changes in the format, thus the user will not have to change the usage of the services on the Maritime Connectivity Platform (MCP) due to this.

This document is split in three main sections. Section 2 describes the developments of the Arctic model systems, section 3 describes the improvements for the Baltic Area and section 4 describes the space weather service.

1.2 Intended Readership

This report is intended to provide an overview of the development created within WP6.5 of Efficiensea 2. Therefore readers should be able to get an overview of the developments including references to peer reviewed articles that provide further descriptions of the services or the data behind the service.

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2 Arctic developments

The Arctic developments are based on three different products. These are

1. Improvements to the operational ocean and sea ice model (section 2.1 and 2.2)
2. New wave model of the none ice covered Arctic (section 2.3)
3. Ice charts and icebergs (section 2.4)

2.1 Operational Ocean and sea ice model

DMI runs an Arctic and North Atlantic operational ocean and sea ice model based on a coupling between HYCOM (ocean, [5]) and sea ice (CICE, [6]). The forecast length is 6 days and it is updated twice a day. The model runs on a grid with a horizontal resolution of 10 km. It is forced by the ECMWF weather model and the model system uses satellite products of sea-surface temperature and sea-ice concentration for assimilation. These satellite products are typically based on daily averages of multiple images that originate from multiple overpasses of satellites. In order to be able to account for the exact time of the image it is planned to improve the assimilation scheme before the end of the project.

The model setup provides information on the sea-ice state (concentration, thickness, velocities etc.) and ocean state (currents, water level, salinity and temperature). The current operational domain is shown in Figure 1 and the setup is described in [7].

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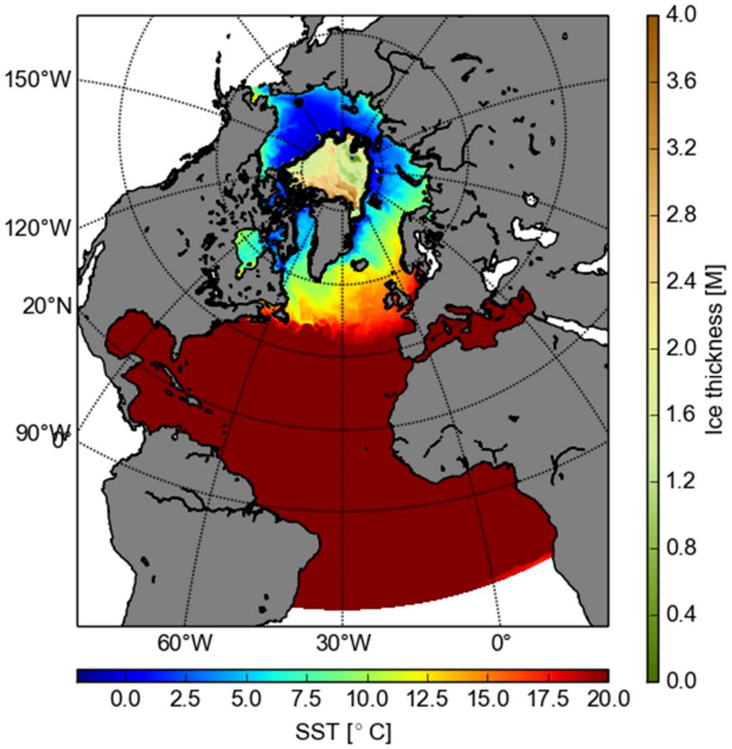

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Figure 1 Domain of Arctic and North Atlantic model setup. Lower colorbar shows sea surface temperature (SST). Vertical colorbar shows ice thickness. The figure shows an example from the 1/9 – 2017. The black contour around the sea ice shows the observed ice edge defined by the 15% ice concentration contour.

The recent increased interest and presence within the Arctic region has put focus on especially the sea-ice state, which is a hazard for maritime operations.

Within EfficientSea2, we have developed the sea-ice component of our Arctic model system. This is done without changing the data feed to the services described in deliverable 4.5 and 4.6.

We have updated the sea-ice version including new features and thereby more correct sea-ice physics:

- Melt ponds on the sea-ice during summer, which is important for the energy budget and therefore for the melt/freeze of the sea-ice.
- Sea-ice age.
- Grounding scheme. This will enable modelling of landfast ice, which is important for the timing of the breakup of sea ice. It occurs when sea ice is locked to and does not move despite forcing of ocean currents and winds.
- Resolution of the model is decreased from 10km to ~3km, which will improve the forecast especially in the near coastal regions.

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The implementation of this into the operational system requires additional computational resources. These will be available during 2018 when DMI has implemented the new High Performance computer (HPC).

2.2 Model efficiency

Modern HPC systems require that the code is structured in a proper way that takes advantage of the system. Therefore we have evaluated the numerical implementation of the physics which showed that the code is in a very good shape, however there are a potential for an optimization of the code. In order to demonstrate that, we analysed the most time consuming part of the code and showed that there is a potential speed-up of the computational time with a factor of 10 or more. This is done without changing the physical representation of sea ice in the code and the results are binary identical (see Figure 2).

The method used is a conversion of 2D data matrices to contiguous vectors, which allows the compiler to do calculations directly on the data from memory without copying variables in/out from memory when transferred to subroutines. Copying in/out is very time demanding and uses additional memory resources. To conclude in addition to the speed-up we have optimized the OpenMp threads and the total memory required to do the calculations.

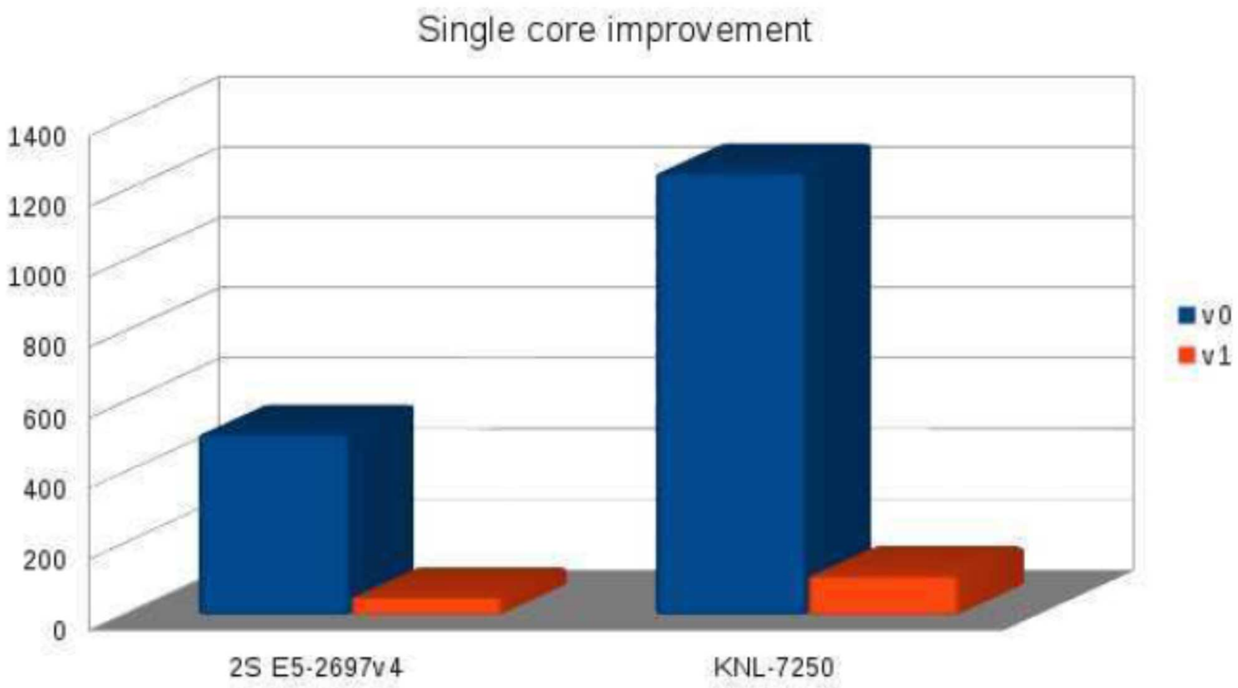

Figure 2 ***Single core performance using original (v0) and refactored (v1) code on two different computer architectures for the present operational setup at DMI.***

This speedup is not only interesting from an academic point of view. The speed is what ultimate sets our limits regarding resolution in an operational forecasting model. The new developments will be added to the original code repository, thus the improvements will

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benefit other users of the sea ice code including the Arctic component of the Copernicus Marine Environment Monitoring Service (CMEMS).

The optimization has been described in [3]. It has been submitted as an article to the Cray User Group meeting in Stockholm May 2018 (https://cug.org/CUG2018). This includes a peer review of the article.

2.3 Arctic wave model

DMI has been running a wave model for the inner Danish waters and the Baltic region (see section 3). Within Efficiensea 2 this has been expanded with a global wave model and a high resolution Arctic wave model that produces high resolution wave forecast with a resolution of approximately 5km.

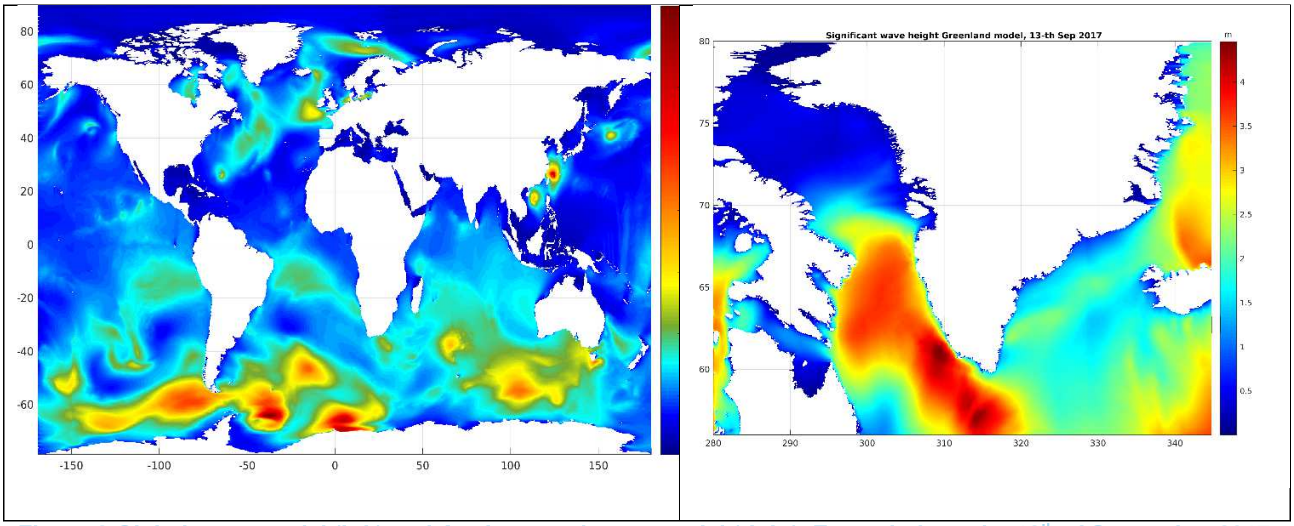

Figure 3 Global wave model (left) and Arctic nested wave model (right). Example from the 13th of September 2017.

The wave model is WAM [4] version 4.6, which describes the propagation of wave energy in waters, where the ice concentrations is less than 30%.

The inclusion of the high resolution wave model expands the area, where wave height, wave period and wave lengths are forecasted within the METOC service.

2.4 Sea-ice charts (Greenland and Baltic Sea)

The ice service at DMI produces ice charts that cover the Greenlandic Waters twice a week (Mondays and Thursdays) as well as more detailed regional sea-ice charts. In Efficiensea 2, the bi-weekly ice charts from DMI are now available through MCP in S-411 standardized format. Additionally (through the MCP), DMI provides regional sea-ice charts for the Baltic Sea created by the Finnish Meteorological Institute (FMI) in S-411 standard.

2.5 Icebergs

As a partner of CMEMS DMI daily receives between 50 and 60 Sentinel-1 A/B Synthetic Aperture Radar (SAR) satellite scenes covering the waters around Greenland. Automated

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iceberg detection is performed on every SAR scene that covers open water areas. Sea-ice infested areas are masked out from SAR imagery using the latest sea-ice charts. Within Efficiensea 2 iceberg information is currently available as icebergs per unit area. I.e. number density grids with the number of detected icebergs per 10x10 km^2 grid cell. Daily updated mosaics of iceberg concentration are available through MCP. Each product consists of two geotiffs in 10 km spatial resolution: the first contains iceberg concentrations; the second contains satellite acquisition times for each corresponding satellite scene, given as “hours older than the newest scene in the mosaic” (see Figure 4).

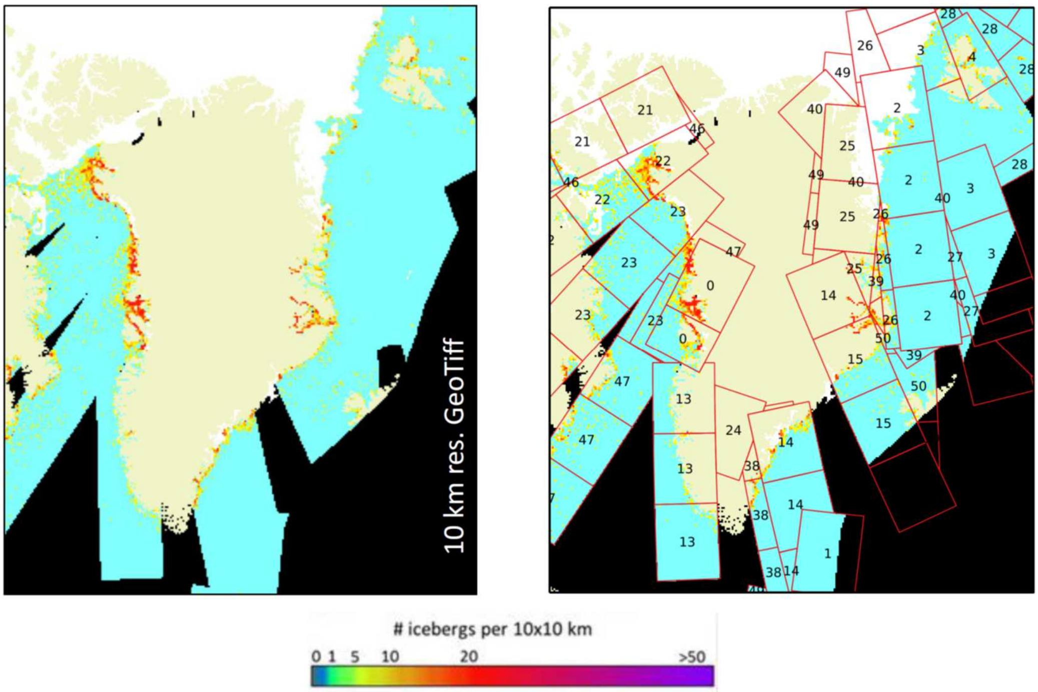

Figure 4 Iceberg concentration in open water around Greenland inferred from Sentinel-1 EW scenes acquired during the 3 days 5/10 – 7/10, 2017. Left: Iceberg concentration map based geo-tiff in 10 km resolution. Right: The same map shown with acquisition time of the Sentinel-1 images.

The detection algorithm is based on Constant False Alarm Rate (CFAR) target detection technique. This means that if a given pixel (backscatter value - see also Figure 5) in the SAR imagery is so high that it is extremely unlikely to belong to the same statistical distribution as the nearby background-pixels (usually representing open sea); then this pixel will be classified as an “iceberg-pixel”. Each cluster of adjacent iceberg-pixels makes up an iceberg target to be registered in the corresponding iceberg concentration map.

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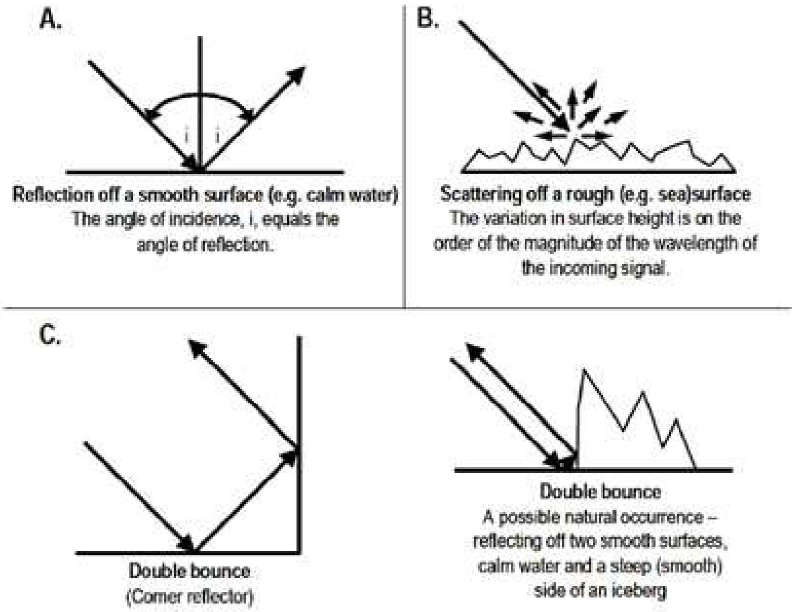

Figure 5 Scattering/reflection off SAR pulses off different surfaces

In Efficiency 2 further developments on iceberg detection has included post processing procedures utilizing dual polarized SAR imagery to reduce the amount of falsely detected targets. Finally, in addition to iceberg concentration products, DMI plans to also make datasets holding the detected positions of all individual icebergs available during the first quarter of 2018.

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3 Baltic developments

DMI's engagement within this area of interest is focused on developments for the BalticWeb and services to this.

3.1 Baltic ocean and sea ice model services

EfficienSea2 Baltic ocean service for MCP collects a number of products that have been set-up and developed in the past three years. State of the art was and is ensured by employing ocean services that are developed and supported by CMEMS. In the course of the project, the ocean circulation model HBM has been improved technically to handle complex and high-resolution applications efficiently and new features have been implemented: new drift ice dynamic and fast ice model, tidal potential, upgrade of the turbulence mixing. The HBM[1] ocean forecasting system is further improved by the use of the Parallel Data Assimilation Framework PDAF, a work that is still under development. New river forcing data from SMHI's E-Hype model, now covering hundreds of outlets and not just the major rivers.

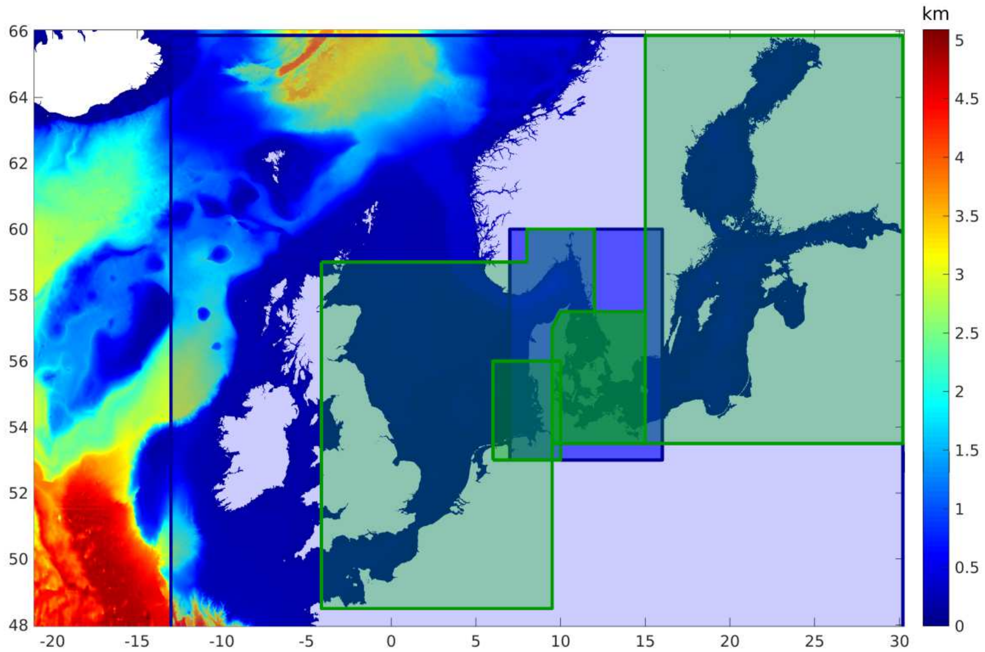

Figure 6 **Ocean circulation model domain (green): North Sea (5km), Baltic Sea (2km), Wadden Sea (2km), Denmark (1km) and wave model domains (Blue): Shelf sea (5km), Denmark (1km).**

3.1.1 Turbulence mixing

HBM turbulence mixing parameterisations have been upgraded using a new set of structure functions [13], which was extended by non-linear stability and realisability analysis implemented as run-time modifications of local turbulent time scale and shear numbers. Compared to earlier HBM versions [12] the new structure functions are more general and apply in rare situations when strong driving factors (strong wind or cooling) could lead to unphysical behaviour.

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3.1.2 Sea Ice

Sea Ice is of vital importance for the correct forecast of the northern oceans. In CMEMS and EfficienSea2, the improvement of the sea ice model performance has been approached from two sides: (1.) revision of the thermodynamic representation of the growth and melt of sea ice, including fast ice and (2.) development of a new drift ice dynamic formulation.

Re-tuning of the HBM ice-thermodynamic routine to improve ice coverage predictions of earlier HBM versions has led to a new version with improved performance during the ice forming and melting period. In the new HBM version (CMEMS V4), the ice forms slower and more gradual due to an improved treatment of the near surface heat transport in the ocean. This prevents the fast formation of an overly cool surface layer at the beginning of winter and leads to a more gradual build-up of ice coverage. Secondly, to improve the melting performance of the HBM sea ice model and to achieve a more gradual reduction of sea ice coverage in spring, ocean-atmosphere heat exchange through sea ice leads has been permitted. The ocean heat from the incoming solar radiation is partially lost to the atmosphere by heat exchange, which results in a slower heating of the ocean and a slower melting of the sea ice.

Modelling coastal fast ice remains to be a challenge for all ice models. A phenomenological sub-module has been developed that describes the transition from rigid coastal fast ice, which resists any stress to freely drifting ice, which admits no stress at all. A set of field equations for characteristic properties has been devised, of which intactness and fragility are the most important ones. Freezing conditions improve the intactness of sea ice, whereas work done by currents and winds gradually degrades the sea ice intactness, which ultimately leads to deformation.

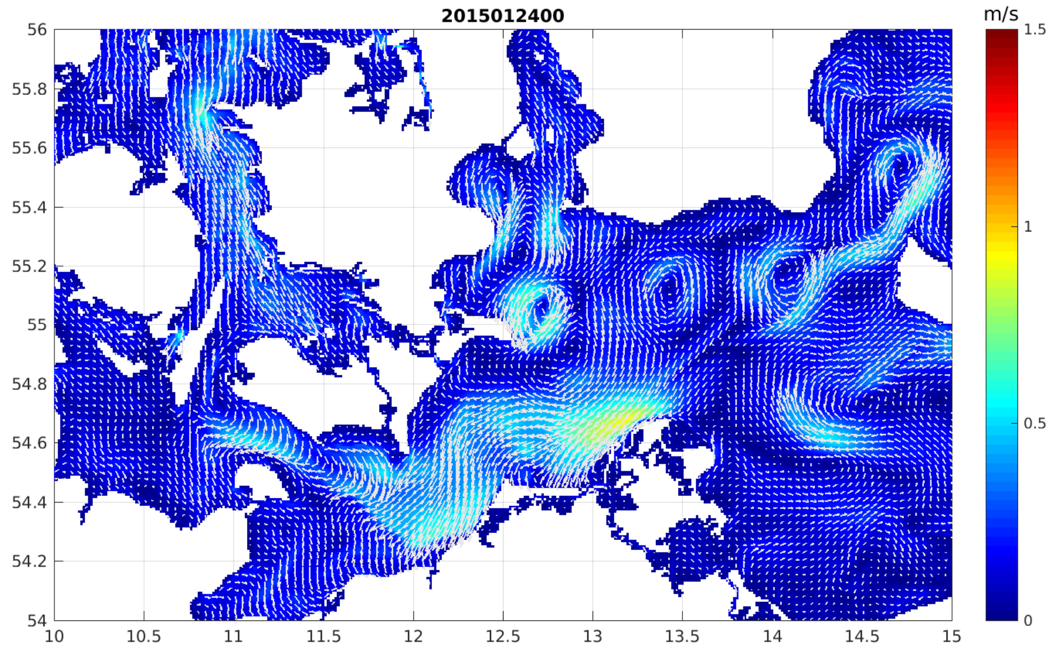

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Figure 7 HBM surface currents in the southern Baltic Sea. Detail of a 900m resolution model that has been set-up with the same resolution for the entire Baltic Sea that we are currently using in the seas around Denmark (Figure 6).

3.1.3 Seamless services

To bridge the gap from basin scale-to coastal-estuary-and fjord applications operational model have been continuously upgraded. The limit of what can be represented by local model has been shifted to higher and higher spatial resolution, with the aim to better resolve the local dynamic and to improve the quality of the forecast. Current hardware trends demand a stronger focus on the development of efficient, highly parallelised software and require a refactoring of the code with a solid focus on portable performance. In EfficienSea2 the potential for future service applications was analysed [1]. The gained model performance can be used for running high resolution model with a larger coverage in a time effective way. Figure 7 shows the HBM surface currents in the southern Baltic Sea, taken from a run with the same horizontal resolution (900m) in the entire Baltic Sea, that HBM is currently only using in the seas around Denmark. The increase in resolution leads to a better representation of the currents, as well as a better vertical dynamic, leading to stronger inflows.

[1] was submitted for peer review as part of Efficiensea 2.

3.2 Assimilation

During the Efficiensea 2 project, a data assimilation suite (the Parallel Data Assimilation Framework (PDAF)) is implemented into HBM with the intention of improving the sea surface temperature (SST) and the sea ice forecast in the inner Danish waters and the Baltic Sea. The data assimilation system uses the “Local Ensemble Square Root Transform Kalman Filter” (LESTKF), which has been setup to assimilate the level 3 SST CMEMS dataset. The HBM-PDAF system incorporated the error covariance model based on ensemble approach, similar to the Ensemble Optimal Interpolation system. This means that the ensemble anomalies were sampled from a multi-year historical hindcast run without data assimilation.

It was shown that assimilation of SST greatly reduced not only the SST bias and the Root Mean Square error of SST; it also had a positive impact on the sea-ice forecast of sea-ice concentration and sea-ice thickness.

As an example of the assessment, the SST bias and RMSE are shown for October 2014. Compared to the reference run (without DA) the SST bias is reduced from -0.54C to 0.0084C and the RMSE was reduced by half.

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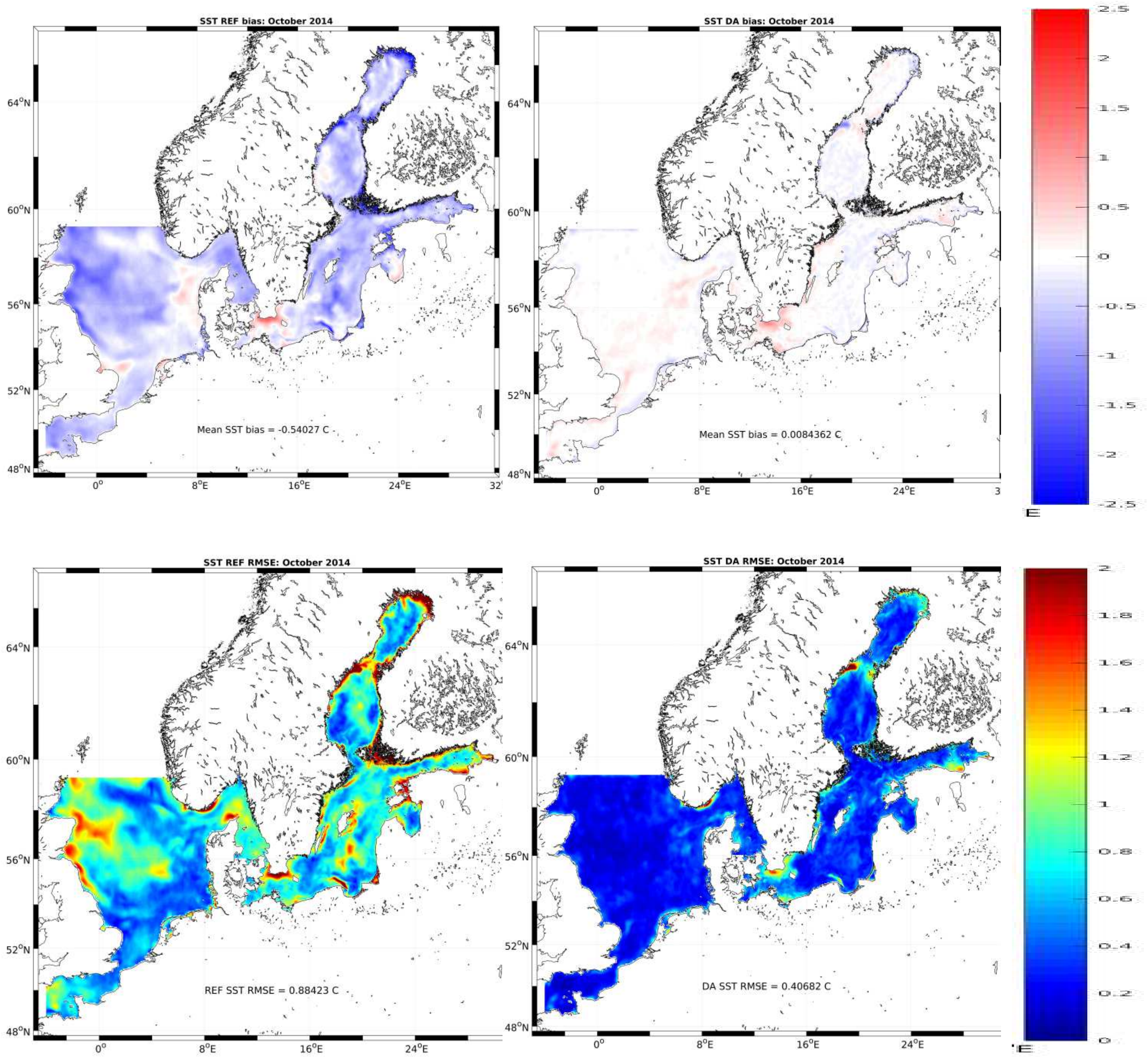

Figure 8 BIAS (top row) and RMSE (bottom row) for October 2014. Left column is reference run without data assimilation. Right column is run with data assimilation

Several additional tests of the assimilation system have been performed for the region between the North Sea and the Baltic Sea. An experiment that covers the period from 2013 to 2104 was executed in order to assess the influence of the data assimilation on the sea-ice.

Figure 9 shows the ice cover and the ice volume of the reference run (Blue), the run including data assimilation (red) and independent observations from FMI's ice charts (Black) integrated over the entire domain.

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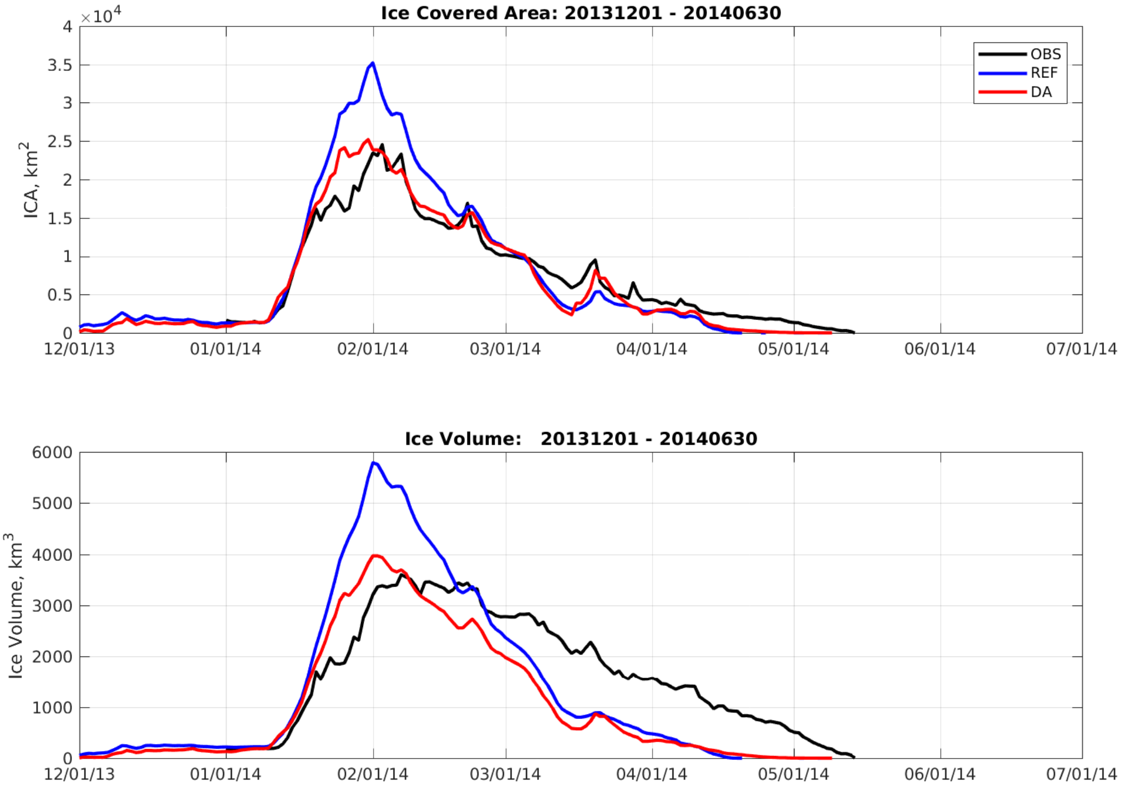

Figure 9 Time evolution of the integrated sea ice cover (top) and sea ice volume (bottom)

The model without DA greatly overestimates both the ice covered area and the ice volume. With assimilation of SST, the corrected heat balance at the surface help to correct the ice covered area and also improves the sea-ice volume. It should be noted that the ice thickness (and therefore the observed ice volume) estimates of the ice charts have their limitations as well.

The assimilation scheme is also being implemented into the Arctic coupled ocean and sea ice model.

3.3 Intercomparison of deterministic and ensemble wave forecasts for the Baltic Sea

Improvements of forecast can be achieved using different methods as for instance increased resolution or multi –ensemble approaches. Both improvements will consume more CPU time. This is a typical limitation of operational models, thus often it is necessary to choose which improvement result in the best improvement of forecast skill.

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This work will result in a publication [2]. It is expected that a first submission will be ready before the project ends. In addition it will be presented at the European Geophysical Union general assembly held in Vienna, April 2018. Both presentation and peer reviewed article has the title Operational wave model in Baltic

3.3.1 Model and setup

The DMI operational wave forecasting system DMI-WAM uses the 3rd generation spectral wave model WAM Cycle4.5 [9], forced by the regional numerical weather prediction (NWP) model DMI-HIRLAM and the global NWP model ECMWF/GLM. The WAM Cycle4.5 solves the spectral wave equation and calculates the wave energy as a function of position, time, wave period and direction. Derived variables, such as the significant wave height, are calculated as suitable integrals of the wave energy spectrum.

The DMI-WAM suite is configured on three nested spatial domains of gradually smaller geographical extent and finer spatial resolution (see Figure 6): North Atlantic, North Sea/Baltic (NSB), and Transition Area, of which forecast results from the NSB-domain are used in this study. The North Atlantic domain uses the JONSWAP wind-sea spectrum [10] along open model boundaries.

In the North Atlantic domain, bathymetry is taken from Rtopo 30"×30" global bathymetry [11]. In the high-resolution domains, Rtopo is combined with local depth information from various sources in order to obtain an improved bathymetry.

The wave energy is in divided into a number of wave directions and frequencies. To speed up wave growth from calm sea, the spectral energy has a lower limit corresponding to a wave height of 7 cm, which parameterizes capillary waves.

The energy source is the surface wind. The sink terms are wave energy dissipation through wave breaking (white capping), wave breaking in shallow waters, and friction against the sea bed. Depth-induced wave breaking [8] is used in the NSB and Transition Area domains only. In the North Atlantic model, the depth maps are not detailed enough for activation of this effect. The wave energy is redistributed spatially by wave propagation and depth refraction, and spectrally by non-linear wave-wave interaction. Interaction with sea ice is included, while interaction with sea current and effects due to varying sea level caused by tides or storms are not incorporated.

The 10 meter wind forcing is provided by DMI-HIRLAM, version SKA (3 km resolution). Hirlam provides 2½ days of forcing. Forecasts beyond that are based on the ECMWF global weather forecast (16 km resolution). HIRLAM wind is available every hour, ECMWF data every 3 hours. To diminish coastal effects, DMI-WAM uses a special 'water-wind', in which the surface roughness everywhere is assumed to be that of water. This enhances the wind speed in the coastal zone, most important in semi-enclosed areas (bays, fjords, etc.). It is

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basically a way to sharpen the land/sea boundary, reducing influence of land roughness on near-shore winds.

The ice concentration is from OSISAF (http://osisaf.met.no/p/ice/) in daily time resolution and ~10 km horizontal resolution, which is interpolated to the WAM-grid. A WAM grid point is considered ice-covered when the concentration exceeds 30%. The ice cover is kept constant through each model run.

DMI-WAM is cold-started once and for all using fully developed sea. Subsequent model runs are initialized using the sea state at analysis time, calculated by the previous run as a 6 hour forecast. The operational DMI-WAM suite is run 4 times a day. Spatial fields of significant wave height and other variables are outputted in hourly time resolution.

Three different setups of DMI-WAM are compared in this work. The basis setup in low resolution (LOW), is configured with the NSB-domain in approximately 10 km horizontal resolution, and the wave energy is resolved in 24 directions and at 32 frequencies. An ensemble setup (LOWENS), identical to the LOW setup but with parallel run of 11 ensemble members forced with atmospheric fields from HIRLAM with perturbed initial conditions. The ensemble mean of LOWENS defines a forecast. Finally, a setup in high resolution (HIGH) is available with approximately 5 km horizontal resolution and the wave energy resolved in 36 directions and at 35 frequencies ranging from 0.04177 Hz to 1.06417 Hz in 10% steps. That corresponds to wave periods of 0.94-23.94 seconds and wave lengths of 1.37-895 meters (in deep water). For overview, see Table 1.

Table 1 Details of DMI-WAM setup used in this study.

	Horizontal resolution [km]	# wave directions	# wave spectral frequencies	Ensemble members	Start	End	Length [months]
LOW	10	24	32	1	January 2014	January 2017	37
LOWENS	10	24	32	11	January 2015	December 2017	36
HIGH	5	36	35	1	December 2016	(December 2017)	13

Going from LOW to HIGH represents an increase in computational effort of a factor of 2^2 (decrease in horizontal resolution)×2 (decrease in time step) ×1.5 (increase of number of directions) = 12, while going from LOW to LOWENS represents an increase in computational effort of a factor of 11 (number of ensembles). Thus, it is possible to evaluate where additional computer resources returns most forecast skill: as an increase in horizontal resolution or as introduction of ensemble members.

3.3.2 Buoy observations

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Observed series of significant wave height from the Baltic Ocean were downloaded from EMODnet (http://www.emodnet.eu/) from the period January 2014 – December 2017 (incl.). Only series with more than 48% data coverage were used. The stations selected are shown on Figure 10.

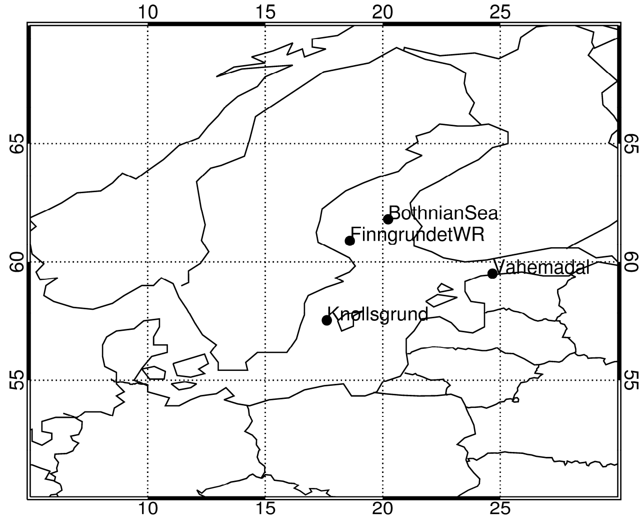

Figure 10 Map with positions of stations

3.3.3 Verification of wave forecasts against buy observations

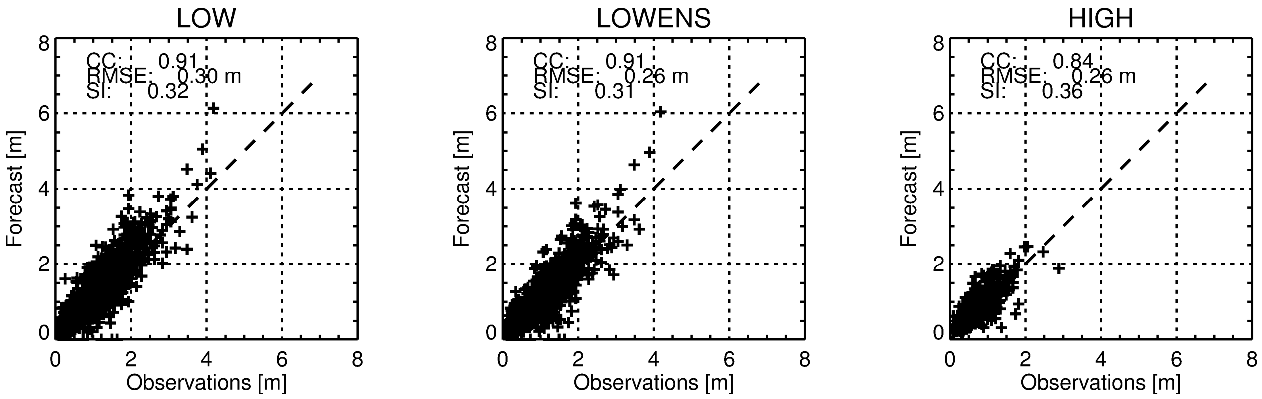

Figure 11 Scatterplot of 24 hr forecasted and observed significant wave height at station Finngrundet for LOW, HIGH and ENSMEAN.

From Figure 11 it appears that LOW and LOWENS overestimates for large SWH-values. Due to the shorter time span where data are available for HIGH, the same is not seen here. This probably means that the skill for HIGH is artificially high, since the range, where the forecast overshoots is never reached. For other stations, the previously mentioned overestimation is not present.

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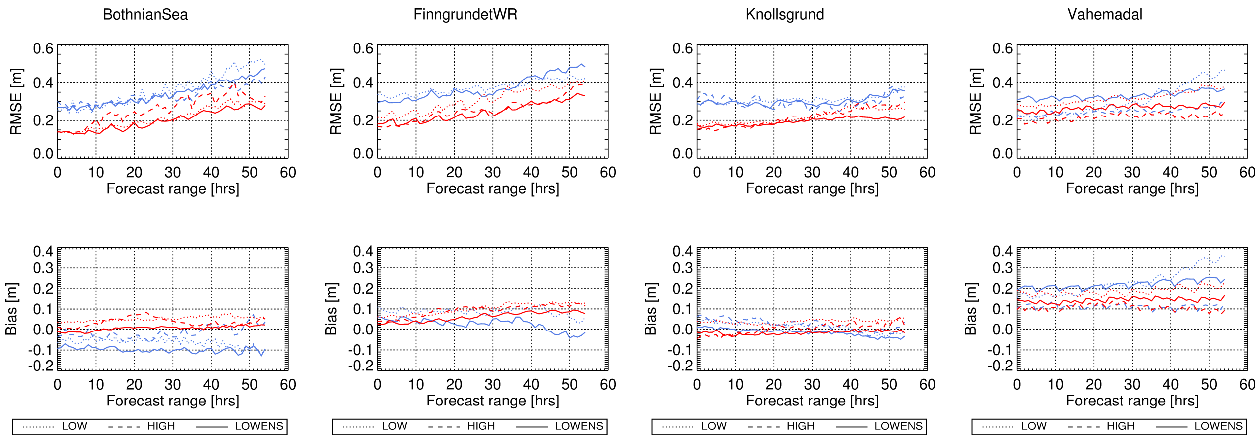

Figure 12 RMSE and bias as function of forecast range for January (blue) and July (red). Dotted lines are LOW, dashed lines HIGH and full lines are for ensemble mean. Leftmost panels are for Bothnian Sea, middle left are for Finngrundet, middle right are for Knolls grund and rightmost are for Vahemadal.

The most prominent feature from Figure 12 the larger RMSE in January compared to July. For some stations, RMSE grows as function of forecast length, for others it is constant. For most stations, the RMSE of LOW and HIGH is larger than for LOWENS. It must, however, be borne in mind, that the RMSE-values for the three model setups are based on data from different time periods.

3.4 Support to simulator test and route guidance

DMI has delivered data to partners who required data in different formats than the ones delivered within the services of WP 4.

The first user case is the simulator test performed by Chalmers University. The aim of this test was to investigate how a captain on a voyage from Bornholm to Øresund reacted to different changes and stress factors. One of these obstacles was weather and ocean (currents, sea level and winds). This was provided in xml format (one per temporal snapshot) as shown in appendix A. An example of this is shown in Figure 13.

In addition the full data fields (winds, currents, water level, (ice cover) has been provided to SSPA who has used this to develop a route guidance service for the Maritime Connectivity Platform.

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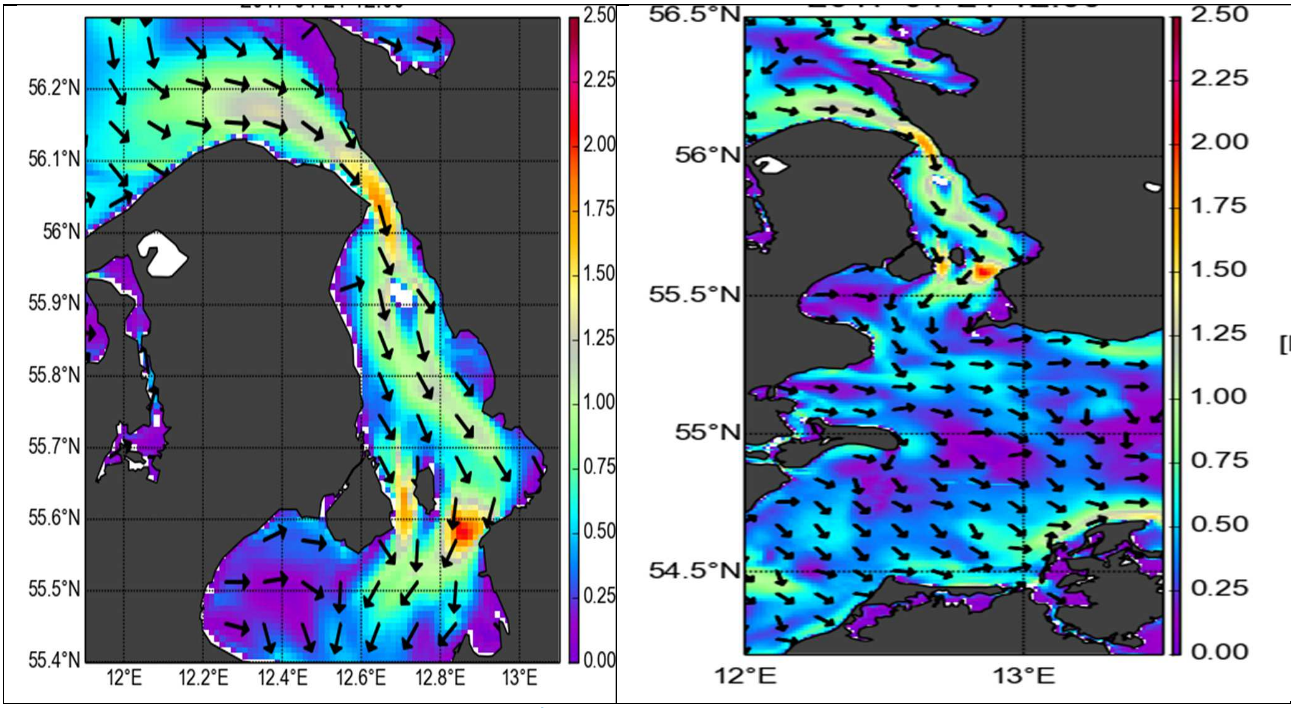

Figure 13 Snapshot of currents on the 21st of April. Left zoom of Øresund. Right full area of target area.

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4 Space weather forecast prototype

4.1.1 Warning service description

The warning service is dedicated to the observation and forecast of scintillations that may affect the GNSS system (and other communication systems). It is composed of (a) a nowcast service that provides the present status of the ionosphere thanks to a network of permanent stations and (b) a forecast service that provides the level of ionospheric scintillations in the near future. This service has been specifically designed for high latitudes. More details about the model development can be found in [7].

4.1.2 GNSS ground monitoring network

This network is of key importance as it provides near real time GNSS data to derive the scintillation parameters for the nowcast and forecast over the Northern region. The following map shows the distribution of high latitudes stations that are operational and have a sufficiently high data rate (1Hz) – for the scintillation detection.

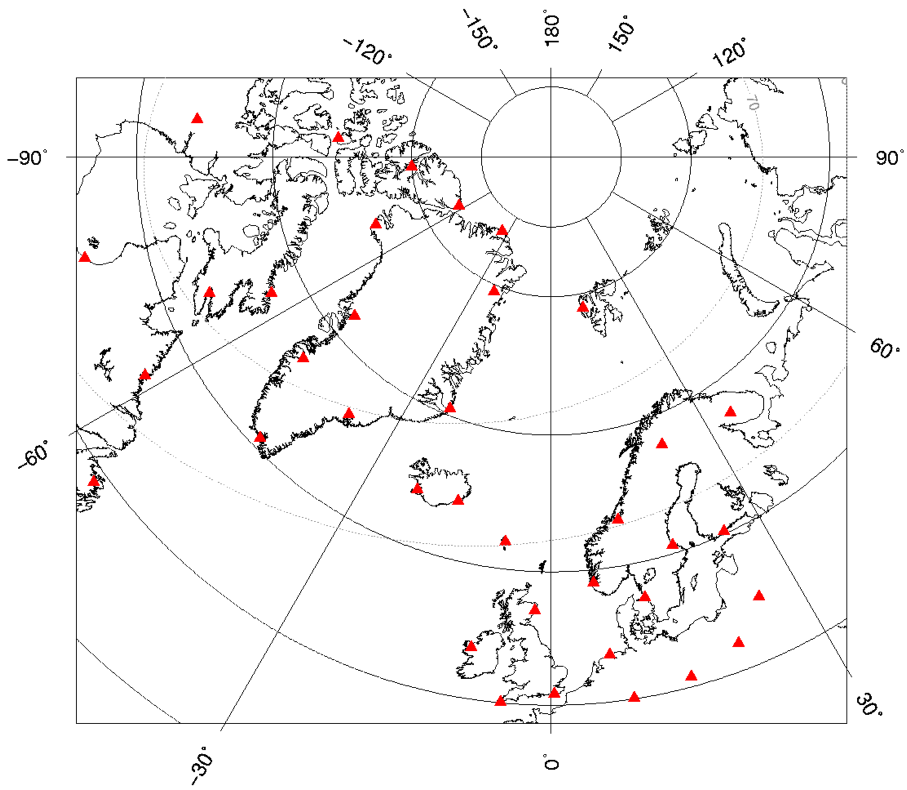

Figure 14 : GNSS network used to monitor the regional ionospheric activity during the campaign

4.1.3 Scintillations nowcast maps

The ionospheric nowcast product is a map that shows the calculated ROTI index that is associated to scintillations. The maps are refreshed every 5th minute, thus dynamics can be seen by the user as propagation of scintillations patches. This delay is estimated as an

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optimum considering the kinematics of the phenomena, the input GNSS data management and processing.

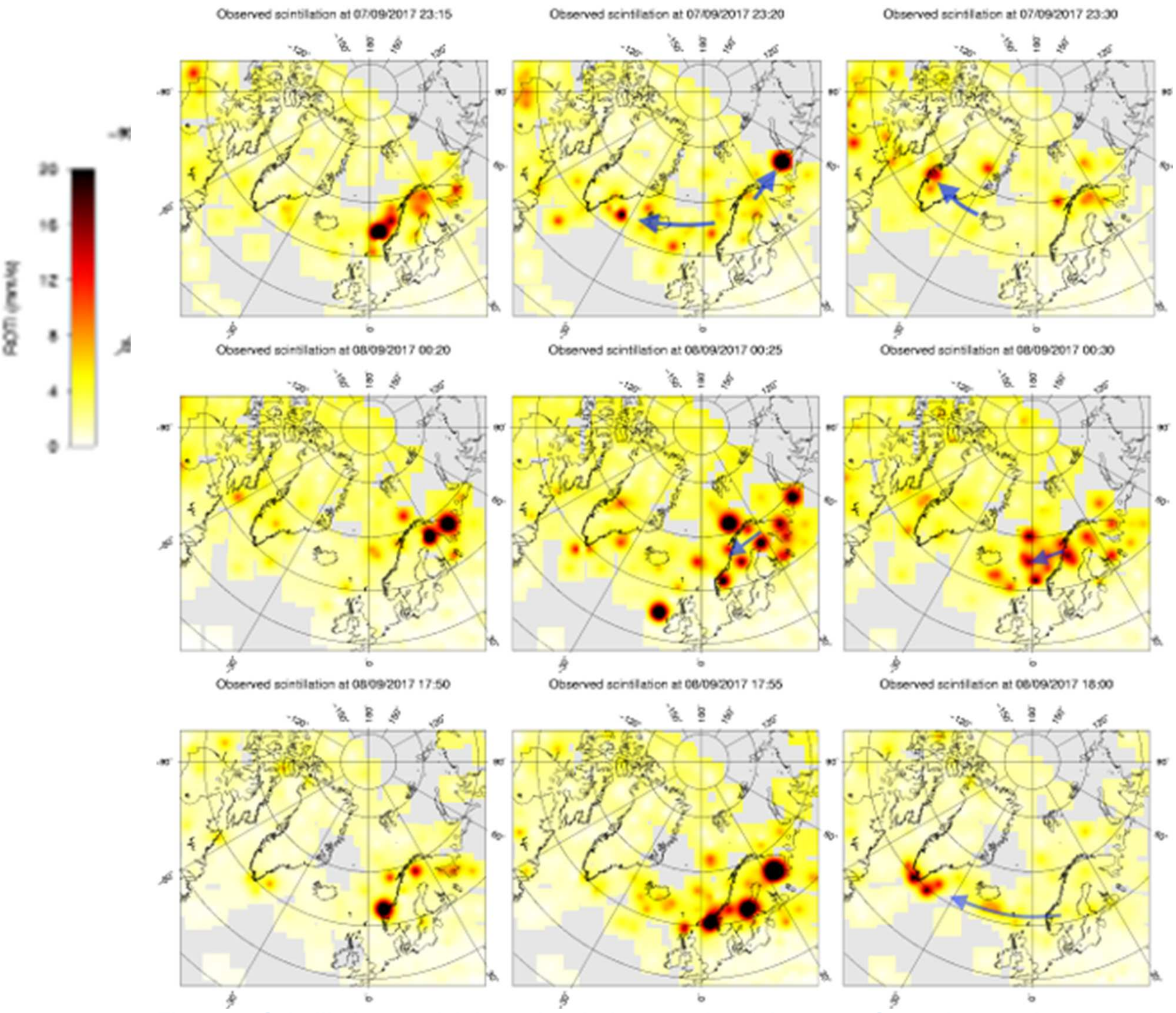

Figure 15 Scintillation spatial dynamics during 3 peaks of the event: Sept 7th around 23:20 (top), Sept 8th around 00:25 (middle) and around 17:55 (bottom). Patches propagation are indicated by blue arrows

The following maps shows additional maps related to present analysis of the ionospheric. In addition to scintillation patches it also includes the TEC (Total Electronic Content). Similarly to the nowcast scintillation maps they can be generated with a frequency of 5 minutes.

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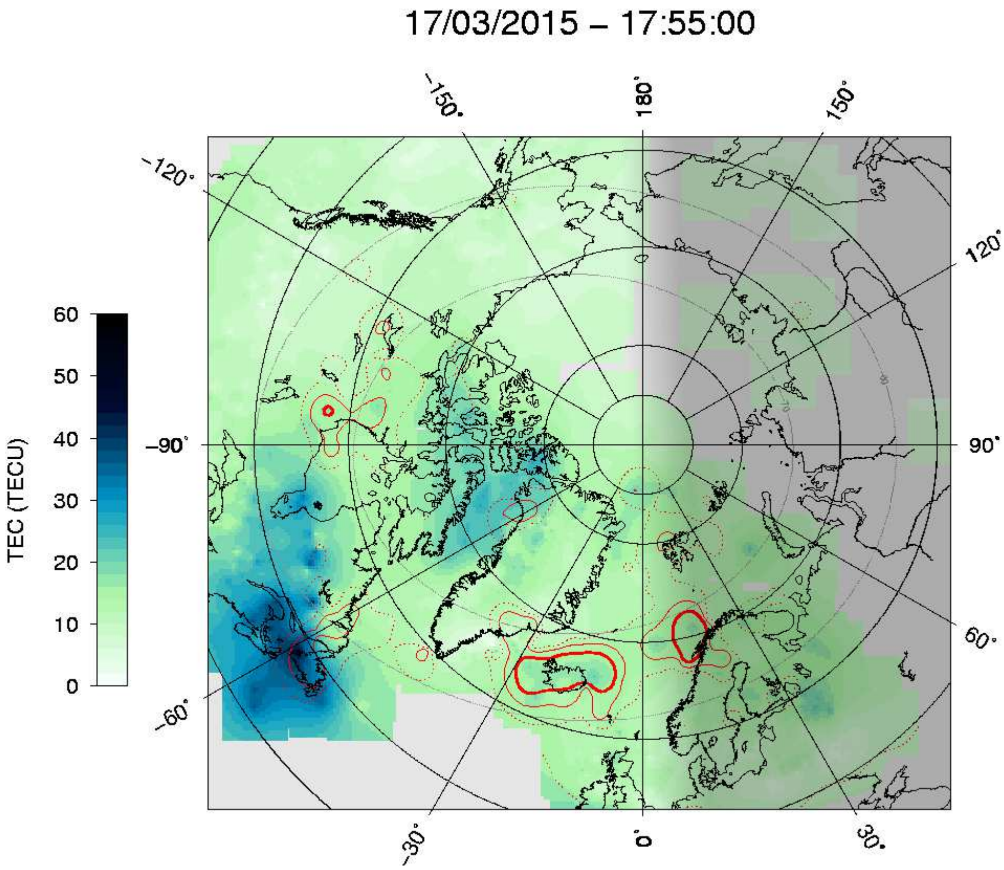

Figure 16 March 17-18th 2015 magnetic event analysis: TEC, scintillation patches in red and location of the terminator as the line that separates the illuminated day side and the dark night

It is useful for internal validation or post processing analysis and understanding of the ionosphere dynamics, however CLS doesn't consider it to be of interest for the end user.

4.1.4 Scintillation forecast maps

The ionospheric forecast product is a map that shows the estimated ROTI index that is associated to scintillations in the next hour. The maps are refreshed every 15th minute. An example is given in Figure 16.

The forecast method has been detailed in [7]. The physics behind the polar scintillations are known to be very complex and it is challenging to forecast their occurrences. Within the scope of Efficiensea 2 – task 2-5, CLS has the responsibility to build a model. This has been done successfully but with a limited forecast length – up to around 1 hour. This is due to the fact that the main driver is the solar wind which is identified as a relevant proxy of geomagnetic activities at high latitudes. Moreover, the solar wind is measured in real time ahead of the Earth, at the L1 Lagrange point, which explains the limited time range of the present scintillations prediction.

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The following maps show two examples of scintillation forecast (blue areas). The forecast is superimposed to the nowcast and in the example on observed patches.

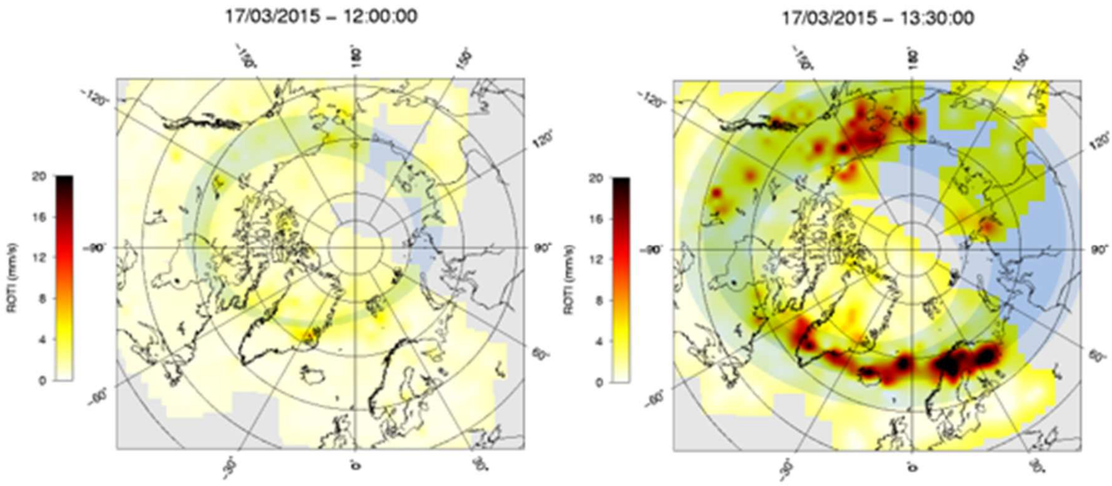

Figure 17 : ROTI Map during March 17th 2015 event: observations are yellow to red levels; model is in shades of blue

Note that the forecast maps can be generated independently of the nowcast information.

4.2 Forecast scintillations product validation

4.2.1 A posteriori validation

Three complementary approaches can be applied to validate the forecast versus the observations:

- Long term comparison of the ROTI proxy (Figure 18),
- Per magnetic event at a regional scale (Figure 19),
- At station level (Figure 20).

The following figure illustrated one months of ROTI comparison. A mean value is estimated per 5 minutes time interval for the different rays between the station antennas and the GNSS tracked satellites. March 2015 has been selected and a significant event happened around the 17th of March (Julian day 23817). One can immediately see that the prediction (blue

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curve) is very consistent with the observations.

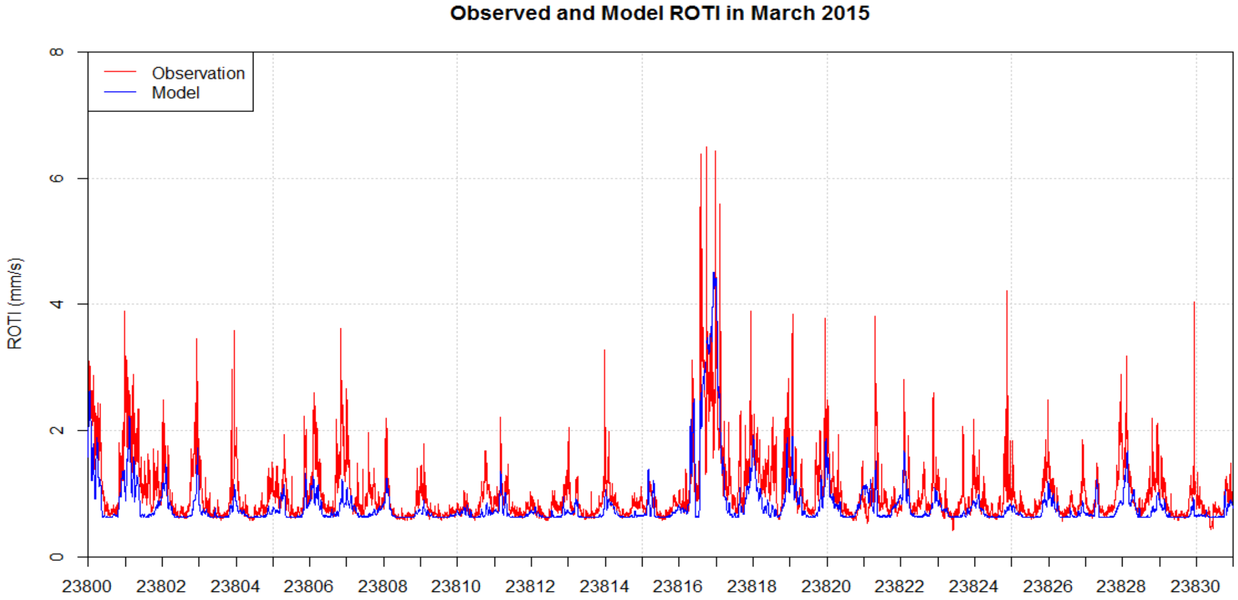

Figure 18. Model ROTI and Observed ROTI in March 2015. X axis is Julian days.

Another relevant validation method is to compare the model with observation of the scintillation proxy (ROTI) at the same time and the same area. An example is given in figure Figure 19 which corresponds to a magnetic storm in Sept. 2017.

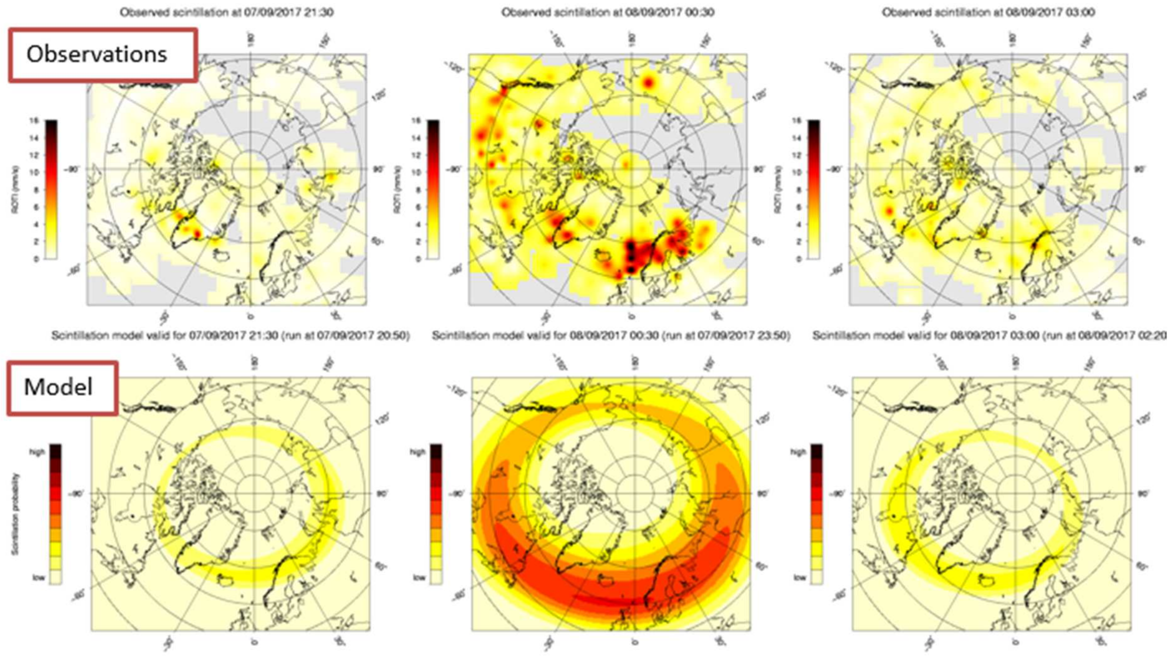

Figure 19. Forecast model validation – Sept. 7-8 2017 geomagnetic storm – as model versus observations

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The following figure illustrates the last comparison approach at GNSS site level. One day is considered, a colour is affected per satellite.

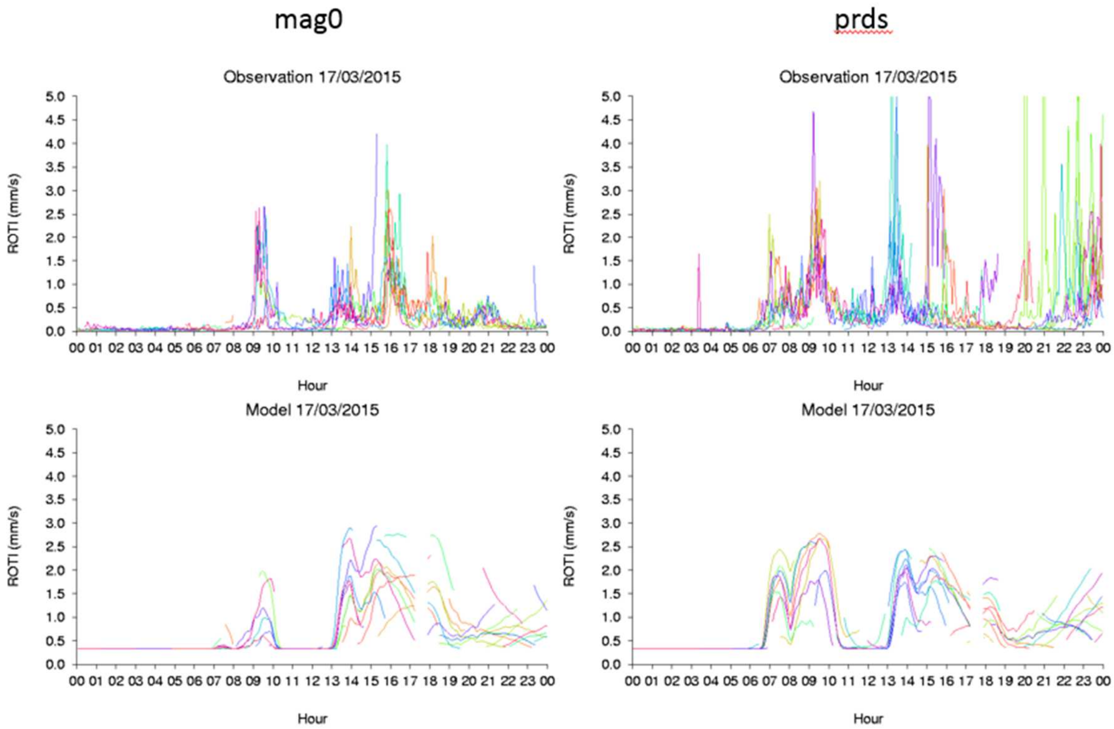

Figure 20. Per station validation of the scintillation forecast –17 March 2015 – 2 polar stations

4.2.2 User/stakeholder involvement with an on-board ship GNSS campaign

The Danish Royal Arctic Line has accepted to host a set of telecommunication and GNSS equipment on-board a cargo that navigates from Denmark to Greenland. A 6 months campaign at sea has been lead from May to October 2017 (Figure 21). The experimentation and results obtained are described in [7].

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Figure 21. Space weather monitoring campaign on-board the Mary Arctica (May-Oct. 2017)

C-NAV[1], a company that provides high precision positioning solutions was also involved. The company has furnished a GNSS geodetic receiver and the service for PPP (Precise Point Positioning) available on-board via the broadcast of GNSS corrections in real time directly to the antenna. The company was interested in the evaluation of possible space weather impacts on its service.

To summarize the campaign analysis, two magnetic events occurred during the monitoring period. These are one in May and one in September. The second was the most interesting with ROTI index up to 5 and 6 (Figure 22). They generate significant losses of lock on the GNSS satellite tracking as shown in Figure 23. According to the antenna positioning, the impact was not significant probably because the multi-constellation (GPS + GLONASS) compensate for the satellite losses.

[1] https://www.oceaneering.com/positioning-solutions/

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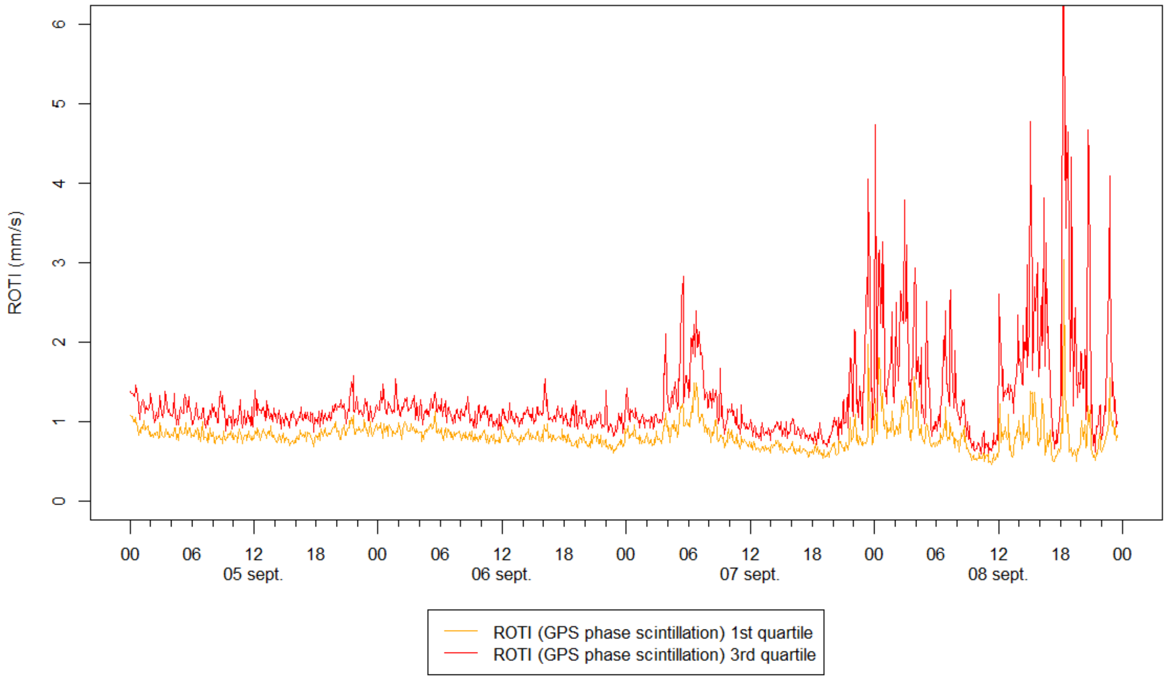

Figure 22. Calculated ROTI on-board the ship (C-NAV receiver) during the Sept. ionospheric event

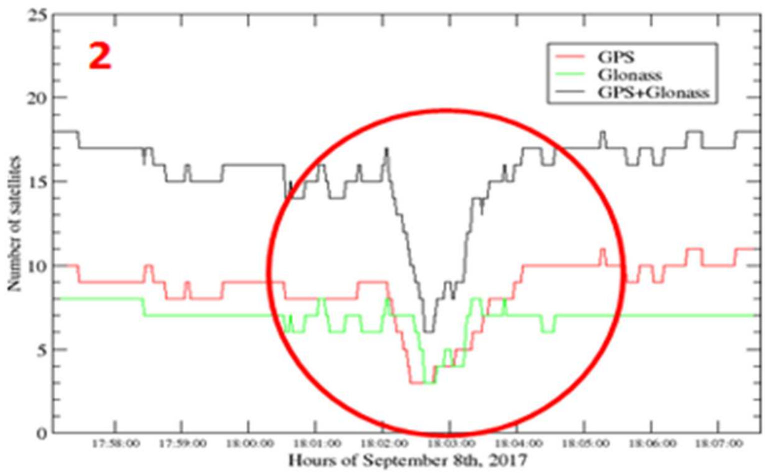

Figure 23. GNSS satellite losses of lack observed during the Sept. ionospheric event (C-NAV receiver)

According to the Royal Arctic Lines, no specific anomalies were observed on-board during the 7-8th September event because of the scintillations.

4.3 From the prototype service to an operational service

Several issues have to be considered when envisaging to implement a maritime operational service derived from the scintillations service prototype. The first issue is the access to GNSS

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raw data in order to build the nowcast and forecast products. The second issue is to improve the presentation of the scintillation level in order to have a ready to use and comprehensible product for the mariners. The third issue is the product format and the dissemination tool and interface.

Each of those issues is discussed in the next paragraphs.

4.3.1 Limitations with regards to GNSS data access

The following figure presents the real time or near real time IGS stations network where it is possible to have a routine access to data. The scintillations affect limited space areas so monitoring and forecasting require the largest coverage.

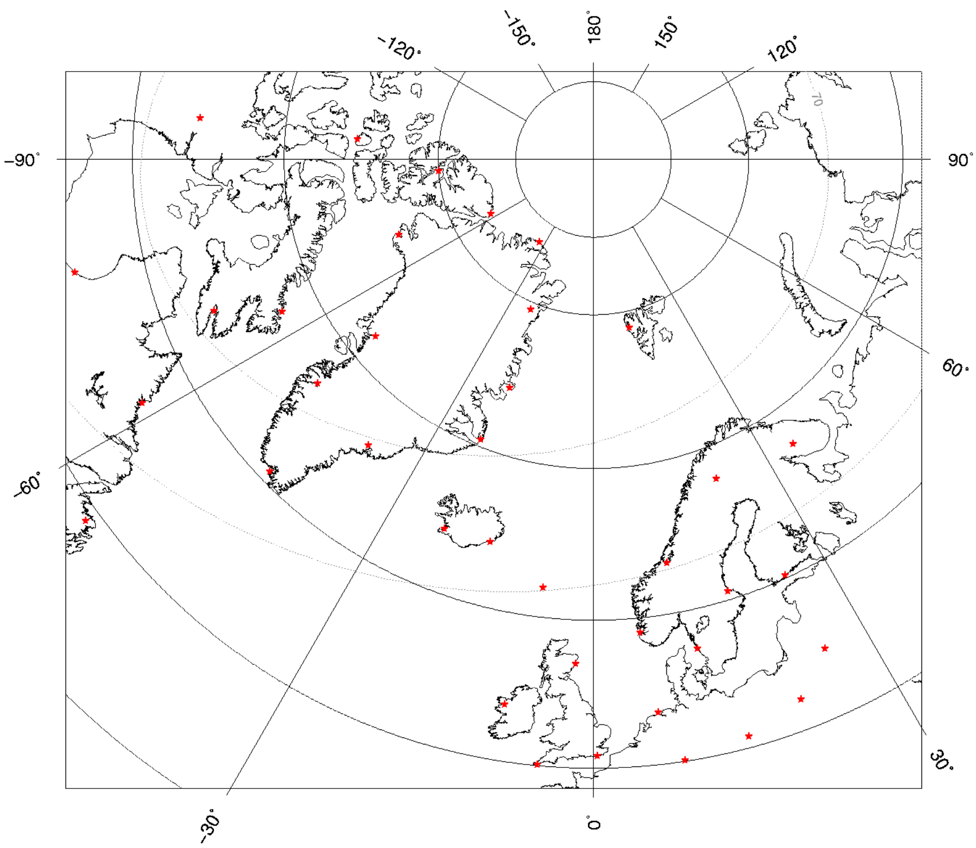

Figure 24. Real time IGS network (high date rate)

The implementation of an operational service shall impose to extend the network with additional stations. This can be obtained with agreements with geodetic entities in charge of maintaining the permanent networks like NMA (Norway Mapping Agency) in Norway or any

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other entity (EGNOS, EUREF…). Note that in chapter 4.5.1, we propose a complementary approach for the provision of GNSS raw data.

4.4 Relevancy of a scintillation service with regards to polar applications

This chapter consider the domains of maritime navigation and the aviation sectors. We could have included the terrestrial sector for which the PPP applications are known as strongly demanding but the associated accuracy requirements are at a much higher level (centimetre level) compared to navigation at sea or on the air.

4.4.1 Maritime domain

Space weather is known as potentially impacting positioning availability and accuracy onboard. It is probably less known that communications may also be affected. However, there are no dramatic impacts reported resulting to an accident or a grounding. Moreover, maps in the high latitudes may have large errors and mariners don't pay too much confidence to the GPS. Consequently, when GNSS perturbations occur they live with it and it is also the case for radio communication failures.

Without any international recommendation or occurrence of a strong ionospheric event that would drastically impact the polar navigation, things and uses will not change. Moreover, it is always complicated to add equipment or tools onboard and the mariners are faced to more and more complex system while they require for efficiency and pragmatism. To summarize, the products is probably not mature enough and the community not prepared enough especially when comparing with the aviation domain as presented in the next chapter.

4.4.2 Civil aviation domain (ICAO initiative)

It is interesting to point out the initiative of the International Civil Aviation Organization (ICAO) envisages the establishment of a new Meteorological Service for International Air Navigation. This service will be an operational space weather information service. The plan is to start the implantation by the end of 2018.

Space weather experts have established the impacts of GNSS ionospheric perturbations to the air navigation systems. "The "amplitude scintillation" can have a serious impact on aircraft using GNSS for Required Navigation Performance (RNP)-based flight navigation. Aircraft lose lock on the signal and find GNSS unavailable for short periods". The future space weather centres will have to generate advisory messages as soon as a key parameter is overpassed see Table 2.

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Table 2 Thresholds for space weather advisory related to GNSS (ICAO source)

		Moderate	Severe
GNSS			
	Amplitude Scintillation (S4)(dimensionless)	0.5	0.8
	Phase Scintillation (Sigma-Phi)(radians)	0.4	0.7
	Vertical TEC (TEC Units)	125	175

4.5 Possible improvements of the scintillation forecast service (EfficienSea3)

4.5.1 Requirements for more real time stations

As discussed in 4.3.1, it is important to have access to raw data in order to predict scintillations. DTU has a large GNSS network in Greenland. DTU would be favorable to collaborate and provide data access to CLS. The major issue is that collecting high data rate (1 Hz) in real time requires a high data speed connection. Satellite communication may be a technical solution for a remote site; however this generates high additional costs. Another solution proposed by CLS would be to develop an equipment to be plugged to the GNSS receiver in order to calculate scintillation parameters instantaneously on site. In case a threshold is reached, the scintillations parameters are transmitted via a satellite (the equipment includes an iridium modem) to CLS data center. The information is then quickly integrated into the forecast model. This strategy could largely benefit to the scintillations service.

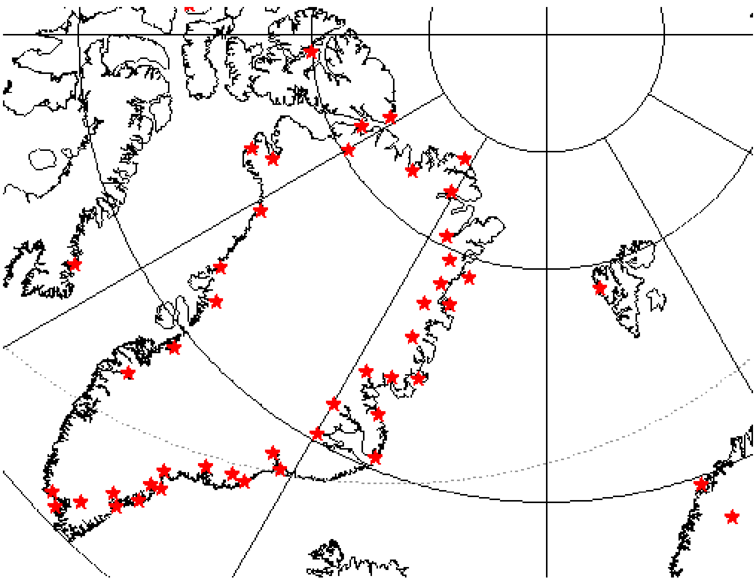

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Figure 25. DTU GNSS high rate station network in Greenland

4.5.2 Improvement on the forecast time projection

The present forecast is restricted to one hour at maximum because it considers the solar wind information and its impact on the ionosphere. An analysis showed that it would be possible to extend the forecast of the magnetic activity to several hours (Kp or other magnetic indices - mainly). This could be done with a fine and routine monitoring and forecast of two specific solar activities: the coronal holes recurrence and the coronal mass ejection.

4.5.3 Possible map and alert dissemination (regional image - ASM format)

Assuming that a relevant and easy readable map product will be available, one can imagine that the associate regional image can be disseminated through Arcticweb[2]. Application Specification Messages (ASM) may also be constructed specifically for that use. The advantage is that they are compatible with the AIS protocol and can be received onboard ship even if internet or high speed communication is not available onboard. Predefined ASM with optimized formats have been established and a catalogue is available here http://www.e-navigation.nl/asm.

Figure 26 shows that several geometrical forms such as polygons, sectors can be plotted.

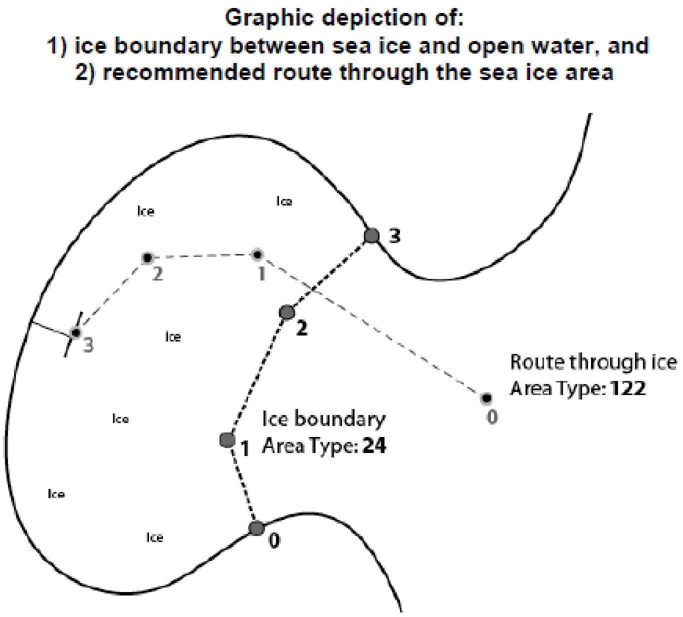

Figure 26. ASM format for polylines

[2] https://arcticweb.e-navigation.net/

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This approach may be an alternative for the scintillation products dissemination independently whether it is for a map or a warning message provided as text.

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5 Summary and conclusions

The work within WP 6.5 described here in deliverable 6.10 has provided improved services to Efficiensea 2 and the MCP. DMI has improved the METOC services including an S-411 ice charting service. CLS and DTU have developed a new innovative solution for space weather that will be of use to the mariner.

In addition DMI has provided gridded data directly to SSPA (route guidance) and Chalmers University (Simulator test). As a consequence of this DMI has submitted or is about to submit three articles to peer reviewed journals or extended abstracts at scientific conferences.

Services build within Efficiensea 2 requires continuously development. For instance the METOC services can be provided with better representation in the fjords of Greenland and the Space weather could be extended from 1 hour to several hours.

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6 References

Reference number	Status	Reference
[1]	Published	She J., Murawski J. (2017), "Towards seamless ocean modelling for the Baltic Sea", Proceedings of the 8-th EuroGOOS international conference: Operational Oceanography serving sustainable marine development, Bergen, Norway, 3-rd to 5-th October 2017
[2]	In preparation	Schmidt, T., Woge and Rasmussen T, Operational wave model in Baltic
[3]	In preparation	Poulsen, J.W., Ribergaard, M.H., Rasmussen, T.A.S., and Hunke, E.C., Refactoring of the code implementing the CICE dynamics. Article submitted to "Cray User Group" meeting 2018.
[4]	Published	Chassignet, E. P., H. E. Hurlburt, O. M. Smedstad, G. R. Halliwel, P. J. Hogan, A. J. Wallcraft, R. Baraille, and R. Bleck (2007), The HYCOM (Hybrid Coordinate Ocean Model) data assimilative system, Journal of Marine Systems, 65, 60–83.
[5]	Published	Hunke, E. C., and J. Dukowicz (1997), An elastic-viscous plastic model for sea ice dynamics., Journal of Physical Oceanography, 27, 1849–1867.
[6]	Published	Madsen, K. S., T. A. S. Rasmussen, M. H. Ribergaard, and I. M. Ringgaard (2016), High resolution sea-ice modelling and validation of the arctic, PolarForschung, 85(2), 101–105.
[7]	Published	D2.6- EfficienSea2 - Task 2.6 / D2.6 Report on Space Weather (SW) forecast warning service, CLS- 27 Oct. 2017
[8]	Published	Battjes, J. A., and J. P. F. M. Janssen, 1978: Energy Loss and Set-Up Due to Breaking of Random Waves. Coastal Engineering 1978 https://ascelibrary.org/doi/abs/10.1061/9780872621909.034.

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Reference number	Status	Reference
[9]	Published	Günther, H., S. Hasselmann, and P. A. E. M. Janssen, 1992: The WAM Model cycle 4. doi:10.2312/WDCC/DKRZ_Report_No04. https://doi.org/10.2312/WDCC/DKRZ_Report_No04.
[10]	Published	Hasselmann, K., and Coauthors, 1973: Measurements of wind-wave growth and swell decay during the {Joint North Sea Wave Project}. Deut Hydrogr Z, 8, 1–95.
[11]	Published	Schaffer, J., R. Timmermann, J. E. Arndt, S. S. Kristensen, C. Mayer, M. Morlighem, and D. Steinhage, 2016: A global, high-resolution data set of ice sheet topography, cavity geometry, and ocean bathymetry. Earth Syst. Sci. Data, 8, 543–557, doi:10.5194/essd-8-543-2016.
[12]	Published	Canuto V.M., Howard A., Cheng Y. Dubovikov S. (2001), "Ocean Turbulence. Part II: Vertical Diffusivities of Momentum, Heat, Salt, Mass, and Passive Scalars", Journal of Physical Oceanography, volume 32
[13]	Published	Canuto V.M., Howard A.M., Cheng Y., Muller C.J., Leboissetier, Jayne S.R. (2010), "Ocean turbulence, III: New GISS vertical mixing scheme", Ocean Modelling 34, 70-91

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7 Acronyms and Terminology

7.1 Acronyms

Term	Definition
METOC	meteorological and oceanographic
HYCOM	HYbrid Coordinate Ocean Model
CICE	The Los Alamos sea ice model
ECMWF	European Center for Medium Ranged Weather Forecast
HPC	High Performance computer
CMEMS	Copernicus – Marine Environment monitoring service
HBM	Hiromb Boos Model
PDAF	Parallel Data Assimilation Framework

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Appendix A Header of xml file for simulator test

Header of xml file for simulator test carried out by Chalmers University


```
?xml version="1.0" encoding="UTF-8" ?>
NTWeatherDB>
Settings>
Description>DMI weather Oresund to Bornholm</Description>
Depth in="meters" />
Speed in="m/s" />
Direction in="deg" />
Time in="HH:MM:SS" />
 </Settings>
Current Format="Time, Speed, Direction" GroupBy="Latitude, Longitude">
Group GroupBy="N 54.2038, E 12.0066">
Value>00:00, 0.255, 110.031</Value>
 </Group>
Group GroupBy="N 54.2038, E 12.0205">
Value>00:00, 0.268, 108.173</Value>
 </Group>
Group GroupBy="N 54.2038, E 12.0344">
Value>00:00, 0.280, 104.891</Value>
 </Group>
```


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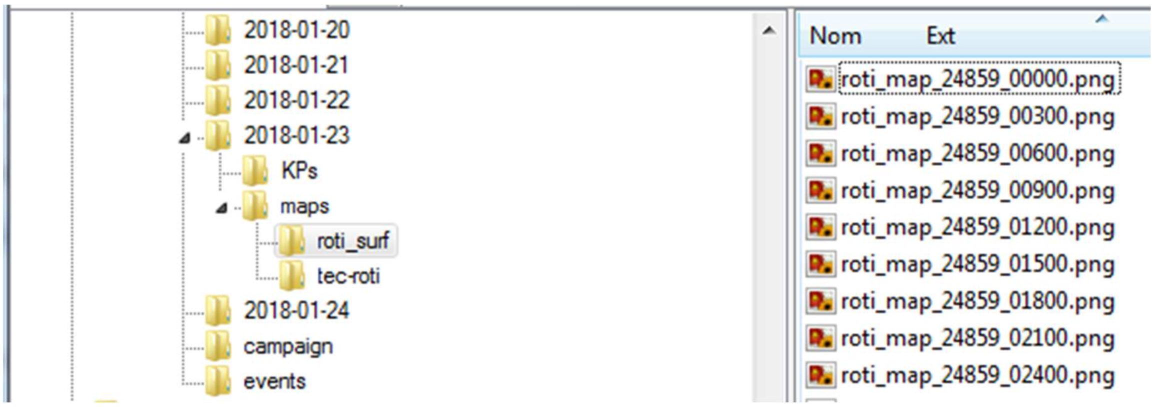
Appendix B Appendix - Prototype service technical information

Data organisation

The processing of the raw GNSS data is realized on a daily basis on a Linux server. Roti and TEC maps that also include the extrapolation of the oval auroral location are also done.



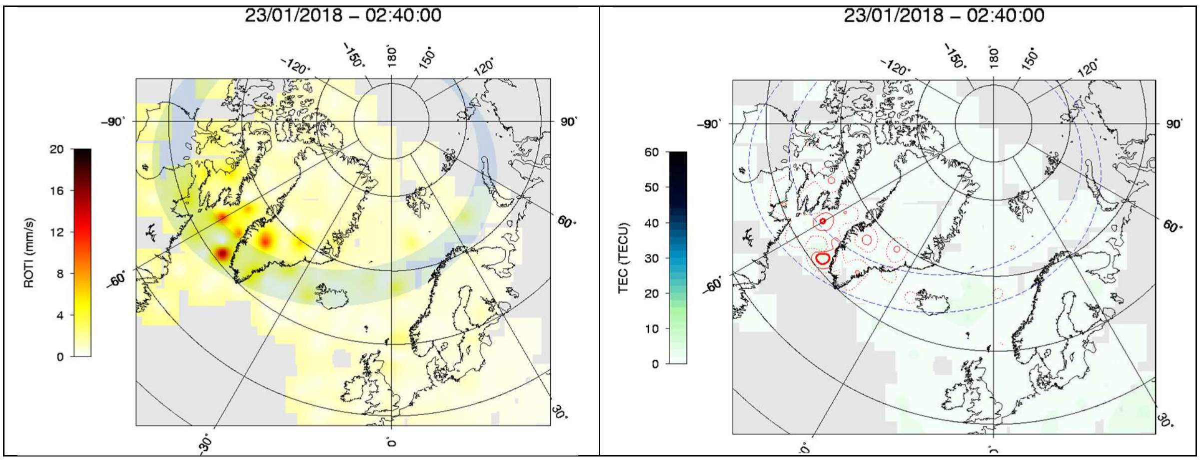


Figure 27. Daily product generation (left: nowcast/forecast scintillations, right: TEC nowcast)

Ionospheric key parameters are calculated and plotted for each of the GNSS stations (Figure 28). They can be examined in case of outliers or any patterns that are related to receiver

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effects or non-ionospheric effects. This is part of an internal process or for post processing validation.

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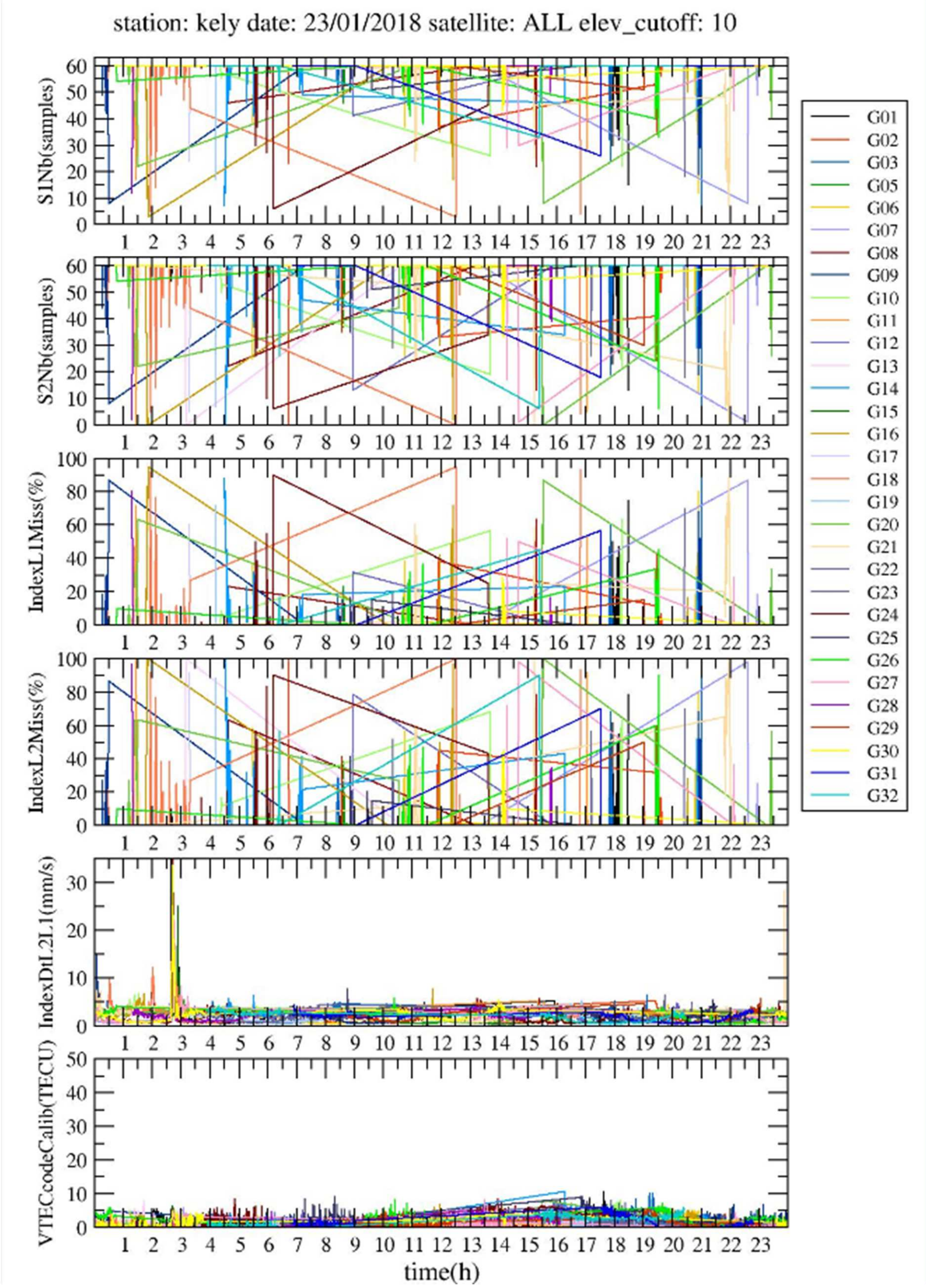

Figure 28. GNSS Ionosphere Key Parameters – Kely station, Kangerlussuaq, Greenland (for internal analysis)

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Data format

Data are available as text or netcdf format.

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