ECMWF COPERNICUS REPORT

Copernicus Climate Change Service

Product user guide for sea level and ocean wave products - time series and indicators

C3S_422_Lot2_Deltares - European Services

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1. Project Summary

1.1 Executive summary

This demonstrator Sectoral Information System (SIS) contract under the auspices of the Copernicus Climate Change Services (C3S), providing a consistent European dataset for tide, storm surge and wave conditions, for both a historical period, reanalysis (ERA5) and future scenarios (Representative Concentration Pathways, RCPs). In addition, five tailor-made use cases demonstrate how various coastal sectors across Europe could be benefit from these data sets in the Climate Data Store (CDS, https://cds.climate.copernicus.eu/#!/home).

Besides pan-European tide, storm surge and wave datasets, will also include a set of Climate Impact Indicators (CII's) and new tools designed to evaluate the impacts of climate change on European coast line in general, as well as different sectors and industries. The resulting data and indicators are fully accessible from the CDS.

Apart from producing meaningful European climate change dataset, Deltares is coordinating five coastal use cases from the Netherlands, UK, Denmark, Ireland and Italy, that are vulnerable to climate change impact. The focus is on coastal issues such as flooding, sedimentation and coastal erosion, industries such as offshore wind and ports are also included. With good practice of the use cases the consortium can demonstrate the extraordinary value of such a climate data service on the management and operation of coastal sectors.

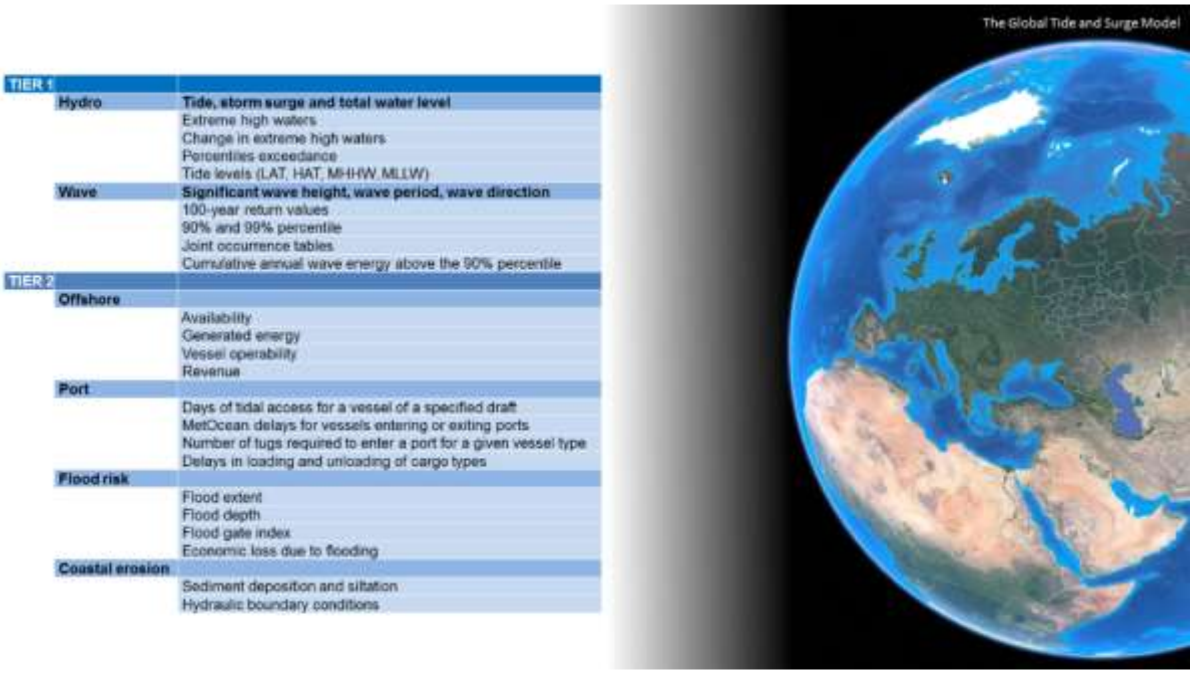

Figure 1 1. Examples of climate change indicators and Global Tide and Surge Model grid. The Tier 1 refers to time series and indicators of Hydrodynamics and Waves, with Pan-European coverage. Their technical details are described in this guide. The Tier 2 refers to indicators with focus of local use cases, which are not covered in this technical guide.

1.2 Data and tools

The core of the service will consist of a high quality and consistent dataset of storm surge, tide and wave conditions, including the effect of sea level rise, for all of Europe's coastal waters. This dataset is generated using the Global Tide and Surge Model (GTSM, Deltares) and the Wave Model (WAM, ECMWF). It consists of a historical reanalysis based on ERA5 and a selection of IPCC climate projections: RCP 4.5 (for period 2070-2100) and RCP 8.5 (for period 2040 – 2070).

From this dataset, a number of Climate Impact Indicators (CII's), such as extreme high waters, exceedance percentiles and changes in tidal levels are derived for all of Europe's coastal waters. These indicators, together with the underlying dataset, will be available through the Climate Data Store (CDS).

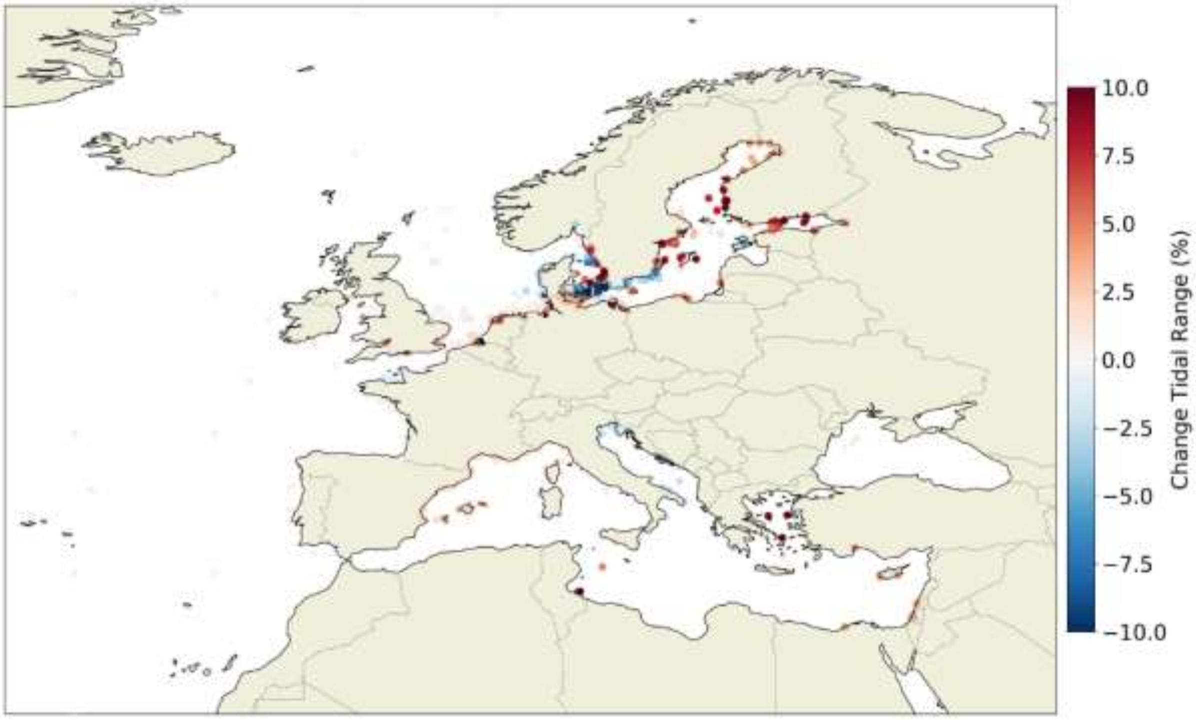

Figure 1 2. Example of impact indicator: changes in tidal range caused by sea level rise (as percentage of current tidal range without sea level rise)

Furthermore, the usability of this dataset to run more detailed local models in order to derive a further set of sector specific CII's is showcased by the use cases. For example, the impact of changes in storminess on the operation and maintenance (O&M) of offshore wind farms is assessed through a specific set of indicators derived from the core dataset. Similarly, the feasibility of nesting local models in the core dataset for further flood modelling and refinement is proven through a number of cases. A number of these CII's will become available in the CDS, to be calculated on the fly for these use cases. Others will become part of best practice guidelines on how to use the core dataset to derive further sector specific CII's.

1.3 Scenario and epoch

This dataset consists of a historical reanalysis based on ERA5 and a selection of IPCC climate projections: RCP 4.5 (for period 2070-2100) and RCP 8.5 (for period 2040 – 2070). There are few reasons why these scenario and epoch were chosen, from both scientific and user perspective. We apply the high-resolution regional climate change ensemble that have been developed for Europe within the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) initiative. The climate simulations are based on Representative Concentration Pathways (RCPs), a set of four global carbon emissions pathways developed for climate modeling. The four RCPs together span the range of year 2100 radiative forcing values from 2.6 to 8.5 W/m2. While RCPs have not been assigned a likelihood, we select those RCPs that we found most plausible.
Due to the large climate variability in sea level, that is mean sea level but extreme sea levels in particular, takes multiple decades before the climate signal can be detected from the natural climate variability. Therefore, we propose to start our future climate simulations in 2040. At present global carbon emissions are tracking just above the RCP8.5 pathway. As such, regarding the mid-term future (2040-2070) we apply the RCP8.5 pathway. This is a high-emission scenario that assumes high population growth combined with relatively slow income growth with modest rates of technological change. However, countries across the world have committed to limit the global temperature change to 1.5 degree Celsius in the Paris Agreement. This requires very rigorous reductions in the global carbon emissions reductions. It is argued that RCP 2.6 is currently unfeasible, therefore, we apply the RCP 4.5 pathway to the long-term future (2070-2100). RCP4.5 is one of the more optimistic pathways that assumes human emissions of greenhouse gases will stabilize soon and then decline after a few decades.

The industry users from offshore wind and ports would like to see climate impact in 30 to 50 years` time, which is the lifetime of most their infrastructure. Regarding planning and operation & maintenance, a worst-case scenario (i.e. RCP8.5) is expected. For flooding use cases, the impact of SLR with a longer term seem more interesting (end-century) from flood risk management point of view. Meanwhile, the extreme SLR projected by a high emission scenario might conclude very high flood risk in the use cases. Thus we choose a low emission scenario (i.e. RCP4.5). Our users who care about coastal flooding in Italy thinks It might also be important to include adaptation into scenario choices. It reasonable to think that after 2050, due to strong flood events in the near future, society will choose to adapt carbon emission scenarios in order to make the far future scenario less extreme.

The CDS will also indicate where the local use cases have been carried out, give background information with regard to these use cases, e.g. how they can serve as best practice examples for further usage of the data, and will give access to a selection of CII's derived from these use cases. Similarly to the core dataset, this will allow users to intercompare the CII's between the baseline and the available climate projections, to assess relative change. For example, whether flood control barriers will need to close more frequent due to climate change, or whether weather windows for offshore activities will be affected.

2. The Modelling Chain

2.1 Pan-European Modelling

2.1.1 Pan-European Hydrodynamics

The Tier 1 Hydro refers to Pan-European Hydrodynamic dataset and indicators (see Figure 1-1), it consists of time-series and climate change indicators computed European-wide and that relate the water levels resulting from sea level, tides and surges. In order to compute these water levels and assess changes, we use the GTSMv3.0 barotropic hydrodynamic model together with climate forcing and sea level rise initial conditions. The European-wide coverage and high-resolution of both forcing and hydrodynamic models guarantees a consistent and high quality dataset.

In order to assess sea level changes associated to climate change, the hydrodynamic model is run for three different climates: current climate, RCP4.5 and RCP8.5. The RCP scenarios correspond to an optimistic emission scenario where emissions start declining beyond 2040 (RCP4.5) and a pessimistic scenario where emissions continue to rise throughout the century, often called business-as-usual scenario (RCP8.5). The climate forcing for these scenarios are combined with the corresponding relative sea level rise forcing.

The periods considered for each of the scenarios are summarized in Table 2-1, together with the criteria behind the selection of the periods.

Table 2 1. Selected climate scenario and simulation period

Scenario	Period considered	Criteria
Current climate	1977 - 2005	Consistent with IPCC's definition of today's mean sea level. SLR forcing is relative to this period.
RCP8.5	2041 - 2070	Consistent with IPCC's definition of RCP8.5 (strong increase in emissions), considered to be the more relevant scenario to assess on the medium term (2041-2070), given that for RCP4.5 the differences

		between the medium term (2041-2070) and the long term (2071-2100) are relatively small.
RCP4.5	2071 - 2100	Consistent with IPCC's definition of RCP4.5 (moderate increase in emissions), considered to be the more relevant scenario to assess on the long term (2071-2100), assuming that the extreme scenarios may still be avoided.

From each of these simulation periods, indicators characterizing the tides, storm-surges and mean-sea level are derived. By comparing the indicators between periods, climate change related indicators are derived.

In addition to the climate runs mentioned above, a reanalysis dataset is computed by forcing the hydrodynamic model with the newly available ERA-5 product. This dataset provides information on real historical water-levels that can be used to look at specific (extreme) events in the past. The time-coverage of this dataset is 1979-2018.

Since tides and associated changes due to climate change are also of relevance, separate tide-only runs are performed in addition to the total water level runs. The specifics of the forcing included in these tide-only runs are described in the sections below. With total water level and tide-only runs, the surge can be calculated as the residual between the two. For the future cases where sea level rise is present, sea level rise forcing is also included in the tide-only runs. This means that the interactions of the tide with the sea level rise will be present in both total water-level and tide-only outputs, leading to a consistent surge residual and devoid of sea level rise/mean sea level. Additionally, indicators associated to tides and their changes due to climate change can be derived from the tide-only runs, avoiding complicated tidal analysis procedures.

In the following sections, a thorough description of the hydrodynamic model and forcing models and datasets used in the modelling chain is provided. Furthermore, the model output components that define the Tier1 dataset are described and considerations for the use of the dataset are outlined.

2.1.1.1 The Global Tide and Surge Model version 3.0 (GTSMv3.0)

The Global Tide and Surge Model v3.0 (GTSMv3.0) is a depth-averaged hydrodynamic model with global coverage that dynamically simulates tides and storm surges. The GTSMv3.0 uses the unstructured Delft3D-FM (Kernkamp et al. 2011) and as such employs a smart distribution of resolution, which leads high accuracy at relatively low computational costs. It has an unprecedented high coastal resolution globally (2.5 km, 1.25km in Europe). The resolution decreases from the coast to the deep ocean to a maximum of 25km. Increased resolution has also been added in the deep ocean with steep topography areas to enable the dissipation of barotropic energy through generation of internal tides. The bathymetry used consists of a combination of EMODnet high-resolution (250m) bathymetry for Europe (http://www.emodnet.eu/bathymetry) corrected for LAT-MSL differences and General Bathymetric Chart of the Ocean 2014 (GEBCO 2014, https://www.gebco.net/) with a 30 arc seconds resolution. The vertical reference of the model is mean sea level, given that the bathymetric data is referenced to that vertical datum.

Figure 2 1.Model grid of GTSM in Southeast Asia and Europe

The model lacks open boundaries and therefore is purely forced by the tide-generating forces and external forcing fields (e.g. winds, surface pressure), making the model independent of external open boundary conditions. In terms of calibration, the model uniform bottom friction coefficient and internal wave drag coefficient have been tuned to match observed total rates of energy dissipation and show spatial energy dissipation distributions that are in good agreement with observed rates in Egbert and Ray (2001). For surges, the relation by Charnock (1955) to model the wind stress at the ocean surface is used, and the user-defined drag coefficient has also been tuned during the calibration process.

GTSM is a free-running model without assimilation of observed tides or surges that constrains the solution. Since in this study changes in water levels are studied, this is a required feature for the model. Therefore, the performance of the model is evaluated under these conditions, where a good model performance is proved that all relevant physical processes that determine (barotropic) water levels are captured in the model and can therefore confidently be used to project future water levels. Additionally, the lack of boundary conditions stemming from the global coverage ensures that any large scale changes in water levels (such as changes in tides due to interaction with sea level rise) are propagated into the European domain, as opposed to a European regional model that is forced with historical tidal conditions.

The accuracy of the model in terms of total water levels is presented in Table 1, for the European coasts. The validation is performed for the year 2012. Overall, the model shows good performance, with an average error of 21.2 cm. The correlation in all the areas is very high, showing a good model performance. The Black Sea region is omitted due to lack of high-quality observations in the area for the period considered.

Table 2 2.Validation of GTSM3.0 for modelling water levels in 2012.

Area	No. stations	Bias	STDE	RMSE	R
Arctic Ocean	1	0.017	0.113	0.114	0.96
Baltic Sea	114	-0.014	0.098	0.107	0.89

Barentz Sea	3	-0.004	0.210	0.210	0.96
Canary Current	7	0.102	0.128	0.164	0.99
Celtic-Biscay Shelf	50	0.058	0.275	0.290	0.98
Iberian Coast	12	0.089	0.159	0.209	0.99
North Sea	37	-0.043	0.342	0.356	0.94
Norwegian Shelf	10	-0.024	0.208	0.209	0.94
Mediterranean Sea	24	0.087	0.069	0.111	0.85
total	260	-0.027	0.154	0.212	0.91

2.1.1.2 Forcing datasets: Meteorological forcing and Relative Sea Level Rise (RSLR)

While the area of interest is constrained to Europe, the fact that GTSMv3.0 has a global coverage enforces forcing fields that also have global coverage. While for the reanalysis ERA-5 dataset this is already the case, for the climate forcing the combination of a regional (European) product with a global product is made. The regional climate model has a considerably higher resolution than the global climate model, which is desired for the dataset generated in this contract. The selection of the global climate model is done so that it is the one originally used to force the regional climate model at the boundaries (denoted as driving model), ensuring matching fields at the transition zones.

The regional climate forcing employed is the HIRHAM5 model from the Danish Meteorological Institute (DMI), member of the EURO-CORDEX climate model ensemble. Its driving model is the EC-EARTH global climate model developed by the Royal Netherlands Meteorological Institute (KNMI). Details about model temporal and spatial resolutions are given in Table 2-3.

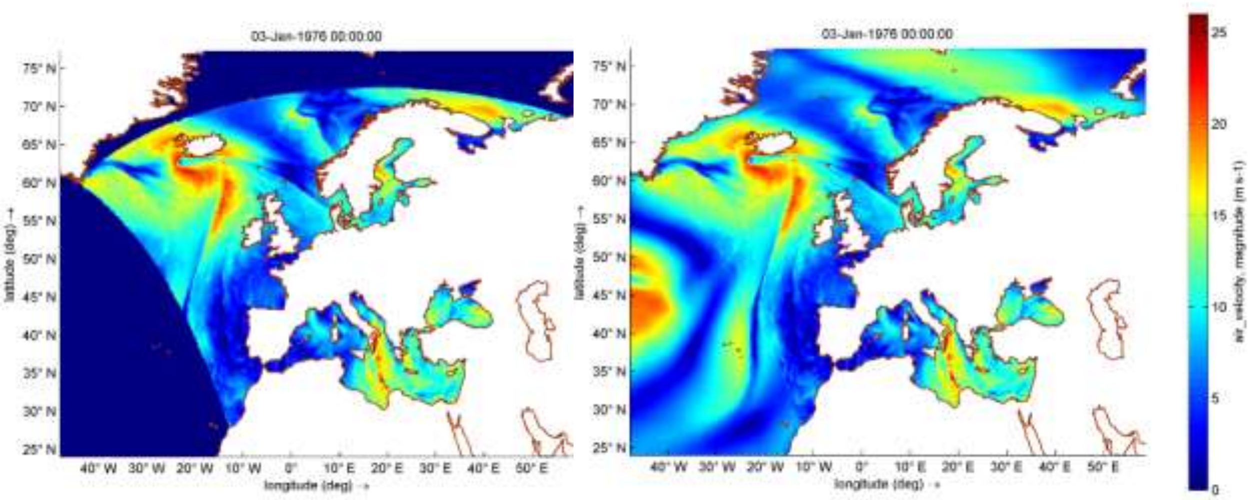

Figure 2 2. Wind velocity magnitude for the HIRHAM5 regional dataset (left) and combination with the background EC-EARTH model for the same timestamp (right)

Mean sea level pressure

The GTSMv3.0 natural vertical reference is mean-sea level (MSL), as determined by its bathymetry data. In order to keep model vertical datum as close to MSL as possible, mean contributions from meteorological forcing to such MSL have to be removed. Furthermore, the model MSL definition has to be consistent with the reference vertical level used in the relative sea level rise field from CMIP5. According to their definition, present mean-sea level is defined as the mean over the period 1985-2005. Therefore, mean contributions of the meteorological forcing over that period should be removed in all runs (historical and future). In order to decouple the mean contribution from the hydrodynamic model, the mean field removal should be based purely on the meteorological forcing field. This is possible through the calculation of the mean-sea level pressure and mean wind stress fields over 1985-2005. To avoid re-processing all meteorological (reanalysis and climate, regional and global) forcing, the mean field is made negative and added to the model forcing along all the other components, so that the total summation will be relative to the historical mean. However, since the hydrodynamic model doesn't read wind stress as input but wind velocity, the removal of the mean wind stress contribution as a negative field in the meteorological forcing chain is not trivial. For simplicity, and given that the mean wind stress contribution to the MSL is a lot smaller than the mean sea level pressure contribution, only the mean contribution of the atmospheric pressure is removed in the forcing side.

Since at the time of the runs ERA-5 data was only available from 2000 onwards, ERA-Interim was used for 1985-2005 to calculate the mean sea level pressure field (MSLP). This (negative) field is included in all total water level runs: reanalysis, historical climate and future climate. This way, mean wind stress contributions to mean sea level disappear in the relative comparison between datasets.

Relative SLR forcing: CMIP5 ensemble mean

The sea level rise corresponding to the two emission scenarios considered is forced through the ensemble-mean relative sea level rise fields (RSLR) in the Coupled Model Intercomparison Project Phase 5 (CMIP5). These fields are given as yearly fields for each emission scenario, up to 2100. Coverage issues between the RSLR forcing field and the hydrodynamic model have been taken care of through an extrapolation procedure. This is particularly necessary in areas such as the coast (e.g. delta areas, narrow connections), model outer lat/lon boundaries and sea areas under permanent ice shelves in Antarctica, which are included in the hydrodynamic model and not in the RSLR field.

For the implementation of the spatially varying sea level rise fields, the model water level is initialized with such field and forced throughout the simulation with the corresponding surface pressure field which guarantees an equilibrium situation of the mean sea level. The RSLR field is included in all future (RCP4.5 and RCP8.5) runs, for both total water level runs and tide-only runs.

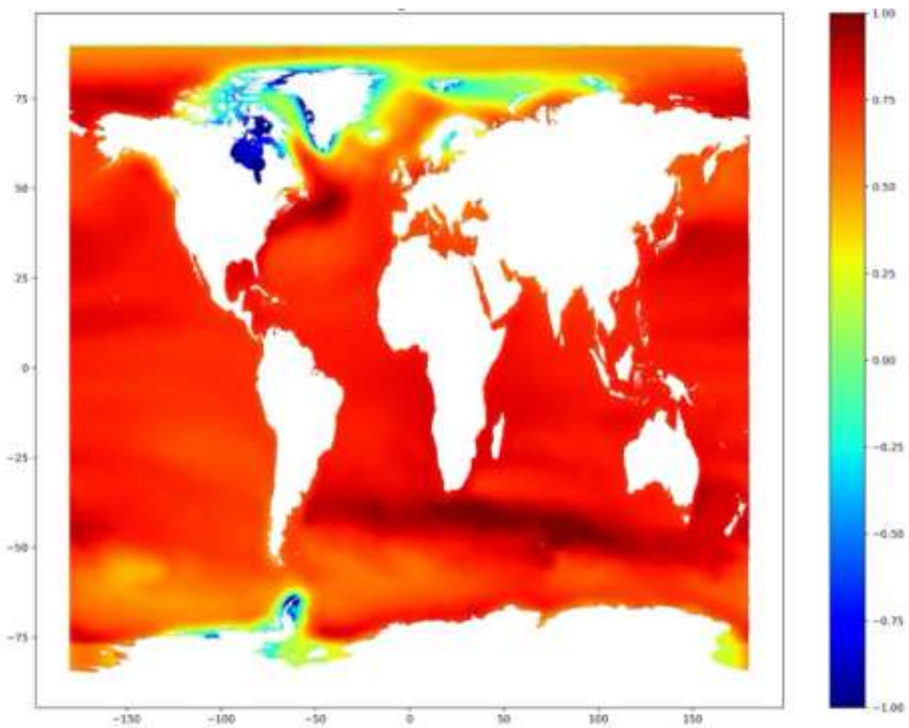

Figure 2 3. Example of GTSM model mean-sea level when forced with 2100 RSLR field for RCP8.5 (CMIP5)

Table 2-3 gives an overview of the forcing fields used for the different datasets produced.

Used in dataset	Forcing field	Spatial coverage	Spatial resolution	Temporal resolution
Reanalysis	ERA-5	Global	0.25x0.25deg	1 hour
Climate(all)	HIRHAM5	Europe	0.11x0.11deg	1 hour
Climate (all)	EC-EARTH	Global	1x1 deg	3 hours
Climate (future scenarios)	RSLR CMIP5 ensemble mean	Global	0.5x0.5 deg	1 year
Reanalysis and Climate (all)	MSLP from ERA-Interim (negative)	Global	0.75x0.75 deg	X

Radiational tides

While most of the tidal signal that is observed in tide-gauge observations is due to the gravitational forcing of the sun and the moon, there are some tidal components that have an origin/contribution from other sources. For the components S2, S1, SSA and SA, atmospheric tides at those frequencies induce an ocean response. This response is called radiational tides. In order to distinguish these meteorological periodic contributions from the surge (computed as the residual between total water level and tides), the radiational tides are included in all tidal runs. The atmospheric tide forcing is derived through a Fourier analysis of 7 years of ERA-5 atmospheric pressure and wind forcing data (2010-2017).

2.1.1.3 Output variables

The output generated in the model runs is 10-minute time-series in predefined locations. In order to have a good coverage along the coast, coastal points with spacing of 10km are defined in Europe. Furthermore, nesting points are defined in a regular grid, with resolution decaying towards the ocean. The resolution of these nesting points varies from 0.25, 0.5 and 1 degrees within 100 km ,500 km, and further from land. See figure 2-4 for predefined output points in the Adriatic Sea. Additionally, to these predefined points, tide-gauge locations are also included in the output. These include the UHSLC network locations, the GESLA locations and the CMEMS locations. Overlapping/duplicate tide-gauge locations between networks are not removed.

Figure 2 4 Illustration of output points (red dots) in GTSM for the Adriatic Sea.

The output variables include total water levels, tides and surges. The surges are calculated as the residual between the total water level runs and the tide-only runs (including atmospheric tide forcing and sea level rise for the future periods).

2.1.2 Pan-European Wave

2.1.2.1 Introduction

The goal of the wave modelling is to produce Pan-European wave data along the offshore of the European coast. With this purpose a pan-European wave model needs to be set up, validated and used to compute the Tier 1 wave data. In order to assess the quality of the wave model results a current climate wave hindcast that could be benchmarked has been produced. The chosen benchmark is ECMWF's ERA5 reanalysis dataset (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation). The strength of the

ERA5 dataset is that it combines one of the leading numerical weather prediction models (the ECMWF model) with an advanced data assimilation system. Furthermore, the wave data produced by ECMWF are known for its high quality, which is reflected in the high correlation between ECMWF wave data and observations (e.g. Dee et al., 2011, and Caires et al., 2004).

2.1.2.2 Model Description

Requirements

The main goal of the wave modelling task is to obtain reliable wave conditions offshore the European coastline. The offshore region has been informally defined as the off-coastal region with depth of at least 20 m. Based on this definition the main requirements that have been defined for the wave model are that it should provide reliable wave parameters along the 20 m depth contour line of the European coastal waters. These data are to be used as direct input for offshore studies and as boundary conditions for nearshore, harbor and inlet studies.

Model setup

Based on the above requirements a standalone version of the Wave Model (WAM) of ECMWF (ECMWF, 2015), referred to as Stand Alone WAM (SAW) has been setup in the ECMWF computational facility by Jean Bidlot (ECMWF). The model resolution and extent have been defined based on the Tier 1 needs of accurate wave data offshore Europe, the available wind data (covered region and resolution) and expert judgement.

In terms of spatial characteristics, the chosen model grid resolution is about 0.1° x 0.1° (11 km x 11 km) and it covers the region 98°W to 45°E and 9°N to 88°N. The model bathymetry is based on the ETOPO1 dataset (https://www.ngdc.noaa.gov/mgg/global/global.html). The model is run solely in hindcast mode, which is not standard in the way models are setup at ECMWF and is achieved by setting a long period 0h forecast with analysis forcing forecast in the end. In terms of physics, the wave model of ECMWF Integrated Forecasting System (IFS) cycle 43r3 has been used with the latest development in terms of wave growth and dissipation, referred to as ST4 physics (Ardhuin et al., 2010). Initial trial runs have shown that these new physics lead to SAW results that are more accurate than the ERA5 results which benefit from data assimilation (Jean Bidlot, personal communication).

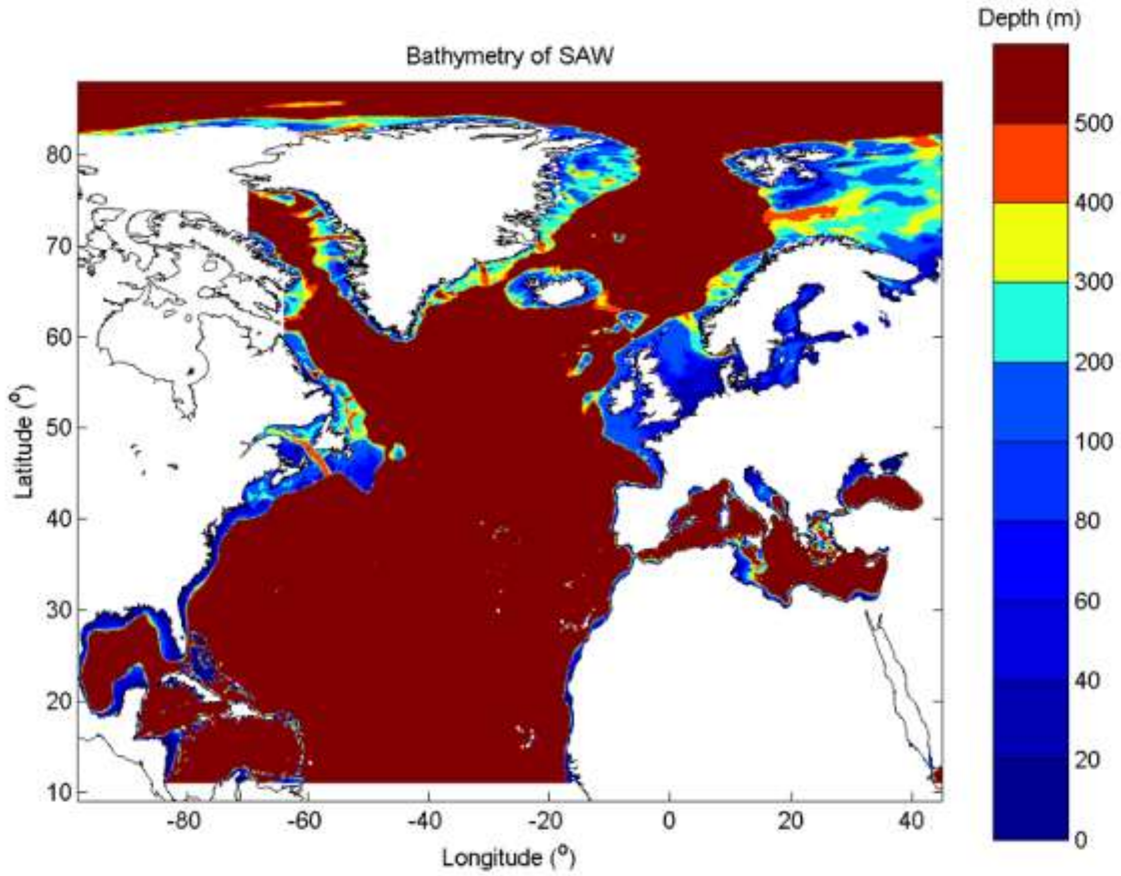

Figure 2 5. Domain and bathymetry of the SAW model

The model input and output is being transferred between Deltares and ECMWF using PrepIFS (http://www.prism.enes.org/Software/WSS/prepifs/prepIFSUserGuide/prepIFSUserGuide.html).
The data handling and model runs are being done using computational credits from DMI.

Model input

The SAW model needs as input time and space varying wind fields and ice-coverage fields (optional).

Model output

The model output is directly stored in ECMWF's Meteorological Archival and Retrieval System (MARS) and consists of hourly directional wave spectra and integral wave parameters at the model grid points.

2.1.2.3 Model validation and calibration

Approach

The ECMWF WAM model is already a fully calibrated model setting the standard for global and coastal wave modelling. Nevertheless, given that the runs will not benefit from data assimilation, model runs have been carried out using as forcing the hourly ERA5 winds and ice-coverage with a resolution of 0.3° x 0.3° and the resulting hourly SAW wave hindcast are validated against the wave reanalysis of ERA5 and observations from two stations located along the Europeans 20 m depth contour.

The hindcast period is 2010 to 2016, the period for which the ERA5 data were available. The considered wave parameters are the significant wave height, HS, the mean wave period , Tm-1,0, and the mean wave direction, MWD.

The considered measurements are from the Dutch Government North Sea stations of Lichteiland Goeree (LEG) and IJmuiden (YM), both located in waters of about 20 m depth. The measurements have a frequency of 10 minutes and, in order to approximate the time scales of the measurements with the spatial scales of the models, hourly timeseries of 30 min moving averages of the 10-minute HS. and Tm-1,0, data have been created.

The comparisons between the SAW and the ERA5 data are carried out at a number of locations along the 20 m depth contour of the European coastal waters. Note that deviations between the SAW data and the ERA5 data do not invalidate the SAW data. In fact, given that the SAW model has a higher resolution than the ERA5 data, 0.1° x 0.1° in the case of SAW and 0.3° x 0.3° in the case of ERA5 and its bathymetry is also based on a higher resolution bathymetric dataset, ETOPO1 in case of SAW and ETOPO2 (https://www.ngdc.noaa.gov/mgg/global/etopo2.html) in case of ERA5, the SAW model will in some locations be better suited to model the waves at 20 m depths. The bathymetry of ERA5 in the SAW domain can be seen in Figure 2 6. Comparing Figure 2-5 with Figure 2 6 one can indeed see that the ERA5 model has a representation of the coastal bathymetry which is poorer than that of the SAW model.

The validation of the SAW data at the YM and LEG locations is given in the next section, followed by a general validation of the SAW data against ERA5 data at 100 locations along Europe’s 20 m depth contour.

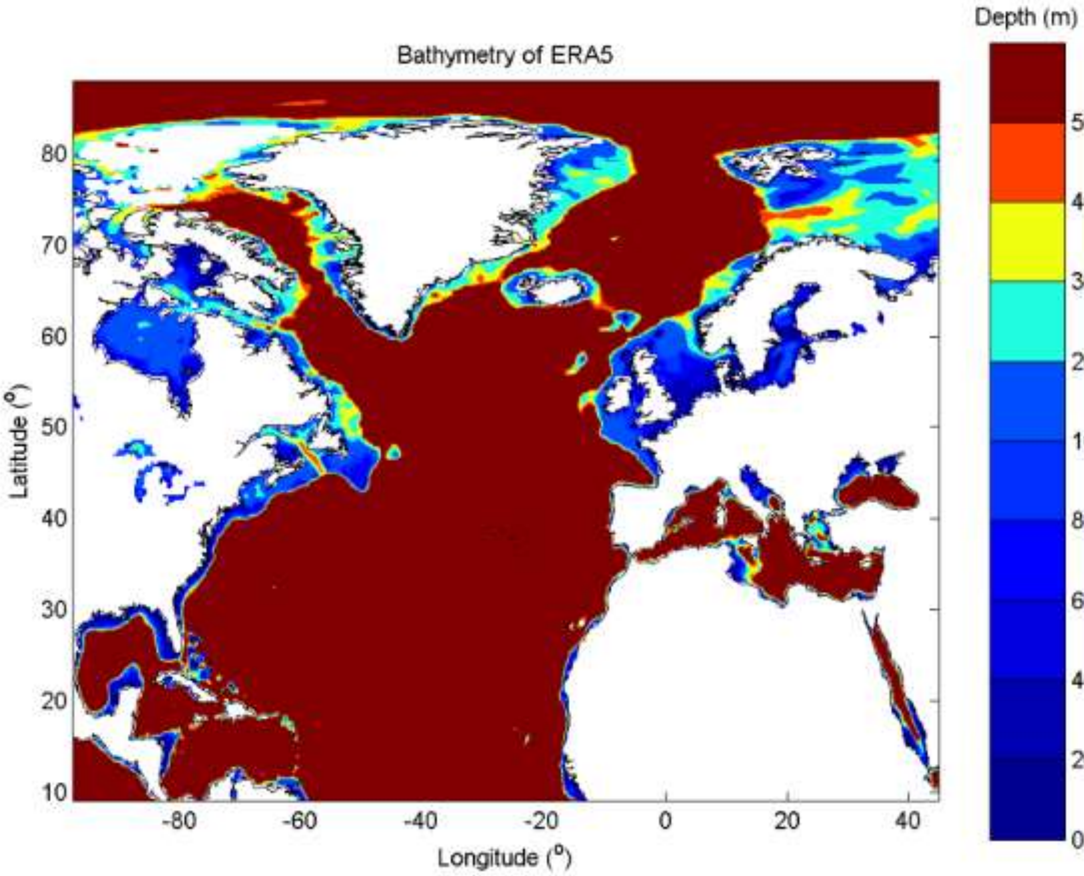

Figure 2 6 Bathymetry of the ERA5 wave model in the region covered by the SAW model.

Local validation

The SAW model has been run and provided hourly data for the entire period form 2010 till 2016. Figure 2 7 shows density scatters between the LEG HS and Tm-1,0 measurements and the SAW and ERA5 data from the respective grid locations closest to the LEG station. The error statistics given in this and all other plots in this chapter have been computed. The figure shows that the SAW and the ERA5 data compare rather well with the LEG data, with in both cases correlations above 96% with the HS observations and above 86% with the Tm-1,0 observations. The bulk of the ERA5 data underestimate HS observations and the SAW and ERA5 Tm-1,0 data are slightly biased low.

In order to look further at the relation between the SAW and ERA5 data closer to the LEG station, Figure 2 8 shows the density scatters between their HS, Tm-1,0 and MWD data and the quantile-quantile plots of the HS data. The figure shows a very good agreement between the data, with correlations above 90% for all parameters and very little scatter. Although not clearly underestimating the measurements, the SAW HS data are lower than the ERA 5 HS data for high values of HS. The bias between the SAW and ERA5 data MWD data is about 5 degrees and probably due to differences in the bathymetry of the models, see Figure 2-9.

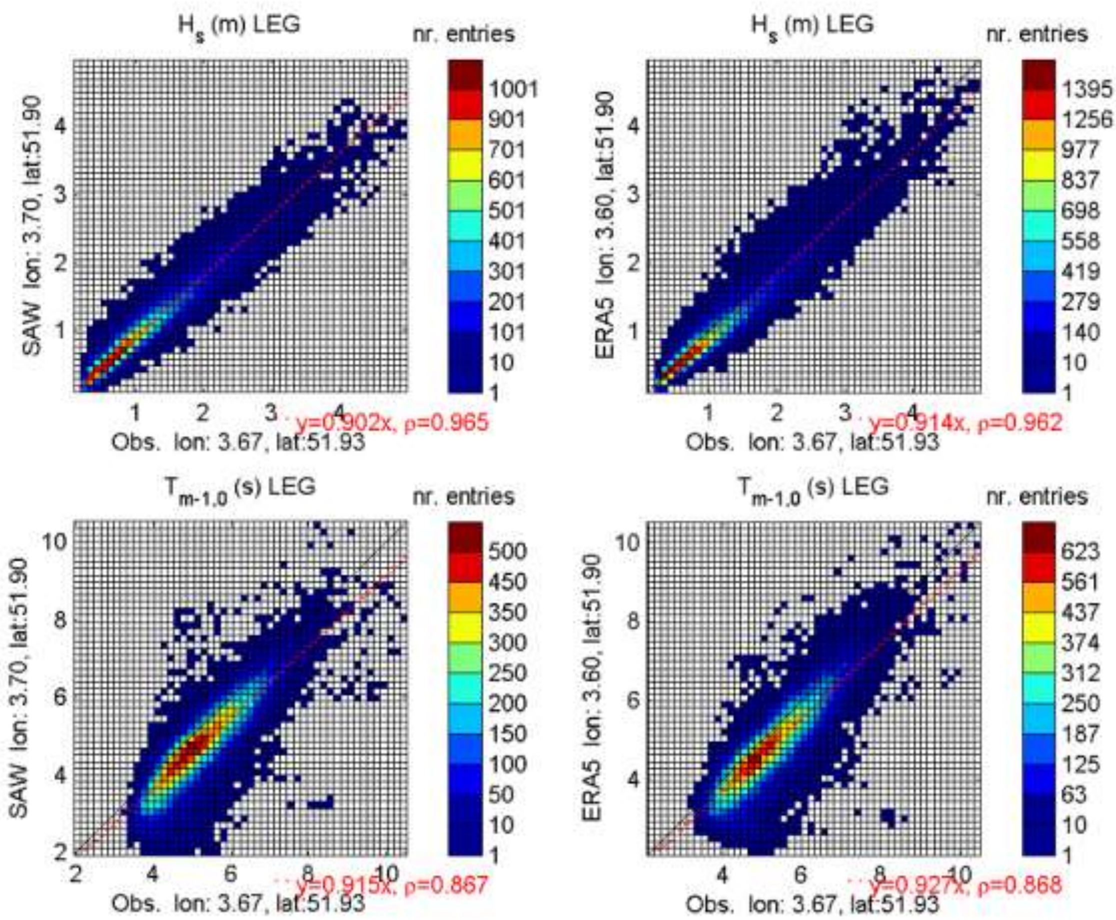

Figure 2 7 – Density scatter comparisons between the LEG measurements and the SAW (left column) and ERA5 (right column) significant wave height (top row) and mean wave period (bottom row) data. The symmetric slopes and correlations between the data are printed in red in the panels.

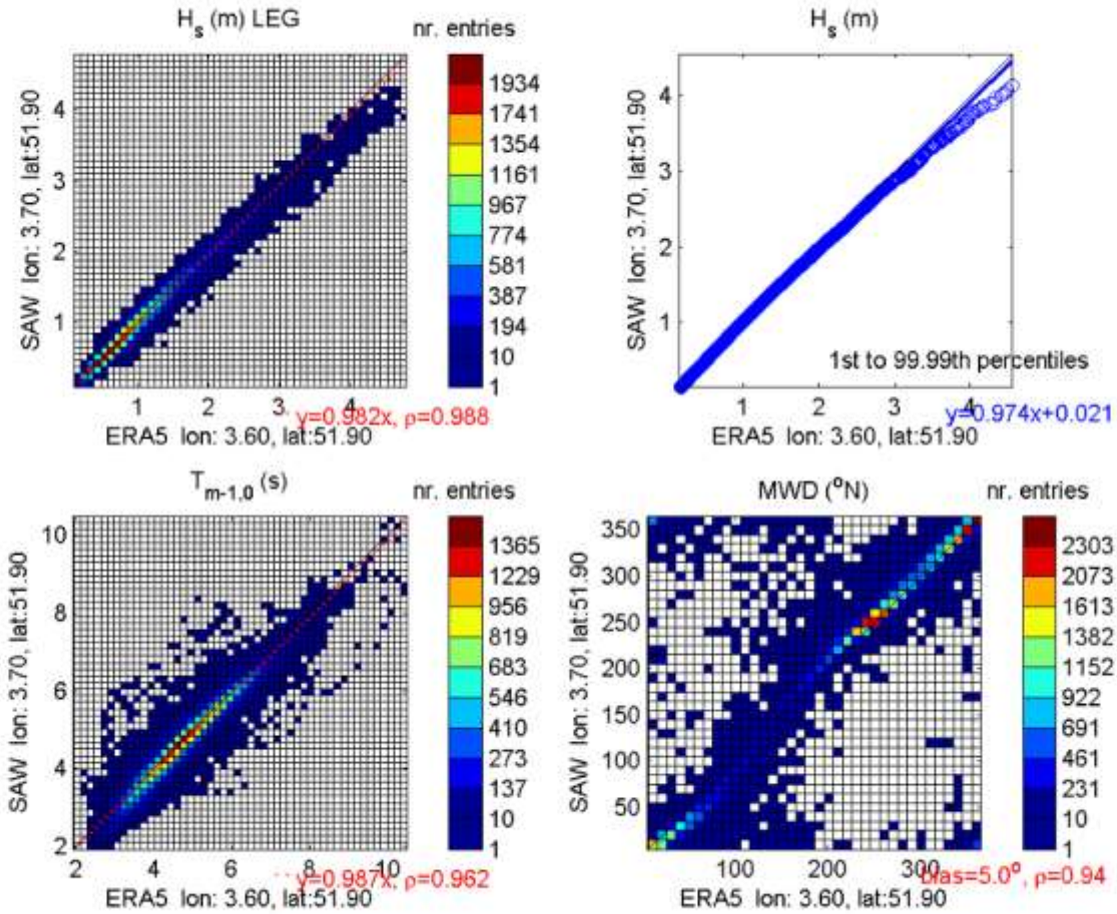

Figure 2 8 – Comparison between the SAW and ERA5 data from the grid locations closer to the location of the LEG station. Top left: Density scatter between the SAW and ERA5 significant wave height data. Top right: Quantile-quantile plot of the SAW and ERA5 significant wave height data. Bottom left: Density scatter between the SAW and ERA5 mean wave period data. Bottom right: Density scatter between the SAW and ERA5 mean wave direction data.

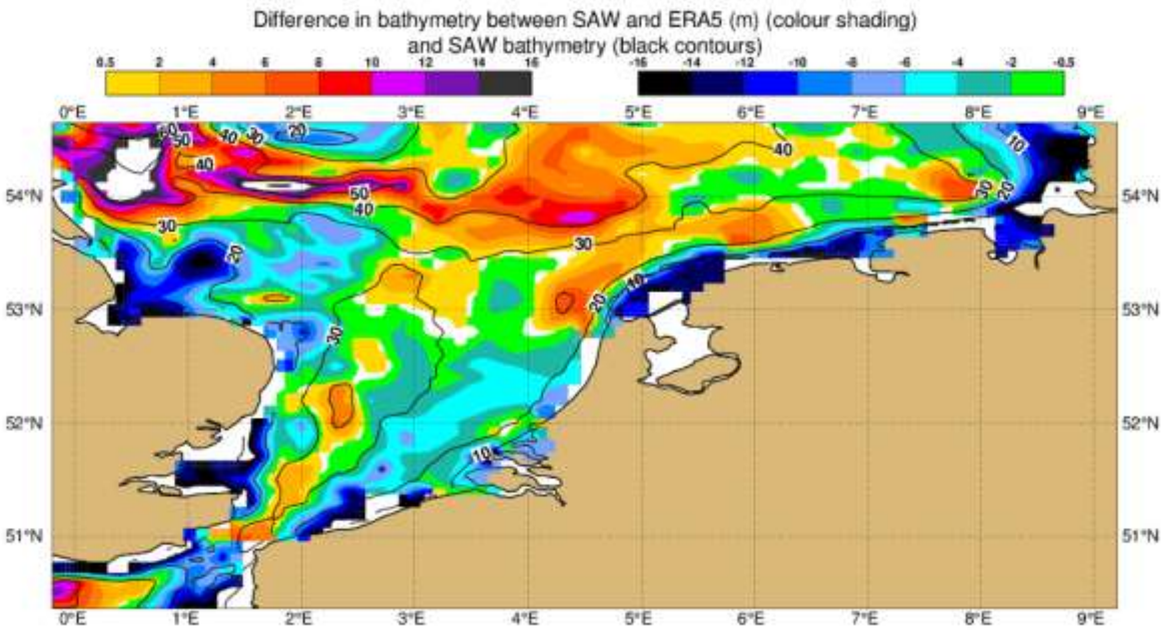

Figure 2 9. – Differences in metres between the bathymetry of SAW and ERA5 in the Southern North Sea. The contour lines indicate the SAW bathymetry. Credits: Jean Bidlot (ECMWF).

Figure 2 10 shows density scatters between the YM HS and Tm-1,0 measurements and the SAW and ERA5 data from the respective grid locations closer to the YM station and Figure 2 11 shows the density scatters between their HS, Tm-1,0 and MWD data and the quantile-quantile plots of the HS data. The figure shows that also in this location the SAW and the ERA5 data compare rather well with the observations, with in both cases correlations above 96% with the HS observations and above 84% with the Tm-1,0 observations. Both the SAW and ERA5 underestimate HS observations, by about 8.5% and 8.9%, respectively and they also both underestimate Tm-1,0 data by 10.6% and 8.6%, respectively. This is comparable to the error statistics at LEG. Again there is a very good agreement between the SAW and ERA5 data, with correlations above 90% for all parameters and very little scatter, and also at this location SAW HS data are lower than the ERA 5 HS data for high values of HS, see Figure 2 11.

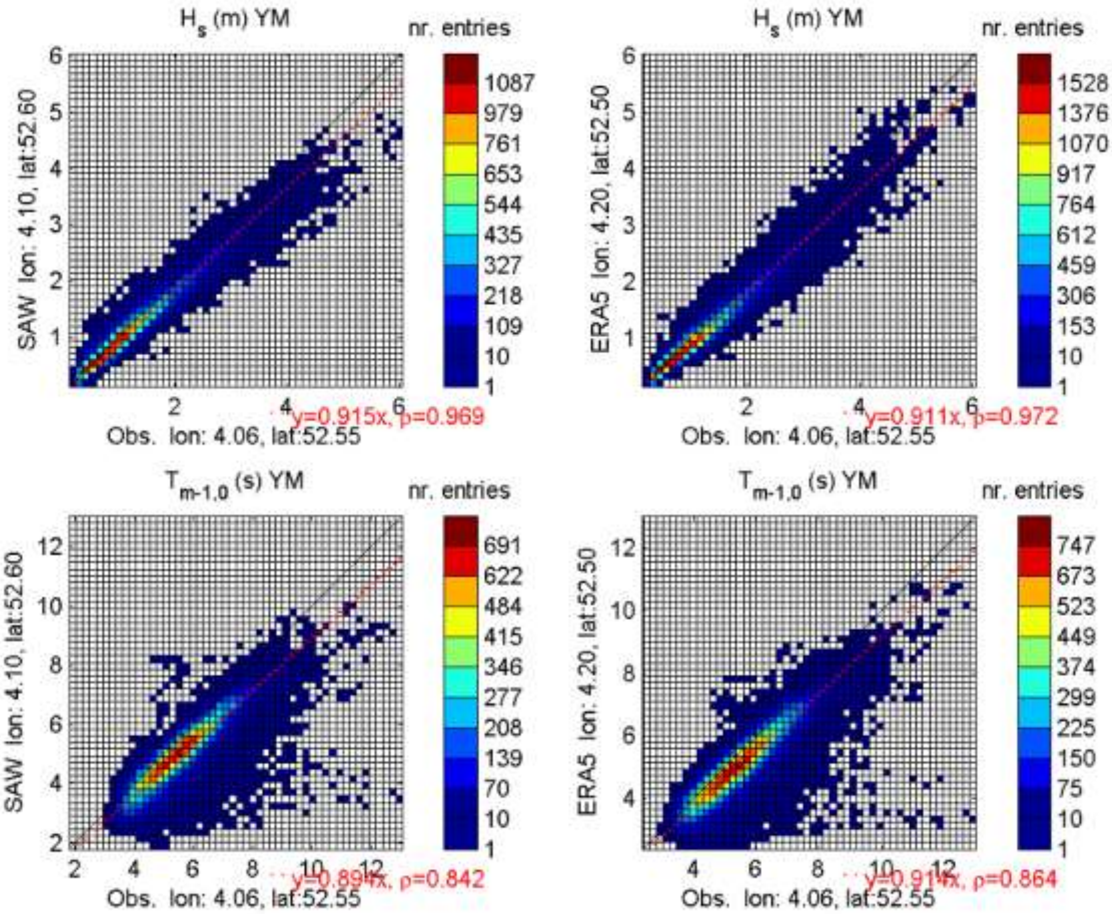

Figure 2 10 - Density scatter comparisons between the YM measurements and the SAW (left column) and ERA5 (right column) significant wave height (top row) and mean wave period (bottom row) data. The symmetric slopes and correlations between the data are printed in red in the panels.

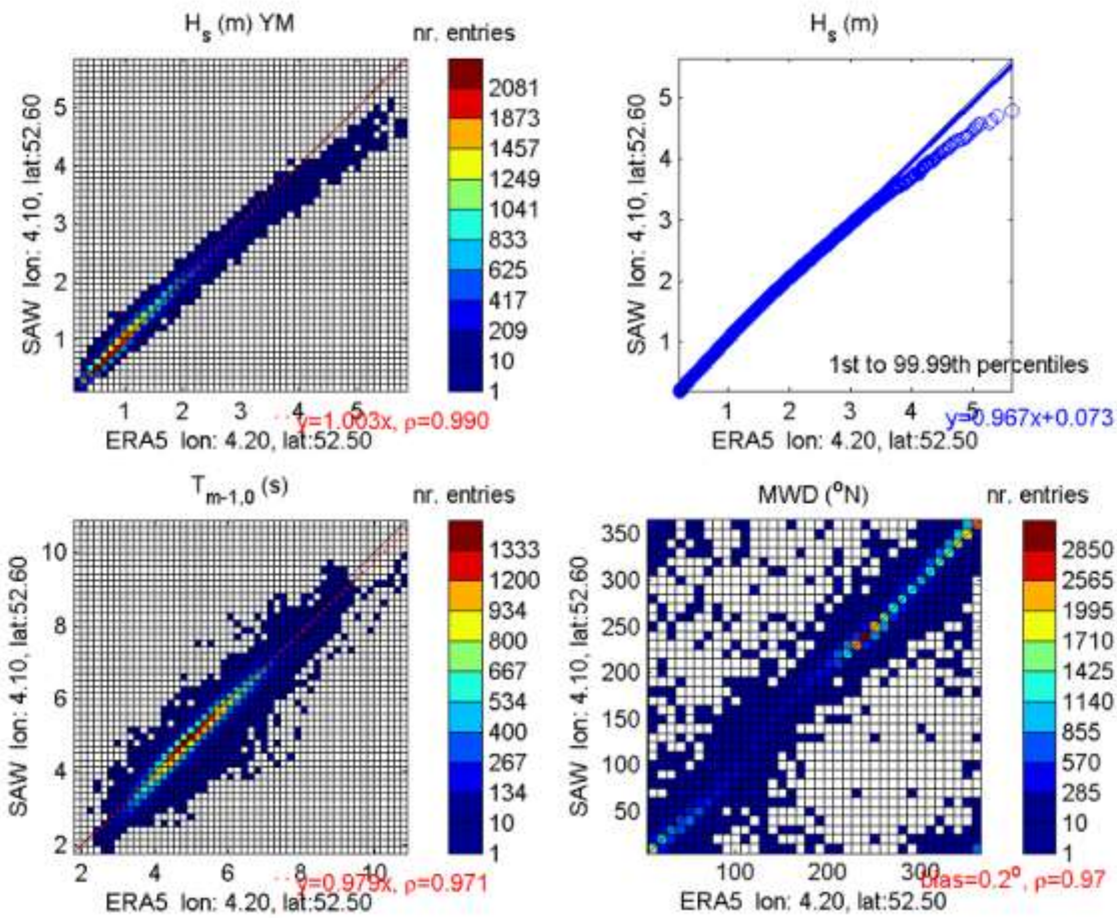

Figure 2 11 Comparison between the SAW and ERA5 data from the grid locations closer to the location of the YM station. Top left: Density scatter between the SAW and ERA5 significant wave height data. Top right: Quantile-quantile plot of the SAW and ERA5 significant wave height data. Bottom left: Density scatter between the SAW and ERA5 mean wave period data. Bottom right: Density scatter between the SAW and ERA5 mean wave direction data.

From these comparisons it can be concluded that the quality of the SAW data is at least as high as that of the ERA5 data, with the SAW results comparing slightly better with the observations, probably due to a better representation of the shallow bathymetry by the SAW model.

General validation

In order to have a general overview of the accuracy of the SAW model, SAW and ERA5 timeseries of HS, Tm-1,0 and MWD at ERA5 grid locations with water depths of about 20 m have been compared. Figure 2 12 shows the correlation and Figure 2 13 the scatter-index between the HS, Tm-1,0 and MWD data. Figure 2 14 shows the symmetric slope between the HS and Tm-1,0 data . The figures show that the correlations between the datasets are very high, generally above 95% for Hs, 85% for Tm-1,0 and 80% for MWD. The locations where the correlations are lower are generally locations with local obstructions or depth gradients and these lower correlations are therefore mostly due to differences in the bathymetry of the SAW and ERA5 models. The scatter-indexes are generally low, cf. Figure 2 13, with the locations where these are higher being those with also lower correlations between the data. The symmetric slopes show no general underestimation or overestimation of the ERA5 HS and Tm-1,0 data by the SAW model. The amount of over- or underestimation depends on the location and therefore probably also the local bathymetry representation of both models.

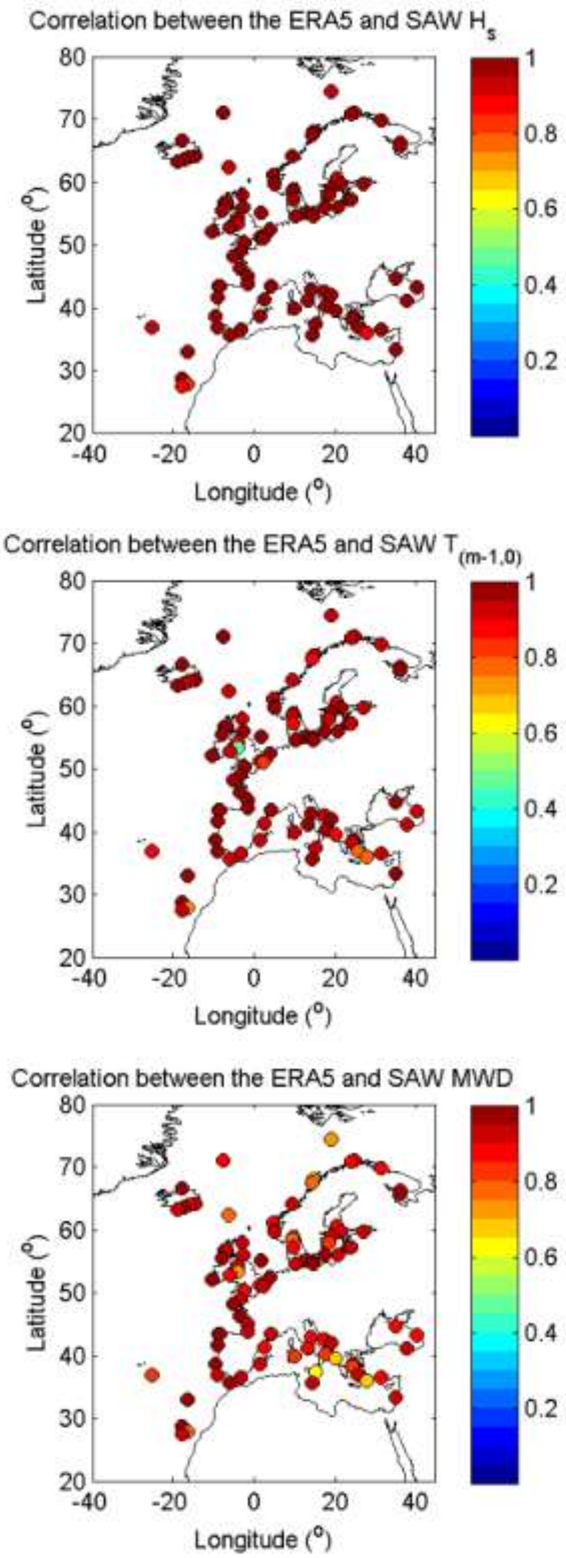

Figure 2 12 – Correlation between the hourly timeseries of ERA5 and SAW significant wave heigth (top panel), mean wave period (middel panel) and mean wave direction (bottom panel) from 2010 to 2016 offshore the European coast.

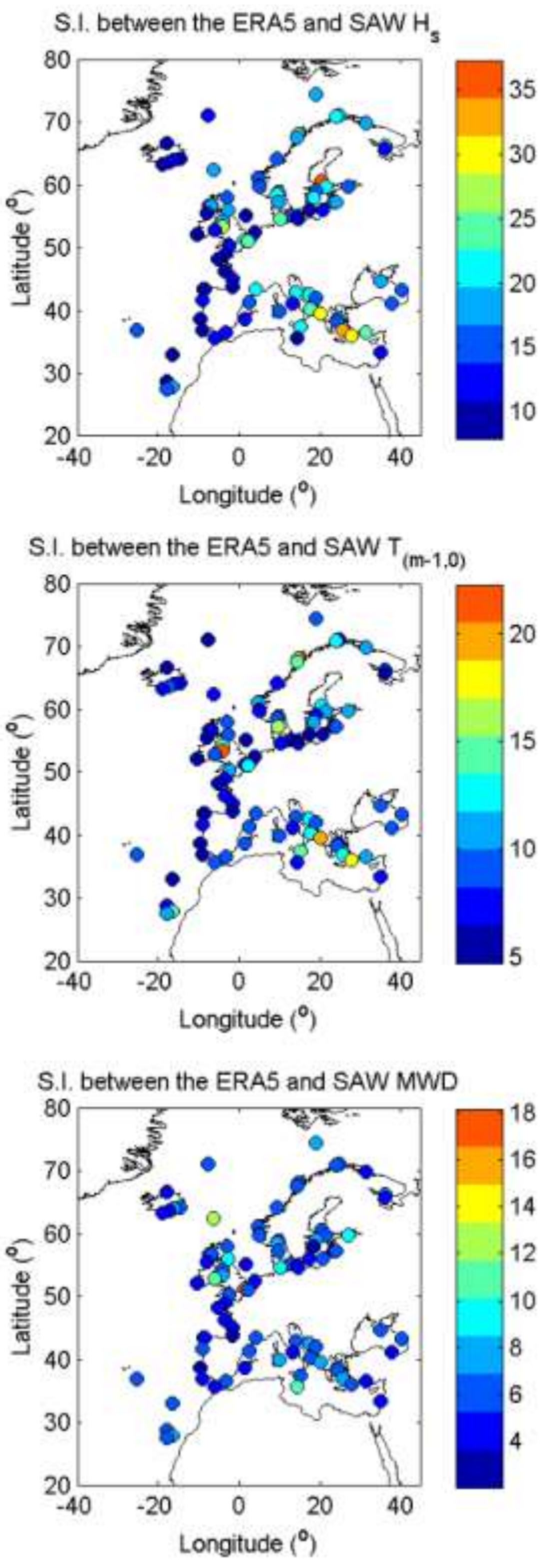

Figure 2 13 –Scatter-index between the hourly timeseries of ERA5 and SAW significant wave heigth (top panel), mean wave period (middel panel) and mean wave direction (bottom panel) from 2010 to 2016 offshore the European coast.

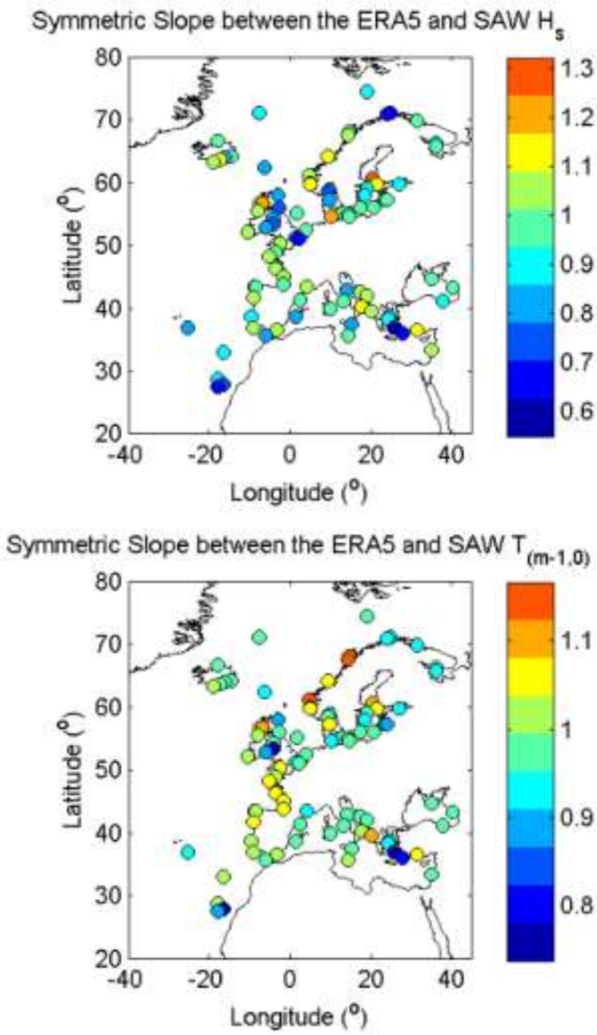

Figure 2 14 –Symmetric slope between the hourly timeseries of ERA5 and SAW significant wave height (top panel) and mean wave period (bottom panel) from 2010 to 2016 offshore the European coast.

Discussion and remarks

The validation the SAW model results shows that quality of the SAW data is at least as high as that of the ERA5 data, with differences between the ERA5 and SAW model results being most likely due to a better representation of the shallow bathymetry by the SAW model. These lead us to conclude that there is no need to further calibrate the SAW model results.

ECMWF's Stand Alone WAM (SAW) model has been set up in order to generate Tier 1 wave data and has been validated against wave measurements and ERA5 wave data. The validation indicates that the SAW waves compare well with measurements and are consistent with those from the most accurate presently available reanalysis, the ERA5 reanalysis. The validation results also indicate that there is no need for further calibration of the SAW waves. The model is, therefore, considered suitable for the computation of the Tier 1 wave data.

Model runs
The SAW model is to be used to determine the Tier 1 wave data which will consist of 30-year slices of historical (1976-2005), RCP4.5 (2071-2100) and RCP8.5 (2071-2100) data. To generate these data the model will be forced with wind (no ice-coverage) data provided by DMI. The DMI wind data consists of

- 3-hourly global wind fields generated using the EC-EARTH Global Climate Model (GCM) with a resolution of about 1.125° x 1.125°.
- Hourly downscaled European winds, for the region outlined in orange in Figure 2 15, from the EURO-CORDEX (http://www.euro-cordex.net/) Regional Climate Model (RCM) computations. The RCM covers Europe's main land with a resolution of about 12 km x 12 km (longitudinal resolution varies between 0.05° and 0.16° and the latitudinal resolution varies between 0.05° and 0.10°).

Given that the RCM winds do not cover the SAW domain (cf. Figure 2 15 Figure 2 5.) the RCM and GCM winds have been merged to create hourly wind fields with a resolution of 0.2° x 0.2°, covering the SAW model domain, and forcing the SAW model.

Figure 2 15 - Outline in orange of the domain of the DMI EURO-CORDEX RCM model.

The output locations will consist of wave model grid locations approximately along the European coastal waters 20 m depth contour. Given that the model resolution is of 11 km x 11 km in most regions the spacing between the output locations will vary between 11 and 16 km. In addition to these locations the set will also contain wave model grid locations at depths of 20 m or higher, close to output points defined by the contract user cases.

2.2 Climate forcing - comparison of climate models

In this chapter, the regional climate model (RCM) simulation used within this contract, DMI-HIRHAM5 (Christensen, 1998) downscaled from global climate model (GCM) EC-EARTH, is compared with and related to other Euro-CORDEX members. In this report, we choose to study annual maximum wind speed, which the parameter of main interest to storm surge and wave climate changes in the coastal

region. We focus on two questions: 1) How does DMI-HIRHAM5 perform in relation to other CORDEX members; 2) Is ensemble mean of the wind fields suitable for impact research, like coastal climate studies in this project.
The comparison of the extreme wind events of EURO-CORDEX, in particular for climate scenario simulations was not fully investigated in the previous ensemble studies (Kunz, 2010). The other relevant parameters, like averaged wind field and mean sea level pressure were extensively evaluated in many studies (Kotlarski, et al., 2014; Jacob, et al., 2014; Tobin, et al., 2016; Moemken, et al., 2018). Some of these evaluations are shown in the section 2.1. Section 2.2 provides a time-series example (Køge, the Baltic case study site in this report) to demonstrate why the ensemble means of the maximum wind fields is not suitable for this project. In the third section (1.3) we illustrate the results from the generalized extreme value (GEV) analysis, further explore how the extreme wind events in HIRHAM5 comparing with other RCMs.

2.2.1 Mean sea level pressure and averaged wind field

The evaluation of the mean sea level pressure provides a better handle on dynamical aspects of bias characteristics in the wind fields. The ensemble study in Kotlarski et al. (2014) consists of 17 EURO-CORDEX members (nine EUR-11 experiments and eight EUR-44 experiments) (Fig. 4-16). In both winter and summer seasons, HIRHAM5 (last member in Fig. 4-16) reproduced the large-scale pattern of mean sea level pressure fairly well and biases do not exceed 2 hPa, while some RCMs, like RCA4 from SMHI, WRF from IPSL-INERIS, UHOH, CRP-GL exhibit larger bias (Fig. 4-16).
Unlike for temperature and precipitation (Jacob, et al., 2014), there is no consistent gridded data set of observations for wind speed potentials available over Europe (e.g., Kjellström et al., 2011). The accessible wind speed data are station-based for every individual country, with diverse quality and spatial and temporal coverage, which results in a large inhomogeneity of the observed wind field. Several studies have investigated the performance of RCMs to represent near surface wind speeds, typically focusing on individual countries with available wind observations. Many studies generally agree on a good representation of wind speed distributions in RCM ensembles compared to observations in individual countries and these results may be regarded as representative for other European countries (Haas & Pinto, 2012). In this report, we show the results from Tobin et al. (2016). They evaluated 15 EURO-CORDEX members (include HIRHAM), and showed the ensemble mean changes in wind speed at 10 m at the end of the century (2071–2100) relative to the recent period (1971–2000) under scenario RCP8.5 (Fig. 4.17). Robust and significant decreases were found over most of the Mediterranean region and to a lesser extent over the Atlantic Ocean; robust and significant increases are projected over the Bosporus–Aegean Sea, the Gibraltar Strait and over the northern Baltic Sea (Fig. 4.17).

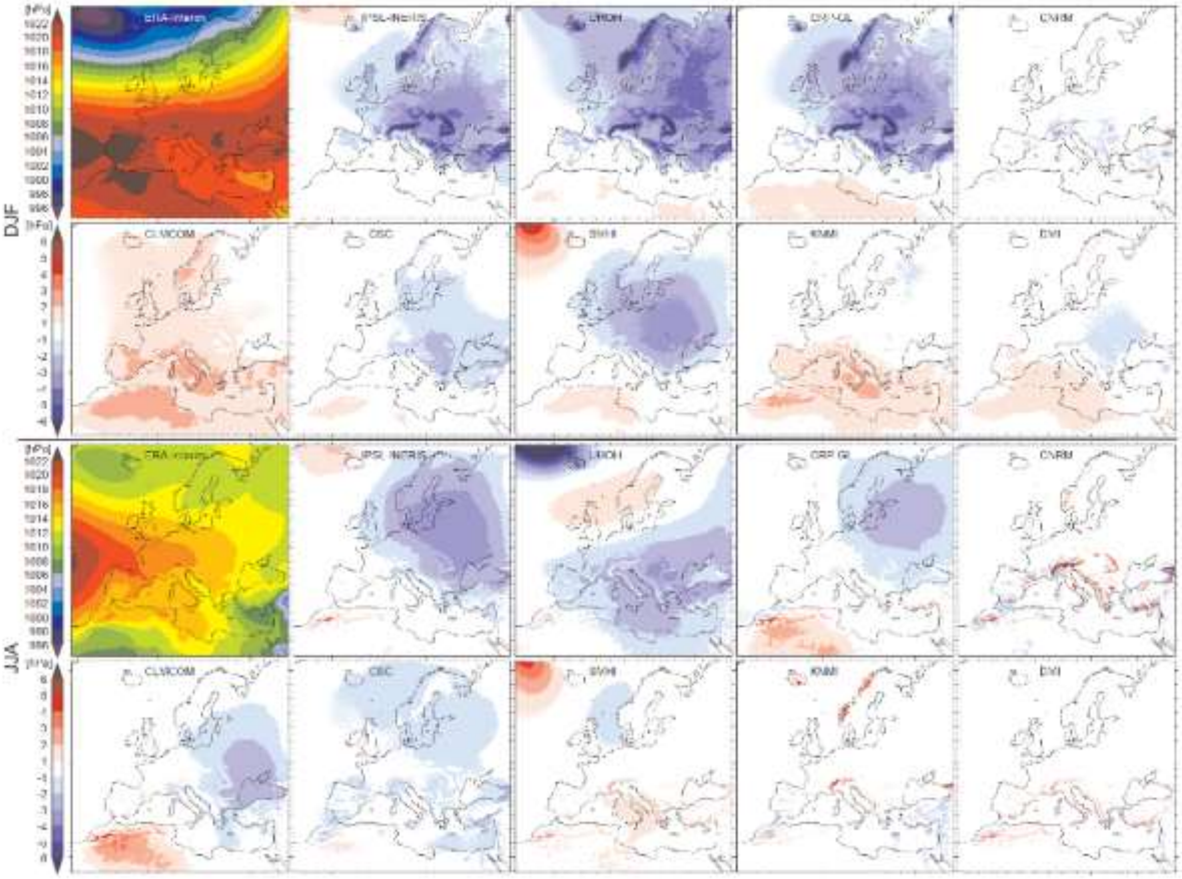

Figure 2-16 Mean seasonal sea level pressure (upper-left panel) and bias (hPa) for all experiments of the EUR-11 ensemble and the period 1989–2008. Upper rows: winter (DJF), lower rows: summer (JJA). The upper-left panel of each section shows the horizontal pattern of mean sea level as provided by the ERA-Interim (hPa). DMI-HIRHAM5 is displayed as the last member in each section. This figure is from Fig 4 in Kotlarski et al. (2014).

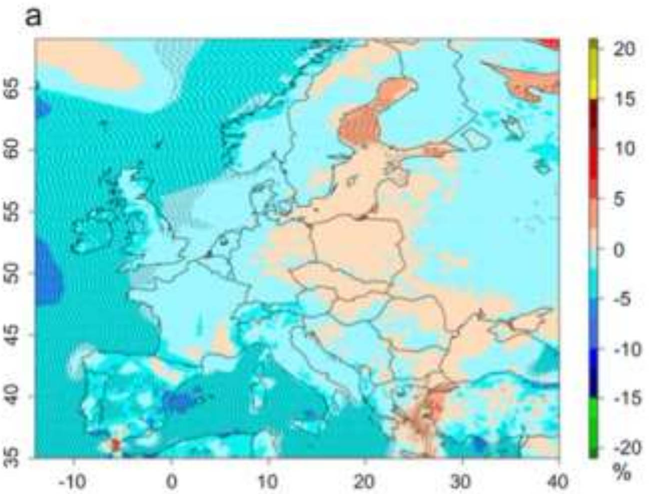

Figure 2-17 Ensemble mean future changes in wind speed at 10 m at the end of the century (2071–2100) relative to the recent 1971–2000 period under scenario RCP8.5. The black dots indicate where

the changes are robust (95% significance over the model ensemble, according to Wilcoxon–Mann–Whitney test, and sign agreement over 80% of the models). This figure is from Fig 2 in Tobin et al. (2016).

2.2.2 Ensemble extreme wind results

The ensemble approach aims at presenting a high-resolution (12.5 km) data set from a multi-model multi-scenario ensemble of regional climate simulations for impact research. The statistical methods for some high-impact phenomena, like heavy precipitation, dry spells and heat waves can be found in Jacob et al. (2014). However, a clear definition of ensemble statistical method for the extreme wind cannot reach a consensus. We showed an example of the ensemble annual maximum wind speed time series (16 members) at the study site Køge (Baltic Sea case study in this report) (Fig. 4-18). The ensemble annual maximum wind speed (thick black line) is the median of the multi-model results, which shows a very small variance (< 2m/s). Such a small variable time-series is not suitable for the extreme analysis.

At Køge station, annual maximum wind speed in HIRHAM5 was larger than other RCMs (Fig. 4-18). The coastal wind is rather dynamic, which is the combination of many factors, like differential heating between land and sea, the topography and the shape of the coastline, etc. The coastline generally represents a marked discontinuity in surface roughness. The resulting mechanical forcing leads to a secondary circulation in the boundary layer, leading to localised vertical motion which may, in turn, have a strong influence on weather in the coastal zone. Therefore, different coast sites in this report should be studied individually.

2.2.3 Extreme value analysis

The generalized extreme value (GEV) distribution is often used to model the largest value among a large set of independent, identically distributed random values. It is often used to fit the annual maximum wind speed distribution (known as block maxima). Probability density function of the annual maximum wind speed in HIRHAM5 showed a larger location parameter (Fig. 4-19), which further confirm the conclusion that HIRHAM5 showed larger wind speed at Køge station. One RCM (different colours in Fig. 4) downscaled from different GCMs shows very similar fitting parameters of GEV, e.g. shape parameters are between 0.3 and 0.5 (Type II distribution). It indicates that the physics in RCMs determines the maximum wind distribution at Køge station.

It is notable that HIRHAM shows larger annual maximum coastal winds at Køge, but this conclusion cannot be generalized. We analysed many different sites (not shown), which actually gives different ranking of the RCMs. As mentioned above in section 2.2, coastal wind is a combination of many factors, which represented differently in different RCMs.

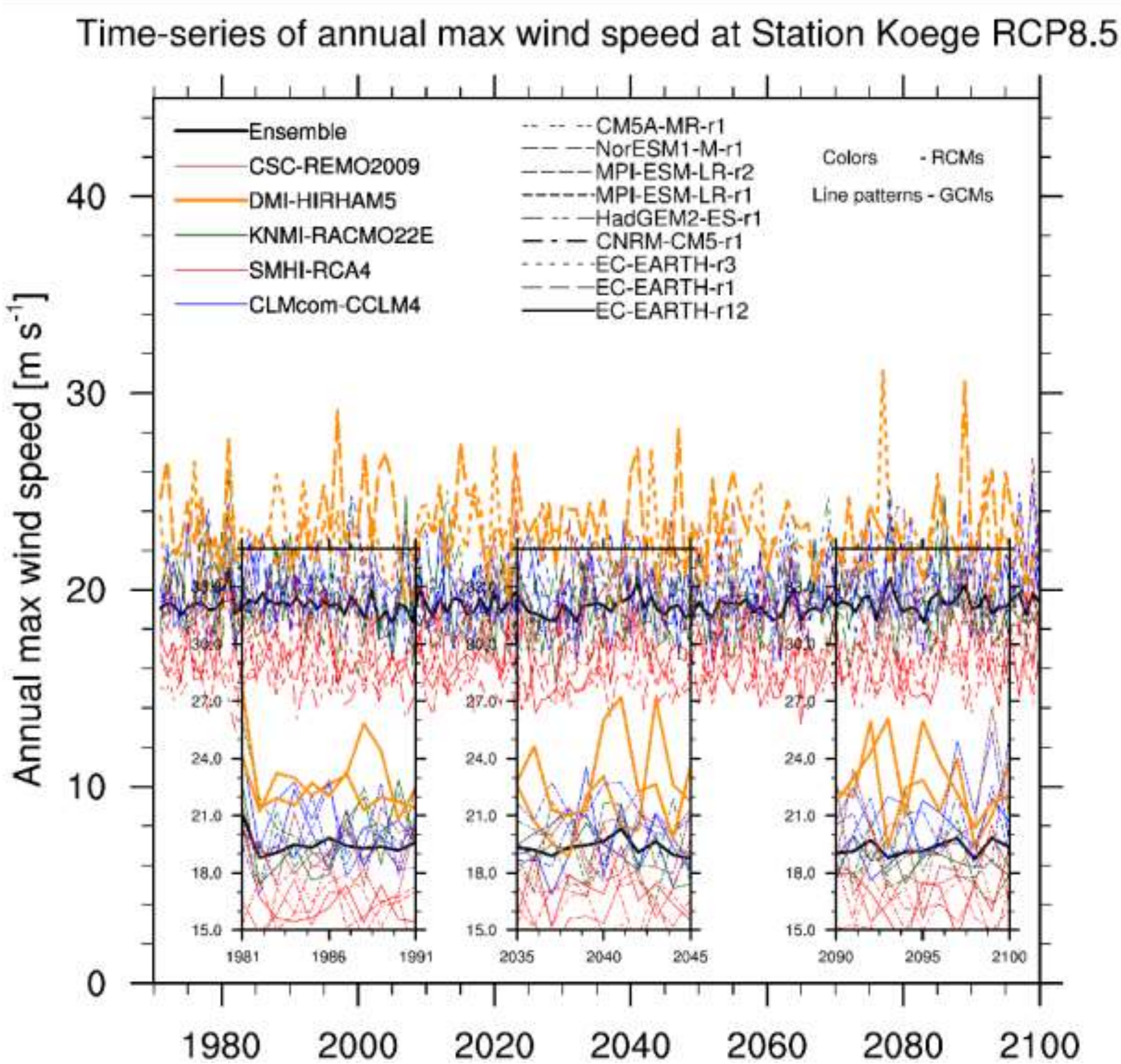

Figure 2 18 Time series of annual maximum wind speed at the Køge station for 130 years simulations from multi-RCMs (16 members, including 5 RCMs, REMO2009: 2; HIRHAM5: 2; RACMO22E: 3; RCA4: 5; CCLM4: 4 members) under RCP 8.5 scenario. The line colours indicate different RCMs, while different line patterns refer to GCMs (downscale to RCMs). DMI-HIRHAM5 downscaled from EC-EARTH (used in this project) is the single dashed thick yellow line.

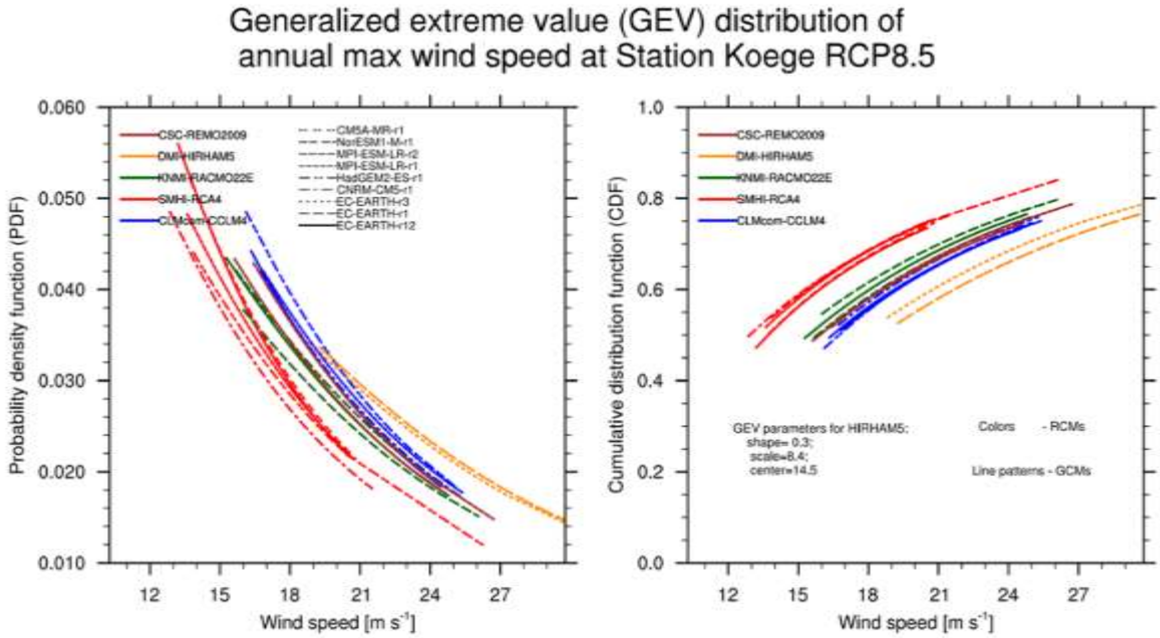

Figure 2-19 Extreme value analysis by fitting the annual maximum wind speed at Køge station (Fig. 3) to a generalized extreme value (GEV) distribution. Left panel: the probability density function (PDF) of the GEV. Right panel: the cumulative distribution function (CDF) of the GEV. GEV fitting parameters of HIRHAM5 are showed in the figure, and the distributions belong to type II distribution family. The line colours indicate different RCMs, while different line patterns refer to GCMs (downscale to RCMs).

2.2.4 Summary and short discussion

- HIRHAM5 reproduced the large-scale pattern of mean sea level pressure fairly well.
- Ensemble mean future changes in wind speed at 10 m shows robust and significant decreases over most of the Mediterranean region and to a lesser extent over the Atlantic Ocean; robust and significant increases over the Bosporus–Aegan Sea, the Gibraltar Strait and over the northern Baltic Sea.
- At Køge station, annual maximum wind speed in HIRHAM5 was larger than other RCMs.
- One RCM downscaled from different GCMs shows very similar fitting parameters of GEV distribution.

In general, we can conclude that the extreme winds of DMI-HIRHAM5 are in the range of the ensemble spread. However, extreme winds over the Europe should be studied in more detail, in particular they should be compared with the observed winds during extreme events. The uncertainty index based on such study would provide solid conclusions.

3. Climate Impact Indicators

3.1 Tier 1 Climate Impact Indicators

3.1.1 Hydro

The Tier 1 indicators for the hydro dataset can be split in 3 groups: Tidal indicators, extreme-value indicators and probability indicators. Implications and applicability of each indicator set is explained in the following sections.

3.1.1.1 Extreme-value indicators

Concept

Extreme water level values are of relevance for flood-risk assessments. They not only point out the highest water-level one can expect in a specific location, but also how frequently one can expect such unusually high value. The frequency with which the extreme value can be expected is described by the return period. Therefore, the indicator can be defined as the return water level associated to a certain return period.

There are two perspectives from which changes in extreme-value indicators can be viewed: an increase in the extreme value associated to a fixed return period or frequency, or an increase in the frequency (decrease of return period) of a given extreme water level value. With rising sea levels there is a general upward shift in the extreme values, so that historical extreme values will be reached with milder storms, and extreme storm events will lead to higher extreme water level values. Furthermore, changes in the intensity and frequency of extreme storms potentially present in the climate models will also impact extreme values. Last but not least, changes in tides will also impact the extreme values reached. All these processes that change the extreme values are captured in the hydrodynamic model runs performed in this project, and are therefore reflected in the indicators.

In order to separate the effects of stronger extreme surges from the rest of the components (as this provides additional information of the changes), the extreme value analysis is also performed over the surge series only, and separate indicators are defined for the surge and water levels.

Calculation method

To model the distribution of the extreme values, we use the Gumbel distribution over the annual maxima values for each epoch. Each epoch/scenario consist of 29 years of data (1976-2005, 2041-2070, 2071-2100), from which the annual maxima value for each station is computed for both total water levels and surge variables. These 29 values are then fitted to the Gumbel distribution to derive the parameters defining the function, which can in theory be evaluated for any given return period. See Figure 3-1 as illustration for a coastal location in East UK. The starting value for low return periods will be strongly determined by the location's sea level rise and tidal range.

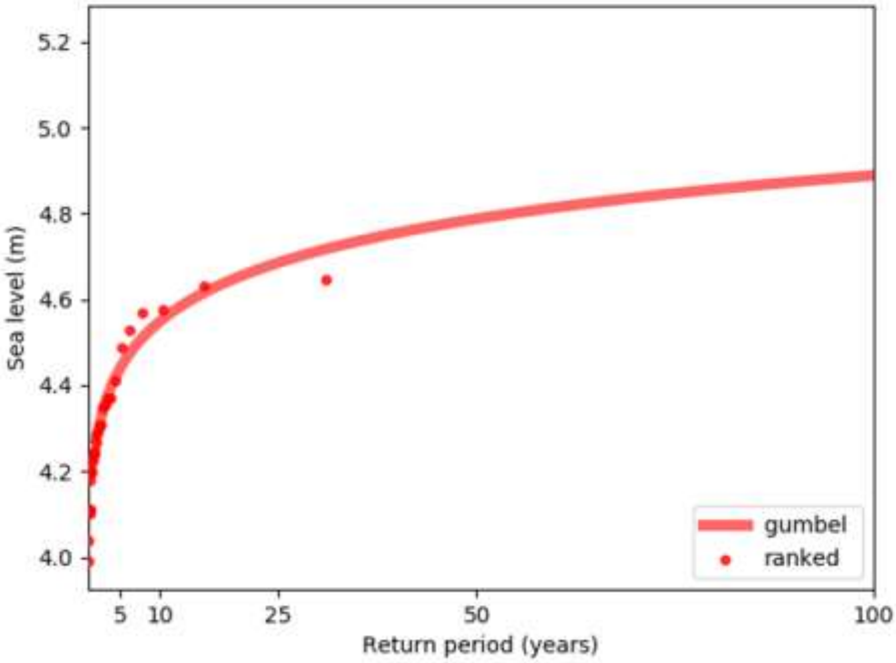

Figure 3 1. Gumbel extreme water level frequency curve for Immingham, UK, fitting the underlying annual maxima data (dots) for mid-century RCP8.5

While the Gumble method is simple and widely used it has a number of limitations. The maximum return period for which the Gumbel function is evaluated here is 100 years. This is on the limits of the extrapolation capabilities of the method for a set of 30 year sample values, as the uncertainty greatly increases for increasing return periods. Limitations of the Gumble fit relate to both efficiency of use of the available data and the flexibility of the distribution. In the detection of extreme values, other methods like peaks-over-threshold (POT) and r-largest method (selecting more than one extreme event per year) make better use of the data than the annual maxima used here. On the distribution shape side, method like Generalized Extreme Value (GEV) or Generalized Pareto distribution (GPD) allow more flexibility to the shape of the distribution by introducing a third parameter shape. This has the pottential to better represent the most extreme events (1000 -10000 year return periods). Due to this known limitation of the Gumble fit, the maximum return period is limited to 100 years in this dataset.

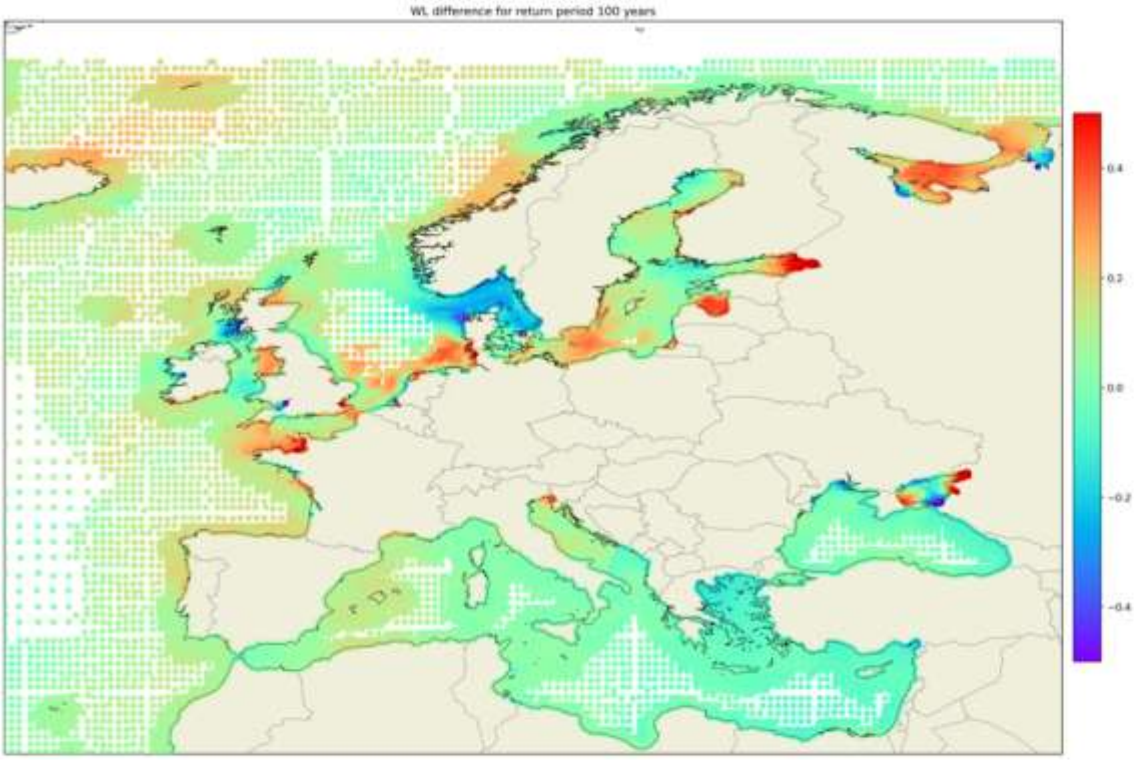

Figure 3 2. Return level difference between mid-century RCP8.5 and current climate for water levels (top) and surge only (bottom).

Impact of indicator

The impacts of changes to extreme values are numerous. The most intuitive are the impacts related to flood risk. Figure 3-2 shows the changes in return level associated to the 100 year return period between the RCP8.5 scenario (2050) and the current climate. In many places, this change observed will be dominated by the relative sea level rise. In other places, storm surge intensities might be dominating, or even counteracting sea level rise effects. Such information will be extremely relevant for example for the operation of existing storm-surge barriers and design of future ones. Such storm-surges are often designed taking into account past conditions of high waters and frequency. The closure operations of these barriers are often expensive, and so are maintenance costs. With increasing extreme values, frequency of closure will increase, inflicting high costs and potentially reducing the lifetime of the structures, impacting the efficiency of the initial and continuous investment. Constructors of coastal and offshore structures usually look at such extreme values for design conditions.

An increased coastal flood risk can have severe impacts on safety of populations living by the sea, and others like economic impacts on agriculture. Furthermore, increased storm intensity and frequency can change coastal morphodynamics and greatly impact coastal ecosystems and their services.

3.1.1.2 Tidal indicators

Concept

Tidal levels play an important role in our everyday lives. For example, port operators rely on accurate tidal levels and time prediction to manage the maritime traffic. At the coast, tidal currents are strong and often dominate the total current, becoming therefore important for navigation. While tides are in general deemed predictable and strong knowledge on tidal dynamics has been developed over the last centuries, the evolution of tides under future climate change scenarios is not well explored. Changing water-depths due to sea level rise can impact tidal propagation, and the dependence of the tides on the resonance characteristics of the ocean basins suggests that important changes can be triggered by sea level rise. In particular in wide shallow areas like the European North-West continental shelf, tidal dynamics are complicated and sensitive to geometry.

Furthermore, changes in tides will impact extreme water level values. While this information is already contained in the extreme value indicators in Section 3.1.1.1, tide-induced changes in extreme values have a different nature and time-scale than surge-induced changes. A considerable increase of tidal high waters will be experienced in an everyday basis, while extreme storm surges have a time-scale of years. Thus, adaptation measures will be very different for tides than for surges. It is therefore of relevance to derive indicators that quantify changes in tides and isolate them from the total change in water levels.

Calculation method

Several tidal indicators are defined based on the different impacts that they trigger. We determine that important indicators are : Changes in mean high-high waters – MHHW- and highest astronomical tide (coastal flooding), changes in mean low-low water –MLLW- and lowest astronomical tide (navigation clearance), changes in tidal range (intertidal ecology), changes in mean sea level (coastal management). These indicators are defined as a single value for each station for the period considered (29 years) for each scenario, and the effect of sea level rise is removed from them in order to purely characterize the tide and its changes.

Alongside these temporal indicators characterizing the period, we also calculate yearly values for the same tidal levels. In the case of highest astronomical tide (HAT), this becomes the yearly highest tidal value, and similarly for lowest astronomical tide (LAT). The yearly MHHW and MLLW are calculated as the mean over the year, instead of the mean over the whole period. These time-dependent indicators (with 29 values per station) also include effects of sea level rise. In this way, these series give additional temporal information, not contained in the previous tidal indicators, about the evolution of the tidal levels over time. An example where this becomes relevant is the time-dependent highest tidal water. The tide highest value (HAT) has a cycle of 18.6 years (nodal cycle). While sea level is continuously rising, the nodal cycle can be such that the highest tidal level doesn't happen at the end of the considered period (highest sea level rise) but before when the modulation is at its maximum. Therefore, information on timing becomes important and can be calculated due to the predictive and periodic nature of the tide.

For the MHHW and MLLW calculations, windows of 25 hours are used in which the corresponding peak is detected. Then, the average of these values in calculated per year. For the temporal indicators, a final average is performed over the 29 year data points.

Impact of indicator

One of the most obvious impacts of changes in tides is changes flood risk. It is known that there are places around the world already threatened by tidal high waters, like Florida. Increased tidal high waters also lead to reduced thresholds to accommodate storm surges, while storm intensities might not change. Since tides have generally periodicities of diurnal or semi-diurnal, increased tidal high water has a greater impact on flood-risk than intensification of storm surges. Together, the effects can be devastating.

For daily activities, impacts could be expected for the port-operations, navigation activities (both commercial and leisure) and design of shipping routes. Furthermore, tidal dynamics govern several coastal physical processes and ecosystems. Amongst these we find sediment transport and budgets. A change in tides can lead to a new sediment budget and therefore change in shape of the beaches. Salt-marshes in inter tidal zones could drown under higher tidal ranges, and tidal mixing changes can lead to changes in vertical stratification and its modulation, affecting organisms like phytoplankton.

3.1.1.3 Probability indicators

Concept

Besides information on the frequency and intensity of the extreme events described in 3.1.1.1, it is useful to know the probability distribution of the water-levels. This provides information about the intensity and probability of all other conditions besides extreme, and overall provides information about the shape of the distribution.

In a similar fashion to the extreme value indicators, we distinguish between probability indicators for total water levels and surges.

Calculation method

In order to look at the distribution, we use percentiles. The percentile indicates the value below which a given percentage of observations (or in this case, modelled values) in a group falls. For example, the 75th percentile is the value (of water level or surge) below which 75% of the modelled values may be found.

By looking at changes for a given percentile between the future and present scenarios, one can assess how the distribution changes and shifts (Figure 3-3). As an example, when comparing surge distributions between historical period and the RCP8.5 scenario for the mid-century period, we observe that the lower percentiles show a bigger change than the higher. The change is in general showing lower values for the low percentiles (although it varies spatially). This indicates that the spread of the surge distribution is larger for the future scenarios.

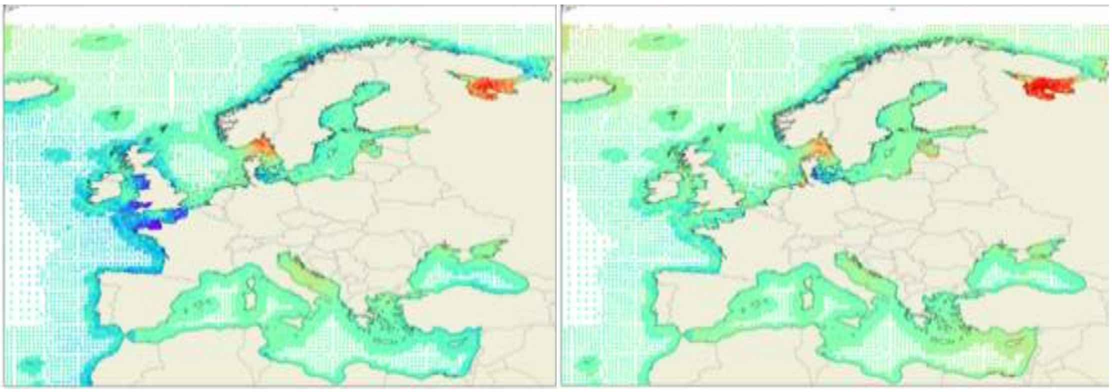

Figure 3 3. Left: Change in surge 25th percentile level between mid-century RCP8.5 and current climate. Right: Change in surge 75th percentile level between mid-century RCP8.5 and current climate

Impact of indicator

Probabilities are often used for flood risk and corresponding impact assessments by, for example, insurance companies and coastal managers to guide their decision making. They use the information provided by the distribution to design, for example, effective long-term measures that can cope with the wide range of conditions that the coastal system is characterized by and its probabilities. Changes to these distributions due to climate change can entail the failure of such measures and propagate changes to the joint probability assessments often used to combine risks from different threats like extreme precipitation or river discharge with extreme sea levels.

3.1.2 Waves

The Pan-European wave indicators characterize the stormy wave conditions along the European coast in terms of wave height and wave period. We provide indicators based on percentile analysis and extreme value theory (see Table 3-1).

Table 3 1 Summary of Tier 1 Wave indicators

ID	Name	Description	Calculation of CII`s in SC2	Connection to CDS (from webservice)	Foreseen usage
1	100-yr return values: significant wave height and wave period	The 100-year return value is the value that is exceeded on average every 100-years. It will be determined from the extreme value analysis of the data.	Derived from wave dataset for all output locations included.	Pre-calculated dataset, available for each output location included in the CDS.	Return values are the main input parameter for design of for instance offshore platform and structures.
2	90% and 99% percentiles of significant wave height and peak wave period.	The percentiles will be determined empirically (no fit) from the data.	Derived from wave dataset for all output locations included.	Pre-calculated dataset, available for each output location included in the CDS.	Percentiles are the standard indicators used in (wave) climate change studies.

Concept and Impact of indicator

The analysis of wave storminess is of great relevance for several coastal sectors (ports, flooding defense, tourism, renewable energy, navigation, ecosystems, etc, see example elaborated in Offshore wind Use Case linked to this dataset). The design of coastal infrastructure--for example, breakwaters, dikes, or offshore platforms-- is based on the most extreme wave climate conditions. Often relying on wave climates that have never been measured, but they might happen based on extreme value theory with the current wave climate properties. Several reference design standards focus on the analysis of the ultimate limit state failure modes, producing the collapse of the maritime structure (Coastal Engineering manual, 2002; the Spanish Recommendations of Maritime Works ROM, 2001; the EUROTOP Manual, 2018; and the ROCK Manual, 2007). In addition, more regular wave climate conditions also play a big role in the coastal zone management, for example sediment siltation of navigation channels, port operability, marine ecosystems, and in defining beach nourishment strategies for enhancing tourism or coastal protection.

Significant weight height and peak period are the basic parameters that define a wave climate. Both are relevant for various coastal applications. For example, predicting extreme significant wave heights is key for damage evolution of breakwaters. In contrast, extreme peak periods can have a great influence in agitation by the docks and therefore in port operability. We provide indicators for the 90% and 99% percentile, and the 100-year return period level of significant wave height and peak wave period. Both, 90% and 99% percentiles, characterize the upper tail of the marginal distributions of significant wave height and peak wave period. Looking at these indicators in the past, present and future wave climate, we can unravel future changes in wave storminess persistence and its consequences in the coastal sectors. The 100-year return period value is a good estimator of the robustness and reliability of the current designs in a future wave climate.

Calculation method

90% and 99% percentiles are obtained from the empirical distribution of the modelled hourly wave climate parameters, significant wave height (SWH) and peak wave period (PP1D). The 100-year return period value is computed by extrapolation following extreme value theory (Coles et al., 2001). The Peak Over Threshold (POT) method is applied in each epoch (~30 years of data) for identifying maxima values. Storms are defined by those values above the 90% and 95% percentiles for SWH and PP1D respectively. For guaranteeing independence between storm events, a minimum duration of 4 days between the peak of the event is considered. The peaks of each storm are taken for fitting the scale parameter of an exponential distribution using the maximum likelihood estimation method. Once the scale parameter characterizing the extreme regime distribution of significant wave height or peak wave period is known, the extrapolation of the 100-year return period is possible, assuming that the average rate of storms will remain stationary.

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