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Climate services for marine applications in Europe

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Abstract

The term "climate services" is commonly used to refer to the generation of climate information, their transformation according to user needs and the subsequent use of the information in decision making processes. More generally, the concept also involves contextualization of information and knowledge. In the following a series of examples from the marine sector is described covering the generation, transformation and the use of climate information in decision making processes while contextualization is not considered. Examples comprise applications from naval architecture, offshore wind and more generally renewable energies, shipping emissions, and tidal basin water exchange and eutrophication levels. Moreover effects of climate change on coastal flood damages and the need for coastal protection are considered. Based on the analysis of these examples it is concluded that reliable climate information in data sparse regions is urgently needed, that for many applications historical climate information may be as or even more important as future long-term projections, and that the specific needs of different sectors substantially depend on their planning horizons.

Keywords: Climate service; North Sea; Hindcast; Naval architecture; Ship emissions; Offshore wind; Renewable energies; Coastal protection

Introduction

The need to provide climate information to society has been recognized for many decades of years. For example, the first World Climate Conference held in 1979 by the World Meteorological Organization called for establishing a World Climate Programme with the objective to improve our understanding of the climate system and its impacts on society (Vaughan and Dessai 2014). More recently, the phrase *climate services* became more common to describe user-oriented approaches to make climate information available.

So far, there appears to be no generally accepted definition of what constitutes a climate service. A rather comprehensive and general definition was provided recently by Vaughan and Dessai (2014) who refer to climate services as the "generation, provision, and contextualization of information and knowledge derived from climate research for decision making at all levels of society" targeted mainly "at informing adaptation to climate variability and change". According to Vaughan and Dessai (2014) the objective of climate services is "to provide people and organizations with timely, tailored climate-related knowledge and information that they can use to reduce climate-related losses and enhance benefits". The process involves a range of different actors. Among them, the most crucial ones are the *climate service providers* who supply climate information and knowledge, and the *climate service users* who employ this information and knowledge for their decision making and who may or may not be involved in the development of the service itself (Vaughan and Dessai 2014).

In recent years the concept of climate services has received considerable attention, mainly as a central issue embedded in national or regional adaptation agendas. For example, the national German Strategy for Adaptation to

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Climate Change adopted by the German Federal Cabinet emphasizes the creation of a German Climate Service Center focusing on “networking and coordinating function in the field of evaluating and preparing climate scenario and model data, and disseminating them in the form of suitable data products and advisory services” (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2008). As such, the focus of most climate services is mostly on long-term projections and partly on decadal forecasts, while historical information has received less attention.

In this paper we bring together climate service providers and users and discuss their experiences and needs. We demonstrate, by means of a range of user examples, that historical climate information is often as important as future projections and should receive more attention in future frameworks for climate services. In particular, we concentrate on climate services for marine applications in Europe for which we have a long experience (see e.g. Weisse et al. 2009). In the next section we briefly describe the coastDat-2 met-ocean data base that provides the basic source of climate information provided to the users. Next we discuss specific examples from the users of the climate service. This comprises examples from marine industry such as offshore wind or naval architecture but also more general cases such as ship-emissions or tidal basin water exchange. Both, examples using historical climate information and long-term climate projections are provided. Finally our findings are summarized and discussed and some key conclusions from our cooperation with climate service users are provided.

The coastDat-2 met-ocean data base

Statistics of marine environmental conditions are needed by a variety of climate service users comprising marine scientists as well as providers of commercial near-shore and offshore activities. The basis for deriving such statistics is reliable, consistent and homogeneous long-term data. For marine areas, such data are often unavailable for various reasons: In many cases observational records are too short to cover the full spectrum of time scales. In some cases, sampling in space and time is insufficient or data for the parameters of interest are unavailable. For example, within the North Sea (often referred to as one of the most densely monitored continental shelf seas) the number of sea surface temperature measurements per year decreases rapidly with increasing distance from the coast (e.g. Loewe et al. 2002) leaving vast offshore areas that are hardly monitored at all. When other parameters such as wave heights or wave periods are considered the situation is often worse as long-term measurements at a site are usually not launched before the site was selected for example, for commercial development. At the time when statistical analyzes are needed to further develop the site, the length of the observational record is too short to cover the full range of variability and the record is hence unsuited as a basis for reliable statistics. In cases where longer records do exist, they are often not homogeneous; that is, technical changes, for example in measurement techniques, exist and may introduce artificial variability or spurious trends in the data (for a discussion see e.g. Weisse and von Storch 2009). The coastDat approach was developed to address such problems.

In the following we limit ourselves to a brief description and discussion of the core simulations and data available from the coastDat-2 data base that is the successor of coastDat-1 (Weisse et al. 2009). The core simulations most frequently used for marine climate services are the consistent wind, waves and tide-surge hindcasts that are complemented by corresponding long-term climate change projections. We further only concentrate on examples for the North Sea for which the longest experience in providing climate services to users exists.

The coastDat-2 data set is based upon the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) global reanalysis (Kalnay et al. 1996) that was used in combination with a spectral nudging technique (von Storch et al. 2000) to first drive a regional atmosphere model for an area covering most of Europe and the adjacent seas. The atmospheric model used was the COSMO model in CLimate Mode (COSMO-CLM) version 4.8_clm11 (Baldauf et al. 2011; Rockel et al. 2008; Steppeler et al. 2003) which is a non-hydrostatic operational weather prediction model that is developed and applied by a number of national weather services affiliated in the COnsortium for SMall-scale MOdeling (COSMO). The climate mode of this model is developed and applied by the Climate Limited-area Modelling Community (The CLM community 2007-2015). For coastDat-2, the model was run at a spatial resolution of about 24 km $\times$ 24 km to hindcast the period 1948-2014 (Geyer 2014).

From the atmospheric simulation, near-surface marine wind fields and atmospheric sea level pressure were used to drive high-resolution wave and tide-surge models. For the waves, the most recent release of the wave model WAM (WAM 4.5.3) (WAMDI-Group 1988) was used. The model was run in a nested mode with a coarse grid (approximately 50 km $\times$ 50 km) covering most of the Northeast Atlantic and a fine grid (about 5.5 km $\times$ 5.5 km) covering the North Sea. For tide-surges a 2D version of TRIM-NP (Kapitza 2008) was used, a nested non-hydrostatic shelf sea model with spatial resolutions increasing from 12.8 km $\times$ 12.8 km in the North Atlantic to 1.6 km $\times$ 1.6 km in the German Bight. Tides were included in the simulation by forcing the model with amplitudes and phases from a global tidal data set (Lyard et al. 2006). For all simulations, full model output was stored every hour providing a high-resolution (in space and time) met-ocean data base that is continuously extended and updated.

For the first version of coastDat validation is extensively described in the peer-reviewed literature. For example, Weisse et al. (2005) compared wind speed percentiles and storm counts derived from North Sea station data with data obtained from coastDat-1 and generally found a good agreement for both, average conditions and variability. Similar results for tide-surges and wind waves are inferred and described in Weisse and Pluess (2006) and Weisse and Günther (2007). Using both, in-situ wind speed measurements from a series of buoys and wind speeds derived from different satellite products Winterfeldt and Weisse (2009); Winterfeldt et al. (2010); Winterfeldt et al. (2011) assessed the added value of coastDat-1 compared to the driving global NCEP/NCAR reanalysis and found that wind speeds from coastDat-1 are improved, in particular in coastal areas and along coastlines with complex orography.

Since coastDat-2 is a relatively recent product, less comprehensive results for validation are available so far. Validation of the atmospheric hindcast is described in Geyer (2014) focusing mostly on the validation of near-surface temperatures and precipitation. For near-surface wind speeds Geyer (2014) compared results from coastDat-2 with observations from two buoys confirming the good offshore quality of coastDat-2 wind fields and the findings of Winterfeldt et al. (2011) regarding the added value of coastDat. In Geyer (2014) wind speeds derived from coastDat-2 were used to estimate wind energy potential in the North Sea. Here generally good agreement was found with results published in the literature. In particular the author demonstrated an improved representation of extreme wind speeds and wind speeds at typical hub heights while quality of near-surface marine wind fields is comparable to that from coastDat-1.

Figure 1 shows some additional validation for wind speed, significant wave heights and tide-surges from coastDat-2. The so-called Taylor diagram shows a comparison of validation statistics between modeled and measured data in terms of correlation (blue lines), centered root mean square error (green lines) and standard deviation (black lines). The latter two are normalized by the standard deviation of the corresponding observational data sets. In general, correlations between hindcast and modeled data vary between about 0.8 for wind speeds and 0.9 for high water levels for both, coastDat-1 and coastDat-2. Centered root mean square errors range from about 0.4 for tide-surges to 0.6 for wave heights and they are somewhat larger for wind speeds. For high water levels, the standard deviation of the modeled data is close to the observed values, while for wave height and wind speed it appears to be somewhat larger with a tendency towards higher values in coastDat-2. Generally, however, both versions of coastDat are hardly distinguishable in the diagram indicating similar quality. The added value of the coastDat approach is further illustrated by a comparison with wind speeds derived directly from the driving global NCEP reanalysis which show too small variability compared to observations.

Climate services for marine applications

In the following some example of marine climate services utilizing data from coastDat are described. We begin with a series of examples using mostly historical climate information. The section is concluded with two examples concentrating on long-term projections.

Applications using historical climate information

Naval architecture

Modern ship design is synonymous with tailor-made, customer oriented ship design. Thus, any new vessel should optimally fit it's designated tasks. Apart from questions related to cargo capacity and deck layout, also the hydrodynamic abilities of the new vessel require special attention. This includes, for example, an optimization with respect to speed/power, the design of a highly efficient propeller, or design modifications to warrant good maneuvering and sea-keeping abilities. The latter heavily depends on the wave climate in the region the vessel is going to operate in. Historical information on the wave climate in the designated sea-area are therefore essential to simulate the behavior of the ship and to make assessments of the potential impact of any proposed design modification. For example, the combination of the simulated ship motions within a given sea state together with the probability of its occurrence allows an evaluation of the motion behavior and the identification of critical aspects related to, e.g., passenger comfort, safety against capsizing or special operation scenarios such as helicopter landings.

Typically, the wave climate information needed for these types of assessment are unavailable for many marine areas. Data from the met-ocean hindcasts described in the previous section were therefore integrated into the operational design system at the Flensburger Schiffbau Gesellschaft (FSG), a shipyard situated in Flensburg, Germany. The data are typically used in the form of scatter diagrams showing the long-term distribution of expected wave height/wave length combinations. Commonly the most frequent combinations of wave height and wave length are used first to simulate the expected ship motions. Subsequently, design modifications or the influence of integrating additional roll-damping devices may be tested.

Further, the behavior of the vessel in extreme situations can be assessed using wave climate extremes. As an example, Figure 2 shows one of the recent FSG RoPax ferry

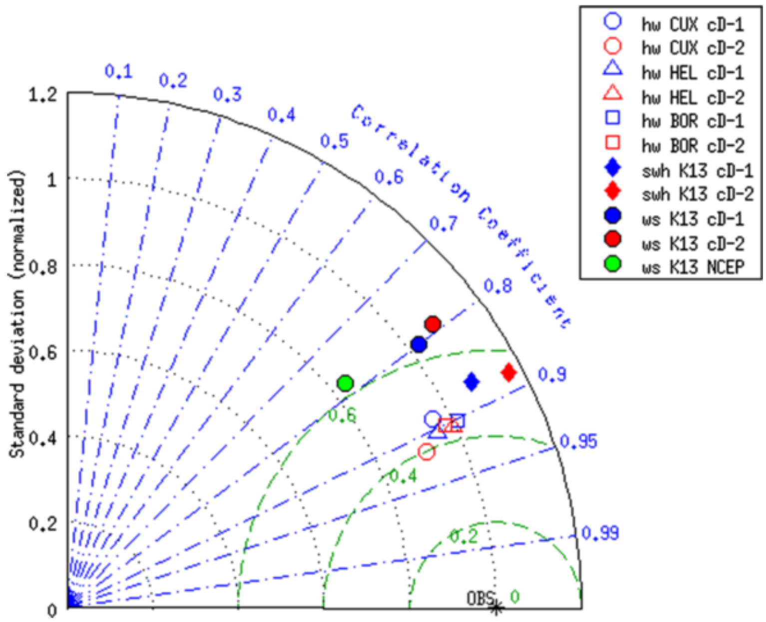

Figure 1 Validation statistics. Taylor diagram for wind speed (filled circles) and significant wave height (filled diamonds) at platform K13 as well as for high water levels at Cuxhaven (open circles), Helgoland (open triangles) and Borkum (open squares) for 1980-1999 comparing results from coastDat-1 (blue) and coastDat-2 (red) with observations. For wind speed, also a comparison with the driving global NCEP reanalysis is shown (green). The black star denotes the location of a data set that would perfectly match observations.

Figure 2 Design of the Caledonian MacBrayne. The figure shows one of the recent FSG RoPax ferry designs developed for the Scottish route between Ullapool and Stornoway. The bow door can be inferred by the white lines on the right hand side of the figure.

designs developed for the Scottish route between Ullapool and Stornoway. The vessel is equipped with a bow door to facilitate loading and unloading of cars and trailers. Accidents, like the one of the MV Estonia indicate that dynamic loads on such bow structures can be quite significant in severe sea conditions. Thus, a direct dimensioning of the bow-door was applied by FSG. The design procedure consists of the following steps: First sea-keeping simulations were performed using historical extreme wave climate information from the coastDat-2 data base. Subsequently, from each simulation critical immersion events of the bow with respect to large impact velocities were obtained and the probability distribution of the observed impact velocities was determined. Next, in combination with the probability of occurrence of the sea state (derived from the coastDat-2 data base) and the encounter angle, a probability level of each immersion event was obtained to estimate how often such a situation could be expected during the lifetime of the vessel. Afterwards, the motion sequences from selected immersion events are used to compute the wave induced loads acting on the bow with the help of a viscous-flow simulation. These loads can finally be used to determine the stresses and possible deformations with a finite-element method. As a result, the dimensioning of the steel structure could be adapted according to the expected loads during the design phase of the vessel. Figure 3 illustrates exemplarily the results from this procedure. On the upper panel, the bow of the vessel immerses into a large wave. The lower panel illustrates the corresponding pressure distribution on the bow door.

Renewable energies

Europe's energy system is in a process of fundamental transition from a mainly fossil fuel based to a low carbon energy system. Suggestions how future electricity systems mainly based on renewable energies may look like differ substantially (e.g. FVEE 2010; Klaus et al. 2010; German Advisory Council on the Environment 2014; Hohmeier and Bohm 2014; Pahle et al. 2012). However, despite their differences, the backbone of almost all proposed future systems are renewable energy sources, especially the weather dependent solar, wind and water power. The latter are often referred to as variable renewable energies (VRE). Due to their weather dependence not only the sources of energy supply but also the electricity feed-in characteristic will change. Due to the complexity and interrelations of the electricity system, computer models are required to simulate effects of different combinations of sources, flexibility options and grid infrastructure. So far, a wealth of energy system models exist (Connolly et al. 2010) all of them requiring climate information, in particular weather sequences at high temporal and spatial detail and their probability of occurrence that are often unavailable. To address this shortcoming, the Renewable Energy Pathways Simulation System (renpass) developed at the University of Flensburg utilizes historical climate information from the coastDat-2 data base. The model simulates different transition pathways between the present and future energy systems. To do so, first solar and wind feed-in are calculated on an hourly basis based on coastDat-2. In the simulation electricity feed-in of solar, wind and run-of-river power is then used first to supply the electricity demand, since they are not associated with any fuel costs. The remaining so-called residual load is then supplied by dispatchable power plants. If, for any specific time, the supply provided by VRE exceeds the demand it is either stored or remains unused. In a system with high shares of VRE, their feed-in characteristics determine the flexibility required of the other components of the system. Thus, modeling the renewable feed-in time series in a realistic way is an essential prerequisite to address any question regarding the efficiency of future systems. For this purpose, high resolution climate information such as provided by coastDat-2 is urgently needed. More information about the model and example of application can be found in Wiese et al. (2014) and Wiese (2014).

Offshore wind

Increasing the shares from renewable energies is a central target of the German Government. Offshore wind energy plays a crucial role within this concept. In the German Exclusive Economic Zone challenges associated with water depth and increasing distances to the shore make the development of profitable projects particularly difficult. In the following we demonstrate, by means of two examples, how historical climate information may support decision making during the project development phase.

Offshore wind logistics The serial installation of wind farms consisting of 90 wind turbines takes several months or more. Thus, offshore installation works have to take place even in the rough autumn and winter seasons when wind and wave conditions bear one of the most prominent risks for the delay in the installation of offshore wind farms. For realistic project scheduling it is essential to include realistic assessments of the probability of the weather downtime which is typically based on data bases such as coastDat-2. In the following the procedure is described to some extent.

Usually, jack-up vessels are utilized that travel to the offshore location carrying wind turbine components weighing up to 1000 t on the deck. At the offshore location the installation vessels elevate their hull out of the water (jack-up) after a period of preloading to achieve a consolidation of the soil under the legs to have a firm stance. Installation works are carried out by the main crane either by sea bed lifting and piling of foundation structures or by elevating

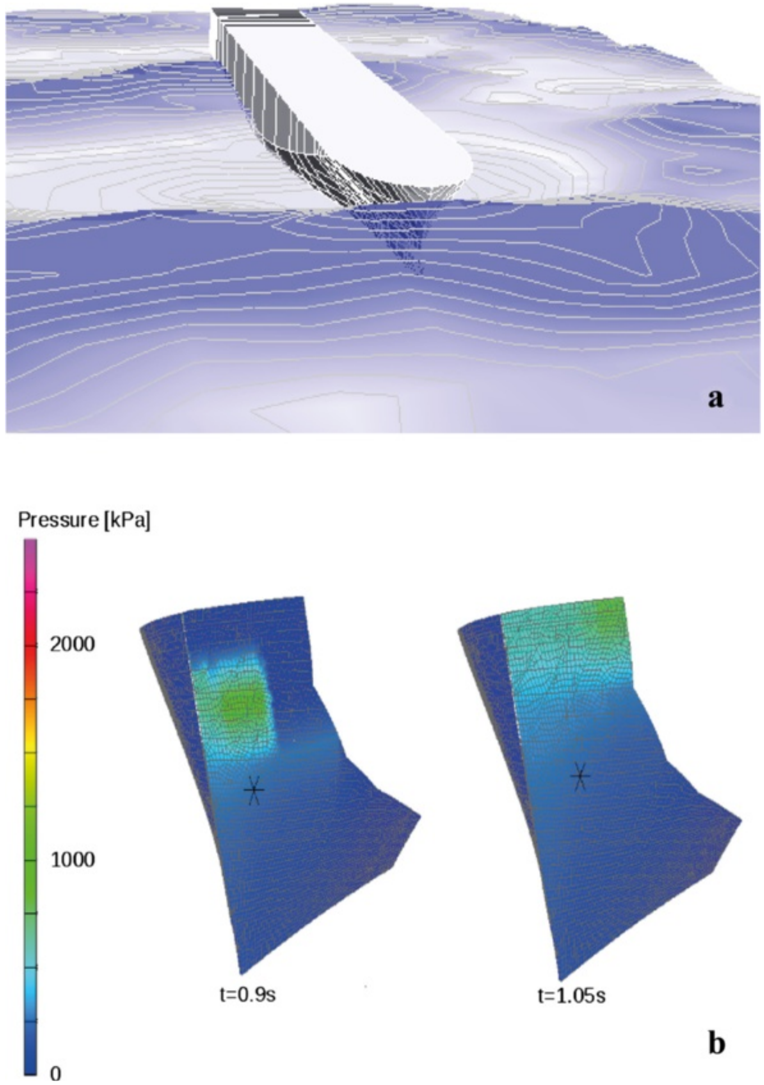

Figure 3 Illustration of a severe immersion event. (a) Visualization of a simulation where the bow of the vessel immerses into a large wave; **(b)** corresponding pressures on the bow door in kPa as indicated in the color bar.

tower sections, nacelles, and blades in large heights. Each operation requires a so-called weather window; that is, a period of time in which operation dependent thresholds for wind speed and significant wave height are not exceeded. The limiting conditions have to be determined for each operation separately. Typical limits are shown in Table 1.

Furthermore, an escape procedure needs to be established in case survival conditions at the installation vessel (corresponding to the once-in-fifty-years wind speed in combination with the once-in-fifty-years wave height) are exceeded. If smaller vessels are chosen or if the soil conditions require so, lower survival criteria may be imperative.

In order to schedule offshore installation projects, the operational limits need to be combined with historical climate information at the site that are often unavailable. Therefore, time series of wind and waves derived from data bases such as coastDat are frequently used. Using these data, logistic simulations may be carried out many times depending on season providing corresponding frequency distributions which may subsequently be used in detailed development of the project. Figure 4 shows an example from such simulations for an installation sequence of 90 tripod foundations in the North Sea starting on 26 October. The simulation has been executed 48 times showing that on average the installation will take about 427 days while the minimum/maximum time needed in the simulation were 335 days and 511 days respectively. Such statistics of expected project durations represent essential factors not only for cost estimation,

Table 1 Typical values of limiting weather conditions for offshore wind installations

Operation	Weather window [h]	Significant wave height [m]	Wind speed [ms^{-1}]	Duration [h]
Loading at port	23	-	14	23
Transit offshore	18	2.5	18	12
Infield transit and jack up	18	2	18	3
Installation	3 × 10	-	14	49
Jack down	15	2	18	2
Transit to port	15	2.5	18	11

project risk management, and logistics planning but also for developing improvements of installation methods and design of future installation vessels.

EEG remuneration The Renewable Energies Act (EEG) is the central instrument for the development of renewable electricity production in Germany. It regulates the remuneration by sector; that is, the power produced by renewable energies will be rewarded according fixed feed-in rates. For offshore wind farms going into operation before 2020, the EEG 2014 currently provides for two different remuneration models (Foundation Offshore-Windenergie 2014). Roughly speaking, the first model allows the operator to claim 15.4 Cent/kWh over an initial period of at least 12 years. The second so-called optional acceleration model plans for remuneration of 19.4 Cent/kWh for an initial period of 8 years. After the initial period has passed remuneration in both models decreases to 3.9 Cent/kWh. Further regulations depending on the water depth at the site and its distance from the coast may further modify these figures.

It may be interesting for any offshore wind farm operator to ask, which of the models would have been more successful in the past; that is, in producing higher revenues taking the historical wind climate at the site into account. Again such an estimate could be derived based on information contained in the coastDat-2 data base. Figure 5 shows an example in which the revenues for both remuneration models were computed for successive 20 year periods for an offshore array in the German Exclusive Economic Zone. It can be inferred that the optional acceleration model generally outperforms the standard model by providing, on average, 1.5% higher revenues. Effects caused by increasing distances from the coast and larger water depths were ignored in this simple example but may be accounted for in detailed calculations for specific wind farms. Similarly, other effects such as caused by weather dependent downtime or maintenance of the array should be considered in more realistic simulations.

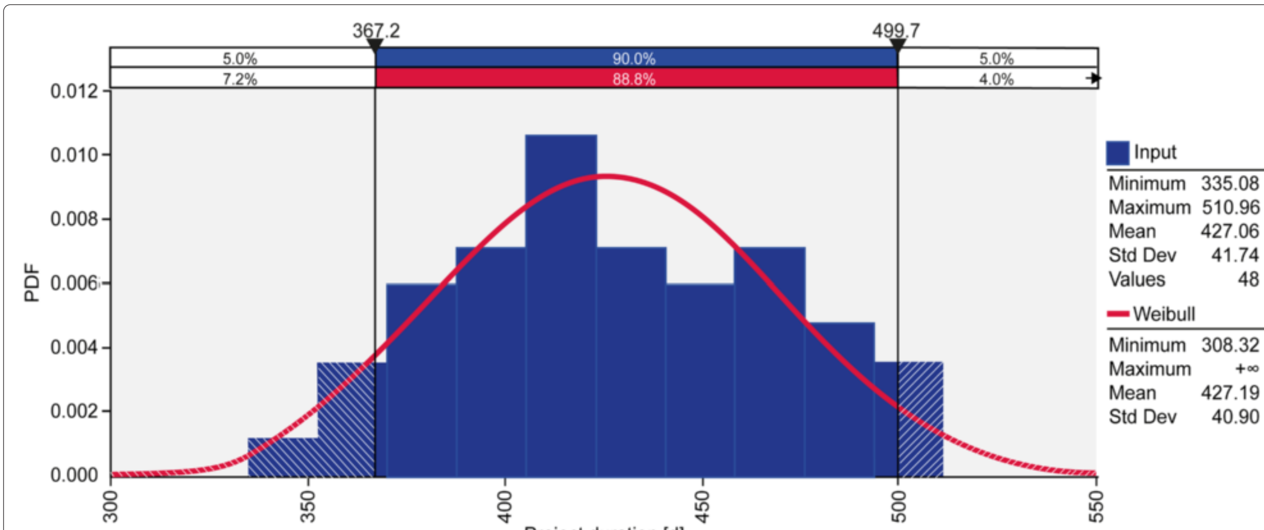

Figure 4 Frequency distribution of project duration. Shown is the distribution of project duration in days for an installation sequence of 90 tripod foundations in the North Sea starting on 26 October based on 48 simulations using corresponding weather sequences from coastDat-2. The frequency distribution and corresponding estimates of the 5 and 95 percentile are shown in blue. Similarly a fitted Weibull distribution is shown in red. Summary statistics for both distributions are indicated on the right.

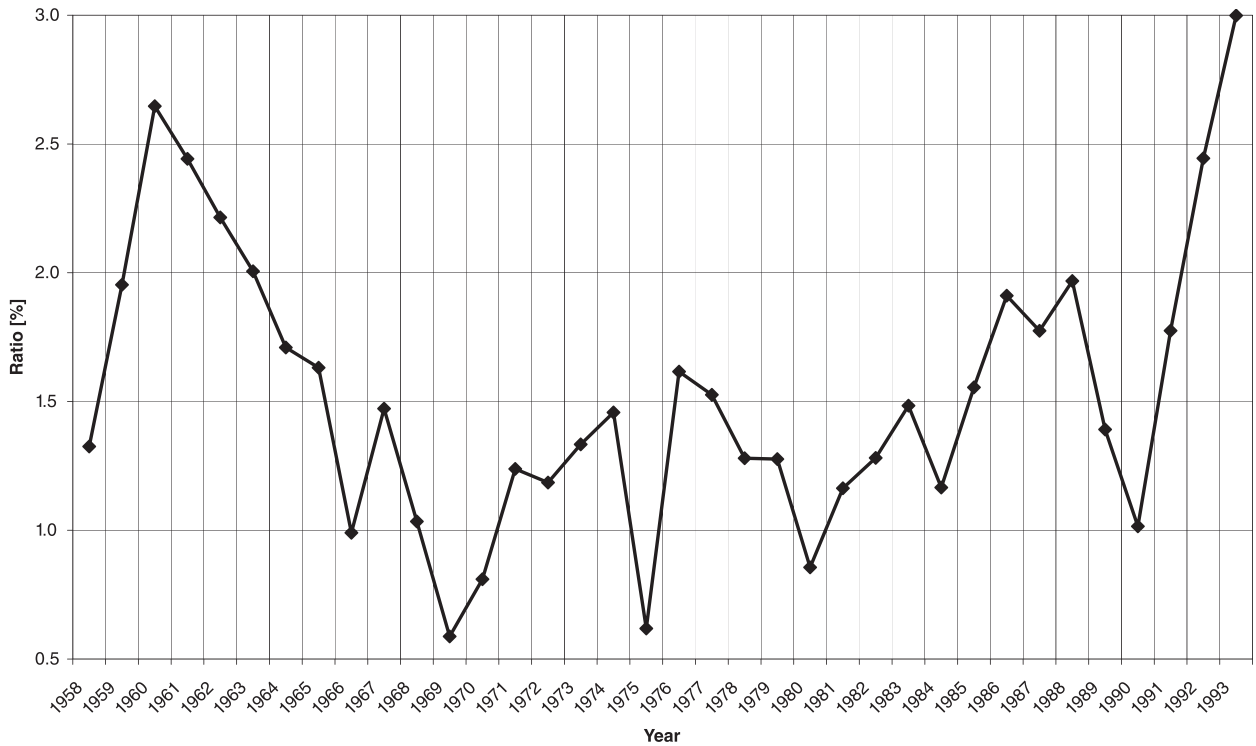

Figure 5 EEG remuneration. Ratio per year [%] between revenues from the acceleration model and the standard model based on coastDat-2. Shown are revenues for successive 20 year periods starting in the years indicated in figure.

Shipping emissions

International trade is mainly done by large ships. More than 90% of the global trade volume is transported on the world seas, thereby causing high emissions of pollutants into the atmosphere. In Europe, the biggest harbors are in the North Sea area. Consequently, North Sea coastal areas can be highly affected by emissions from shipping.

To investigate the effects of shipping emissions on air quality and deposition of pollutants in the North Sea, accurate emissions and information about transport and transformation of pollutants in the atmosphere are needed. In Aulinger et al. (2014) a comprehensive inventory for shipping emissions in the North Sea based on individual ship movements and detailed information about the ship's technical specifications was developed. The emissions are fed into the three-dimensional Eulerian chemistry transport model (CTM) CMAQ (Community Multiscale Air Quality model system) (Byun and Ching 1999). Moreover, a number of meteorological parameters have strong influence on the concentrations of the air pollutants calculated by CMAQ. The most important ones are wind speed and wind direction (horizontal transport), planetary boundary layer height (vertical mixing), temperature and radiation (gas phase chemistry), and cloud coverage (liquid phase and aerosol chemistry). Therefore, accurate information about the meteorological conditions in the model area is needed further as model input. CMAQ uses hourly input historical meteorological data derived from coastDat-2 as input data. The meteorological variables and the results of the CTM have been evaluated with good success in the European-American model intercomparison study AQMEII (Solazzo et al. 2012, 2013; Vautard et al. 2012).

The contribution of shipping on the concentrations of nitrogen oxides, nitrate aerosol particles and ozone was investigated for present conditions by Aulinger et al. (2014), future scenarios are analyzed in Matthias et al. (2014). Figure 6 shows the average NO_2 concentrations close to ground and the contribution of ship emissions to the modeled concentrations in the North Sea area as average of three winter months (December, January, February). The model results show that ships contribute 30-40% to the NO_2 concentration in the southern North Sea. At land, the contribution from ships decreases rapidly with distance from the coast, however in Denmark for example, ships contribute 10-30% to the NO_2 concentrations in the entire country.

Tidal basin water exchange and eutrophication levels

Evaluation of Wadden Sea monitoring data revealed regional differences in eutrophication status (Bakker et al. 1998). In general, eutrophication levels were highest in

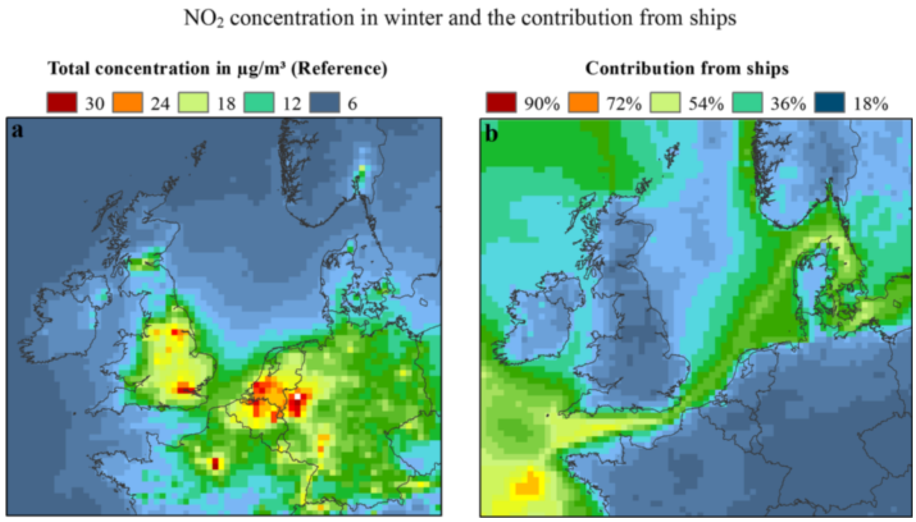

Figure 6 NO_2 concentration and contributions from ships. (a) Average NO_2 concentration in the North Sea area in winter in µg/m^3 and **(b)** the contribution from ships in %.

the southern Wadden Sea and lowest in the northern Wadden Sea due to differences in organic matter import from the North Sea and the size of the receiving tidal basin (van Beusekom et al. 2012). In addition to water mass exchange rates between the North Sea and the Wadden Sea exchange rates between tidal basins will also impact the eutrophication levels. In this context, the application of historical climate information from coastDat-2 covering the monitored period can help to investigate the prevailing hydrodynamic conditions that may be responsible for the observed differences.

The particle drift model PELETS (Callies et al. 2011) was applied to compute backward trajectories of particles entering three different tidal basins at the islands of Schiermonnikoog, Norderney and Wangerooge (Figure 7) using the historical hydrodynamic and atmospheric data from coastDat-2. The simulations were initialized at every high tide corresponding to approximately 700 simulations per year. As the simulations ran backward in time for 56 days, it is possible to calculate how long the water was in any tidal basin at depths below 2 m for each simulation before reaching one of the three target basins. The latter is referred to as Wadden Sea impact. It was found that the Wadden Sea impact is decreasing from west to east, similarly to regional differences in eutrophication. Mostly, water masses in the tidal basin at Schiermonnikoog have already stayed in other basins or even the same basin for a substantial amount of time (Figure 7).

Moreover, only little exchange between the Dutch and the German part of the Wadden Sea was found mainly due to the influence of the Ems estuary acting as a barrier for water exchange between these two regions. As a consequence, water exchange with the North Sea was found to be more dominant in the German tidal basins compared to those in the Netherlands. These findings can provide substantial aid for the interpretation of measurements of biogeochemical time series. For example, measurements performed during high tide can be alternately influenced by the North Sea or by other tidal basins. If sampled water masses have high Wadden Sea signals they can have high eutrophication levels, although the respective eutrophication processes took place in other tidal basins. Connecting measurements of eutrophication parameters with these simulations can help to further understand the Wadden Sea system as a continuum of interconnected tidal basins and the North Sea, influencing the biogeochemistry in each other.

Applications using long-term projections

Effects of climate change on coastal flood damage

In the re-insurance industry storm surges are a challenging peril. So far the storm surge insurance coverage is sporadic in most of the north-western European countries. The lack of systematic insurance coverage put a strain on affordability for the small number of highly exposed risks. Additionally, present day coasts are well protected and the absence of recent storm events with high damage impact limits the statistics necessary to establish the insurance portfolio as well as awareness of the potential risks. Moreover, possible changes in the future atmospheric and sea level conditions increase the uncertainty of the exposure extension and magnitude. To partially address these issues coastDat was used in the joint Swiss Reinsurance Company (Swiss Re) and Bern University coastal hazard assessment study (Gaslikova et al. 2011).

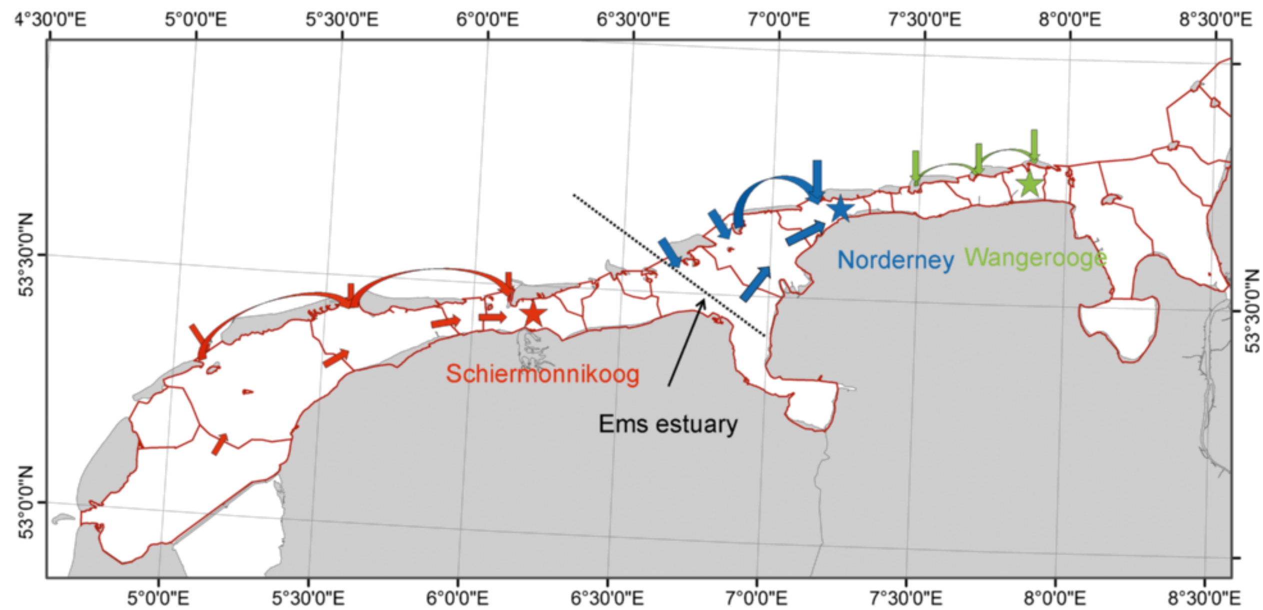

Figure 7 Major transport pathways. The arrows indicate the major pathways of particles over 56 days before reaching the tidal basins of Schiermonnigkoog (red), Norderney (blue), and Wangerooge (green). The location of the tidal basins is indicated by the stars.

The coastDat water level for the reconstructed past and projected future scenarios was used to establish the probabilistic storm surge loss model and to study the possible future implications of the changing storm surge climatology and rising sea level on the coastal flood damage in the North Sea region. The study focused on a number of countries which have considerable coastal areas potentially exposed to the storms. The modeling approach combined the storm surge events with different sea level rise estimates and various tidal phases to assess the hazard potential at the coastline. This further was transferred into the inland flood damage estimates taking into account present day coastal protection information and failure probabilities, land elevation and potentially insurable property distribution.

The regular spatial and temporal coverage of the long-term coastDat data allowed the selection of quasi-historical storm surge event set. Based on this, the hazard set of equally possible, physically plausible but not happened in reality surge events was generated for the present and future climate scenarios. The probabilities of each event were estimated for 200 locations along the North Sea coasts. The hazard set was further expanded by considering 0.5 m and 1 m sea level rise (SLR) scenarios. The constructed hazard sets were further used for the probabilistic dam failure estimates, based on the crest height and facility safety data. Consequently, the extension and depth of inland flooded areas were estimated based on a digital elevation model with 90 m spatial resolution. The associated property damage was transferred in annual expected losses (AEL) and aggregated country-wise.

Figure 8 shows an AEL change for different future scenarios with respect to present-day conditions. The results from scenarios were combined and the error bars show the uncertainties associated with each scenario. In general, an increase of AEL was found for all countries and all future development scenarios. Changes vary between 5% and 200%. For some countries (e.g., Germany, UK) the changes of the storm surge climatology according to the selected scenarios have comparable effect on the insurable losses as the 0.5 m SLR under the present-day atmospheric conditions. The combinations of those, thus, almost double the estimated AEL. The expected losses for other countries, e.g. the Netherlands and Belgium, show almost no response on the changed climate conditions. This can be partially explained by the more frequent south-westerly rather than north-westerly winds and their intensification in the considered future development scenarios described e.g. in Sterl et al. (2009), which affects mainly the eastern coast of the North Sea. The disproportional growth of the loss potential for the sea level rise scenarios reflects the non-linearity in the coastal protection facilities response to the considerably higher loads. The coastal defenses are designed to efficiently protect against the present day exposure and to have a safety margin for the case of the hazard intensification. However, when the hazard increases substantially, the today's coastal protection is exhausting its initial design

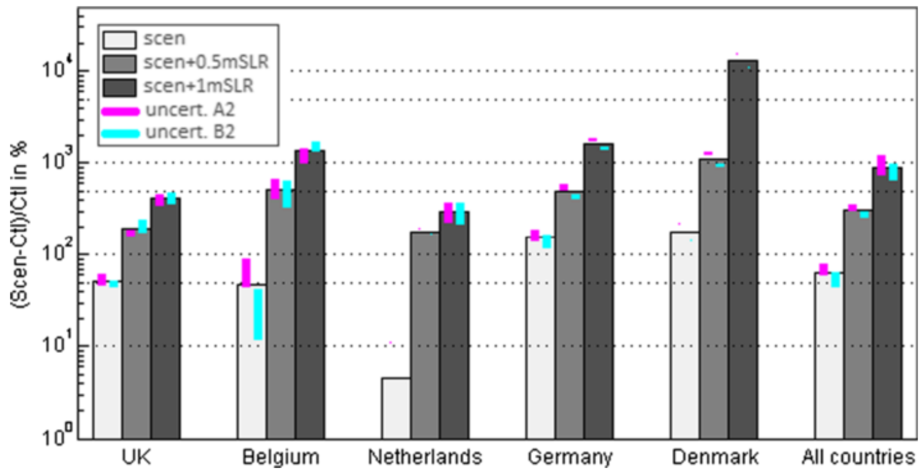

Figure 8 Expected annual losses. Increase of annual expected losses for future scenarios with respect to present day conditions in percent. The bars show the mean value of the A2 and B2 estimates. The error bars show the uncertainty for each scenario around the corresponding mean.

capability resulting in abrupt growth of the loss potential, as can be seen to some extent for all countries by SLR scenarios. Altogether, these results demonstrate a necessity to consider the storm surge statistics along with the SLR estimates for more accurate flood impact assessments.

The need for coastal protection

The Northern German Climate Office maintains a long-term stakeholder dialog regarding regional climate change in Northern Germany (von Storch and Meinke 2008). Based on that experience, an interactive web tool available at the Norddeutsches Klimabüro (2014) was developed that provides an interactive map of the areas protected by coastal defense along the German coast line for three different situations: normal high tides and during storm surge conditions under present and future climate conditions. Historical climate information and corresponding long-term projections necessary to develop the data were derived from coastDat.

Figure 9 shows a screen shot from the web tool. It can be inferred that there is a substantial area which is already nowadays successfully protected during normal high tides (7,500 km^2, 4.5 million inhabitants). When the effects from storm surges are added, the area at risk substantially increases. Here these effects were simulated using water levels from the destructive North Sea storm surge occurring on 16-17 February 1962 along the German North Sea coast based on coastDat-2. The region nowadays protected from such an event corresponds to about 11,000 km^2 including 5.3 million inhabitants.

These water levels may further increase in the course of anthropogenic climate change. The increase can be primarily due to two factors: an increase in mean sea level increasing the baseline upon which a storm surge may act and a change in the storm surge climate itself. Both effects were additionally accounted for in the web tool by including a maximum mean sea level rise of 80 cm until 2100 as suggested by (Bindoff et al. 2007) in the 4th Assessment Report of the Intergovernmental Panel on Climate Change and a maximum wind-induced increase in storm surge water levels of 30 cm until 2100 (Gaslikova et al. 2013). This increase only threatens a small additional area. In total it covers about 12,000 km^2 (compared to the 11,000 km^2 for the 1962 storm surge) which today is inhabited by roughly 5.4 million people. However, in this case coastal defense measures need to be adapted to ensure the same level of safety as today.

Summary and discussion

A number of marine climate services based on the met-ocean coastDat data base was presented and discussed. The data base consists of a series of consistent regional met-ocean hindcasts that are complemented with corresponding long-term projections. Data from coastDat were successfully used for both, research and more economically oriented questions sharing similar data needs. Both require long, consistent and homogeneous data sets to derive statistics such as the mean, the variability or the extremes of marine environmental conditions and their long-term changes. Frequently such data are unavailable and the coastDat approach described here provides one possibility to address such issues.

As of mid-2014, there were about 80 registered users of the coastDat data base with about 45% of them coming from the industrial sector while about 40% are from academic and 15% from authorities. Added values derived are manifold. In this paper examples from naval architecture, renewable energies and offshore wind farming, shipping emissions, tidal basin water exchange and eutrophication, and coastal flooding and risks were disccussed.

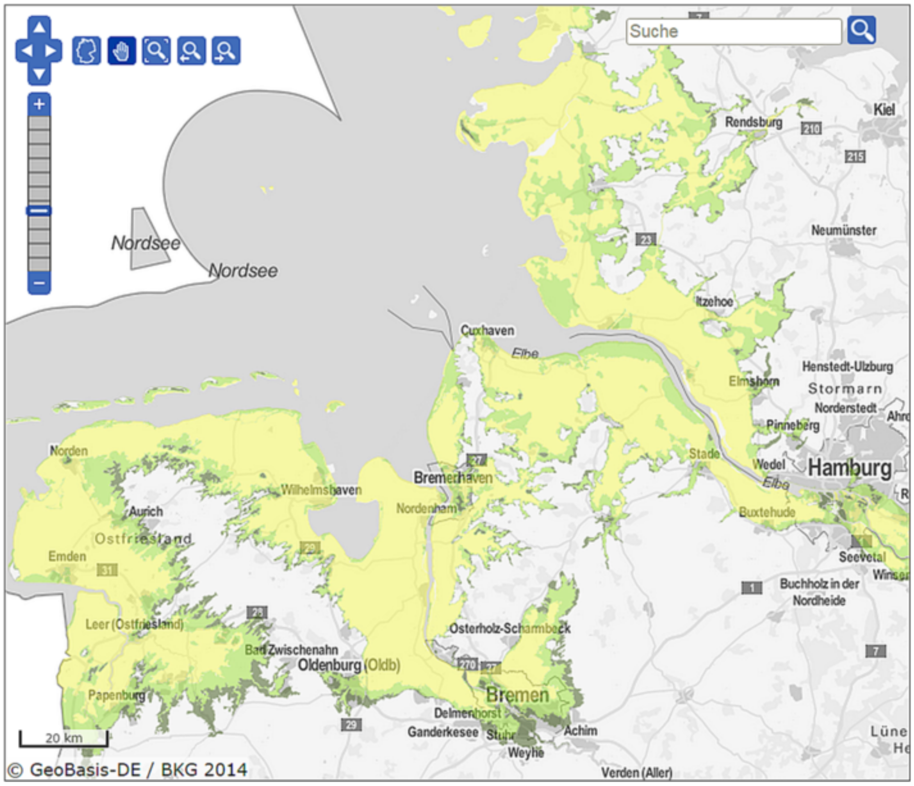

Figure 9 Areas along the German North Sea coast protected from storm surges. Based on coastDat-2 data the map shows areas that are protected by coastal defenses during twice daily normal high tides (yellow), present day storm surges (based on the data from the storm surge 16-17 February 1962, light green) and future storm surge conditions (additional 1.1 m on top of present day conditions accounting for the effects of rising mean sea levels and changing storm surge climate, dark green).

Following the terminology provided in Vaughan and Dessai (2014), we may refer to these as examples of marine climate services; that is, the generation, the provision and the contextualization of information derived from climate research for decision making at all levels. Our examples comprise the generation and supply of climate information by climate providers (the coastDat data base) as well as employing the information and knowledge for very specific decision making processes by the climate service users while contextualization was not considered.

Based on our experiences from the interaction between climate service providers and users two major conclusions can be drawn: (i) Marine areas are often data sparse regions with insufficient data coverage to provide the basis for reliable statistics often needed for any offshore activity. Met-ocean hindcasts and long-term projections such as provided for example by coastDat are often an appropriate alternative in case observational data are insufficient. (ii) Historical climate information is often as important as long-term projections. While scenarios are mostly important for sectors planning for long time horizons (e.g. coastal protection, policy regulations), hindcasts and historical data are more often requested from sectors planning for shorter periods or operating in data sparse regions (e.g. offshore wind, naval architecture).

This need for seamless climate information across time scales is also clearly emphasized in the implementation plan of the Global Framework for Climate Services (GFCS) (GFCS 2014a). In particular, in the annex focusing on the implementation of the research, modeling, and prediction component of the GFCS the need for reliable and comprehensive information on past and current climate conditions including, statistical distributions of relevant meteorological and oceanographic variables such as wind, wind waves, and storm surges is strongly highlighted (GFCS 2014b). So far such aspects are frequently unaccounted for from climate service perspectives and we proposed that their value may be substantially enhanced taking shorter time scales and natural climate variability into account.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
RW conceived the manuscript and was responsible for drafting and writing. BG, LG, RW and NG provided the validation of the meteorological-oceanographic model data. LG further contributed the analysis of effects of climate change on

coastal flood damage. KWK contributed the section on naval architecture, VM the section on shipping emissions, FS and MH the section on offshore wind logistics, PB and EM the section on EEG remuneration, FW the section on renewable energies, FS the section on tracer studies, and MM and IM the section on coastal flood protection. All authors revised and approved the final version.

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