Reconstructions of marine environmental conditions and scenarios for future changes

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1. Introduction

Assessment and management of the impacts of climate change on the maritime industry will become a major issue in the following years. In order to assess and to cope with such impacts profound knowledge is required on how marine environmental conditions have changed in the recent past and how they may evolve in the future. This particularly is important for weather related marine hazards such as wind storms, extreme sea states or storm surges.

Unfortunately over the oceans homogeneous long-term observations that allow for an assessment of recent changes are sparse. Also the spatial coverage (observation density) is usually insufficient. The problem can be addressed using quasi-realistic dynamical models of the marine environment or parts of it. In this context the major benefit from using models is that they can be applied to interpolate between and extrapolate observations that are sparsely distributed in space and time or to derive information on quantities that have not been measured directly. In more advanced studies data assimilation techniques are used that blend in an optimal way observations and dynamical models. This way high-resolution gridded reconstructions (also referred to as hindcasts) of past environmental conditions can be obtained. In turn, such reconstructions may be used to develop climatologies (also of extreme events) that may be used to assess recent changes or the natural variability against which potential future changes have to be assessed.

Models can also be used to estimate future changes of the marine environment. In the context of anthropogenic climate change this is usually provided in forms of scenarios. In scenario simulations the response of a model to a given treatment (here changing greenhouse gas concentrations) is evaluated. As the future development of greenhouse gas concentrations is associated with a high degree of uncertainty (related to uncertainties in socio-economic development) different scenarios are derived that are in themselves consistent and plausible but not necessarily likely. It is therefore essential to consider a wide range of scenarios in order to determine the response of the system to changing greenhouse gas concentrations and to separate the more robust signals from the less certain ones. Hindcasts may be used later to assess whether or not the projected future signals deviate from the recently observed natural variability (so called detection).

In addition high-resolution gridded data from scenario simulations and dynamical reconstructions of past conditions offer a superior test-bed for assessing impacts and effects on the maritime industry and for developing and testing adaptation strategies. In the following we briefly sketch and illustrate the situation for extra-tropical wind storms, extreme sea states and storm surges. Our discussion focuses on an example for the North Sea but we also briefly illustrate the skills and the limitations of the approach.

2. Present situation

2.1 Reconstructions

A major obstacle in analysing long-term changes is represented by the often incomplete and insufficient spatial coverage of the observational record. In a process called *analysis* such observations may be blended with dynamical models in order to obtain a gridded and *dynamically consistent*[1] data set. Initially such analyses have been used to derive gridded atmospheric data from which weather forecast models have been initialised to provide forecasts. Because of their consistency and gridded nature these analyses have later been used also to derive climatologies and to assess long-term climatic trends. For these purposes however, the analyses had originally not been designed. As models and analysis techniques have been constantly improving in order to improve weather forecasting, such changes in the analysis system introduced artificial signals (so called in-

[1] Here *consistency* refers to the fact that the different variables are in agreement according to the principal physical laws, i.e. observational errors have been reduced.

homogeneities) that may later have been interpreted as climate trends or detected as changes. The situation was improved significantly when major re-analysis projects were initiated a few years ago. In these projects the old weather data were re-processed using frozen state-of-the-art dynamical models and data assimilation schemes thereby significantly reducing in-homogeneities present in the weather analyses. Presently the longest available weather re-analyses are those produced by the ECMWF (Uppala et al. 2005) and by NCEP/NCAR (Kalnay et al. 1996). The latter meanwhile covers a period from 1948-present providing a rather long record for assessing long-term weather changes and variability. An examples of assessing storm activity from such data is provided e.g. in Bengtsson et al. (2006).

While the situation has improved with the availability of these global weather reanalyses their spatial coverage (about 210 x 210 km in the case of the NCEP/NCAR re-analysis) remains limited for coastal or continual shelf sea applications and smaller scale or intense synoptic features such as polar lows or tropical cyclones may not be adequately resolved (e.g. Zahn et al. 2007). Further, information on marine conditions such as sea states, storm surges, ocean temperatures, salinity etc. are usually not available (an exception is the ECMWF ERA-40 re-analysis, for which sea states are available). The problem can be addressed with a chain of dynamical regional models in combination with observational data. In the following an example is provided for the North Sea.

2.2 Reconstruction of recent meteo-marine changes in the North Sea

A regional atmosphere model with focus on Europe and adjacent seas was driven by the global NCEP/NCAR re-analysis in combination with some simple data assimilation (Feser et al. 2001) in order to obtain a better representation of near-surface marine wind fields (von Storch et al. 2000). From this regional simulation, near-surface marine wind-fields and other parameters have been stored hourly. They have been used subsequently to drive storm surge and wind wave models for the North Sea (Figure 1). This way a high-resolution and consistent meteo-marine reconstruction for the past 50 years has been generated. Here *consistency* refers to the fact that the output fields from the different models (wind, waves and storm surges) are in physical agreement, a fact that is frequently ignored e.g., when waves and surges from different sources are analysed jointly.

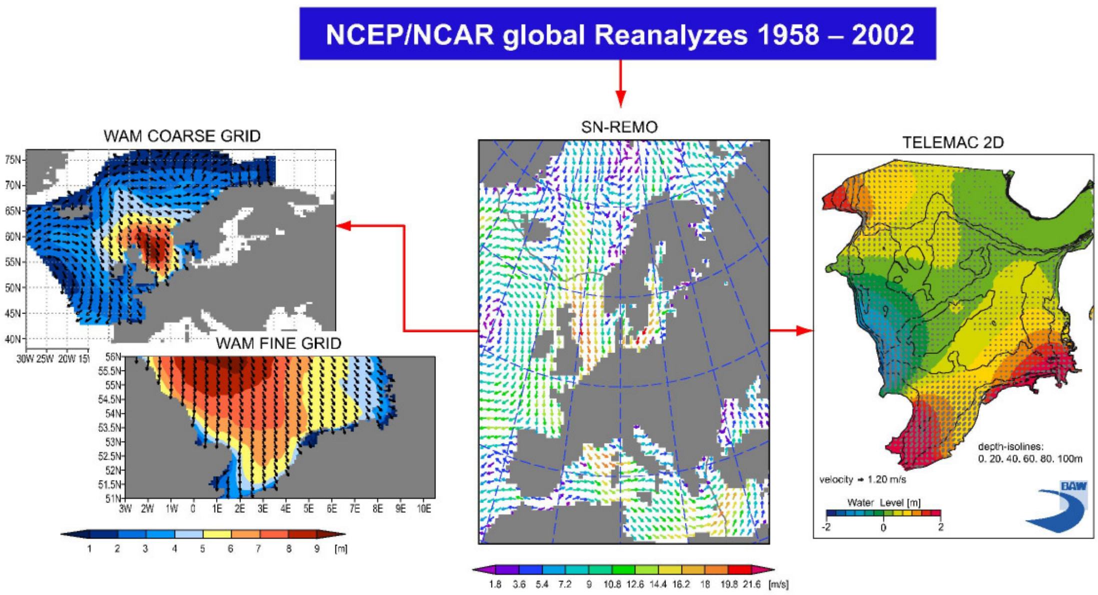

Fig. 1: Layout of the consistent meteo-marine hindcast for the North Sea. From the regional atmosphere hindcast (middle), hourly wind fields were used to force a tide-surge (right) and a wave model hindcast (left). The tide-surge model was integrated on an unstructured grid with typical resolutions of about 5–10 km in the open North Sea and about 100 m near the coast and the estuaries. The figure shows an example of consistent meteo-marine conditions obtained from the hindcast for 12 UTC on 21 February 1993. Middle: Near-surface (10-m height) marine wind fields in ms^{-1} and corresponding wind direction obtained from the regional atmospheric reconstruction. Left: Corresponding significant wave height fields in m and mean wave direction from the coarse and the fine grid wave model hindcast. Right Tide-surge levels in m from the corresponding tide-surge hindcast (from Weisse and Günther 2007).

The capabilities and limitations of the hindcast in simulating changing *statistics* of meteo-marine conditions in the North Sea have been demonstrated in a number of studies (e.g., Weisse et al. 2005; Weisse and Plüß 2006; Weisse and Günther 2007). An illustrative example is provided in Figure 2. It shows a time series of significant wave height for a three months period at a location in the Southern North Sea. Generally, a rather good agreement between measurements and hindcast can be inferred. However, closer inspection reveals that individual extreme events (such as those after 16 February and around 01 March) may or may not be reproduced by the hindcast. Regardless of this, when the *statistics* of such events are considered, the situation is much better as these are reproduced within error bounds (Table 1). In other words, while such multi-decadal reconstructions provide high-resolution meteo-marine data sets and are perfectly suited to study the *statistics* of events, their variability and their-long term changes, they are not *necessarily* useful to study individual extreme events as these may or may not be reproduced by the hindcast.

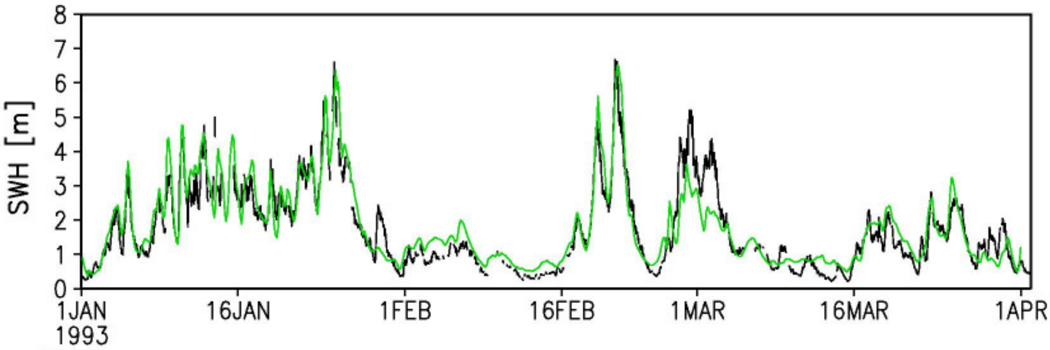

Fig. 2: Time series of significant wave height [m] at K13 for a three months period 01 January 1993–31 March 1993; observations, black; model results, green (from Weisse and Günther 2007).

		Wind [m/s]					
		Hipocas			**Observed**		
	Years	x_r^{90}	x_r	x_r^{90}	x_r^{90}	x_r	x_r^{90}
K13	**2**	24.38	25.17	25.96	24.05	25.21	26.37
	5	25.86	27.28	28.70	25.75	27.64	29.53
	25	28.44	31.33	34.22	28.09	32.77	37.45
EUR	**2**	22.50	23.16	23.82	23.16	24.03	24.90
	5	23.76	24.82	25.88	24.33	25.94	27.55
	25	25.67	28.00	30.33	26.43	29.75	33.07
SON	**2**	23.29	24.15	25.01	23.11	24.03	24.95
	5	24.89	26.32	27.75	24.15	25.94	27.73
	25	26.68	30.70	34.72	26.42	29.75	33.08

Table 1: Comparison of 2, 5, and 25-year return values (x_r) estimated from hindcast (left column) and observed (right column) wind speed at K13, EUR, and SON (three stations in the Southern North Sea). Additionally shown is the 90% confidence interval x^{90}_r obtained from 1,000 Monte Carlo simulations each (after Weisse and Günther 2007).

2.3 Scenarios of future meteo-marine conditions in the North Sea

Scenarios of future wind conditions have been derived by several groups. The most useful possibly is the set of simulations with the model of the Swedish Rossby Centre, which features not only an atmospheric component but also lakes and a dynamical description of the Baltic Sea (Räisänen et al. 2004). This model was run with boundary conditions provided by two global climate models; also, the effects of two different emission scenarios were simulated. This way not only climate change induced signals, but also model uncertainties and uncertainties caused by different assumptions about the future economic developments (greenhouse gas emission scenarios) could be investigated. From these simulations, near-surface wind and atmospheric pressure fields have been used to drive regional storm surge and ocean wave models and to derive projections of future storm surge and sea state extremes for the North Sea.

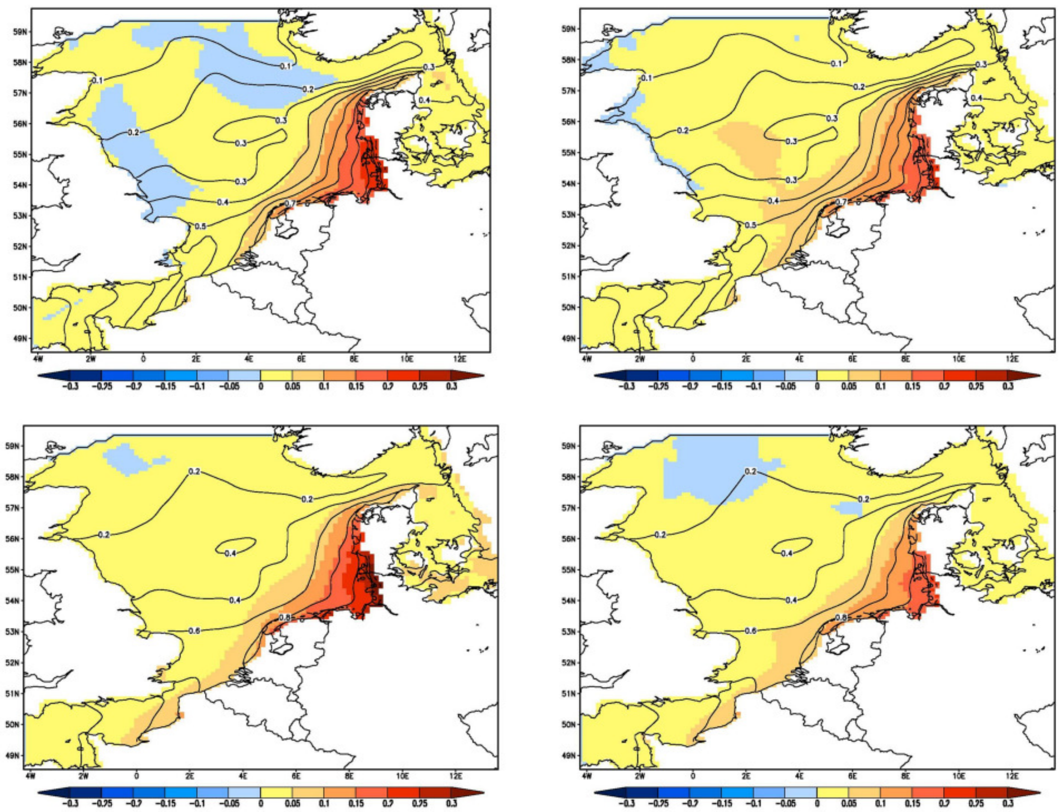

Fig. 3: Simulated changes in annual maximum storm surge height in m for the North See. Changes are representative for the period 2071-2100 vs. today. Changes are obtained using two different state-of-the-art climate models (upper and lower row) and under different greenhouse gas forcing (lower column pessimistic scenario [A2], right column optimistic scenario [B2]) (after Woth et al. 2006).

Figure 3 shows an example of climate change signals (here annual maximum storm surges) and uncertainties obtained from such simulations. The differences between the two rows represent differences due to the choice of different state-of-the-art climate models (model uncertainties) while the differences between the columns represent the uncertainty due to different possible global economic developments in the future. For the case of extreme storm surges in the North Sea it can be inferred that, although the patterns differ in detail, a robust signal (namely an increase of extreme events in the German Bight) emerges despite the existing uncertainties. Note that signals for other variables and/or areas (e.g. sea states in the North Sea) may be less robust.

2.4 North Sea Storm Climate and Related Marine Hazards

In the following we briefly review, for the larger North Sea area, the knowledge on how wind storms and related marine hazards have changed during the previous decades and how they may develop in the future in the course of anthropogenic climate change. The analysis is based on both, analysis of homogeneous observational proxy data and results from dynamical models.

Storm activity over the northeast Atlantic and northern Europe increased for a few decades after the 1960s following an earlier downward trend that started in about 1900. When longer periods have been considered (such as by analyzing air pressure readings at stations in Sweden since about 1800), no significant changes have been found (e.g. Alexandersson et al. 2000; Bärring and von Storch 2004).

Regionally detailed reconstructions of near-surface winds since 1958 (Feser et al. 2001) have been used to run dynamical models of water levels, currents, and ocean waves in the North Sea (Weisse and Plüß 2006, Weisse and Günther 2007). Changes were found to be consistent with the changes of storm activity; namely, a general increase since 1960 to the mid-1990s and thereafter a decline. Scenarios prepared by a chain of assumed emission scenarios, and global and regional climate models point to a future of slightly more violent storminess, storm surges, and waves in the North Sea. For the end of the century, an intensification of up to 10% is envisaged, mostly independently of the emission scenario used. When a linear increase is assumed (resulting in an overestimation of the effect in the first decades) an increase of 1% per decade can be inferred. Compared to the natural variability this comprises a rather weak signal. It is therefore natural that presently no anthropogenic signal in strong winds can be detected. When not only the change in windiness but also the thermal expansion of the ocean is considered, increases of 20–30 cm by 2030 and of 50 cm by 2085 appear to be reasonable guesses for future extreme water levels along the German Bight coastline (Woth et al. 2006).

3. Likely future developments

The approach presented for the North Sea has been implemented for both NCEP/NCAR reanalysis and a series of climate change scenarios. Data have been combined into the coastDat[2] data set. To our knowledge this presently comprises the most comprehensive and consistent data set that has been applied for large variety of maritime applications. Examples include applications of coastDat in ship design, oil risk modelling and assessment, and the construction and operation of offshore wind farms. The situation is less matured for other marine areas where such data are either existing only partially or do not exist at all. The approach presented has potentials for applications in other areas. Presently efforts are underway to implement the approach for the Baltic Sea. Similarly, feasibility studies are underway for polar (e.g. Zahn et al. 2007) and tropical regions, in particular for SE Asia (Feser pers. comm.). The latter comprise an assessment to which degree the statistics of polar lows and tropical storms can be reproduced.

4. Recommendations

The approach presented provides a superior test-bed to develop adaptation strategies to manage the impacts of climate change on the maritime industry and to test the robustness of proposed measures. So far, this potential has only been partially exploited. An essential bottleneck is the lack of regionally detailed reconstructions and scenarios for water temperatures and salinities where major efforts should be placed to improve the situation. The similar holds for the estimation of regional deviations from global sea level rise. A major disadvantage of the existing sea state and storm surge projections is that they are presently available only for the time frame 2070-2100. In order to cope with the earlier impacts transient simulations that continuously cover the time from present until 2100 are needed.

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[2] see www.coastdat.de