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climate simulations for coastal areas**



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## Applications of dynamical and statistical downscaling methods to small-scale wave climate simulations for coastal areas

Lidia Gaslikova and Ralf Weisse

*26 pages with 9 figures and 2 tables*

### Abstract

Several downscaling techniques comprising fully dynamical and statistical-dynamical methods applied to near-shore local wave climate are tested and assessed in terms of wave statistics with respect to the added value that can be achieved compared to larger scale data. The techniques are applied for the example of Helgoland, a small island in the German Bight. Comparing the near-shore wave climate it was found that generally an improved representation could be obtained from all downscaling techniques. Based on a balance between the required computer resources and the improvements achieved it is suggested that, to this end, a dynamical-statistical approach based on high-resolution coastal wave modeling and linear regression provides the optimal choice.

### Verwendung dynamischer und statistischer Downscaling Methoden zur Simulation des küstennahen Seegangsklimas am Beispiel Helgolands

#### Zusammenfassung

Das küstennahe Seegangsklima Helgolands wurde mittels verschiedener statistisch-dynamischer sowie dynamischer Downscaling-Methoden simuliert. Es wurde untersucht, inwieweit sich die unterschiedlichen Methoden hinsichtlich ihres Mehrwertes bei der Berechnung von Seegangsstatistiken im Vergleich zu großskaligen Daten unterscheiden. Generell konnte für alle Methoden eine Verbesserung gegenüber dem Ausgangszustand erreicht werden. Unter Berücksichtigung des unterschiedlich hohen Aufwands und des unterschiedlichen Rechenzeitbedarfs der verschiedenen Methoden, stellt eine Kombination aus zeitlich limitierten, hoch aufgelösten Seegangssimulationen in Verbindung mit linearer Regression die derzeit günstigste und effektivste Variante zur Verbesserung küstennaher Seegangsstatistiken dar.



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# 1 Introduction

In coastal engineering many applications require knowledge about extreme wave statistics at or near the coastal facilities. Often the data for such statistics are limited or sometimes even not existing. Frequently, measurements from a nearby location are used instead, and in combination with more or less sophisticated methods to transfer the information to the place of interest, are used to derive the relevant statistics (e.g., Coastal Engineering Manual). When such measurements are not available or lacking homogeneity that prevents the estimation of reliable statistics, multi-decadal wave hindcasts may be an alternative. In recent years multi-decadal simulations of ocean waves have become more and more common (e.g. WASA Group 1998, Cox and Swail 2001, Weisse et al. 2002, Caires et al. 2002, Sterl et al. 1998, Kushnir et al. 1997). Most of these studies have been motivated by concerns about possible ongoing long-term changes in the wave climate (especially in the extreme sea states) and their consequences for coastal protection and the safety of humans living at the coast. While large scale changes may be reasonably estimated from these simulations, their value for design and safety assessment of coastal protection structures may be limited due to their relatively coarse spatial and temporal resolutions and due to the fact that shallow water effects are usually not accounted for in most of these simulations. In addition, because of computational constraints their spatial resolution remains limited and may be too coarse to be used directly for coastal design purposes. For the latter, additional techniques are required to transfer the wave information from such a hindcast to the site of the construction. A number of different methods (hereafter referred to as downscaling techniques) exist for that purpose. First principles of shallow water wave processes (e.g. Coastal Engineering Manual) are frequently applied. Alternatively, a shallow water high-resolution wave model can be used to downscale large-scale wave data in cases where such data are available as boundary conditions. Optimally such simulations would be performed for multi-decadal periods. However, due to rather high computational costs or restricted availability of adequate boundary conditions, simulations are usually limited to a number of cases with different meteorological and wave conditions, for instance a few selected severe storm situations (e.g. Vierfuss 2002). While such hindcasts for selected cases may provide some additional insight, their usability for the estimation of extreme wave statistics remains limited.

The objective of this study is twofold. First, we investigate to which extent extreme wave statistics obtained from an existing multi-decadal wave hindcast reproduce the small scale near-shore features. Next, we apply different downscaling techniques and assess the additional value in the representation of extreme wave statistics with respect to additional

computing costs required. The paper is structured as follows. In Section 2 the multi-decadal wave hindcast that has been used as reference run is described. Next, the shallow water wave model that has been used to downscale the large scale wave hindcast, its set-up and the experiment, are described. Validation of this experiment is provided in the last part of Section 2. In Section 3 we first investigate the extent to which observed near-coastal extreme wave statistics are reproduced in the existing large-scale multi-decadal wave hindcast. We also elaborate on differences in the representation of these statistics, when derived directly from the reference hindcast and the downscaled shallow water wave model experiment. Based on both simulations, different downscaling techniques are tested and assessed (Section 4) with respect to the improvement that could be achieved in the representation of extreme wave statistics when compared to those obtained from the coarse-grid reference run. In Section 5 our results are summarized and discussed.

## **2 Model and Experiments**

### **2.1 The large-scale multi-decadal wave hindcast**

As the reference large-scale wave data, we use the multi-decadal wave hindcast 1958-2002 for the Southern North Sea provided by Weisse et al. (2003). This simulation has been produced within the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) project (Soares et al. 2002). The dataset been chosen because, to our knowledge, it represents the longest homogeneous wave hindcast available at the presently unsurpassed spatial resolution of about 5.5 km and also takes into account shallow water effects. Here, the wave model WAM (WAMDI 1988) has been used to produce the hindcast. Two runs with different spatial resolution were produced. A coarse run with approximately resolution 50 x 50 km covered part of the North Atlantic and the North Sea and is referred further as HCG run. A finer run with resolution 5 x 5 km covered the North Sea south from 56°N (referred as HFG run) and used the HCG data as boundary conditions. In both simulations wave integrated parameters (such as significant wave height, peak period, peak direction etc.) were stored hourly, wave spectra were stored every 3 hours. Both runs were driven by hourly wind fields at 50 km resolution obtained from an atmospheric hindcast performed with the REMO model (Feser et al. 2001). For the HFG run, water level variations were taken into account. Hourly water level and current components at non-regular grid (about 200 m for the German Bight) were obtained within the hindcast provided by BAW (Coastal Division of the Federal Waterways Engineering and Research Institute) with the storm-surge model TELEMAC-2D (Pluess, pers. comm. 2003).

## 2.2 The shallow water wave model and experiment

For the dynamical downscaling of the reference data the K-model (Schneggenburger 1997) was adopted. The K-model represents a third generation shallow water wave model that captures features of the large-scale forcing and adds to them the small-scale effects not resolved by the driving large-scale data. It is a discrete spectral wave model solving the wave action balance equation in the wave number domain. Energy input by the wind is parameterized by a modified Philips linear function (Cavaleri et al. 1981) and a modified Snyder exponential function (WAMDI 1988). Non-linear wave-wave interactions have been neglected following the argumentation of Schneggenburger et al. (2000) who argued that in shallow water the assumptions of homogeneity for the application of this theory are violated. Instead, a non-linear dissipation source function (Rosenthal 1995, Günther and Rosenthal 1995, Schneggenburger 1997) accounting for the dissipation by wave turbulence is used. Bottom dissipation is taken into account according to Hasselmann (1973) and wave breaking is simulated by non-linear energy dissipation depending on water depth (Hasselmann 1974). In addition, refractions caused by currents and depth are also included. For a detailed description of the K-model we refer to Schneggenburger (1998). A comparison of the model performance relative to other shallow water wave models is presented in Moghimi et al. (2004).

The model was set-up for the vicinity of Helgoland, an island located in the German Bight (Figure 1). The model domain comprises an area of about 15 x 15 km at a spatial resolution of 100 x 100 m. The bathymetry was obtained from the BAW (Norbert Winkel, pers. comm.) with a resolution of about 50m on an unstructured grid and was interpolated to the K-model resolution. A propagation time step of 4 seconds was adopted. Forcing sources comprise hourly near surface wind fields, water level and current fields obtained from the HIPOCAS hindcasts and have been interpolated to K-model grid. As boundary conditions, 3-hourly wave spectra from the HFG reference run were used. The K-model was integrated for the 12-year period 1990-2001. The results of this simulation have been stored hourly in the form of integrated wave parameters such as significant wave height, peak period, peak wave direction etc. at all grid points and as two-dimensional wave spectra at selected model grid points (see Fig.1). In this set-up the K-model simulation can be considered as dynamical downscaling of the HIPOCAS wave hindcast. In the following we will refer to this simulation as the K-model hindcast (KMH).

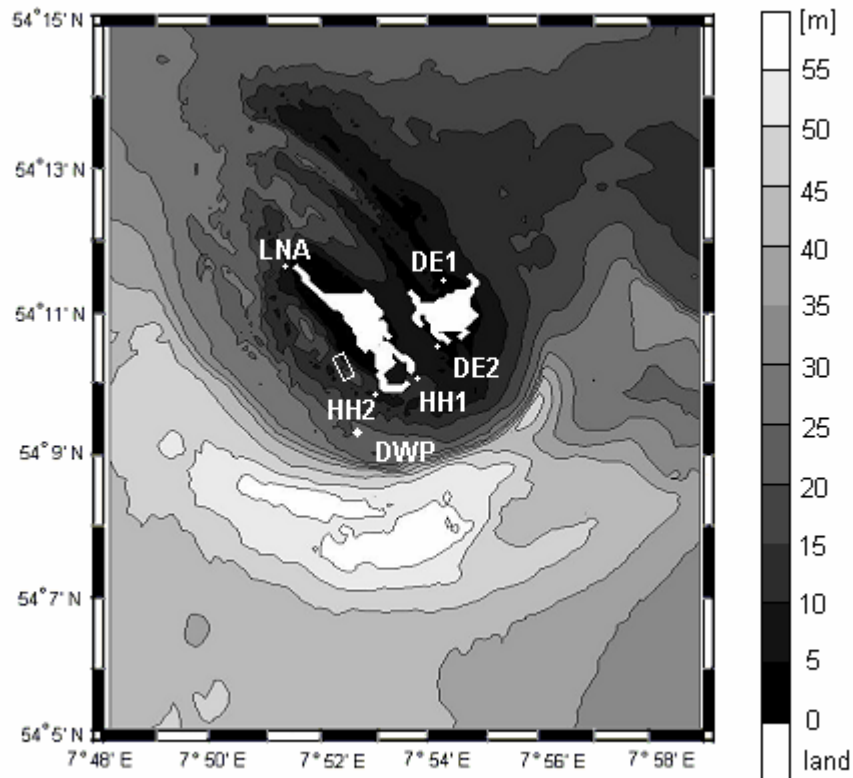


Figure 1. K-model domain and bathymetry in meters. The location of a deep water buoy used for validation is indicated by DWP. The rectangle indicates the area for which radar measurements taken from a telecommunication tower at the main island are representative. LNA, HH1, HH2, DE1 and DE2 represent model points near coastal facilities and are used for assessing model performance.

### 2.3 Validation of K-model results

In this section we elaborate on the quality of the K-model simulation and the extent to which observed conditions are reproduced. Unfortunately only limited data are available for the comparison. No long term measurements exist close to coastal facilities. A waverider buoy is located in deep water (here about 20 m) approximately one kilometer southwest of the island and measures significant wave height, peak period and peak direction. Data from this buoy for the period March 1998 to October 2001 were available. In addition, data from a WaMoS II (Wave and Surface Current Monitoring System) radar (Hessner et al., 2001), permanently mounted on a telecommunication tower on the main island since March 1998, were available for some periods within the years 1998-2001. The location of the deep water buoy and the area covered by the radar are shown in Figure 1. As an example, Figure 2 shows modeled and observed significant wave height, peak period and peak direction for October 1998. In general a good agreement between the KMH and the observations can be inferred. For some high wave situations significant wave heights appear to be overestimated by the

model. Peak periods are slightly overestimated by the simulated data for very high waves. Wave directions are hindcast quite reasonably.

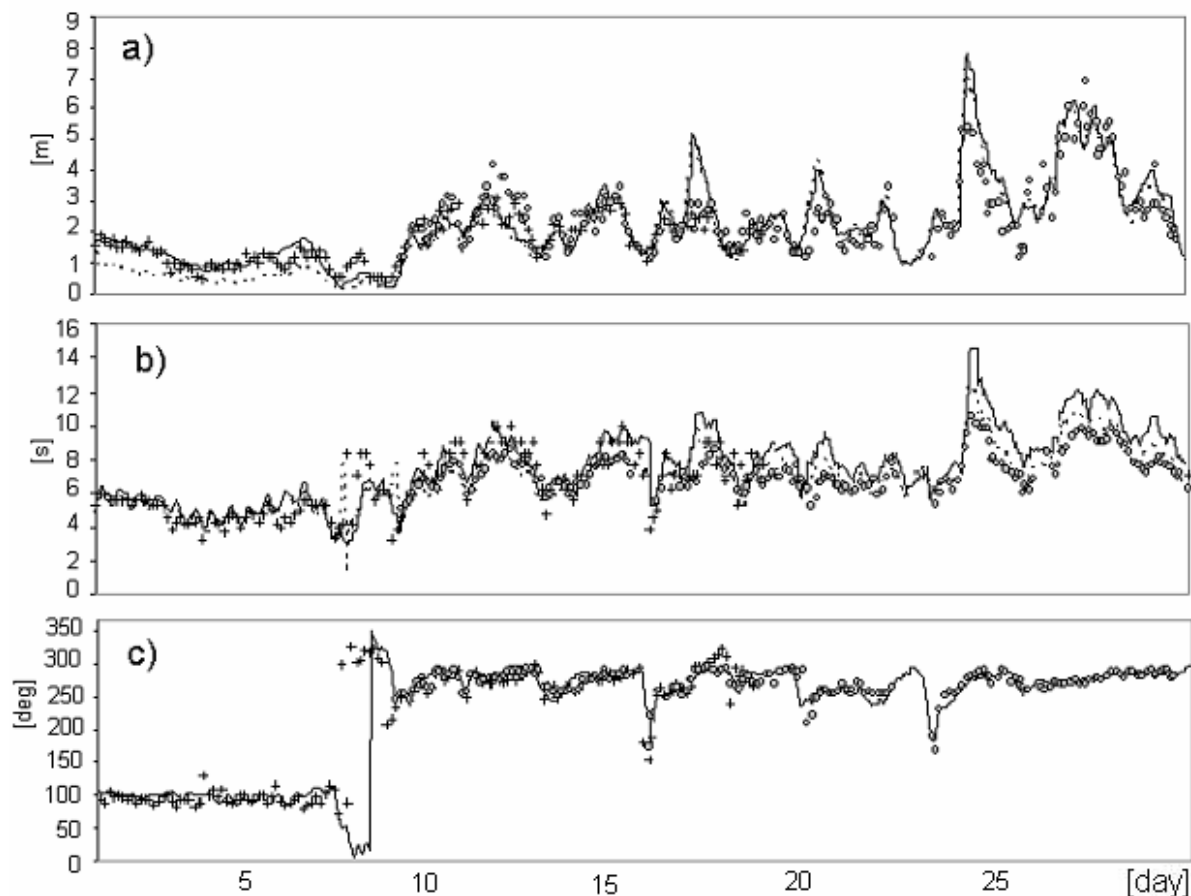


Figure 2. Hindcast (KMH) and observed wave parameters at DWP and the central point from the area covered by radar measurements for October 1998. From top to bottom: significant wave height in meters, peak period in seconds and peak direction (coming from) in degrees. Buoy measurements are shown as crosses, radar measurements are shown as circles. The K-model hindcast at the buoy location is given by a solid line, for the radar by a dashed line.

Figure 3a shows a comparison of modeled and observed significant wave height distribution for the period 1998-2001. For the lower 90% of the distribution a rather good agreement between model and observations can be inferred. In the range between about 1.0 to 1.5 meters the K-model slightly underestimates the buoy data. For the highest 10% of the waves an overestimation by the K-model of up to 80 cm can be inferred, indicating that the highest waves occur too often or are too severe in the KMH simulation. To check whether this behavior is caused mainly by the driving boundary conditions or by K-model physics a similar comparison between the HFG hindcast and the buoy data was made (not shown). The overestimation of observed high waves was found to be in the same order of magnitude for the HFG run as for the K-model. So it can be concluded that the overestimation of the most

severe wave events is primarily a result of too high waves provided at the K-model boundaries rather than caused by internal K-model processes.

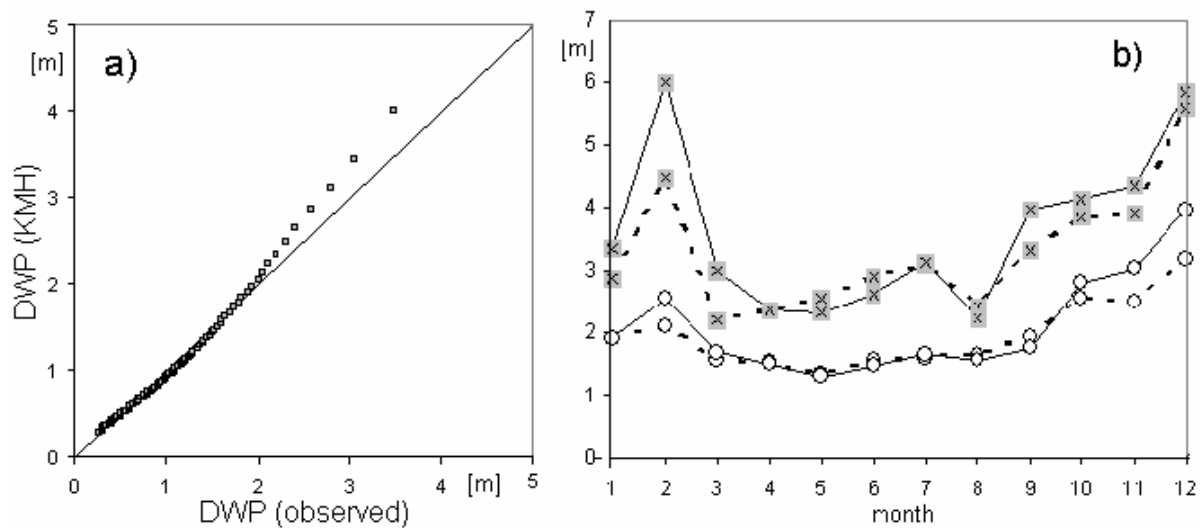


Figure 3. a) Quantile-quantile plot 1998-2001 of observed by buoy and hindcast significant wave height at DWP. Shown are the 5–99 percentiles. b) Comparison of observed (dashed) and hindcast (solid) monthly 90%-tiles (circles) and 99%-tiles (crosses) of significant wave height at DWP. In all cases quantiles have been compared only for dates for which observational data have been available.

Figure 3b shows a more detailed comparison of observed and hindcast averaged monthly 90 and 99-percentiles. For the 90-percentile a reasonable agreement can be inferred. An exception is found in the months November, December and February for which the model tends to show higher extremes. A similar condition holds for the 99-percentile that represents the most extreme events. For the 99-percentile KMH values are somewhat higher also for September and October. Possible reasons include systematic effects in the driving boundary conditions, uncertainties in bathymetry and wind data, as well as measurement errors. Longer observational data are required to fully assess whether the described differences between observed and hindcast frequency distribution appear to be systematic.

Despite the limited amount of available observations we are nevertheless able to test whether systematic differences between the observations and the K-model do occur for periods for which both buoy and radar measurements have been available. Although the locations of the measurements are slightly different, the radar was calibrated to the buoy observations, which gives the opportunity to compare these two datasets and to allow them both to be compared with the results from the same location of the model domain, namely DWP. Figure 4 shows scatter plots between significant wave heights obtained from the KMH experiment at DWP, radar and buoy data. Although a considerable scatter can be inferred between buoy and KMH (green), especially for the waves higher than 2 meters, and for the pair radar – KMH in the interval 1–2 meters and also for the highest waves, similar scatter is

obtained also for the pair buoy – radar. Both K-model and radar have a tendency to overestimate the highest waves with respect to the buoy but there is no systematic bias between KMH and radar extremes. From Figure 4 it can be further concluded that the KMH experiment appears to be calibrated except for the largest waves, i.e. there appears to be no systematic bias of the modeled dataset conditioned upon the expectation of the observed data. There is a slight tendency of the radar to show too high waves, in particular for buoy wave heights more than about 1 m.

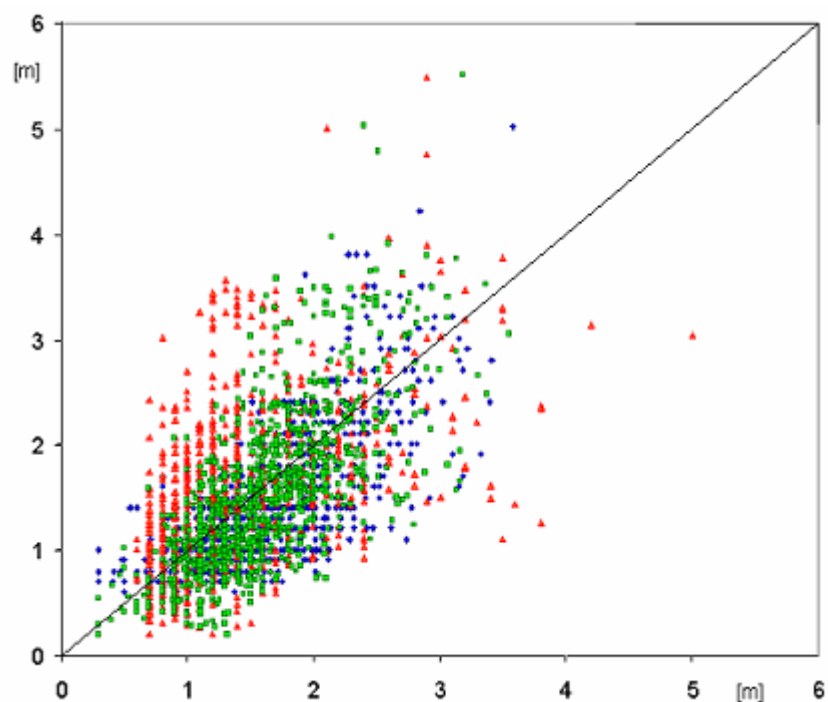


Figure 4. Scatter plot between modeled and observed significant wave height in meters at DWP. Green: buoy measurements (x-axis) vs. KMH (y-axis); Red: radar (x-axis) vs. KMH (y-axis); Blue: buoy (x-axis) vs. radar (y-axis).

From a statistical perspective, buoy, radar and KMH data may be regarded as realizations of random processes. In the following we test the null-hypothesis whether all three samples (buoy, radar and model) can be considered as realizations of the same random process, i.e. whether they stem from the same population or whether systematic differences suggest the rejection of this hypothesis. To do so, the data were sub-sampled such that only time steps for which buoy, radar, and model data have been available are taken into account. Subsequently, instantaneous differences between buoy and radar data have been computed. The standard deviation ( $\sigma$ ) and the lag-1 autocorrelation ( $\alpha$ ) of these differences have then been used to model the differences by a first order autoregressive process (AR(1)-process) (von Storch and Zwiers, 1999) :

$$x_t = \alpha x_{t-1} + z_t \quad (1)$$

Here  $x_t$  represents instantaneous differences at time  $t$ ,  $z_t$  is a white noise with variance  $\sigma$ . Subsequently 10000 realizations  $k$  of this AR(1)-process have been obtained from Monte Carlo simulations and the realizations  $k$  of the wave height  $y_t^k$  at DWP have been computed from

$$y_t^k = b_t + x_t^k \quad (2)$$

where  $b_t$  represents the buoy measurements. Assuming that all three samples are realizations of the same random process it is expected that 95% of all radar and model data fell within a 95% confidence interval for each time-step. The result of this exercise is shown in Figure 5. It can be inferred that, for most of the time, buoy, radar and K-model indeed fall within the range given by 95% of the Monte Carlo simulations. In particular this comprises 95% of the K-model and 96% of the radar data. The null-hypothesis (model and observations are realizations of the same population) can thus not be rejected with 5% error probability. Finally it is concluded that the KMH shares some resemblance with reality and in the following will therefore be considered as a “substitute reality”.

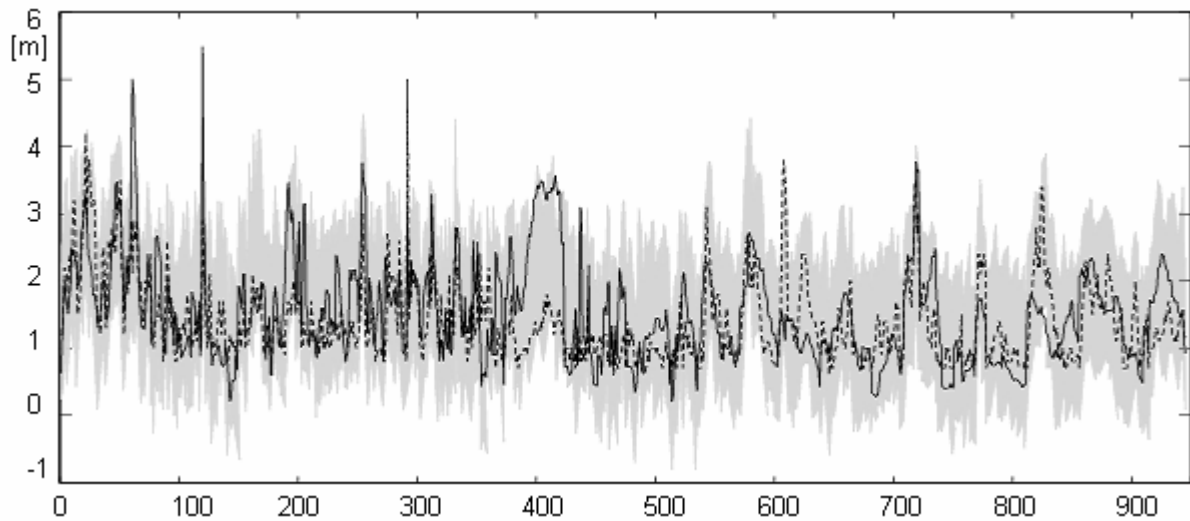


Figure 5. Significant wave height in meters at DWP obtained from radar measurements (dashed) and the KMH (solid). The shadowed area shows the 95% confidence interval obtained from the Monte Carlo experiments. The analysis is made for the period October 1998 – August 2001, with data gaps being excluded from the analysis resulting in 945 values.



### 3 Comparison of near-shore extreme wave statistics from hindcasts with different spatial resolutions

In the previous section we showed that differences between model and observations at DWP can partially be attributed to the driving HFG hindcast. In addition it was demonstrated that the null hypothesis KMH, radar and buoy data represent realization of the same random process can not be rejected at 95% confidence level. Based on that, we assume in the following that the small scale features simulated by the K-model share some resemblance with reality. We will therefore consider in the following the KMH experiment as a substitute for reality. This allow us to test to what extent improvements in the representation of near shore extreme wave events can be achieved with several statistical downscaling techniques. The improvement will be assessed relative to the HFG hindcast, as these data are readily available and thus can be considered as a first guess of the prevailing near-shore wave conditions.

We first investigate the extent to which the HFG hindcast may be used to reasonably assess long-term wave statistics in the coastal zone. We focus mainly on the statistics of extreme events as they are essential for coastal protection. Three datasets are analyzed, namely significant wave height from the HIPOCAS coarse grid hindcast with about 50 km resolution (HCG), the HIPOCAS fine grid hindcast with about 5 km resolution (HFG) driven by the HCG simulation, and the KMH hindcast with 100 m resolution driven by the HFG run.

Figure 6 shows a comparison between the 99-percentiles of significant wave height for the period 1990–2001 obtained from the HFG and in the K-model hindcasts. It can be inferred that for both simulations a similar large-scale pattern of extreme wave statistics is reproduced. The pattern is characterized by highest waves occurring in the western part of the K-model domain that continuously decrease eastwards. East of Helgoland a distinct area with relatively low wave extremes can be found which is mainly caused by the shadowing effect of the islands against the prevailing wind and wave directions. The large-scale similarity between both simulations is primarily a consequence of both simulations having identical wave conditions at the K-model boundaries or, in other words, that the K-model uses boundary conditions from the HFG hindcast. In addition, the same wind fields have been used in both simulations.

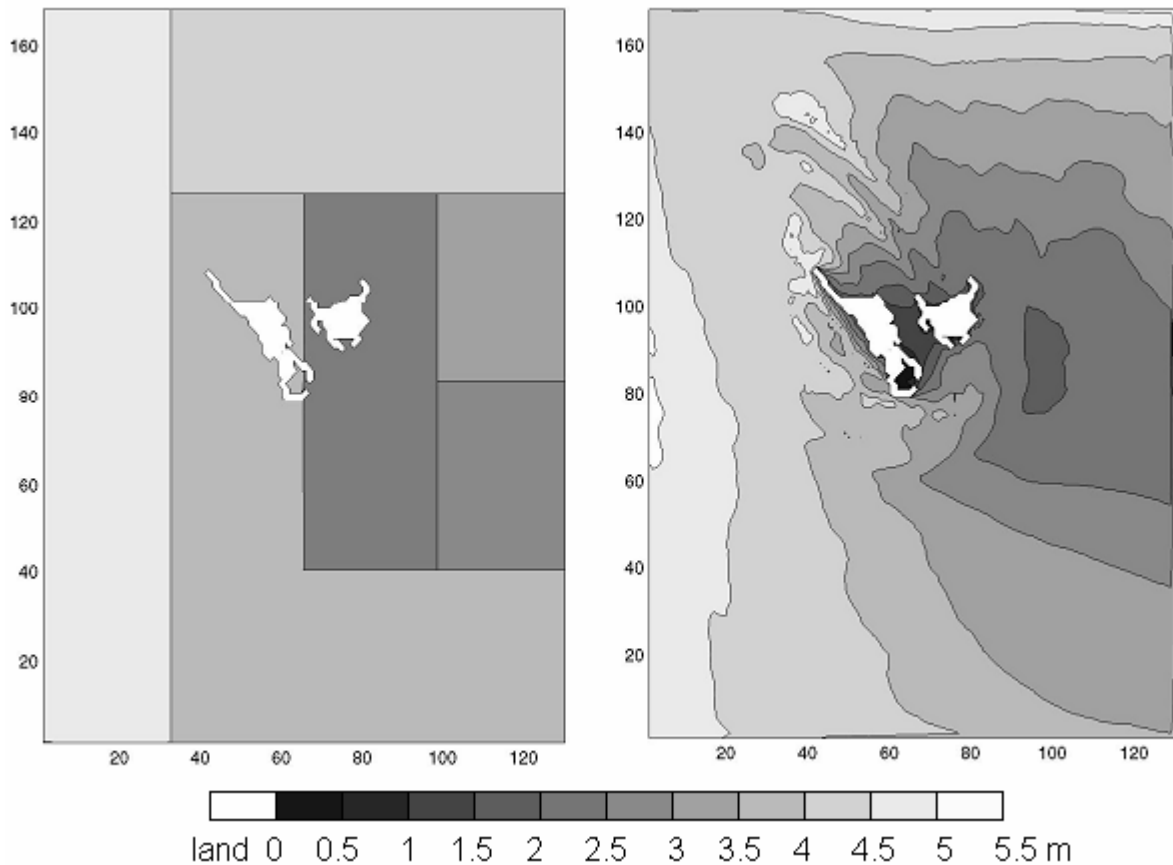


Figure 6. 99%-tile of significant wave height in meters derived from 3-hourly values for the period 1990–2001 from the HFG hindcast (left) and KMH experiment (right).

Despite the large-scale similarity between the HFG and the KMH hindcasts small scale differences in extreme wave statistics are obvious (Figure 6). In particular, the island shadow effects are more pronounced and extend further eastward in the K-model simulation. Southeastwards of Helgoland the 99-percentile of significant wave height is about one meter higher compared to the HFG simulation. Furthermore, for the K-model run, small scale features of the bathymetry are visible in the distribution of the wave extremes.

While large-scale features of extreme wave statistics are quite similar in both simulations the small scale differences may be significant for coastal protection. Figure 7 shows a comparison of the frequency distribution for total significant wave height near different coastal facilities obtained from the HFG and the KMH hindcasts. The location of analysis points can be inferred from Figure 1. Although the K-model is driven with boundary conditions from the HFG run and both simulations utilize the same wind forcing, differences in the frequency distributions in particular for near coastal locations do emerge. The details of these differences depend on the location. At DWP both hindcasts are rather similar. Here water depth is about 22 meters and the shadowing effect of the island plays a minor role as the prevailing wind and wave directions are from the southwest to the northwest. At LNA the

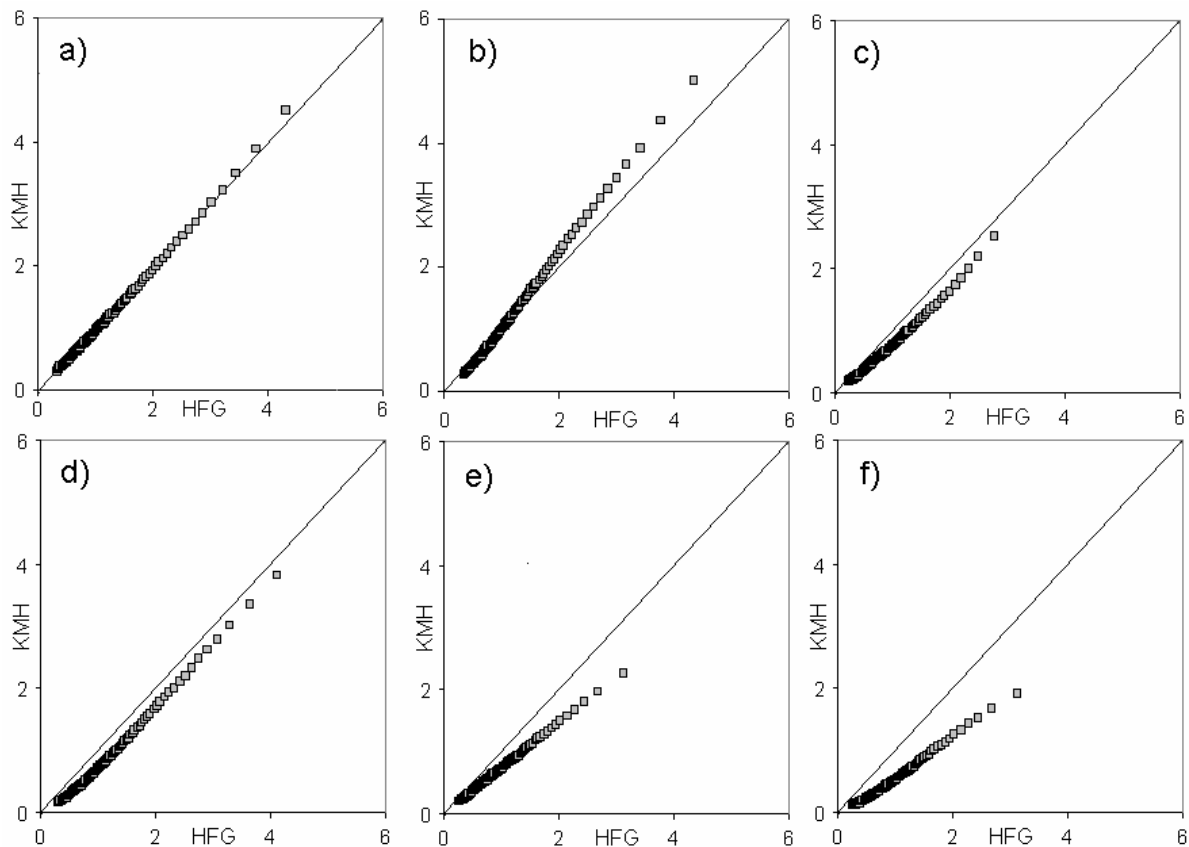


Figure 7. Quantile-quantile plots of HFG and KMH simulated significant wave height in meters for the period 1990-2001 at points a) DWP b) LNA c) HH1 d) HH2 e) DE1 f) DE2.

situation is different. LNA is also located at the western side of the island, but here bathymetry effects become important. While the lower 75% of the simulated wave height distributions are still rather similar in the HFG and the KMH, the uppermost 20% are remarkably higher in the K-model simulation (Fig. 7b). Near Helgoland harbor (HH1, HH2) shallow water effects and the strong gradients in the bathymetry play a significant role. Here water depth generally reduces wave heights and, independent of their heights, waves are generally lower in KMH. East of the main island, waves are also generally smaller in the K-model hindcast. This can be inferred from the comparison of the wave height frequency distributions at DE1 and DE2, two locations near the coastal protection structures at the north and south shores of the smaller Dune Island (Figures 7e, 7f). Generally, the effect is larger for higher waves and mainly results from a combination of lee and shallow water effects.

For completeness an analogous comparison has been made also between the HCG and the HFG hindcast. Results for LNA and DE2 are shown in Figure 8. The situation is similar to the comparison of the HFG and the K-model hindcasts. Both simulations (HFG and HCG) utilize the same wind forcing and the coarse grid simulation provides the wave boundary conditions for the fine grid hindcast. Comparing the HCG and the HFG simulations, generally the same structure of results is obtained as in the case of the K-model and HFG hindcasts.

However, while differences in the bathymetry between the HCG and HFG hindcast certainly play a role, a large fraction of the differences in the simulated wave height distribution may be attributed to the presence of the islands. While they are present in the HFG simulation, they have been neglected in the HCG hindcast as they are too small at this resolution. As a result waves are generally higher in the HCG hindcast.

Summarizing, we found that spatial resolution and shallow water effects may have a significant impact on the wave frequency distributions obtained from long-term wave hindcasts. Depending on location these effects can be crucial for the assessment of near-coastal wave climate which in turn is essential for planning and construction of coastal defense. As very high resolution hindcasts (such as the one provided by our K-model simulation) are usually available only for selected cases or for restricted time periods due to their extremely high computing costs, some methodology is needed to transfer (downscale) the information that can be obtained from a multi-decadal, but less well resolved hindcasts (such as the HFG simulation) to near-shore conditions. In the following we investigate the capability of different statistical downscaling techniques in combination with time limited high resolution wave hindcasts (here KMH) to provide improved representation of near shore extreme wave statistics.

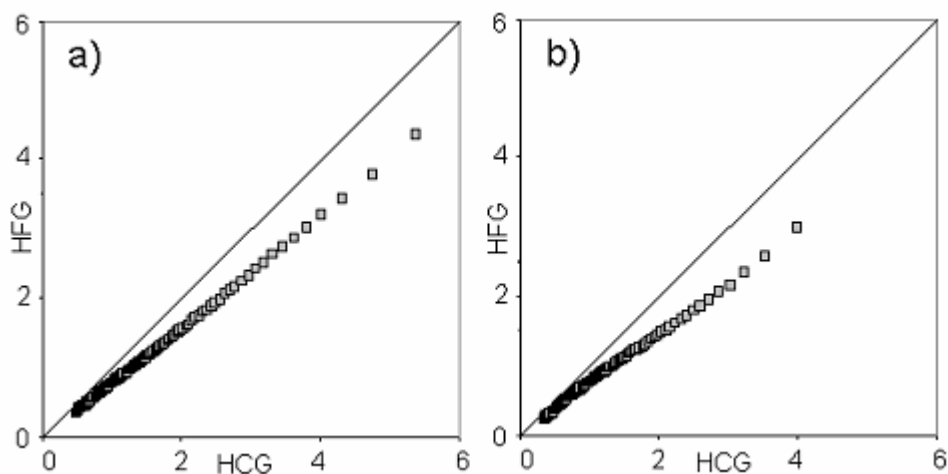


Figure 8. Quantile-quantile plots of HCG and HFG simulated significant wave height in meters for the period 1990-2001 at points a) LNA and b) DE1

## 4 Skill of different downscaling techniques in the representation of near shore extreme wave statistics

### 4.1 Methods

To test the extent to which statistical downscaling in combination with high-resolution dynamical wave modeling can be used to assess the near-shore wave climate three different

statistical approaches have been tested. These are canonical correlation analysis (CCA), linear regression and analogs (e.g., von Storch and Zwiers, 1999). In all approaches the large-scale wave field obtained from the HFG hindcast is linked statistically to the local wave data from the K-model simulation. In the case of reliable and sufficiently homogeneous long-term measurements being available at the site of the construction, these may be used instead of the K-model data. However, when such data are not available, or information is required also for some surrounding area, a very high-resolution wave model simulation (such as KMH) validated with at least some existing data will represent the best possible option.

Usually downscaling techniques such as CCA or analogs are applied to monthly, annual or seasonal statistics (e.g. Zorita and von Storch 1999). However, some applications, such as the simulation of ship movements, would require high-resolution instantaneous data. We therefore extended the downscaling concept and here tested its skill in the estimation of 3-hourly wave data. Instead of directly linking large and small scale wave statistics all statistical models relate 3-hourly wave data from the HFG and the K-model hindcast and statistics have been computed subsequently for comparison. For simplicity and as a first step, in the following all analyses are limited to significant wave height (SWH) only.

In order to fit and test the statistical models the K-model hindcast period was split into a five year fitting period (1990-1994) and a seven year validation period (1995-2001). For linear regression (LR) 3-hourly SWH and wind direction from a single grid point in the HFG simulation located near the southwestern boundary of the K-model domain have been chosen as predictors. The regression model is conditioned upon the wind directions such that eight different regression models are built depending on wind coming from the 45 degree eight sectors starting from  $[-22.5, 22.5]$ . For each grid point  $i$  in the K-model domain and each of the eight wind direction sectors  $j$  a regression model

$$y_{i,t} = a_{i,j}x_t + b_{i,j} \quad (3)$$

was built, where  $y_{i,t}$  represents downscaled wave height, and  $x_t$  represents the predictor (HFG wave height) . The coefficients  $a_{i,j}$  and  $b_{i,j}$  were fitted using a least square method.

For the CCA empirical orthogonal functions (EOFs) (e.g., von Storch and Zwiers 1999) have been computed for the HFG and the K-model SWH anomaly fields. For the HFG hindcast the leading two EOFs explain about 99.1% and for the K-model hindcast about 98.3% of the total SWH variability. Based on the leading two EOFs CCA patterns were computed subsequently and SWHs for the validation period have been derived on the basis of those patterns.

For the analog method a pool of analogs was constructed from the 3-hourly SWH fields 1990-1994 of the K-model hindcast and the corresponding principal components of the leading two EOFs of the 3-hourly HFG SWH anomaly field. Subsequently an analog for each date of the validation period was determined. For this, the HFG SWH data of the validation period were projected onto the first two EOFs for the fitting period and for each pair of obtained principal components the nearest pair (analog) from the fitting period was determined. The K-model wave height field that belongs to this pair was then selected as analog wave height field for the corresponding date in the validation period.

## 4.2 Results

To test the skill of the different downscaling methods in representing near shore wave climate and statistics results from the different techniques have been compared with that from the KMH simulation. Table 1 shows the bias and the standard deviation of the error at the various locations for the different downscaling models. It can be inferred that the error is generally largest when coarse grid data from the HFG simulation are used directly to estimate the wave conditions at the near-shore locations. For linear regression and CCA the results are comparable with LR providing slightly smaller error with standard deviation up to 0.17 m and bias less than 0.02 m depending on the location. For the analog method errors are generally larger and sometimes comparable to that of the HFG simulation.

<b>STDEV(error)</b> [m]	DWP	LNA	HH1	HH2	DE1	DE2
KMH – HFG	0.159	0.302	0.191	0.286	0.272	0.289
KMH – LR	0.097	0.163	0.104	0.159	0.128	0.085
KMH – CCA	0.108	0.255	0.179	0.19	0.163	0.13
KMH - Analog	0.224	0.364	0.234	0.385	0.218	0.184
<b>BIAS</b> [m]						
KMH – HFG	-0.04	0.045	-0.17	-0.257	-0.228	-0.39
KMH – LR	-0.004	-0.011	0.0002	-0.0008	-0.019	0.0006
KMH – CCA	-0.005	-0.023	0.015	-0.004	-0.025	0.009
KMH - Analog	-0.012	-0.022	0.007	-0.012	-0.2	0.004

Table 1. Bias and standard deviation of errors in meters between significant wave heights obtained from KMH and different downscaling techniques for the points near coastal facilities.

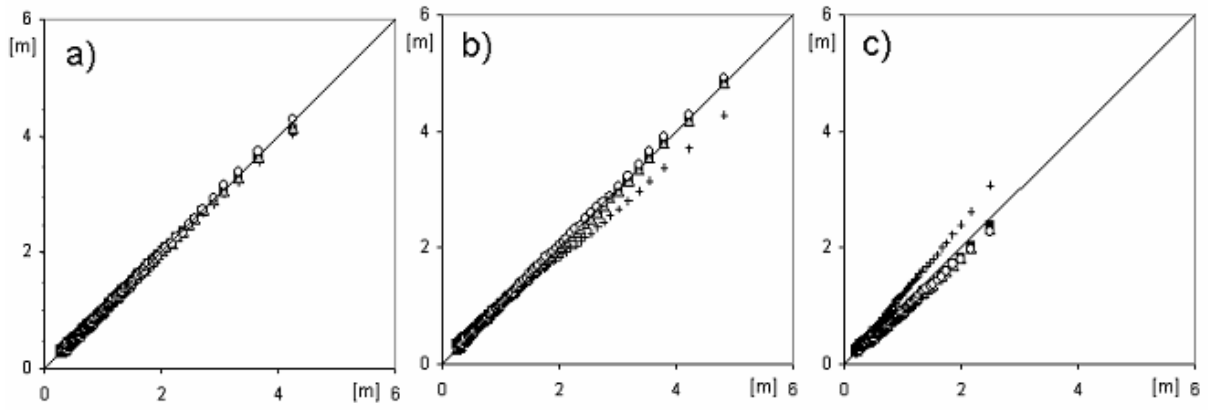


Figure 9. Quantile-quantile plots of simulated significant wave height with different techniques in meters for the period 1990–2001 at points a) DWP b) LNA c) DE1. HFG (crosses), LR (black squares), CCA (triangles) and Analog (circles) at y-axis against KMH (x-axis).

Figure 9 shows a comparison of wave frequency distributions obtained from the different statistical models and the HFG with KMH simulation. It can be inferred that, despite the differences in representing instantaneous values, the capability of the statistical models in reproducing the wave statistics of KMH run appears reasonable. The degree of agreement slightly differs depending on location. For the comparison the quantile-quantile plot of the KMH with the HFG reference run is also shown. For deep water points the agreement between downscaled and KMH derived frequency distributions is comparable for linear regression, CCA, and HFG. For the areas where the influence of topography (LNA) and other external forces (e.g. DE1, DE2) is larger, the distributions obtained from downscaled data are closer to that derived from the K-model for all the methods, while that derived from HFG provides stronger systematic deviations.

In order to assess the skill of different downscaling techniques in representation of extreme wave statistics in the entire model domain we compared the 99% of SWH at each grid point for the validation period 1995-2001. The skill was measured using the Brier skill score ( $B$ ) (von Storch and Zwiers 1999).

$$B = 1 - S_{for}^2 / S_{ref}^2 \quad (4)$$

Here  $S_{for}^2$  and  $S_{ref}^2$  represent the mean squared errors of the “forecast” (in our case provided by different downscaled data sets LR, CCA and Analog) and “reference forecast” (here HFG hindcast) with respect to observational data. In face of missing observations the K-model simulation represents our substitute reality. Thus any positive value of  $B$  indicates that the downscaling method represents an improvement relative to the HFG data. The best performance corresponds with  $B$  equal 1, which means that downscaled data are as good as

“observations”. A negative value of  $B$  indicates that the method performs worse than the HFG reference. The result is shown in Table 2. As it can be seen, all statistical methods introduce enormous additional skill in representation of the spatial distribution of the SWH 99-percentile relative to using data from the HFG hindcast directly. Depending on method the skill varies from 0.975 to 0.992. That means that the improvement is in the same order of magnitude independent of the chosen statistical technique. It is therefore suggested that in the face of limited computer resources and compared to the direct use of less well resolved data, high-resolution wave model simulations in combination with coarse grid boundaries and statistical downscaling approaches can yield an improved representation of extreme wave statistics for near-coastal areas.

LR	CCA	Analog
0.992	0.98	0.975

Table 2. Brier scores for the 99%-tile of SWH from 3 statistical methods.

## 5 Summary and Discussion

Different approaches for obtaining high-resolution near-shore wave statistics have been considered. Based on an existing multi-decadal wave hindcast for the North Sea a high-resolution wave simulation (KMH) for the area around Helgoland for the period 1990–2001 has been performed and found to reasonably represent observed wave conditions. Results of the KMH simulation were compared with the buoy and radar wave observations and demonstrated that in general the simulated wave data (SWH, peak period, peak direction) show good agreement with measurements in terms of distributions, although upper percentiles of the modeled SWH appeared to be overestimated. The latter is mainly caused by the boundary conditions which provide too high waves in case of severe storms. As differences occur also between different measurements (buoy, radar) we tested whether the range of errors between observed and modeled data is comparable to that between different measurements and whether model and observations can be considered as realizations of the same random process. It was found that this hypothesis could not be rejected with 5% error probability indicating that there is some skill in the KMH wave simulation.

As alternative to time consuming high resolution wave modeling the use of less expensive statistical-dynamical methods to obtain detailed wave statistics was investigated. Three statistical methods, namely linear regression, CCA and analogs were examined. It was found that all three methods considerably improve the estimation of extreme wave statistics



compared to the driving large scale hindcast and can be used as alternatives in case of limited computing resources.

So far, the methods have been applied to SWH only and most of the study is founded on SWH statistics. Although SWH represents one of the most frequently analyzed and most crucial wave parameter, other parameters are important for particular applications. For instance, from wave periods and wave heights wave steepness can be inferred, which represent an important criteria in the design of ships and vessels. Another example that depends on wave period is the derivation of wave induced bottom stress which is important for the sediment transport and coastal erosion evaluations. Other parameters, such as wave direction, are crucial, especially for extreme wave analysis within the coastal protection problem where it is important to know from which direction the severe waves are coming. Nevertheless, here we concentrate on SWH as a starting point and propose to extend the methodology to other wave parameters in future studies.

Turning to the discussion of the potential limitations and benefits of the downscaling methods, we start from the analog. As it can be inferred from Tables 1, 2 this method shows the worst performance among the tested methods in terms of error deviation. At the same time the data obtained with the analog method are not more biased than that from the other statistical methods. This unbiased but too variable behavior can be partially explained by incompleteness of the analog pool, i.e. for this method a fitting period longer than 5 years is required to accumulate the sufficient set of significant wave height patterns. This problem could be a strong limitation in case of applications to scenario studies, as wave situations which did not occur during the fitting period or which were not included in the analog pool can not be detected and reproduced by this method. The results of the CCA are quite close to that from the KMH simulation but the computational costs for CCA are higher than that for LR and analogs. The linear regression model shows the best results in comparison with the dynamically downscaled data (Table 1, 2) and gives the opportunity for the construction of more than one integrated wave parameter.

Based on a balance between the quality of simulated data and required computational resources, LR appeared to be the most acceptable method for downscaling long-term wave data and obtaining small scale wave statistics. It solves both, the problem of insufficient time and space resolution presented in multi-decadal wave hindcasts and extremely high computational costs for long-term high resolution wave hindcasts. We conclude that the combination of existing coarse grid long-term wave hindcasts (such as HFG) with shallow water wave modeling for short time periods and linear regression represents a cost-efficient

way to estimate near shore wave climate and to provide required statistics for coastal management needs.

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