A STOCHASTIC WEATHER GENERATOR TO ESTIMATE THE RECENT AND FUTURE WAVE CLIMATE AT THE GERMAN NORTH SEA COAST

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1. INTRODUCTION

Weather Generators can be used to produce long periods of synthetic weather records from a limited amount of input data. A number of studies have demonstrated the application area, e.g.: precipitation (Corte-Real et al., 1999; Wilks; 1999), wind speed (Bogardi and Matyasovszky, 1996; Burrows und Pandolfo, 1999), temperature. On overview and the history of the weather generation can be found in Wilks and Wilby (1999).
In this study we designed a weather generator for 3-hourly wave heights and directions conditioned by the monthly mean air pressure state or only by the CO_2 concentration. The wave generator used three statitical models. An autoregressive model is used to describe the monthly sea level pressure as input for a downscaling model. This part of the wave generator is conditioned by the CO_2 concentration. A linear multivariate statistical method is used to downscale the large scale sea level pressure information to the local wave statistic. A second autoregressive model is used to simulate the wave heights and directions conditioned to the local wave statistic. Finally the statistical model is able to produce arbitrary long realistic time series of the local wave climate. The model successfully ran with the SLP from observation or the results of global climate models as well as only a fixed or transient time dependent CO_2 concentration. The model design allowed examination of changes in the distribution of the wave heights and wave directions, including the extreme value analysis.

2. A WAVE GENERATOR CONDITIONED ON CO2 CONCENTRATION

The wave generator used three statitical models (Fig. 1). An autoregressive model is used to describe the monthly sea level pressure as input for a downscaling model (Fig. 1, I). This part of the wave generator is conditioned by

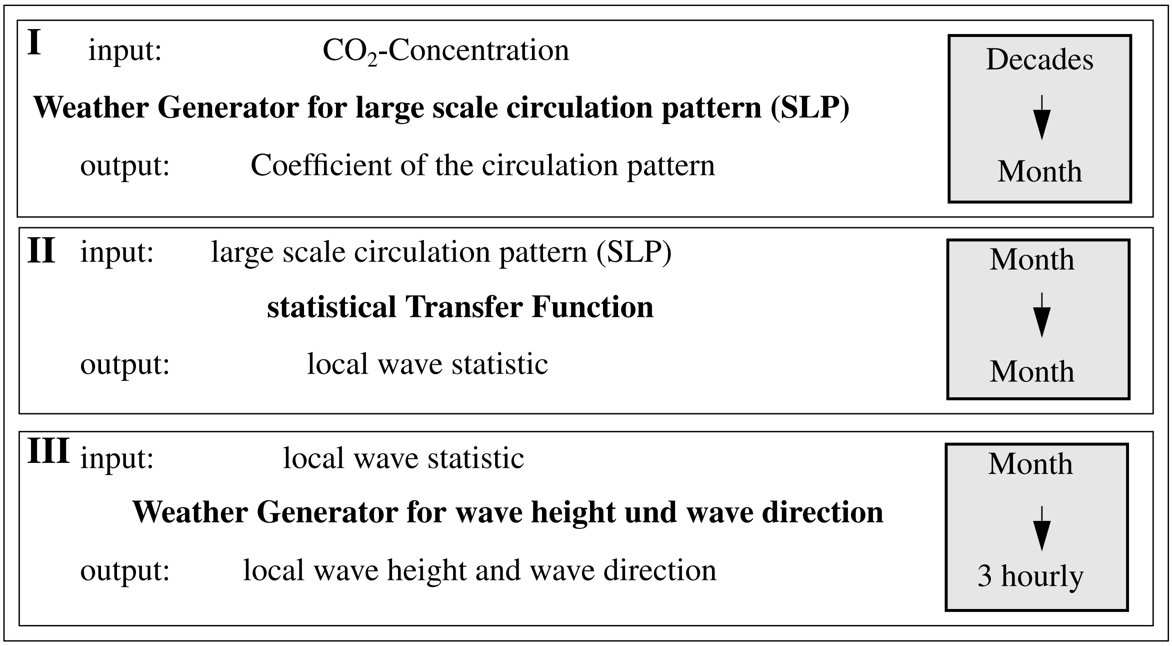
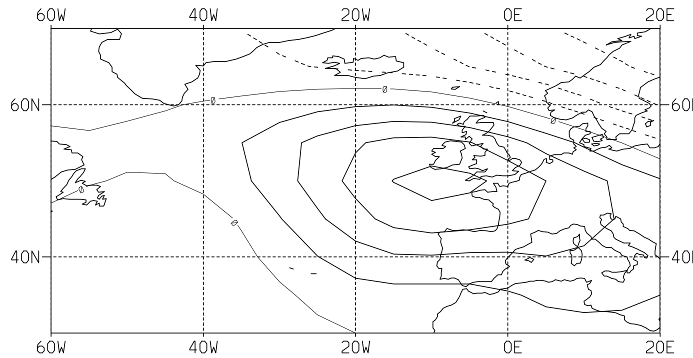


Fig. 1: The three components of the weather generator for 3 hourly wave height and wave direction conditioned to the CO_2-Concentration (time scale grey underlay).

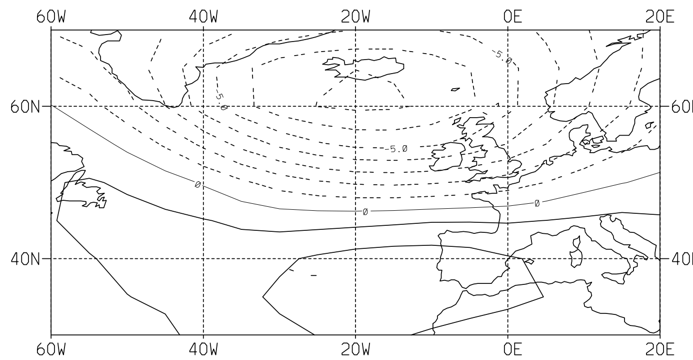
the CO_2 concentration. A linear multivariate statistical method is used to downscale the large scale sea level pressure information to the local wave statistic (Fig. 1, II). A second autoregressive model is used to simulate the wave heights and directions conditioned to the local wave statistic (Fig. 1, III).
As input data we used observed monthly mean sea level pressure (SLP) over the North Atlantic and Europe and 3-hourly wave heights and direction (1954-1994) at one selected grid point in the North Sea (close to the island Sylt) from a 40-year hindcast performed in the WASA project (WASA group, 1998). The grid box has a longitude of 0.7 and a latitude of 0.5, the location is 55.5˚N, 7.5˚E. A detailed description of the model can be found in Pfizenmayer (2002).

2.1 Downscaling of the atmospheric circulation to the monthly wave statistic

In a first step the monthly distributions of wave heights for the meridional and zonal direction were modelled using a statistical downscaling technic (Fig. 1, II). Here we used a multivariate technique, namely redundancy analysis (RDA), that calculates patterns of two different fields that are coupled, so that for the predictant field (monthly wave statistic) the amount of the represented variance is maximized. Details about RDA can be found in von Storch and Zwiers (1999).
As a predictor for the wave climate we chose the monthly mean SLP field. This field is representative for the atmospheric circulation and is related to the surface wind through the geostrophic relation. Surface waves are a response to the forcing of this wind field. To describe the monthly wave statistic we used different percentiles of the wave distribution. and the minumum and maximum value. Each direction is represented by 17 percentiles and the minumum and maximum value



per	10	20	50	80	90
z	.84	.82	.61	.64	.64
m	-.50	-.36	-.41	-.26	-.15



per	10	20	50	80	90
z	.03	.08	.27	.39	.39
m	.25	.33	.56	.63	.66

Fig. 2: The two pairs of redundancy pattern of observed winter (ONDJFM, 1955-64) SLP (hPa) in the North Atlantic sector (left) and selected percentiles for the intramonthly wave distribution for zonal (z) and meridional (m) direction (right). Top (first pair); The correlation between the time coefficients is 0.82. The pattern for the wave distribution explains 43% of the variance. Bottom (Second pair): The correlation between the time coefficients is 0.73. The pattern for the wave frequency explains 21% of the variance.

The RDA model is fitted with data from 1955 to 1974, for the reconstruction of this century and for the climate experiments we used the whole period of available wave data (1955-94).
The first RDA pair (Fig. 2, top) describes 43% of the explained variance of the monthly wave distribution. The time coefficients are correlated with 0.82. The first SLP pattern is characterized by a low-pressure system over

Scandinavia and a high-pressure system west of Ireland. The associated pattern for the wave distribution shows an increase of all percentiles in zonal direction and a decrease in meridional direction. This means higher eastward waves, smaller and less westward waves and also more and increased southwards waves. When such an SLP pattern prevails, more low pressure systems pass Scandinavia in a southwestward direction. Consequently we get more northwesterly winds behind the front of cyclones over the North Sea. The pattern with the negative sign represents a situation with low pressure systems passing southwards off England. Therefore we expect southeast wind for Sylt.
The second RDA pattern pair (Fig. 2, bottom) is correlated with 0.73 and exhibits a small increase in eastward and a decrease in southward directions for the wave probability. In this case the SLP pattern is dominated by a high pressure system over the North Atlantic. On the east side of the anticyclone we get a southward airstream for the North Sea. In the opposite case the northerly winds are weakened, so we get a decrease of southwards and westwards waves. The third pattern pair (not shown) describe the expanation and re-expanation of the zonal and meridional distribution.

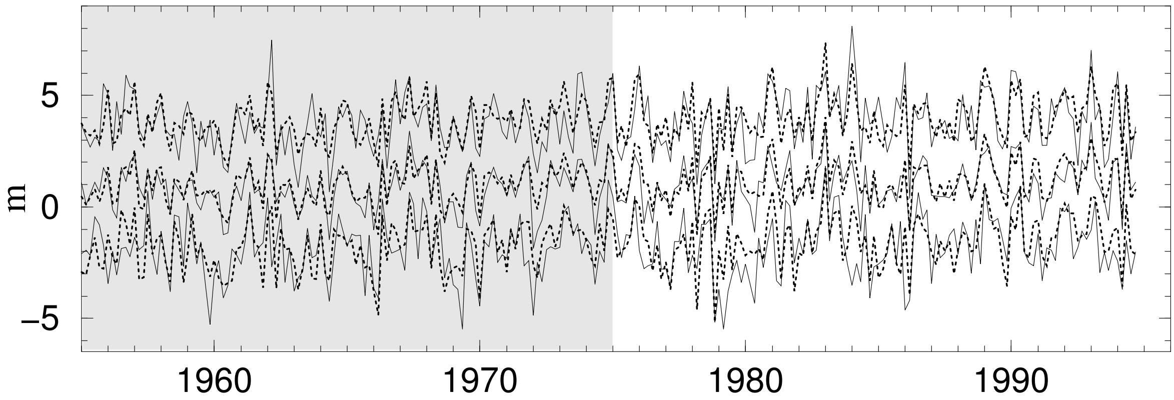


Fig. 3: Time-series of the 5%, 50% and 95% quantile of the monthly wave heights in zonal direction, as derived from 'observed' (solid) and estimated from the monthly mean air-pressure field (dotted). The fitting period is shaded.

The model is validated in an independent period by comparing observed intramonthly percentiles of wave directions with estimated values. Figure 3 shows the time-series of the 5th, 50th and 95th percentile of the monthly waves in zonal direction, as derived from 'observed' (solid) and estimated from the monthly mean air-pressure field (dotted). The fitting period is shaded. We used two conventional measures of skill for the comparison, the correlation skill score and the percentage of represented variance. For all percentiles the correlation is around 0.75 and the explained variance is around 50%. The good agreement demonstrates that the mean atmospheric pressure state is a good indicator for the wave climate.

1.2. Second-order autoregressive model conditioned to the monthly wavestatistic

In a next step 3-hourly wave heights for each direction were modelled using an autoregressive second-order process (Fig.1, III). In the whole period (1955-94) the autocorrelation parameter is fairly independent of the seasons and independent of the direction, so two constant values were used. Between both time series there is no significant autocorrelation, consequently we used two independent processes.
To determine the monthly distribution of the zonal and meridional wave distribution, we used the calculated percentile from the statistical downscaling model. To estimate the values between the available percentiles we use a spline interpolation. Using diagnostics such as autocorrelation functions, quantiles, spectrum and distribution functions the wave generator is validated against the observed wave statistics in the independent period.

2.3 Downscaling model conditioned to the CO_2 concentration

In the last step we needed synthetic timeseries as input for our statistical downscaling model (Fig.1, I). For each RDA pattern we need the corresponding coefficient. Here we also use an autoregressive model, whereas one term is conditioned on the CO_2 concentration. We used a seasonal cycle for the standard deviation and a seasonal cycle for the autocorrelation parameter from month to month. A relevant point is that these three autoregressive processes together produce a realistic long term wave climate variability, that allow us to use the wave generator to estimate the possible variability of the prediction using the output of GCM's. We successfully investigated the ability of the method to produce similar decadal variability compared with a 300 year control run (ECHAM4-OPYC3, not shown).

	WASA in m	SLP in m	$1\times CO_2$ in m
mean	2,73	2,67	2,64
90%	4,60	4,70	4,63
95%	5,50	5,52	5,42
99%	7,40	7,52	7,11

Table 1: Mean wave height and the 90%, 95% and 99% quantile of the wave height from 1955 -1994. 1. row: results from the dynamical wave model WAM. 2. row: weather generator forced with observed SLP. 3. row: weather generator forced with 1 x CO_2 concentration.

To validate the complete statistical model we compared the output with the results of the dynamical wave models (WASA project). Therefore we used the mean wave height and different percentiles to estimate the quality of the wave generator. Table 1 shows the results. The first line is the results of the WASA project where the dynamical wave model (WAM) is forced by a reanalysed wind field. The second line is the output of the statistical model forced by the observed SLP. Third line are the results of the wave generator only conditioned to the control CO_2 concentration.

3. RESULTS FOR THE WAVE CLIMATE UNDER CHANGING CO_2 CONCENTRATION

The model run with default SLP or a fixed or transient time dependent CO_2 concentration. Consequently we could reconstructe the wave climate of the past century with the observed SLP and also produce the future wave climate forced by different GCM's. The wave generator is also able to produce time series of wave data for a fixed CO_2 concentration or a transient change of CO_2 concentration. The 'realistic' long term variability means we could estimate the 'best case' or 'worst case' for the future wave climate.

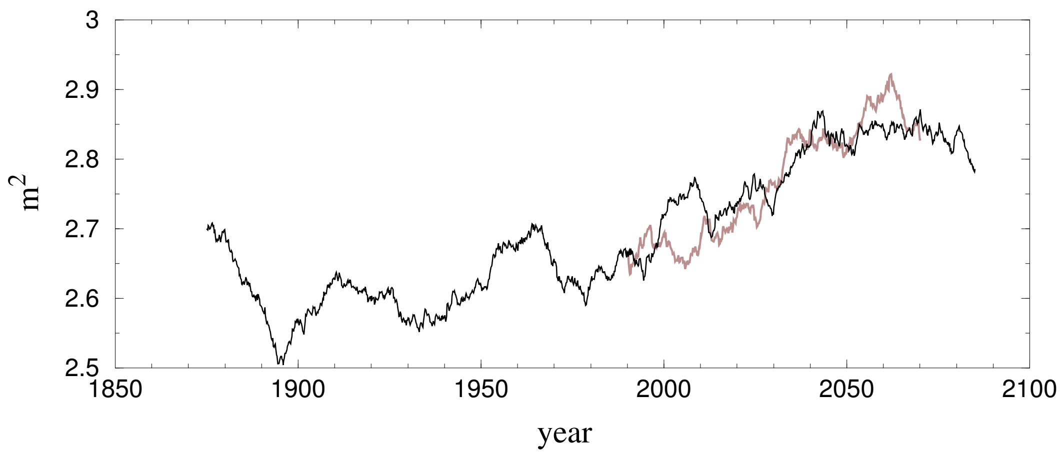
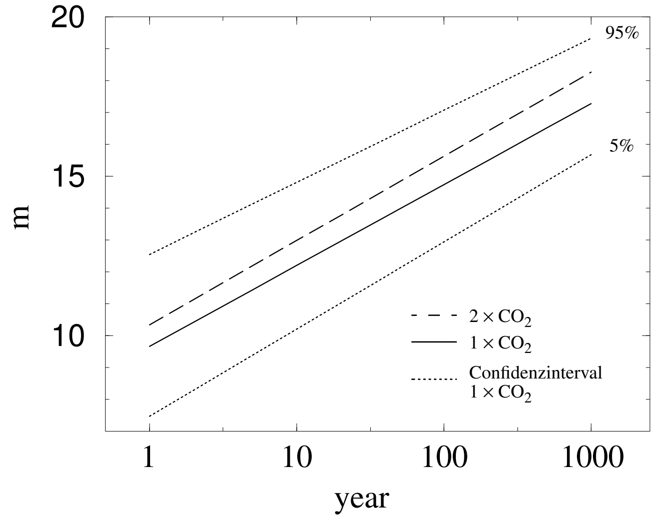


Fig.4 : 30-year running mean of the wave height in the central North Sea (Ekofisk). Forced with SLP of the transient T42 run (1860-2099, black line) and forced with CO_2 concentration (1975-2085, grey line).

Figure 4 show the evolution of the 30-year running mean of the wave height forced with the SLP of a GCM with continiously increasing CO_2 concentration (black line). The grey line demonstrate one result of the weater generator forced only with increasing CO_2 concentration.

For the extreme values of the wave height different return values were calculated. The results for 1 x CO_2 and 2 x CO_2 are shown in Fig. 5.

Investigations for the mean wave heights and intramonthly wave frequency for the directions show an expected



Periode in years	$1{\times}CO_2$ in m	$2{\times}C0_2$ in m	Diff. in m
1	9,4	9,9	0.5
2	10,4	11,1	0,7
5	11,4	12,2	0,8
10	12,3	13,1	0,8
50	14,1	15,0	0,9
100	14,9	15,8	0,9
500	16,3	17,2	0,9
1000	17,1	18,0	0,9

Fig.5: 1 - 1000 year return wave height for the central North Sea. Solid line for $1 \times CO_2$ and dashed line for $2 \times CO_2$ concentration (left). Right: Selected values.

increase of the mean eastward wave heights and also an increase of the duration (Pfizenmayer and Storch, 2001) of these waves.

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