# THE WAVE CLIMATE OF THE NORTH ATLANTIC - PAST, PRESENT AND FUTURE

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# 1. INTRODUCTION

The oceans are an important component of the climate system. Ocean wave height is one of the climate variables that could be affected by anthropogenic forcing. Since the design of off-shore oil platforms and other marine and coastal infrastructures, which are designed to last for several decades, is constrained by the largest wave height event anticipated during a fixed design period, changes in the extremes of wave height could have an impact on the life-span of these infrastructures, which will be in excess of impacts anticipated from the rising sea level. Ocean waves also provide an excellent proxy for trends and variability of storminess. Analysis of wave and storm variability, detection of climate changes therein, and projection of possible future wave climate, are of great importance to the operation/planning and safety of shipping, off-shore industries and coastal development, and to climate research.

The purpose of this study is twofold. First, we will assess changes in the North Atlantic wave heights observed in the 40-year period from 1958 to 1997. Second, we will construct climate change scenarios of wave height in the North Atlantic. We will apply non-stationary Generalized Extreme Value (GEV) analyses to both the observed and projected wave height extremes, to assess distributional changes and their implications.

The remainder of this paper is organized as follows: The datasets and methodologies used in this study are briefly described in sections 2 and 3, subsequently. The observed and projected changes are presented in sections 4 and 5, respectively. Finally, we conclude this study with a summary and discussion in section 6.

### 2. DATA SETS

An intensive reanalysis of surface winds over the North Atlantic basin has recently been completed for the Climate Research Branch of the Meteorological Service of Canada (Swail and Cox, 2000). The reanalyzed wind fields were then used to drive a third generation ocean wave model (OWI 3G) to produce a 40-year numerical hindcast of ocean waves in the North Atlantic for 1958-1997 that compares well with both altimeter and in situ data (Swail and Cox, 2000; Cox et al., 2001). This reconstructed wave height dataset will therefore be used in this study as observed waves. GEV analysis will first be applied to the seasonal maxima of significant wave height (SWH) derived from this wave hindcast, to assess observed changes therein.

Our previous studies (Wang and Swail, 2002 and 2001) revealed that, on the seasonal time scale, significant wave height (SWH) changes in the North Atlantic over the 1958-1997 period are closely associated with changes in the sea level pressure (SLP) observed in the region for the same period. This suggests that SLP can be used to predict SWH, and that possible future SWH anomalies can be projected by feeding GCM projected SLP anomalies into the observed SLP-SWH relationship with the assumption that the relationship will continue to hold in the projected climate. This approach was

adopted in this study. Since the SLP-SWH relationship is much more profound in the winter season (JFM) than in the other seasons, we will just focus on the winter season in the present study.

The observed SLP-SWH relationship will be represented by linear regression. To train a regression model for that purpose, we need observations of seasonal SWH and SLP anomalies. For the reason given above, the 40-year North Atlantic wave hindcast was used here as ocean waves observed in the 40-year period. More specifically, seasonal means and maxima of SWH were first derived from 6-hourly wave data of the hindcast. Then, anomalies of these seasonal statistics, relative to the baseline climate of 1961-1990, were calculated and used as observations of seasonal SWH anomalies. Similarly, anomalies of seasonal mean SLP, relative to its baseline climate, were derived from the twice-daily SLP data of the NCEP/NCAR reanalysis (Kalnay et al., 1996) for the 1958-1997 period and used as observations of seasonal SLP anomalies.

Projections of future SLP anomalies were obtained from the CGCM2 (Canadian second generation general circulation model) ensemble simulations performed with the following three forcing scenarios: i) a modified version of the IPCC IS92a scenario, in which the change in GHG forcing corresponds to that observed from 1850 to 1990 and increases at a rate of 1% per year thereafter until year 2100 (cf. Boer et al., 2000); ii) the SRES A2 and B2 forcing scenarios, which are described in detail in the Special Report on Emissions Scenarios (IPCC, 2000). The forcing includes both greenhouse gas and aerosol loadings. The A2 scenario is similar to the IS92a scenario. The B2 scenario reflects slower economic development and population growth and thus a slower increase in GHG forcing.

For each forcing scenario, an ensemble of 3 integrations was carried out, with each individual integration being initiated from different initial conditions. The integration period is 251 years (1850-2100) for the IS92a scenario and 111 years (1990-2100) for both the A2 and B2 scenarios. The initial conditions for the A2 and B2 scenarios runs are taken from the IS92a scenario run. There are differences between the individual integrations in an ensemble, which are entirely due to natural variability and not due to the differences in the model or forcing (Flato and Boer, 2001). Thus, the 3 members of the ensemble can be considered as 3 samples from the same probability distribution.

For each of the three forcing scenarios, the CGCM2 simulated anomalies of seasonal mean SLP, relative to the baseline 1961-1990 climate simulated using the IS92a forcing scenario, were calculated and used as predictor in the SLP-SWH regression relationship to project possible future anomalies of the seasonal SWH statistics.

The observed SWH data are on a  $0.625^{\circ}$ -latitude by  $0.833^{\circ}$ -longitude grid over the North Atlantic (80°W-20°E, 20°N-70°N). Both the observed and the projected SLP data are on a 96-by-48 Gaussian grid over the globe; but only those data over the Atlantic sector (82.5°W-22.5°E, 16.7°N-72.36°N) were used in this study.

To reduce the dimensionality of the data sets and to focus on their trend components and large scale variabilities, seven leading principal components (PCs/EOFs) of the SWH and SLP anomalies were used instead of the original datasets (cf. Wang and Swail (2002) for more details about the EOF truncation). The seven retained PCs/EOFs account for about 66% of the total variance of winter seasonal maxima of SWH, and for about 93% of the total variance of observed winter seasonal mean SLP (NCEP reanalysis). Most importantly, the observed changes in SWH and SLP are well represented in the retained leading PCs/EOFs. Since there is evidence suggesting that the climate response to external forcing is a change in the occupation statistics of the preferred modes of variability, rather than changes in the modes themselves (Palmer, 1999; Monahan et al., 2000), the CGCM2 simulated SLP anomalies were projected onto the observed EOFs (i.e., EOFs estimated from the SLP of NCEP reanalysis) to obtain simulated PCs of SLP anomalies. The seven retained PCs of the simulated SLP, which represent 87-89% of the total simulated variance of winter SLP, were then fed into the regression model to produce EOF-space projections of SWH anomalies. The EOF-space projections were then converted back to the physical space using the related EOFs.

## 3. METHODOLOGIES

#### 3.1 Redundancy Analysis

The observed SLP-SWH relationship was determined by using a least squares regression technique called redundancy analysis (RA). RA seeks to maximize the associated predictand variance while searching for a hierarchy of the best predicted SWH patterns and the corresponding SLP predictor patterns. RA is similar to canonical correlation analysis (CCA) but in contrast to CCA, treats predictor and predictand asymmetrically in a manner more suited to the SWH specification problem at hand. Details about RA can be found in Wang and Swail (2001 and 2002), Wang and Zwiers (2001), von Storch and Zwiers (1999), and Tyler (1982).

To remove possible artificial dependencies in the fitted regression model, both the predictor and the predictand time series were detrended before being used to train the regression model. Note that the regression model was trained using the anomalies of seasonal means/maxima of SWH, derived from 6-hourly hindcast wave data, and anomalies of seasonal mean SLP of the NCEP reanalysis for the 40-year period from 1958 to 1997. Then, the CGCM2 simulated anomalies of seasonal mean SLP (not detrended) were fed into the RA regression model to project possible future anomalies of seasonal means/maxima of SWH. The projected SWH anomalies were then superimposed on the observed SWH baseline climate, to obtain projections of seasonal means/maxima of SWH. Such a projection was produced using the SLP anomalies derived from each member of each 3-member ensemble of CGCM2 simulations, resulting in three ensembles of 3 member-projections of SWH statistics.

# 3.2 Linear Trend Analysis

The observed and projected time series of SWH statistics at each grid-point was then subject to linear trend analysis, to identify changes in the SWH statistics, and to assess their statistical significance.

The linear trend analysis was performed on seasonal means and maxima of SWH. Since non-Gaussian behaviour is a particular concern for extremes, and the least squares estimator of linear trend is vulnerable to gross errors and the associated confidence interval is sensitive to non-normality of the parent distribution, the nonparametric trend estimator proposed by Sen (1968), which is based on Kendall's rank correlation, was used in this study. The statistical significance of these estimates was evaluated with the Mann-Kendall test for randomness against trend (see Wang and Swail 2001 for more details). For the projected waves, the samples used in the trend assessment are obtained by combining the 3 integrations in the ensemble into a single sample with 3 "observations" at each sampling time  $t_i$ . This is a case of ties in the variable  $t_i$  of the linear regression  $y_i = a + bt_i$ . Thus, the test statistic and the estimator of trend b are modified to incorporate the standard correction for tied observations in variable  $t_i$  (Sen, 1968). In order to reduce the effect of serial correlation on the estimate of trend, the projected SWH time series are pre-whitened by removing the lag-1 auto-correlation as in Wang and Swail (2002).

#### 3.3 Generalized Extreme Value Analysis

In order to assess possible changes in terms of the distribution of wave height extremes, generalized extreme value (GEV) analysis was performed on the seasonal maxima of SWH observed in 1958-1997, and on those projected for the 21st century (2000-2099). The GEV family has distribution functions of the form

$$G(z) = \exp\{-[1 + \xi(\frac{z - \mu}{\sigma})]^{-1/\xi}\}; -\infty < \mu < \infty, \sigma > 0, -\infty < \xi < \infty$$

where  $\mu$ ,  $\sigma$ , and  $\xi$  are the location, scale, and shape parameters, respectively. In order to account for the non-stationarity of SWH extremes, GEV distributions with trends in the location and/or log-scale parameters (details below) were adopted in this study. Extreme value model shape parameters are difficult to estimate with precision, so it is usually unrealistic to try modelling  $\xi$  as a smooth function of time. We assume that  $\xi$  is constant in a season. Let the notation  $\text{GEV}(\mu, \sigma, \xi)$  denote the GEV distribution with location parameter  $\mu$ , scale parameter  $\sigma$ , and shape parameter  $\xi$ . Then, the following five nested GEV models,  $\text{GEV}_i$  with the subscript i (i = 0, 1, 2, 3, 4) denoting the number of trend-parameters ( $\beta$ s and  $\theta$ s) in the GEV distribution, were fitted to the observed and projected seasonal maxima of SWH (see section 3.1) at each grid-point, separately:

- GEV<sub>0</sub> ( $\mu$ ,  $\sigma$ ,  $\xi$ ), i.e., all parameters are constant (no trends);
- GEV<sub>1</sub> ( $\mu_t = \mu_o + \beta_1 t, \sigma, \xi$ ), i.e., linear trends in the location parameter only;
- GEV<sub>2</sub> ( $\mu_t = \mu_o + \beta_1 t$ , log( $\sigma_t$ ) =  $b_o + \beta_2 t$ ,  $\xi$ ), i.e., linear trends in both the location and the log-scale parameters;
- GEV<sub>3</sub> ( $\mu_t = \mu_o + \beta_1 t + \theta_1 t^2$ ,  $\log(\sigma_t) = b_o + \beta_2 t$ ,  $\xi$ ), i.e., quadratic trends in the location parameter and linear trends in the log-scale parameter;
- GEV<sub>4</sub> ( $\mu_t = \mu_o + \beta_1 t + \theta_1 t^2$ ,  $\log(\sigma_t) = b_o + \beta_2 t + \theta_2 t^2$ ,  $\xi$ ), i.e., quadratic trends in both the location and the log-scale parameters.

Let  $L_i$  denote the maximized value of the log-likelihood for model GEV<sub>i</sub> (i = 0, 1, 2, 3, 4). Then, a test (likelihood ratio test) of the validity of model GEV<sub>j</sub> relative to model GEV<sub>i</sub> (i < j) at the  $\alpha$  level of significance is to reject model GEV<sub>i</sub> in favor of model GEV<sub>j</sub> if the deviance statistic  $D_{ji} = 2(L_j - L_i) > \chi_k^2(\alpha)$ , where  $\chi_k^2(\alpha)$  is the (1- $\alpha$ ) quantile of the  $\chi_k^2$  distribution, with k (number of degree of freedom) being the difference in the number of estimated parameters in models GEV<sub>j</sub> and GEV<sub>i</sub>. Here, we set  $\alpha = 0.05$ . The first four likelihood ratio tests were carried out for models GEV<sub>i</sub> (i = 1, 2, 3, 4) relative to model GEV<sub>0</sub>, to assess the significance of linear/quadratic trends in the location and/or log-scale parameters. Then, further tests were carried out for model GEV<sub>i</sub> over model GEV<sub>i-1</sub> (for i = 2, 3, 4), to ensure that the performance improvement of model GEV<sub>i</sub> over model GEV<sub>i-1</sub> is significant at the specified level. The results of these tests show that, for the SWH extremes observed in 1958-1997, only linear trends in the location parameter were found to be of field significance (Livezey and Chen, 1983), while for the waves projected for the next century (2000-2099), the quadratic components of trend are of field significance for both parameters. Therefore, the fitted model GEV<sub>4</sub> (GEV<sub>1</sub>) is chosen for use in the estimate of return values/periods of the projected (observed) wave heights later.

The ultimate goal of extreme value analysis is to make inferences about the size and frequency of extreme events. Changes in the extreme value of a fixed return period or in the return period of a fixed extreme value are manifestations of the effect of climate change on the extremes. Based on the fitted GEV distribution whose location and/or log-scale parameters could vary with time, on the one hand, 20-yr return values ( $Z_{20yr}$ ) of SWH were estimated using the parameters values of years 1960, 1980, and 2000 for the observed waves, and using those of years 2000, 2050, and 2080 for the projected waves. (20-yr return values are thresholds which are exceeded, on average, once every 20-yr period.) The differences between 2000's and 1960's, and between the 2050's and the 2000's 20-yr return values were calculated as a measure of climatic changes in terms of SWH extremes. To show the effect of the quadratic nature of trend in the projected waves, the differences between the 2080's and the 2000's 20-yr return values were calculated. On the other hand, the possible future return periods of the 2000's 20-yr return values were estimated using the parameters values of year 2050, to assess projected changes in the frequency of the fixed extreme wave heights.

### 4. CHANGES IN OBSERVED WAVE HEIGHTS

Fig. 1 shows the results of performing linear trend analysis on the 1958-1997 time series of winter seasonal means and maxima of SWH at each grid-point, separately. For both the means and maxima, significant increases were identified in the northeast North Atlantic, which are accompanied by decreases in the subtropical North Atlantic. Although the seasonal means and maxima share similar

patterns of trend, the rates of increase of the seasonal means (2-4 cm/yr) are much smaller than those of the seasonal maxima (4-9 cm/yr).

The GEV analysis (see section 3.3) reveals that the changes of SWH extremes observed in the 40-year period can well be represented by a linear trend in the location parameter only. Changes in the scale parameter were found to have no field significance (Livezey and Chen, 1983). Therefore, the fitted  $\text{GEV}_1$ , i.e., a GEV distribution with linear trends in the location parameter, was chosen for use to estimate the return values for the observed wave height extremes, and to assess changes therein.

The 20-year return values estimated using the parameter values of year 1960 is shown in Fig. 2a. We also estimated the 20-year return values using the parameter values of year 2000. The differences between 2000's and 1960's 20-year return values are shown in Fig. 2b. Clearly, the 20-year return value of SWH in the northeast North Atlantic increased by 180-380 cm in the 40-year period from 1961 to 2000. In other words, the increase rate for the 20-year return value of SWH in this region is 4.5-9.5 cm/yr. The increases in the northeast North Atlantic are accompanied by decreases in the subtropical North Atlantic (Fig. 2b). Not surprisingly, the pattern of changes in the 20-year return value of SWH is very similar to the pattern of changes in the seasonal maxima (cf. Figs. 1b and 2b).

# 5. WAVE HEIGHT CLIMATE CHANGE SCENARIOS

In this section, we first describe the wave height changes projected for the 21st century, as well as the wave climate change scenarios for 2050s and 2080s. Then, we discuss the implications of projected changes for extreme wave height events.

#### 5.1 Changes Projected for the 21st Century

Using datasets described in section 2 and the regression technique described in section 3.1, for each of the three forcing scenarios, we constructed an ensemble of 3 projections of seasonal means and maxima of SWH. The 3 projections in each ensemble are considered to be 3 samples for the same series of sampling times, which are the 201 years from 1900 to 2100 for the IS92a scenario, and the 101 years from 1990 to 2100 for both the A2 and B2 scenarios. To assess projected changes in the 21st century, time series of the SWH statistics at each grid point spanning the 100-year period from 2000 to 2099 were first subject to the linear trend analysis described in section 3.2. The results are shown in Fig. 3.

Clearly, all the three scenarios share similar patterns of trend, but the trends associated with the IS92a and A2 scenarios are generally more significant than those related to the B2 scenario (see Fig. 3 and Table 1). Besides, the projected changes are larger, and statistically more significant, in the high latitudes for the A2 scenario, and in the mid-latitudes for the IS92a scenario. These between scenarios differences are more apparent for the extremes than for the means of SWH. Overall, similar forcing scenarios (IS92a and A2) lead to similar changes in SWH, while a scenario (B2) with a slower rate of increase in GHG forcing leads to a slower rate of change in SWH.

Table 1. The maximum rates of increase (cm/yr) in the winter seasonal means (Havg) and maxima (Hmax) of SWH and the maximum differences (D in cm) between 2080s' (2070-2099) and 1970s' (1961-1990) climates as projected with the IS92a, A2 and B2 forcing scenarios.

	Rates of increase			D $(2080s' - 1970s')$		
	IS92a	A2	B2	IS92a	A2	B2
Havg	0.27  cm/yr	0.35  cm/yr	0.13  cm/yr	$35~\mathrm{cm}$	$29~\mathrm{cm}$	14 cm
Hmax	1.11  cm/yr	1.18  cm/yr	0.50  cm/yr	$115 \mathrm{~cm}$	110  cm	68  cm

The projected patterns of trend for the seasonal means are also similar to those for the seasonal maxima of SWH. However, the rates of change projected for the maxima are much higher than those projected for the means. For the northeast North Atlantic, for example, the projected increase is

0.1-0.4 cm/yr for the means, and 0.2-1.2 cm/yr for the maxima. In particular, much greater increases are projected for the maxima in the region off the French-Iberian coast than for the means (cf. Figs. 3c and 3d), especially with the IS92a and A2 forcing scenarios (see also Table 1).

#### 5.2 Climate Change Scenarios for 2050s and 2080s

In this study, a climate change scenario for 2050s (or 2080s) refers to the difference between the climate projected for 2050s (or 2080s) and the observed baseline climate (i.e., projected minus observed), where 2050s (or 2080s) means the 30-year period from 2040-2069 (or 2070-2099).

As shown in Fig. 4, the patterns of climate change scenarios generally bear substantial similarity to the corresponding trend patterns shown in Fig. 3. The wave height climate projected for 2080s was found to be significantly different from the corresponding observed baseline (1961-1990) climate for most areas of the ocean, for both seasonal means and maxima (cf. panels b, d, e, and f in Fig. 4). However, the wave height climate changes by 2050s will be much less significant (cf. Figs. 4a and 4c).

Climate changes appear to be more significant and extensive for the seasonal maxima than for the seasonal means. By 2080s, increases of 35-115 cm are projected for the seasonal maxima of SWH in the northeast North Atlantic, but the increases projected for the seasonal means in this region are only 20-35 cm (cf. Figs. 4b and 4d). The significant changes in the seasonal maxima in the region off the French-Iberian coast were not found for the corresponding seasonal means (cf. Figs. 4b and 4d).

All the three forcing scenarios share similar patterns of ocean wave climate change (cf. panels d-f in Fig. 4), but the changes associated with the IS92a and A2 scenarios are more significant than those related to the B2 scenario (see also Table 1). Again, this indicates that similar forcing scenarios lead to similar changes in ocean waves, and that a scenario of slower rate of increase in GHG forcing leads to smaller changes in ocean waves.

#### 5.3 Implications of Projected Changes for Extreme Wave Height Events

The GEV analysis described in section 3.3 was carried out for the 3 IS92a scenario projections (combined) of winter seasonal maxima of SWH of the 21st century (2000-2099). The results show that there exist significant quadratic trends in both the location and log-scale parameters. Therefore, the fitted  $\text{GEV}_4$ , .i.e, a GEV distribution with quadratic trends in both the location and log-scale parameters, was chosen for use to estimate the return values/periods for the projected seasonal maxima of SWH.

Fig. 5a shows the 20-yr return values of the projected SWH using the parameters values as of year 2000, i.e., the 2000's 20-yr return values of SWH, which are expected to occur on average once every 20 years in the present (2000's) climate. To explore changes in the frequency of extreme wave height events, we estimated the possible future return periods of these 2000's 20-yr return values using the parameters values as of year 2050. The results are shown in Fig. 5b. In the northeast North Atlantic, for example, the extreme wave events that occur on average once every 20 years in the present climate are projected to occur on average once every 5-15 years in the climate projected for year 2050 (cf. Fig. 5b).

To measure changes in the size of extreme wave height events, we also estimated the 20-yr return values of the projected SWH using the parameters values as of years 2050 and 2080. The differences between the 2050's (or 2080's) 20-yr return values of SWH are shown in Fig. 5c (or 5d). In the 50-year period from 2001 to 2050, for example, there is a total of 20-80 cm increase in the 20-yr return values of SWH in the northeast North Atlantic (cf. Fig. 5c). However, the changes by 2080 (cf. Fig. 5d) are a little smaller than those by 2050, which is a manifestation of the quadratic nature of trend, for example, in the region west of Scotland (cf. Figs. 5c and 5d).

## 6. CONCLUDING REMARKS

We have assessed changes of significant wave height in the North Atlantic, as observed in the 1958-1997 period, and as projected using the CGCM2 simulations with three forcing scenarios. The

implication of climate change for extreme wave height events was also explored.

It has been shown that both the seasonal means and extremes of SWH in the northeast North Atlantic experienced significant increases in the 40-year period from 1958 to 1997, which is accompanied by decreases in the subtropical North Atlantic. The rate of increase was 4.5-9.5 cm/yr for the extreme wave height events that occur on average once every 20 years. For the seasonal means, the rate of change is about half of that for the corresponding seasonal maxima. The changes can well be represented as linear trends.

With all the three forcing scenarios, the northeast and southwest North Atlantic were projected to have significant increases in both seasonal means and maxima of SWH in winters of the 21st century, which is qualitatively consistent with the double  $CO_2$  scenario of the WASA group (1998). However, the rates of change projected for the next century are much smaller than those observed in the 1958-1997 period. The projected changes have significant quadratic components.

The wave height climate projected for 2080s (2070-2099) is highly significantly different from the climate observed in 1970s (1961-1990), with increases of 52-115 cm (or 14-35 cm) in the climate of seasonal maxima (or means) of SWH (cf. Table 1). However, the wave height climate changes will not be very apparent by 2050s.

The GEV analysis on the projected seasonal maxima of SWH showed that climate change can result in changes in the location and/or scale parameters of the distribution of wave height extremes, eventually leading to changes in the size and frequency of extreme wave height events. For example, in the region west of the southern Scandinavian coast, an extreme wave height event that occurs on average once every 20 years in the present (2000's) climate will occur on average once every 5-15 years in the climate projected for year 2050 (IS92a scenario). Such significant changes will have an impact on the life-span of marine and coastal infrastructures in the area. The possible changes in future wave extremes should be taken into account in the design/planing and operation of coastal and off-shore industries.

The anthropogenic forcing affects the ocean wave climate probably by changing the occupation statistics of atmospheric circulation regimes. On the one hand, using the CGCM1 simulations of the Canadian Centre for Climate Modelling and Analysis, Monahan et al. (2000) concluded that under global warming, the episodic split-flow regime (which resembles the extreme negative phase of the NAO in SLP) occurs less frequently while the standing oscillation regime (which resembles the Arctic Oscillation) occurs more frequently. On the other hand, the northeast North Atlantic was projected in the present study to have significant wave height increases in the warmer climate. In other words, global warming is associated with less frequent occurrence of the extreme negative phase of NAO (or relatively more frequent occurrence of the positive phase of NAO) on the one hand, and with increases of wave height in the northeast North Atlantic on the other hand. The implication here is that the projected wave height increases in the northeast North Atlantic are associated with the anthropogenic changes related to NAO. Such a relationship between NAO and the wave height makes sense physically and is well supported by observational evidence: the significant increases of winter wave height observed in the northeast North Atlantic in 1958-1997 were found to be closely related to an "enhanced" positive phase of NAO prevailing in the season (or an upward trend in the winter seasonal NAO index; Wang and Swail, 2001 and 2002).

Note that the basic assumption for the wave height projections in this study is that the SLP-SWH relationship developed for the present day climate also hold under the different forcing conditions of possible future climates. Although the empirical based technique is economic and practical, it cannot account for possible systematic changes in regional forcing conditions or feedback processes. The various sources of uncertainty related to climate scenario construction (IPCC 2001) should be kept in mind when interpreting/using the climate change scenarios.

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Figure 1. Changes of winter (JFM) seasonal means and maxima of Significant Wave Height (SWH) observed in 1958-1997. The contour interval is 1 cm/yr. Solid and dashed lines are positive and negative contours, respectively (zero contours are not drawn). Hatching indicates areas of significant changes.



Figure 2. a. The 20-yr return values  $(Z_{20yr} \text{ in } m)$  of the observed winter SWH, estimated using the GEV parameters of year 1960. The contour interval is 0.5 m. b. The difference (cm) between 2000's and 1960's (2000's - 1960's)  $Z_{20yr}$  of the observed SWH. The contour interval is 30 cm. Solid and dashed lines indicate positive and negative contours, respectively.



**Figure 3.** The same as in Fig. 1 but for changes of winter (JFM) seasonal means (a, c, e) and maxima (b, d, f) of SWH, as projected for the 21st century (2000-2099) from the CGCM2 simulations of SLP using the indicated forcing scenarios. Note that the contour interval here is 0.1 cm/yr.



**Figure 4.** The differences (cm) between the climate of winter seasonal means (a, b) and maxima (c, d) of SWH projected for 2050s (2040-2069) or 2080s (2070-2099) and the corresponding observed baseline climate (i.e., projected minus observed). The contour interval is 5 cm. Solid and dashed lines are positive and negative contours, respectively (zero contours are not drawn). Hatching indicates areas of significant changes.



Figure 5. a. The 20-yr return values  $(Z_{20yr} \text{ in m})$  of the projected winter SWH, estimated using the GEV parameters of year 2000. The contour interval is 0.5 m. b. The return periods of the 2000's 20-yr return values  $(Z_{20yr})$  of the projected SWH, estimated using the GEV parameters of year 2050. The contour interval is 2.5 year. Solid and dashed contours indicate return periods shorter and longer than 20 year, respectively. c. The difference (cm) between 2050's and 2000's (2050's - 2000's)  $Z_{20yr}$  of the projected SWH. The contour interval is 10 cm. Solid and dashed lines indicate positive and negative contours, respectively. d. The same as in c but for the difference between 2080's and 2000's (2080's - 2000's)  $Z_{20yr}$ .