CHAPTER 12

Climatic trends and scenarios

In the preceding chapters we have described in detail several methods of performing extremal analysis for wave heights, which can be applied to any time series of wave data, whether in situ measurements, satellite estimates or produced from numerical models. However, by virtue of the very long temporal extent of the time series required to produce these long return period estimates, e.g. 50- or 100-year (or longer) wave heights, the requirement of stationarity in the data set may not be met due to changes in the wave regime caused by climate variability and/or trend. It is therefore relevant to consider possible implications of intensification or weakening of waves on decadal or century time scales for estimating long return period wave heights.

The first indication that such changes were taking place in the North Atlantic was given by [Carter, Draper, 1988] using wave measurements at the Ocean Weather Stations. Subsequent analysis of similar data by [Hogben, 1988] showed that such trends were characteristic for mean wave heights, but they were not present in maximum wave heights. [Hogben, 1988] suggested that the mean wave height trend is explained by some intensification of background swell, which is associated with oscillations of the North Atlantic current.

Subsequently, Bouws et al. (1996) at the Netherlands Meteorological Institute, using operational ship routing wave analyses, found trends in a box west of Ireland (50-55N, 10-20W) over the period 1961-1987 on the order of 0.3% per year for both the annual maximum and the 99th percentile wave height. The trend in the 90th percentile values was larger, 0.7 % per year. These trends were considered (WASA, 1998) to suffer from some inhomogeneity, leading to an artificial increase in wave heights, and thus to be an upper bound on real trends.

A significant advance on the issue of wave height variability and trend was made by the project WASA (Waves and Storms in the North Atlantic [WASA group, 1998]). Within the WASA project Gunther et al. (1998) attempted to reconstruct the time-space wave fields statistics using a proven wave model driven by a 40-year time series (1955 to 1994) of 6-hourly wind fields for the Northeast Atlantic ocean. While the wind fields used in the analysis (Fleet Numerical Meteorological and Oceanographic Center operational winds, and Norwegian Meteorological Institute operational analyses) contained some inconsistencies and inhomogeneities over the 40-year period of the hindcast, comparison of the resultant wave fields with in situ measurements showed reliable results.

Analysis of the resulting wave fields in the northeast Atlantic showed the existence of areas of wave growth and decrease. The 90% percentile value of significant wave height was shown to increase at 2 cm/year rate in the area to NW of Scotland, and 1 cm/yr over a wide area extending from the North Sea through the Norwegian Sea. The same percentile decreased at rate of 1 cm/year in the open ocean west of Ireland and the Bay of Biscay. Comparison of the 99th percentile and maximum wave heights at OWS Mike, and the Brent and Ekofisk platforms showed the largest increases in wave height (and wind speed) to be associated with the maxima, the lowest for the 90th percentiles; this results in a widening of the distribution. Off the coast of Ireland the increases are much smaller (1 cm/yr) than those derived by Bouws et al. (1996) (2.7 cm/yr). This analysis is also notable in that, when the full 40-year hindcast period is considered in contrast to the shorter ship routing analysis, that the trend west of Ireland is actually decreasing.

WASA (1998) extended the time series of the hindcast through statistical reconstruction based on redundancy analysis (RDA; von Storch and Zwiers, 1998). This technique predicts the intramonthly wave height patterns based on monthly mean air pressure patterns. Using this approach the statistically derived wave heights for Brent and Ekofisk were generated for the period 1899 to 1994. The reconstruction confirmed the increase in the 40 years of the numerical hindcast. What is noteworthy is that the trends were not apparent when the longer period was considered, i.e. the reconstructed wave heights from the early part of the century were similar to those in the last decades of the hindcast.

Gunther et al. (1998) explicitly looked at trends in the tails of the distributions, representing the most extreme events. Extremal analysis was carried out for each point in the northeast Atlantic for the four ten-year time slices in the hindcast. A peak-over-threshold technique (average 5 peaks per year), using least squares fitting with a Fisher-Tippet III distribution (at most points) was applied in the analysis.

The results of this analysis showed clear spatial patterns. In the area between Scotland and Iceland the trend in 100-year wave height was increasing (exceeding 2m/decade), while this statistic decreased southwest of Ireland (< 1m/decade).

The trends in storminess were also found in geostrophic wind analyses by Alexandersson et al. (1998) for the British Isles, North Sea and Norwegian Sea. The trends increased significantly from 1960 onward, but when extended back to the beginning of the record in 1881 no trends were apparent.

The WASA project also attempted to predict the effects on extreme waves of a double CO_2 scenario. A time-slice experiment was performed on two 5-year intervals (Rider et al. 1996). Gunther et al. (1998) calculated the 20-year return period wave height on both the control and 2X CO_2 runs. The results were very similar to the patterns found in the 40-year hindcast, increases south of Iceland, and decreases southwest of Ireland.

A significant advance in numerical wave hindcasts resulted from the NCEP/NCAR meteorological re-analysis project (see, e.g. [Kalnay et al., 1996]), which produced global data series of great interest to wave modelling. NCEP reanalysis data were used in [Swail and Cox, 2000; Cox and Swail, 2000] for both a global reconstruction of past wave fields, and a detailed wave reconstruction of the North Atlantic Ocean. The use of the reanalysis products to drive the wave model removed many of the inhomogeneities present in earlier data sets; the further analysis efforts described by Swail and Cox (2000) for the North Atlantic Ocean removed still more inhomogeneities, and equally importantly produced a much finer grid scale analysis which resolved to a much greater degree both tropical and extratropical storms. This additional analysis is critical in the modelling of the most extreme waves, as selected in the computation of long return period estimates.

Wang and Swail (2000) analyzed the global model hindcast results for the Northern Hemisphere. As in the WASA study, the analysis showed areas of increasing wave height and corresponding areas of decrease. In both the North Atlantic and North Pacific, significant linear trends in the seasonal extremes (90th, 99th percentiles) were identified. In the North Atlantic, significant increases in the northeast Atlantic over the last four decades (similar to WASA) are matched by significant decreases in the subtropical Atlantic.

Increases in the 99th percentile wave height in the area between Scotland and Iceland are typically 0.4 to0.5 %/yr. In the North Pacific, significant changes are found in the winter and spring wave heights, with increases over much of the north Pacific, and some decrease in the subtropics. Increases in winter 99th percentile waves of 0.25 to 0.50 %/yr are common across the area.

As in WASA, Wang and Swail (2000) also extended the time series of the hindcast through statistical reconstruction based on redundancy analysis. Statistically derived wave heights were generated for the period 1899 to 1997. The reconstruction confirmed the increase in the 40 years of the numerical hindcast for both the North Atlantic and North Pacific. For both oceans, no significant trends of seasonal wave extremes are found for the last century, though significant changes do exist in the past four decades. There is, however, significant long-term variability, especially in the North Pacific.

Analysis of the detailed North Atlantic hindcast, described by Swail et al. (2000), was carried out by Swail and Wang (2001). The seasonal patterns were very similar to those from the global hindcast, but with generally greater rates of change. In the North Atlantic hindcast a larger area of significant decreases of SWH was observed in the western subtropical Atlantic in winter. Significant increases are identified off the coast of Canada in summer, and for the central North Atlantic in fall. These differences result from the enhanced wind fields for tropical storms and kinematic reanalysis of wind fields.

In the North Atlantic study, monthly statistics were also described. There were large variations from month to month. Rates of change were generally larger than for the seasonal analysis.

Extremal analysis was also carried out, as in WASA. A Gumbel (and Weibull) analysis was applied for each grid point in the North Atlantic using a peak-over-threshold-approach. Since the hindcast covered the entire North Atlantic, and not just the northeast portion as in WASA, separate analyses were run on tropical and extratropical system peaks. Ten- and twenty-year time slices were analyzed; results of the four 10-year slices for extratropical storms are shown in Figure 12.1.

Details of the extremal analysis are given in Swail et al. (2000). Examination of Figure 12.1 shows that, while there is some consistency among the four time slices, there is considerable variability in the magnitude of the return period wave heights, and in the spatial patterns of the extremes, as storm tracks migrate from one position to another.

The decadal time slice extremal analyses done in both WASA and Swail et al. (2000) are one way to try and gauge the change and variability of the most extreme wave conditions. However, the sample for the trend analysis is necessarily reduced to four, in a 40-year hindcast. Another approach which is often taken is to compute time slices is based on a running sample. As an example, the 100-year wave based on years 1-10 is computed and assigned to year 10; the 100-year wave is recomputed for years 2-11 and assigned to year 11, and so on. The number of points then available for the trend and variability analysis is then (N-(m-1)), where N is the length of the database (e.g. 40 years) and m is the length of the slice (e.g. 10 years).

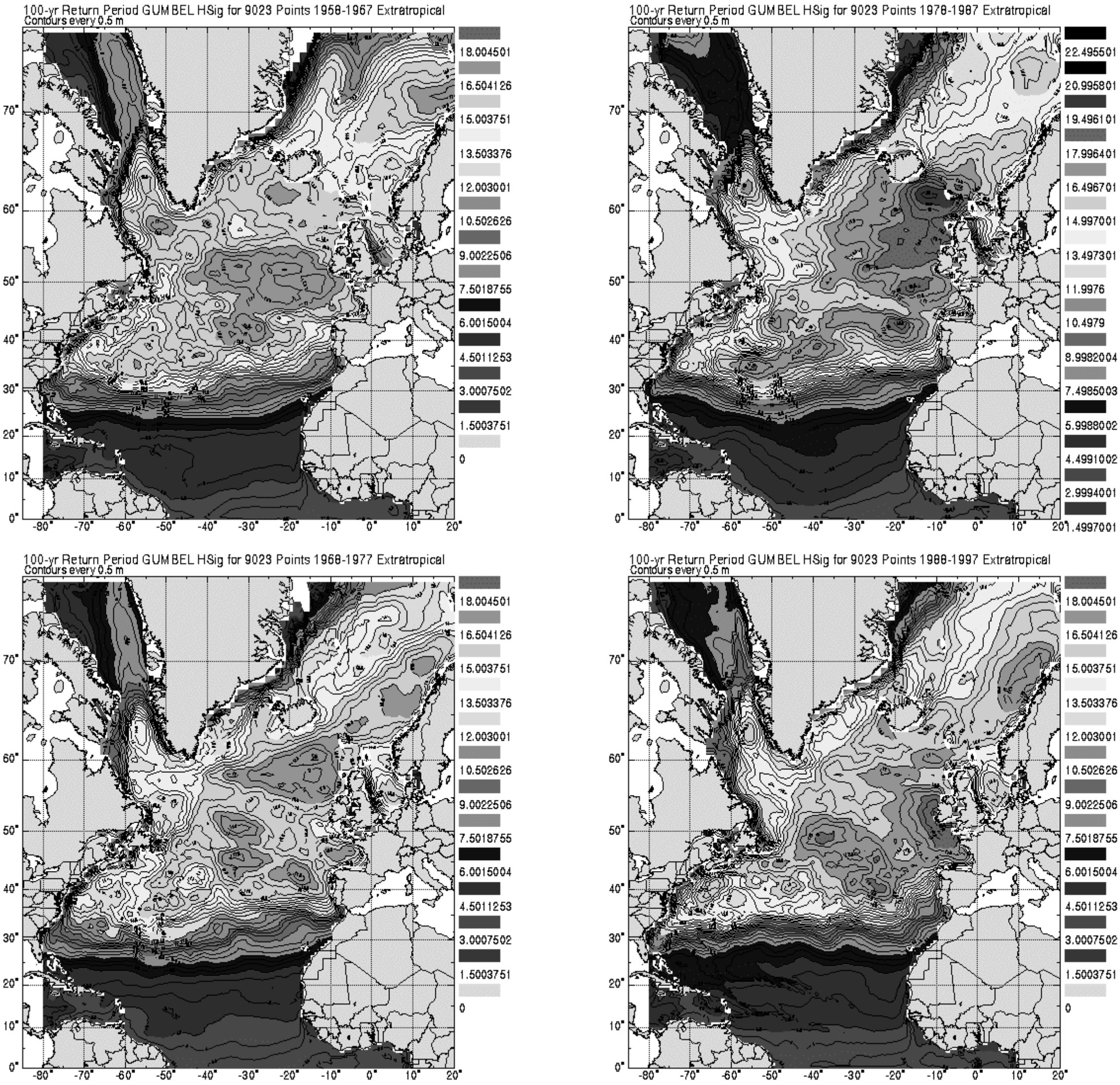

Figure 12.1: Decadal time slice extremal analysis (Gumbel) of extratropical storms

This method is easiest to visualize with the Annual Maximum method, but can also be used with other approaches, e.g. peak-over-threshold. An example of the year-to-year variability and trend in the 100-year return period wave height at Hibernia is shown in Fig. 12.2. Two things are immediately evident from this figure: (1) the 100-year wave height varies considerably depending on which 10-year slice it is based on and, (2) the 100-year wave height has a slight increasing, but statistically insignificant trend over the sampled time interval.

Another area of important research is the analysis of different scenarios of climate change and their implications for wind waves and storm surges. This is the subject of the project STOWASUS-2100 (STOrm WAves and SUrges Scenarios for the 21st century, [http://gate.dmi.dk/pub/project/STOWASUS-2100/]) The project envisages modelling of storm conditions in the 21st century according to several different scenarios on the atmospheric CO_2 increase. Two 30-year time slice simulations with the ECHAM4 climate model are performed. Investigations regarding systematic anomalies in frequency, intensity or location of extreme events, and the physical mechanisms responsible for them are carried out. Preliminary analysis has shown (STOWASUS-2100, 2nd Progress Report) that significant wave heights are slightly increased in the Northeast Atlantic and North Sea region, with increases in the 99th percentile values at some locations of almost 10%. Differences in the mean wave heights between the control run and the 2X CO_2 model run are small, mostly less than 0.15m.

The preceding paragraphs present a bewildering array of information on trend and variability of extreme wave conditions. Trends may be either increasing or decreasing; similarly, the variability may be increasing or decreasing. The uncertainties in the estimates of variability can be large. This presents something of a dilemma in how to account for such changes. Are these changes the result of anthropogenic climate change, which can be expected to continue? Or are they merely part of the natural variability of the atmosphere-ocean system, which can be accounted for if the sampling period is sufficiently long?

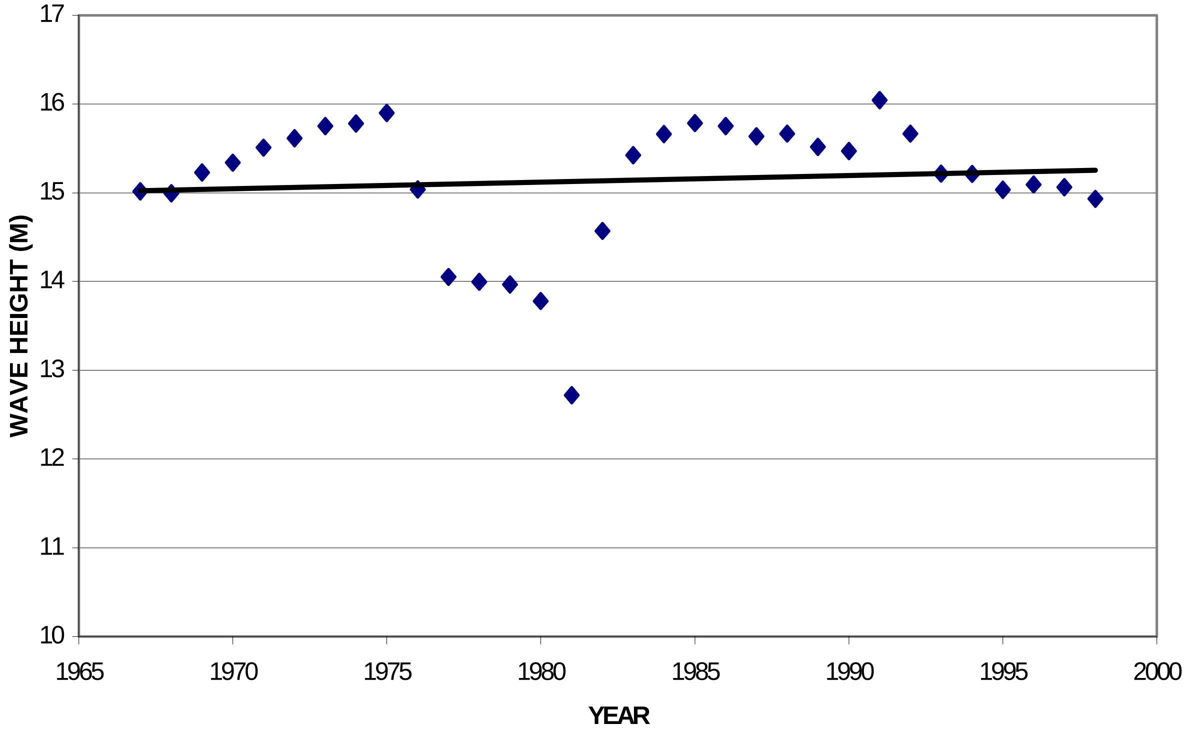

Figure 12.2: 100-year return period wave height variations. Hibernia

The basic issue for the analysis of long-term data series or simulation output is the significance of trend estimates. Various statistical models can be used to estimate the trends. The simplest model is parametric linear regression

$$\zeta(t)=b_0+b_1t+\varepsilon \tag{12.1}$$

where b_0, b_1 are parameters and ε denotes white noise.

If the white noise ε, which in fact is the deviation of annual averages from the trend, is Gaussian, then it is possible to use the following relations to estimate parameters in (12.1):

$$b_1=\frac{\sum\limits_i(t_i-\bar{t})(\zeta_i-\bar{\zeta})}{\sum\limits_i(t_i-\bar{t})^2};\quad b_0=\bar{\zeta}-b_1\bar{t} \tag{12.2}$$

For data series of finite length the estimates (β_0, β_1) for parameters *(b_0,b_1)* represent a system of random values. Let us introduce a new notation:

$$\gamma=\begin{bmatrix}\gamma_0\\ \gamma_1\end{bmatrix}=\begin{bmatrix}\beta_0-b_0\\ \beta_1-b_1\end{bmatrix} \tag{12.3}$$

Using it we can represent a two-dimensional confidence range (1–α)% for values (β_0, β_1) as the internal part of the ellipse

$$n\gamma_0^2+2\gamma_0\gamma_1\sum_i t_i+\gamma_1^2\sum_i t_i^2=c \tag{12.4}$$

and express the solution in variables (γ_0,γ_1). The roots of the equation are

$$\begin{bmatrix}\gamma_{11}\\ \gamma_{12}\end{bmatrix}=\left\{\left(-\gamma_0\sum_i t_i\right)\mp\sqrt{\left(\gamma_0\sum_i t_i\right)^2-\left(\sum_i t_i^2\right)(n-c)}\right\}\Bigg/\sum_i t_i^2 \tag{12.5}$$

where $c=pS^2F(p,v,1-\alpha)$, p=2, v=n–p and α is the confidence level. They determine the orientation of the ellipse main axes.

If the point (β_0,0) is covered by the (1–α)% confidence limit ellipse, we can say that the significant criterion for the trend is satisfied. Then we can assume that the original data series is stationary. If the criterion is not satisfied, the series is not stationary.

More detailed quantitative analysis of trends in the parameters of probability distributions requires processing of mixture of various distributions, which goes beyond the scope of this review.

Importantly, possible existence of trends in the data series does not alter basic conclusions of this review.

---oooOooo---