NORTH ATLANTIC WAVE CLIMATE EXTREMES AND THEIR VARIABILITY

E. A. Orelup[1], A. Niitsoo[2], and V. J. Cardone[1]

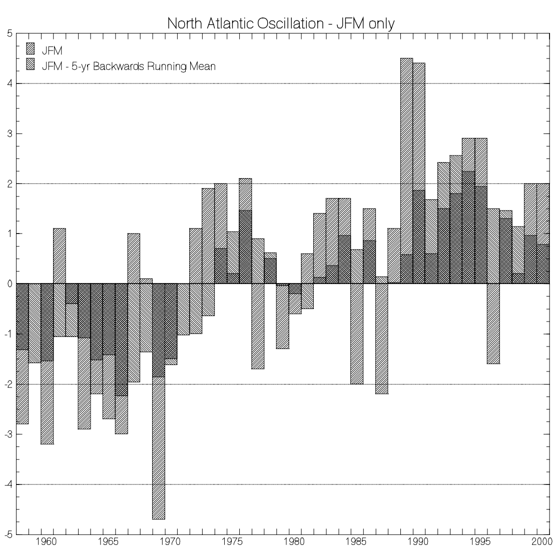
Oceanweather inc., Cos Cob, CT, USA[1], Meteorological Service of Canada, Downsview, Ontario, Canada[2]

1. INTRODUCTION

Three characteristics of the MSC40 wave hindcast make it particularly appropriate to study the spatial and temporal variability of North Atlantic (NA) wave extremes. First, an interactive objective kinematic analysis (IOKA) system (Cox *et al.*, 1995) was employed to generate wind fields to ensure that the major jet streaks around extratropical storms were resolved correctly and that wind speed maxima were not biased low. Second, wind fields in all tropical cyclones were derived with a mesoscale model and blended into the full basin forcing wind fields before the wave hindcast was carried out. Finally, since the background wind field (NCAR/NCEP ReAnalyses or NRA), the processing of all basic data sources and the analysis method (IOKA) were applied in a consistent manner (Cox *et al.*, 1998) over time, the MSC40 hindcast is largely free of the "creeping inhomogeneities" in previous efforts that make difficult the isolation of the effects of true trend and variability from hindcast bias. Much work has already been carried out using MSC40 to study trends in the wave climate of the NA (Swail and Cox, 2000; Swail *et al.*, 2000; Wang and Swail, 2002) and to relate those trends to past and possible future secular changes in pressure patterns over the North Atlantic (Swail *et al.*, 2002). This paper presents preliminary results on the variability of the model simulated extremes of significant wave height (SWH) and examples of possible coupling of variability of extremes to sources of climate variability known to affect NA weather patterns.

2. WINTER MEAN NORTH ATLANTIC OSCILLATION (NAO) AND BASIN AVERAGE SEA SURFACE TEMPERATURE ANOMALIES OVER THE PERIOD OF MSC40 (1958-2000)

As shown in Figure 1, the North Atlantic Oscillation (NAO) index, a simple measure of mean NA sea level pressure distributions that also reflects preferred storm track patterns, exhibits considerable inter-annual as well as more systematic inter-decadal and longer term variability. The multi-decadal cycles in particular have been linked to long term cycles in NA sea surface temperature anomalies (Kushnir, 1994) and compatible cycles in the mean wave climate of the NA, especially the observed worsening of the sea state climate over the northeastern NA between the late 1950s and the early 1990s (Wang and Swail, 2002; Kushnir *et al.*, 1997). The SST anomalies in Figure 2 have also been recently linked to multi-decadal cycles in the frequency and intensities of NA tropical cyclones (Goldenberg *et al.*, 2001). "Warm" years, including 1926-1970 and 1995- are characterized by increased activity and "cold" years (1971-1994) by below normal activity. The 43 years of MSC40 (1958-2000) include 24 cold years and 19 warm years, suggesting that the long term wave climate associated with tropical cyclones may not have yet stabilized.



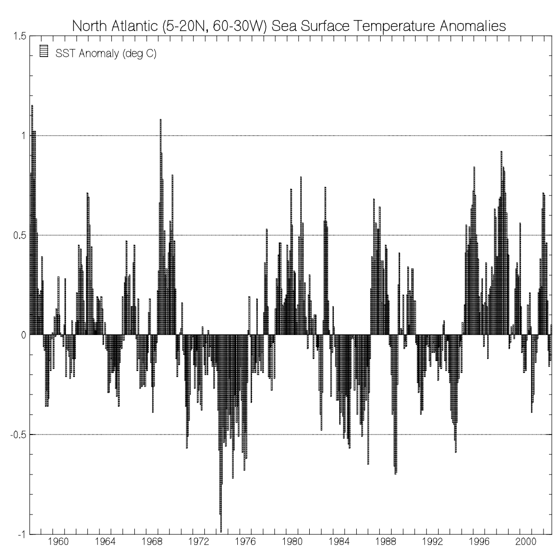


Figure 1

Figure 2

3. MSC40 TIME HISTORY AND SPATIAL PATTERNS OF WINTER (J-F-M) 90% SWH

MSC40 hindcast results have been analyzed to yield statistics such as monthly, seasonal and annual means and standard deviations (each year and all years combined) of wind speed and SWH, as well as measures more indicative of the extreme wave climate such as shown in Figures 3-8. Figure 9 shows the annual time series of the 90% winter SWH (SWH_JFM_90) at grid points in the western and eastern NA. Figure 10 gives the number of time steps (6-hourly) in the winter SWH above 6 m. The inter-annual variability of the extremes is larger in the east than the west and appears to be increasing over the past two decades. There appears to be a correlation with NAO, especially in the eastern NA. For example, the large flip in the NAO from 1987 to 1988/1989 seems to be associated with large changes in SWH_JFM_90. The spatial distribution of SWH_JFM_90 for the three years (Figures 3, 5, and 7) and their anomalies (Figures 4, 6, and 8) reveal radical shifts in the more extreme SWH events in response to the pressure pattern shifts indicated by NAO. None of the patterns in these winters resemble the 40-year mean (not shown).

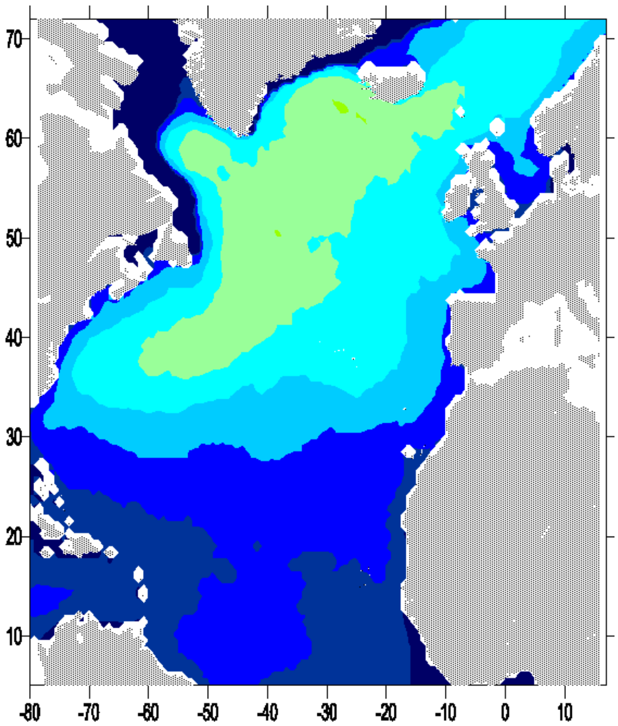


Figure 3: 1987 SWH_JFM_90

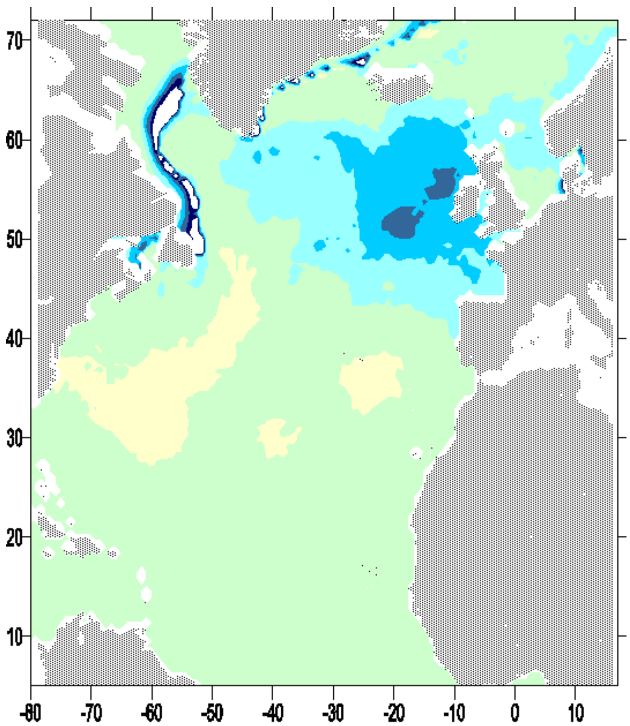


Figure 4: 1987 SWF_JFM_ANOM

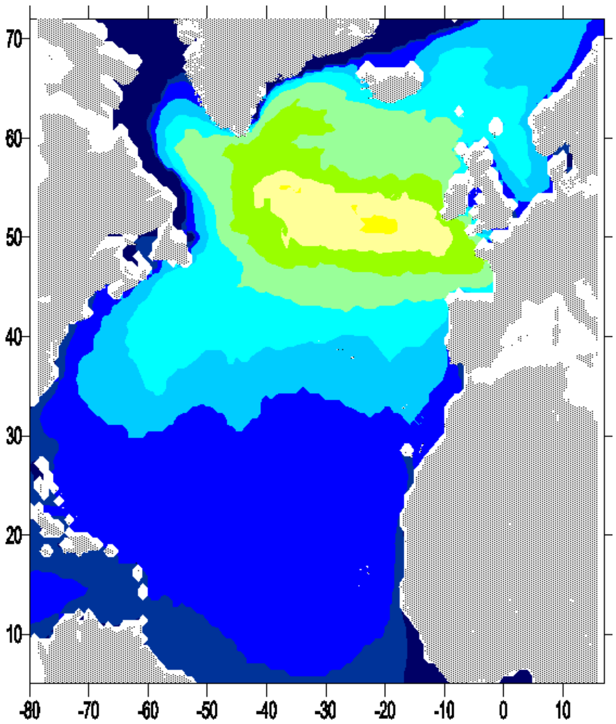


Figure 5: 1988 SWH_JFM_90

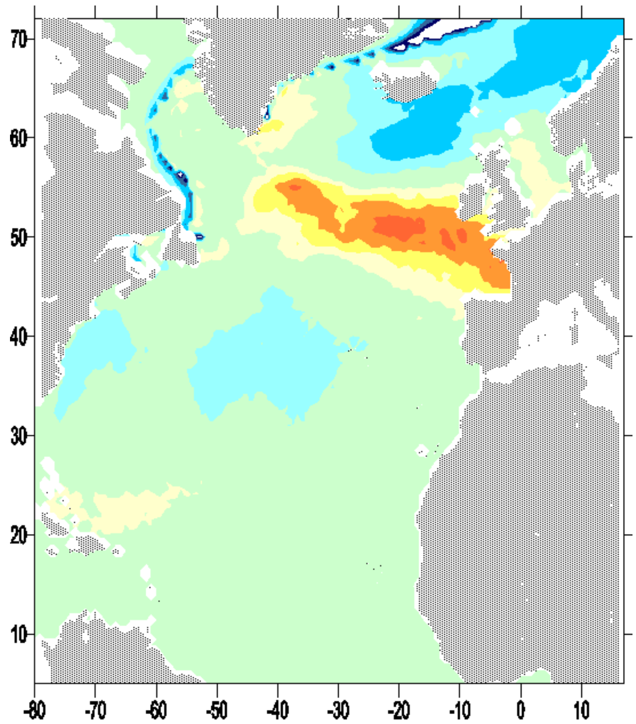


Figure 6: 1988 SWF_JFM_ANOM

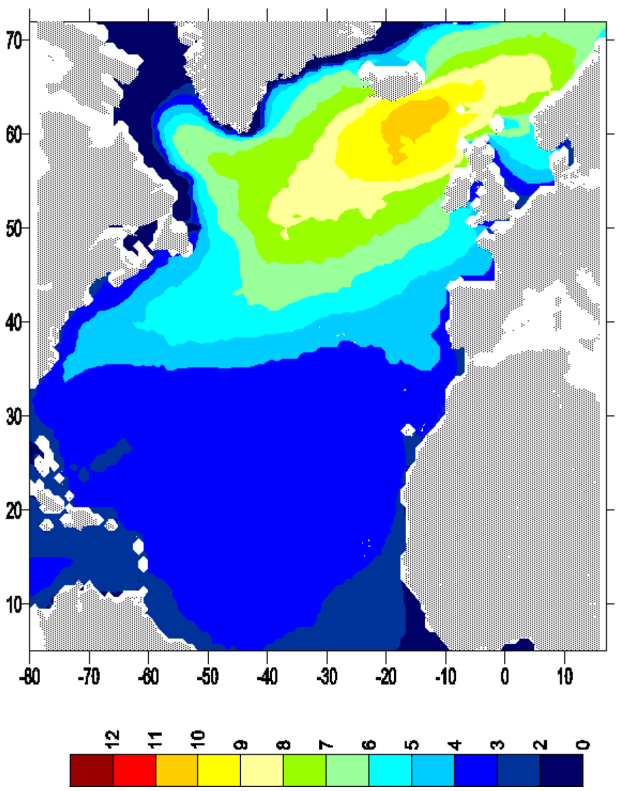


Figure 7: 1989 SWH_JFM_90

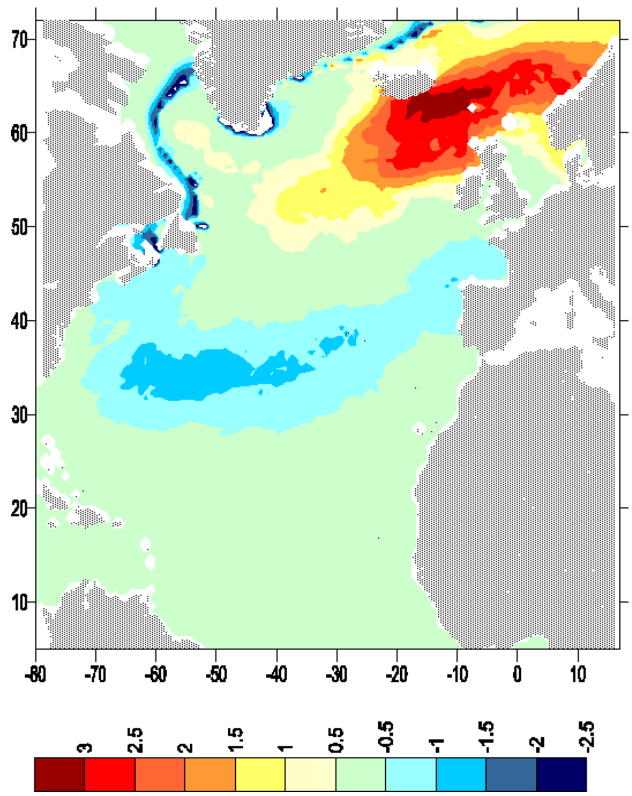


Figure 8: 1989 SWF_JFM_ANOM

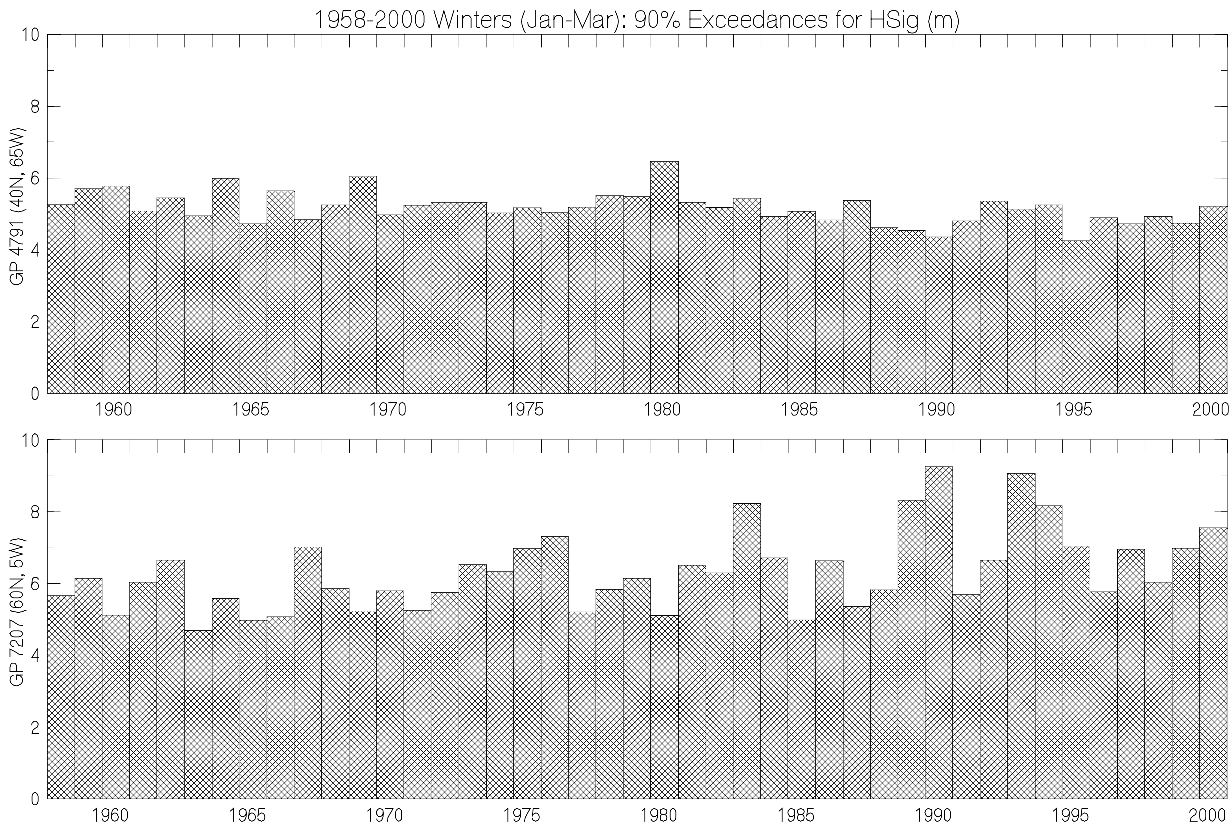


Figure 9

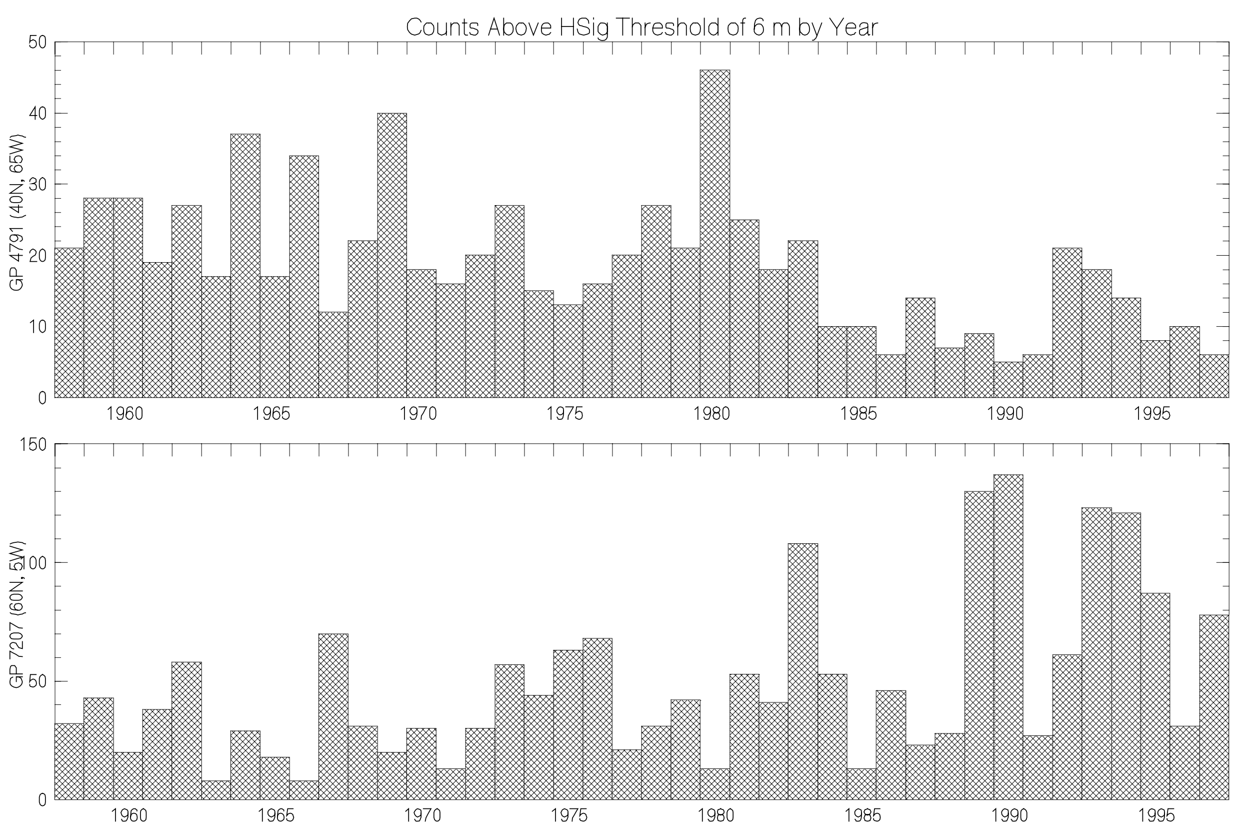


Figure 10

4. 100-YEAR RETURN PERIOD SWH FROM 40 YEARS AND BY DECADE - ALL PEAK EVENTS

A peaks-over-threshold extremal analysis of the MSC40 hindcast of storm maxima of WS and SWH yields, for example, contour maps of 100-year SWH, derived from the Gumbel distribution fitted with method of moments to the top-40 peaks whether associated with a tropical or extratropical storm. Figures 11-15 show the 100-year SWH extremes when the analysis was applied to all peaks within 40 years (1958-1997) and using peaks only within the indicated 10-year time bins. The remarkable decade-decade shifts in the spatial pattern and level of extremes indicate how variable the extreme wave climate is on the time scale of a decade from its longer term pattern. This variability suggests that estimates of the return period extremes, as typically needed for engineering design purposes, from multi-year but relatively short measurement series or even satellite WS and SWH measurements, which currently cover little more than one decade, can be quite unrepresentative of the true extreme wave climate. The variability in extremes is also illustrated more thoroughly when the extremal analysis is applied to running 10-year time windows, as shown in Figure 16 for sites in the eastern and western NA (Hogg and Swail, 2002). There is a variability of about 20% in the extremes over the different time windows. In the eastern NA, the trend to higher extremes in the last two decades of the hindcast reflects the worsening of the observed wave climate as linked to the preferred positive state of the NAO during that period. However, there are indications that the NAO is trending toward a negative preferred state so the trend to worsening may cease, unless secular effects such as global warming alter the typical historical cycling of the NAO.

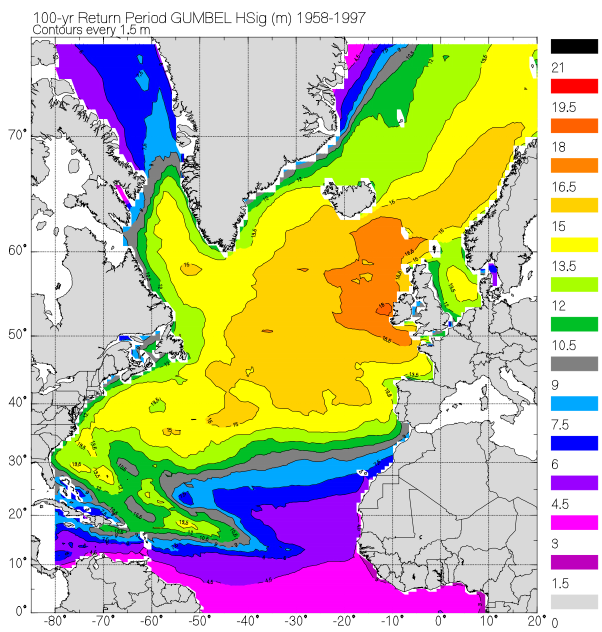


Figure 11: 100-year return period HSig based on 40 years of peaks (1958-1997)

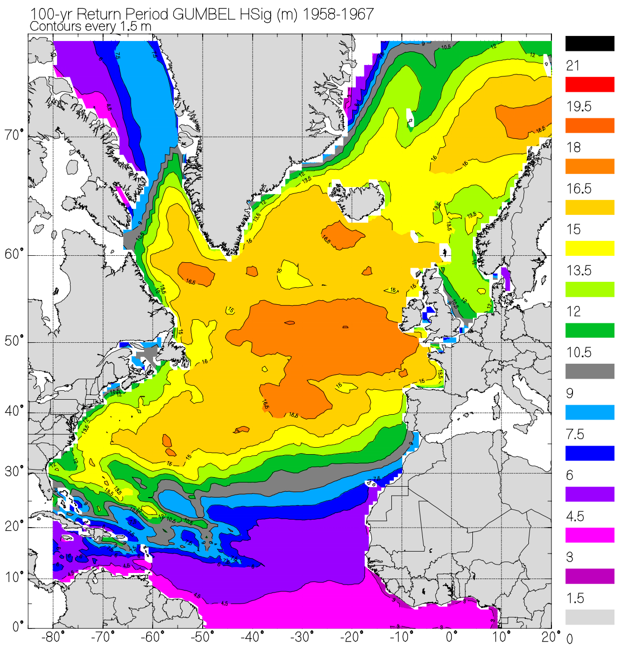


Figure 12: Same but with peaks from 1958-1967

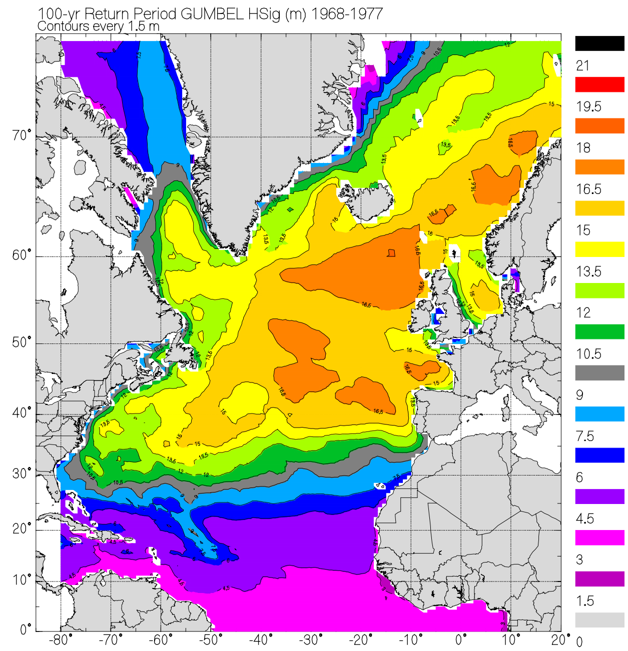


Figure 13: Same but with peaks from 1968-1977

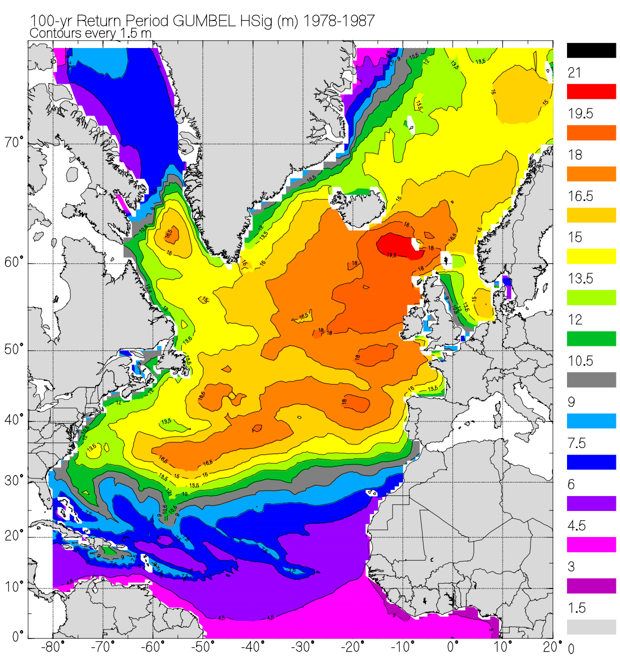


Figure 14: Same but with peaks from 1978-1987

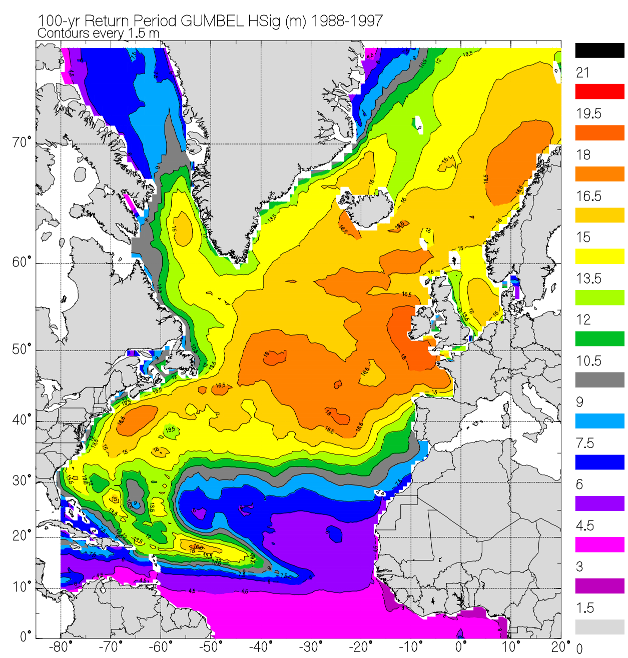


Figure 15: Same but with peaks from 1988-1997

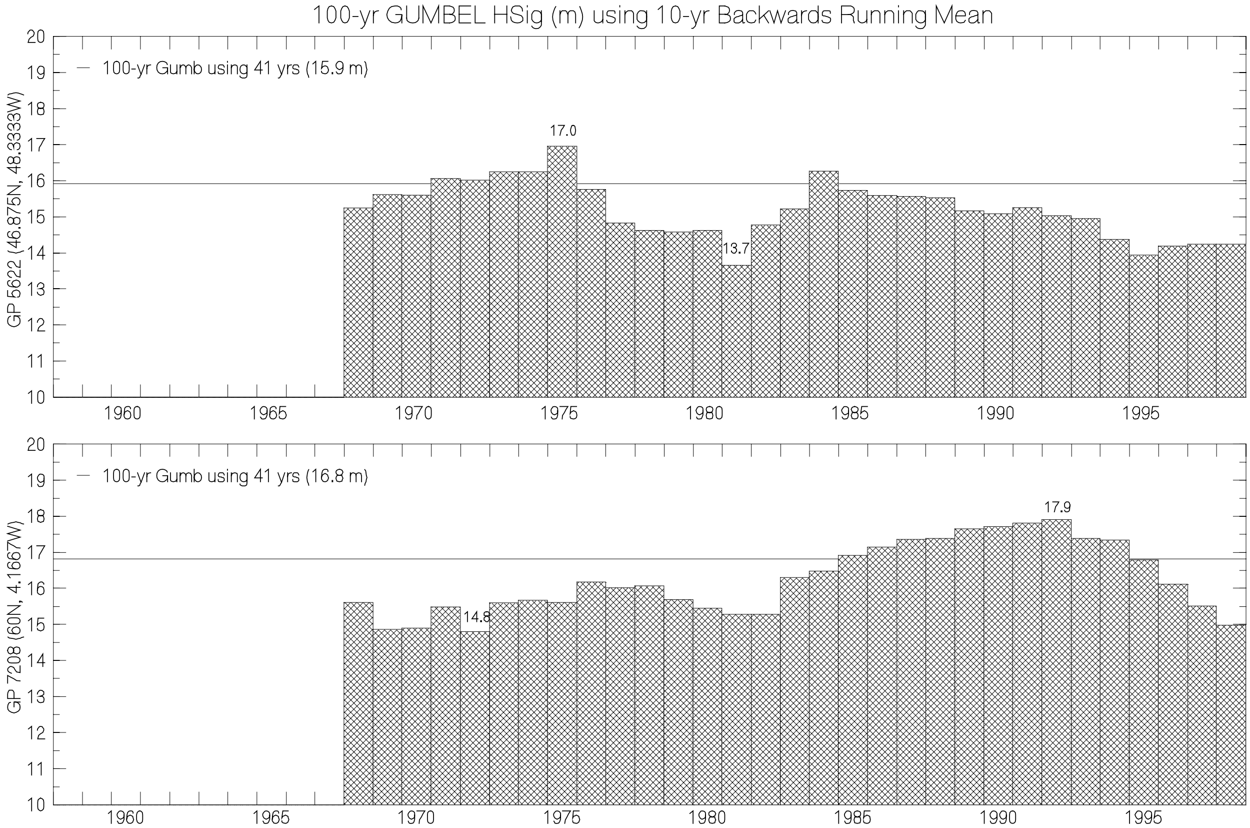


Figure 16

5. FUTURE WORK

The MSC40 hindcast is being extended back and forward in time to cover at least 50 years to allow even more reliable estimation of the normal and extreme wave climates.

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