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An analysis of the correlation of offshore wave climate with the NAO Index

Correlation analysis has been used to seek the optimal prediction of wave height at designated geographical locations off the coast of England and Wales that can be made on the basis of the NAO index alone. North Atlantic mean wave statistics measured by altimeter are used. The principal sites of interest are Lyme Bay, Camarthen Bay and Holderness. An offshore location, the Rockall Bank is also featured.

The method of analysis described here is an extension of EOF analysis (Cotton and Challenor, 1999), in which the sum of the first several EOFs that has greatest covariance with the NAO index is calculated. If the eigenvalue (time series) simulates the NAO index, then the eigenvector (spatial pattern) describes the linear coefficient linking the wave statistic and the NAO index at each site.

For these coastal sites, the finest spatial grid possible is important. Altimeter monthly statistics are only sufficient for a 1°latitude x 2°longitude grid with two operational altimeters. In the first instance, the analysis was performed on the entire North Atlantic (20-70N, 80W-10E). The first month satisfying this condition is October 1992. So far, processed data has been extended to September 1998, giving a total of six years. This data has been used in its entirety, but we have also restricted the analysis to the winter months (December, January, February and March [DJFM]) of the six years.

Full annual analysis

At present, the NAO index used from May 1996 to September 1998 is the Jones et al. Index which is not satisfactory for winter months.

Solutions for the monthly mean wave height of the form

$$H = A + B * NAO$$

are sought. The coefficient "B" varies spatially but cannot vary seasonally. "A" varies spatially and seasonally.

The form of this solution is not wholly satisfactory since the sensitivity to the NAO is probably greater in the winter months.

The correlation analysis is performed on the variation of monthly mean wave heights from the climatological mean wave height for the month in question. Both these variations and the corresponding NAO indexes were also subjected to smoothing to a 3 month running mean. (The correlations without this smoothing are much weaker).

The success of the solution in describing the actual variation of mean wave height relative to the climatological values at a given site was assessed by calculating the covariance of the predicted and actual variation as a fraction of the actual variance.

Rockall Bank	72.3%
Holderness	-0.3%
Camarthen Bay	28.4%
Lyme Bay	11.6%

The values for Camarthen Bay and Lyme Bay are not high (compare the value for Rockall Bank) but do represent a significant predictive ability. The relationship between NAO and wave statistics at Holderness is insignificant.

The coefficients A (metres) and B (metres/unit NAO index) are tabulated below

A:	Month	Lyme Bay	Camarthen Bay	Holderness	Rockall Bank
	Jan	2.44	2.51	1.97	5.28
	Feb	1.78	2.32	2.04	5.15
	Mar	1.60	1.96	1.75	4.72
	Apr	1.30	1.61	1.56	3.42
	May	1.09	1.32	1.29	2.37
	Jun	0.97	1.49	1.04	2.50
	Jul	0.92	1.27	0.83	2.18
	Aug	0.89	1.18	1.13	2.16
	Sep	1.29	1.35	1.69	3.01
	Oct	1.45	1.79	1.72	3.37
	Nov	1.50	2.11	1.97	4.12
	Dec	2.11	2.39	1.54	4.57
B:		0.075	0.156	0.008	0.435

Winter (DJFM) Analysis

The analysis described above was refined to consider only the correlation of wintertime wave heights with the NAO index. It is found in this case that the correlation is strong in each month without smoothing. Thus, the results described below are for unmodified variations in monthly mean wave height and monthly NAO indices. In this analysis, we also used a consistent source of the NAO index (Jones *et al.*,1997). The correlations are generally stronger than for the full year analysis. In all respects, the DJFM analysis is more satisfactory than the annual analysis.

For the full North Atlantic region, the covariance and model coefficients are as follows:

Rockall Bank	77.0%
Holderness	10.3%
Camarthen Bay	47.4%
Lyme Bay	10.8%

	Month	Lyme Bay	Camarthen Bay	Holderness	Rockall Bank
A:					
	Jan	2.50	2.54	1.91	5.38
	Feb	1.84	2.35	1.97	5.25
	Mar	1.66	1.99	1.68	4.82
	Dec	2.17	2.42	1.47	4.67
B:		0.083	0.186	0.060	0.415

We have investigated the robustness of solutions to the geographical region chosen for analysis. (N.B. in a canonical analysis, solutions at a given site are affected by data at other sites with the region analysed). Two "sub-regions" have been analysed: East Atlantic (20-70N, 20W- 10E) and North East Atlantic (20-70N, 20W-10E). Generally results are fairly insensitive to the region. For the North East Atlantic, we find,

Rockall Bank	78.9%
Holderness	
Camarthen Bay	54.2%
Lyme Bay	13.3%

	Month	Lyme Bay	Camarthen Bay	Holderness	Rockall Bank
A:					
	Jan	2.50	2.54		5.38
	Feb	1.84	2.35		5.25
	Mar	1.66	1.99		4.82
	Dec	2.17	2.42		4.67
B:		0.102	0.213		0.424

Variance and spread

In order to further investigate the wave climate, we have analysed not only the variations in mean wave height for each month, but also the variation in the variance of wave height. Repeating the analysis described already (for DJFM; 20-70N, 80W-10E) but substituting "variance" for "mean", we find a generally similar pattern of correlation but generally weaker.

Rockall Bank	59.7%
Holderness	-0.6%
Camarthen Bay	28.2%
Lyme Bay	14.5%

	Month	Lyme Bay	Camarthen Bay	Holderness	Rockall Bank
A:					
	Jan	1.25	0.92	0.70	4.27

	Feb	0.83	1.13	0.81	4.59
	Mar	0.52	0.86	0.68	3.77
	Dec	0.82	1.14	0.62	3.72
B:		0.066	0.100	0.040	0.422

It is not reasonable to extrapolate variations of mean wave height to variations in "percentile statistics" of waves unless the probability density function of wave height at each site scales solely with the mean wave height. We have demonstrated that this is not the case by demonstrating that variations in a statistic of the shape of the pdf, "spread = standard deviation / mean", at sites over a large area are variable and consistently correlated to the NAO. Analysis of the "spread statistic" are generally negatively correlated to the NAO in the North East Atlantic and in British Coastal Waters.

Estimating extreme waves

It is possible to estimate extreme waves systematically from the mean wave height and variance wave height alone, if a "two-parameter" description of the probability density function of wave height is assumed. An established two-parameter distribution is the FT1-distribution. We have calculated 100 year waves for winter months assuming an FT1 distribution using the method described by Cotton (1999) combined with the correlation analysis described already. Analysing the North East Atlantic region, we calculate the following for 100 year waves:

Rockall Bank	72.3%
Holderness	0.2%
Camarthen Bay	45.9%
Lyme Bay	16.9%

A:	Month	Lyme Bay	Camarthen Bay	Holderness	Rockall Bank
	Jan	10.47	9.47	7.93	20.43
	Feb	8.25	10.01	8.70	20.89
	Mar	6.81	8.70	7.61	18.86
	Dec	8.65	9.87	6.99	18.65
B:		0.38	0.69	0.28	1.28

Sensitivity and Success

The sensitivity of winter wave climate to the North Atlantic Oscillation can be expressed simply as the ratio of B and A (averaged over the winter months) for the particular statistic. This sensitivity is greatest in the North East Atlantic. Off the coastline of the British Isles exposed to Westerly wind and swell the sensitivity of mean wave height is typically 8% per unit NAO index, while 100 year wave height sensitivity is typically 6%.

The degree to which variations in wave climate can be described solely in terms of a linear dependence on the NAO index can be judged from the covariance of the linear model with observations. The "success" exceeds 60% over much of the North East Atlantic including offshore west of Ireland and Scotland. The success is still significant in the Western approaches, but is largely absent off the East Coast of England and Scotland.

Statistics of NAO

We have shown that wave climate is sensitive to the North Atlantic Oscillation. For example, the 100 year wave offshore of Camarthen Bay is predicted to increase by 69cm for every point increase in the NAO Index. This implies that the future behaviour of the North Atlantic Oscillation will strongly influence future wave climate. Now we consider the historical behaviour of the NAO and prospects for predicting its future behaviour and, by implication , wave climate.

The historical behaviour of the NAO Index

Over the last 30-40 years there has been a general upward trend in the NAO index amounting to ~1.5 index points. This trend in the NAO may largely account for observations of increases in wave height during this period. It is unclear whether this trend will continue. Comparing to the full historical record of the North Atlantic Oscillation, the recent trend in the NAO is fairly unusual but might nevertheless be part of a natural chaotic cycle.

Any long term trends are confused by variations on time scales from multi-decadal to annual. For instance, the NAO index dipped in the last few years, and it is uncertain if this dip is only part of a decadal scale oscillation, or if the upward trend of the past few decades has ceased, or perhaps reversed. Also, though the index has been generally high (~1) in the nineties, one exceptionally low value of the winter mean (-2.22 in 1995/6) has been recorded. Future general trends in the NAO do not determine on their own the maximum index that may be experienced in a given decade or century.

The mean DJFM NAO index for a given year does not tell the full story. The correlation analysis described previously was performed on monthly values. We have not statistically tested the separate response, but it is apparent from the data that wave climate responds to both inter-annual and monthly (intra-seasonal) variations in the NAO. The winter of 1996/7 is interesting (if inconclusive) in this respect. The NAO index shifted rapidly from large negative values in December and January to large positive values in February and March; the wave climate closely mirrored this shift. The index for February 1997 (+5.37) was much higher than the mean index for that winter (+0.30), or even the highest of the six winter mean values (+2.56). Monthly values of the index vary through a range of ~10, representing changes in monthly mean wave height of –50% to +50% of the climatological mean at some sites.

General trends in the NAO are likely to influence extreme wave events, but monthly and annual variability both exceed long-term variability. Any long term trends in inter-annual or intra-seasonal variability may be just as important to extreme wave prediction as trends in running means.

Future behaviour of the NAO

As described above, in the past few decades there has been an upward trend in the North Atlantic Oscillation index, but it is unclear whether this trend will continue. In order to predict the future behaviour of the North Atlantic Oscillation, it is necessary to have some understanding of its physical forcing. Climate models should include sufficient physics and also can incorporate in different runs possible future scenarios of radiative forcing. Climate models are run at a few centres, including the Hadley Centre in the UK and in Hamburg in Germany.

We shall concentrate on data available from the Hadley Centre. These include calculated mean pressure fields for model runs spanning over 100 years in the past to 100 years in the future, with various scenarios of constant or varying greenhouse gas and aerosol concentrations in each model run. At present, only the DJFM winter mean value of the NAO index for each year has been extracted. The value of the model predictions is assessed by comparing these predictions to the actual historical behaviour of the NAO index. The first observation is that none of the model runs reproduce the recent upward trend in the index. This observation does not immediately damn the model, since if the recent trend is only part of a chaotic oscillation, then its timing and strength is not predictable. The models do exhibit multi-decadal, decadal and annual variability; indeed a major defect is that the NAO is more unstable in the models than has been observed in the past century or so.

We compare below the statistics (mean and inter-annual variability) of the DJFM Jones *et al.* NAO index, and the simulated DJFM index from three model runs:

Year begin : year end Statistic	Jones	Control	GGa1	GSa1

1862:1999, mean	0.4191	-0.0212	-0.0950	-0.5635
variance	1.1935	2.8429	2.5171	2.6296
2000:2099, mean		-0.0919	-0.7239	-1.1515
variance		3.6911	2.5732	4.6545
2030:2070, mean		-0.4312	-0.4724	-1.1566
variance		3.8598	2.6730	5.6555

All models differ significantly from the historical behaviour of the NAO. The mean historical value of the NAO index is under-predicted, while the inter-annual variability is greatly exaggerated. The "Control" model exhibits non-stationary behaviour; therefore it is difficult to trust in the long term trends predicted for the other scenarios. Osborn *et al.* (1999) have recently assessed in more detail climate model representations of the North Atlantic Oscillation. The Hamburg model predicts a generally increasing trend in the NAO index. We must be sceptical of the ability of the current generation of climate models to represent the NAO. Nevertheless, we will briefly consider the implications of the GGa1 and GSa1 scenario predictions.

Both GGa1 and GSa1 show large decreasing trends in the NAO index. This observation suggests generally increasing winter wave heights at affected sites. However, GSa1 also shows a large increase in variance. Thus, though the NAO index is generally decreasing, the maximum value in the period 2030-2070 (3.48) actually exceeds the maximum value in the period 1862-1999 (3.25). Note also that the highest values are much higher than any historical values of the DJFM mean. This observation reinforces the point that even if a generally decreasing trend in the NAO were established, this would be no guarantee against freakishly stormy winters in the future, particularly if inter-annual variability increases. The possibility of changes in intra-seasonal variability, or even the maximum possible intensity of an individual depression add yet more uncertainty.

Any confident assessment of future winter wave climate must await a later generation of climate models which incorporates a physically sound understanding of the North Atlantic Oscillation. Note also, that only a fraction of the variance at any site can be described by a linear dependence on the NAO index. We have not yet investigated whether the residuals at each site might exhibit long term variability, possibly associated with another global or regional index of changing climate.

It may be only prudent to plan for a 20% increase in extreme waves offshore of the British Isles (corresponding for Camarthen Bay to a 2-3 point rise in the NAO index).

Concluding remarks and suggestions for future research

A simple linear model linking wave climate to the NAO index is remarkably successful in describing the variations in winter wave climate revealed by data from the TOPEX and ERS altimeters. In the long term, it is desirable to analyse in more detail the relationship of wave climate to atmospheric pressure fields, and also to compare contemporary wave data that supplement the altimeter data. (e.g. **Are variations in offshore wave climate largely the result of variations in swell or locally-generated wind waves?**). First though, we suggest further investigation and exploitation of the simple linear model.

Does the simple linear model describe earlier winter wave climate data?

Compare the (back-)predictions of the linear model to the Geosat altimeter data and to buoy and weather ship data.

Are long term trends in winter wave climate (at e.g., SSLV and OWS-L) solely explained by trends in the NAO index at the time?

Is the correlation of wave climate to the NAO index limited to DJFM?

Are there long term trends in wave climate in April-November?

N. B., Bacon and Carter (1991 and 1993) discuss trends in the annual mean wave height, but we can reanalyse this data to determine if significant trends are actually limited to particular months.

Can a different pattern of forcing explain variation in other seasons?

For example, it is proverbial that autumnal weather in North West Europe is punctuated by exceptional atmospheric depressions which are identified as "down-graded" hurricanes which did not "landfall" on continental North America. Statistics of hurricanes and tropical storms in the Tropical Atlantic and landfall statistics for these storms both show considerable variability. It should be fairly straightforward to test if there is any statistical relationship between autumnal wave climate in the North Atlantic and statistics of "non-landfall ex-tropical storms". Offshore wave heights are generally lower in the autumn than winter, but exceptional autumnal events may affect coastal defences especially when they coincide with tidal surges and the high astronomical tides of September and early October.

Is the dependence of wave climate on the NAO index linear?

If the linear dependence on NAO index is removed from variations in wave climate, are there any coherent patterns in the residual?

In the first instance, an EOF analysis could be performed on the residual.

Figures

Figure 1. Percentage of interannual variance in monthly mean signficant wave height explained by 1st CCA mode.

Figure 2. First Cca mode, and observed and predicted winter monthly mean significant wave heights at Rockall Bank (from model derived in report).

Figure 3. From NAO and CCA model, change in winter mean and 100 year return value of significant wave height (m) per unit change in the NAO.

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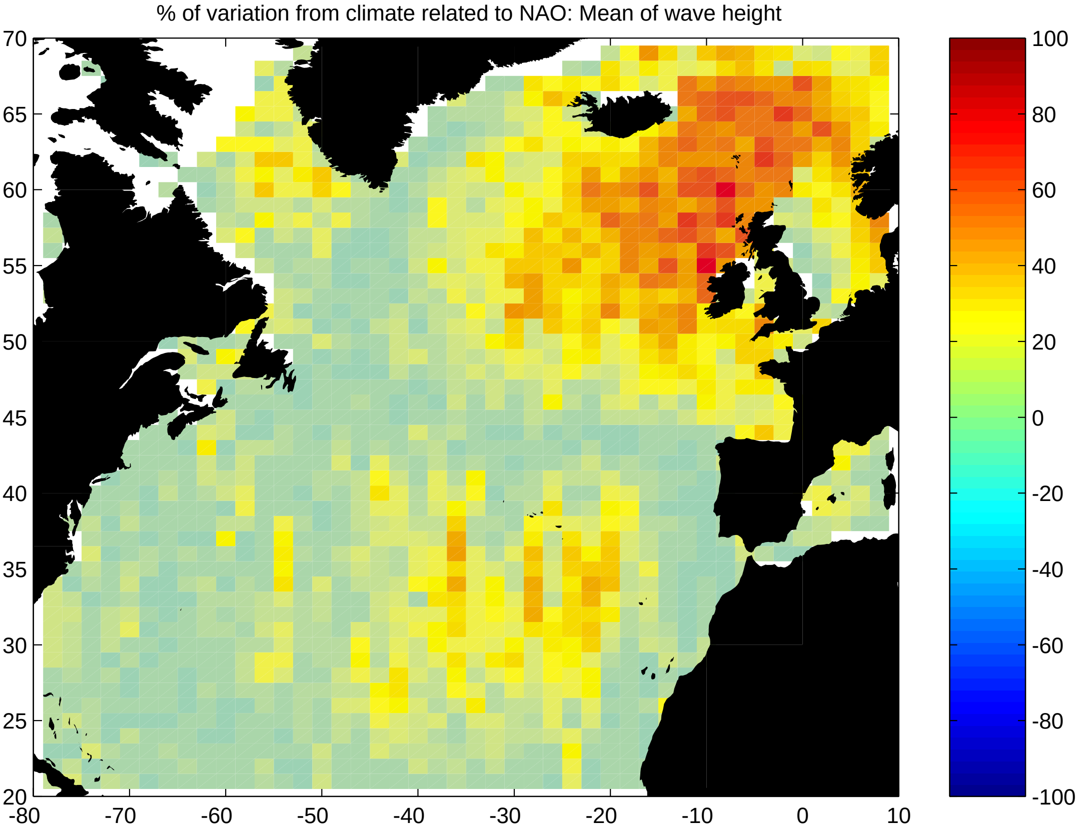

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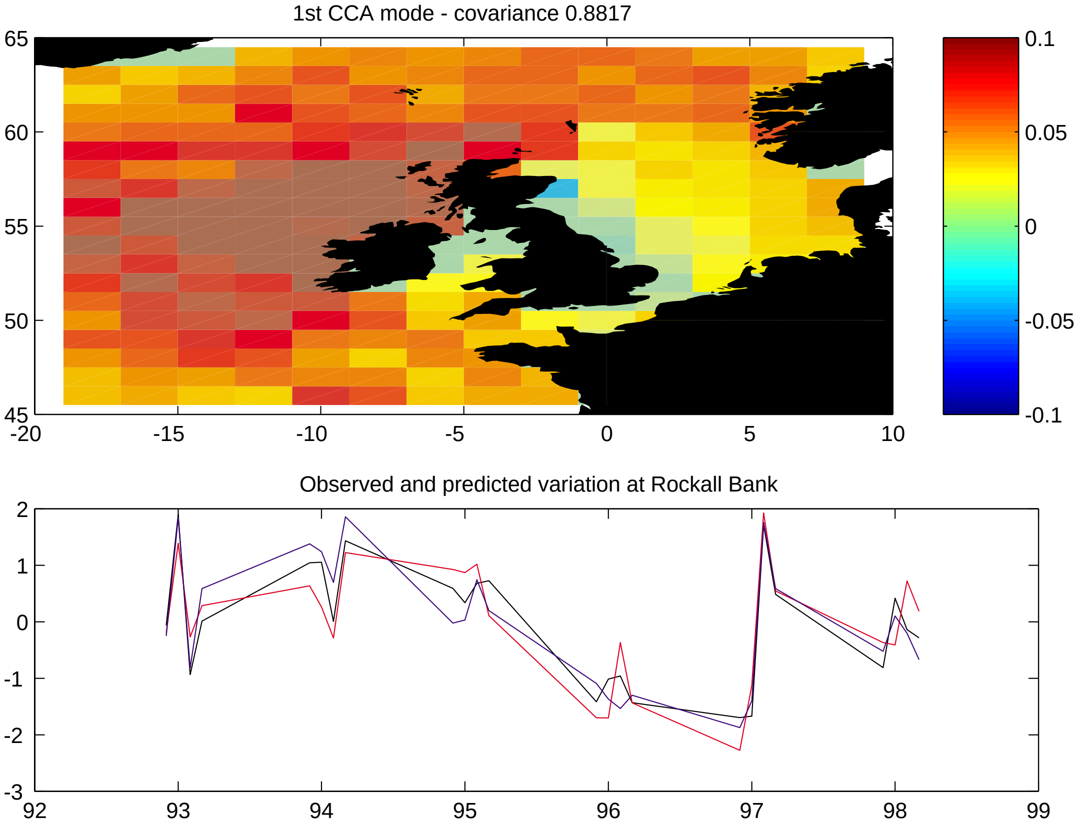

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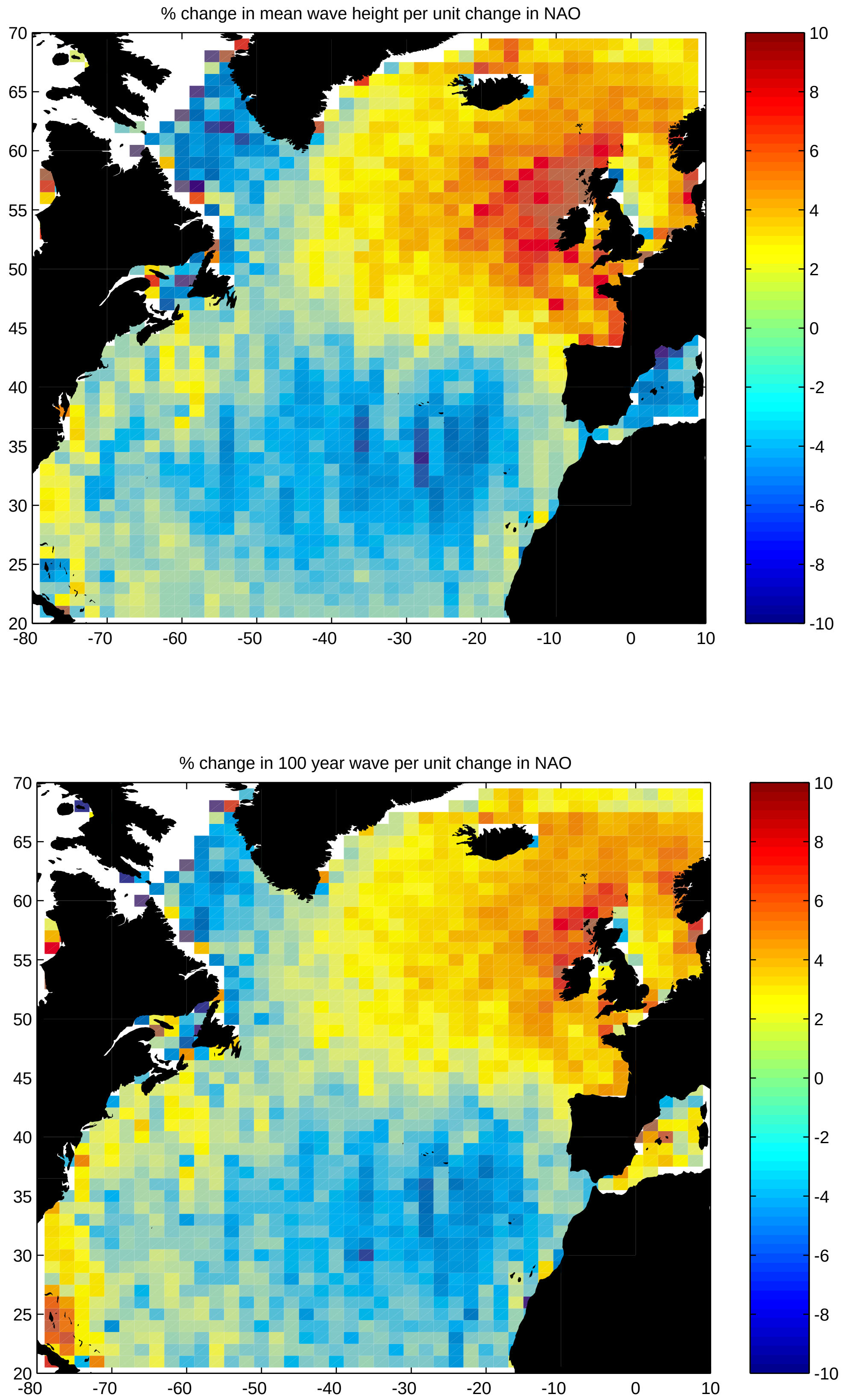

Figure 3. From NAO and CCA model, change in winter mean (top) and 100 year return value (bottom) of significant wave height (m) per unit change in the NAO.