The dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation

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Abstract

The role of the North Atlantic Oscillation (NAO) in effecting changes in winter extreme high and low waters and storm surges in UK waters has been investigated with the use of a depth-averaged tide + surge numerical model. Spatial patterns of correlation of extreme high and low waters (extreme still water sea levels) with the NAO index are similar to those of median or mean sea level studied previously. Explanations for the similarities, and for differences where they occur, are proposed. Spatial patterns of correlations of extreme high and low and median surge with the NAO index are similar to the corresponding extreme sea-level patterns. Suggestions are made as to which properties of surges (frequency, duration, magnitude) are linked most closely to NAO variability. Several climate models suggest higher (more positive) average values of NAO index during the next 100 years. However, the impact on the UK coastline in terms of increased flood risk should be low (aside from other consequences of climate change such as a global sea-level rise) if the existing relationships between extreme high waters and NAO index are maintained.

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1. Introduction

This paper investigates the dependence of UK extreme sea levels and storm surges upon the North Atlantic Oscillation (NAO). The NAO is the major mode of North Atlantic atmospheric variability, with an NAO index defined by the difference between normalised sea-level pressures representative of the Azores High and Icelandic Low (Hurrell, 1995; Jones et al., 1997). Periods with large positive index correspond to strong westerly winds over the UK and northern Europe. As the magnitude of storm surges depends primarily upon the wind stress over the continental shelf (Pugh, 2004), some kind of relationship between extreme sea levels and storm surges and the NAO can be anticipated. However, so far as we are aware, the topic has not been studied before in detail, and has been noted as requiring investigation (NERC, 2005).

There are two particular motivations for such an investigation. The first is a practical one. Rodwell et al. (1999) proposed that ocean-atmosphere interactions provide a link between summertime central Atlantic sea surface temperatures and conditions in the atmosphere during the following winter, which determine storminess over Europe.
As a consequence, the NAO index in winter (DJFM) is to some extent predictable from knowledge of central Atlantic sea surface temperatures in the preceding summer. Therefore, if a relationship between extreme sea levels and NAO exists, there is the possibility to provide advance warning of anomalous winter flood risk on the basis of summertime sea surface temperature observations.

The second motivation stems from an interest in knowing whether major changes are likely in the climatology of UK extreme sea levels and surges, for input to studies such as the UK Climate Impacts Programme (Hulme et al., 2002). One approach to this question is to employ an Atmosphere Ocean General Circulation Model (AOGCM) to simulate time series of future regional wind and air pressure fields, and to use those forcing fields in a storm surge model to predict extreme sea levels. Several groups have demonstrated that such studies are feasible (e.g. Von Storch and Reichardt, 1997; Flather and Smith, 1998; Lowe et al., 2001; Woth et al., 2006). However, an alternative approach is to make use of the predictions of future winter NAO index by the same AOGCM. If the dependence of extreme sea levels on the NAO is known, one should then be able to infer changes in the climatology of extremes. In practice, both approaches are desirable.

2. Data sets

Our analysis makes use of 49 year (1955–2003) runs of a two-dimensional tide + surge model for the NW European continental shelf (Flather et al., 1998). The model has a relatively coarse spatial resolution (1/3° latitude by 1/2° longitude). However, it has been demonstrated to provide a good representation of tides and surges on the shelf and was formerly the model used for operational flood forecasting and warning in the UK (Flather, 2000). Eight tidal constituents (Q1, O1, P1, K1, M2, S2, K2 and N2) are included with tidal forcing at the open boundary taken from a model of the NE Atlantic (Flather, 1981). Meteorological forcing is provided by 6-hourly winds and atmospheric pressures from the Norwegian Meteorological Institute (Det Norske Meteorologiske Institutt, DNMI). An inverse barometer approximation is assumed at the open boundary which, although necessarily imperfect in its omission of dynamic air-pressure-induced signals, should be a good approximation of sea-level change in deep water (cf. Ponte, 1994). As a consequence, one expects the limitations of such an approximation to have little impact on the effective computation of surge heights over the model domain. Reservations have been expressed concerning the temporal–spatial homogeneity of the DNMI data set in data-sparse ocean areas, especially around Greenland (WASA Group, 1998). However, such inhomogeneities are considered to be small over the NW European continental shelf (Günther et al., 1998; Langenberg et al., 1999), and comparisons of the observed and modelled heights of individual major surges have been found to be of acceptable (sub-decimetric) accuracy at UK locations (Flather et al., 1998).

Two model runs were made, first with tidal forcing only (‘t’), and then with both tidal and meteorological forcing (‘tm’). Hourly fields of sea-level elevations were output in each run. The difference between the ‘tm’ and ‘t’ elevation fields provides storm surge fields (‘s’), where ‘surge’ defined in this way includes tide–surge interaction. In this study, we shall use primarily the ‘tm’ hourly values, which in principle will correspond to the sea levels which would be recorded by tide gauges and are of most interest with regard to flood risk, and the ‘s’ values, which one might anticipate to be most sensitive to variability in the NAO.

The NAO index values, defined as the difference between the normalised sea-level pressures at Gibraltar and southwest Iceland (Jones et al., 1997), were taken from the Climatic Research Unit, University of East Anglia web site (www.cru.uea.ac.uk).

3. Sea-level relationships to the NAO

The 49 years of model run have 48 winter (DJFM) periods. For each winter, the ‘tm’ values were used to calculate extreme high and low waters, median sea level (MeSL) and mean sea level (MSL). Unless stated otherwise, extreme high (and low) waters were defined in terms of the 99 (and 1) percentiles of the winter hourly sea-level values, i.e. as the levels, which the sea is above (or below) 1% of the time (29 h each winter). The choice of such percentiles, instead of the true extremes (the 100 and 0 percentiles), guards against the presence of anomalous sea-level values, and is often essential in analysis of tide gauge data (e.g. Woodworth and Blackman, 2004). Differences in findings due to such choices are mentioned below. MSL time series
were defined as the arithmetic average of the ‘tm’ hourly values in each winter period.

Fig. 1(b) shows the correlation coefficients between winter MeSL and NAO index, while Fig. 1(c) presents the sensitivity of MeSL to changes in the NAO index obtained by linear regression. Correlation coefficients larger than 0.28 can be considered significantly different from zero at 95% confidence level given 48 independent samples. The largest positive and negative correlations are found in the NE and SW of the shelf, respectively, with the largest sensitivities in the shallow waters of the eastern North Sea and German Bight, where large surges are generated by the westerly winds. Almost identical distributions are obtained with the use of MSL instead of MeSL. Figs. 1(b,e) are very similar to those of Wakelin et al. (2003), who investigated winter MSL from the same model for a slightly shorter period (1955–2000), and of Woolf et al. (2003), who studied North Atlantic altimeter and tide gauge data with particular attention to the 1990s.

Fig. 1(a,d) and (c,f) show the corresponding distributions for extreme high and low sea levels (99 and 1 percentiles), respectively. Figs. 1(a,c) indicate that extreme sea levels have weaker correlations with the NAO than does MeSL, reflecting the fact that the index and MeSL are winter-average quantities. Nevertheless, the spatial patterns of correlation coefficients and of sensitivity to the NAO are similar. This indicates that changes in NAO index affect sea levels in a similar way throughout the tidal range.

This conclusion is confirmed if one considers correlations with, and sensitivities to, the NAO for
extreme high and low waters, where the extremes are expressed relative to MeSL in the same winter. Fig. 2(a) demonstrates that almost no significant correlation remains between high water extremes and NAO, except for part of the NE North Sea and Skaggerak, where sensitivities are also relatively large (Fig. 2(c)). This is consistent with findings from tide gauge data by Woodworth and Blackman (2004) and Tsimpilis et al. (2005) who observed a greater response of extreme high waters to NAO change than of MSL at some Scandinavian stations. Correlations between extreme low waters, after median subtraction, and NAO are negatively correlated in the western North Sea (Fig. 2(b)). However, the corresponding sensitivities are small (Fig. 2(d)).

It is well known that the winter NAO index in the second half of the 20th century contained a large secular trend (0.23 units/decade over 1956–2003). Therefore, a question arises as to whether the correlations in Fig. 1(a–c) are due to the long term trend rather than interannual or decadal variability. This has been addressed by detrending the NAO index and the extreme high and low water and MeSL time series yielding distributions similar to those of Fig. 1(a–c). This indicates a similar sea-level response to the NAO at shorter and longer timescales.

Tests were made to see if the choice of 99 (and 1) percentiles as extreme high (and low) water levels yielded similar conclusions to the choice of percentiles nearer to the true extremes (99.9 and 0.1) or to

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Fig. 2. (a) As Fig. 1(a) but with extreme high water values expressed relative to the winter median; (b) as Fig. 1(c) but for extreme low water values expressed relative to the winter median; (c) sensitivity of change in winter extreme high water relative to median (mm/unit index); (d) corresponding sensitivity for extreme low water.
the use of the true extremes themselves. Distributions of correlation coefficients and sensitivities for the 99.9 and 0.1 percentiles and for the true extremes were found to be very similar at most locations to those of Figs. 1 and 2, with slightly weaker correlations and larger sensitivity values. The original choice was maintained for this paper so as to treat the model information in the same way to which tide gauge data are likely to be analysed.

The present study does not require a removal of perigean (approximately 4.5 year) tidal effects from percentiles in addition to medians, as in the Woodworth and Blackman (2004) analysis of a quasi-global tide gauge data set. That is because the numerical model omits those smaller tidal constituents which result in perigean variations (e.g. L2) (Pugh, 1987).

4. Properties of Storm Surges

It is of interest to ask why the extreme high and low waters and MeSL have broadly similar correlations with the NAO. Fig. 3 shows an estimate of the duration of large winter storm surge events obtained by considering periods of data for which ‘s’ values exceed the time-averaged (over 48 winters) 95 percentile surge at each grid box in the model. This choice of threshold selects 145 h of large surge in a typical winter. The duration of a large storm surge event is determined by the difference between the up- and down-crossing times of ‘s’ values across the threshold level, in a similar manner to which wave periods are calculated (e.g. Vassie et al., 2004). A similar method was employed previously by Woth et al. (2006). Values of large surge duration vary spatially, with larger values in the deeper Atlantic waters where air pressure changes are relatively more important than winds in generating surge events. Smaller values are found in the shallow waters of the North Sea. The averaged duration across the model domain is 14.4 h. However one selects reasonable values for the threshold, it is clear that the typical large surge duration will be at least comparable to the tidal period and, therefore, will contribute to the still water level throughout the tidal range.

Fig. 4(a) demonstrates an alternative way of making the same point with the use of all ‘s’ values, not just the largest ones. It shows power spectra of ‘s’ at the 7 representative locations indicated in Fig. 4(b). Small amounts of tidal energy are apparent which originate from the modelled tide in the ‘t’ and ‘tm’ runs being slightly different, owing to the modifications in water depth. It can be seen that there is little energy in ‘s’ at frequencies higher than that of the semidiurnal tide (0.081 cycles/h).

It is also of interest to ask why there are differences between the relationships of extreme high and low waters and MeSL to the NAO. These can be inferred from the statistical properties of winter ‘s’ values displayed in Fig. 5. It is well known that the prevailing westerlies result in decimetric values of wind-setup in the German Bight, and that the standard deviation of ‘s’ is also largest there. The distribution of ‘s’ values departs from a normal one in several ways. For one thing, it is clear that time series will be highly serially correlated. In addition, the distribution on the shelf is skewed towards large positive values, especially in the shallow waters of the southern North Sea, English Channel and eastern Irish Sea, and has large kurtosis (peakiness). The skewness arises partly from tide–surge interaction, but primarily from the fact that the meteorological forcing is itself skewed with long tails in low air pressures and high wind speeds (Wilks, 1995; Barry et al., 2003). Therefore, it is inevitable that there will be some differences between extreme high and low waters and MeSL, with the former usually presenting the larger differences, as indicated by comparing Fig. 2(c–d).
5. Surge relationships to the NAO

Fig. 6 presents distributions of correlation coefficients and sensitivities for the 99, 50 and 1 percentiles of winter ‘s’ values, instead of the ‘tm’ values of Fig. 1. The 50 percentile distributions (Figs. 1(b,e) and 6(b,e)) are almost identical as one would expect, while those for low waters are also almost the same. The 99 percentile correlation coefficients are also similar (Figs. 1(a) and 6(a)), with larger sensitivity values for ‘s’ in the eastern North Sea (Figs. 1(d) and 6(d)).

It is important to realise that the hours of data, which contain the extreme values for ‘s’ are not necessarily the same as those, which form the extremes for ‘tm’. Surges can occur throughout the tidal cycle, and, for example, a large positive surge could occur at low tide resulting in a middling ‘tm’ value. Nevertheless, it is of interest to consider in more detail the relationship of large positive surges to the NAO as they would be of potential importance to flood risk if they did occur at high tide. If there is a clear relationship, one can ask whether it is due to there being more surges, or ones with larger amplitude or duration.

As before, use is made of the time-averaged (over 48 winters) 95 percentile surge at each model grid box to define the threshold for a large surge event. Fig. 7(a) shows the correlation between the number of large surge events in a winter and the NAO index. The pattern is similar to those seen before. The sensitivity between the number of events and NAO, obtained by linear regression, is shown in Fig. 7(d). An increase of one NAO unit results in typically 3 or 4 extra events in the North Sea compared to an average of 10 events in a typical winter (with this choice of threshold). Fig. 7(b) and (c) show the corresponding correlation coefficients for the total number of hours each winter with a surge over threshold, and the average height of the surges above the threshold, respectively, while Fig. 7(e) and (f) give the corresponding sensitivities. Comparison of Fig. 7(d) and (e) confirms that surge events correspond to approximately 14 h over threshold. One concludes that, in the North Sea where correlations are relatively large, any increase in the NAO index results in (1) an increase in the number of hours over threshold, (2) for a band stretching from northern Scotland to northern Denmark and the Skaggerak, an allocation of those hours preferentially into more events, and (3) only minor change in the surge amplitude. Point (2) will be returned to below.

6. Secular trends in extreme high and low waters, MeSL and storm surges

The NAO trend during the past few decades has resulted in long term trends in sea level on the NW European continental shelf. Fig. 8(a)–(c) demonstrates that secular trends in winter extreme high water, MeSL and extreme low water during 1956–2003 were similar in having largest values in the eastern North Sea and Skaggerak. Trends
around the UK were considerably smaller than those in the German Bight, as noted previously by Langenberg et al. (1999). (Trends for the April–November part of the year were negligible throughout the entire region, reflecting partially the lower energy in air pressure and zonal wind variability in that part of the year.) In addition, there were large differences between extreme high and low waters and MeSL in UK waters.

Fig. 8(a) contains an additional band of large trend across the northern part of the North Sea, located approximately at the areas of maximum sensitivity of number of large surge events and hours over threshold to NAO change in Fig. 7(d,e) (i.e. point 2 above).

Large differences in trends in extremes are obtained when selecting model data for slightly different epochs, as applies to the study of mean sea-level trends from tide gauge data (e.g. Pugh, 1987; Tsimplis et al., 2005). For example, it is known that the winter NAO index was particularly large and positive during the mid-1990s (Hurrell, 1995). Consequently, the use of data sets, which end in the mid-1990s (e.g. choice of epoch 1956–1994 instead of 1956–2003) results in much larger trends in NAO index (0.38 units/decade) and in the sea levels of the eastern North Sea (Fig. 8d–f).

Secular trends in 99, 50 and 1 percentile surge (‘s’) during 1956–2003 (not shown) were broadly consistent with those in still water level (‘tm’). The 50 percentile trends were identical to those of Fig. 8(b), as one would expect. The spatial patterns for the 99 and 1 percentiles were in close agreement with their

Fig. 5. (a) Average value, (b) standard deviation, (c) skewness and (d) reduced kurtosis of ‘s’ using values from 48 winter periods.
‘tm’ counterparts but with values larger by approximately 25% in the areas of large trend in the North Sea. Such differences can be anticipated as, it will be recalled, surges occur throughout the tidal cycle and the 29 h each winter which define the 99 (or 1) percentile need not be the same for both ‘s’ and ‘tm’.

7. Discussion and conclusions

There will be differences between sea-level changes in the real ocean and those in the present model study. In particular, a depth-averaged model cannot simulate sea-level variations arising from steric (density) changes in the ocean. For example, the trends discussed above (Fig. 8) do not include steric and other (glacial, hydrological, etc.) contributions which are a consequence of climate change (Church et al., 2001). Steric and other climate-related changes can be expected to occur on timescales longer than a typical storm surge, and therefore to contribute approximately equally to all percentiles (high and low water extremes and MeSL). Such a link between sea level and the NAO, via thermosteric changes, has been explored recently by Tsimpis et al. (2006). They concluded that sensitivities of the order 10 mm per unit index could arise from thermosteric fluctuations linked to the NAO, additional to those due to winds and air pressures investigated in the present study.

The present study has shown that extreme sea levels and storm surges around the UK do exhibit a dependence on the NAO, with sensitivities of the order of several 10 s mm per unit index (Fig. 1). The sensitivities for extreme high waters tend to be larger than those for MeSL and extreme low waters in the eastern North Sea. However, for most of the
model domain, and in particular for waters around the UK, there are no major differences between the relationships of each parameter to the NAO averaged over the epoch of the data set (cf. Fig. 2). Any time-dependence of such relationships, as have been studied for MSL (Yan et al., 2004; Tsimplis et al., 2005; Jevrejeva et al., 2005), will require the analysis of longer model data sets.

A conservative assessment would suggest sensitivities of extreme high water (Fig. 1(d)) or large surges (Fig. 6(d)) of several 10 s mm per unit NAO index, with largest values on the east coast. However, this hardly amounts to major flood risk, even if the NAO index becomes more positive in the 21st century as suggested by several AOGCMs (Osborn, 2004; Tsimplis et al., 2005). For comparison, one may note that the standard deviation of the interannual variability of MSL around the UK is approximately 50 mm (Woodworth et al., 1999). Consequently, we do not believe that the UK will be subject in future to significantly enhanced flood risk due to NAO-related changes in air pressures and winds. This finding is consistent with that for the North Sea by Butler et al. (2006), who employed the same model data sets as in the present study, and with those of other recent modelling investigations (e.g. EU PRUDENCE study, Woth et al., 2006). Of course, other increased risks associated with climate change could result from an overall MSL rise (Flather et al., 2001).

Several directions for further work can be identified. While we do not consider the coarse
resolution of the present model to impact seriously on our general conclusions for the NW European shelf, the existence of any short spatial scale NAO dependence will be studied more effectively with a new model with an order of magnitude improvement in spatial resolution. This will shortly be implemented by the Proudman Oceanographic Laboratory at the Storm Tide Forecasting Service of the Met Office and will eventually be employed to hindcast extreme sea levels around UK coasts utilising European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis fields.

For estimation of coastal flood risk, the computation of joint probabilities of a number of parameters is required including tide, surge, waves, river flow and precipitation. Pugh and Vassie (1980), Dixon and Tawn (1992) and Svensson and Jones (2002, 2004) provide examples of joint probability methods and applications. The special relationship between the NAO and extremes has so far been focused on individual regional parameters: for example, extreme still water levels and surge levels in the present paper, North Sea surges also by Butler et al. (2006), waves by Tsimplis et al. (2005) and Wolf and Woolf (2006), severe storms by Alexander et al. (2005) and rainfall by Fowler and Kilsby (2002). Tsimplis et al. (2005) went some way in assessing the overall importance of the NAO to coastal sea levels and by implication to a range of UK and northern European coastal processes. However, a considerable amount of further work is required using statistically rigorous methods before a full appreciation of the impact of the NAO on UK coastal flood risk can be obtained.

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References


NERC, 2005. Flood risk from extreme events (FREE), the science of flooding. Science Plan of a Research Programme of the UK Natural Environment Research Council. 16pp. ⟨http://www.nerc.ac.uk/funding/thematics/free/⟩.


