Coastline configuration disrupts the effects of large-scale climatic forcing, leading to divergent temporal trends in wave exposure

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Abstract

Both climate change and the North Atlantic Oscillation (NAO) may influence coastal systems by altering wave exposure. The effects of such climatic forcing are often coherent over relatively large geographic areas. Temporal trends in wave exposure at any particular shore are, however, the result of an interaction between site-specific fetch characteristics and changes in wind climate. This leads to contrasting trends in wave exposure at locations separated by no more than a few km. Wave exposures were estimated at locations around a sea lough over 32 years to characterise these scales of variability. Locations separated by approximately 5 km had independent dynamics with respect to the temporal trend (correlation range -0.35 to 0.44) and to associations with the NAO (correlation range -0.18 to 0.40). Wave exposure can therefore be increasing for a section of shore while nearby areas have the opposite trend. Mean exposure at a location was not a good predictor of the temporal trend. More exposed sites were, however, sensitive to variations in the strength of the NAO. The reduction of large scale forcing to small-scale variability has implications for the detection and mitigation of potential climate change impacts.

Keywords: wave action, scales, wind wave generation, climatic changes, NAO, Ireland, Strangford Lough

1. Introduction

One of the mechanisms whereby global climate change may alter ecological communities is by changing wind speeds. For example, increased wave action associated with greater storminess or wind speeds may change ecosystem function along coastlines (a switch from macroalgae to filter feeders, Thompson et al., 2002). Over the United Kingdom, the predicted changes in wind climate are for increases in average wind speeds (particularly for southern coasts) and for an increased frequency of storms during winter (between a 2 and 6% increase in average wind speeds and a 40 % increase in winter depressions (storms) by 2080 under a medium-high greenhouse gas emission scenario, Hulme et al., 2002). The wind climate can be indirectly summarized through variables such as the North Atlantic Oscillation index (NAO, Hurrell, 1995). Positive NAO values are associated with windier, wetter winters. The mean NAO index has increased in the latter part of the twentieth century, with relatively high winter NAO index values associated with a greater frequency of storms (Lozano et al., 2004). Climate change predictions are for an increase in mean NAO values, implying an increase in winter storms in the northeast Atlantic (Hulme et al., 2002).

Detailed prediction of the impacts of changes in wind speeds is hindered by a degree of uncertainty in climate change models. Simulated wind speeds are thought to be among the model variables with the highest degree of uncertainty (Hulme et al., 2002). There are also issues of scale: the wind responds to topographic features, yet climate models typically have a relatively coarse resolution (250 km grid squares in the output from the regional model in Hulme et al., 2002). Leaving aside the uncertainty in climate models, the effects of scale can be addressed by looking at spatial scaling of key variables among locations. We follow this approach by deriving indices of wave exposure for sites separated with a minimum spacing of 500 m.

Resolving the scale at which climate forcing affects systems is clearly important for making predictions with respect to climate change. Large-scale indices, such as the NAO, have repeatedly been shown to be better predictors of population dynamics than small-scale weather data (Stenseth & Mysterud 2005). The utility of large-scale variables may be in the way that they summarize covariation in individual variables over time and space scales relevant to individual fitness (Stenseth & Mysterud 2005). Variable topography may interact with large-scale forcing to produce more complex variation in local populations. This includes greater spatial variability in populations at small scales (Loe et al., 2005). Where an organism has migratory behaviour, an overall link may be retained with large-scale climatic forcing (Pettorelli et al., 2005), but organisms living on the shore are more likely to respond to site-specific differences in physical forcing.

For any particular shore, local variation in orientation to prevailing winds and coastline configuration (e.g., bays or headlands) will modify the effects of wind-driven waves. To characterise the likely patterns in a coastal system, we used historical wind data and estimates of fetch distances at 400 locations to hindcast recent changes in wave exposure. This allows an estimation of the spatial scales over which temporal trends in wave exposure are similar. Our hypothesis was that wind driven impacts on coastal ecosystems will vary at a scale below the broad scale climatic response patterns generally identified in other systems (Stenseth et al., 2002, Stenseth et al., 2004).

2. Material and Methods

Wave exposure has long been recognised as a key structuring force for littoral communities (Lewis, 1964). The size and frequency of waves arriving at a shore are the result of an interaction between wind speed and duration, the distance of water over which the wind has been blowing (fetch) and the sea bed topography. In the face of difficulties in maintaining instruments directly measuring wave exposure across a number of sites over extended periods, the use of indirect measurements is common. There are a number of different ways of applying such methods to estimate wave exposure. Most methods are based on fetch distances and wind records from meteorological stations (also known as cartographic methods). While there is continual development in the engineering and oceanographic literature of techniques for obtaining accurate estimates of wave heights, the application of wave theory to shallow waters is complex, placing restrictions on the accuracy of predicted wave heights. Even quite sophisticated models include empirical approximations and omit certain processes (Ekebom et al., 2003). As a result of their structure, models vary from relative measures of wave exposure to more specific predictions of wave patterns. For the purposes of this study, we used a relative measure of exposure as such simple techniques have repeatedly been shown to be sufficient predictors of variation in littoral communities (Keddy, 1982; Lindegarth and Gamfeldt, 2005).

Relative exposure was estimated for 400 locations spaced at 0.5 km intervals around the shoreline of Strangford Lough in Northern Ireland (54° 27’ 60” N, 5° 35’ 39” W). As the Lough has a narrow connection to the Irish Sea (Fig. 1), waves are determined by local winds without any influence from open water swells. Daily wind records from three meteorological stations within two kilometres of Strangford Lough were used to create a ‘consensus’ wind data set for 1972-2003. Data from the separate stations were transformed to a mean of zero with unit standard deviation to allow time series with different mean speeds to be averaged (producing a consensus wind time series). This is the simplest model for interpolating wind patterns across different locations in the Lough. Given local (topographic) influences on wind speeds at the meteorological stations, a consensus (average) across all the data was considered to be a more robust estimate of wind speed than to interpolate differences based on distances from each station. With only three meteorological stations, there are not enough data to support the derivation of a spatially referenced interpolation model. The consensus dataset was positively correlated with all the individual wind record data sets, implying that it is representative of trends across the study area.

Relative exposure at each site was estimated from the sum of annual consensus wind speed along each of 36 equidistant bearings multiplied by the fetch distance along the same bearing. Fetch distances for each of the 400 locations around the Lough were estimated using a GIS routine, with fetch calculated as the distance of open water along each of the 36 bearings. The equation for relative exposure at a location in any particular year was therefore:

$$RE = \sum_{i=10}^{i=360} f_i . v_i \qquad (1)$$

where RE is relative exposure, i is the compass bearing (in steps of 10º), f is the fetch distance and v is the annual average wind speed along bearing i. Deviations of mean exposure index from zero therefore indicate the interaction of fetch distances with particular wind directions.

Two alternative indices were calculated for comparison with the average wind speed data. These involved looking at the frequency of wind records. In particular, the frequency of strong winds was examined as these may have more influence on the biota of the shore than the wave climate associated with average conditions. The indices were derived from the proportion of wind records along each bearing (frequency of wind events) and the proportion of records exceeding 12 m s^{-1} along each bearing (frequency of strong to gale events). Data for each site were expressed at the number of wind records per year per bearing relative to the average number of records over the entire time series per bearing at a site. A proportion above one therefore indicates relatively more records (or strong to gale records) along a particular bearing in a particular year. Again, a consensus among the metrological stations was drawn by averaging data from the three data sets. Finally, the relative proportion values were substituted into equation 1 (as annual values of v) to give a relative exposure index based on record frequency rather than wind speed. These indices therefore increase when there are relatively more wind records along bearings with a long fetch (and would increase over time if there were more strong to gale events towards the end of the time series). The results of these alternative indices (data not presented) were comparable to those of the initial relative exposure index, suggesting that the overall conclusions are not dependant on any particular method of estimating relative exposure.

The strengths of two types of association were estimated for each location's exposure time series. Firstly exposure was correlated against year ('temporal trend') to examine the evidence for the type of progressive changes in exposure that may be associated with climate change. Secondly, the time series were correlated against the annual values for the NAO index to examine to role of this source of regional climate variability. Correlations between relative exposure and the NAO used the annual NAO index (Hurrell, 1995). Within the time period 1972-2003, there was no temporal trend in the annual NAO index (Spearman's correlation between NAO index and year = 0.055, $p > 0.05$, mean NAO = 1.077, SE 0.35, range -3.78 to 5.08). As there was no expectation that correlations between relative exposure and time or the NAO were necessarily linear, Spearman's rank correlation was used as an estimate of the strength of any monotonic trend (critical value at $\alpha = 0.05$ for 32 pairs = 0.349). Temporal autocorrelation may influence the inference drawn from correlations between time series. However, the focus of this study is not in estimating the significance of individual correlations. The exact level of Type I error does not affect conclusions about spatial scales and relationships between derived variables.

The temporal patterns in wave exposure (association with the NAO and temporal trend) are likely to vary with location. In a uniform environment, temporal changes across locations will be synchronous. Variations in the coastline will reduce the synchrony of response between locations. The scales at which synchronicity between locations breaks down were identified used spatial autocorrelation (Rossi et al., 1992). Distances between locations in this analysis were calculated from the 500 m step distances along the shore rather than from Euclidian distances (which confound distances across the Lough with distances along the shore). It may be that more exposed locations are more sensitive to changes in the wind climate. This possibility was investigated by correlating the average exposure level at a location (1972-2003) with the temporal trend and association with the NAO.

3. Results and Discussion

A striking feature of the calculated exposure time series was the high divergence between locations. As one shore experiences a peak in estimated exposure, the opposite pattern may be occurring less than a kilometre away (Fig. 2). The divergence is created by the interaction between the particular orientation of fetch distances at each location and annual changes in the average wind speed along different bearings. The average correlation with time was -0.001, reflecting the overall lack of trend in average wind speeds at Strangford over the 32-year period (this overall pattern is consistent with climate change predictions for Northern Ireland, Hulme et al., 2002). The range of temporal correlations for individual shores, however, was from –0.35 to 0.44. Hence, some locations became more exposed over time while other locations were simultaneously becoming more sheltered. The same pattern is repeated in associations with the NAO. The NAO index could have a positive, negative or no association with estimated exposure at different locations (mean correlation 0.126, range –0.18 to 0.40).

There were differences in spatial scale between the mean estimated exposure values and trends. Mean exposure over the 32-year period was correlated among adjacent sites up to a lag distance of approximately 20 km (Fig. 3). In contrast, temporal trends and associations with the NAO both lacked consistent spatial dependence at separations beyond a few km. The pattern for correlation in temporal trend is quite noisy, but the first departures from positive correlation between locations occur at separations above 3 km. The spatial dependence in NAO correlation first breaks down at separations above 5 km. These results demonstrate how locations may share similar mean exposure levels by virtue of proximity, but this does not necessarily mean that the corresponding temporal patterns in exposure are comparable.

Shores are often classified somewhere on a gradient between sheltered and exposed. The mean relative exposure index at a site, however, was a poor predictor of the estimated temporal trend (Fig. 4a). We artificially created a rising trend in average wind speeds: 10% change over the 32 years. Although, as would be expected, this increased the average temporal trend in exposure time series (mean correlation coefficient 0.14), there was no association with mean exposure at a site (Fig. 4b). Even with an increasing trend in the underlying wind data, 10 % of locations still showed no overall trend or a slight decrease in relative exposure over time. In these circumstances, it is difficult to predict which type of shore will respond most to changes in the pattern of winds. Detailed analyses using wind speed by direction and fetch distances would be needed for a risk assessment of locations vulnerable to any predicted climate change.

Unlike the pattern for temporal trends, correlations with the NAO could be related to average exposure (Fig. 4c). More exposed sites were more likely to increase in exposure during years with positive NAO values. Positive NAO index values imply stronger westerly winds, so the link with mean exposure level reflects the predominance of more exposed sites along the eastern shoreline of the Lough.

Divergent temporal patterns of wave exposure among locations are likely to be the norm for coastlines. Most coastlines have an undulating configuration, where small changes in the directions of swell or winds will alter the waves experienced by any particular location. The results presented here echo previous results for patterns of thermal stress (Helmuth et al., 2002): external forcing is variable on a finer scale than might be expected and there are divergent temporal trends in the physical conditions experienced at different locations. The breakdown of apparently regional forcing of shore communities may help explain observations of population and community asynchrony among shores separated by 10s of km (Burrows et al., 2002). In contrast, the dynamics of deeper benthic communities, beyond influences such as surface waves and aerial emersion, can be driven over relatively large scales by the NAO (Hagberg and Tunberg, 2000). Synchronous dynamics among populations are thought to arise through dispersal, shared environmental forcing (the ‘Moran effect’) or through trophic forcing of populations (Liebhold et al., 2004). As coastline configuration effectively modifies the scale of environmental forcing, we predict that the degree of synchrony among intertidal populations will decrease with increasing coastline complexity (Kendall et al., 1982).

The relatively small scales over which temporal patterns of wave exposure diverge have implications for the way in which change in coastal systems should be viewed. Indeed, studies that ignore the small-scale divergence may misinterpret temporal changes in ecosystems. For example, the NAO is often seen as a regional influence on ecosystems and species abundances (Greene et al., 2003). In contrast, we would not predict regional scale effects of variation in NAO for wave exposure along coastlines. In our study, positive associations between exposure and the NAO were more likely at more wave-exposed locations and there was little correlation between locations separated by more than about 10 km. If time series are averaged over widely separated locations, associations with the NAO are likely to be undetected. Similarly, isolated small-scale studies may produce conflicting results on the temporal patterns of wave exposure. The same conclusions apply to the potential effects of climate change: the effects of a large scale forcing occur at local, not regional scales. This offers some hope for mitigating the effects of climate change on coastal systems. For example in conservation planning, it should be possible to optimise the number and scale of reserves so that changes in wind climate are effectively neutral, with no overall increase in wave exposure across a network of sites.

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Figure Legends

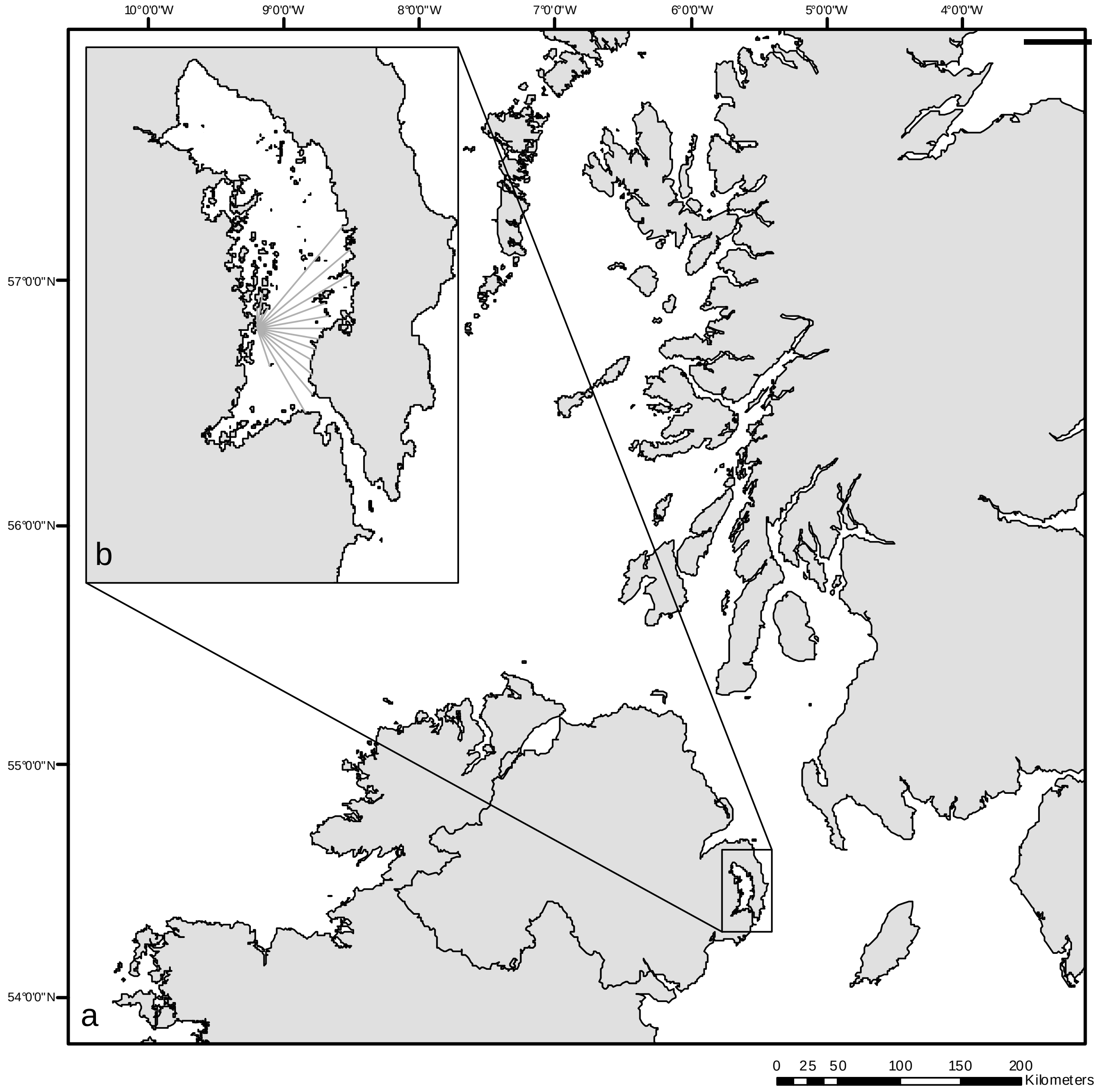
Fig. 1. Geographical location of Strangford Lough, Northern Ireland **a**, and **b**, illustration of fetch calculation routine for a single site.

Fig. 2. Relative exposure indices for two adjacent sites (separated by 0.5 km). The correlation between time series is –0.03, ns.

Fig. 3. Autocorrelation among locations along the shoreline for **a.** mean exposure index, **b.** estimated temporal trend in wave exposure and **c.** correlation of wave exposure with the NAO index. Dotted lines show confidence intervals assuming that the spatial variability is a white noise process with no spatial dependence.

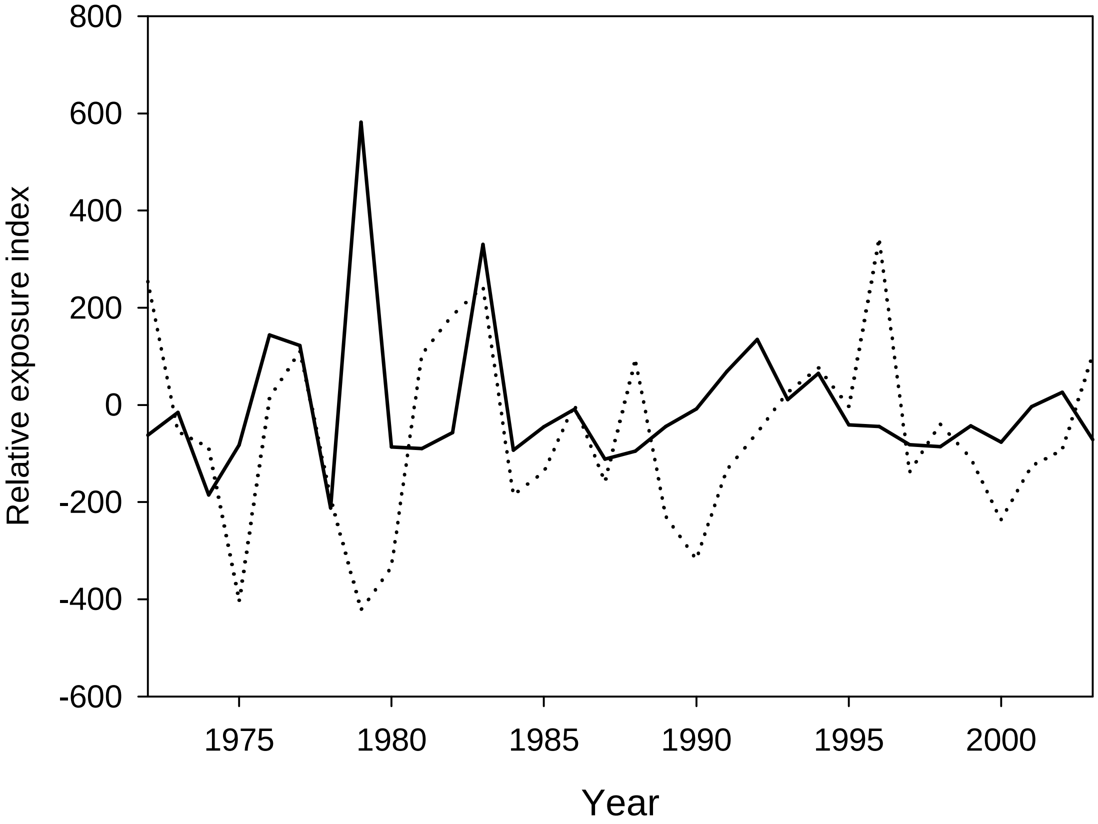
Fig. 4. Relationship between the mean exposure index over time at each location and **a**. the estimated temporal trend ($r = 0.053$, ns), **b.** the estimated temporal trend under conditions of an artificial 10 % increase in average wind speeds over the time series ($r = 0.087$, ns) and **c**. the correlation of each location's time series with the NAO index ($r = 0.474$, $p < 0.001$).

Fig. 1.



10°0'0"W
9°0'0"W
8°0'0"W
7°0'0"W
6°0'0"W
5°0'0"W
4°0'0"W
57°0'0"N
56°0'0"N
55°0'0"N
54°0'0"N
b
a
0
25
50
100
150
200
Kilometers

Fig 2.



800
600
400
200
0
-200
-400
-600
Relative exposure index
1975
1980
1985
1990
1995
2000
Year

Fig. 3.

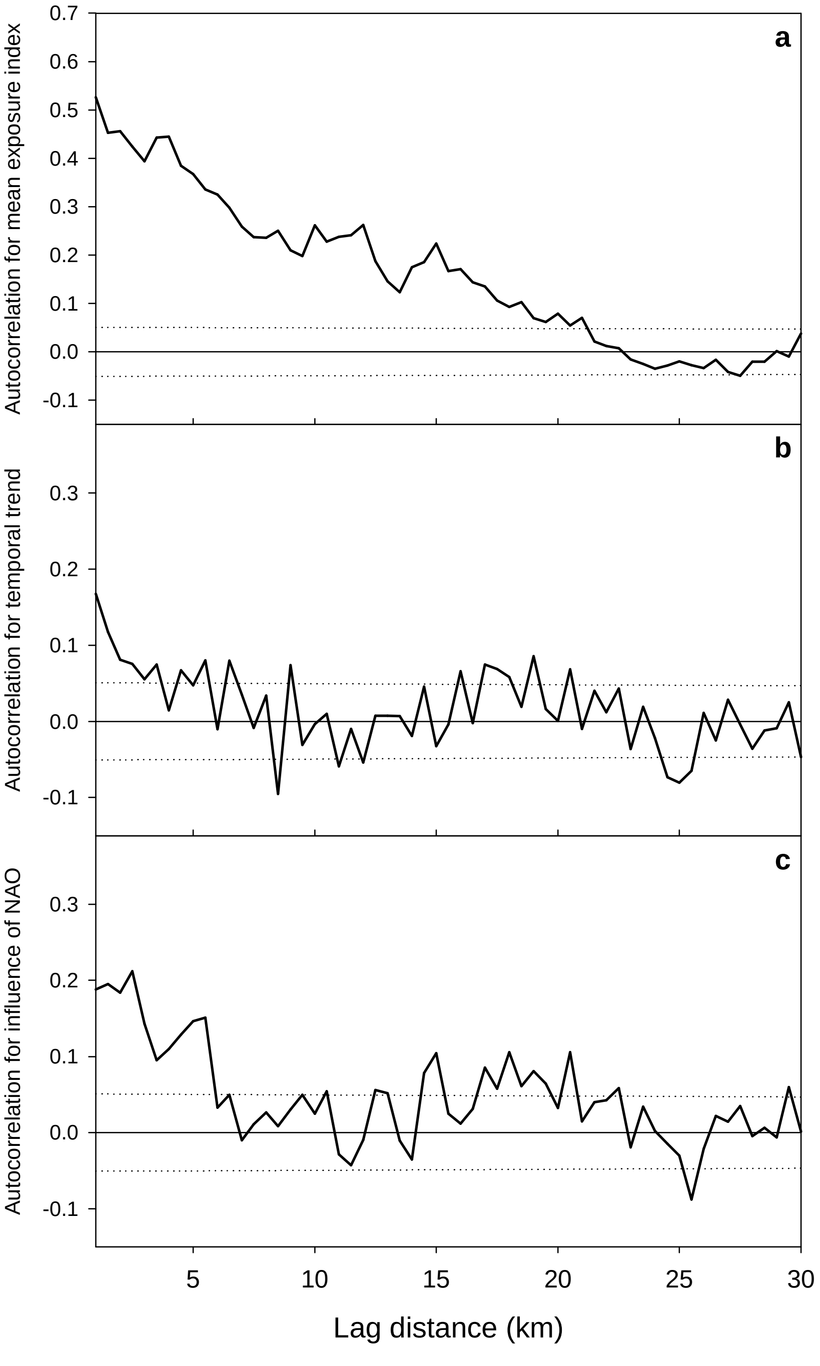
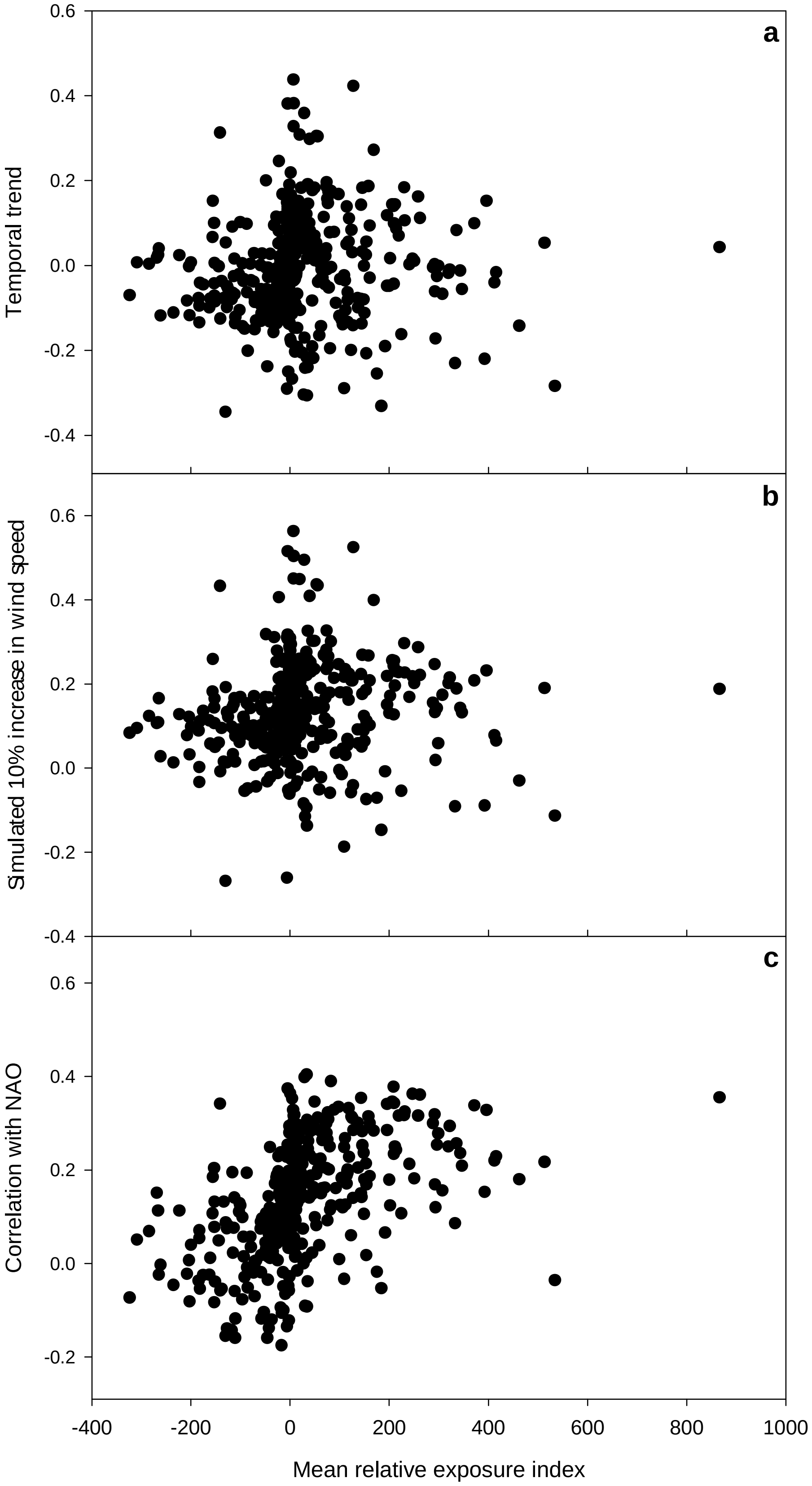

a
b
c
Autocorrelation for mean exposure index
Autocorrelation for temporal trend
Autocorrelation for influence of NAO
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
5
10
15
20
25
30
Lag distance (km)

Fig. 4


a
b
c
Temporal trend
Simulated 10% increase in wind speed
Correlation with NAO
Mean relative exposure index
0.6
0.4
0.2
0.0
-0.2
-0.4
0.6
0.4
0.2
0.0
-0.2
-0.4
0.6
0.4
0.2
0.0
-0.2
-400
-200
0
200
400
600
800
1000