Sensitivity of Ferry Services to the Western Isles of Scotland to Changes in Wave and Wind Climate

JOHN COLL

Irish Climate Analysis and Research Units, Department of Geography, National University of Ireland Maynooth, Maynooth, County Kildare, Ireland, and Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, United Kingdom

DAVID K. WOOLF

Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, and Laboratory for Satellite Oceanography, National Oceanography Centre, Southampton, United Kingdom

STUART W. GIBB

Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, United Kingdom

PETER G. CHALLENOR

Laboratory for Satellite Oceanography, National Oceanography Centre, Southampton, United Kingdom

(Manuscript received 28 May 2012, in final form 9 October 2012)

ABSTRACT

The roughness of the seas is rarely mentioned as a major factor in the economic or social welfare of a region. In this study, the relationship between the ocean wave climate and the economy of the Western Isles of Scotland is examined. This sparsely populated region has a high dependency on marine activities, and ferry services provide vital links between communities. The seas in the region are among the roughest in the world during autumn and winter, however, making maintenance of a reliable ferry service both difficult and expensive. A deterioration in wave and wind climate either in response to natural variability or as a regional response to anthropogenic climate change is possible. Satellite altimetry and gale-frequency data are used to analyze the contemporary response of wave and wind climate to the North Atlantic Oscillation (NAO). The sensitivity of wave climate to the NAO extends to ferry routes that are only partially sheltered and are exposed to ocean waves; thus, the reliability of ferry services is sensitive to NAO. Any deterioration of the wave climate will result in a disproportionately large increase in ferry-service disruption. The impacts associated with an unusually large storm event that affected the region in January 2005 are briefly explored to provide an insight into vulnerability to future storm events.

1. Introduction

a. Regional susceptibility to changes in the wave and wind climate

The Western Isles region of the Highlands and Islands of Scotland is situated on the seaward western edge of northwestern Europe (Figs. 1a,b). Here the coastline may be buffered against anticipated sea level rises as a result of ongoing isostatic recovery (Lambeck 1995; Dawson et al. 2001). A recent reanalysis of uplift data and sea level change projections challenges this view, however (Rennie and Hansom 2011). The region is exposed to easterly tracking Atlantic Ocean storms and is subject to some of the roughest seas in the world during the winter months (Woolf et al. 2002, 2003).

As is the case for all coastlines, episodes of storminess have an impact on the physical and cultural environments of the Western Isles (Smith et al. 2000; Hickey 2002), and all marine and coastal activities must contend with the state of the seas. The winter wave climate of the region exhibits high interannual variability, largely driven by

Corresponding author address: John Coll, Irish Climate Analysis and Research Units (ICARUS), Dept. of Geography, NUI Maynooth, Maynooth, Co. Kildare, Ireland.
E-mail: john.coll@nuim.ie

DOI: 10.1175/JAMC-D-12-0138.1

© 2013 American Meteorological Society

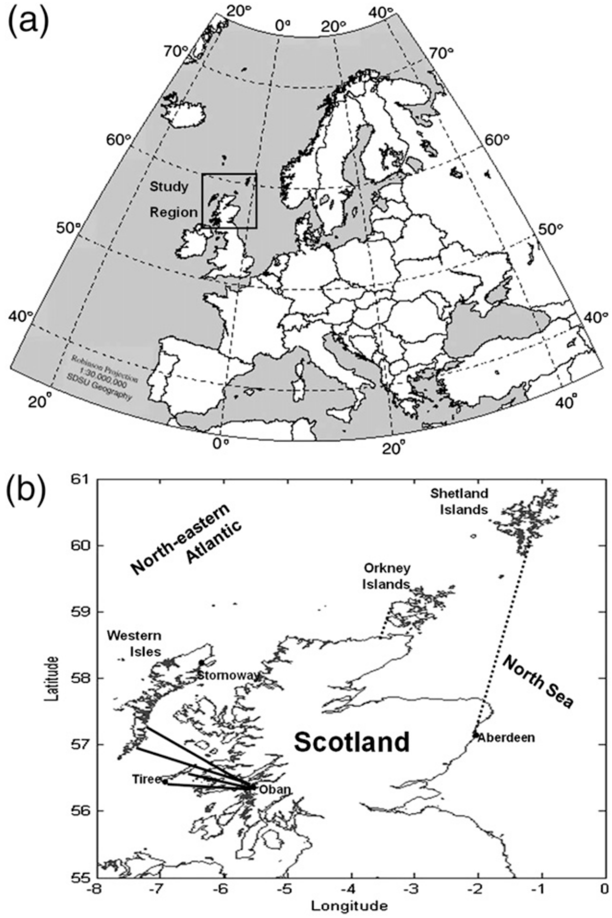

FIG. 1. The study region, showing (a) the North Atlantic and northwestern European context and (b) the study region in detail. In (b), analyzed ferry routes are indicated by solid black lines and other sailings referred to in the text (to the Orkney and Shetland Islands) are indicated by dashed black lines. Route indications are schematic only.

the North Atlantic Oscillation (NAO). The NAO is described by numerous authors (e.g., Hurrell 1995; Jones et al. 1997) as the primary mode of wintertime variability in the North Atlantic region (NA), affecting numerous climate parameters. The NAO is related to the strength and track of storms and depressions across the NA and into Europe and to the strength of the prevailing westerly winds (Osborn 2006; Vallis and Gerber 2008). NAO variability influences the mean winter climate over Europe, climate extremes (Scaife et al. 2008), ocean circulation (Bellucci et al. 2008), and wave heights in basin seas (Cañellas et al. 2010). The sensitivity of wave climate to the NAO extends beyond the open ocean into exposed coastal waters and partially sheltered waters, including the Sea of the Hebrides, where fishing activities and transport infrastructure, including ferry services, are vital to the prosperity of the region.

Since interannual variability in winter storminess and the sea state is closely related to changes in the strength and sign of the winter NAO, any intensification of positive trends in the winter NAO over the coming century could affect ferry services. For example, operators report berthing and operational difficulties when wind speeds exceed 40 kt (1 kt $\approx$ 0.5 m s^{-1}) and wave heights increase (B. Ward 2005, personal communication).

Worsening storminess in the NA associated with future NAO changes has been proposed as a possible regional manifestation of wider global warming. For coastlines exposed to the long Atlantic fetch and the passage of deep depressions, the impacts could be considerable. Few studies have considered specific economic effects such as the implications for marine-transport infrastructure, however.

b. Aims

This paper considers the impact of wave and wind climate on the Western Isles of Scotland. These impacts are broad and difficult to quantify in most cases, but the impact on ferry services is identified as something that is both important and quantifiable. Detailed quantitative analysis concentrates on selected west-coast ferry services under recent climatic conditions and, in particular, on the response to fluctuations in the NAO. An initial quantification is provided in relation to how shifts in the mean state of the winter NAO could affect the reliability of future services. To achieve this goal, relationships are established between winter half-year (October–March) NAO index (NAOI) values and both the wave climate in the Sea of the Hebrides and gale-day frequencies for representative stations. Using statistics on reliability of ferry services for selected routes, the role of adverse weather in disrupting sailings is investigated. A provisional calculation of the implications for ferry disruption associated with a shift in the mean state of the NAO is then provided. The implications of regional changes projected by global climate models (GCMs) are considered in the context of our results.

2. Wider social and economic context

a. Study region

The study region covers a large land area (~20 100 km^2), if the west-coast coastal area and Western Isles are considered together (Scottish Executive 2002). The population density is low, ranging from 8.1 to 13.2 persons per kilometer squared (Scottish Government 2008), and the gross domestic product (GDP) is well below the European Union average (Scottish Executive 2002). Over 20% of jobs are fisheries related, and together with

TABLE 1. Operating losses (£) incurred by Caledonian MacBrayne for 2001 and 2002.

Destination	2001	2002
Upper Clyde	4 481 000	4 796 000
Outer Isles	5 510 000	8 075 000
Islay/Gigha	1 079 000	1 320 000
Mull/Colonsay	1 567 000	1 387 000
Skye and Small Isles	2 941 000	2 770 000
Arran/Kintyre	509 000	678 000
Total	16 087 000	19 026 000

fish farming the industry accounts for ~16% of GDP (Western Isles Enterprise and Western Isles Tourist Board 2003). Therefore any future changes to sea state could affect the viability of communities that are heavily reliant on marine resources.

Marine transport is also vital, and ferry services form vital trade and communication networks (Kerr et al. 1999). Caledonian MacBrayne Hebridean and Clyde Ferries (CalMac) has held a monopoly on marine transport to the Western Isles since 1973, and these are heavily subsidized services. For this study, CalMac provided statistics on disruption to their services, as well as a series of financial results and detailed carrying statistics for the routes of interest. Overall the ferries are probably more important to the island communities than is the fishing industry, and the data provided by CalMac allow for a quantitative study.

b. *The importance of lifeline ferry links to the region*

Western Isles ferry services are rarely disrupted by severe weather, and thus the social stress is not severe. This fact does not equate to these services being easily maintained, however, but reflects a political decision to maintain a high standard of reliability and safety. CalMac (2006) describes the high standards the company must maintain and specifies the level of subsidy necessary to maintain loss-making services (Table 1). These data are interpreted here as indicating the scale of the task in maintaining a reliable service and, in particular, the role of adverse weather in compounding the challenge.

The ferries are therefore essential links between the mainland and all of the islands except Skye. Despite a rise in revenue from all sources from 1992 to 2001, however, the level of lifeline subsidy nearly doubled over the same period (Fig. 2a). Ferry traffic is much heavier during the summer tourist season, but services must be maintained through the unprofitable winter months. Services must meet a minimum standard, with the minimum standard of service as defined in the Services Specification including a ''*quality performance target, currently set at 98%*.''

To reach this target, the service must be safe, reliable, and punctual despite a severe winter climate. Measures to achieve this goal include the acquisition of ships designed and built to suit the severe conditions and the limited slipway and harbor facilities. Since the ships are designed and built to purpose, they cannot usually be replaced in case of emergency or breakdown by a charter vessel; therefore, the fleet includes nine large (''class IIa'') vessels and two small relief vessels. These expensive measures are necessary to maintain an adequate service in an adverse climate.

The adverse climate therefore dictates the running of robust vessels through the winter months as necessary but unprofitable, and it is during the winter that much of the revenue deficit subsidy (RDS) is spent on maintaining services (A. McNicoll 2005, personal communication).

The heaviest subsidy is necessary to maintain the major routes to the islands. This is reflected in operational loss figures, with services to the Outer Isles being particularly expensive to maintain as seen in the 10-yr data for all service-area operational losses (Fig. 3). Operating-loss figures detailed for the first time by CalMac in 2006 indicate that losses on sailings to the Western Isles are among the heaviest on all approved services qualifying for RDS support (CalMac 2006).

The class-IIa vessels are required to serve such mainland-to-island routes, generally involving fairly lengthy crossings of exposed seas. Cancellation, diversion, or major delay (defined as greater than 1 h) is in the great majority of cases attributed to adverse weather. The high cost of RDS extends to other Scottish ferries primarily serving the Shetlands and the Orkneys; the level of RDS required to maintain these services is lower (Figs. 2b,c), however, reflecting the smaller scale of operations.

3. Wind climate

a. *Variations in storminess and the influence of the NAO*

Most Atlantic cyclones approach Europe from the west following a well-defined northeastward route from near Newfoundland, Canada, and the midlatitude North Atlantic Ocean between eastern Canada and the British Isles is the stormiest region in the boreal winter (Hurrell 1995; Jones and Conway 1997; Chen and Hellstrom 1999; Osborn et al. 1999). Associated with NAO positive winters are strong storm tracks bringing maritime flow far into northern Europe (Rogers 1997; Hurrell 2003). An NAOI is defined from opposing sea level pressure anomalies in two centers, such that a deep Icelandic low pressure center and an intense Azores high pressure center imply positive NAOI.

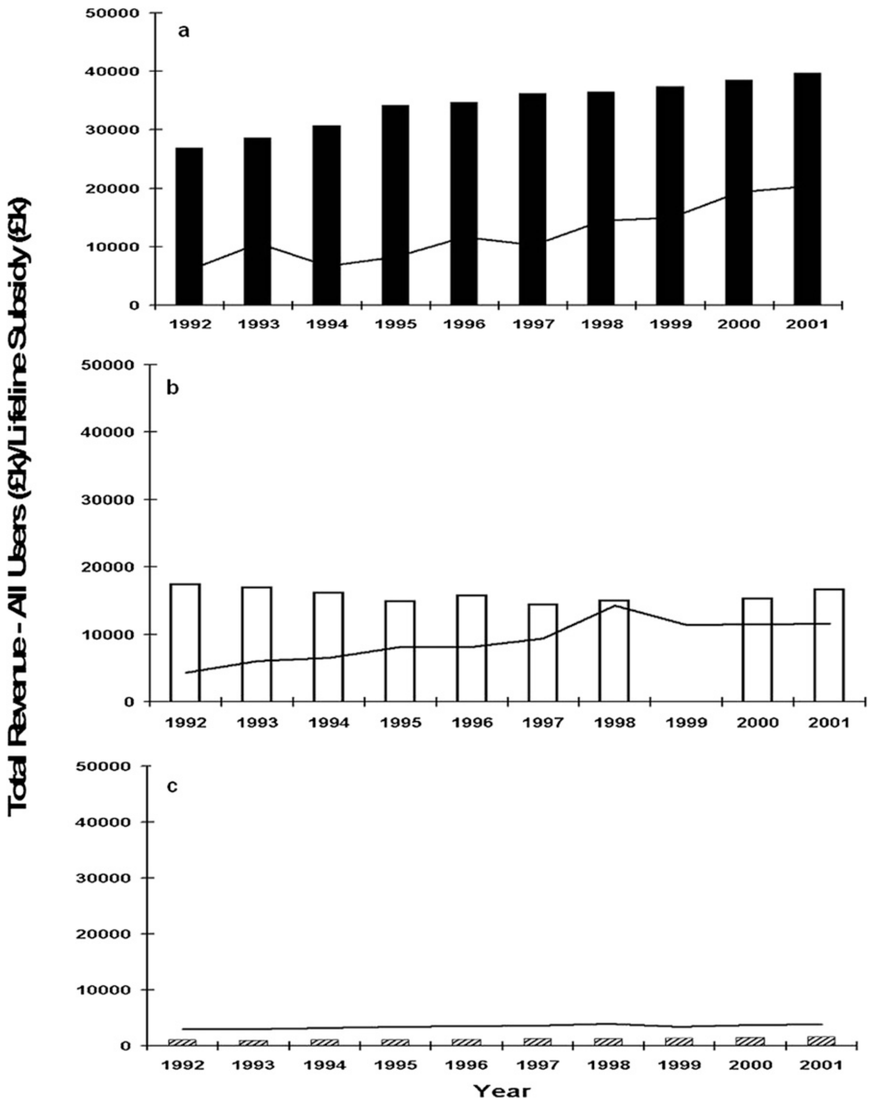

FIG. 2. Scottish ferry operators' revenue and lifeline subsidy data over 1992–2001: (a) CalMac, (b) P&O Scottish Ferries, and (c) Orkney Ferries. Histograms denote revenue information, and the solid lines show the lifeline subsidy. Data for P&O Scottish Ferries refer to sailings to the Shetland Islands.

During the second half of the twentieth century, the NAO underwent two kinds of interdecadal change (Dong et al. 2011). First, there was a pronounced positive trend from low values during the 1960s to high values in the 1990s (Hurrell 1995; Gillett et al. 2005; Kuzmina et al. 2005; Scaife et al. 2005). Second, the NAO action centers of interannual variability shifted eastward in the late 1970s (Hilmer and Jung 2000; Jung et al. 2003). High values of wintertime NAOI in the 1990s coincided with a pattern of increased storminess across Scotland (Dawson et al. 2001). Such shifts may be chance fluctuations, however, rather than indicating a forced change (Jung et al. 2003).

Trends toward a dominantly westerly flow throughout the 1990s have also been detected in pressure gradients measured over Fennoscandia (Tuomenvirta et al. 2001), and a 45-yr atmospheric pressure series indicates an increase in the number of winter storms around the United Kingdom (Alexander et al. 2005). Distinguishing natural versus anthropogenic variability in the NAO on the basis of observed sea level pressure (SLP) is challenging (Kuzmina et al. 2005), however—other work indicates that SLP variability over the North Atlantic is not entirely described by the NAO alone (Skeie 2000; Cavalieri and Hakkinen 2001; Bornemann and Brummer 2009).

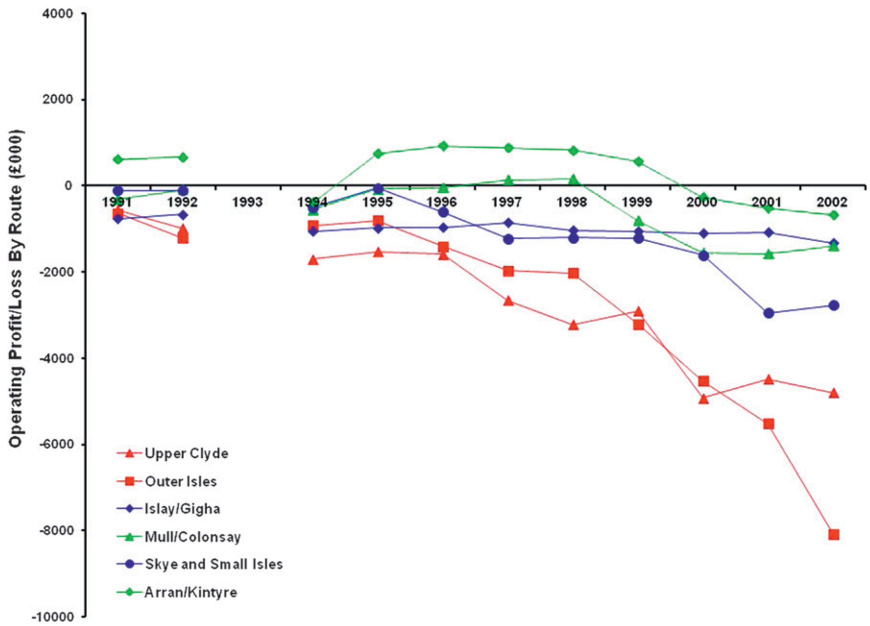

FIG. 3. CalMac service losses (profits) by operational area for 1991–2002.

We will show that if a shift to a higher frequency of NAO-positive winters occurred, ferry services to the Western Isles would be sensitive to gale-day frequency increases, both through their influence on sea state and through the direct operational impacts in creating berthing difficulties.

b. *Gale days around the Sea of the Hebrides*

Satellite altimeters measure wind speed over water in addition to wave height and other products. Analysis of these wind speed data coincident to the wave-height data described in section 4 suggests that wind speeds, while not as highly correlated with NAO as wave heights are, do have a proportionate sensitivity to NAO. More extensive data on wind speed, with higher temporal resolution, are available from meteorological stations onshore; hence these stations are the preferred data source here. For consistency, the Met Office (UKMO) definition is applied; that is, "A gale day is defined as a day on which the wind speed attains a mean value of 34 kt or more over any period of 10 consecutive minutes."

Forty-one-year daily gale-day datasets (1960–2000) for stations at Stornoway and Tiree were supplied by UKMO. The difference between the normalized SLP over Gibraltar and the normalized SLP over southwestern Iceland is a useful index of the strength of the winter NAO (Jones et al. 1997); hence these are the NAOI values used here. The analysis focuses on the extended winter period (October–March) since the majority of cyclones in the NA region occur in these months (Schinke 1993). Following conversion to monthly frequencies, gale-day frequencies were regressed against the corresponding NAOI values (Jones et al. 1997) for October–March (Tables 2 and 3). We follow the suggestion that comparisons of regional features such as coastal storminess with the NAOI should be performed on monthly rather than annual/seasonal data (Smith et al. 2000) where practical.

The positive and significant correlations of gale-day frequencies with the monthly NAOI for January and February at Stornoway and Tiree reflect the proximity of the stations to the deep depressions of the winter months (Figs. 4a,b). The positive correlation ($r = 0.76$; $p < 0.001$) with the NAOI for Stornoway in January reflects the close link between the climatic wind behavior and the influence of the NAO. The highest percentage of gale days for Tiree (23.9%) and Stornoway (13.8%), and some of the higher correlations with the NAOI—$r = 0.60$; $p < 0.001$ (Tiree) and $r = 0.76$; $p < 0.001$ (Stornoway)—occur in January. Tiree is more exposed to southwesterlies and records a higher mean gale-day frequency, whereas Stornoway has more topographic shelter to the south and west. Despite this situation, gale-day frequencies are more closely correlated to the corresponding NAOI at Stornoway than at Tiree other than in December.

4. Wave climate

a. *Wave-climate measurement by satellite altimetry*

Sea state is a complicated property but can be reduced to a single variable that describes the variability of

TABLE 2. Stornoway autumn/winter gale climatological description and Pearson rank correlation coefficients r and associated significance (p values) for monthly gale frequency and NAOI (1960–2000).

Month	Oct	Nov	Dec	Jan	Feb	Mar
Mean gale days	2.2	2.6	3.8	4.3	3.1	2.4
Std dev	1.9	2.2	3.0	3.5	2.7	2.5
Percent of gale days	7.0	8.5	12.3	13.8	11.0	7.6
Correlation with NAO	$r = 0.54$	$r = 0.52$	$r = 0.17$	$r = 0.76$	$r = 0.71$	$r = 0.59$
	($p < 0.001$)	($p < 0.001$)	($p = 0.297$)	($p < 0.001$)	($p < 0.001$)	($p < 0.001$)

surface elevation about sea level. The standard definition is ''significant wave height'' (SWH, equal to 4 times root-mean-square elevation), which is close to the wave height typically reported by an experienced mariner. Some historical records of visual observations of wave height are available, but the systematic study of waves is a recent practice.

Instrumental wave measurements in the NA and United Kingdom waters began in the 1940s, with most activity between the 1960s and 1980s. Draper (1980, 1991) described wave climatological behavior (''climatology'') in the region primarily on the basis of diverse in situ measurements in the preceding decades. To the west of Scotland, the main information came from deployments at three mooring sites to the west of South Uist (Fortnum 1981; Stanton 1984). These sites were fully exposed to the Atlantic and do not directly address the climate within relatively sheltered waters. Draper (1991) described the process of ''contouring'' wave climatology as using ''*what may well have to be described as intuition or, at best, experience.*'' Draper used his experience, very sparse instrumental measurements, and some visual observations to describe the near-shore variation of wave climate and the partial penetration of rough seas into sea areas such as The Minches (east of Lewis) and the Sea of the Hebrides (southwest of Skye). UKMO maintained a wave buoy near the edge of the Hebridean shelf—buoy ''RARH'' at 57°N, 9.9°W, as reported by Alcock and Rickards (2001)—but no systematic in situ measurements on the inner shelf since the mid-1980s have been reported.

Wave climatologies are also available from wave modeling and ''hindcasts'' of the last few decades; for example, the Waves and Storms in the North Atlantic (WASA) study (Günther et al. 1998). These hindcasts of the NA are with deep-sea wave models and a fairly coarse resolution—for example, the WASA study used a 1.5° latitude by 1.5° longitude grid—that is appropriate to large-scale, oceanic wave climatologies but cannot describe near-shore variation of wave climate and wave climate affected by the complicated topography and bathymetry in the Hebrides area. Wave climate of the Western Isles requires specific modeling at a finer resolution, and some high-resolution modeling of this area was conducted by Wolf et al. (2002, 2005) but was only for case studies and no appropriate hindcast was available. Since the conclusion of our analysis, however, a 1957–2002 hindcast at a 10-km resolution downscaled from the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) has been made available for the study location (Reistad et al. 2011).

Satellite altimetry has offered a new tool for measuring wave climate since the 1980s and has been used to provide a more modern alternative to the traditional U.K. wave climatology (Woolf et al. 2003). Each satellite altimeter can only measure surface roughness immediately below the instrument, and therefore sampling by one or a few satellites is sparse. With a footprint of several kilometers in diameter, resulting in a limited spatial resolution, they also are unreliable if the footprint overlaps land and for tens of kilometers after the footprint leaves land. Most altimeter studies are based on ''gridded data'' (Woolf et al. 2002, 2003) and are limited to a resolution of 1° or worse, and therefore they are as limited as the model hindcasts in describing local variations. Useful coastal information can be extracted along selected satellite orbits, however, and below we summarize analysis

TABLE 3. As in Table 2, but for Tiree.

Month	Oct	Nov	Dec	Jan	Feb	Mar
Mean gale days	3.1	4.4	5.9	7.4	5.3	3.9
Std dev	2.5	2.5	3.0	4.4	3.9	2.9
Percent gale days	9.9	14.6	19.0	23.9	18.7	12.7
Correlation with NAO	$r = 0.51$	$r = 0.36$	$r = 0.46$	$r = 0.60$	$r = 0.63$	$r = 0.32$
	($p < 0.001$)	($p = 0.020$)	($p = 0.003$)	($p < 0.001$)	($p < 0.001$)	($p = 0.045$)

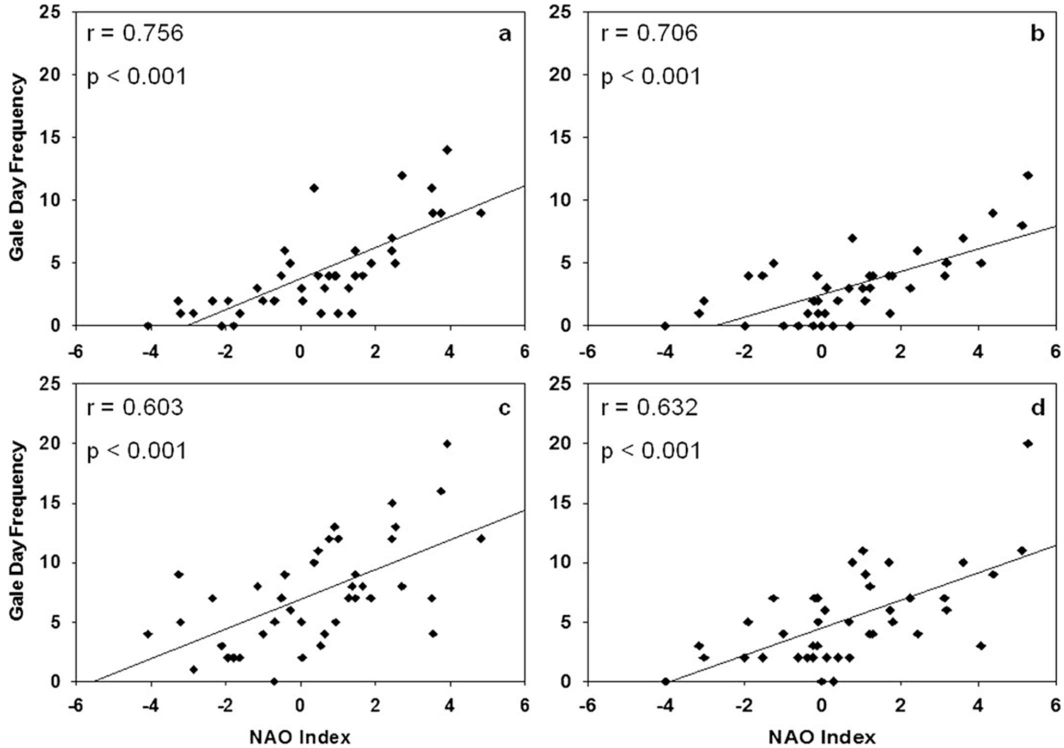

FIG. 4. Gale-day frequencies vs monthly NAOI for the 1960–2000 dataset for selected winter months with Pearson correlation coefficient values r and associated significance values p: (a) Stornoway for January, (b) Stornoway for February, (c) Tiree for January, and (d) Tiree for February.

at one partially sheltered location of special interest as it is along one of the most frequently disrupted ferry routes. An advantage of using gridded data is that data from a number of satellites can contribute—this allows robust relationships to be developed and then validated (Woolf et al. 2002)—whereas studies using data along specific tracks are limited to a specific satellite or series of satellites following the desired ground track. In this study, only the regular orbits of the Ocean Topography Experiment (TOPEX)/Poseidon (since succeeded by *Jason* and *Jason-2*) provided suitable data.

b. Wave climate of the Sea of the Hebrides

Analysis of satellite wave data is here focused on the problem of ferry-service disruption and uses data from a single location. The satellite TOPEX/Poseidon was launched in August of 1992 and was held in an orbit that precisely repeated the same ground track every 9 days and 22 h. Figure 5 presents a map of the region and shows the ground track of two ‘‘passes’’ (44 and 189) of the TOPEX/Poseidon satellite across the region, as well as the bathymetry of the coastal shelf waters around the Sea of the Hebrides. The position of ‘‘reference points’’ on each track is also shown. Values of wave height at each reference point are based on satellite returns averaged over 1 s, but values include a calibration recommended by Challenor and Cotton (2003). Ground tracks are directed from west to east, and, since the system electronics have difficulty adjusting from over the land to over the sea, the data quality is generally better near west-facing coasts than near east-facing coasts. In this case, the footprint of one of the tracks (44) clips islands as the satellite passes over the Sound of Barra, and data are lost over a few tens of kilometers. Symbols show where data are usually retrievable, but careful analysis has shown that data at the first three points beyond the Sound of Barra are slightly erratic.

Altimeter data are generally very reliable, but the occasional ‘‘rogue value’’ does occur, and analysis should filter these out. One simple pragmatic scheme is to take the median of a few consecutive 1-s values to eliminate the influence of a single rogue value. Here we take the median value for three points (the diamonds that are connected with a thick bar in Fig. 5) on each of the two regular passes, on each repetition of the pass. To avoid some slightly less reliable data on track 44, the chosen points on track 44 are not precisely on the crossover of the two passes and will represent a slightly different wave climate than that from the other pass (track 189). Taken together, however, the values from the two tracks are

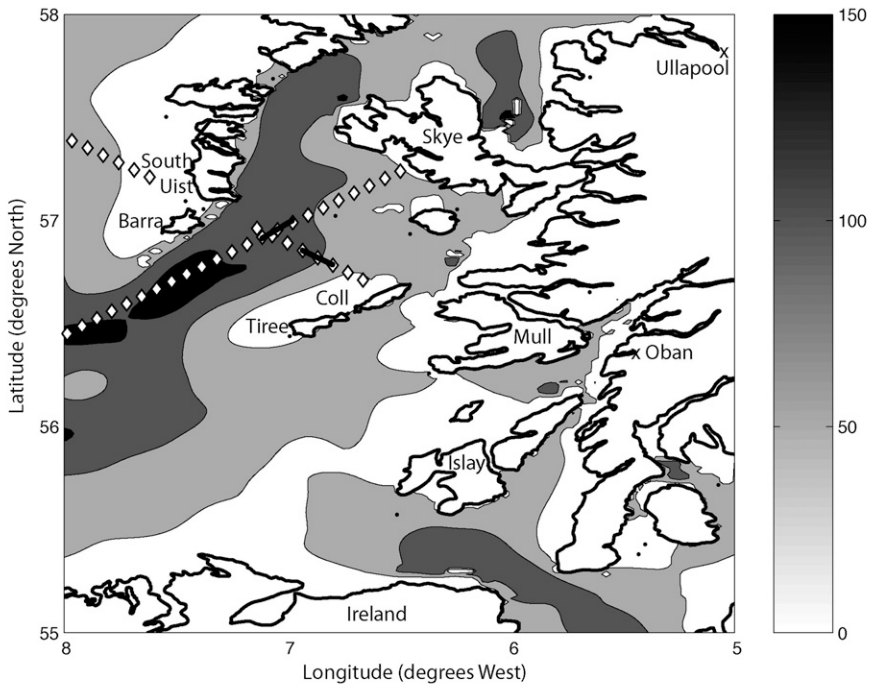

FIG. 5. Map of the region, indicating the two satellite altimeter tracks (denoted by the diamonds) used for wave-height analysis within the Sea of the Hebrides and the surrounding bathymetry (contoured in multiples of 50 m, with darker shading corresponding to successively deeper water).

a reasonable representation of the wave climate within the central waters of the Sea of the Hebrides. Ferry services from the mainland (Oban) to Barra and South Uist must cross these waters; services to Coll and Tiree cross open waters to the south that are similarly exposed to the west and southwest. Ferry services to the more northerly islands, for example, Lewis, are relatively sheltered from southwesterly winds but are relatively exposed to northerly winds (Tsimplis et al. 2005). Alternate tracks are repeated almost uniformly, approximately every 5 days, and give a reasonable sample of the wave climate at monthly or lower resolution.

Nine years of TOPEX/Poseidon data from September 1992 onward are used to assess wave climate within the Sea of the Hebrides, and the seasonal and annual climatologies of SWH are summarized in Table 4. The mean and standard deviation are included together with "exceedance values." These are values of wave height that are exceeded on a particular fraction (here 50%, 25%, 10%, and 5%) of occasions. Note that the risk of very large seas (say, SWH > 4 m) is almost entirely limited to the autumn and winter seasons. Another method of summarizing wave climate is to find an analytical function that accurately describes the empirical probability distribution. We have found that in each season the "Fisher–Tippett Type I" (FT I) distribution (described mathematically below) is a fair representation of wave climate in the Sea of the Hebrides. The cumulative FT I probability distribution is described by

$$p(\text{significant wave height} < x) = \exp\{-\exp[-(x-\alpha)/\beta]\}. \quad (1)$$

This is a two-parameter distribution with constants α and β. A practical method of testing whether the wave

TABLE 4. Annual and seasonal climate in the Sea of the Hebrides on the basis of tracks 189 and 44, for 1992–2001. Season definitions are January–March for winter, April–June for spring, July–September for summer, and October–December for Autumn. Number (No.) is the number of data values. All other values are significant wave height in meters.

	Annual	Winter	Spring	Summer	Autumn
No.	632	152	159	161	160
Mean	1.77	2.42	1.28	1.21	2.18
Std dev	1.09	1.16	0.71	0.65	1.19
50% exceedance	1.52	2.31	1.08	0.99	2.00
25% exceedance	2.38	3.22	1.73	1.56	2.71
10% exceedance	3.28	3.77	2.12	1.99	3.81
5% exceedance	3.83	4.50	2.39	2.38	4.33

climate is consistent with a particular distribution is to sort the measured values in ascending order, assign each value (ith of n) to an expected cumulative probability $E(x_i)$, and plot FT $= -\ln\{-\ln[E(x_i)]\}$ against x_i. Rearranging (1), we find

$$-\ln(\ln p) = (x - \alpha)/\beta. \quad (2)$$

Therefore, the plotting procedure should result in points lying on a straight line with gradient $1/\beta$ and intercept $-\alpha/\beta$ for a climate following this FT I distribution. A slight complication is the assignment of $E(x_i)$. Carter and Challenor (1981) recommend the procedure introduced by Gringorten (1963):

$$E(x_i) = (i - 0.44)/(n + 0.12). \quad (3)$$

The combined autumn and winter climate that includes the ‘‘period of risk’’ in the Sea of the Hebrides is plotted in Fig. 6 and strongly suggests that the autumn–winter climate follows an FT I distribution. The parameters α and β can be estimated by ordinary linear regression, but instead we can exploit the theoretical relationships between these parameters and the mean μ and standard deviation σ for an FT I distribution:

$$\beta = (6^{0.5}/\pi)\sigma, \quad (4)$$

$$\text{Euler's constant } \gamma = 0.5772, \quad \text{and} \quad (5)$$

$$\alpha = \mu - \gamma\beta. \quad (6)$$

The parameters are calculated from the sample mean and sample standard deviation (μ = 2.2965 m and σ = 1.18 m for autumn–winter). The resulting ‘‘fit’’ is shown as a solid line in Fig. 6, and the origin of the dashed line is described below.

We can be reasonably satisfied that the wave climate of 1992–2001 in the Sea of the Hebrides is fairly described by Table 5 and the FT I distribution implicit in Fig. 6. A major limitation of this description is that it does not address climate variability or climate change. Thus we can only ascribe the estimated climate to this period of time; likewise every other climate of the region will be ‘‘of its time’’ as summarized below.

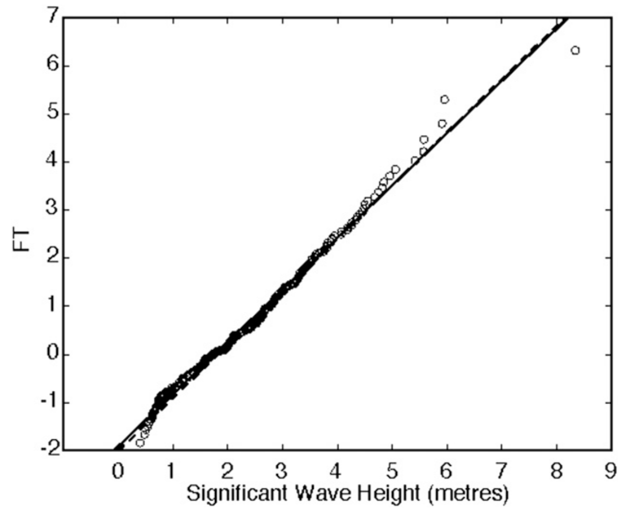

FIG. 6. Distribution of wave heights in the Sea of the Hebrides in autumn–winter (October–March) 1992–2001. The plot shows independent measurements of wave height in order of height. The ‘‘y ordinate,’’ FT I, is defined in the text and is designed such that wave heights following a Fisher-Tippett type-I distribution should fall on a straight line. Two fits to the data are shown, as described in the text.

Strong variability and decadal trends in wave climate are a feature of the northeastern Atlantic and northern North Sea, particularly in the winter (Woolf et al. 2002). This variability is greatest to the west of Scotland where the variability in significant wave height can be ascribed primarily to a linear response of wave climate in the winter (primarily December–March) to the NAO. Here the apparent sensitivity of wave climate to the NAO in the entire ‘‘period of risk,’’ October–March, is analyzed. The altimeter data from the Sea of the Hebrides described above

TABLE 5. Sensitivity of rough seas to NAOI for three models. The predicted frequency is given with which two threshold wave heights will be exceeded for several values of NAOI and for three different models. Each model is based on plausible assumptions of the response of the distribution of wave heights to the NAOI (as explained in the text).

NAOI	Model 1 (standard) probability > 4 m (%)	Model 1 (standard) probability > 5 m (%)	Model 2 probability > 4 m (%)	Model 2 probability > 5 m (%)	Model 3 probability > 4 m (%)	Model 3 probability > 5 m (%)
−3	1.99	0.52	3.34	1.09	0.90	0.17
−2	3.26	0.93	4.36	1.43	2.21	0.53
−1	5.03	1.55	5.68	1.87	4.36	1.25
0	7.39	2.45	7.39	2.45	7.39	2.45
1	10.40	3.68	9.58	3.20	11.22	4.19
2	14.08	5.31	12.38	4.18	15.68	6.50
3	18.42	7.38	15.92	5.44	20.61	9.34

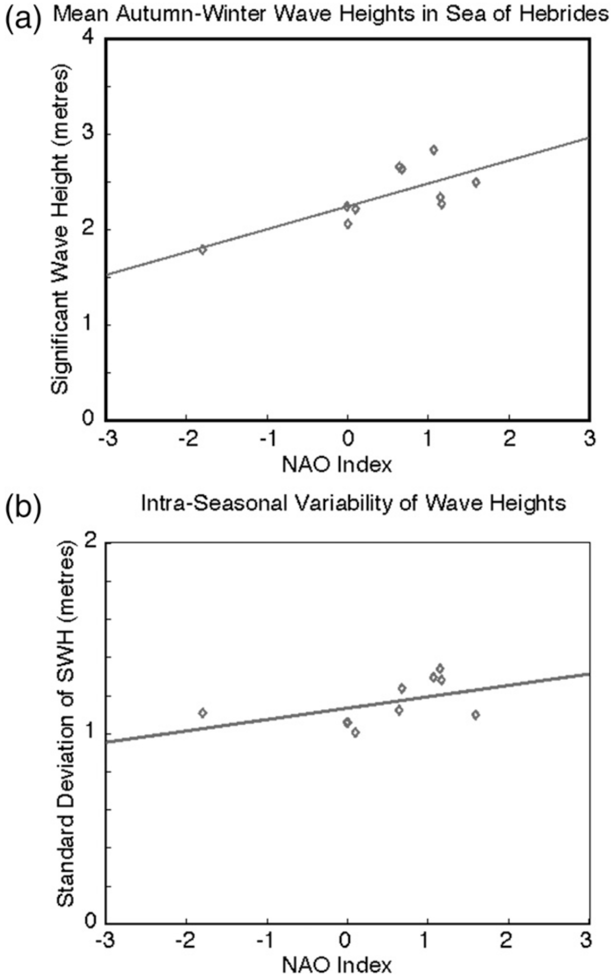

FIG. 7. Sensitivity of (a) mean significant wave height and (b) standard deviation of significant wave height to a seasonal (autumn–winter) NAOI. Values are shown for 10 seasons from 1992/93 to 2001/02; simple linear regression fits are shown as straight lines.

are used together with the NAOI data (Jones et al. 1997). Satellite altimeter data from a 10th autumn–winter (2001/02) are included. The sample mean and standard deviation of SWH are calculated from all passes across the Sea of the Hebrides in each autumn–winter. A seasonal NAOI is calculated as the simple mean of the published index in each of the six constituent months. Wave-height statistics are plotted against the NAOI in Fig. 7 with simple regression fits included as lines. The statistics of the relationship between a wave statistic and the NAOI can be reported in terms of a correlation coefficient r and the sensitivity of the wave parameter to NAOI (reported with confidence limits). In common with sites to the west of the Hebrides a strong relationship of the seasonal mean SWH to NAOI is implied [Fig. 7a; $r = 0.7464$, with sensitivity = 0.24 (±0.14 at 90% confidence limits) meters per index unit]. The intraseasonal variability in SWH may also be sensitive to NAO, but this possibility cannot be determined with any confidence. The linear relationship of standard deviation to NAO is shown in Fig. 7b [$r = 0.4910$, with sensitivity = 0.06 (±0.07) meters per index unit]. Stronger correlations of wave-climate parameters with the NAOI are found for subsets of the autumn–winter period, for example, December–March, but the autumn–winter values described above are used.

Given a simple model of how the mean and standard deviation of wave height might vary, for example, in response to NAO, it is possible to construct the entire probability distribution of a future wave climate by assuming that the climate will follow an FT I distribution with these two parameters. This method is preferred to directly calculating the linear regression of a particular wave statistic on the NAOI, because there are generally far too few observations in each year for a robust calculation of this kind for most wave statistics (seasonal mean and standard deviation are relatively undemanding). We apply this method in section 5, but first we test the validity of this scheme by calculating the distribution that is predicted for 1992–2001 autumn–winter climate, on the basis of the mean value of the NAOI in this period (0.4339) and the calculated relationship of μ and σ to NAO. The predicted distribution ($\mu = 2.3456$ m and $\sigma = 1.16$ m) is shown as a dashed line in Fig. 6 and almost coincides with the observed distribution (solid line) as might be expected. This does not imply that a future wave climate can be predicted solely from the NAOI, but Woolf et al. (2002) have shown that the relationship between wave climate and NAO is remarkably robust between decades and therefore the method is credible. Work by Wang et al. (2004) also generally supports the linkages identified here between the NAO and wave climate in the northeastern Atlantic, and this linkage is explored further in section 6a.

5. Ferry services and the influence of the NAO

a. Statistics on ferry-service disruption

CalMac supplied statistics on the reliability of all their ferry routes and details of the ships assigned to these routes, together with accounts of the meteorological conditions affecting ferry services. Among the most disrupted routes are those from Oban on the mainland to some of the small islands around the Sea of the Hebrides. Up to ~5% of services to Barra, South Uist, Tiree, and Coll can be canceled, diverted, or delayed by more than 1 h (cancellation is the most common of these) because of adverse weather. Adverse weather is the dominant cause of major disruption and the "knock-on delay from previous sailing'' is the second most common cause of major delay. Adverse weather is rare in spring and summer. Disruption is largely a midwinter phenomenon and can be chronic. In the study period, these services were maintained by two of CalMac's larger and better vessels, *Clansman* and *Lord of the Isles*. These large vessels are not (at least outside the tourist season) necessary for the passenger demand but primarily reflect the rigorous demands of the routes. Data individual to these two services and separated by calendar year from 1999 to 2003 were made available and are used quantitatively in the next section.

Detailed analysis is restricted to the above two routes, but CalMac data show that all routes are disrupted occasionally by adverse weather. Routes vary in susceptibility to the weather and different routes are particularly susceptible to distinct weather patterns. Thus, for example, other services to the Outer Hebrides, across the Minch or Little Minch, are generally more reliable than those to Barra and South Uist. The services across the Minches are not exposed to ocean waves from the southwest or west and therefore respond very differently to changes in weather patterns.

b. *NAO impact on disruption of ferry services across the Sea of the Hebrides*

In sections 3a and 3b, evidence has been provided that wind climate relates to the NAO, and in sections 4a and 4b we demonstrate that wave climate also responds to the NAO. For simplicity, we now develop a predictor for ferry disruption that is based solely on the relationship of wave height to the NAOI. This relationship can be summarized in the calculated linear regressions of the mean autumn–winter SWH μ and the standard deviation of SWH σ to NAOI I:

$$\mu = 2.24 + 0.24I \quad \text{and} \tag{7}$$

$$\sigma = 1.13 + 0.06I. \tag{8}$$

By assuming an FT I distribution always applies, the complete probability distribution of wave climate can be described for any value of I by combining (7) and (8) with (1), (4), (5), and (6). For example, we can calculate the probability of SWH exceeding 4 or 5 m (Fig. 8). Note that the sensitivity of the probability of rough seas is much more sensitive to NAO than might be guessed from Fig. 7. This is a familiar property when dealing with ''the tail'' of probability distributions; exceedance of a critical value in the tail is highly sensitive to only small changes in mean or variance.

Because the sensitivity of σ to NAO is highly uncertain, it is also important to note that the sensitivity of the

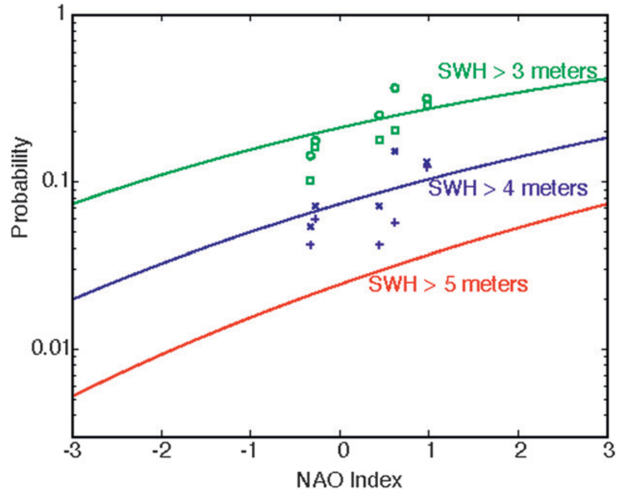

FIG. 8. Probability of rough seas and ferry disruption as a function of NAOI. The curves denote the estimated probability of significant wave height in the Sea of the Hebrides exceeding the given values. The circles and squares denote statistics on any disruption by adverse weather on the Oban/Barra/South Uist service and the Oban/Coll/Tiree service, respectively. The times signs and plus signs denote statistics on major disruption (cancellation, diversion, or delay greater than 1 h) by adverse weather on the Oban/Barra/South Uist service and the Oban/Coll/Tiree service, respectively.

''probability (SWH $>$ 4 m)'' to NAO derives mostly from the sensitivity of μ to NAO. This is illustrated in Table 5, in which the exceedance probabilities for various cases are tabulated under similar assumptions for the behavior of the mean but three separate assumptions for standard deviation: 1) the ''standard model'' already described, 2) an assumption that standard deviation is insensitive to NAO, and 3) an assumption of an invariant coefficient of variation—that is, standard deviation is as equally sensitive to NAO as is the mean so that the ''shape'' of the probability distribution is invariant. These are fairly crude models of the sensitivity of rough seas to the NAO but are reasonable. Shifts in mean state of the NAOI to -2, 0, or $+2$ are plausible, and these values correspond to greatly different risks of 4-m seas (3.26%, 7.39%, and 14.08%, respectively, for the standard model). These probabilities are only slightly altered if σ is fixed at 1.13 m (4.36%, 7.39%, and 12.38%). Exceedance probabilities for more extreme seas, for example, 5-m exceedance, are more sensitive to assumptions about the behavior of the standard deviation.

It is important to establish the ''threshold condition'' for ferry disruption and also to validate the results of the model with respect to future NAO shifts. In a strict sense, the model applies to long-term changes, but some validation is possible from the annually resolved statistics. Figures for both major disruption by adverse weather and any disruption by adverse weather on the two routes (Oban/Barra/South Uist and Oban/Coll/Tiree) of primary interest are analyzed. The available data are not separated by season, but it is known that disruption by adverse weather is highly unusual in spring and summer and that ~30% of services are scheduled for autumn–winter; therefore, the annual fractions are trebled to give approximate statistics for autumn and winter. Values of NAO for each year are calculated from winter and autumn monthly values, and pairs of disruption and NAO values are provided (Fig. 8). Together with the testimony of the ferry operators, it seems reasonable to conclude that disruption of ferry services across the Sea of the Hebrides generally coincides with rough seas and that a ''critical SWH'' of ~4 m is appropriate for major disruption, whereas disruption begins at a critical SWH of ~3 m. Also, the ferry data support the interpretation that the sensitivity of ferry disruption to the NAO will be broadly similar to that of rough seas. In summary, we might reasonably expect that ferry-disruption statistics will follow a similar sensitivity to NAO as presented for ''probability (SWH > 4 m)'' in Fig. 8 and Table 5.

6. Discussion

a. Future NAO and storm-track changes

Factors related to the wind such as storminess and sea state are important features of climate but are recognized as difficult to predict within climate change scenarios (e.g., Jenkins et al. 2003). The NAO influence on the wind speed over northern Europe is documented (e.g., Hurrell and van Loon 1997; Marshall et al. 2001; Trigo et al. 2002), however, and the NAOI correlates well with winter wind speed over northern Europe (Sušelj et al. 2010). It has been shown here that both are closely related to the behavior of the wintertime NAO. With a northward shift in storm activity, northwesterly and northerly winds may be predominant for some of the winter months, which may explain the closer correlations with the NAOI at Stornoway.

At the same time, the behavior of the NAO must be considered a ''wild card'' with a large but unpredictable impact on interannual, decadal, and centennial time scales. To date the NAO has been difficult to predict, but there is hope for future skill in decadal forecasting and there has been some indication from GCMs of how the NAO may respond to greenhouse gas forcing. Gillett et al. (2003) and others identify a trend toward a positive NAO with global warming (Osborn 2004; Kuzmina et al. 2005; Ulbrich et al. 2008). There are also indications that the northeastern end of the NA storm track is shifted south in winter, giving more storms and increased frequency of strong winds over the United Kingdom. These changes are linked to an increase in baroclinicity rather than the NAO becoming more positive, however (Lionello et al. 2008; Bengtsson et al. 2009; McDonald 2010).

Overall therefore, there is a weak consensus for a poleward shift of the storm tracks (e.g., Meehl et al. 2007), and some models project fewer but more intense storms (e.g., Lambert and Fyfe 2006; Leckebusch et al. 2008). Indications elsewhere are for fewer storms, but with heavier precipitation (e.g., Finnis et al. 2007; Bengtsson et al. 2009) and even more uncertain local changes (e.g., Ulbrich et al. 2009). Nonetheless, if future storminess increases were realized as a feature of climate change, there would be clear implications for gale-day frequencies and their impact on sea state and ferry services.

Contradicting this interpretation, however, in the period since our primary analysis, the NAOI has exhibited a negative trend culminating in 2009/10 with one of the most negative NAOIs on record (Pinto and Raible 2012). In particular, the harsh winters of 2010/11 but especially 2009/10 across the Northern Hemisphere midlatitudes coupled with a record minimum value in the NAO and Arctic Oscillation (AO) index have refocused attention on the NAO/AO and its strong relationship with Northern Hemisphere winter climate anomalies. Studies of that winter have mostly concluded that internal atmospheric dynamics drive the phase and amplitude of the NAO/AO and that it is therefore unpredictable (Seager et al. 2010; Jung et al. 2011). Associated with a rapid decline in average solar activity since 1985 there are indications that, despite hemispheric warming, the United Kingdom and Europe could experience more cold winters than during recent decades (Lockwood et al. 2010). This assumes that all other factors that can modulate U.K. winter temperatures (including the regional influence of anthropogenic climate change) remain the same, however, which is unlikely to be a valid assumption (Lockwood et al. 2011).

b. Implications for lifeline ferry services

The calculations described in section 4 illustrate that shifts in the value of the NAO, particularly to more ''positive'' extremes, are expected to have a strong effect on the probability of rough seas around the Hebrides and along ferry routes to some of the islands. These results will need to be validated against new wave data—for example, from the *Jason* and *Jason-2* altimeters.

While data availability focused the analysis here on the two routes where an NAO influence seemed most likely, the sensitivity of other Hebrides routes to changing weather patterns should also be considered. Other Scottish ferries may also be affected by weather patterns; in particular an NAO influence on ferries serving the Orkneys or Shetlands seems likely given the large-scale pattern of the NAO influence on waves (Woolf et al. 2002, 2003). Therefore, more detailed statistics from the ferry companies and other stakeholders are required to describe and validate the extent of impacts. It is already clear that this is a ''multimillion dollar'' issue for the Western Isles, however. We have not studied the persistence or close succession of storm events, but it is clear that isolation of islands due to lengthy periods of rough weather is a risk and could have serious social consequences.

By way of an example, the region was subject to an exceptional storm event on the night of 11 and 12 January 2005 associated with a deep depression (944 hPa) that was tracking just north of Scotland. This resulted in sustained high winds across the region, with recorded gust speeds of 101 and 106 mi h^{-1} (1 mi $h^{-1} \approx 0.447$ m s^{-1}) at Stornoway and Barra, respectively (UKMO 2011). This culminated a 12-day period during which a succession of deep depressions tracked eastward from Iceland to the Norwegian Sea, resulting in a gust speed exceeding 70 mi h^{-1} being recorded somewhere in Scotland in all but 2 of the first 12 days of January 2005 (UKMO 2011).

The direct cost of this storm for local authorities was considerable. Damage to roads, major harbors, piers and jetties, property, and other built infrastructure totaled ~£15 million in the Western Isles Council region, and amounted to ~£5 million for the Highland Council region (Highland Council 2005). Internal challenges were identified for emergency services as communications networks failed and the scale of coastal flooding prompted a procedures review (Highlands and Islands Fire Brigade 2005). The wider coastal impacts and the longer climate-record context of this ''Great Storm'' are reviewed in Dawson et al. (2007).

As a direct result of the bad weather on 11–12 January 2005, all CalMac services were suspended for the first time ''in living memory,'' and in the preceding 2 weeks ship captains were reporting exceptionally severe sea conditions on many west-coast sailings (H. D. MacLennan 2005, personal communication). The storm actually saved CalMac money because of a combination of factors. Winter carryings are small, and sailings are heavily subsidized by the RDS; therefore, the revenue loss is minor. Also, as most winter travel is not discretionary, traffic for the canceled sailings was displaced to other sailings once services resumed, thereby offsetting the revenue loss (A. McNicoll 2005, personal communication). CalMac also benefited from savings on fuel and through nonpayment of berthing dues for the canceled services at non-CalMac harbors (A. McNicoll 2005, personal communication). Cancellations due to severe weather are classed as a ''relief event'' whereby the decision of a captain on the grounds of vessel safety takes precedence over the service-level agreement (G. Laidlaw 2005, personal communication).

Despite these ''savings'' to CalMac, the cancellation of sailings represents a social cost for island communities in terms of disruption to the supply of vital goods. In a similar way, any future increase in the levels of disruption to services is likely to be reflected in the local economy of communities already subject to high freight and transportation costs that affect the price of goods.

c. Outlook: Ferry-service disruption

Future disruption to the ferries resulting from increased storm activity in the winter half-year could hinder initiatives to tackle some of the socioeconomic difficulties of this region. As well as affecting the level of subsidy required to maintain reliable services, freight costs of supplying communities via ferry links could be adversely affected. As the weather event in January of 2005 illustrates, however, caution must be exercised in how the impacts are interpreted. Although ferry operators may benefit from some short-term savings, there are likely to be more pernicious social and economic impacts associated with an increased frequency of severe-weather events.

Considerable uncertainties remain in relation to the nature and magnitude of regional climate change, and the future behavior of the NAO and storm tracking remains unclear. Doubts also remain as to whether changes in large-scale atmospheric phenomenon such as the NAO constitute the best proxy indicator for regional-scale patterns of variability. Trends in severe weather are difficult to detect because of the spatial and temporal variability of these events (Houghton et al. 2001), and extreme events also have short detection lifetimes (Weisse et al. 2005). Nonetheless, the empirical evidence suggests a correlation between NAO and storms.

There is a need to better quantify future changes in the wintertime NAO and its influence on sea state and to clarify the relationship between such regional-scale drivers of variability and the manifestation of local-scale weather events. Although no detailed economic modeling has been attempted here, the linkages revealed in our predictor for ferry disruption could lend themselves to a scenario-based approach to impact assessment.

7. Summary

The Western Isles rely heavily on the surrounding seas for employment and to maintain transport links. The neighboring seas are exceptionally rough in autumn and winter, resulting in some disruption to present economic activity, including some ferry routes. Allied to their influence on sea state, days with gales can also severely hamper ferry operations.

The sea state is sensitive to the NAO, and the winter wind climate of the region is also closely linked to the behavior of the NAO. Any changes in the seasonality or frequency of deep cyclones have implications for transport infrastructure and other marine and coastal activities.

With a disproportionately large increase in the risk of rough seas associated with an increase in mean wave height, ferry services could face increased levels of disruption. A deterioration of the wave climate through either natural variability or anthropogenic climate change could adversely affect the future economic development of the region.

Acknowledgments. This research was largely supported by the Tyndall Centre for Climate Change Research project ''Toward a vulnerability assessment for the UK coastline'' (IT 1.15). We thank A.Taylor, A. McNicoll, B. Ward, H. D. MacLennan, and G. McKenzie at Caledonian MacBrayne Hebridean and Clyde Ferries for providing operational data and information. Thanks are also given to G. Laidlaw at the Scottish Executive Maritime State Aids Unit for clarifying how severe weather cancellations are interpreted in relation to CalMac's Service Level Agreement.

REFERENCES

Alcock, G., and L. Rickards, 2001: Climate of UK waters at the millennium: Status and trends. Inter-Agency Committee on Marine Science and Technology Information Doc. 9, 48 pp.

Alexander, L. V., S. F. B. Tett, and T. Jonsson, 2005: Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophys. Res. Lett.,* **32,** L13704, doi:10.1029/2005GL022371.

Bellucci, A., S. Gualdi, E. Scoccimarro, and A. Navarra, 2008: NAO–ocean circulation interactions in a coupled general circulation model. *Climate Dyn.,* **31,** 759–777.

Bengtsson, L., K. I. Hodges, and N. Keenlyside, 2009: Will extratropical storms intensify in a warmer climate? *J. Climate,* **22,** 2276–2301.

Bornemann, A. J., and B. Brummer, 2009: The Iceland–Lofotes pressure difference: Different states of the North Atlantic low-pressure zone. *Tellus,* **61A,** 466–475.

CalMac, 2006: Annual report and consolidated financial statements 2006. Caledonian MacBrayne Hebridean and Clyde Ferries Rep., 42 pp.

Cañellas, B., A. Orfila, F. Méndez, A. Álvarez, and J. Tintoré, 2010: Influence of the NAO on the northwestern Mediterranean wave climate. *Sci. Mar.,* **74,** 55–64.

Carter, D. J. T., and P. G. Challenor, 1981: Estimating return values of wave height. Institute of Oceanographic Sciences Rep. 116, 111 pp.

Cavalieri, D., and S. Hakkinen, 2001: Arctic climate and atmospheric planetary waves. *Geophys. Res. Lett.,* **28,** 791–794.

Challenor, P. G., and P. D. Cotton, 2003: The joint calibration of altimeter and in situ wave heights. Advances in the applications of marine climatology: The dynamic part of the WMO guide to the applications of marine meteorology, World Meteorological Organization Tech. Doc. WMO/TD 1081 and JCOMM Tech. Rep. 13, 139–148. [Available online at ftp://ftp.wmo.int/Documents/PublicWeb/amp/mmop/documents/JCOMM-TR/J-TR-13-Marine-Climatology/JCOMM-TR-13.pdf.]

Chen, D., and C. Hellstrom, 1999: The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: Spatial and temporal variations. *Tellus,* **51A,** 505–516.

Dawson, A. G., D. E. Smith, and S. Dawson, 2001: Potential impacts of climate change on sea levels around Scotland. Scottish Natural Heritage Research, Survey, and Monitoring Rep. 178, 77 pp. [Available online at http://www.snh.org.uk/pdfs/publications/research/178.pdf.]

——, S. Dawson, and W. Ritchie, 2007: Historical climatology and coastal change associated with the 'Great Storm' of January 2005, South Uist and Benbecula, Scottish Outer Hebrides. *Scott. Geogr. J.,* **123,** 135–149.

Dong, B., R. T. Sutton, and T. Woollings, 2011: Changes of interannual NAO variability in response to greenhouse gases forcing. *Climate Dyn.,* **37,** 1621–1641.

Draper, L., 1980: Wave climatology of the UK continental shelf. *Physical and Chemical Oceanography and Physical Resources,* F. T Banner, M. B. Collins, and K. S. Massie, Eds., Vol. II, *The North-West European Shelf Seas: The Sea Bed and Sea in Motion,* Elsevier, 353–368.

——, 1991: Wave climate atlas of the British Isles. HMSO Offshore Tech. Rep. OTH 89 303, 22 pp.

Finnis, J., M. M. Holland, M. C. Serreze, and J. J. Cassano, 2007: Response of Northern Hemisphere extratropical cyclone activity and associated precipitation to climate change, as represented by the Community Climate System Model. *J. Geophys. Res.,* **112,** G04S42, doi:10.1029/2006JG000286.

Fortnum, B. C. H., 1981: Waves recorded off South Uist in the Hebrides. Institute of Oceanographic Sciences Rep. 115, 14 pp.

Gillett, N. P., H. F. Graf, and T. J. Osborn, 2003: Climate change and the North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophys. Monogr.,* Vol. 134, Amer. Geophys. Union, 193–209.

——, R. J. Allan, and T. J. Ansell, 2005: Detection of external influence on sea level pressure with a multi-model ensemble. *Geophys. Res. Lett.,* **32,** L19714, doi:10.1029/2005GL023640.

Gringorten, I. I., 1963: A plotting rule for extreme probability paper. *J. Geophys. Res.,* **68,** 813–814.

Günther, H., W. Rosenthal, M. Stawarz, J. C. Carretero, M. Gomez, I. Lozano, O. Serrano, and M. Reistad, 1998: The wave climate of the Northeast Atlantic over the period 1955–1994: The WASA wave hindcast. *Global Atmos. Ocean Syst.,* **6,** 121–163.

Hickey, K. R., 2002: The storm of 31 January to 1 February 1953 and its impact on Scotland. *Scott. Geogr. J.,* **117,** 283–295.

Highland Council, 2005: Storm damage report by Director of Finance to Resources Committee. Highland Council Rep., 5 pp. [Available online at http://www.highland.gov.uk/NR/rdonlyres/EBCA0449-2110-4885-934E-93926AF9FCD0/0/Item9res1105.pdf.]

Highlands and Islands Fire Brigade, 2005: Report: The storms of January 11th and 12th 2005. Highlands and Islands Fire Brigade Rep., 78 pp.

Hilmer, M., and T. Jung, 2000: Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. *Geophys. Res. Lett.,* **27,** 989–992.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, 881 pp.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

——, 2003: Climate variability: North Atlantic and Arctic Oscillation. *Encyclopedia of Atmospheric Sciences,* J. Holton, J. Pyle, and J. Curry, Eds., Elsevier, 439–445.

——, and H. van Loon, 1997: Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change,* **36,** 301–326.

Jenkins, G., C. Cooper, D. Hassell, and R. Jones, 2003: Scenarios of climate change for islands within the BIC region. Met Office Rep. for the British-Irish Council, 50 pp.

Jones, P. D., and D. Conway, 1997: Precipitation in the British Isles: An analysis of area-average data updated to 1995. *Int. J. Climatol.,* **17,** 427–438.

——, T. Jónsson, and D. Wheeler, 1997: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *Int. J. Climatol.,* **17,** 1433–1450.

Jung, T., M. Hilmer, E. Ruprecht, S. Kleppeck, S. K. Gulev, and O. Zolina, 2003: Characteristics of the recent eastward shift of interannual NAO variability. *J. Climate,* **16,** 3371–3382.

——, F. Vitart, L. Ferranti, and J.-J. Morcrette, 2011: Origin and predictability of the extreme negative NAO winter of 2009/10. *Geophys. Res. Lett.,* **38,** L07701, doi:10.1029/2011GL046786.

Kerr, A., S. Shackley, R. Milne, and S. Allen, 1999: Climate change: Scottish implications scoping study. The Scottish Executive Central Research Unit Rep., 75 pp. [Available online at http://www.ukcip.org.uk/wordpress/wp-content/PDFs/Scotland_scoping.pdf.]

Kuzmina, S. I., L. Bengtsson, O. M. Johannessen, H. Drange, L. P. Bobylev, and M. W. Miles, 2005: The North Atlantic Oscillation and greenhouse-gas forcing. *Geophys. Res. Lett.,* **32,** L04703, doi:10.1029/2004GL021064.

Lambeck, K., 1995: Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *J. Geol. Soc. London,* **152,** 437–448.

Lambert, S. J., and J. C. Fyfe, 2006: Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: Results from the models participating in the IPCC diagnostic exercise. *Climate Dyn.,* **26,** 713–728.

Leckebusch, G. C., A. Weimer, J. G. Pinto, M. Reyers, and P. Speth, 2008: Extreme wind storms over Europe in present and future climate: A cluster analysis approach. *Meteor. Z.,* **17,** 67–82.

Lionello, P., U. Boldrin, and F. Giorgi, 2010: Future changes in cyclone climatology over Europe as inferred from a regional climate simulation. *Climate Dyn.,* **30,** 657–671.

Lockwood, M., R. G. Harrison, T. Woollings, and S. K. Solanki, 2010: Are cold winters in Europe associated with low solar activity? *Environ. Res. Lett.,* **5,** 024001, doi:10.1088/1748-9326/5/2/024001.

——, ——, M. J. Owens, L. Barnard, T. Woollings, and F. Steinhilber, 2011: The solar influence on the probability of relatively cold UK winters in the future. *Environ. Res. Lett.,* **6,** 034004, doi:10.1088/1748-9326/6/3/034004.

Marshall, J., and Coauthors, 2001: North Atlantic climate variability: Phenomena, impacts and mechanisms. *Int. J. Climatol.,* **21,** 1863–1898.

McDonald, R., 2010: Understanding the impact of climate change on Northern Hemisphere extra-tropical cyclones. *Climate Dyn.,* **37,** 1399–1425.

Meehl, G. A., and Coauthors, 2007: Global climate projections. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 747–846.

Osborn, T. J., 2004: Simulating the winter North Atlantic Oscillation: The roles of internal variability and greenhouse gas forcing. *Climate Dyn.,* **22,** 605–623.

——, 2006: Recent variations in the winter North Atlantic Oscillation. *Weather,* **61,** 353–355.

——, D. Conway, M. Hulme, J. M. Gregory, and P. D. Jones, 1999: Air flow influences on local climate: Observed and simulated mean relationships for the UK. *Climate Res.,* **13,** 173–191.

Pinto, J. G., and C. C. Raible, 2012: Past and recent changes in the North Atlantic Oscillation. *Wiley Interdiscip. Rev.: Climate Change,* **3,** 79–90.

Reistad, M., Ø. Breivik, H. Haakenstad, O. J. Aarnes, B. R. Furevik, and J. Bidlot, 2011: A high-resolution hindcast of wind and waves for the North Sea, the Norwegian Sea, and the Barents Sea. *J. Geophys. Res.,* **116,** C05019, doi:10.1029/2010JC006402.

Rennie, A. F., and J. D. Hansom, 2011: Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology,* **125,** 193–202.

Rogers, J. C., 1997: North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe. *J. Climate,* **10,** 1635–1647.

Scaife, A. A., J. R. Knight, C. K. Folland, and G. K. Vallis, 2005: A stratospheric influence on the winter NAO and North Atlantic surface climate. *Geophys. Res. Lett.,* **32,** L18715, doi:10.1029/2005GL023226.

——, C. K. Folland, L. V. Alexander, A. Moberg, and J. R. Knight, 2008: European climate extremes and the North Atlantic Oscillation. *J. Climate,* **21,** 72–83.

Schinke, H., 1993: On the occurrence of deep cyclones over Europe and the North Atlantic in the period 1930–1991. *Contrib. Atmos. Phys.,* **66,** 223–237.

Scottish Executive, 2002: Scottish coastal socio-economic scoping study. School of Resources, Environment, and Society Rep., 104 pp. [Available online at http://www.scotland.gov.uk/Resource/Doc/47007/0014791.pdf.]

Scottish Government, 2008: Highlands and Islands Scotland Operational Programme—European Regional Development Fund: 2007-2013. Scottish Gov. Final Rep. 2007UK161PO001, 181 pp. [Available online at http://www.scotland.gov.uk/Resource/0039/00393532.pdf.]

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik, 2010: Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophys. Res. Lett.,* **37,** L14703, doi:10.1029/2010GL043830.

Skeie, P., 2000: Meridional flow variability over the Nordic Seas in the Arctic oscillation framework. *Geophys. Res. Lett.,* **27,** 2569–2572.

Smith, D. E., and Coauthors, 2000: *Storminess and Environmentally Sensitive Atlantic Coastal Regions of the European Union.* Commission of European Communities, 320 pp.

Stanton, B. R., 1984: Return wave heights off South Uist estimated from seven years of data. Institute of Oceanographic Sciences Rep. 164, 54 pp.

Sušelj, K., A. Sood, and D. Heinemann, 2010: North Sea near-surface wind climate and its relation to the large-scale circulation patterns. *Theor. Appl. Climatol.,* **99,** 403–419.

Trigo, R. M., T. J. Osborn, and J. M. Corte-Real, 2002: The North Atlantic Oscillation influence on Europe: Climate impacts and associated physical mechanisms. *Climate Res.,* **20,** 9–17.

Tsimplis, M. N., and Coauthors, 2005: Towards a vulnerability assessment of the UK and northern European coasts: The role of regional climate variability. *Philos. Trans. Roy. Soc. London,* **363,** 1329–1358.

Tuomenvirta, H., A. Drebs, E. Førland, O.-E. Tveito, H. Alexandersson, E. Vaarby-Laursen, and T. Jónsson, 2001: NORDKLIM data set 1.0—Description and illustrations. DNMI-Rep. 08/01 Klima, 27 pp.

UKMO, cited 2011: January 2005 Monthly weather assessment. [Available online at http://www.metoffice.gov.uk/climate/uk/2005/january.html.]

Ulbrich, U. J., J. G. Pinto, H. Kupfer, G. C. Leckebusch, T. Spangehl, and M. Reyers, 2008: Changing Northern Hemisphere storm tracks in an ensemble of IPCC climate change simulations. *J. Climate,* **21,** 1669–1679.

——, G. C. Leckebusch, and J. G. Pinto, 2009: Extra-tropical cyclones in the present and future climate: A review. *Theor. Appl. Climatol.,* **96,** 117–131.

Vallis, G. K., and E. P. Gerber, 2008: Local and hemispheric dynamics of the North Atlantic Oscillation, annular patterns and the zonal index. *Dyn. Atmos. Oceans,* **44,** 184–212.

Wang, X. L., F. W. Zwiers, and V. R. Swail, 2004: North Atlantic ocean wave climate change scenarios for the twenty-first century. *J. Climate,* **17,** 2368–2383.

Weisse, R., H. von Storch, and F. Feser, 2005: Northeast Atlantic and North Sea storminess as simulated by a regional climate during 1958–2001 and comparison with observations. *J. Climate,* **18,** 465–479.

Western Isles Enterprise and Western Isles Tourist Board, 2003: Western Isles tourism facts and figures update. Western Isles Enterprise Review of 2002 Season, 66 pp.

Wolf, J., and D. K. Woolf, 2005: Waves and climate change in the Sea of the Hebrides. *Proc. 15th (2005) Int. Offshore and Polar Engineering Conf.,* Seoul, South Korea, ISOPE, 100–107.

——, S. L. Wakelin, and R. A. Flather, 2002: Effects of climate change on wave height at the coast. *Proc. 12th (2002) Int. Offshore and Polar Engineering Conf.,* Vol. 3, Kitakyushu, Japan, ISOPE, 135–142.

Woolf, D. K., P. G. Challenor, and P. D. Cotton, 2002: The variability and predictability of North Atlantic wave climate. *J. Geophys. Res.,* **107,** 3145, doi:10.1029/2001JC001124.

——, P. D. Cotton, and P. G. Challenor, 2003: Measurements of the offshore wave climate around the British Isles by satellite altimeter. *Philos. Trans. Roy. Soc. London,* **361,** 27–31.