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WIND TRENDS IN THE HIGHLANDS AND ISLANDS OF SCOTLAND AND THEIR RELATION TO THE NORTH ATLANTIC OSCILLATION

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1. INTRODUCTION

Several studies based on observational data as well as with global climate models (GCMs) suggest that the wind regime is impacted by climate change. Changes in circulation patterns and shifts in the storm tracks have been predicted (e.g. Andersen *et al.*, 2001, Bengtsson *et al.*, 2006). Besides, there is an indication of enhanced westerly winds and an increase in extreme events and/or storminess (Schmith *et al.*, 1998, Ekström, 2002, Bromirski *et al.*, 2003).
The North Atlantic Oscillation (NAO) is a complex mode of variability in the atmosphere and is normally represented by an index that describes the change in strength of the pressure gradient between the 'Greenland low' and the 'Azores high'. Most climate models suggest that the winter NAO index is likely to increase in response to increasing concentrations of greenhouse gases. Since positive NAO is associated with stronger than average westerlies (Hurrell and Van Loon, 1997), any increase or change in the index would be relevant for a regional wind climate variability.
Located on the north-western fringe of Europe, Scotland has a wind climate largely dominated by the Atlantic depressions. Average wind speeds and frequency of strong winds and gales are higher than in other parts of the United Kingdom. In addition, the flow of the wind over the region can be significantly influenced by the complex topography (figure 1). As a result, variations of the wind regime and its extremes may be important in considering the regional impact of climate variability for the Scottish Highlands and Islands and may have an important impact on a wide range of environmental processes and human activities (e.g. forestry, agriculture, transport).
Although several regional climate change studies have been conducted for Scotland, little attention has been given to the wind compared to the precipitation and temperature. This study aims to address this gap in knowledge and to answer the following questions:

- Can we detect any changes in the wind climate and weather extremes in the Highlands and Islands of Scotland?
- Does a relation exists between the regional winter climate variability and the NAO index?

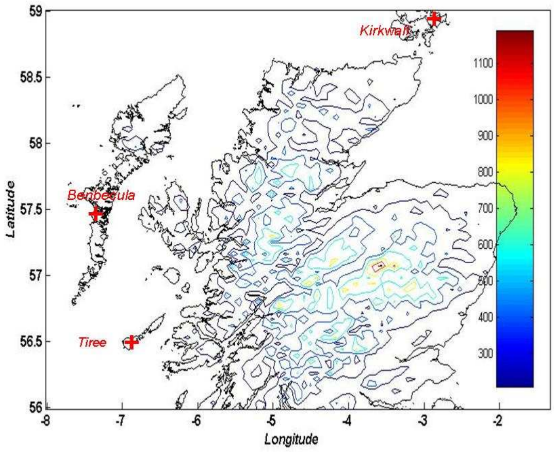

FIGURE 1 : North Scotland map with surface elevation (meters) at 5km resolution and location of the meteorological stations.

2. DATA

a. Weather station records

Station records were obtained from the Meteorological Office, UK. Wind direction, wind speed and maximum wind speed (gust) were provided at an hourly resolution for the period 1960-2004 in an Excel format.

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Three coastal weather stations were used for this study. Details about each station are given in figure1 and table 1.

Station	*WMO No.*	*HASL (m)*	*EFFH (m)*	*Record period*
Kirkwall	03017	26	10	1969-2004
Benbecula	03022	6	10	1969-1996
Tiree	03100	12	10	1960-2004

WMO No.: World Meteorological Organisation station number, HASL: Height Above Sea Level, EFFH: Effective Height of the anemometer.

TABLE 1 : Meteorological stations used in the study.

b. NAO index

The NAO index calculated from Gibraltar and Reykjavik, Iceland (Jones *et al.*, 1997) for the years 1960 to 2004 were downloaded from the Climate Research Unit website (CRU, 2004).

3. METHODS

The data were processed using Matlab® and Oriana software.

a. Averaging

Standards statistical methods for linear datasets were used to average the wind speed.
Since wind direction is a circular function with a crossover point between 0˚ and 359˚, standard statistical methods for linear datasets could not be used directly for calculating the mean wind direction (Turner, 1986). The statistical methodology considers a unit vector wind, characterised by a northwards and an eastwards component in the Cartesian representation (Fisher, 1993).

b. Linear regression

When the existence of trend or the relation with the NAO is examined, simple linear regression is applied to the data, defined by the equation $y = ax + b$, where x is either the time or the NAO value and y is the wind parameter analysed.
In addition, the probability coefficient p is given. By default it is considered that if p<0.05, the correlation is significant at 95% confidence interval.

c. Definitions

For the purpose of the study, the terms extended winter, gale day and extended south westerlies are defined as followed:

- *Extended winter* includes the months of December, January, February and March. The analysis of extremes and south westerlies winds will be conducted only for extended winter months.
- *A gale day* was defined as a day on which the wind speed at a standard height of 10m attains a mean value of 34 knots (63 km/h) or more at any period of 10 consecutive minutes during the day and/or a gust reaching 43 knots (80 km/h) or more over any period of record during the day (Meteorological Office, 1991).
- The wind is identified as an *extended south westerly wind* (SW_{ext}) if the wind direction θ is :

$$180° < \theta \leq 270°$$

4. RESULTS AND DISCUSSION

a. Mean wind climate conditions

The mean wind climate conditions over the period 1960-2004 were examined by computing the mean annual wind speed and direction at each station. The results are presented in figures 2 and 3.
The average annual wind speeds for the whole period are respectively 13.7, 14.7 and 13.3 knots for Kirkwall, Tiree and Benbecula. This confirms that the region of Highlands and Islands is one of the windiest parts of the UK. For example Blackpool has an average wind speed of 11.2 knots for the period 1961-1990 (Meteorological Office, 2006)

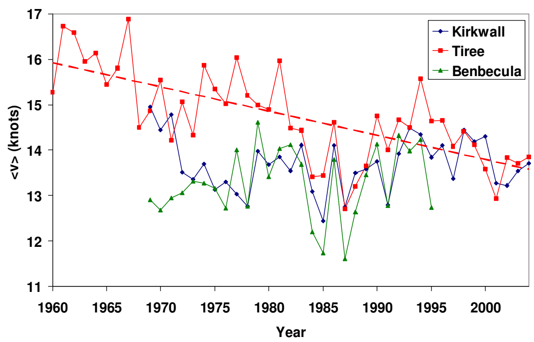

FIGURE 2 : trends in annual wind speeds at Kirkwall, Tiree and Benbecula.

The highest wind speeds were obtained for Tiree which is the most exposed and flattest of the stations studied. Moreover, over the whole period Tiree shows a trend toward reduced mean wind speeds (-2.4 knots=-1.24 m.s^{-1} for the whole 45 years period, R^2=0.485). Although the speeds for the Kirkwall and Benbecula are comparable in magnitude, no particular trends were detected in these datasets.
The differences observed between the stations could be attributed to the contrasting locations and change in roughness.

The results shown in figure 3 indicate that the winds are predominantly in the South West direction for the three stations. As the most exposed and flat terrain, Tiree shows the greatest variability.
Over the period, no overall trend in the wind direction was observed. However, when using a 10 years moving average for the winter months (not shown here), the results suggest a shift of the wind direction towards the South West (4.8°per decade for Kirkwall). This could be due to an increase of the occurrence of the south westerly winds (change in atmospheric circulation pattern).

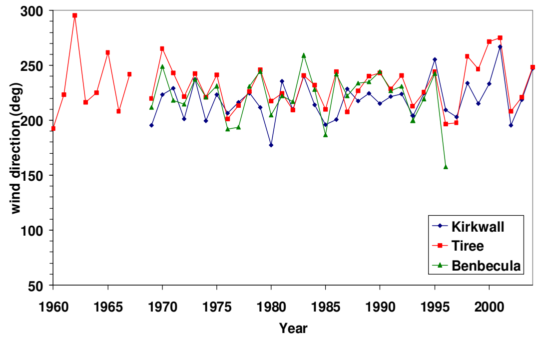

FIGURE 3 : trends in annual wind direction at Kirkwall, Tiree and Benbecula.

b. Extremes

Several studies report an increase in the North Atlantic winter storminess in the past 2-3 decades (e.g. Schmith et al., 1998). The results obtained in this study for the gale and maximum wind speed data are given in figures 4.
The number of gale days recorded over the period 1969-2004 exhibits two distinct periods. During the first period, from 1969 to early 1990s, the number of gale days appears to increase gradually while in the second period, from early 1990s until 2004, the number of gale days declines.

The maximum wind speed corresponds to the maximum wind speed reached per extended winter period within the gale force dataset. As with the mean wind direction, it is difficult to recognise any clear trend for Kirkwall and Benbecula. However, the maximum wind speed at Tiree seems to decrease from 1993.

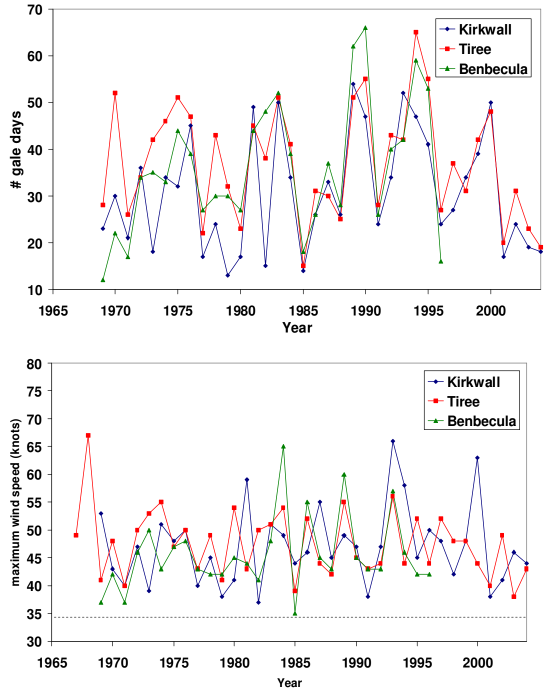

FIGURE 4 : Trends in the number of gale days (top) and maximum wind speed (bottom) per extended winter for Kirkwall, Tiree and Benbecula. The dotted line corresponds to the 34 knots threshold.

Since it has also been suggested that changes in storminess is associated with changes in teleconnection patterns such as ENSO or NAO (Enloe *et al.*, 2004: Rogers, 1997),we examined the relations between the frequency and intensity of extremes and the NAO. Results are presented in figure 5.
As it can be seen, there is a clear relation between the NAO index and the number of gale days per extended winter period (figure 5, top). The strongest relation was found for Benbecula (R^2=0.772, $p<0.001$) and the weakest is found for Tiree (R^2=0.489, $p<0.001$).
These results suggest that if in the future the NAO increases in response to climate change, the number of gale days would increase during the season December to March.
However, it was also noted while there is a linear correlation between the NAO index and the occurrence of gale days, no relation was found for the maximum wind speed. The NAO can not therefore, on its own, explain the full variability in extremes (figure 5, bottom).

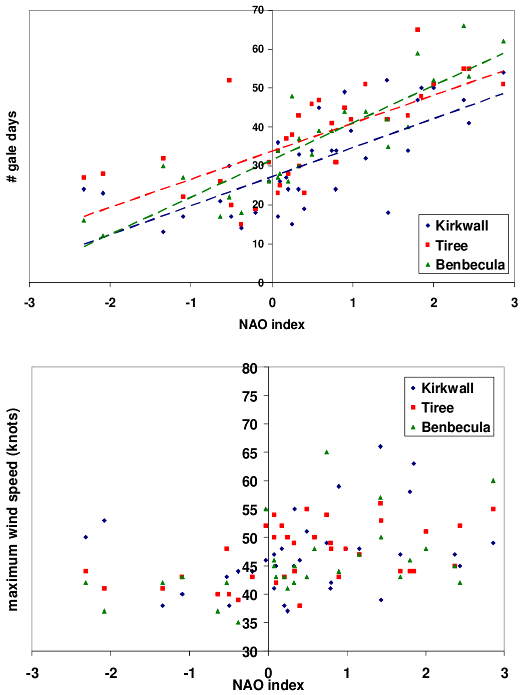

FIGURE 5 : Relation between the number of gale days (top) and the maximum wind speed (bottom) per extended winter and the NAO index for Kirkwall, Tiree and Benbecula.

c. South Westerlies

It has been shown in section 4a that the winds regime over the Highlands and Islands are predominantly from the South West direction. And further investigation on the occurrence and intensity of the extended South Westerlies, as defined in section 3c, are presented in Fig. 6.

The plots for the three stations are very similar. From the mid 1970s until 1990, there is a general increase in the number of days with SW_{ext} winds for the three stations followed by a slight decrease in the 1990s until 2004.

The SW_{ext} wind speeds are higher than the mean conditions presented in figure 3 and are 15.8, 17.8 and 16.1 knots for Kirkwall, Tiree and Benbecula respectively. Again, the wind speeds at Tiree are the highest.

The potential relationship between the NAO and the SW_{ext} winds has been considered. The results are shown in figure 7.

The correlation coefficients obtained demonstrate the strong relation between the NAO and the occurrence of SW_{ext} winds as all the coefficients are above 0.7 (table3). Additionally, a linear trend is also found when plotting the SW_{ext} wind speed versus the NAO index (figure 7, bottom and table 2). The correlation is weaker than the one obtained for the occurrence but is still significant for Benbecula (R^2=0.590, p<0.001).

The increase of the SW_{ext} winds both in frequency and intensity with increasing NAO index suggests a more zonal motion of the atmosphere.

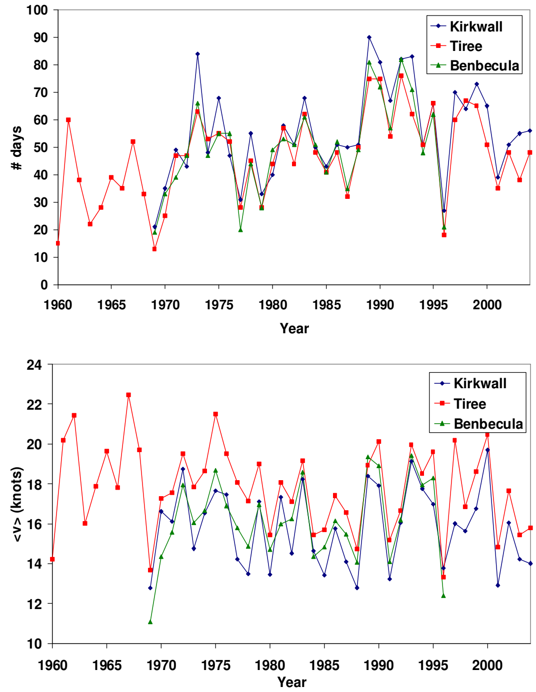

FIGURE 6 : Trends in the occurrence (top) and the mean wind speed (bottom) of the south westerlies for Kirkwall, Tiree and Benbecula.

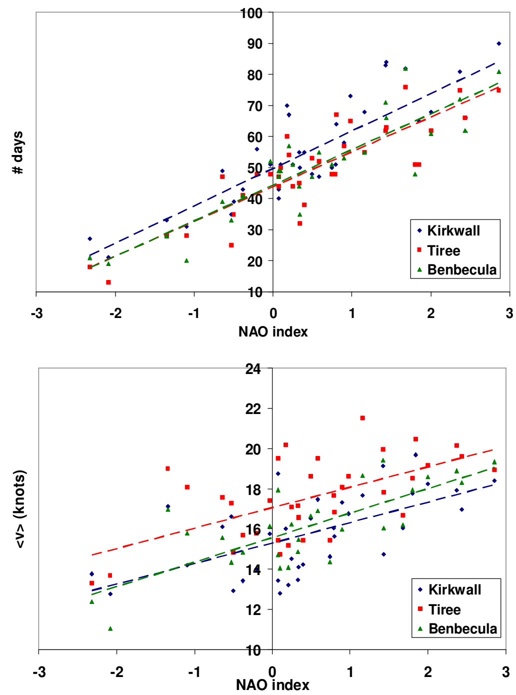

FIGURE 7 : Relation between the occurrence (top) and the mean wind speed (bottom) of south westerlies and the NAO index for Kirkwall, Tiree and Benbecula.

		a	*b*	*R^2*	*p*
occurrence	Kirkwall	12.05	49.72	0.710	<0.001
	Tiree	11.21	43.87	0.750	<0.001
	Benbecula	11.47	44.35	0.793	<0.001
<v>	Kirkwall	1.02	15.30	0.365	<0.001
	Tiree	1.02	17.06	0.356	<0.001
	Benbecula	1.22	15.57	0.590	<0.001

TABLE 2 : Variables and coefficient for the linear trend lines for the SW_{ext} data.

5. CONCLUSION

The wind regime for the Highlands and Islands of Scotland was studied for the period 1960-2004. The region is dominated by high winds in the south west direction. The differences observed between the stations are attributed to the location (West or North) as well as to the topography.
This investigation shows that there has been no significant change of the mean wind conditions in the Highlands and Islands of Scotland over the period 1960-2004, as observed trends (if any) were concentrated in a limited period. Further investigation is needed before being able to draw any conclusion regarding a change of wind direction for the three stations and the apparent of the wind speed observed for Tiree.
Nevertheless, strong relations with the NAO have been found in extended winter period for the occurrence of gale days (R^2=0.772, $p<0.001$ for Benbecula) and the occurrence and frequency of south westerly winds (R^2=0.793, and R^2=0.590 for Benbecula). It suggests that the NAO index could be used as an indicator of possible regional climate change.

It would be of a great interest to supplement this study by a similar analysis of additional stations and for a longer period of time. Moreover, a detailed study on the effect of the complex topography on the wind flow using a diagnostic model should be conducted.
Further insights should also be gained through the examination of the mean sea level pressure fields for the same region.

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