

Seasonal Predictability of Wintertime Storminess Over the North Atlantic

BUDONG QIAN and MARK A. SAUNDERS

*Department of Space and Climate Physics, University College London,
Holmbury St. Mary, UK*

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Corresponding author address: Dr Mark A. Saunders, Department of Space and Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, United Kingdom. (E-mail: mas@mssl.ucl.ac.uk).

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Benfield Hazard Research Centre, Department of Space and Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, U.K.

Abstract. Interannual variability in winter storminess over the North Atlantic and Europe causes significant risk and uncertainty. Attempts to seasonally predict winter storminess levels have identified little skill to date. However, recent statistical studies of observational data indicate the presence of marginal but useful skill in predicting the winter North Atlantic Oscillation (NAO). This predictability arises from a significant ($p < 0.01$) link between northern hemisphere summer snow extent and the coming winter NAO state. We apply this link to assess the seasonal predictability in winter storminess 1972/3-2000/1 at a given point. The correlation skill for predicting, by early September, the numbers of winter gale days and storm force days in the main North Atlantic winter storm track region is between 0.5 and 0.6. Our finding suggests the seasonal predictability of North Atlantic winter storminess may be higher and extend to longer leads than thought previously.

1. Introduction

European windstorms caused damages of US \$ 2.9 bn per year 1990-1999 and rank as the second highest cause of global insured loss after US hurricanes. While satellites and numerical weather models provide warnings of strong winds out to ~1-week ahead, the ability to skilfully predict activity at longer range would bring significant socio-economic benefits by reducing the risk, uncertainty and financial volatility associated with the year-to-year variability in storminess levels. Beneficiaries would include the insurance industry, the offshore oil industry through improved rig operation planning, power and energy companies and maritime operators through cost effective ship routing and scheduling. However, attempts to seasonally predict North Atlantic winter storminess; namely, to anticipate the number of gales, strong gales and storms over the 3-month winter period December-January-February (DJF) have identified little skill to date [Palutikof *et al.*, 2002].

Interannual variability in North Atlantic winter storminess is associated with year-to-year variability in the strength and sign of the winter North Atlantic Oscillation (NAO), the dominant mode of boreal winter atmospheric variability over the North Atlantic [Walker and Bliss, 1932; Rogers, 1997; Marshall *et al.*, 2001]. Correlations between surface windspeed and the NAO reach 0.8 ($p < 0.001$, 1948/9-1999/2000) at certain locations [George and Saunders, 2001]. This strong association suggests that winter storminess predictability is likely to be linked to winter NAO predictability. Research has related autumn (September-October-November) Eurasian snow cover extent to upcoming boreal winter climate variability [Cohen and Entekhabi, 1999; Cohen *et al.*, 2001; Saito *et al.*, 2001]. However, recent work shows that it is summer, rather than autumn, snow cover which is related more strongly and robustly to the upcoming NAO_{DJF} [Saunders *et al.*, 2003; Bojariu and Gimeno, 2003; Saito and Cohen, 2003]. Based on the most up-to-date snow cover records available, there is a

significant covariance ($p < 0.01$) between North American and Eurasian summer snow extent and the coming winter NAO state [Saunders *et al.*, 2003]. This covariance permits the NAO_{DJF} to be anticipated in early September with a correlation of ~ 0.6 for a range of NAO indices 1972/3-2001/2. Saunders *et al.* [2003] also suggest a dynamic link between summer and winter through the influence of snow cover on subpolar North Atlantic circulation which couples to North Atlantic sea surface temperature thereby enabling signal transfer through to winter [Wu and Gordon, 2002; Saunders and Qian, 2002].

In this paper we use the NCEP/NCAR global reanalysis project data [Kalnay *et al.*, 1996] to present a climatology for wintertime storminess over the North Atlantic. We link this climatology to summer northern hemisphere (NH) snow cover extent to assess the predictive skill of the latter for wintertime near gale, gale, strong gale and storm force days 1972/3-2000/1.

2. Data

We analyse wintertime storminess over the North Atlantic using 6-hourly 10m windspeed data from the NCEP/NCAR reanalysis on a 2.5° latitude by 2.5° longitude grid. The suitability of these windfields for generating a long-term wave hindcast of the North Atlantic Ocean has been confirmed by Swail and Cox [2000]. Due to the limitation of available snow cover, storminess is studied only for the period 1971-2001. We define storminess as the numbers of days with strong winds reaching different force levels on the Beaufort Wind Scale/World Meteorological Organisation windspeed classification. These levels are 'near gale' force (Beaufort Scale 7, $13.9-17.1 \text{ ms}^{-1}$), 'gale' force (Beaufort Scale 8, $17.2-20.7 \text{ ms}^{-1}$), 'strong gale' force (Beaufort Scale 9, $20.8-24.4 \text{ ms}^{-1}$) and 'storm' force (Beaufort Scale 10, $24.5-28.4 \text{ ms}^{-1}$). A 'day' is counted for a particular grid cell and Beaufort Scale level if the windspeed within that cell exceeds the lower limit of the particular Scale level for any of the four 6-hourly data records during that day. For example, a 'day' is counted for near gale, gale, strong gale and storm force if the windspeed reaches 24.5 ms^{-1} at any one of the four recording times 00, 06, 12 or 18UT during that day. The total number of 'days' is then accumulated for each grid cell, Beaufort Wind Scale level and winter (DJF) season.

We employ monthly NH ground snow extent records from January 1972 through February 2001. These data are provided by the Snow Data Resource Center at Rutgers University and comprise, after recent processing corrections, the most up-to-date snow cover records currently available. Values are derived from weekly snow cover charts produced by the National Oceanic and Atmospheric Administration from visible satellite images [Robinson *et al.*, 1993]. Charting improved considerably in 1972 with the satellite deployment of the Very High Resolution Radiometer having a spatial resolution of 1.0 km. Since then the snow extent records are considered reliable for climate analysis studies [Robinson *et al.*, 1993].

3. Storminess Climatology

Figure 1 shows the climatology of wintertime storminess for the North Atlantic sector $35^\circ\text{N}-70^\circ\text{N}$. The mean numbers of days with near gales, gales and strong gales are displayed for the 30 winter period 1971/2-2000/1. It is clear that strong winds rarely extend far inland and that the mid-latitude North Atlantic Ocean between the British Isles and eastern Canada is the stormiest

region. The maximum mean numbers of days with near gales, gales and strong gales are 53.3, 26.1 and 8.4 respectively. Highest interannual variability in the number of winter strong wind days is observed to the northwest of the British Isles where storminess is moderately strong. The largest standard deviations are 12.6, 9.9 and 5.1 days respectively for near gale, gale and strong gale days. Storm force winds are observed rarely; their maximum mean number and standard deviation for a grid cell being 1.4 and 1.8 days respectively. The storminess climatology in Figure 1 compares well with a climatology for winter gale frequency in the North Atlantic derived from the Comprehensive Ocean and Atmosphere Data Set (COADS) (for details visit the US Naval European Meteorology and Oceanography Center at <https://www.nemoc.navy.mil:443>). However, it should be noted that since the 10m windspeeds in the NCEP/NCAR reanalysis are presented as averages over 2.5° latitude-longitude grid boxes, peak wind speeds are likely to be underestimated. This is particularly true for major jet streak features propagating about intense mid-latitude cyclones [Swail and Cox, 2000] and in coastal regions with special geographical characteristics.

4. Linking Storminess to Summer Snow Cover

Our analysis uses linear detrended time series throughout to remove the influence of time series trends on the strength and significance of the computed correlations and the deduced storminess predictability. The use of raw (not detrended) time series gives, in all cases, links of similar or stronger magnitude and significance to those described herein.

Figure 2 shows the correlation pattern between winter numbers of near gale days, gale days and strong gale days over the North Atlantic/European sector poleward of 45°N and the prior July-August NH snow extent 1972/3-2000/1. Only values significant at levels < 0.10 are plotted. Highest correlations are observed in the stormiest region (Figure 1) with a peak (negative) correlation of -0.70. Correlations significant to 0.05 are also observed over the North Sea and Scotland for all storminess levels. The correlation sign shows that summers with high/low snow extent precede winters of low/high North Atlantic winter storminess poleward of 45°N . This relationship is consistent with the link between winter NAO and prior summer snow cover [Saunders *et al.*, 2003; Bojariu and Gimeno, 2003; Saito and Cohen, 2003]. Areas of significant positive correlation are observed in the subtropical North Atlantic (not shown in Figure 2) but since the incidence of strong winds therein is low (Figure 1) these areas are not considered further.

In view of the spatial variability in the strength of the correlation link in Figure 2, we have also examined the magnitude and significance of this link for a larger agglomerated North Atlantic region (53.75°N - 61.25°N , 46.25°W - 11.25°E), extending from southern Greenland to the Scandinavian coast. This rectangular region, which straddles the main North Atlantic winter storm track, is referred to henceforth as the high-latitude North Atlantic (HLNA) region. The winter numbers of near gale days, gale days, strong gale days and storm days over the HLNA region are obtained by averaging the corresponding numbers from each grid cell in the region. The means and standard deviations (in brackets) for the numbers of near gale, gale, strong gale and storm force days over the HLNA region 1971/2-2000/1 are 38.3 (6.2), 16.6 (4.0), 4.0 (1.5) and 0.5 (0.3) respectively. The percentage of winter (DJF) days with near gale, gale, strong gale and storm force winds occurring within the HLNA are 42.6%,

18.4%, 4.4% and 0.6% respectively. Storminess in winter over the HLNA region is correlated significantly ($p < 0.001$ for all Beaufort wind categories) to prior July-August NH snow cover extent. The correlation values are -0.58 for number of near gale days, -0.61 for gale days, -0.68 for strong gale days and -0.58 for storm days.

5. Prediction Skill for Winter Storminess

The significant correlations shown above between July-August NH snow cover extent and upcoming winter North Atlantic storminess suggest the potential for predicting the latter from summer NH snow cover in early September. We assess the seasonal prediction skill for winter storminess from this single predictor in two ways: using standard cross-validated hindcasts [Michaelson, 1987; WMO, 2002] for the 29 year period 1972/3-2000/1, and using replicated real-time forecasts [Saunders and Qian, 2002] for the recent 15 year period 1986/7-2000/1. In the cross-validation scheme a uni-variate regressive model is calibrated for each hindcast winter by withholding the predictor and predictand of the hindcast year and using the remaining 28 years. A hindcast for each withdrawn year is then made by placing the prior July-August NH snow cover extent from that year into the model. In the replicated real-time forecast scheme an initial training period from July 1972 to February 1986 is employed, leaving the remaining 15 winters for model forecast assessment. The training period increases one year at a time as each forecast is made thereby replicating the operation of a real-time forecast. However, the short initial training period of just 14 years may make these forecasts unreliable. The cross-validated and replicated real-time prediction models are both built on linear detrended data 1972/3-2000/1. We compute the predictive deterministic skill for winter storminess using three skill measures: the correlation (r) between forecast and observed storminess values, the percentage of variance explained (PVE), and the percentage improvement in mean square error over a climatological forecast (MSE_{Clim}). The climatology used here is the standard 30-year 1971/2-2000/1 climate norm. MSE_{Clim} is the standard skill metric recommended by the World Meteorological Organisation for verification of deterministic seasonal forecasts [WMO, 2002].

Figure 3 shows the gridded correlation skill from cross-validation for the winter numbers of near gale, gale and strong gale days over the North Atlantic sector. As in Figure 2, largest skills are observed over the most stormy waters with the spatial distribution in skill being similar for all strong wind scales. The highest correlation skill exceeds 0.6, explaining over 40% of the observed variance and providing a 45% improvement in MSE_{Clim} . The skills from the replicated real-time forecasts (not shown) display similar spatial distributions to those in Figure 3 suggesting a quasi-stable relationship between summer NH snow cover and North Atlantic winter storminess during the period 1972~2000.

Table 1 displays the predictive skill for winter storminess over the high latitude North Atlantic region defined in Section 3. The predictand is the average number of strong wind days from all grid cells within the HLNA region. Table 1 shows that irrespective of hindcast model, skill measure and Beaufort Scale, the wintertime number of high wind days within the HLNA is predictable from NH summer snow extent with a correlation skill of 0.52 to 0.67, with 26% to 45% of its variance being explained and with an MSE skill improvement over climatology of 28% to

45%. Using the interpretation for the value of a forecast based on its correlation skill [Barnston and Ropelewski, 1992], this predictive skill is ‘marginal but useable’.

6. Conclusions

Winter storminess over the North Atlantic and European sector is analysed using the NCEP/NCAR reanalysis 6-hourly gridded windspeed data. Storminess is examined in terms of the numbers of days with windspeeds reaching Beaufort Scales 7, 8, 9 or 10 (ranging from near gale to storm force in strength). The suitability of these windspeeds for climate studies has been confirmed by Swail and Cox [2000] and the deduced climatology for the number of gale days over the North Atlantic appears consistent with that obtained from the Comprehensive Ocean and Atmosphere Data Set (COADS).

We find that winter storminess over large parts of the high latitude North Atlantic, including the North Sea and Scotland, is linked significantly to the prior summer extent of northern hemisphere snow cover 1972/3-2000/1. We assess the predictive skill of winter storminess, based on September forecasts, in terms of cross-validation and replicated real-time skill. The prediction skill is found to be useable especially for the high latitude North Atlantic as a whole rather than at the individual grid square level. These results are based on just 29 years of reliable snow cover records and clearly a longer data series would provide greater confidence in the temporal stability of this predictability.

The winter storminess link to prior summer snow cover is associated with the winter NAO link to summer snow extent [Saunders *et al.*, 2003; Bojariu and Gimeno, 2003; Saito and Cohen, 2003]. A plausible mechanism for this association is that summer snow cover — which occurs over the Canadian Northwest Territories and the Siberian region adjacent to the Barents and Kara Seas - gives rise to anomalous longitudinal differences in summer surface air temperature with the subpolar North Atlantic [Saunders *et al.*, 2003]. However, another underlying root influence which forces the variability in summer snow cover as well as all associated linking variables can not be ruled out. Numerical model experiments with prescribed snow cover conditions are required to resolve this question.

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B. Qian and M. A. Saunders, Benfield Hazard Research Centre, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking Surrey, RH5 6NT, U.K.. (mas@mssl.ucl.ac.uk).

Table 1. The predictive skill for winter storminess over the North Atlantic and North Sea region 53.75°N-61.25°N, 46.25°W-11.25°E.

Skill Measure	Near Gale		Gale		Strong Gale		Storm	
	1972/3-2000/1	1986/7-2000/1	1972/3-2000/1	1986/7-2000/1	1972/3-2000/1	1986/7-2000/1	1972/3-2000/1	1986/7-2000/1
r	0.53	0.53	0.60	0.52	0.67	0.62	0.52	0.52
PVE	27	28	35	26	45	37	27	27
MSE _{Clim} (%)	28	33	36	34	45	45	28	29

Winter storminess is defined by number of days in December-January-February where the mean wind strength reaches near gale, gale, strong gale or storm force on the Beaufort Scale. Predictive skills for 1972/3-2000/1 are computed from cross-validated hindcasts while those for 1986/7-2000/1 are calculated from replicated real-time forecasts.

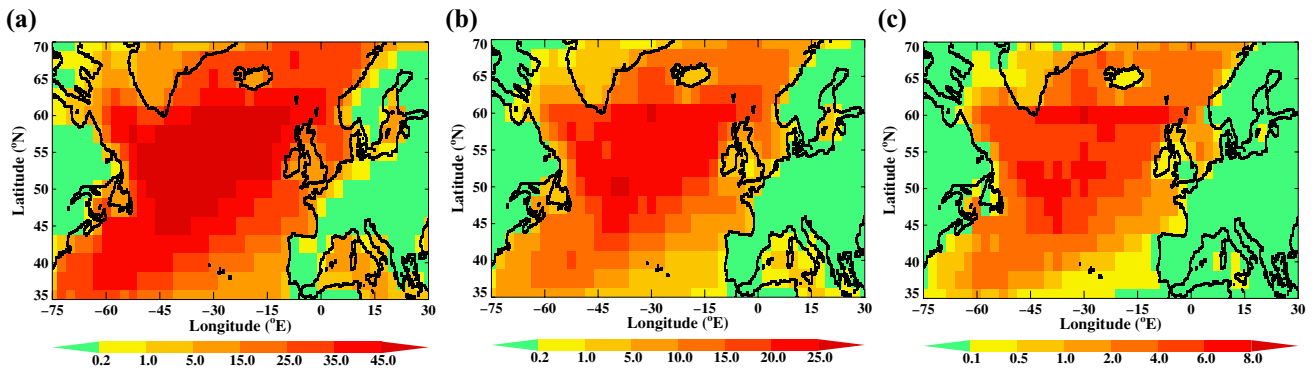


Figure 1. The climatology (1971/2-2000/1) for winter storminess over the North Atlantic sector in terms of the mean number of December-January-February (a) near gale days (windspeed reaching Beaufort Scale 7), (b) gale days (windspeed reaching Beaufort Scale 8) and (c) strong gale days (windspeed reaching Beaufort Scale 9).

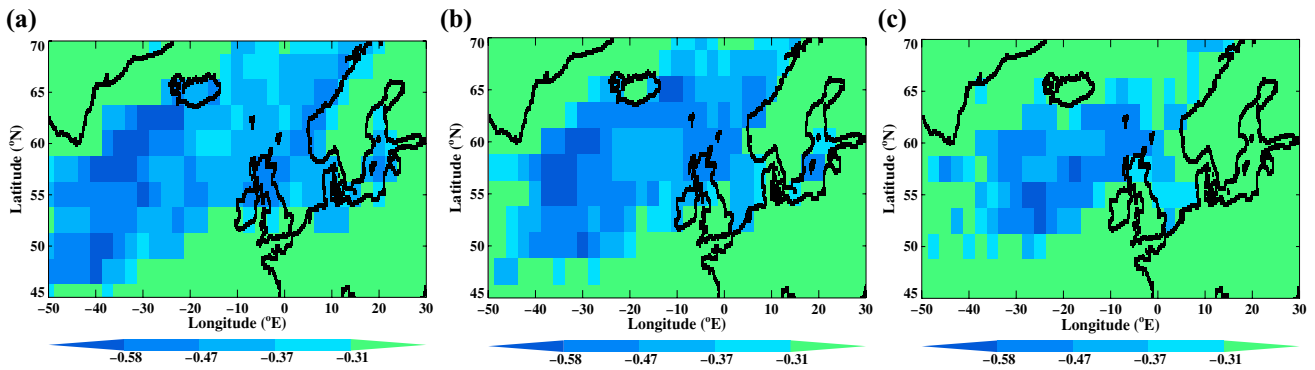


Figure 2. The correlation patterns between July-August northern hemisphere snow cover and the upcoming winter number of (a) near gale days, (b) gale days and (c) strong gale days. Correlation coefficients are computed after detrending. The correlation coefficient thresholds of 0.31, 0.37, 0.47 and 0.58 correspond respectively to significance levels of 0.10, 0.05, 0.01 and 0.001.

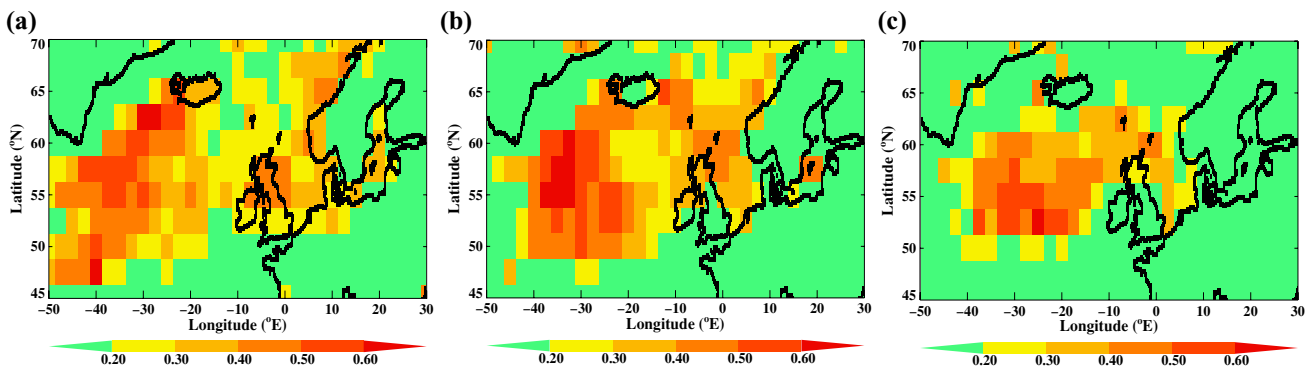


Figure 3. The correlation skill for predicting winter storminess from July-August northern hemisphere snow cover extent based on a cross-validation of 1972/3-2000/1 data. Skill values are shown for (a) near gale days, (b) gale days and (c) strong gale days.