Scottish snow cover dependence on the North Atlantic Oscillation index

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ABSTRACT

Forecasting seasonal snow cover is useful for planning resources and mitigating natural hazards. We present a link between the North Atlantic Oscillation (NAO) index and days of snow cover in Scotland between winters beginning from 1875 to 2013. Using broad (5 km resolution), national scale data sets like UK Climate Projections 2009 (UKCP09) to extract nationwide patterns, we support these findings using hillslope scale data from the Snow Survey of Great Britain (SSGB). Currently collected snow cover data are considered using remotely sensed satellite observations, from moderate-resolution imaging spectroradiometer; but the results are inconclusive due to cloud. The strongest correlations between the NAO index and snow cover are found in eastern and southern Scotland; these results are supported by both SSGB and UKCP09 data. Correlations between NAO index and snow cover are negative with the strongest relationships found for elevations below 750 m. Four SSGB sites (two in eastern Scotland, two in southern Scotland) were modelled linearly with resulting slopes between −6 and −16 days of snow cover per NAO index integer value. This is the first time the relationship between NAO index and snow cover duration has been quantified and mapped in Scotland.

Key words | climate, North Atlantic Oscillation, Scotland, snow

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INTRODUCTION

Snow is important in Scotland for water resources, e.g., the largest instrument-measured flow in Scotland's largest catchment, the River Tay, was partly caused by snowmelt (Black & Anderson 1994). Dunn *et al.* (2001) showed that snow can contribute to river baseflow until July, as melted snow takes a generally slower sub-surface pathway to a water course. Also, Gibbins *et al.* (2001) discussed the importance of snowmelt for freshwater invertebrate habitat in the Cairngorms. Knowledge of snow extent and duration can help understand habitat change (Trivedi *et al.* 2007), and global snow cover data are collated by the Intergovernmental Panel on Climate Change (Vaughan *et al.* 2013).

The North Atlantic Oscillation (NAO) index is the normalised pressure difference between the Icelandic low and the Azores high (Walker & Bliss 1932). Positive winter NAO phases are typified by strong westerly winds carrying moist warm air from the Atlantic, with negative winter NAO phases bringing colder air masses from the east (Hurrell 1995; Simpson & Jones 2014). Logically then, the NAO index could indicate the duration of snow cover as colder weather means a greater chance of snow and its persistence, but this signal may be confused by positive NAO phases bringing increased precipitation.

NAO index relates to hydrological processes: Hannaford *et al.* (2005) showed river flow and NAO index have strong positive correlations (e.g., River Nith: 0.63) in the north and west of the UK, but eastern catchments had a weaker correlation (e.g., River Tweed: 0.38). Harrison *et al.* (2001) suggested that an association between snow cover and NAO phase is likely. Trivedi *et al.* (2007) found snow cover in the Ben Lawers region north of Loch Tay, at 300 m and below to be significantly ($P < 0.05$) negatively correlated

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with NAO index, between −0.55 and −0.38, with lower elevations having a stronger relationship. Trivedi *et al.* (2007) also found no correlation between NAO index and falling snow, perhaps because it is often cold enough for snow to fall during a Scottish winter, irrespective of NAO phase, but during positive NAO phases the warmer air causes snow to melt and only with the colder temperatures associated with negative NAO indices does snow lie for longer. There has been more research on snow cover links to the NAO index in continental Europe, where snow cover has a greater impact (e.g., Beniston 1997; Bednorz 2004; Scherrer *et al.* 2004; Lopez-Moreno *et al.* 2011; Kim *et al.* 2013).

There has recently been an increase in winter variability of the NAO phase (Osborn 2006; Hanna *et al.* 2014), including a record low NAO index in 2009 to 2010 (Osborn 2010). The 2009 to 2010 low occurred the same year as an exceptionally cold and snowy winter in the UK (National Climate Information Centre 2010; Prior & Kendon 2011). Goodkin *et al.* (2008) linked variability in the NAO index to northern hemisphere mean temperature and stated that any future predictions should take this into account.

The UK Met Office are beginning to more successfully forecast seasonal NAO indices (Scaife *et al.* 2014), which could be used to plan for heavy snow in advance of a winter season. For a forecast made on the 1st of November, Scaife *et al.* (2014) gave a correlation value of 0.62 (significant at 99%) between forecast and observed DJF NAO indices for the years 1993 to 2012.

We hypothesise that snow cover in Scotland is negatively correlated with the NAO index. We establish this by looking at nationwide snow cover data sets, before further investigating relationships at a hillslope scale, using case studies with more detailed data available. Our paper is laid out as follows: methods and data, results, discussion and conclusion. The methods and results sections are split by data set.

DATA AND METHODS

We used NAO index data from the Climate Research Unit University of East Anglia (undated) and Osborn (undated) as these comprise a long and definitive record (Table 1). The longest data series of Scottish snow cover is from UK Met Office stations which record snow presence at a given point at 09:00 hours UTC each morning; the longest of these is Braemar which has recorded since 1927 (Harrison *et al.* 2001). Ninety-six per cent of UK Met Office snow recording stations lie below 300 m elevation (Spencer *et al.* 2014) and so are unrepresentative of the 31% of Scottish landmass that is higher (Spencer *et al.* 2014). These UK Met Office station data are used by proxy via the UK Climate Projections 2009 (UKCP09) snow cover data set (Met Office undated). Table 1 shows a non-definitive list of Scottish snow cover data sets, which are all used within this study.

Snow in Scotland is often ephemeral and so metrics like average snowline and maximum snow cover extent are meaningless because each winter can see many snow accumulation and melt cycles. We solved this by using a count of the days of snow cover during a given time period. We define a winter period for snow cover as November to April to help differentiate the snowiest winters, while being short enough to not discount many Snow Survey of Great Britain (SSGB) records, as some are missing (Spencer

Table 1 | Study data sources

Name	Abbreviation	Reference	Type	Time span
Bonacina snowfall catalogue	Bonacina	O'Hara & Bonacina (undated)	Classification of snowiness of UK winter	1875 onwards
UK Climate Projections 2009 snow lying grid	UKCP09	Perry & Hollis (2005)	Interpolated grid of UK Met Office station data (days per month)	1971–2006
MODIS satellite snow cover, daily L3 500 m grid v005	MODIS	Hall *et al.* (2006)	Daily classified raster image	2000 onwards
North Atlantic Oscillation Index	NAO index	Osborn (undated)	Single annual value (DJFM mean)	1821 onwards
Snow Survey of Great Britain	SSGB	Spencer *et al.* (2014)	Daily observations of snowline elevation	1945–2007

et al. 2014). A short winter period (e.g., DJF) would mean, particularly at higher elevations, a count of days with snow lying would result in saturated values of days of snow cover, i.e., there cannot be more than 31 days with snow lying in January, but 31 days of cover is often the case at higher elevations in Scotland. Using a 6-month period will help identify the snowiest winters, where greater snow depths take longer to melt. Analysis was undertaken using the R language (R Core Team 2015).

NAO

NAO index data have been averaged (mean) over DJFM, as described by Osborn *et al.* (1999), to better represent the prevailing winter NAO index. Note this winter period is different to the NDJFMA period used for snow cover. Figure 1 shows the predominant NAO index is positive, aligning with our understanding that the UK is more likely to experience weather systems from the west.

Bonacina

The Bonacina snow index was originally compiled by Leo Bonacina (Bonacina 1966) and is now maintained as a website (O'Hara & Bonacina undated). Each winter is subjectively categorised into one of four groups: little, average, snowy and very snowy. This is based on how much snow fell and how much of the country it covered using anecdotal data from weather journals, UK Met Office stations and websites. Other snow cover data sets used in this work state the number of days of snow cover over a given time period. Bonacina data have been included because they cover a much longer time period than the other snow cover data sets (Table 1).

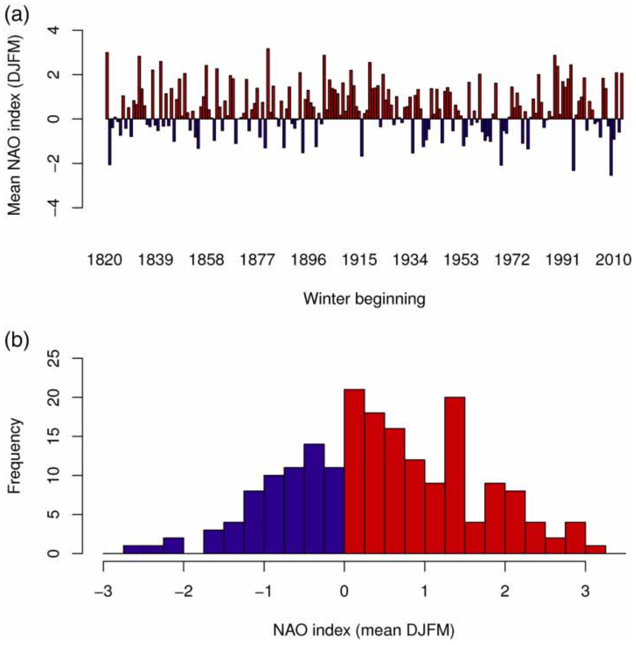

Figure 1 | Mean DJFM NAO index shown: (a) through time and (b) as a histogram.

Mean DJFM NAO index values are grouped by Bonacina categories. The differences between groups of the NAO index are compared visually using boxplots (Figure 2) and statistically using an analysis of variance (ANOVA) and Tukey honest significant differences (HSD) (Yandell 1997) tests, the latter to account for family-wise analysis (Table 2).

UKCP09

The UKCP09 snow data set comprises a 5 km resolution raster image for each month, where each grid value

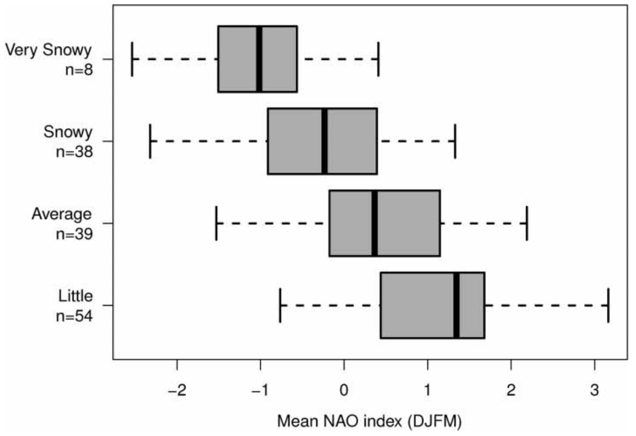

Figure 2 | Boxplots (median, upper and lower quartiles and range) showing winter NAO index grouped by Bonacina snowiness categories.

Table 2 | Tukey HSD difference in medians of NAO indices between pairs of Bonacina classes

Pair	Difference	*P*-value
Very snowy–snowy	−0.823	0.093
Snowy–average	−0.670	0.008
Average–little	−0.697	0.002

represents the number of days of snow cover for that cell. November to April data are available from 1971/72 until 2005/06. These were interpolated from UK Met Office station data by Perry & Hollis (2005). These data have been shown (Spencer *et al.* 2014) to poorly represent reality at higher elevations. The data set is used here to identify regions for more detailed exploration. UKCP09 snow data were downloaded from the Met Office (undated). The November to April sum of days of snow cover are compared using a Pearson correlation to the mean DJFM NAO index. The resulting Pearson correlation is plotted (Figure 3) to show spatial patterns.

SSGB

The SSGB reported at 145 stations in Scotland at differing times between 1945 and 2007, but some records are missing (Spencer *et al.* 2014). Stations were selected for inclusion in this study based on whether they recorded for all months between November and April. The number of SSGB stations meeting this criterion each year is shown in Figure 4. The gaps in the number of reporting stations are because data are missing from part of these years. This is directly related to only including stations that recorded all months between November and April each winter.

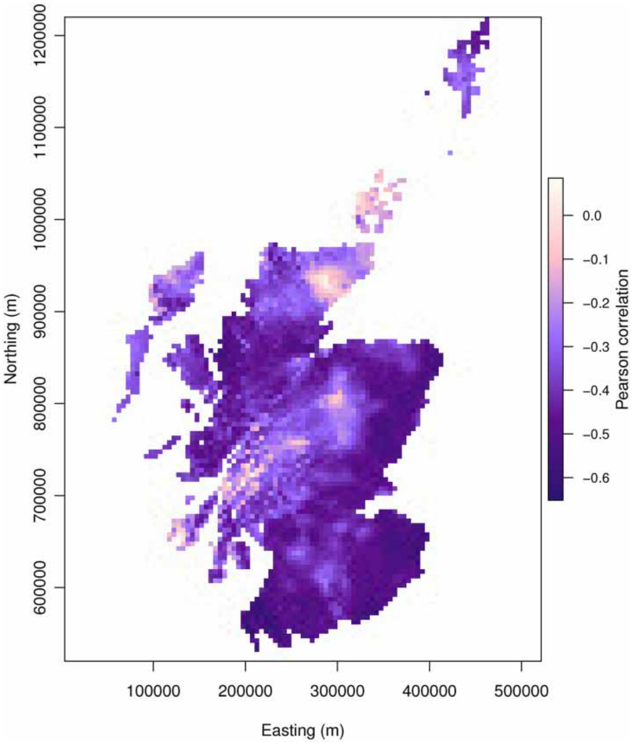

Figure 3 | Map of Pearson correlation values between UKCP09 snow and the NAO index. Contains Met Office data © Crown copyright and database right 2015.

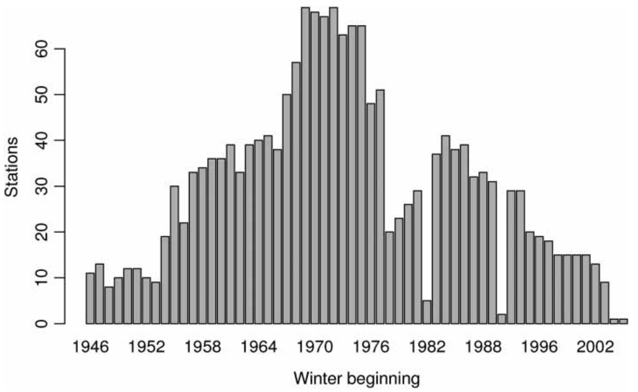

Figure 4 | Number of SSGB stations each year recording all 6 months between November and April.

SSGB observers recorded the elevation of snowline on visible hillslopes surrounding each station. We constructed snow accumulation curves, where the number of days of snow cover over a range of elevations are shown. These accumulation curves are split by NAO index and shown in Figure 5. The primary purpose of these curves is to assess the break point between higher and lower elevation snow cover.

Three groups of individual stations are also considered, again meeting the criterion of 6 months of record for a winter: group one, stations with the longest record; group two, stations in the east of Scotland; group three, a single station on Orkney. Details of these stations are shown in

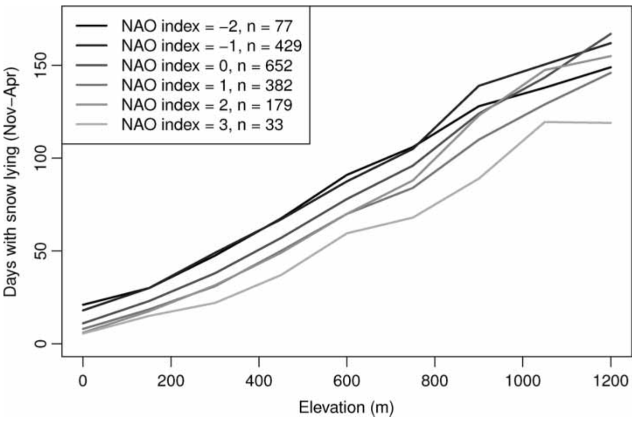

Figure 5 | Snow cover duration curves derived from SSGB data between 1946 and 2006 (November to April), grouped by (rounded) mean DJFM NAO index.

Table 3 and their location in Figure 6. The second and third groups have much shorter records than the longest-running stations; they have been included to help test whether eastern sites are more likely to have snow cover influenced by the NAO index and whether the UKCP09 snow data are a good approximation of snow cover. The groups of stations in Table 3 are compared to the NAO index using a high and low elevation split (at 750 m) and a locally weighted scatterplot smoothing (LOESS) (Cleveland 1979; Cleveland & Devlin 1988) with 95% confidence limits (Figures 7 and 8).

Stations from Table 3, judged by eye to have a LOESS close to a straight line, are plotted in Figure 9 with linear models, showing the Pearson correlation value and line parameters (slope and intercept). This allows us to relate a given NAO index to an expected number of days snow cover duration for a high or low elevation.

Table 3 | Longest, eastern and Orkney SSGB stations details

Station	Easting	Northing	Description	Complete winters
Eskdalemuir	323,500	602,600	Longest	46
Couligarton	245,400	700,700	Longest	44
Forrest Lodge	255,500	586,600	Longest	44
Ardtalnaig	270,200	739,400	Longest	39
Fersit	235,100	778,200	Longest	39
Drummuir	337,200	844,100	Eastern	24
Derry Lodge	303,600	793,200	Eastern	21
Crathes	375,800	796,900	Eastern	20
Whitehillocks	344,860	779,790	Eastern	27
Stenness	329,800	1,011,200	Orkney	21

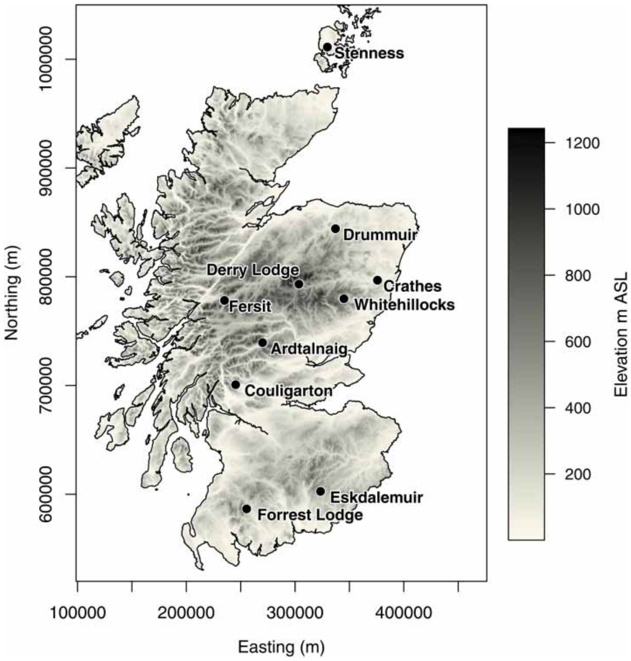

Figure 6 | Selected SSGB station locations. Contains Ordnance Survey data © Crown copyright and database right 2015.

Moderate-resolution imaging spectroradiometer

There are two main methods for remote sensing of snow: microwave and visible. Using microwave to detect snow cover is very challenging in mountainous terrain (Snehmani *et al.* 2015) or when snow is wet (Rees & Steel 2001). Snehmani *et al.* (2015) reviewed methods that improve microwave assessment of snow cover, but these are data and computing intensive, and trialling them in Scotland where it is very cloudy, wet and mountainous is beyond the scope of this study. Some snow cover data sets amalgamate different data sources, including Robinson *et al.* (undated) and Foster *et al.* (2011), which have grid resolutions of 190.5 km and 25 km, respectively; these are coarse grids which would miss spatial detail. Foster *et al.* (2011) found that Earth Observation System moderate-resolution imaging spectroradiometer (MODIS) outperformed microwave snow detection in cloud-free areas. MODIS is freely available on a 500 m grid at a twice daily resolution, and there are some reanalysis products, (e.g., Notarnicola *et al.* 2013), which recalculate snow cover at a 250 m grid, but are only available for the Alps. MODIS data are used in this study because of the temporal overlap with SSGB data and fine resolution of the data set. The MODIS data set chosen was the tile set which records as binary whether snow covered each cell, rather than the fractional or albedo data sets. Coverage of Scotland is split across two tiles: these were downloaded from the National Snow and Ice Data Centre (Hall *et al.* 2006) for both the Aqua (2002-07-04 onwards) and Terra (2000-02-24 onwards) satellites. Each pair of tiles were merged together and reprojected to the British National Grid using GDAL (GDAL Development Team 2015). Using GRASS GIS (geographic information system) software (GRASS Development Team undated), a combination of both satellites was created to reduce the incidence of cloud pixels by approximately 15%. This method was

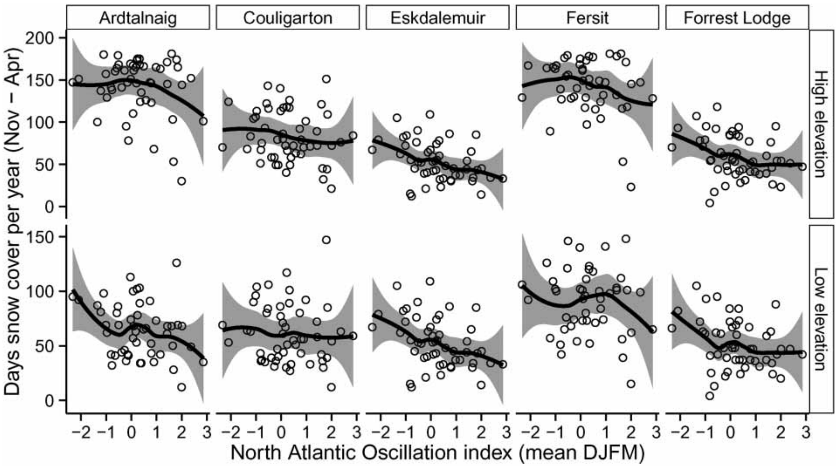

Figure 7 | Long-record SSGB stations snow cover plotted against the NAO index, shown with a LOESS and 95% confidence bounds.

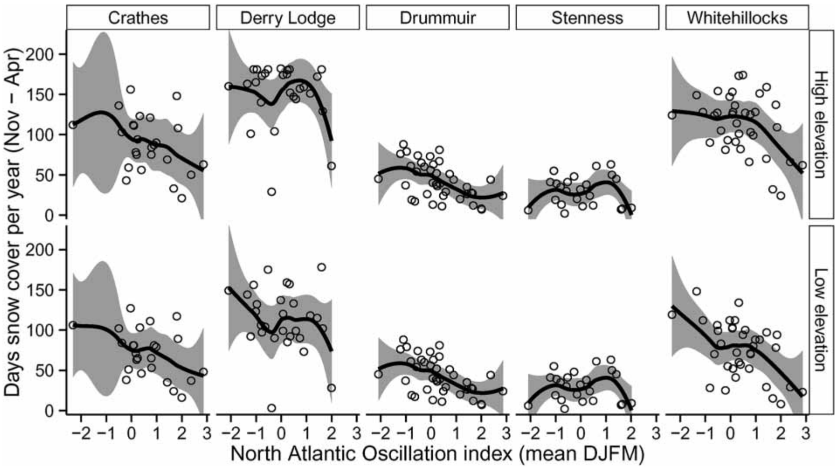

Figure 8 | Eastern and Orkney SSGB stations snow cover plotted against the NAO index, shown with a LOESS and 95% confidence bounds.

only possible from 2002-07-04 onwards, when the Aqua satellite became operational. Prior to this the Terra satellite alone was used, creating a data set containing full winters from 2000/01 until 2013/14. These November to April period data were summed and correlated against the DJFM NAO mean index, presented in Figure 10(a). Figure 10(b) shows the same analysis, repeated for cloud cover observed by MODIS.

Data comparison

To relate SSGB station and national results, Pearson correlations from SSGB, MODIS and UKCP09 are compared. Values from MODIS and UKCP09 rasters were extracted at SSGB station locations and are shown together in Table 4.

RESULTS

Bonacina

Figure 2 shows boxplots of the difference between DJFM NAO index as grouped by the Bonacina classification. A general trend can be seen where less snowy winters have a more positive NAO index. This is

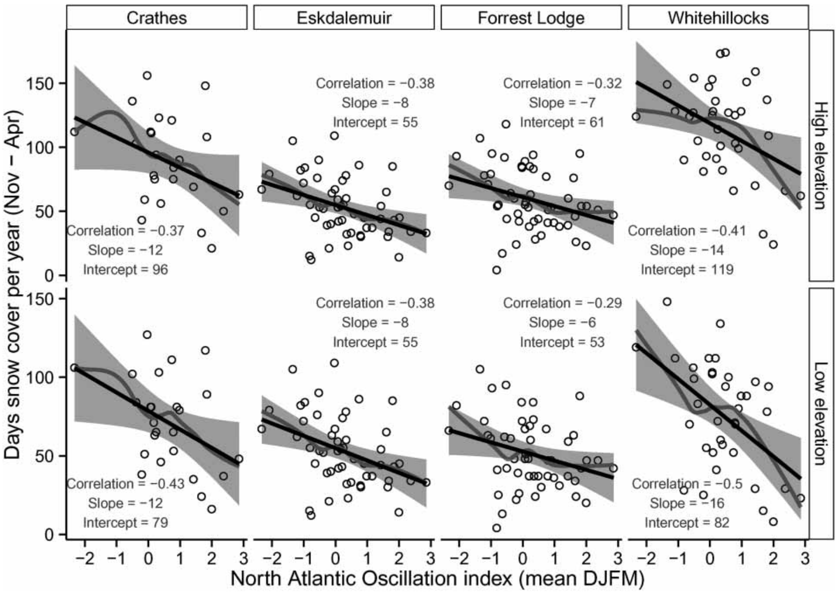

Figure 9 | Comparison between days of snow cover at select SSGB stations in years that reported all months between November and April and the NAO index. Shown with a linear model with 95% confidence bounds and a LOESS smoother (dark grey) for comparison.

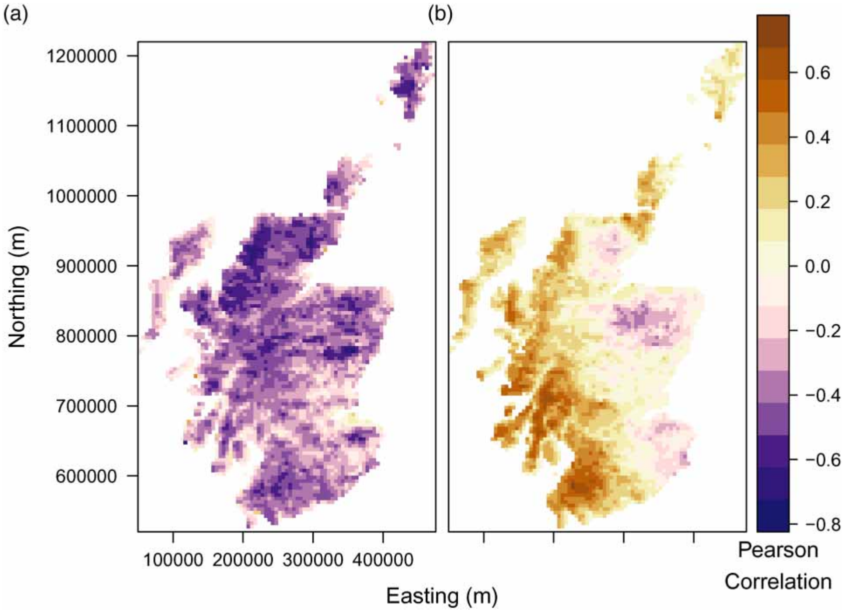

Figure 10 | (a) Correlation between number of days MODIS recorded snow cover each winter (November to April) and the mean DJFM NAO index. (b) Correlation between number of days MODIS recorded cloud cover each winter (November to April) and the mean DJFM NAO index.

demonstrated statistically using ANOVA (F value = 25.07) and a Tukey HSD analysis (Table 2) where each adjacent pair is shown with a best estimate of difference and significance value. All pairs are different at greater than 5% significance, except very snowy–snowy. This could be a product of the very snowy small sample size, for which the Tukey HSD test performs less well.

Table 4 | Pearson correlations of snow cover and NAO at SSGB stations with geographically corresponding values extracted from MODIS and UKCP09 rasters

Station	Elevation	SSGB	UKCP09	MODIS
Ardtalnaig	High	−0.20	−0.41	−0.40
Ardtalnaig	Low	−0.27	−0.41	−0.40
Couligarton	High	−0.18	−0.30	−0.34
Couligarton	Low	−0.10	−0.30	−0.34
Crathes	Low	−0.43	−0.52	−0.33
Crathes	High	−0.37	−0.52	−0.33
Derry Lodge	Low	−0.23	−0.22	−0.53
Derry Lodge	High	−0.13	−0.22	−0.53
Drummuir	High	−0.52	−0.46	−0.53
Drummuir	Low	−0.52	−0.46	−0.53
Eskdalemuir	High	−0.38	−0.49	−0.30
Eskdalemuir	Low	−0.38	−0.49	−0.30
Fersit	Low	−0.11	−0.27	−0.53
Fersit	High	−0.25	−0.27	−0.53
Forrest Lodge	Low	−0.29	−0.51	−0.48
Forrest Lodge	High	−0.32	−0.51	−0.48
Stenness	High	0.02	−0.05	−0.51
Stenness	Low	0.02	−0.05	−0.51
Whitehillocks	High	−0.41	−0.55	−0.54
Whitehillocks	Low	−0.50	−0.55	−0.54

UKCP09 snow

Figure 3 shows some strongly negatively correlated areas of Scotland. The strongest correlations are in the south west and along the east coast. Areas of poor correlation are predominantly in central and northern mainland Scotland and Orkney.

SSGB

Figure 5, showing SSGB snow accumulation curves, displays a marked difference in duration of snow cover at all elevations between winters with the highest and lowest NAO indices, with positive NAO phases having less snow cover than negative NAO phases. Below 750 m the changes in days of snow cover as elevation increases are broadly linear, while above 750 m the relationship is unclear, with lines crossing. This 750 m change-point is used to distinguish between high and low snow cover for the SSGB station analysis.

Individual SSGB stations with the longest record of complete winters and some other stations are considered (Table 3). Other stations, in the east and Orkney, were used to investigate the more extreme correlations between the NAO index and UKCP09 snow data (Figure 3), accepting that they do not have the longest records. These results corroborate what is shown in the UKCP09 snow results (Figure 3), that south western sites like Forrest Lodge (Figure 7) show a negative correlation with the NAO index. This is repeated in Figure 8 where eastern sites, Crathes and Whitehillocks, show a strong relationship with the NAO index. Also in line with the UKCP09 results, Stenness, chosen because of a poor UKCP09 snow correlation with the NAO index, shows a weak relationship to NAO index (Figure 8).

SSGB stations Crathes, Eskdalemuir, Forrest Lodge and Whitehillocks have been plotted with linear regression lines (Figure 9). Line slopes vary from −7 to −14 days for higher elevations and from −6 to −16 days for lower elevations. As can be seen in Figures 5–8, the NAO index has a larger impact at lower elevations, but Pearson correlation values are variable; this could be a function of stations not observing the same time periods and hence some sampling produces better correlations than others. None of the SSGB stations were observing during the record NAO index low winter of 2009 to 2010.

MODIS

Figure 10 was resampled (bilinear) to a 5 km resolution, to better show correlations. Figure 10(a) shows a generally weak correlation between MODIS snow cover and the NAO index. The strongest correlations are in north west Scotland, with the weakest in central eastern Scotland. Orkney shows a strong correlation, in contrast to the UKCP09 and SSGB results. A small proportion of the plot, east of Edinburgh, has a very weak but positive correlation, in disagreement with Figures 2–9.

Differences from UKCP09 and SSGB results are most likely because of the frequency of cloud, as it is difficult for visible remote sensing to see through cloud. The problem is illustrated in Figure 10(b), which shows cloud cover as interpreted by MODIS, correlated with the NAO index. The area of positive correlation exceeds the area of negative correlation. An east–west split in correlation is clearly shown, with the east coast negatively correlated to the NAO index and the west coast positively correlated to the NAO index. This will have an impact on seeing spatial snow cover trends; if we expect the east to get more days of snow cover when there is a negative NAO index, a corresponding increase in cloud cover will obscure snow observations.

Data comparison

A comparison of correlations from different data sets can be seen in Table 4. These results are summarised by Pearson correlations between data sets (UKCP09: 0.87 and MODIS: −0.07), demonstrating that the SSGB and UKCP09 results corroborate each other, but that MODIS results do not correlate with SSGB results.

DISCUSSION

There is a strong correlation between UKCP09 and SSGB results, with highlighted areas like south west Scotland and east Scotland showing strong negative correlations between snow cover and the NAO index and Orkney with no correlation. This indicates that UKCP09 is an appropriate method for analysing the spatial relationship between snow cover and NAO phase at a national scale. The SSGB data have shown stronger correlation between the NAO index and snow cover at lower elevations. We believe this is because lower elevations have more transient snow as they are generally warmer than higher elevations and so snow will be less likely to fall and lying snow will more readily melt. This makes snow in these areas susceptible to even small changes in temperature. Perhaps most importantly, the persistence of snow at lower elevations is less, because increases in temperature from westerly air flows have a greater impact on areas that are closer to melt. This low elevation correlation is supported, by proxy, by the Bonacina index correlation with the NAO index (Figure 2), as the majority of Great Britain is low lying, so the Bonacina index is more likely to reflect the more common (lower) elevation zone than more remote mountain areas. Our correlations of NAO index and snow cover are weaker for higher elevations, which are often cold enough for deeper snow to accumulate and taking longer to melt for a wider range of typical winter temperatures. The most recent example of this was winter 2013/14, which was comparatively mild and very wet, but vast quantities of snow fell at higher elevations in Scotland (Kendon & McCarthy 2015). Kendon & McCarthy (2015) discuss a lapse rate of approximately 6 °C/km between Aviemore and Cairngorm summit, which was linked to the persistent Atlantic weather type and absence of temperature inversions. This lapse rate is higher than the long-term (1983 to 2008) average of 5.2 °C/km for Aviemore and Cairngorm chair lift calculated by Burt & Holden (2010), helping to explain the depth and duration of snow cover accumulated that winter.

Inland areas generally have a poorer correlation with the NAO index. As much of this area is high in elevation this can partly be attributed to it being cold enough for snow to accumulate and persist, irrespective of the NAO index. These continental areas may also be dominated more by local weather systems and micro-climates, enabling snow to persist for longer.

Those stations that showed a more easily defined relationship with a LOESS have had linear models fitted (Figure 9), with Pearson correlation values, from −0.29 to −0.5. This range of results could be explained by microclimates having a bigger impact on snow cover than long-term weather patterns. This would be especially true on the east side of the Cairngorms, where wind (predominantly westerly) driven snow often accumulates on eastern slopes and can take a long time to melt. These spatial local discrepancies can also be temporal, given that the SSGB sites did not all observe the same winters, and some may have been more closely correlated with the NAO index than others. The obvious solution is to consider the results from Figure 5, which average over a greater number of SSGB stations, helping to reduce uncertainty.

CONCLUSION

Spatial variability of snow cover is a big challenge and is difficult to observe and quantify. This is typified by the contrasting results of UKCP09 snow and MODIS data correlations. We have overcome this by using disparate snow cover data sets, encompassing anecdotal type data (Bonacina index), interpolated ground observed data (UKCP09), the SSGB and satellite observations (MODIS). With the exception of the MODIS analysis, these have all shown the same results: that Scottish snow cover is generally negatively correlated with the NAO index, with stronger correlations at lower elevations and in southern and eastern Scotland. Results from individual SSGB stations and UKCP09 grids correlate well demonstrating the value of UKCP09 data for national scale assessment of spatial trends. At sample locations, snow lying between November and April increase by 6 to 16 days for each unit reduction in the NAO index. These estimates could be used in conjunction with seasonal NAO forecasts in preparation for upcoming winters by groups like highways and local authority planners and snow sports industries.

As new snow data sets become available, particularly from satellite and reanalysis products, it will be worthwhile revisiting and updating this research to help constrain uncertainty. This will be particularly pertinent if predictions of a more volatile NAO index come to pass, as we will be able to better link snow cover to climate variability, helping our understanding of snow cover in a changing climate.

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