Reanalysis of Scottish mountain snow conditions

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Abstract

Mountain snowline is important as it is an easily identifiable measure of the phase state of water in the landscape. However, frequent observation of the snowline in Scotland is difficult as reduced visibility is common, obscuring ground based and remotely sensed methods. Changes in seasonal snowline elevation can indicate long-term climate trends. Snow cover influences local flora and fauna, and knowledge of snowline can inform management of water and associated risks.

Complete Scottish Snow Survey of Great Britain (SSGB) records were transcribed and form the primary snow cover dataset used for this work. Voluntary observers collected the SSGB between 1945 and 2007. Other snow cover data used includes remotely sensed (Moderate-resolution Imaging Spectroradiometer: MODIS) and Met Office station observations (as point observations and interpolated to form UK Climate Projections 2009, UKCP09).

I present a link between the North Atlantic Oscillation (NAO) index and days of snow cover in Scotland between winters from 1875 to 2013. Broad (5 km resolution) scale datasets (e.g. UKCP09) are used to extract nationwide patterns, supporting these findings using SSGB hillslope scale data. 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.

A degree-day snow model was developed using daily precipitation and temperature data to derive snow cover and melt. This model was run between 1960 and 2011 using point data from five Met Office stations and data on a 5 km grid (UKCP09 temperature and CEH GEAR precipitation) across Scotland. Due to CEH GEAR data underestimating precipitation at higher elevations, absolute values of melt are uncertain. However, relative correlations are apparent, e.g. the proportion of precipitation as melt and number of days with snow cover each year are generally decreasing through time, except around Ben Nevis. Notably, this increase correlates with positive NAO, and it is thought Ben Nevis remains cold enough to accumulate lying snow in the face of a warming climate. Snowmelt rates were found to annually exceed the maximum snowmelt rate used for fluvial impoundment structure design, but this was only at the highest elevations in areas like the Cairngorms.

Author's Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, either in whole or in part, in any previous application for a degree. Except where otherwise acknowledged, the work presented is entirely my own.

I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. The contribution of myself and the other authors to this work has been explicitly indicated below. I confirm that appropriate credit has been given within the thesis where reference has been made to the work of others.

Two publications form the basis for parts of this thesis and are included in Appendix B. These are described below with my contributions and which parts of the thesis they form.

Spencer, M., Essery, R., Chambers, L., and Hogg, S. The historical snow survey of Great Britain: Digitised data for Scotland. *Scottish Geographical Journal*, 130(4): 252–265, 2014, DOI: 10.1080/14702541.2014.900184.

Sections 2.3, 2.4.1, 2.4.2, 3.2.3 and 3.3 are almost entirely based on Spencer et al. (2014). Chapter 7 has some content from this publication. I was the lead author on this publication; Richard Essery (primary supervisor) contributed major edits and Lynne Chambers and Shona Hogg (both from the Met Office) proof read and arranged Met Office approval. Met Office staff provided no academic supervision, but smoothed the logistics of working within the Met Office archives.

Spencer, M. and Essery, R. Scottish snow cover dependence on the North Atlantic Oscillation index. *Hydrology Research*, 47(3): 619–629, 2016, DOI: 10.2166/nh.2016.085.

Sections 2.4.3, 2.4.4, 2.4.5 and Chapter 4 are almost entirely based on Spencer and Essery (2016). Chapter 7 has some content from this publication. I was the lead author on this publication and Richard Essery contributed edits.

Michael Spencer
27th January 2016

Acknowledgments

I extend great thanks to my primary supervisor, Richard Essery, for his insight, humour and support over the past few years. I'm grateful for the effort he has expended in steering me through my research and integrating me into the wider research community. My second supervisor, Nick Hulton, provided excellent discussions on catchment snow modelling, while Richard took a sabbatical in 2013. Both Neil Stuart and Kate Heal have given excellent encouragement; Neil in the role of advisor and Kate as an employer on a parallel research project. Lynne Chambers, Shona Hogg and the Met Office Edinburgh staff were welcoming and supportive during the mundane work of transcribing Snow Survey of Great Britain records. My thanks go to the Natural Environment Research Council, without whose funding I would not have been able to undertake this research.

This thesis was examined by Neil Macdonald and Rob Bingham who helped make the viva a really stimulating discussion on the content and implications of the work. I thank them wholeheartedly for taking the time and effort required.

I am especially lucky to have been part of the large research community in the University of Edinburgh's School of GeoSciences. In particular I'd like to thank Tim Reid, John Stevenson, Mark Naylor, Kit Carruthers and Emma Knowland for taking an interest and sharing their wisdom. Johannes Miocic created the template I've used for this thesis. Outside of the university, Neil Nutt and Janez Sušnik have kept me focused on the bigger picture and held me to account for my choices. On a technical note, the computing staff of the School of GeoSciences, particularly Magi Hagdorn, Justin MacNeil and Ross Taylor, have offered useful advice on data storage and programming. When doing technical computing work, there are few who could survive without the community supplied answers on Stack Exchange; my thanks go to the often anonymous answerers of questions. The School of GeoSciences' administration staff do an excellent job of looking after students, especially Nicki Reid, Helena Sim, Rosie Maccagnano, Lisa Thorburn and Graham Walker.

I'm really glad my brother, Jeremy Spencer, offered to proof read this thesis, an unenviable task. Finally, thanks and love go to my partner, Laura Burnett, and son, Artie Spencer-Burnett, for keeping me grounded and helping me remember there is life outside research!

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List of Abbreviations

AEP	Annual exceedance probability
AMAX	Annual maxima
ANOVA	Analysis of variance
ASL	Above sea level
°C	Degrees Centigrade
CEH	Centre for Ecology and Hydrology
d.50	Depth at which snow covers 50% of given area (model parameter)
DDF	Degree-day factor (model parameter)
DDF.d	Daily decrease of degree-day factor (model parameter)
den	Density of snow on the first day it fell (model parameter)
den.i	Daily increase of snow density (model parameter)
DJF(M)	December, January, February (March)
DTM	Digital terrain model
GDAL	Geospatial data abstraction library
GEAR	Gridded estimates of areal rainfall
GEV	Generalised extreme value
GIS	Geographic information system
GLUE	Generalised likelihood uncertainty estimation
GRASS	Geographic resources analysis support system
HSD	Honest significant differences
IPCC	Intergovernmental Panel on Climate Change
JJAS	Period June to September, inclusive
kg	Kilogram
km	Kilometre
m	Metre
mm	Millimetre
MODIS	Moderate-resolution Imaging Spectroradiometer
NAO	North Atlantic oscillation
NDVI	Normalised difference vegetation index
NRFA	National river flow archive
PE	Potential evapotranspiration
POT	Peaks over threshold
QGIS	Quantum geographic information system
RMSE	Root mean square error
SEPA	Scottish Environment Protection Agency
SSGB	Snow survey of Great Britain
SWE	Snow water equivalent
Temp.b	Temperature threshold between precipitation falling as snow or rain (model parameter)
UKCP09	United Kingdom climate projections 2009

CHAPTER 1

Introduction

1.1 Background

> Snow originates in clouds at temperatures below the freezing point. As moist air rises, expands and cools, water vapour condenses on minute nuclei to form cloud droplets [of] the order of 10 microns in radius. . . . Once a droplet has frozen it grows quickly at the expense of the remaining water droplets because of the difference in saturation vapour pressure between ice and water. The form of the initial ice crystal, columnar, plate-like, dendritic, etc. depends on the temperature of formation. . . . After deposition snow may dissipate rapidly by melting or sublimation or it may persist for long periods. If it persists it will undergo metamorphism, changing its grain texture, size and shape, primarily as a result of the effects of temperature and overburden pressure as it becomes buried by subsequent snowfalls. (Armstrong et al., 2008)

The above quote summarises the snow accumulation and melt process. Snow is part of the water cycle in parts of the world where precipitation falls at temperatures around or below 0 °C. Snow is important for a number of reasons, including: water storage, melt and land cover. The following examples are from areas with widespread snowy conditions, consequently showing some of the greatest impacts of snow.

This thesis investigates the influences and magnitudes of snowmelt and snow cover in Scotland. Snowmelt and snow cover are important for flooding and water supply, climate indicators and habitat change. The following three sections provide a literature review to demonstrate this importance, the first two sections in a global context and the final one for Scotland.

1.1.1 Importance of snowmelt

Snowmelt has caused Europe-wide flooding. Brazdil et al. (2010) investigated the Little Ice Age winter of 1783 to 1784. They found that, following large snow accumulation several phases of flooding passed across Europe between December and April caused by rain-on-snow events and rising air temperatures. The initial flooding phase began in more temperate areas, like England, France and the Netherlands, spreading through central Europe as spring arrived. Investigations into more recent (1950 to 2011) European rain-on-snow flooding and associated trends have found that, as spring snowfall has decreased and winter rainfall has increased, the early winter flood risk in medium-elevation mountain ranges has increased (Freudiger et al., 2014).

On the west coast of the United States, much of the annual precipitation falls as snow between November and April. This is then released gradually as snowmelt, providing water through the year (Hughes and Brown, 1992). Compared to the 2000 to 2012 average snow water equivalent (SWE), the years 2012 to 2014 were 60, 33, and 18% respectively (Molotch et al., 2015). This reduction of water storage as snow is causing widespread drought in California.

1.1.2 Importance of snow cover

Snow cover can have an impact on climate; Matsumura et al. (2014) have shown that earlier spring snowmelt in Eurasia is leading to an increase in land surface temperature by reducing albedo. This then causes intensified anticyclonic circulation, which has contributed to a reduction in Arctic sea ice.

The Intergovernmental Panel on Climate Change (IPCC) reports (Vaughan et al., 2013, Section 4.5) on seasonal snow using these indicators: snow cover extent; the seasonal sum of daily snowfall; snow depth; snow cover duration (the number of days with snow exceeding a threshold depth); and snow water equivalent. They summarise that northern hemisphere snow cover is decreasing, most notably in spring, due to increasing temperatures.

Snow cover in temperate climates also has an important role to play. Bicknell and McManus (2006) describe the Australian skiing industry as a "canary in a coal mine" and look at the industry response to climate change. This includes: artificial snow making, development of higher terrain and non-snow related winter activities. Scotland has a temperate climate (McClatchey, 2014), which is subject to temperatures above and below freezing and precipitation depths up to a few metres per year.

1.1.3 Snow research in Scotland

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 and Anderson, 1994). Dunn et al. (2001) show that snow can contribute to river baseflow until July, as melted snow generally takes a slower sub-surface pathway to a water course. Also, Gibbins et al. (2001) and Helliwell et al. (1998) discuss the importance of snowmelt for freshwater invertebrate habitat in the Cairngorms. Winters with increased snow cover tend to mean a more acidic environment, which is then flushed through the river system during subsequent snowmelt periods, making for harsher conditions for invertebrates (Helliwell et al., 1998).

McVean (1958) finds that snow cover affects vegetation in several ways: it re-distributes precipitation; shortens the growing season with prolonged snow cover; causes spring irrigation with melt water; offers protection from frost; and deposits wind-blown mineral and plant debris from snow beds. Therefore, knowledge of snow extent and duration can help understand habitat change (Trivedi et al., 2007). In a changing climate, mammals with a seasonally varying coat colour will find it increasingly difficult to match their camouflage to land cover (Mills et al., 2013), because the period when the animal is white to match the snow may no longer match the times when there is snow cover present. Knowing the duration of current snow conditions is crucial for understanding how future changes may impact these species.

Snow avalanches and debris flows can shape terrain. In the Lairig Ghru (Cairngorms) snow avalanches are locally significant geomorphic events (Luckman, 1992), although, their impact is often confined to reworking existing debris flow material. In the west of Scotland on Ben Nevis, there exists a 75 m boulder rampart formed at the end of an extensive avalanche chute (Ballantyne, 1989). This rampart dams a lochan (small water body), which is thought to have been excavated by repeated avalanche impact, the spoil of which forms the rampart, along with other avalanche debris.

Al Hassan and Barker (1999) used meteorological and traffic data for the Lothians region (around Edinburgh) between 1987 and 1991 to compare traffic volume and weather conditions. They found lying snow caused a 10% weekday and a 15% weekend reduction in traffic activity. Snow also has an impact on recreation. Harrison et al. (2001) reported shortening of the ski season in winters leading to 2001. An update to this publication is due as some winters since then have been very snowy (e.g. Prior and Kendon, 2011).

Finding or collecting meaningful snow data in Scotland is non-trivial. Green (1973) gives a list of disparate observation types of Scottish snow data: 1) number of days when snow fell; 2) number of days of snow lying (by definition: over half of the ground snow-covered at 0900 GMT in the immediate neighbourhood of the station); 3) average depth of snow in the neighbourhood of the station; 4) altitude of the general snow-line. They describe reconciling these observations as a challenge, given that not all are available everywhere; this issue is confounded as none of these variables describe the amount of water available in the snow pack. Challenges in Scottish snow observation continue today as it is difficult to remotely sense predominantly wet snow in mountainous terrain through frequent cloud cover. For a detailed discussion on remotely sensing snow in Scotland, see Section 2.4 and 3.5.

Given the difficulty in collecting traditional snow data, one approach has been to look at the number of snow patches which survive through the summer to the following winter. Watson et al. (1994) examined summer snow patches and climate in northeast Scotland for the years 1974 to 1989 and found snow patch persistence, i.e. the number remaining through the summer, strongly correlated (0.66 to 0.91) with winter and spring temperatures, and spring snow-drift. Green and Pickering (2009) found similar controls of snow patches in the Snowy Mountains, Australia: winter snow accumulation and summer temperatures. Theses Australian snowpacks were found to have declined significantly over a 54 year period causing previously perennial snow patches to melt in 2006.

Jackson (1977b) used snow depth observations collected by the UK Met Office to derive estimates of two and five year return period snow depth, SWE and snowmelt. They used 50 Met Office stations, which each had greater than 15 years of observations. Five year return period values reported by Jackson (1977b) included a snow depth of approximately 35 cm and SWE of 60 mm for high ground areas of Scotland. Jackson (1977b) also summarise a number of studies which have looked at snow densities. Snow densities given were between: 50 and 200 kg/m^3 for freshly fallen snow, 200 and 300 kg/m^3 for snow a few weeks old, and exceed 400 kg/m^3 during periods of rapid thaw.

Unsatisfied with the low estimates of SWE reported in Jackson (1977b), Ferguson (1985) undertook a spring snow survey in the River Feshie catchment of the Cairngorms between February and May 1984. He found extremely high snow densities: from 270 kg/m^3 for what appeared to be fresh powder to 630 kg/m^3 for late lying snow in late April and mid May. He suggests a combination of wind compaction and freeze-thaw cycles led to these high figures. Other work (Green, 1973) on Scottish snow has found a change in its persistence, with an increase in snow cover duration in the months of November and April. These are based on observations from the decades either side of 1960. Green (1973) finds the increase in snow cover mainly attributable to decreasing temperatures and increasing precipitation.

Arnell and Reynard (1996) made an early study on the effects of climate change on UK river flow using projections from the UK Climate Change Impacts Review Group. They found that by 2050, snowfall and snowmelt would be almost eliminated from UK hydrology, but in arriving at this conclusion they used only four river gauging stations in Scotland. Three of these were located in the Southern Uplands (south of Edinburgh) and the remaining one drains the east side of the Cairngorms (River Don). In more recent work (e.g. Hannaford et al., 2005; Hannaford and Marsh, 2006) the effect of climate change on snowmelt and resulting river flows has not been addressed, but they did find significant increases in winter flows in Scotland. Hannaford and Marsh (2008) discuss the possibility of whether this flow increase may relate to a decrease in precipitation falling as snow, or a decrease in the duration of snow cover, but do not investigate specifically what impact this may have had on river flows.

One thing these papers (Hannaford et al., 2005; Hannaford and Marsh, 2006,

2008) all have in common is they find a stronger correlation between river flows and the North Atlantic Oscillation (NAO) index, than with year. The NAO summarises an atmospheric pressure difference, which is strongly related to the UK experiencing weather systems from the east (negative NAO phase) or west (positive NAO phase). For in-depth information on the NAO see Chapter 4. A long record (1861 to 1991) of precipitation is presented by Macdonald and Phillips (2006), who correlate it to, amongst other things, the westerly wind force (WWF). They find WWF strongly correlated ($r=0.896$, $p<0.01$) with NAO, for the period 1951 to 2002; and that significant correlations between precipitation and WWF are strongly positive in the west of Scotland (0.45 to 0.77) and insignificantly negative in the east (-0.04 to -0.14). However, these precipitation with NAO correlations nearly exclusively deal with rainfall and do not investigate the relationship with snow.

The above review shows that better constraining snow cover and snowmelt and its influences is fundamentally important. This is especially the case for Scotland where existing knowledge is underdeveloped, yet snow has a major role to play.

1.2 Thesis aim and objectives

Scottish snow is important; yet how it is changing and the degree of relationship to atmospheric circulations are not understood. This thesis aims to: **demonstrate the importance of snow in a temperate climate - case study Scotland.** This will be achieved by the following objectives:

- Show that a volunteer-collected, snowline-observation dataset can be used to quantify snow duration and melt
- Map and quantify the relationship between snow and the NAO index
- Quantify extreme value statistics of Scottish snow, i.e. snow cover and snowmelt.

These problems are addressed by using a range of data sources, which are outlined in Chapter 2. These data sources are validated and their suitability assessed (Chapter 3). In Chapter 4, correlations between Scottish snow and the NAO index, including the spatial variability and an estimate of impact are presented. The datasets shown in Chapter 2 do not include observations of SWE or snowmelt; to derive these a snow accumulation and melt model was constructed, which is detailed in Chapter 5. This model also produces results where observations are sparse or do not exist. The results from this modelling exercise are shown in Chapter 6, which focuses on temporal trends and extremes of snow cover and melt, and correlation with NAO. Finally, in the conclusions, problems and opportunities for further work appear in Chapter 7.

CHAPTER 2

Data summary and description

Author Contributions: some of the work presented in this chapter has previously been published (Spencer et al., 2014). Richard Essery contributed major edits to the publication and Met Office authors contributed typographical corrections.

2.1 Chapter contents

This chapter covers the datasets used in this research, with a focus on the Snow Survey of Great Britain (SSGB). The SSGB was the initial spark for this research; as an unused data source in a field with little data availability there are many possibilities for its use. A history of the SSGB, the area observed in Scotland, the transcription process and digital data availability are presented. Other datasets described comprise of snow cover, precipitation, temperature, mapping and a climate proxy. A proportion of this chapter is derived from Spencer et al. (2014), which can be found in Appendix B. Discussion on the appropriate application of the differing datasets is in Chapter 3, along with data validation.

2.2 Data overview

Data used in this research fall into two broad categories: point observations and grids. An example of the former are data collated by the Met Office from their network of automated gauges and observers, including variables such as when snow lies on the ground each day, daily precipitation, minimum and maximum temperatures. An example of gridded data is where the Met Office point observations have been interpolated to infill the gaps between stations. Other examples of gridded data are maps and remotely sensed aerial images, e.g. those collected by satellite. Ephemeral snow in Scotland makes metrics like average snowline and beginning and end of continuous snow cover for a given winter meaningless, because each winter can see many snow accumulation and melt cycles. A solution to this is to use a count of the days of snow cover during a given time period; this is the approach generally taken in this research. Unless described otherwise, days with snow lying have been derived as snow cover from October to May over each winter. As this work is concerned with larger snowmelt events and longer duration snow cover, then focusing on the snowiest part of the year is most appropriate. There is interest in snow cover during the summer months, particularly from an ecological perspective, but cover is confined to small patches (Watson et al., 2011).

2.3 Snow Survey of Great Britain

The SSGB is a voluntary observer collected dataset which recorded snow cover each winter (usually October to May) between 1937 and 2007. Volunteers were based at estates, the water authorities, Nature Conservancy (now Scottish Natural Heritage), energy companies, Forestry Commission, and others; they often also collected other weather observation data for use by the Met Office. The SSGB was used to produce the annual publication 'Report on the Snow Survey of Great Britain' between 1947 and 1992. The title of this varied through time but the content was consistent; an example is Hawke and Champion (1949). The annual SSGB reports from autumn 1953 until spring 1992 are available from the Met Office[1]. Until 2014, most SSGB data only existed in paper form and little use had been made of them. Jackson (1978) used the SSGB to discuss the frequency and extent of snow cover in Great Britain. Jackson (1977a) also used SSGB data to help complete a snow index of years from 1875/76 to 1974/75. Trivedi et al. (2007) transcribed data for the Ardtalnaig station on Loch Tay for use in vegetation analysis, undertaking data quality assurance by checking other meteorological stations within the station vicinity. Trivedi et al. (2007) found that further use of the SSGB would be warranted as it gave a deeper insight into climate change.

2.3.1 History of the SSGB

The Snow Survey of Great Britain began in 1937 (Jackson, 1978) and was directed by Mr. Gordon Manley (Anon., 1947). After a hiatus during World War Two, the snow survey was officially resumed in autumn 1946 by the British Glaciological Society. The principal aim was to 'secure representative data relating to the occurrence of snow-cover at different altitudes in the various upland districts of Great Britain over the period October to June' (Anon., 1947). The reorganisation of the survey was undertaken by Mr. E.L. Hawke, Honorary Secretary of the Royal Meteorological Society and a member of the British Glaciological Society and a request for help made in 1947 (Anon., 1947); however paper copy data exist in the Edinburgh Met Office archive from the Autumn of 1945.

In 1953 the collation of data by the British Glaciological Society ceased and was thereafter undertaken by the British Climatology Branch of the Meteorological Office (Met Office, 1954). Hawke and Champion (1954) report in their final snow survey summary that the number of sites had increased from 120 to nearly 400, including land stations, lighthouses and light-vessels.

Between 1946/47 and 1991/92 an annual report was produced summarising the data returns for the season. Until 1954 this report was issued by the British Glaciological Society. From 1954 onwards the Met Office produced the annual SSGB

[1] http://www.metoffice.gov.uk/learning/library/archive-hidden-treasures/snow-survey

report. The survey was administered by the Met Office from the Scottish Weather Observations Centre in Edinburgh, where data were also collated. In 1992, due to the dwindling interest and lack of funding, the annual publication was withdrawn.

Despite the withdrawal of the annual summary publication, data continued to be collected until 2007. In 1994 there was a review of the 77 participating stations and those deemed not to view high ground or those that duplicated other stations were withdrawn from the survey. 32 stations in Great Britain remained after the review. The observer instructions were also updated following the 1994 review; the most important change was that volunteers were no longer required to note when an observation was obscured by cloud or fog or the observer was absent, although some continued to do so. The last SSGB records stored in the Edinburgh Met Office archives were observed in May 2007. It is not documented why the SSGB was terminated, but I speculate that funding cuts and a lack of use are the main reasons.

Scottish data between Autumn 1945 and Summer 2007 are stored in the Met Office archives in Edinburgh. These records pre-date the official commencement of the survey in 1946 as noted by (Anon., 1947). A likely reason for this is that stations continued reporting snow cover during the Second World War, after the initial snow survey beginning in 1937. Some earlier records have been located in the Gordon Manley papers archive[2], but these have not been viewed or transcribed. The Met Office archive in Exeter holds records for English and Welsh stations between 1946 and 1992. I believe the SSGB ceased due to a combination of budget cuts and lack of use of the collected dataset.

2.3.2 Coverage of the SSGB

The SSGB was collected across Great Britain, but this study has only transcribed Scottish records, as few English and Welsh records are kept in the Edinburgh archives and snow falls more often in Scotland. Records for over 140 sites in Scotland were found within the Met Office archive; the most southerly is Kirkbean near Dumfries and the most northerly is Collafirth Hill on the Shetland Isles. The elevation range from which observations were made is from sea level to 724 m ASL (above sea level), at Lowther Hill near Wanlockhead. After examining the locations and observing dates for the SSGB stations, some were found to be the same station, but with a name change - presumably through different volunteers having different opinions. The following changes were made (showing years reported under that name): Shin (1964) into Cassley Power Station, Ardclach (1946) into Glenferness, Tarfside (1958)

[2]http://endure.dur.ac.uk:8080/fedora/get/UkDhU:EADCatalogue.0534

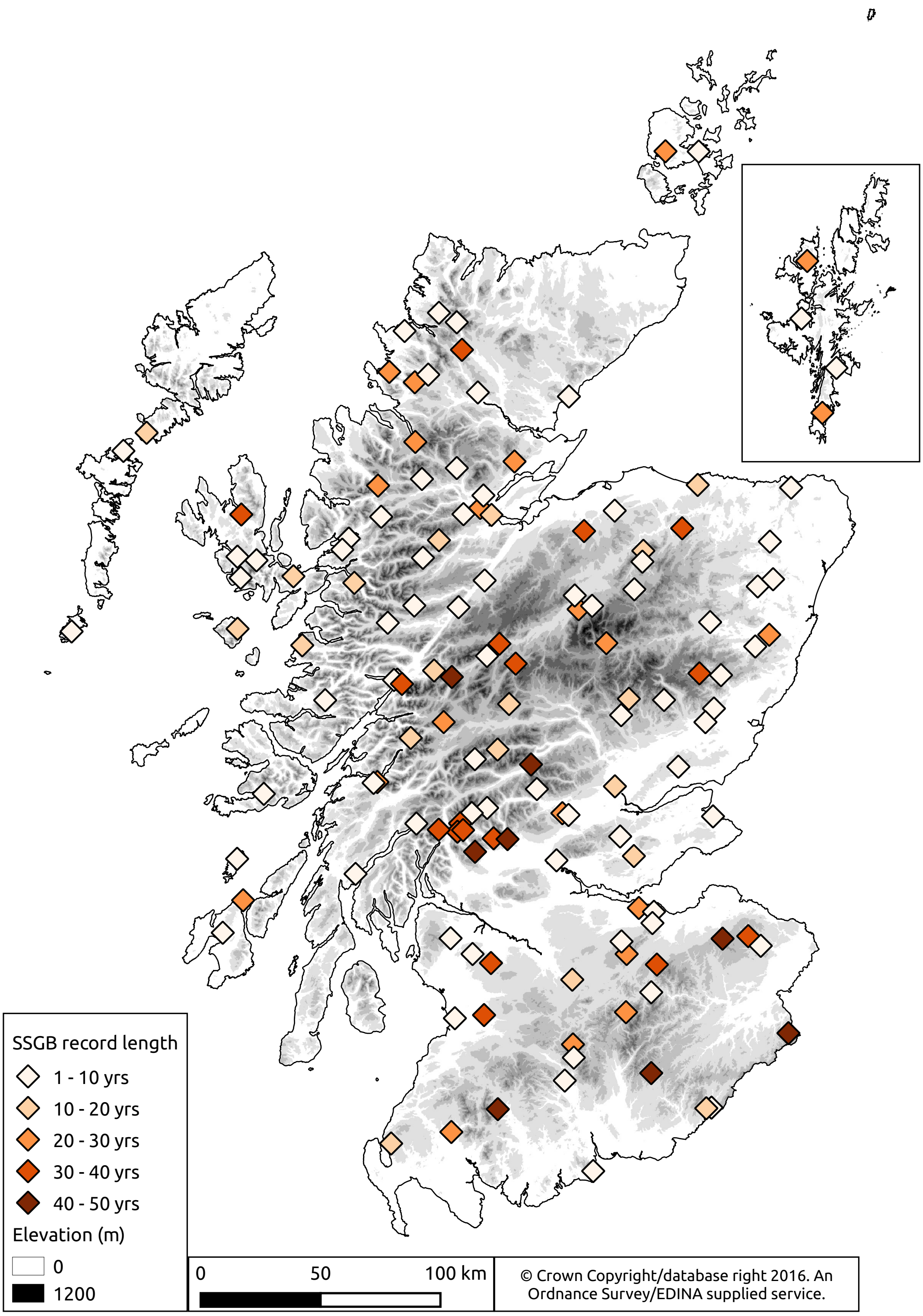


Figure 2.1: *Location of Scottish SSGB stations colour graded by record length in years.*

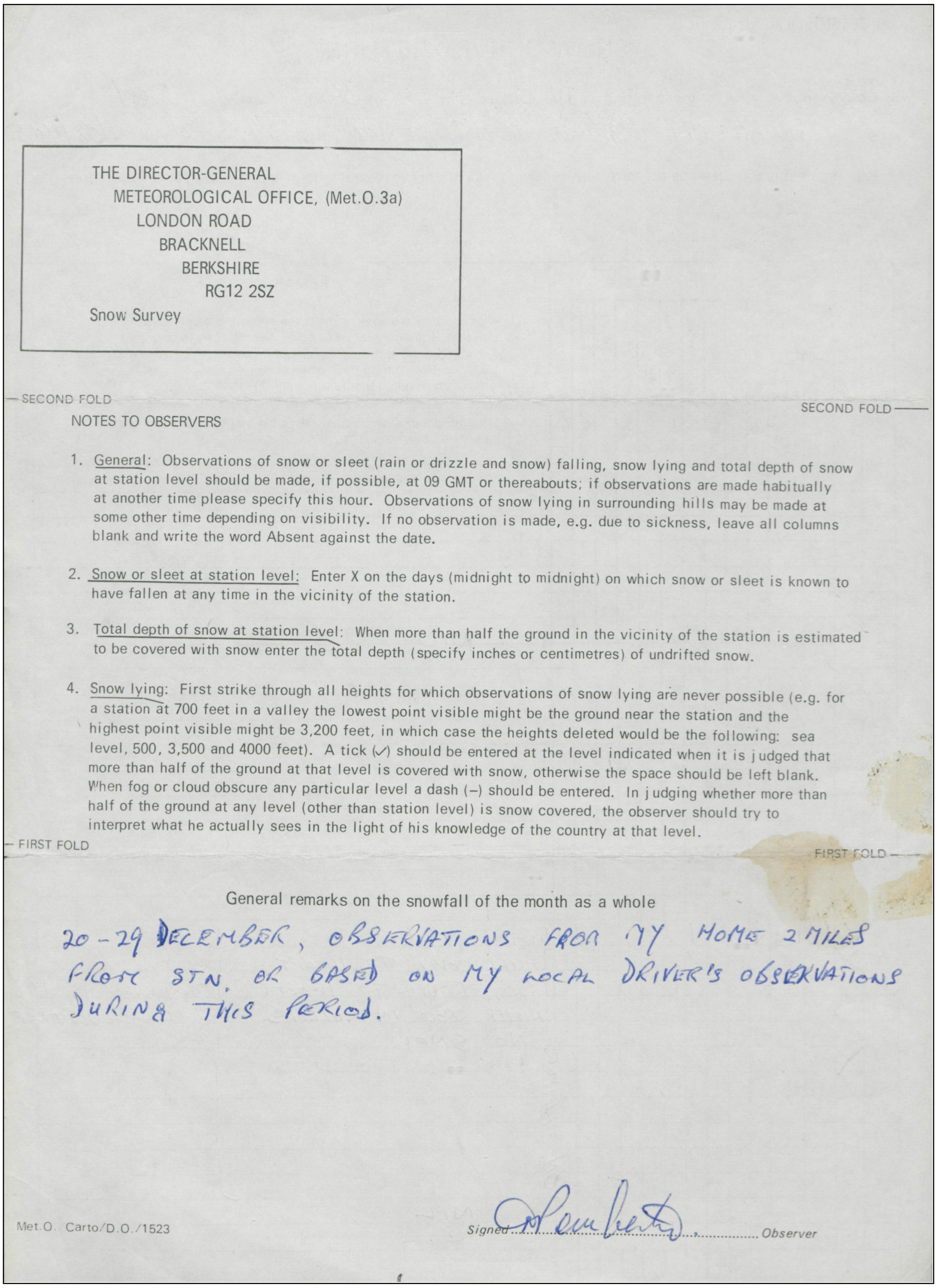
Table 2.1: *10 longest recording SSGB stations.*

Name	Visible hills	Observing years	Start	End
Couligarten	Ben Lomond	47	1954	2006
Loch Venachar	Ben Ledi	47	1954	2004
Eskdalemuir	Ettrick Pen	46	1954	2005
Forrest Lodge	Creag Meagaidh	46	1954	2005
Sourhope	Cheviot	44	1954	2003
Ardtalnaig	Ben Lawers	41	1954	2004
Fersit	Corserine	41	1954	2002
Hopes Reservoir	Pentlands	41	1957	2002
Stronachlachar	Stob a' Choin	38	1954	1997
Glengyle	Ben Venue	36	1954	1993

into Glen Esk. These three stations were straightforward to combine as they were geographically very close and the longer running stations had missing data when the shorter running ones were recording. There is a possibility that Dykecrofts and Newcastleton are the same station, however this is less clear as there is a distinct name change, so perhaps the station moved within the village. Figure 2.1 shows the spatial distribution of the recording stations, with each station colour graded to indicate its record length. Table 2.1 details the 10 stations with the longest records; note these are different to those which have the most data available, as some records are incomplete.

The SSGB observers looked out on the hills that surrounded their location and noted at what level snow was lying. Elevations were grouped into 150 m bands from 0 to 1200 m ASL or 500 feet increments earlier in the record, with most stations supplying metric returns by the early 1980s. The observers were asked (taken from January 1992 instructions) to record at 09:00 GMT "or thereabouts" when snow or sleet was falling at station level and if snow was lying at station level, with depth. Lying snow was to be recorded at visible elevations when it covered greater than half the ground at a given elevation. Finally they were asked to record when fog or cloud obscured observation. These instructions are shown in Figure 2.2. The results of this process can be seen in Figure 2.3, an example return card from Dalwhinnie; note the visible hills listed. Figure 2.2 also shows comments from the observer that for nine days they did not make observations from the station. This comment highlights a challenge of this dataset, that these observations are not standardised.

I have assessed the area visible from each SSGB site using line of sight analysis in the GIS software GRASS (GRASS Development Team, Undated). Using the Panorama digital terrain model (Section 2.4.8), an area was calculated which shows the land visible from each SSGB station (e.g. Figure 3.1) based on grid reference and a viewing



THE DIRECTOR-GENERAL
METEOROLOGICAL OFFICE, (Met.O.3a)
LONDON ROAD
BRACKNELL
BERKSHIRE
RG12 2SZ
Snow Survey

— SECOND FOLD SECOND FOLD —

NOTES TO OBSERVERS

1. General: Observations of snow or sleet (rain or drizzle and snow) falling, snow lying and total depth of snow at station level should be made, if possible, at 09 GMT or thereabouts; if observations are made habitually at another time please specify this hour. Observations of snow lying in surrounding hills may be made at some other time depending on visibility. If no observation is made, e.g. due to sickness, leave all columns blank and write the word Absent against the date.

2. Snow or sleet at station level: Enter X on the days (midnight to midnight) on which snow or sleet is known to have fallen at any time in the vicinity of the station.

3. Total depth of snow at station level: When more than half the ground in the vicinity of the station is estimated to be covered with snow enter the total depth (specify inches or centimetres) of undrifted snow.

4. Snow lying: First strike through all heights for which observations of snow lying are never possible (e.g. for a station at 700 feet in a valley the lowest point visible might be the ground near the station and the highest point visible might be 3,200 feet, in which case the heights deleted would be the following: sea level, 500, 3,500 and 4000 feet). A tick (✓) should be entered at the level indicated when it is judged that more than half of the ground at that level is covered with snow, otherwise the space should be left blank. When fog or cloud obscure any particular level a dash (–) should be entered. In judging whether more than half of the ground at any level (other than station level) is snow covered, the observer should try to interpret what he actually sees in the light of his knowledge of the country at that level.

— FIRST FOLD FIRST FOLD —

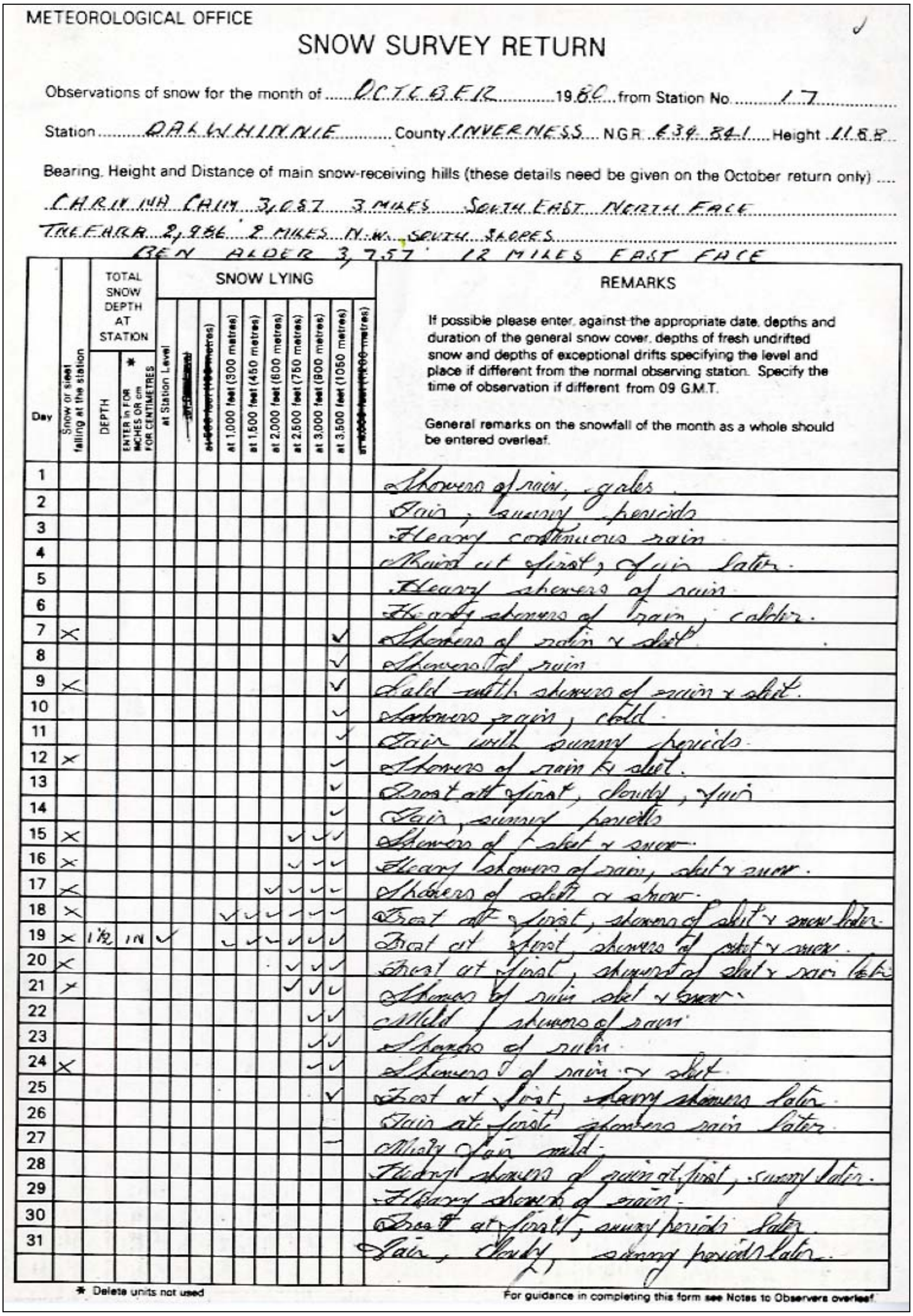
General remarks on the snowfall of the month as a whole

20-29 DECEMBER, OBSERVATIONS FROM MY HOME 2 MILES FROM STN, OR BASED ON MY LOCAL DRIVER'S OBSERVATIONS DURING THIS PERIOD.

Met.O. Carto/D.O./1523

Signed .... Observer

Figure 2.2: *Example SSGB instructions. Contains Met Office data ©Crown copyright and database right 2016.*



METEOROLOGICAL OFFICE

SNOW SURVEY RETURN

Observations of snow for the month of OCTOBER 1980 from Station No. 17

Station DALWHINNIE County INVERNESS NGR 639 841 Height 1168

Bearing, Height and Distance of main snow-receiving hills (these details need be given on the October return only) ....

CHRIN NHA CHUN 3,057 3 MILES SOUTH EAST NORTH FACE

THE FARR 2,986 2 MILES N.W. SOUTH SLOPES

BEN ALDER 3,757 12 MILES EAST FACE

Day	Snow or sleet falling at the station	TOTAL SNOW DEPTH AT STATION: DEPTH	* ENTER in FOR INCHES OR cm FOR CENTIMETRES	SNOW LYING: at Station Level	~~at 250 feet~~	~~at 500 feet (150 metres)~~	at 1,000 feet (300 metres)	at 1,500 feet (450 metres)	at 2,000 feet (600 metres)	at 2,500 feet (750 metres)	at 3,000 feet (900 metres)	at 3,500 feet (1050 metres)	~~at 4,000 feet (1200 metres)~~	REMARKS
1														Showers of rain, gales
2														Fair, sunny periods
3														Heavy continuous rain
4														Rain at first, fair later.
5														Heavy showers of rain
6														Heavy showers of rain, colder.
7	×											✓		Showers of rain & sleet
8												✓		Showers of rain
9	×											✓		Cold with showers of rain & sleet.
10												✓		Showers rain, cold.
11												✓		Fair with sunny periods.
12	×											✓		Showers of rain & sleet.
13												✓		Frost at first, cloudy, fair
14												✓		Fair, sunny periods
15	×									✓	✓	✓		Showers of sleet & snow
16	×									✓	✓	✓		Heavy showers of rain, sleet & snow.
17	×								✓	✓	✓	✓		Showers of sleet & snow.
18	×						✓	✓	✓	✓	✓	✓		Frost at first, showers of sleet & snow later.
19	×	1½	IN	✓			✓	✓	✓	✓	✓	✓		Frost at first, showers of sleet & snow.
20	×									✓	✓	✓		Frost at first, showers of sleet & rain later
21	×									✓	✓	✓		Showers of rain sleet & snow.
22											✓	✓		Mild, showers of rain
23											✓	✓		Showers of rain
24	×										✓	✓		Showers of rain & sleet
25												✓		Frost at first, heavy showers later.
26														Fair at first, showers rain later
27												–		Misty, fair, mild.
28														Heavy showers of rain at first, sunny later.
29														Heavy showers of rain.
30														Frost at first, sunny periods later
31														Fair, cloudy, sunny periods later.

If possible please enter, against the appropriate date, depths and duration of the general snow cover, depths of fresh undrifted snow and depths of exceptional drifts specifying the level and place if different from the normal observing station. Specify the time of observation if different from 09 G.M.T.

General remarks on the snowfall of the month as a whole should be entered overleaf.

* Delete units not used

For guidance in completing this form see Notes to Observers overleaf.

Figure 2.3: *Example SSGB return from Dalwhinnie in October 1980. Contains Met Office data ©Crown copyright and database right 2016.*

elevation of 10 m. An elevation much higher than a person's viewpoint was chosen in the belief it would offset uncertainty in station location and the expectation that observers may not view hillslopes from the exact station location, but may move themselves to get a better view. The visible areas were combined for the 140 sites and split into SSGB elevation bands. Each SSGB visible area band was then divided by the area of Scotland in that elevation band, giving percentages of each elevation band visible. The total fraction of Scotland visible from SSGB sites is 10.1%. These are compared to the number of Met Office stations reporting snow lying in each elevation band (Table 2.2). The SSGB covers a greater proportion of higher than lower elevations and the Met Office stations are the inverse of this, in-line with the 1946 aims of the survey (Anon., 1947).

Table 2.2: *Percentage of each elevation band in Scotland, percentage of each elevation band visible from SSGB stations, compared to percentage of Met Office stations recording snow (total 281) sited in each elevation band.*

Elevation (m ASL)	Scotland (%)	SSGB visible (%)	Met Office Stations (%)
0 to 150	40	11	75
150 to 300	29	9.1	21
300 to 450	17	9.1	3.2
450 to 600	8.1	9.6	0.36
600 to 750	4.1	9.8	0.36
750 to 900	1.6	12	0
900 to 1050	0.36	16	0
1050 to 1200	0.074	23	0
1200 and above	0.008	32	0

From studying the returns and the annual reports it appears that some hard copy data are missing. While disappointing, it is unsurprising as the paper records have changed hands and locations through the years. Figure 2.4 shows the number of stations in Scotland for which paper copies exist, by winter. Data are missing from 1994 and only three station records were found which covered the whole winter. This coincided with the station review and perhaps there was confusion over which stations were still to submit reports. Annual SSGB summary reports before 1955 indicate nearly 400 stations across Great Britain, but fewer than 30 Scottish stations were found in the Edinburgh archives. According to Jackson (1978), there are data from 1937 onwards; some of these are in the Manley archives.

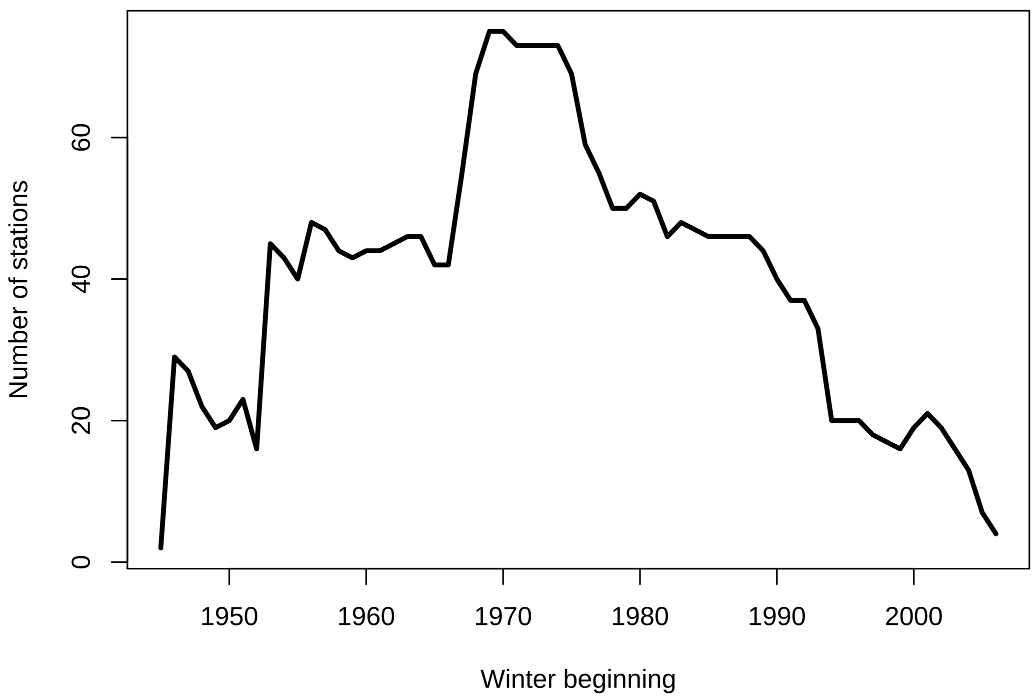


Figure 2.4: *Number of Scottish SSGB stations, with data available by winter, found within the Scottish Met Office archives.*

2.3.3 Transcription of the SSGB

For each station encountered, metadata from the SSGB return sheets were noted. This information was: site name, elevation (m ASL), easting (m), northing (m), hills visible and comments. These data are useful for identifying sites and establishing what was visible from each location. The comments section was used to record notes on data quality. For example, Brig-O-Turk recorded the lowest lying isolated snow patch, not the level of snow cover greater than 50%. Brig-O-Turk also noted where continuous snow lay in the comments; this value was used in the transcription. Where noted, missing values occurring when an observation was obscured by poor visibility or the observer was absent were transcribed. However, these cannot always be distinguished from when there was no snow. The paper copy returns were transcribed into a spreadsheet with each column representing a station and each row representing a day. Data transcription took approximately three months and approximately 16750 return sheets (one sheet for each station, each month) were input. Quality assurance was undertaken to check for typographical errors, but no further data checks were undertaken. Following transcription, data were uploaded to the Met Office database MIDAS (Met Office Integrated Data Archive System), and are now managed by the Met Office and are available through the British Atmospheric Data Centre[3]. For this research data were written to a SQLite[4] database. SQLite was chosen for its cross platform compatibility and the availability of libraries for most analytical programming languages (e.g. Wickham et al., 2014).

2.4 Other data sources

2.4.1 Met Office stations

Met Office data are meteorological observations sampled at point locations and are often only available for lower elevations. Datasets collected include: temperature, precipitation and snow. Snow data collection generally requires a human observer to be present, although the Met Office now operate approximately five automatic snow gauges in Scotland. Snow data were collected at manual Met Office weather sites by observers who noted if snow was lying at the station, and if so with what depth. Snow data collected could include snow presence (binary), snow depth (cm) and fresh snow depth. Precipitation data used for this research are 24 hour accumulations, i.e. the

[3] http://badc.nerc.ac.uk
[4] https://sqlite.org/

precipitation that has fallen between 09:00 GMT on subsequent days. It is notoriously difficult to measure the amount of different kinds of precipitation, particularly snow (Doesken and Robinson, 2009). Problems with undercatch of snowfall become apparent during modelling. Minimum and maximum daily temperature are observed at 09:00 GMT each day. In a hope of overcoming precipitation undercatch, only staffed Met Office stations were used as these would collect lying snow data and hopefully have better representation of precipitation during snowfall, as staff were available to melt snow and measure the resulting depth of water. Met Office stations with long records that were spread across Scotland were sought. Data were subset to only include winters (October to May, inclusive) which had complete observations of temperature, precipitation and snow. Met Office station data were downloaded from the British Atmospheric Data Centre[5] for the stations shown in Table 2.3. All Met Office stations recording lying snow are shown (Figure 2.5), with those used in this research highlighted.

Table 2.3: *Met Office station data used, showing location details and the number of winters (Oct to May) with complete daily observations of temperature, precipitation and snow depth.*

Name	Easting (m)	Northing (m)	Elevation (m ASL)	Complete winters (with snow depth > 0)
Braemar	315200	719400	339	4
Dalwhinnie	263941	785427	351	2
Eskdalemuir	323498	602638	236	1
Inverailort	176418	781616	2	3
Knockanrock	218694	908816	244	3

2.4.2 UKCP09 interpolated grids

The UK climate projections 2009 (UKCP09) grid dataset comprises a 5 km resolution raster image for each month; where each grid value represents a climate parameter for that cell, over a given time period. These grids were interpolated from Met Office station data by Perry and Hollis (2005), using a combination of regression and inverse distance weighting. Factors used in the regression included: easting and northing, terrain elevation, mean altitude over a 5 km radius of the station, percentage of open water within a 5 km radius of the station, and the percentage of urban land use within a 5 km radius of the station. Two UKCP09 datasets have been used: snow cover data, where each cell value is the number of days in a month with snow cover; and average

[5] http://badc.nerc.ac.uk

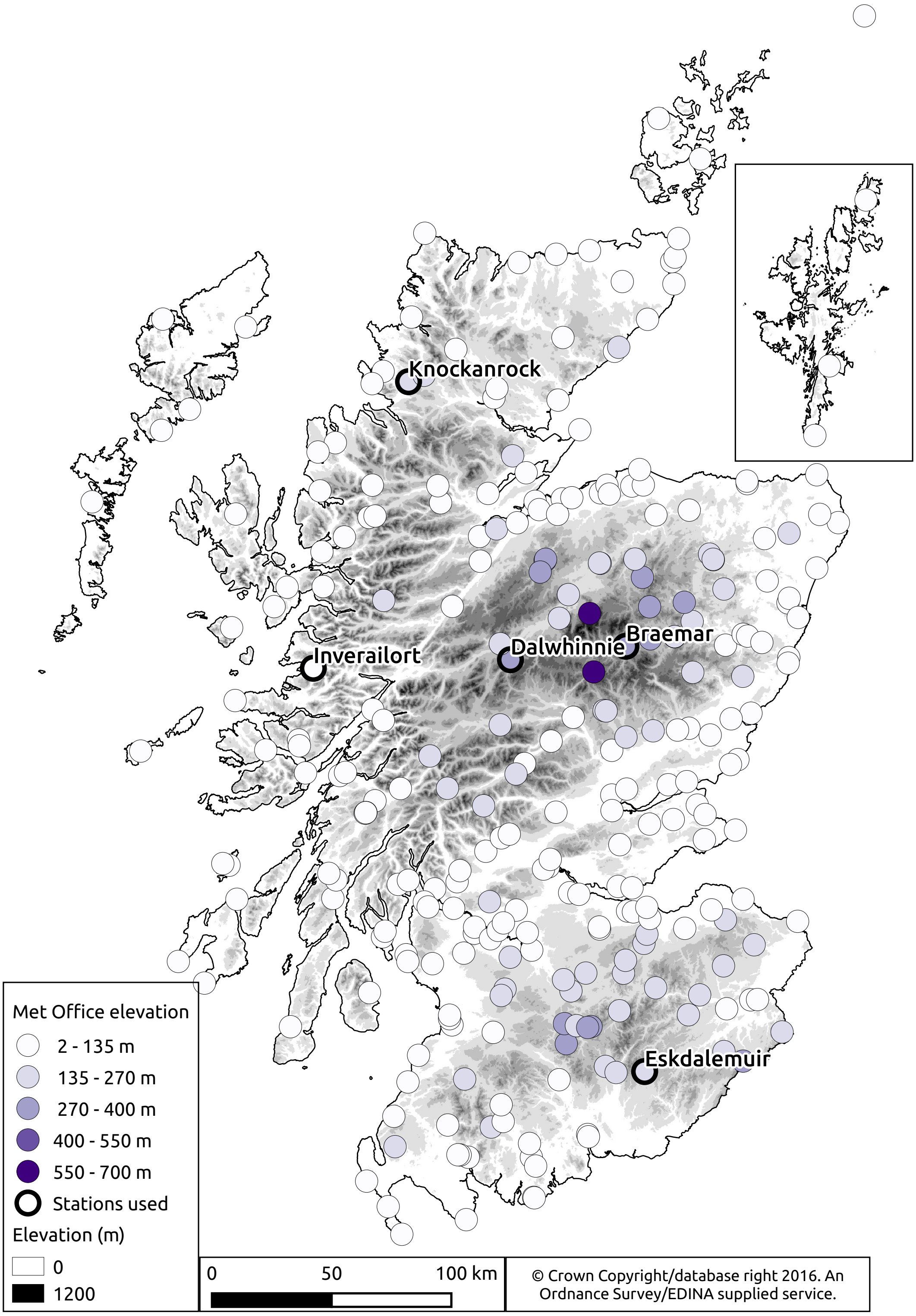


Figure 2.5: *Location of Scottish Met Office stations recording lying snow, colour graded by elevation in metres.*

temperature, where each cell value is the mean of minimum and maximum daily temperature. Full winter (October to May) snow cover data are available from winters beginning 1971 until 2005. The UKCP09 snow lying data have been shown (Spencer et al., 2014) to compare poorly to the SSGB at higher elevations, most likely due to interpolation from low lying stations which do not adequately represent mountain snow. The UKCP09 snow lying grids are useful for broad nationwide assessments, helping to identify regions for further study (Spencer et al., 2014). UKCP09 grid data were downloaded from the Met Office[6].

2.4.3 Moderate-resolution Imaging Spectroradiometer

Data from satellite instruments are used to derive global snow cover products, available from 1966 onwards (Matson, 1991). There are two main methods for remote sensing of snow; microwave and visible.

Visible satellite remote sensing methods are not ideal for measuring snow cover in Scotland because snow cannot be viewed through the frequent cloud cover. Windows of opportunity for sampling may occur less than once a week (Slater et al., 1999). Working in North America, Tang and Lettenmaier (2010) found that MODIS (Moderate-resolution Imaging Spectroradiometer, Hall et al. 2002) had the greatest uncertainty measuring snow covered area during the autumn and spring months, when snow was accumulating or ablating. Dong and Peters-Lidard (2010) investigated the relationship between air temperature and MODIS snow covered area error; as expected from the findings of Tang and Lettenmaier (2010), error increased with temperature. This error was quantified to be 80% for temperatures above 15 °C, reducing to 10% for temperatures below 0 °C or -5 °C depending on location. This is of particular note for remote sensing of snow in Scotland where temperatures do not often stay far below freezing. Snow in Scotland is often wet, which also provides a challenge to microwave satellite observation. Rees and Steel (2001) found that for some types of vegetation cover, notably that without trees, they were able to use remote sensing to detect wet snow by considering a reduction in backscatter attributable to the snow.

Using microwaves to detect snow cover is very challenging in mountainous terrain (Snehmani et al., 2015) or when snow is wet (Rees and Steel, 2001). Snehmani et al. (2015) review 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. There are some

[6] http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/index.html

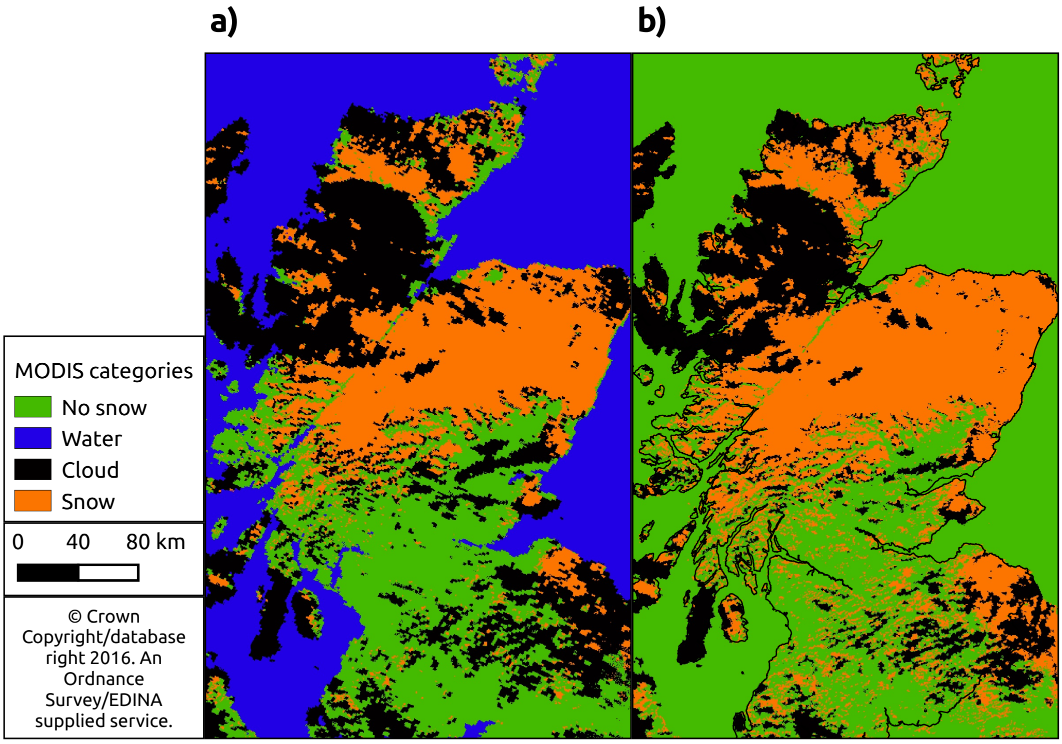


Figure 2.6: *Example images taken on 2010-02-20 from a) the MODIS instrument on the Terra satellite and b) combined with data from the Aqua satellite to reduce cloud pixels.*

snow cover products that amalgamate different data sources, including Robinson et al. (Undated) and Foster et al. (2011). The former of these is a 190.5 km grid resolution and the latter a 25 km grid resolution. Both of these are coarse grid sizes which would miss spatial detail. Foster et al. (2011) found that the Earth Observation System MODIS, outperformed microwave snow detection in cloud free areas. MODIS is freely available on a 500 m grid at a twice daily resolution, one image from the Aqua satellite and one from the Terra satellite. There are some reanalysis products, e.g. Notarnicola et al. (2013), which recalculated snow cover from MODIS observations at a 250 m grid, however these are only available for the Alps. MODIS data were chosen for use in this study because: of the time overlap with SSGB data, it is a dataset still being collected and the fine resolution grid it is available on. MODIS data were downloaded from the National Snow and Ice Data Centre (Hall et al., 2006). The MODIS dataset chosen is the tile set which records as binary whether snow covered each cell, rather than the fractional or albedo datasets. Coverage of Scotland is split across two tiles; these were downloaded for both the Aqua (2002-07-04 onwards) and Terra (2000-02-24 onwards) satellites. Each pair of tiles were merged together and warped to the British National Grid projection using GDAL (GDAL Development Team, 2016). These raster images were then managed in the GIS GRASS (GRASS Development Team, Undated), where combination images of both satellites were created to reduce the incidence of cloud pixels, e.g. Figure 2.6. A cloud pixel reduction of approximately 15 % was achieved when one satellite recorded cloud by taking a cell value from the other satellite. This method was only possible from 2002-07-04 onwards, when the Aqua satellite became operational. Prior to this the Terra satellite alone was used, creating a dataset containing full winters from 2000/01 until 2013/14. Cloud pixel reductions are shown in Figure 2.7, where Figure 2.7a shows the monthly number of cloud pixels from the Aqua and Terra satellites are broadly equal and Figure 2.7b compares Terra and Aqua cloud pixel counts against the combined dataset, showing a marked (approx 15%) difference.

2.4.4 Bonacina snowiness index

The Bonacina snowiness index was originally compiled by Leo Bonacina (Bonacina, 1966; Jackson, 1977a) and is now maintained as a website[7]. It categorises the snowiness of each winter into four subjective categories: Little, Average, Snowy and Very snowy. These categories are based on how much snow fell and how much of Britain it covered, using anecdotal data from weather journals, Met Office stations and websites. In this

[7] http://www.neforum2.co.uk/ferryhillweather/bonacina.html

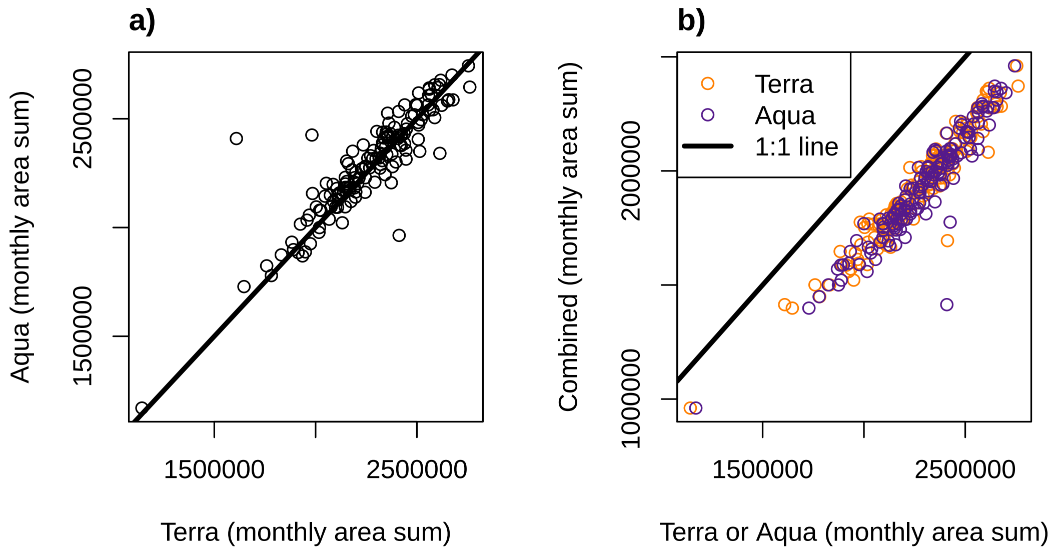


Figure 2.7: *Cloud pixel reduction (km^2) achieved by combining MODIS snow cover data from the Terra and Aqua satellites. a) Shows the number of cloud pixels per month from the Aqua and Terra satellites are roughly equal. b) Shows that by combining data from Aqua and Terra the number of cloud pixels per month can be reduced (approx 15%). The improvement is the difference from the 1:1 line.*

respect it is different to the other snow cover datasets used in this work, as other datasets present snow cover duration. I have used it because it covers a much longer time period than the other snow cover datasets, beginning in 1875 and still being maintained. The category of each winter is shown in Figure 2.8.

2.4.5 North Atlantic Oscillation index

North Atlantic Oscillation (NAO) index data were downloaded from the Climate Research Unit[8] (1821-2000) and Tim Osborn's NAO website[9] (1999 onwards). NAO data have been averaged (mean) over DJFM, as described by Osborn et al. (1999), to better represent the prevailing winter NAO index. Osborn et al. (1999) uses a DJFM winter NAO index as there is greater interdecadal coherence than with other periods, which is more appropriate for the large temporal scales this work considers. A summary of these data is shown in Figure 2.9; the predominant winter NAO index is positive (128 positive winters, 65 negative winters), aligning with our understanding that the UK is more likely to experience weather systems approaching from the west.

[8] http://www.cru.uea.ac.uk/cru/data/nao/
[9] http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm

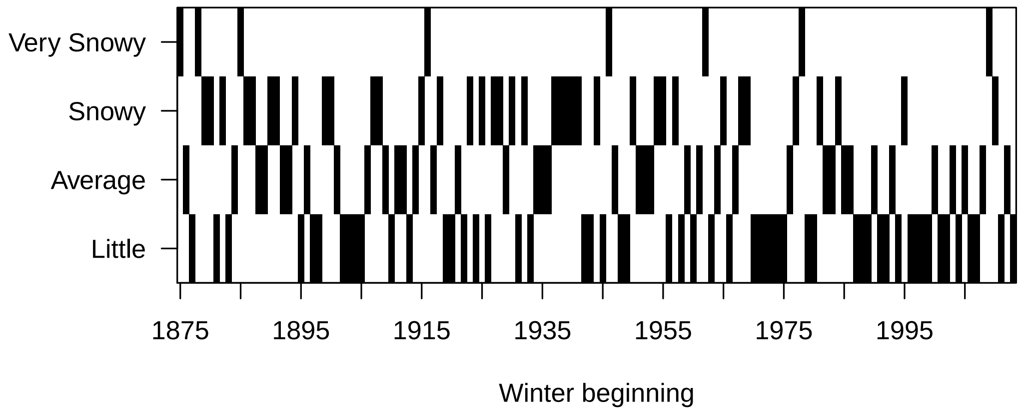


Figure 2.8: *Bonacina snowiness categories through time.*

2.4.6 River level and flow

River level and flow data are collected in Scotland by the Scottish Environment Protection Agency and collated at a UK scale by the Centre for Ecology and Hydrology (CEH). Datasets are available to download from the CEH hosted National River Flow Archive (NRFA). These include: catchment boundaries, annual maximum flow and mean daily flow. Daily flow data for the Mar Lodge catchment, high on the river Dee (Aberdeenshire), have been downloaded (National River Flow Archive, Undated) for the period 1982-09-10 to 2014-09-30. This catchment's key characteristics are shown in Table 2.4 and the catchment location is shown in Figure 2.10.

Table 2.4: *River Dee at Mar Lodge catchment characteristics.*

Parameter	Value
Station ID	12007
Grid reference (m)	309788, 789522
Catchment area (km^2)	289
Period of record	1982 - ongoing
Station elevation (m)	332
Maximum catchment elevation (m)	1309
Annual average rainfall (1961-1990) (mm)	1335

2.4.7 Gridded Estimates of Areal Rainfall

The CEH GEAR (Centre for Ecology and Hydrology Gridded Estimates of Areal Rainfall) dataset comprises 1 km resolution daily precipitation data in NetCDF format.

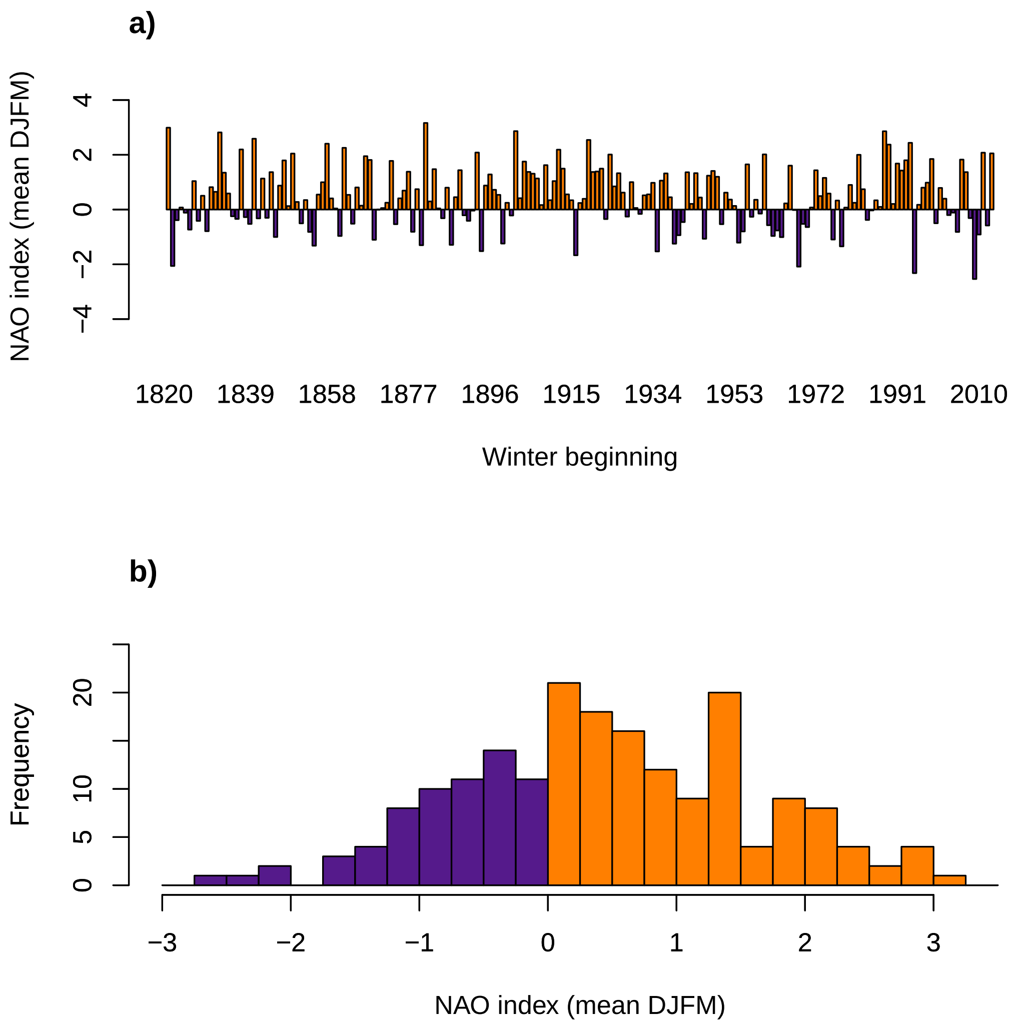


Figure 2.9: *Mean DJFM NAO a) through time b) histogram.*

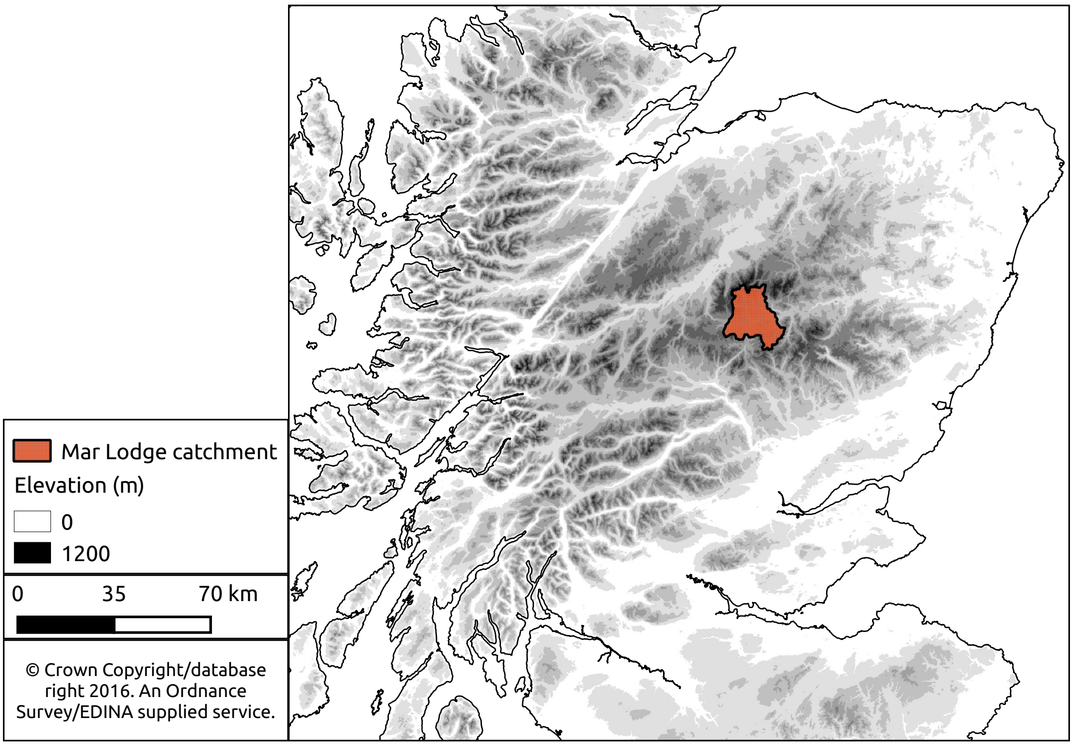


Figure 2.10: *Location of River Dee catchment at Mar Lodge.*

The dataset variables are easting (m), northing (m) (or latitude and longitude) and time (days), hence precipitation can be indexed in two dimensional space and time. The CEH GEAR data were interpolated from Met Office station data (Keller et al., 2015) and cover the time period beginning 1890 to present, with a data release lag while each new year of data is interpolated. No orographic enhancement of precipitation was made during the interpolation, which was accomplished using a natural neighbour method, including a normalisation step against annual average rainfall (Keller et al., 2015). I have used GEAR data from 1960 onwards, to match the availability of gridded temperature data, and to this end I also resampled GEAR data to a 5 km grid using a bilinear method to match the coarser Met Office grid. GEAR data are available from Tanguy et al. (2014).

2.4.8 Ordnance Survey mapping

The Ordnance Survey is the British national mapping agency. Its datasets are available for free through OpenData[10] project or for academic use via Edina[11]. The datasets used

[10] http://www.ordnancesurvey.co.uk/innovate/innovate-with-open-data.html
[11] http://edina.ac.uk/

in this study are shown within Table 2.5. There are two elevation models detailed: Panorama and Terrain 50. Terrain 50 superseded Panorama in 2013 and became a maintained data product, as opposed to Panorama which was never maintained after its creation. I have used both of these elevation models. An abbreviated copyright will appear on figures using Ordnance Survey data, the full copyright is:

> Contains Ordnance Survey data. ©Crown copyright and database right 2016. Data provided by Digimap OpenStream, an EDINA, University of Edinburgh Service.

Table 2.5: *Ordnance Survey mapping data used.*

Name	Description
1:250k Scale Raster	Former OS Travel Map in an image format.
Land-Form Panorama	Elevation model on 50 m grid.
Miniscale	National scale map.
Terrain 50	Current elevation model on 50 m grid.
Strategi	Vector data of road and railway networks, cities and rural areas.

CHAPTER 3

Validation of datasets

Author Contributions: The analysis comparing SSGB and UKCP09 data presented in this chapter has previously been published (Spencer et al., 2014). Richard Essery contributed major edits to the publication and the Met Office authors made mainly typographical changes.

3.1 Chapter contents

This chapter investigates the datasets used for this research; specifically to check them against each other and consider their appropriate use, but in the case of the SSGB to briefly look at temporal trends. The chapter begins with the SSGB, including consideration of the inter-site variability of observations using three geographically close stations. Long term trends in snow cover, as observed by the SSGB, are presented, concluding the SSGB discussion with comments on its viability. Other available snow datasets are examined; UKCP09, MODIS and Bonacina. A comparison of the UKCP09 snow grids and SSGB data is part of Spencer et al. (2014), which is contained in Appendix B. Data used as input for snow modelling are compared to other data sources to check their veracity. Finally digital terrain models (DTMs) used within this research are compared.

3.2 Snow Survey of Great Britain

3.2.1 SSGB variability

Comparing adjacent SSGB stations shows the inter-site variability of SSGB observations. A number of SSGB stations are geographically close. Of these, three have approximately 30 years of data and are within 4 km of each other; these three stations are are located to the east of Loch Lomond and are detailed in Table 3.1.

Table 3.1: *Details of three geographically close SSGB stations, visible hills are those noted by SSGB observers.*

Station	Easting (m)	Northing (m)	Elevation (m)	Start	End	Hills visible
Glengyle	238800	713300	115	1954	1993	Unlisted
Loch Arklet	237600	709600	163	1954	1993	Ben Vane
Stronachlachar	240100	710300	126	1955	1997	Stob a' Choin

To compare the area visible from each station, viewsheds were calculated (Figure 3.1) with a GIS line of sight analysis using the Ordnance Survey Panorama data. A degree of visible area overlap can be seen, but the original SSGB records indicate the Loch Arklet observer was viewing Ben Vane, which can be seen from neither Glengyle or Stronachlachar. The Stronachlachar observer noted Stob a' Choin as visible, which can be seen from neither Glengyle or Loch Arklet. However, Glengyle and Stronachlachar both have visibility in the same glen, while not covering the same peaks, in contrast to Loch Arklet which is primarily observing to the west of Loch Lomond.

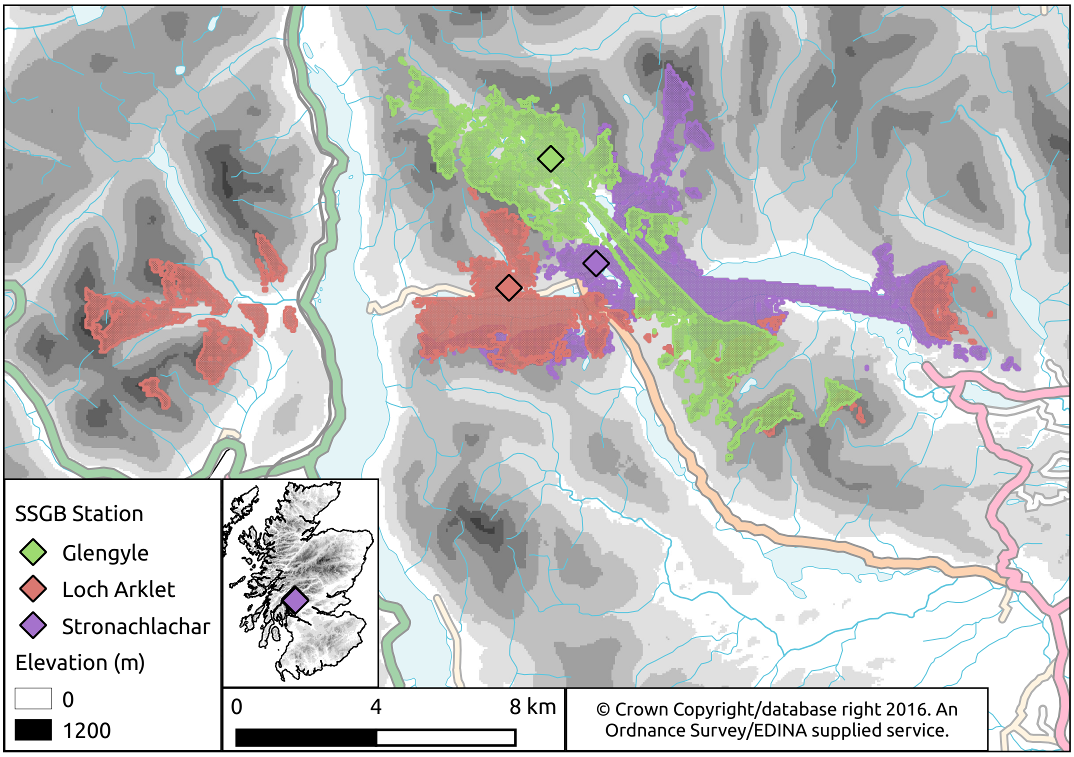


Figure 3.1: *Location of three long record SSGB stations used to understand correlation in the SSGB dataset. Showing elevation, roads, water courses and area visible from each station.*

A comparison between these three stations was made by aggregating data monthly, i.e. counting days per month of snowline observations, including cloud and no snow. There were 264 months where all three stations reported snowline, with observations from 150 to 750 m of elevation. A table of Pearson's correlations was made (Table 3.2) using all observation counts (150 - 750 m snowline, cloud and no snow) per month; the duration of snow cover ranged from 1 to 31 days. Glengyle and Stronachlachar, observing the same glen, correlate strongly, but Loch Arklet shows a weaker correlation with both other stations. From this the inference is that there are contradictory results of inter-station variability. Some stations may be geographically close, but be observing different hillslope aspects; which results in different snow cover records.

Table 3.2: *Pearson correlation matrix between three geographically close and overlapping time period SSGB stations.*

	Glengyle	Loch Arklet	Stronachlachar
Glengyle	1.00	0.45	0.82
Loch Arklet	0.45	1.00	0.56
Stronachlachar	0.82	0.56	1.00

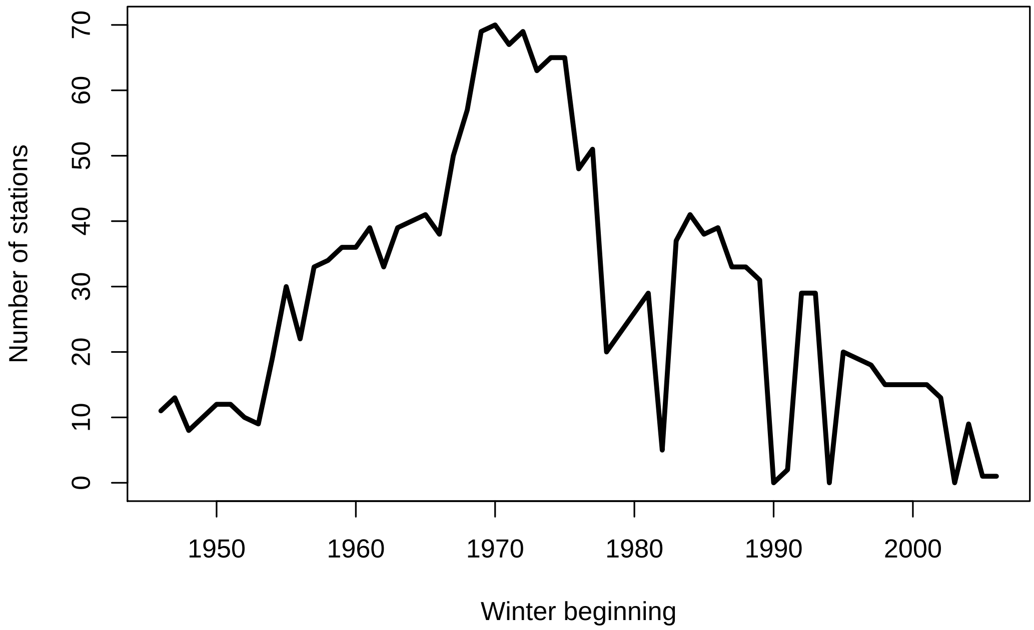


Figure 3.2: *The number of SSGB stations recording all months between November and April each winter.*

3.2.2 SSGB trends

The SSGB recorded data for a long period of time, but use has largely been confined to annual reports (1953 to 1991 reports are available online[1]) or isolated station use (e.g. Trivedi et al., 2007). I think it worthwhile to consider the 60 year record as a whole and whether it shows any trends in snow cover. To do this only stations which recorded all months between November and April have been used. While the SSGB generally reported October to May, many stations did not submit October or May reports so considering a slightly shorter period yields more complete station years; 58 years and 124 stations. The number of stations available peaked around the late 1960s and early 1970s with approximately 70 stations making complete returns each winter (Figure 3.2). The record is much less complete at the beginning and end of the time series.

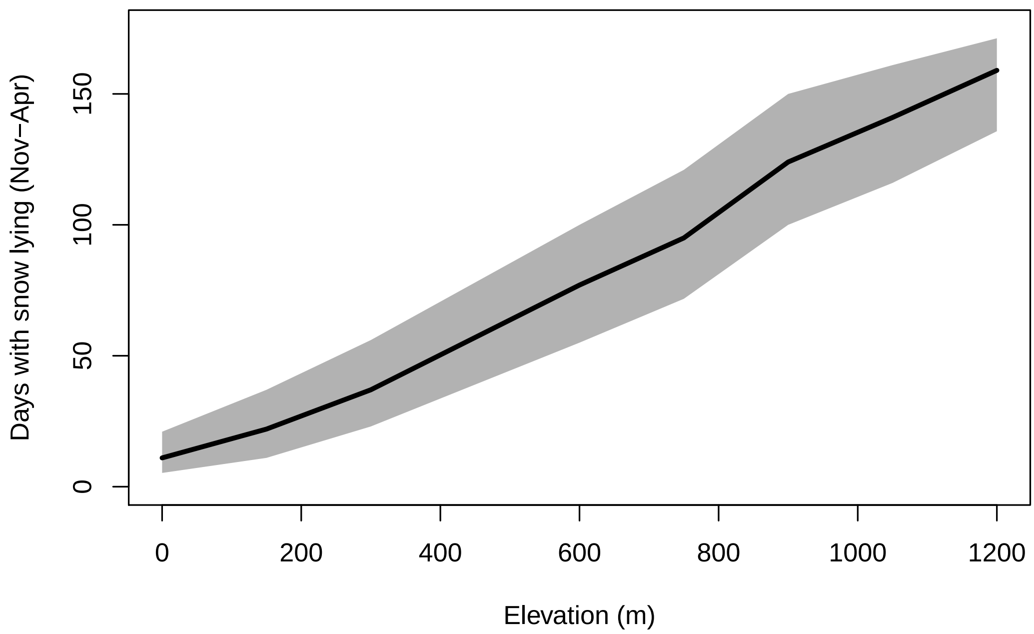


Figure 3.3: *Median snow cover duration curve for all SSGB stations reporting November to April each winter; shaded area shows 25th and 75th percentiles.*

The complete (November to April) SSGB stations have been amalgamated to produce an average winter snow cover duration curve (Figure 3.3), i.e. the median number of days with lying snow at a given altitude between November and April.

[1]http://www.metoffice.gov.uk/learning/library/archive-hidden-treasures/snow-survey

While not showing trends, this does display a long term Scottish average. These data have also been split by decade (Figure 3.4), showing how snow cover has varied through time. More recent decades have tended to have fewer days of snow cover each year, with the 2000s showing markedly less snow. It would be of interest to compare these snow curves to global annual average temperatures and Scottish annual average temperatures, to fit these fluctuations into the bigger climate picture.

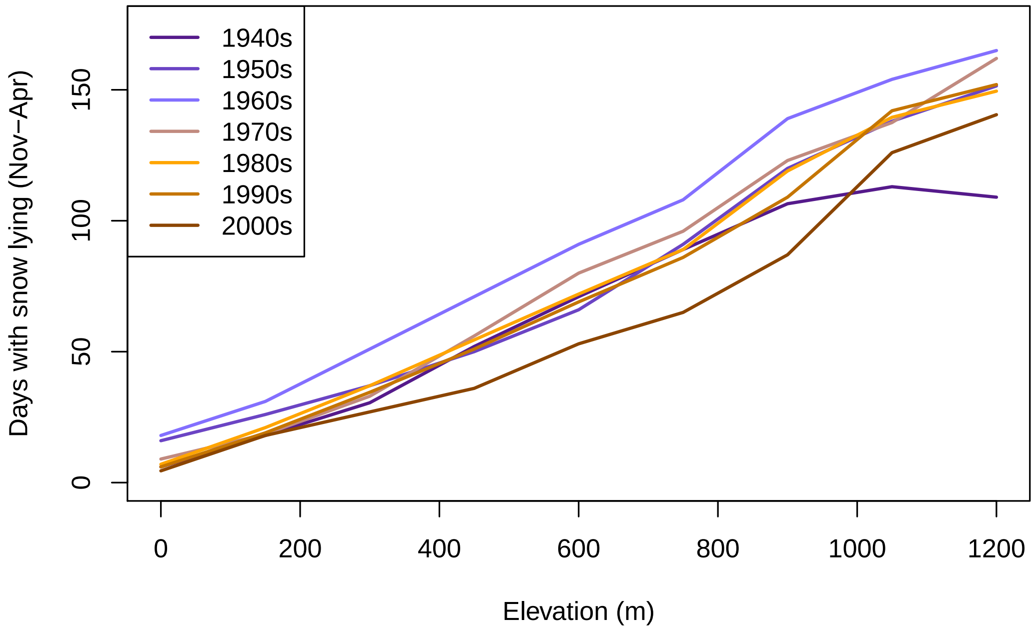


Figure 3.4: *Median snow accumulation curves for all SSGB stations reporting November to April each winter, split by decade. Note that the 1940s and 2000s have fewer contributing years and the dip in days of snow lying at 1200 m in the 1940s is caused by sampling fewer stations.*

3.2.3 SSGB viability

The SSGB is not without its limitations; prominent on this list is observer error. For example, the observer for Blair Castle Gardens stated on an early submission that they did not have access to a 'local' map giving exact elevations. While this is unfortunate, there is still great value in Blair Castle station as is provides relative data and the observer would have known the surrounding area well. In contrast, Crathes station was staffed by Adam Watson between 1979 and 2004, who would have had an excellent understanding of the lie of land and the snow conditions on it, as evidenced by his snow patch work (e.g. Watson and Cameron, 2010; Watson et al., 2011).

Known missing data caused by cloud cover, observer absence or a missing return mark time periods of data uncertainty. What is more challenging are unknown missing data when an observer submitted a monthly return but did not indicate cloud, fog or absence: this would be interpreted as no snow. When working with a small number of sites or short time period this should be verifiable by correlating general weather observations, particularly cloud cover, visibility and temperature, with gaps in the SSGB record. For the latter part of the record, observations can be checked against satellite data, although this may not be straightforward: when cloud cover obscured SSGB observations, it could also have obscured visible satellite observations. This would not be the case with a cloud inversion below the snowline. Known missing values could be in-filled using machine learning methods like self organising maps (Mwale et al., 2012), although this relies on the SSGB observations and their inherent uncertainty.

3.3 UKCP09 snow compared to SSGB snow cover

3.3.1 Method

A data comparison was made between the UKCP09 snow lying grid and the SSGB dataset as both cover a large range of elevations. These data were compared for the Dalwhinnie station, chosen as it has a long record (39 years from winters 1967/68 to 2006/07, missing 1994) that overlapped the UKCP09 record, and it has a good range of visible elevations from the Spey valley at 350 m to Ben Alder at 1148 m, 18.5 km to the south west. It is likely the Dalwhinnie station collected both the Met Office snow lying data used by UKCP09 and also the SSGB. Visible elevations were established from the SSGB return and verified by a GIS line of sight analysis using the Ordnance Survey Panorama data, shown in Figure 3.5.

UKCP09 data were interpolated from, amongst others, Dalwhinnie station data. Data collection began on 1973-09-01 and ended on 2007-01-31. There were whole months missing in October and November 1973, January 1978 and May 1995 until November 1996. The UKCP09 was interpolated from other reporting stations outside these time periods. The closest station with snow lying data for the 95/96 winter is Dall Rannoch School, approximately 30 km to the south.

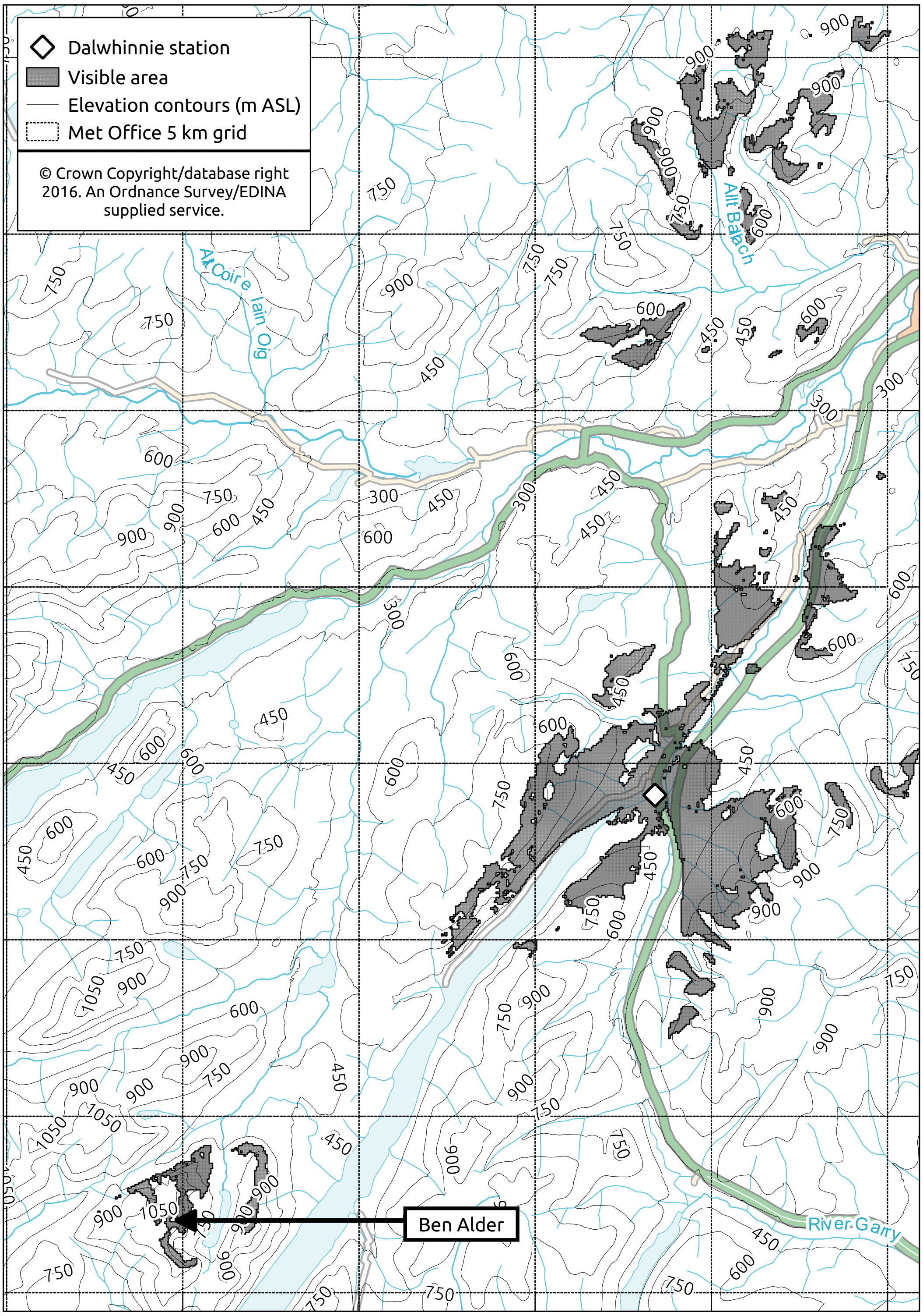


Figure 3.5: *Line of sight analysis for Dalwhinnie SSGB station, showing Ben Alder.*

The monthly UKCP09 data were extracted for the grid cells covering Dalwhinnie and Ben Alder. These were converted to snow years defined, for the purposes of this comparison, as from the beginning of September until the end of August. The mean elevations for these two grid cells were calculated from the Ordnance Survey Panorama DTM as 485 m ASL for the Dalwhinnie cell and 821 m ASL for the Ben Alder cell. The altitude of Dalwhinnie station is 362 m ASL.

SSGB Dalwhinnie data were then lumped into two groups with snowline of 450 m ASL and below and a snowline of 900 m ASL and below, to correspond with snow lying at the elevations of the Dalwhinnie and Ben Alder grid cells.

A summary of the UKCP09 and SSGB datasets for the Dalwhinnie and Ben Alder grid cells is shown in Table 3.3. In order to fill gaps in the SSGB due to missing returns, the days with snow lying at the Dalwhinnie station were added to the SSGB record for Ben Alder and Dalwinnie. Days of snow lying per year in the UKCP09 were subtracted from those in the revised SSGB for both Dalwhinnie and Ben Alder. These differences were plotted as time series with box and whisker plots to show data spread (Figure 3.6). For comparison the number of missing observations per year were also plotted. Missing values comprise two types: those when no monthly return was submitted or has been lost, and when observation was not possible due to observer absence or reduced visibility. The revised SSGB values were compared to the UKCP09 for Dalwhinnie and Ben Alder (Figure 3.7) as scatter plots.

3.3.2 Results

Table 3.3 compares the number of days with snow lying for the Ben Alder and Dalwhinnie average grid cell elevations using the SSGB and UKCP09. Of note is the similarity in the number of days with snow lying between Ben Alder and Dalwhinnie according to the UKCP09; this appears unrealistic as snow often falls more frequently and lies for greater periods at higher elevations. The SSGB values have a greater spread, with the mean value for Ben Alder within 7% of the UKCP09 maximum.

Table 3.3: *Comparison between days of snow lying per winter (1967-2006) at Ben Alder and Dalwhinnie, elevation averaged for 5 km grid cell, using SSGB and UKCP09 data.*

	UKCP09		SSGB	
	Dalwhinnie	Ben Alder	Dalwhinnie	Ben Alder
Minimum	10	25	23	36
Maximum	114	120	126	172
Mean	47	60	63	112
Standard deviation	23	21	27	40

Figure 3.6 shows the difference in duration of snow cover between the SSGB and UKCP09 for Ben Alder and Dalwhinnie. It was expected that the Dalwhinnie difference would be above zero for winters in which data from the station were used in deriving the gridded product because the altitude of Dalwhinnie station is 362 m ASL, while the grid square average is 485 m ASL. The data distribution for Dalwhinnie is not symmetrical around zero, but has a mean of 14 days and a standard deviation of 21 days. There is a greater variation in data than expected, as it is reasonable to suppose the SSGB was collected by the same observer who recorded the Met Office station data used to interpolate the UKCP09. Some of the larger differences coincide with time periods when no Met Office snow lying observations were being made at Dalwhinnie, notably 1971 and 1972. However, other large differences do not match. The greater difference lies with the Ben Alder grid cell data. The mean of these differences is 48 days with a standard deviation of 36 days, indicating that the UKCP09 underestimates the duration of snow cover at higher elevations. An outlier was the 1978/79 winter, during which the SSGB recorded 54 fewer days with snow than the UKCP09 estimated at Ben Alder. This does not coincide with a year of high missing observations, but the SSGB returns for December, February and March were missing. The 1979 snow survey report (Met Office, 1979) describes the season as having frequent snow cover with over twice the 1941-1970 average. The anomaly is caused by the three months of missing returns during the peak snow season: the Met Office Dalwhinnie station data recorded snow lying for nearly all of February and March. In total 58 days with snow lying at the Dalwhinnie station were recorded during December, February and March over the 1978/79 winter. With these added to the SSGB the outlier is reduced. This process was repeated for other months with missing SSGB returns, shown in Figure 3.6 using a dashed line and asterisk.

The two scatter plots comparing sites and datasets in Figure 3.7 show positive correlation. The sites are most strongly related in UKCP09 data, (Figure 3.7b) as data at Ben Alder are generally extrapolated from data recorded at Dalwhinnie. Figure 3.7a shows a weaker correlation between the datasets at each site than each dataset shows with itself in Figure 3.7b.

The UKCP09 snow dataset has value for national assessments. However, there are two key limitations for use at a local scale: the spatial resolution of the grid is coarse, and the underlying observations used to create the grid have been extrapolated horizontally and vertically. The 5 km cell covering Dalwhinnie, for example, varies in elevation from 350 m to 858 m with a mean of 485 m. It is challenging in environmental analysis to work with a single elevation value for a large area, as variation occurs over small vertical and horizontal distances. With nearly all Met Office snow observations recorded at low elevations and interpolated to mountainous areas, there is uncertainty

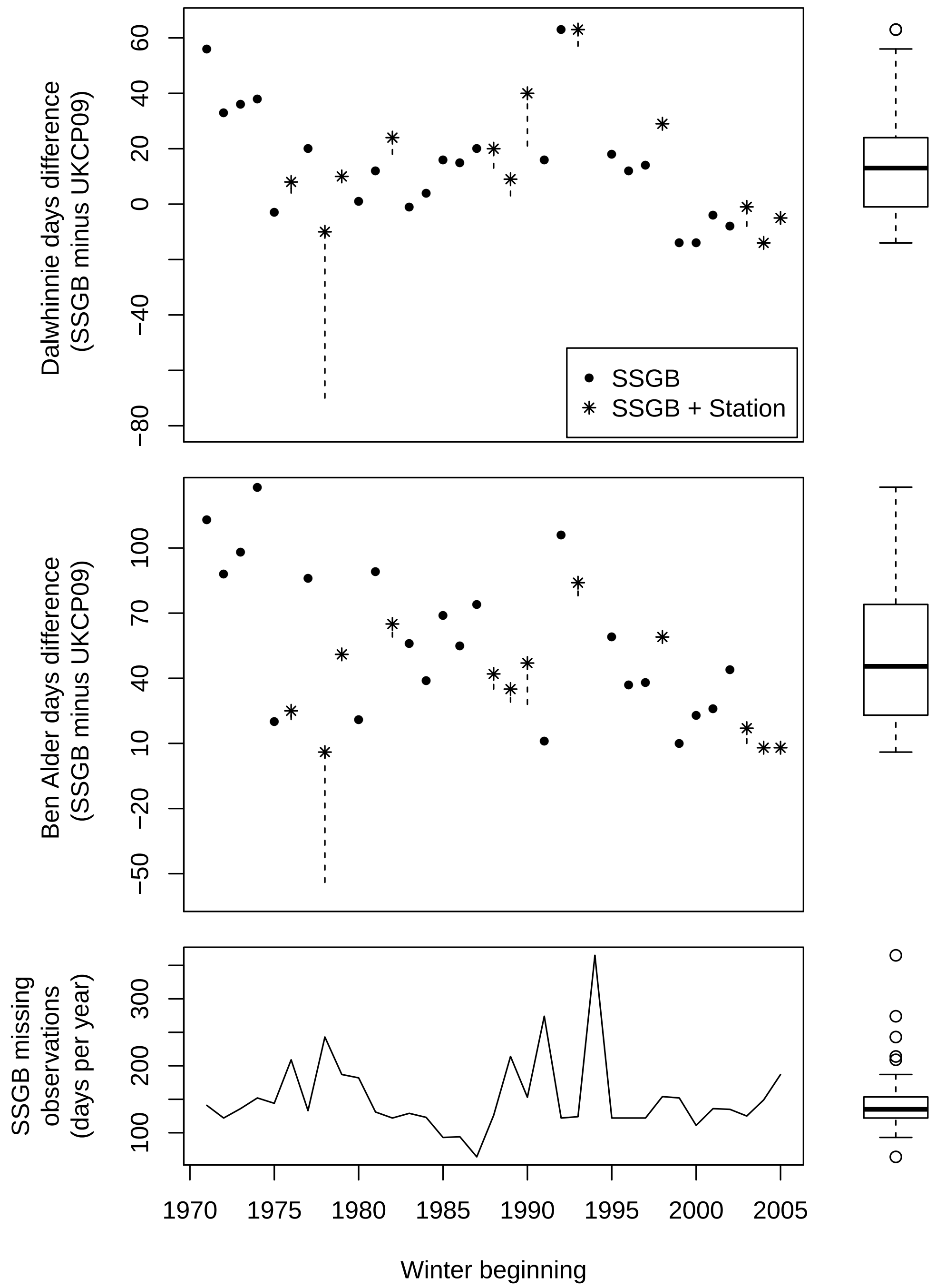


Figure 3.6: *Difference between SSGB and UKCP09 data at Dalwhinnie and Ben Alder, including median and quartiles. SSGB data were selected to match the average elevation of each UKCP09 cell. Where SSGB returns were missing, Met Office station snow data have been added to SSGB records; adjustment is indicated by dashed line from the original SSGB position to the revised value, marked by an asterisk. Numbers of missing values for the SSGB are also shown.*

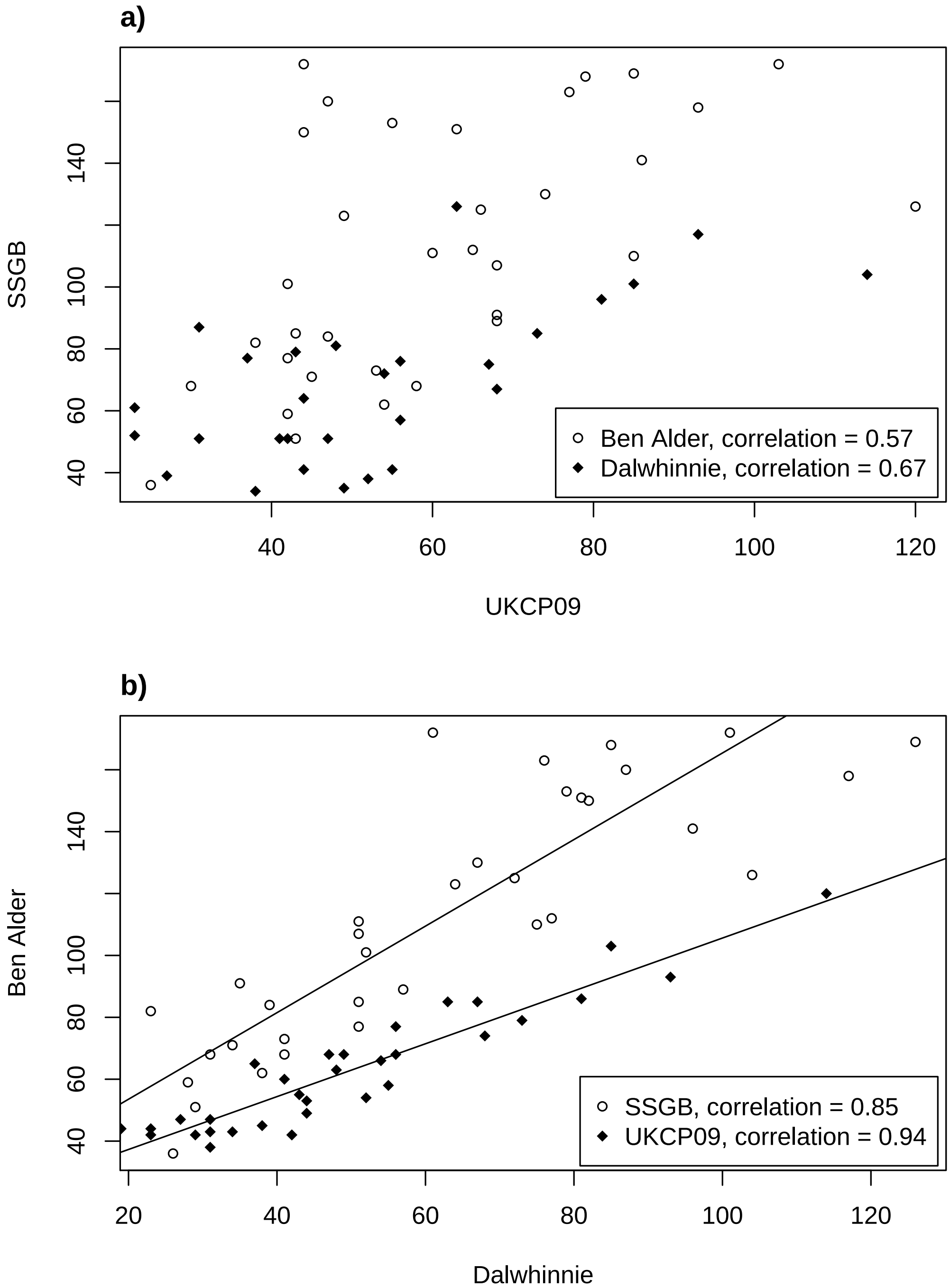


Figure 3.7: *a) Comparison between UKCP09 and SSGB numbers of days of snow lying per snow year for each site. b) Comparison between sites for UKCP09 and SSGB numbers of days of snow lying per snow year.*

in a dataset when the grid cell covers an area with a large elevation range. This is reinforced by the small difference in number of days with snow lying between Ben Alder and Dalwhinnie as given by the UKCP09.

3.4 UKCP09 temperature compared to station data

UKCP09 gridded temperature data are interpolated from Met Office station observations, but these stations are unlikely to represent the average elevation in a grid cell and often do not record the entire period for which UKCP09 data are available. Table 3.4 compares nine, predominantly high altitude, Met Office stations to their corresponding cells in the UKCP09 temperature grid. Pearson correlations are all strong, a minimum of 0.95, with no obvious relationship to elevation difference between cell mean and station. This lack of relationship is also true for linear regression model slope and intercept. However, line slope was expected to negatively correlate to elevation difference; i.e. the lower the cell elevation when compared to station elevation the higher the temperature. These results could be due to such a small sample size or possibly due to elevation correction during the interpolation process. Differences between Met Office station observations and UKCP09 cells are within 10%, and so for use as a temperature input for snow accumulation and melt modelling these data are deemed appropriate.

3.5 MODIS compared to SSGB

The SSGB stopped collecting data in 2007 and with a largely automated network of meteorological stations there is no longer any Scotland-wide ground-based collection of snow cover data. One potential option is to use remotely sensed data, as discussed in Section 2.4.3. Here I test the efficacy of the MODIS snow cover dataset against SSGB. To do this, SSGB stations which recorded during MODIS operation (2000-02-25 onwards) were selected (Figure 3.8). As can been seen (Figure 3.8a) the overlapping time period is short, with many of the 21 stations only recording for part of the 1999 to 2007 period. However, a range of elevations is covered, particularly the 300 to 600 m bands and the stations are spread across Scotland (Figure 3.9).

The SSGB and MODIS datasets describe different things: the SSGB notes the snowline visible from a single ground based point and the MODIS dataset used

Table 3.4: *Correlation and regression line parameters, which compare daily temperature data from UKCP09 and Met Office stations.*

Met Office Station	Met Office Station altitude (m)	Mean UKCP09 5 km cell altitude (m)	Opened	Closed	Correlation	Intercept	Slope
Knockanrock	244	259	1963	1998	0.95	0.07	0.87
Inverailort	2	236	1944		0.98	0.01	1.02
Dalwhinnie	351	426	1973		0.98	-1.70	0.98
Cairngorm chairlift	663	559	1980		0.95	-0.65	0.98
Corgarff, castle lodge	400	538	1972	2002	0.98	-0.90	0.98
Braemar	339	479	1856	2005	0.98	-0.66	0.99
Fealar lodge	560	697	1963	1996	0.97	-4.08	1.01
Eskdalemuir	236	326	1908		0.98	-0.58	0.98
Ledmore	160	266	2000		0.96	-0.80	0.92

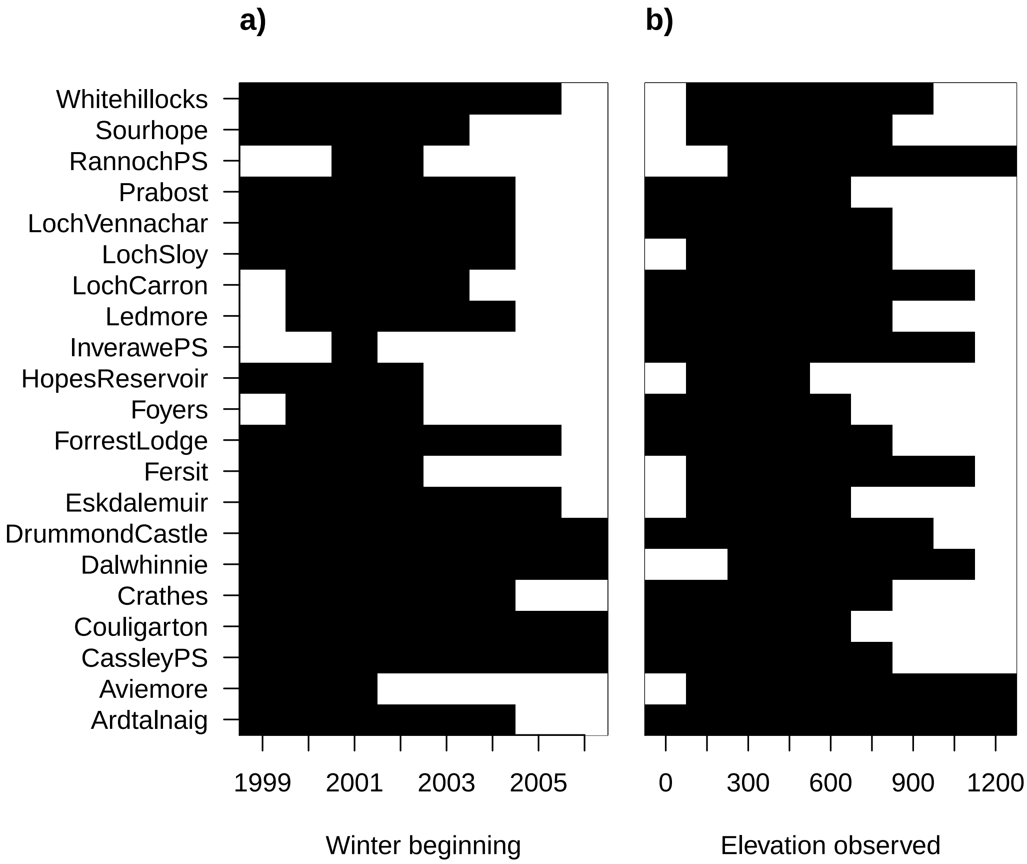


Figure 3.8: *a) SSGB stations with data overlapping the MODIS record. b) Elevations visible from available SSGB stations.*

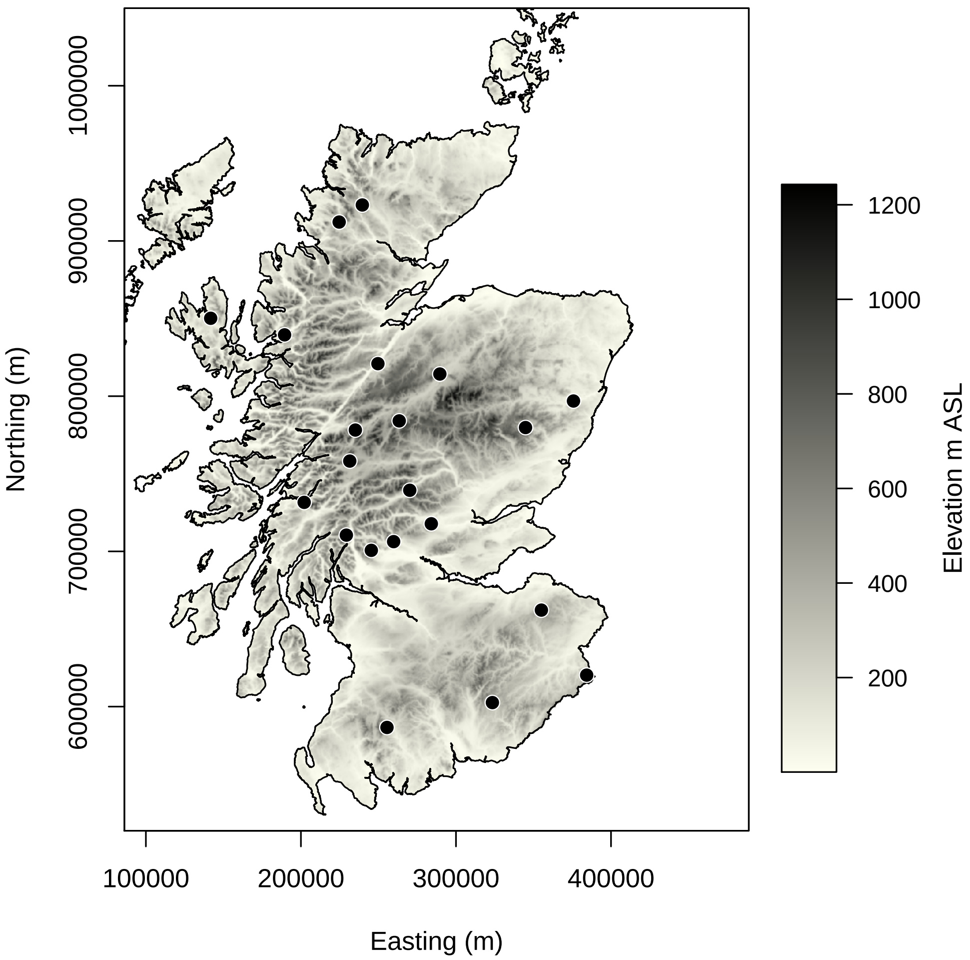


Figure 3.9: *Location of the SSGB stations (black circles) which were compared to the MODIS snow cover dataset.*

classifies grid cells as snow covered or other (e.g. cloud, water, no snow[2]). In order to reconcile these observation differences, SSGB station viewsheds were split into SSGB elevation envelopes (150 m). Processed MODIS data (as described in Section 2.4.3) were sampled for each day and each elevation envelope at each SSGB station, resulting in a percentage area value returned for each variable in an envelope, e.g. 45% snow cover; 50% cloud, 5% no snow. SSGB observations were reduced to three classes in each elevation band: "Snow", "No snow" and "Cloud". To see how well existing MODIS observations can predict snow cover a machine learning decision tree was constructed. The C4.5 method (Quinlan, 2014) was used to construct the decision tree because of its fast computation time and simple scripting. The decision tree was implemented using the C50 package (Kuhn et al., 2015) in R, which is an updated version of the original Quinlan (2014) C4.5 method. The decision tree was trained on data between 2000-02-25 and 2004-12-31 and tested on data after this, giving a training set of 84597 observations and a testing set of 14912 observations. For simplicity, no boosting was applied to the model. The resulting decision tree from this classification is shown in Figure 3.10. Note that while the model was asked to classify observations as cloud, it was unsuccessful because there were few SSGB observations of cloud.

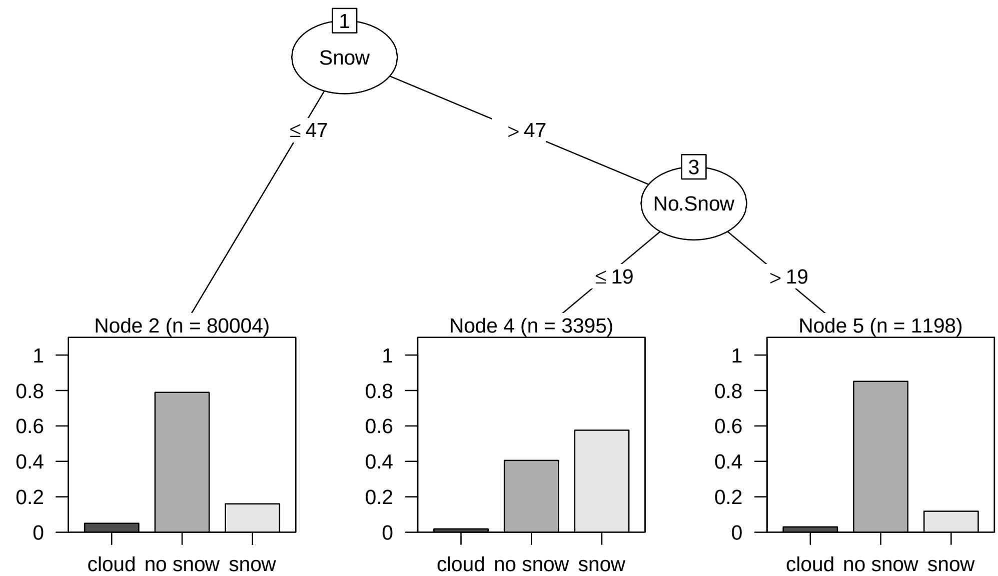


Figure 3.10: *C5.0 decision tree structure to classify snow presence from MODIS observations, when compared to SSGB observations. The bar charts show the proportion of SSGB observation types for each branch, during the model training. Node 2 and 5 correspond to no snow present and node 4 to snow present.*

[2]For a full list see http://nsidc.org/data/docs/daac/modis_v5/mod10a1_modis_terra_snow_daily_global_500m_grid.gd.html

During the model training run the decision tree was correct 78% of the time. The bar charts in Figure 3.10 show that the majority of misclassification came from the presence of snow. Overall in the training run, SSGB observations of snow were misclassified 42% and no snow 21%; 5% of the SSGB observations were of cloud. The decision tree performed slightly better during the testing period, matching the SSGB observations 81% of the time. Table 3.5 shows a confusion matrix between the model predictions and SSGB observations for the training dataset.

Table 3.5: *Confusion matrix of SSGB observations (rows) and MODIS classified by machine learning (columns) daily observation counts.*

	Cloud	No snow	Snow
Cloud	0	4062	64
No snow	0	64175	1376
Snow	0	12965	1955

A final consideration, for MODIS efficacy, is observations during summer months, when the SSGB did not record. Table 3.6 shows broad summer period (JJAS) counts of daily snowline between the dates 2000-02-25 to 2014-12-16; cloud cover is the most prevalent observation. However, the number of days with a snowline recorded is far in excess of expectations; anecdotally I expected 0 to 5 days with snow at higher elevations during summer months in a 15 year period, with 0 days at lower elevations (600 m and below). This is supported by annual snow patch counts where approximately six patches remain until the next winter, with patch sizes around 100 m^2. The results from Tables 3.5 and 3.6 should be read in conjunction, leading to the conclusion that MODIS snow cover observations are not yet a suitable replacement for ground observations of lying snow in a temperate, cloudy and mountainous environment. Details of previous research on satellite snow cover efficacy in a areas similar to the Scottish mountains can be found in Chapter 1.

It would be of value to further explore methods for using MODIS observations in snow covered areas with a cloudy temperate climate like Scotland. Environments like these are unlikely to commit resources to undertake large scale ground monitoring of snow as cover is often short-lived. Notarnicola et al. (2013) have classified raw MODIS data to a 250 m grid of snow cover in the European Alps. They use an algorithm which exploits the 250 m resolution bands of MODIS in the red (B1) and infrared (B2) spectrum, with the Normalized Difference Vegetation Index (NDVI) for snow detection. Clouds are classified using bands at 500 m and 1 km resolution, which could be adapted for Scotland; although cloud is likely to present a bigger challenge in Scotland than the European Alps.

Table 3.6: *Total counts of Jun, Jul, Aug and Sep observations from MODIS cells (years 2000 to 2014) overlapping with SSGB stations shown in Figure 3.8.*

Elevation (m)	Days of snow cover
0	232
150	229
300	233
450	261
600	96
750	66
900	42
1050	15
1200	1
Cloud	27130
No snow	10125

3.6 Bonacina comparison to SSGB

The Bonacina snowiness index is a subjective record describing winters over all of Great Britain; here I present how that compares to the SSGB to help to understand the Bonacina dataset's relationship to snow in mountain areas of Scotland. The snow elevation curves presented in Section 3.2 are here subset by Bonacina category: Very snowy, Snowy, Average and Little (Figure 3.11). As can be seen (Figure 3.11), there is a marked difference between the Very snowy and Little categories, but the Snowy and Average groups overlap. This is likely caused by a bias in the distinction between Average and Snowy winters towards areas of higher population, i.e. central and southern England, whereas further north and at higher elevations these periods would usually already be cold enough for snow to accumulate. The Bonacina index remains useful for its long record and simplicity, but note the likely limitations for its representation of higher elevation snow cover.

3.7 Mar Lodge water balance

To help understand the error associated with using CEH GEAR precipitation data in snowmelt modelling, a water balance was undertaken in the River Dee catchment (Aberdeenshire) at Mar Lodge. Aggregated CEH GEAR data were used, as described in Section 2.4.7, as this 5 km grid size was used for snowmelt modelling. The 5 km grid cells are displayed over the River Dee catchment and river network in Figure 3.12. Daily data from each contributing GEAR cell were multiplied by the cell area to get

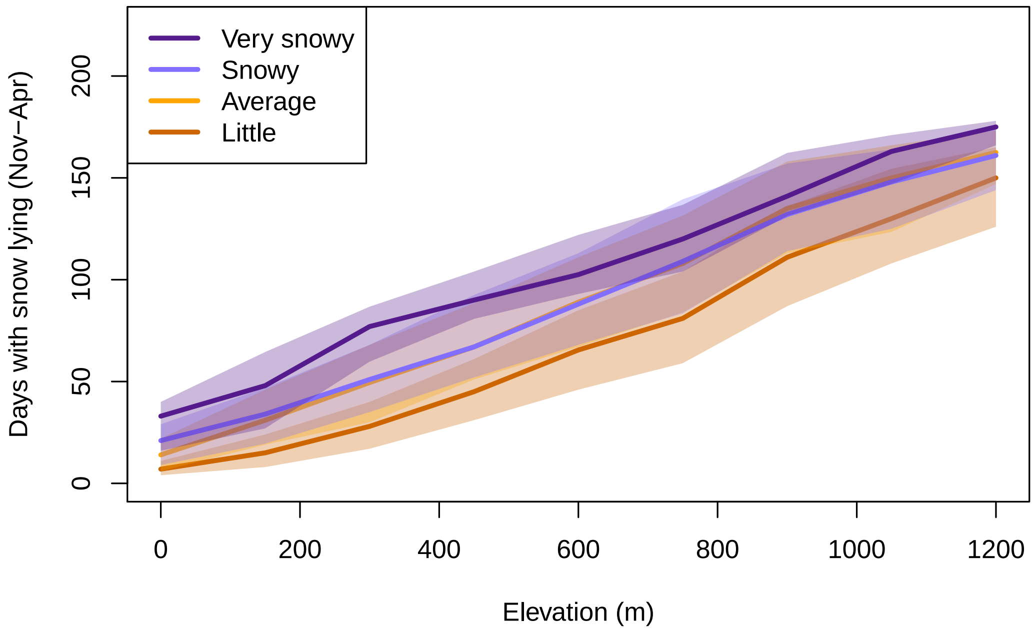


Figure 3.11: *Snow elevation curves derived from SSGB data split into Bonacina snowiness categories. Shading indicates bounds of 25th and 75th percentiles with solid lines representing the median.*

a volume of contributed precipitation. Daily flow data from the NRFA (Section 2.4.6) and CEH GEAR contributing precipitation were summed over water years (October to September); yielding a complete series from water years beginning 1982 until 2011, of input precipitation and output flow. Summing data to a water year, rather than a shorter time scale, will almost eliminate error from water stored as snow during the winter; although there are a number of small areas of semi-perennial snow in the top of the River Dee catchment (Watson and Cameron, 2010) these are insignificant over a large catchment at an annual scale. Note that there is negligible abstraction, but water is expected to be lost to evapotranspiration and groundwater.

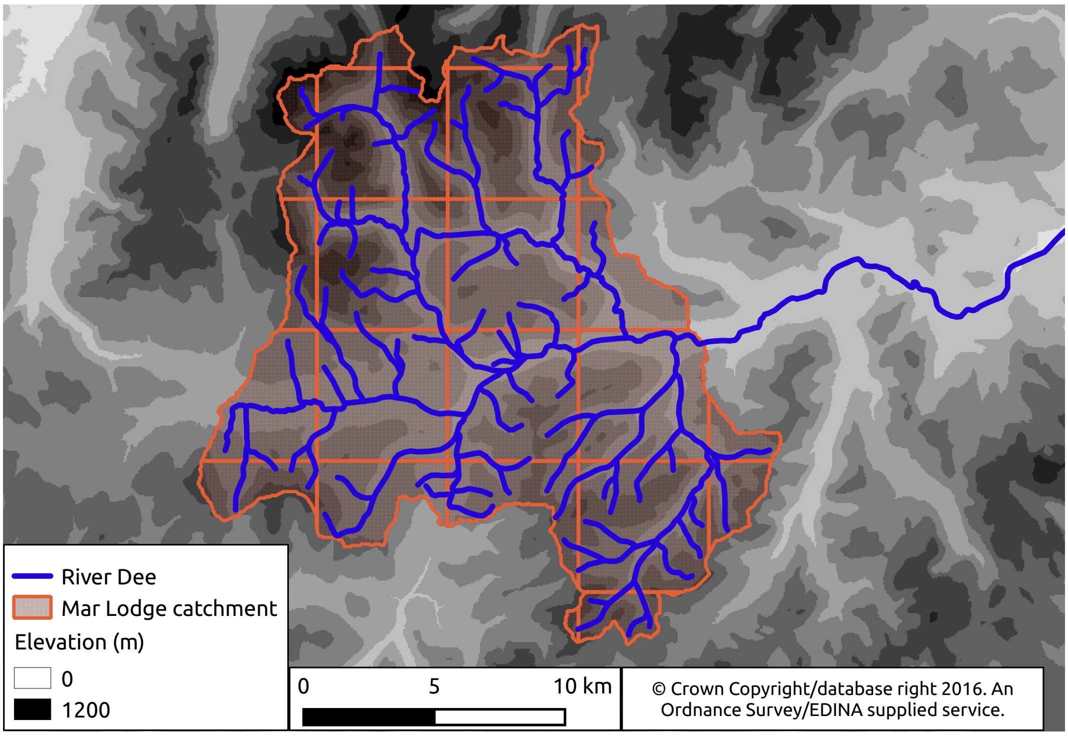


Figure 3.12: *The River Dee and tributaries for the catchment at Mar Lodge, overlain with 5 km grid cells from UKCP09.*

The annual precipitation and flow data for Mar Lodge were compared (Figure 3.13). Figure 3.13a shows GEAR precipitation slightly higher than observed flow: the median precipitation is 106% of flow. Evapotranspiration has been estimated using the method shown in Figure 3.14, which is taken from Kay and Davies (2008). Analysis was completed at a monthly time step and summed to give an annual value for each grid cell. Input data were taken from UKCP09 monthly average temperature grid cells, using the 22 cells which fell within the Mar Lodge catchment. The range of annual evapotranspiration for the Mar Lodge catchment is from 300 to 410 mm/yr with a median of 360 mm/yr; the median is equivalent to 27% of the median annual river flow. If we assume there is some loss to groundwater, and given the precipitation value would include evapotranspiration this 27% is broadly comparable with the figure of 18.5% which Ferrier et al. (1990) calculated for the Allt a'Mharcaidh catchment on the west of the Cairngorms. When the median annual evapotranspiration is subtracted from precipitation, annual effective precipitation is a median 83% of annual river flow. This difference does not include groundwater interaction and is marked, but it is noted that this analysis is for *potential* evapotranspiration only and individual years will likely vary. Assuming the flow series is more reliable than precipitation, the discrepancy is likely attributable to an underestimation of precipitation at higher elevations. The reasons for this include: the GEAR dataset derivation method made no orographic rainfall enhancement, interpolation from low elevation stations, and an under-catch of solid precipitation when it occurs. Flow and precipitation are plotted, coded by colour for number of days per year below 0 °C (Figure 3.13b), to see if larger discrepancies occurred in winters with potentially higher snowfall. These were assumed to be related to the number of days below 0 °C; there is little evidence of a trend, meaning that snow is unlikely to be a primary cause of the mismatch in water balance. Another source of extra water in the catchment is from wind redistribution of snow off the Cairngorm plateau, but at an annual scale in a 289 km ^{2} catchment this seems unlikely to be the source of the large difference previously noted.

I have shown that the CEH GEAR dataset likely underestimate the volume of precipitation falling at higher elevations in a catchment on the east of the Cairngorm plateau. It would be of considerable value to repeat this water balance experiment for other gauging stations across Great Britain to determine if the bias in GEAR is systematic and can be corrected by an elevation and/or spatial multiplier. Work like Herrnegger et al. (2015), where they estimated precipitation from runoff, could also be used to derive a correction factor for CEH GEAR precipitation. These methods should be used in conjunction with observed precipitation lapse rate data from studies like Ballantyne (1983), who summarise precipitation increases in the Scottish Highlands as 2.81 mm/m on western slopes and 0.88 mm/m on eastern slopes. Ballantyne (1983) also undertook an experiment on An Teallach in NW Scotland (September 1976 to August 1979), with gauges at three locations between 468 and 671 m ASL on NE facing slopes compared to a low level site at 23 m ASL. A linear fit between the lowest site and highest gives an increase of 2.67 mm/m in precipitation. However, when all four elevations are considered, precipitation-increase appears to increase with elevation. Snow fall was included in these measurements, in all but one period (January to May 1979) when the gauge overflowed and the measurement was lost.

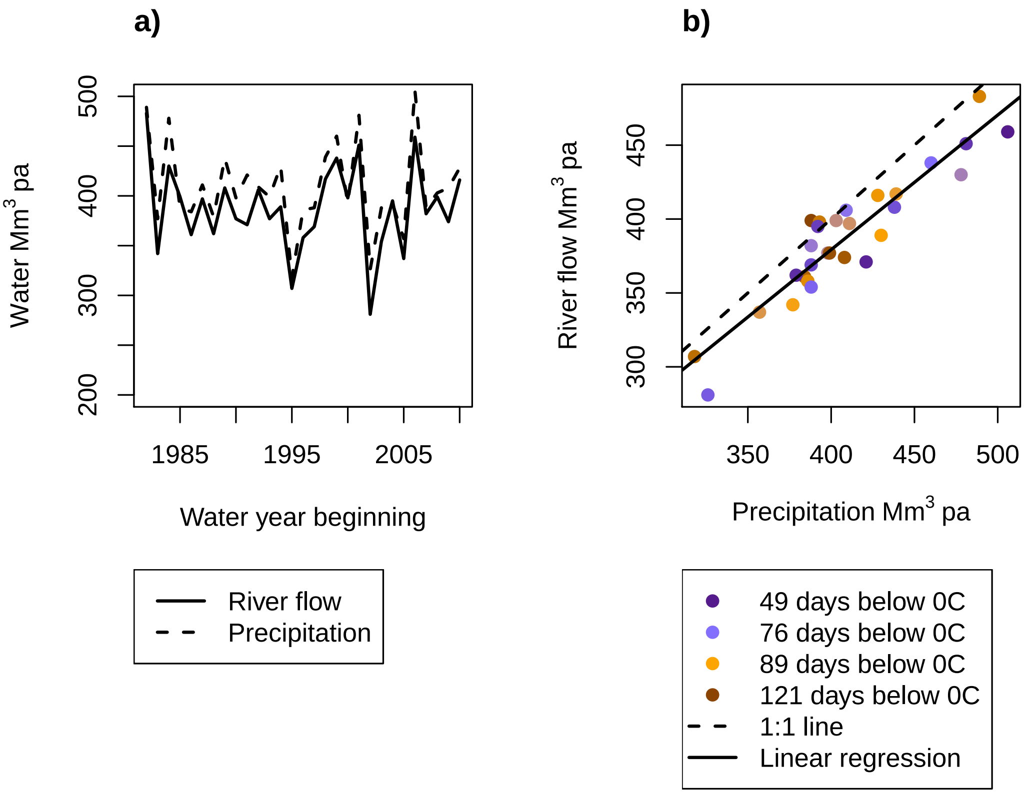


Figure 3.13: *a) River Dee flow as recorded at the Mar Lodge gauging station and precipitation taken from CEH GEAR data. b) River Dee flow at Mar Lodge against CEH GEAR precipitation, colour coded by the number of days below 0 °C each year.*

2.1.2 Temperature-based PE

The simple, temperature-based (T-based) PE formulation suggested by Oudin *et al* (2005), based on a study of the performance of over 25 existing PE formulations when used as input to four different hydrological models for over 300 catchments, is given by:

$$PE_T = \frac{R_e}{\lambda \rho_w} \frac{T_a + 5}{100} \qquad \text{if } T_a + 5 > 0, \qquad (2)$$

$$PE_T = 0 \qquad \text{otherwise,}$$

where λ and ρ_w are as in section 2.1.1, R_e is extraterrestrial radiation (J/m^2/s), which is dependant on latitude and Julian day only (see Allen et al. 1994), and T_a is the mean daily air temperature (°C), giving PE_T in units of m/s. Although this formulation was developed for use with (long-term) mean daily data, there is evidence that monthly data can be used in models similar to this to compute monthly PE_T, without significantly affecting results (Federer et al. 1996). Note that this T-based PE formulation does not allow negative values for PE, however the Penman-Monteith formulation can result in negative values. Here, all negative PE values have been reset to zero.

Figure 3.14: *Taken from Kay and Davies (2008): describing a method to estimate potential evapotranspiration.*

3.8 Ordnance Survey digital elevation models

As discussed in Section 2.4.8, the Ordnance Survey has two freely available digital terrain models - Panorama and Terrain 50. Some work presented here had been completed prior to Terrain 50 availability, so this section demonstrates that for a national scale the digital terrain models are similar enough. Figure 3.15 presents the difference between the Panorama and Terrain 50 DTMs. Upland areas show the greatest absolute difference but, given their greater elevation, a much smaller relative difference. The differences between the two elevation models are generally confined to ± 20 m, with exceptions like quarried areas that have large changes, e.g. Loch Leven in Fife. Some tiles exhibit a greater difference than others, hence some straight lines in Northern Scotland.

A cross section line is shown on Figure 3.15, across the western Highlands; the elevations along this are presented in Figure 3.16, with a) showing the full section and b) a 5 km highlight. As can be seen, there is little difference between the two digital terrain models, although some horizontal shift is evident. The method Ordnance Survey used to develop these two datasets is a likely cause of differences as the newer Terrain 50 uses a pixel centred value, whereas Panorama took elevation from the edge

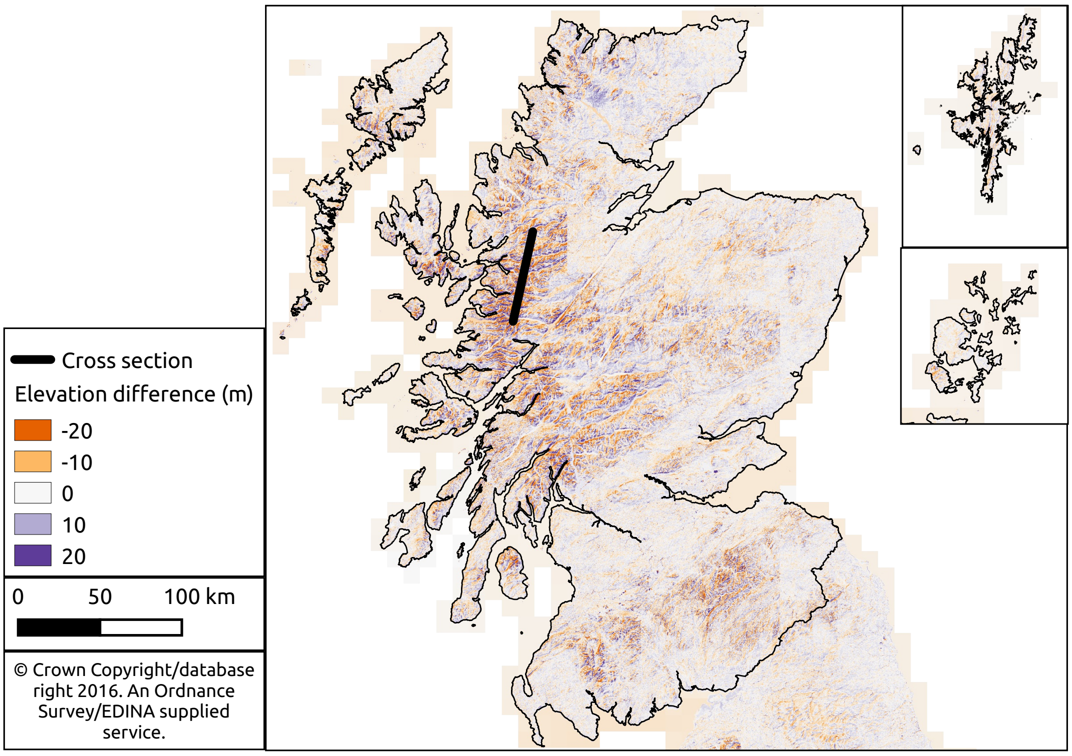


Figure 3.15: *Map of differences between Ordnance Survey Terrain 50 and Panorama digital terrain models.*

of each cell[3]. There should also be an improvement in survey accuracy since the Panorama dataset was constructed, hence some differences with the Terrain 50. Given that Terrain 50 is a maintained data product and Panorama is not, Terrain 50 should be used on new projects, but it does not appear that the difference between these datasets is large enough to warrant re-analysis of previous work.

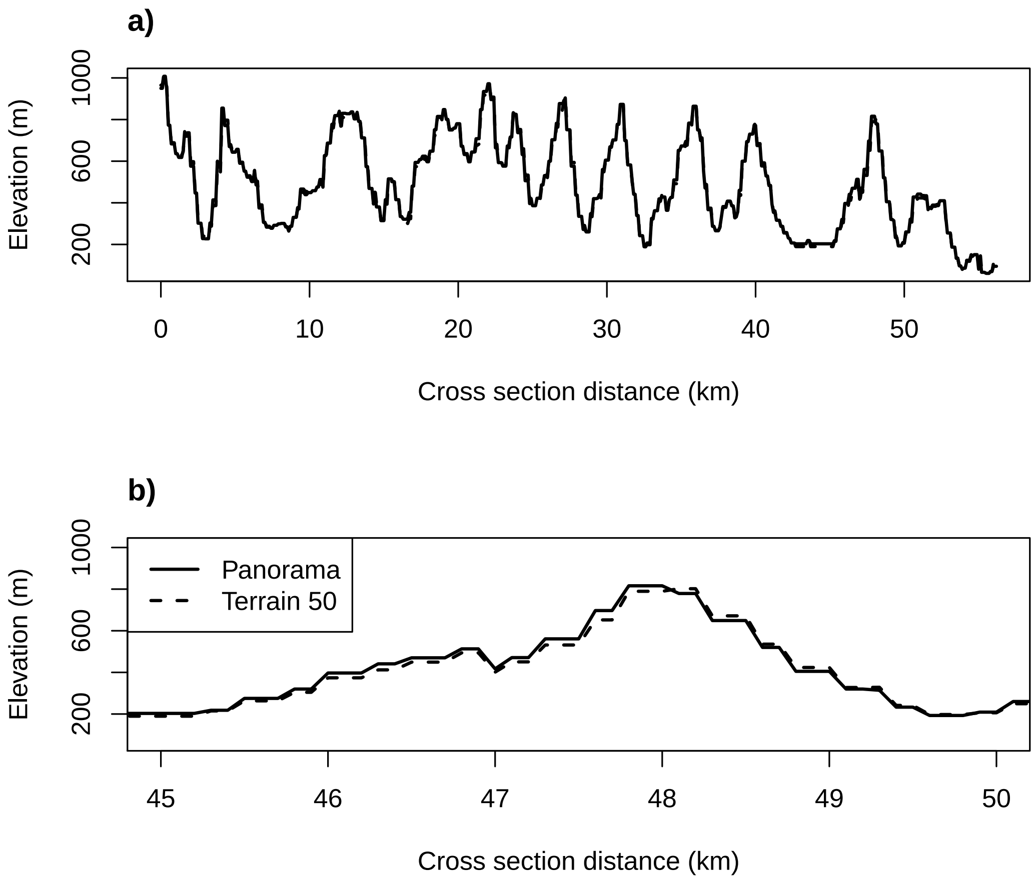


Figure 3.16: *a) Full and b) highlight of a cross section over Ordnance Survey digital terrain models.*

[3]https://www.ordnancesurvey.co.uk/business-and-government/help-and-support/products/terrain-50.html see FAQ 9

CHAPTER 4

Relationship between snow cover and the North Atlantic Oscillation index

Author Contributions: The majority of the work presented in this chapter has been published with Richard Essery as a co-author (Spencer and Essery, 2016). Essery contributed minor edits to the publication.

4.1 Introduction

The North Atlantic Oscillation (NAO) index is the normalised pressure difference between the Icelandic low and the Azores high (Walker and Bliss, 1932). During winter months positive NAO phases are typified by strong westerly winds carrying moist warm air from the Atlantic, with negative NAO phases bringing colder air masses from the east (Hurrell, 1995; Simpson and Jones, 2014). Logically then, the NAO index could indicate the duration of snow cover in Scotland 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) show 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 below 300 m to be significantly negatively correlated with NAO index (-0.55 to -0.44, $p<0.05$), with lower elevations having a stronger relationship. Trivedi et al. (2007) also found no correlation between NAO index and falling snow. This could be 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. Another explanation could be that during a negative phase NAO there is less total precipitation, but a higher proportion of snowfall, meaning the quantity of snowfall stays approximately the same. 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 winter NAO index in 2009 to 2010 (Osborn, 2010). The 2009/10 low occurred the same year as an exceptionally cold and snowy winter in the UK (National Climate Information Centre, 2010; Prior and Kendon, 2011). Goodkin et al. (2008) link variability in the NAO index to northern hemisphere mean temperature and state that any future predictions should take this into account. The mean winter (DJFM) NAO indices are shown in Figure 2.9.

The UK Met Office is beginning to forecast seasonal NAO indices more successfully (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) give a correlation value of 0.62 (significant at 99%) between forecast and observed DJF NAO indices for the years 1993 to 2012.

This chapter aims to quantify the relationship between Scottish snow cover and the NAO index. I establish this by looking at nationwide snow cover datasets, before further investigating relationships at a hillslope scale, using case studies with more detailed data available. This chapter is laid out as follows: data and methods, results, and discussion. The methods and results sections are split by dataset.

4.2 Data and methods

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. I solved this by using a count of the days of snow cover during a given time period, defining a winter period for snow cover as November to April to help differentiate the snowiest winters, while being short enough to not discount many SSGB records, as some are missing (Spencer et al., 2014). A short winter period (e.g. DJF) would mean, particularly at higher elevations, a sum of days with snow lying would result in saturated counts of snow cover duration. For example, 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; so, choosing a shorter observation period means there is little or no distinction between an average winter and a very snowy one. Using a six month period will help identify the snowiest winters, where greater snow depths take longer to melt. Data used for this chapter are shown in Table 4.1. This section details the methods used to compare each data source to the NAO.

4.2.1 Bonacina

Mean DJFM NAO index values are grouped by Bonacina categories. The differences between groups of the NAO index are compared visually using boxplots (Figure 4.1) and statistically using ANOVA and Tukey honest significant differences (HSD) (Yandell, 1997) tests, the latter to account for family-wise analysis (Table 4.2).

4.2.2 UK Climate Projections 2009 (UKCP09)

The November to April sums of days of snow cover from UKCP09 are compared to the mean DJFM NAO index using a Pearson correlation. The resulting Pearson correlation is plotted (Figure 4.2) to show spatial patterns.

Table 4.1: *Data sources of snow cover and NAO index.*

Name	Abbreviation	Reference	Type	Time span
Bonacina snowiness index	Bonacina	O'Hara and Bonacina (Undated)	Classification of snowiness of UK winter	1875 onwards
UK Climate Projections 2009 snow lying grid	UKCP09	Perry and Hollis (2005)	Interpolated grid of UK Met Office station data (days per month)	1971 - 2006
MODIS satellite snow cover, daily L3 500m 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

4.2.3 SSGB

SSGB stations which recorded all months between November and April are used in this chapter. The number of valid stations per year is shown in Figure 3.2.

Snow accumulation curves, as shown in Section 3.2, are used and split by NAO index (Figure 4.3). 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 six 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 Table 4.3 and their location in Figure 4.4. 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 the relationship between snow cover and NAO. The groups of stations in Table 4.3 are compared to the NAO index using a high and low elevation split (at 750 m) and Loess (locally weighted scatterplot smoothing) (Cleveland, 1979; Cleveland and Devlin, 1988) with 95% confidence limits (Figure 4.5 and 4.6).

Stations from Table 4.3, judged by eye to have a Loess close to a straight line, are plotted in Figure 4.7 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.

4.2.4 Moderate-resolution Imaging Spectroradiometer (MODIS)

MODIS data from April to November each year were summed and correlated against the mean DJFM NAO index, presented in Figure 4.8a. Figure 4.8b shows the same analysis, repeated for cloud cover observed by MODIS.

4.2.5 Spatial scales 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 4.4.

4.3 Results

4.3.1 Bonacina

Figure 4.1 shows boxplots of the difference between DJFM NAO indices as grouped by the Bonacina classification. A general trend can be seen where less snowy winters have a more positive NAO index. This is demonstrated statistically using ANOVA (F value = 25.07) and a Tukey HSD analysis (Table 4.2) 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 result of the Very Snowy small sample size, for which the Tukey HSD test performs less well.

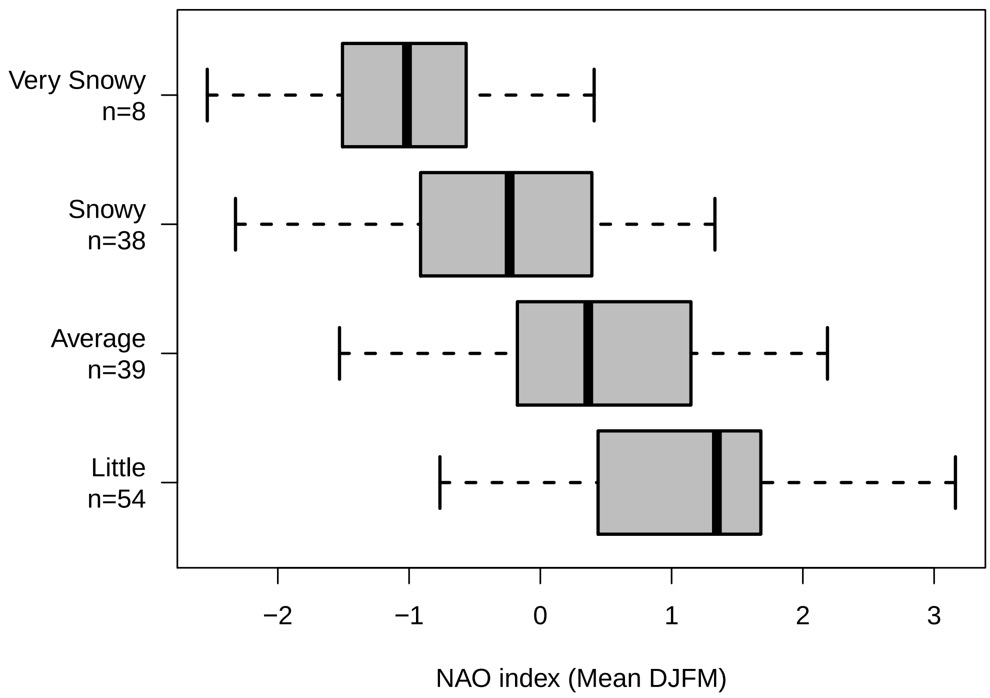


Figure 4.1: *Boxplots (median, upper and lower quartiles and range) showing winter NAO indices grouped by Bonacina snowiness categories.*

4.3.2 UKCP09 snow

Figure 4.2 shows UKCP09 snow cover correlated with NAO across Scotland; some of these areas are strongly negatively correlated. The strongest correlations are in the

Table 4.2: *Tukey HSD difference in medians of NAO indicies 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

south west and along the east coast. Areas of poor correlation are predominantly in central and northern mainland Scotland and Orkney. There are two small areas of stronger correlation near Inverness and east of Skye. Some of the poor correlation areas coincide with areas with few Met Office stations, notably northern Scotland. However, data paucity is not an issue for Orkney and central Scotland. Perhaps snow cover in these regions is much more affected by local weather systems than other areas. Local weather systems could be effected by the presence of open water (e.g. Loch Lomond). The higher mountains in central Scotland are likely to remain cold enough for snow to accumulate and linger, whatever the phase of the NAO index; thus rendering them less susceptible to changes in NAO index.

4.3.3 SSGB

Table 4.3: *Longest, eastern and Orkney SSGB stations details.*

Station	Easting	Northing	Description	Complete winters
Eskdalemuir	323500	602600	Longest	46
Couligarton	245400	700700	Longest	44
Forrest Lodge	255500	586600	Longest	44
Ardtalnaig	270200	739400	Longest	39
Fersit	235100	778200	Longest	39
Drummuir	337200	844100	Eastern	24
Derry Lodge	303600	793200	Eastern	21
Crathes	375800	796900	Eastern	20
Whitehillocks	344860	779790	Eastern	27
Stenness	329800	1011200	Orkney	21

Figure 4.3, 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

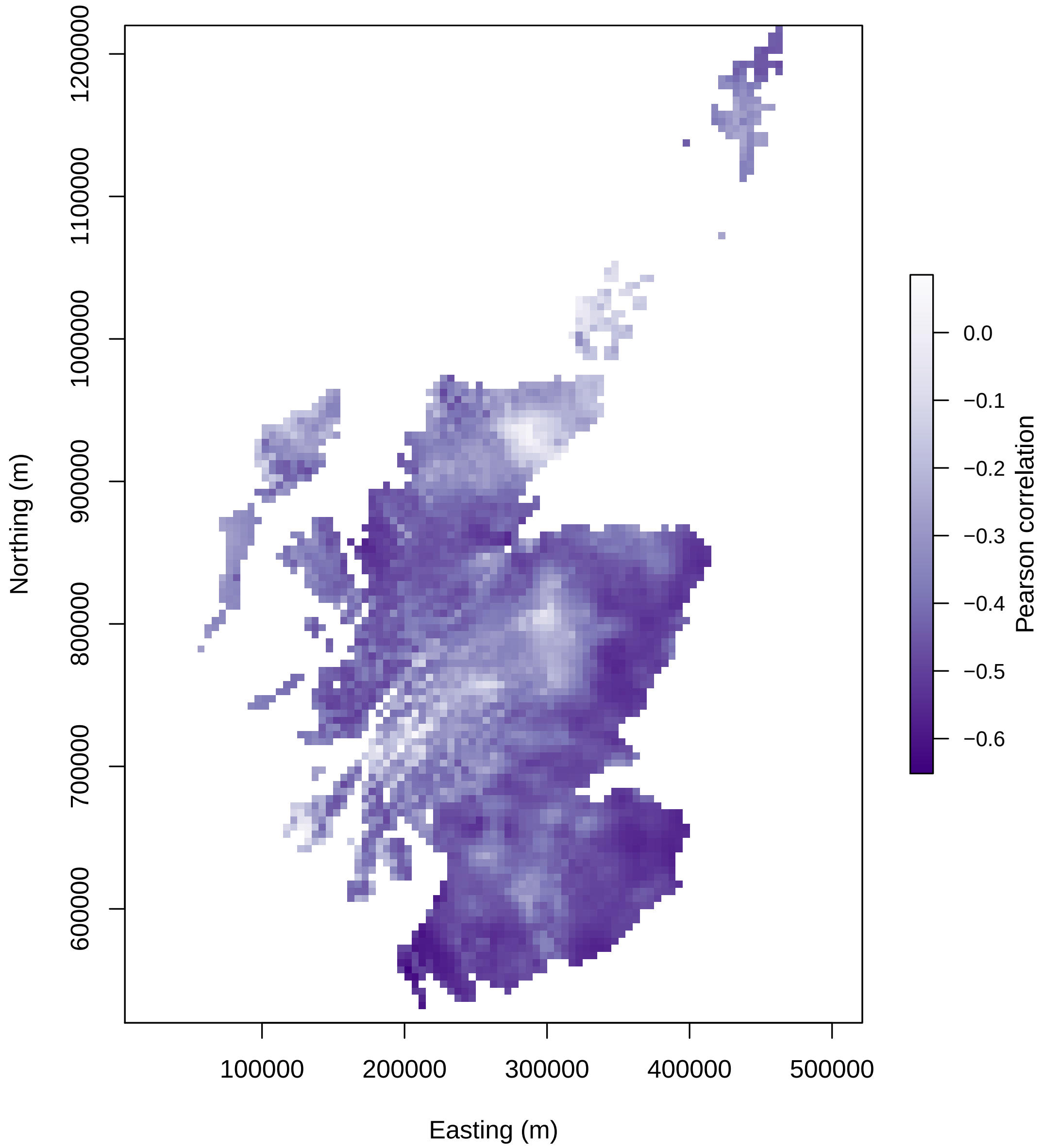


Figure 4.2: *Map of Pearson correlation values between UKCP09 snow and the NAO index, for the period 1971 to 2006. Contains Met Office data ©Crown copyright and database right 2016.*

crossing. This 750 m change-point is used to distinguish between high and low snow cover for the SSGB station analysis.

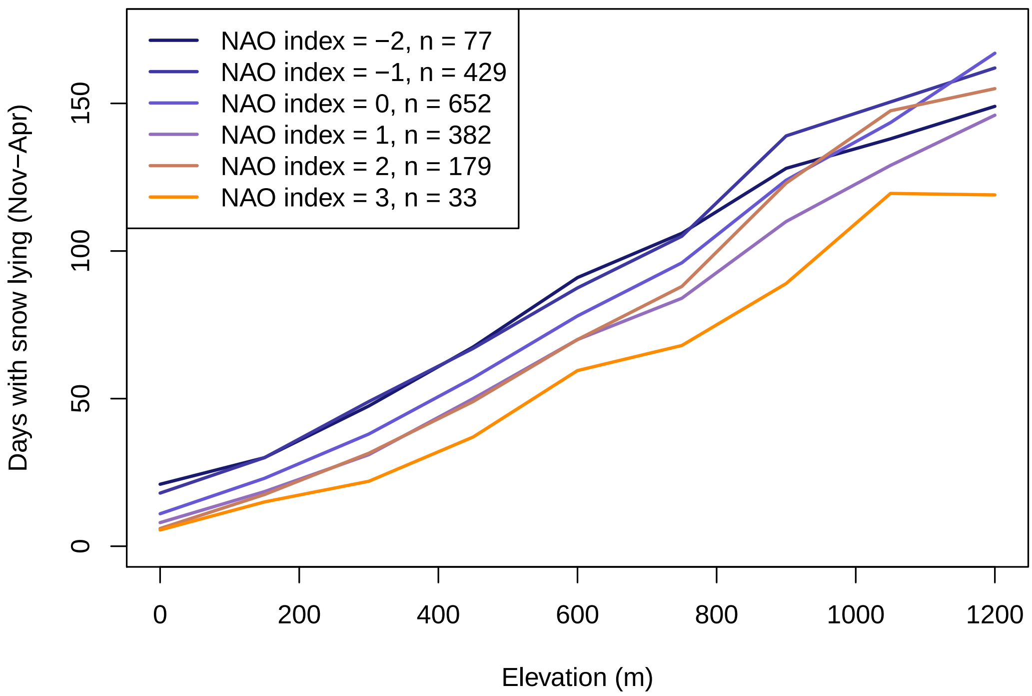


Figure 4.3: *Snow cover duration curves derived from SSGB data between 1946 and 2006 (Nov to Apr), grouped by (rounded) mean DJFM NAO index.*

Individual SSGB stations with the longest record of complete winters and some other stations are considered (Table 4.3). Other stations, in the east and Orkney, were used to investigate the more extreme correlations between the NAO index and UKCP09 snow data (Figure 4.2), accepting that they do not have the longest records. These results (Figures 4.5 and 4.6) corroborate what is shown in the UKCP09 snow results (Figure 4.2); that they all show a negative correlation with the NAO index, with Forrest Lodge, Eskdalemuir and Ardtalnaig showing the strongest correlations. This is repeated in Figure 4.6 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 4.6).

SSGB stations Crathes, Eskdalemuir, Forrest Lodge and Whitehillocks have been plotted with linear regression lines in Figure 4.7. Line slopes vary from -7 to -14 days for higher elevations and from -6 to -16 days for lower elevations. Some results in Figures 4.3 to 4.6 show the NAO index has a larger impact at lower elevations,

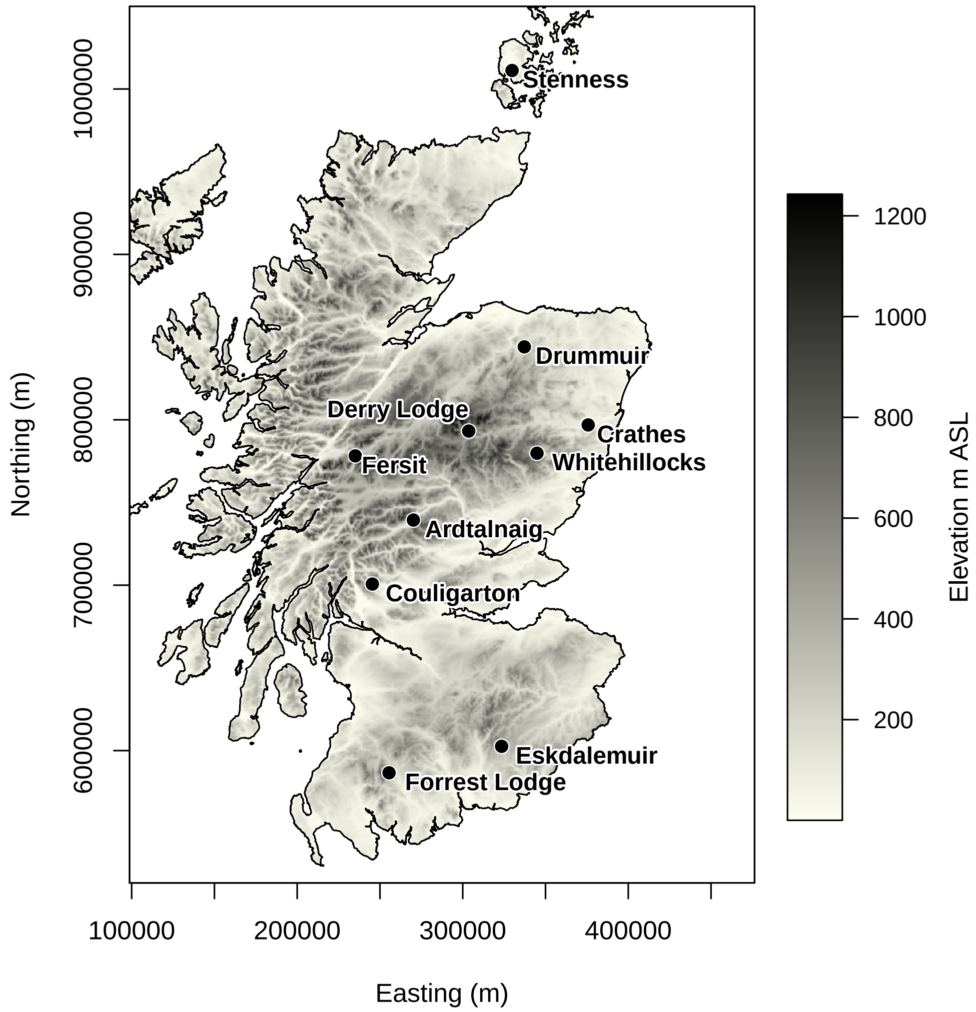


Figure 4.4: *Selected SSGB station locations. Contains Ordnance Survey data ©Crown copyright and database right 2016.*

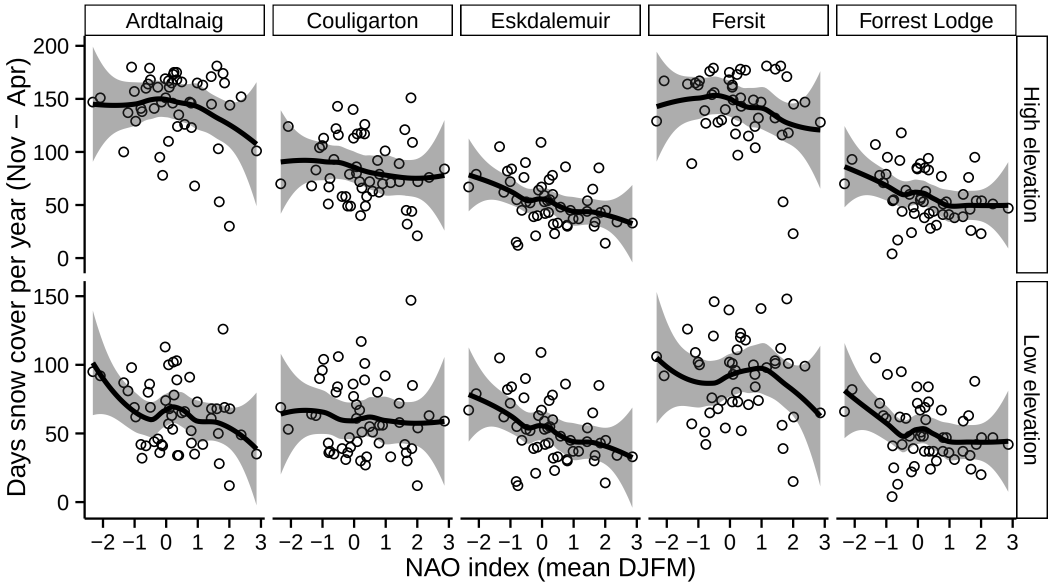


Figure 4.5: *Long-record SSGB stations snow cover plotted against the mean DJFM NAO index, shown with a Loess and 95% confidence bounds.*

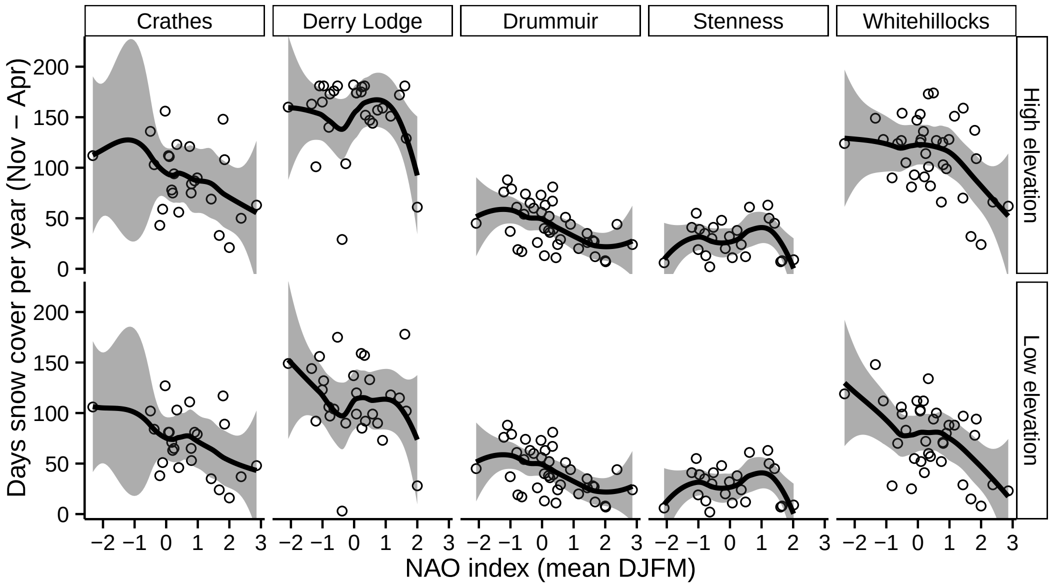


Figure 4.6: *Eastern and Orkney SSGB stations snow cover plotted against the mean DJFM NAO index, shown with a Loess and 95% confidence bounds.*

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 recorded snow cover during the record low NAO index winter of 2009 to 2010.

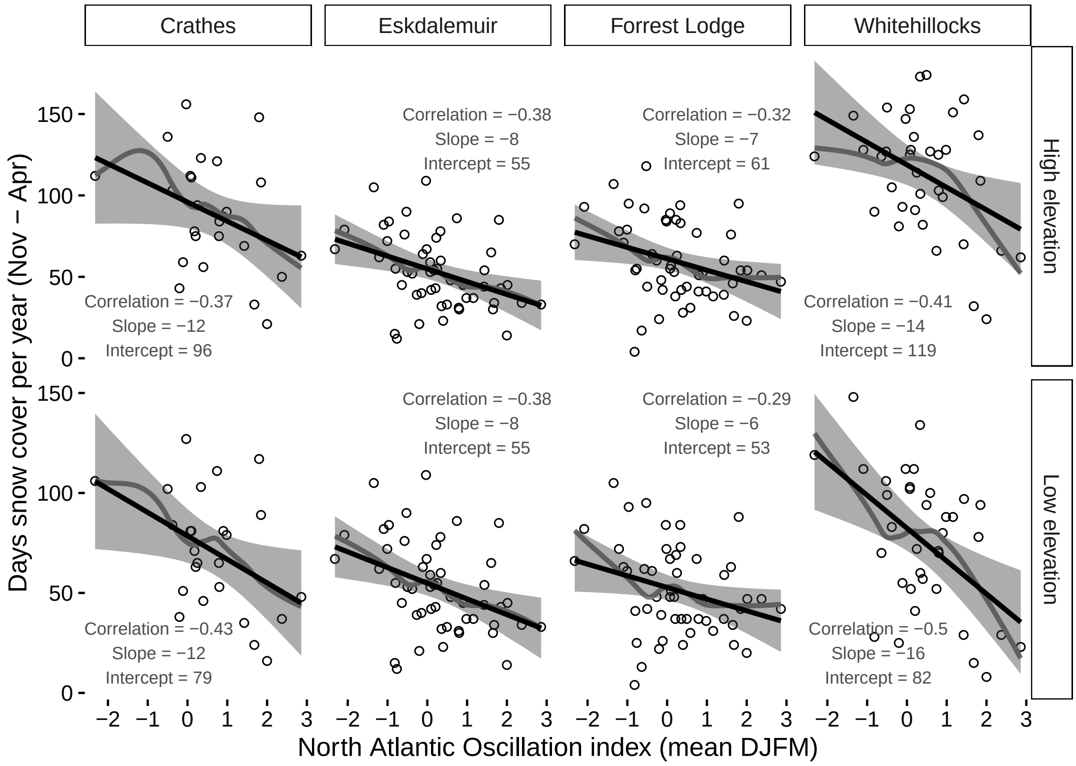


Figure 4.7: *Comparison between days snow cover at select SSGB stations in years that reported all months between November and April and the mean DJFM NAO index. Shown with a linear model with 95% confidence bounds and a Loess (dark grey) for comparison.*

4.3.4 MODIS

Figure 4.8 shows the correlation between NAO index and snow cover (a) and cloud cover (b) from both MODIS satellites; these results were aggregated to a 5 km resolution, to better show correlations. Figure 4.8a 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 Figure 4.1 to 4.7.

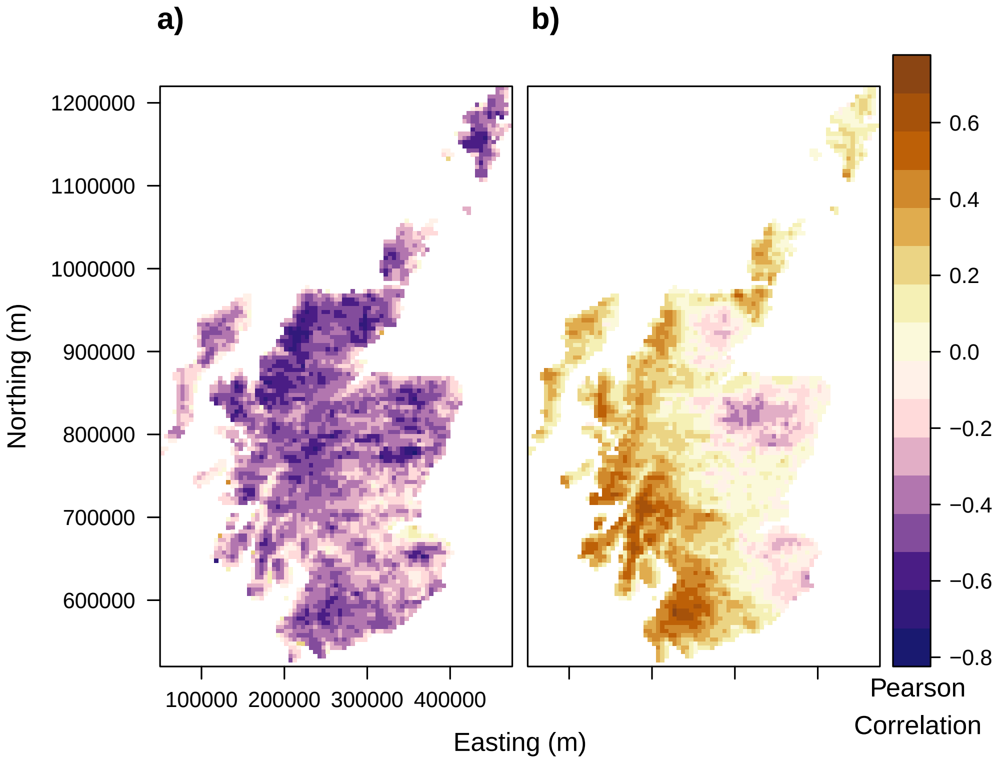


Figure 4.8: *Correlation between number of days of a) snow and b) cloud cover recorded by MODIS each winter (Nov to Apr) and the mean DJFM NAO index.*

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 4.8b, 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 the east of Scotland gets more days of snow cover when there is a negative NAO index, a corresponding increase in cloud cover will obscure snow observations.

4.3.5 Data comparison

A comparison of correlations from different datasets can be seen in Table 4.4. These results are summarised by Pearson correlations between datasets. Correlations between SSGB and UKCP09 are 0.87 and between SSGB and MODIS are -0.07; demonstrating that the SSGB and UKCP09 results corroborate each other, but that MODIS results do not correlate with SSGB results.

4.4 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 methodology is appropriate for analysing the spatial relationship between snow cover and NAO phase at a national scale. SSGB data have shown stronger correlation between the NAO index and snow cover at lower elevations. I believe this is because lower elevations have more transient snow as they are generally warmer than higher elevations, 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 snowiness index correlation with the NAO index (Figure 4.1) as the majority of Great Britain is low lying, so the Bonacina snowiness index is more likely to reflect the more common (lower) elevation zone than more remote mountain areas. The correlations presented in this chapter of NAO index and snow cover are weaker for higher elevations, which are often cold enough for

Table 4.4: *Pearson correlations of snow cover and NAO indices 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

deeper snow to accumulate and take 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 and McCarthy, 2015). Kendon and 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 and 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 areas further from the coast 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 4.7), with Pearson correlation values from -0.29 to -0.5. This range of results could be explained by micro-climates 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 snow driven by wind (predominantly westerly) 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, some may have been more closely correlated with the NAO index than others. The obvious solution is to consider the results from Figure 4.3, which average over a greater number of SSGB stations, helping to reduce uncertainty.

CHAPTER 5

Snow accumulation and melt modelling

5.1 Introduction

The purpose of this chapter is to estimate snowmelt and snow cover, through time, with spatially distributed results. Hydrologically, snowmelt is often incorporated holistically into runoff models with assessment of melt trends and patterns limited by the conceptual model used (e.g. Bell et al., 2016); i.e. if a study looks at the impact of snowmelt on river flows but only calibrates the model on river flows it may arrive at the right answer for the wrong reason and draw the wrong conclusions regarding changes to snowmelt patterns. As discussed in Chapter 1, spatially distributed knowledge of snow cover and melt are important for our understanding of the natural environment, including: extreme hydrological events (Black and Anderson, 1994) and ecology (Helliwell et al., 1998).

Snow cover and melt are popular research topics in cold climates like parts of the United States (e.g. Colorado and Wyoming: Fassnacht et al., 2014), Canada (e.g. Pomeroy et al., 2003) and the Arctic basin (e.g. Lammers et al., 2001) where the hydrological challenge, particularly relating to climate change impacts, is more straightforward (Jefferson, 2011) because snow is the dominant phase of winter precipitation. Few studies consider snow cover and melt in temperate climates and, hence, it is poorly documented.

Methods to estimate snow cover and melt include point observations, inference from other observations (e.g. river flow/runoff), remote sensing and modelling. Point observations, (e.g. Archer, 1981; Hough and Hollis, 1997) are limited as they are often unrepresentative, particularly of higher elevations. Point observations can be interpolated to infill gaps, but they are often on a very coarse grid size (Brasnett, 1999). Archer (1981) compares point and runoff snowmelt estimation in NE England, finding that the former underestimates snowmelt runoff. In Archer (1981) point snowmelt values were derived from data at nine low elevation (<242 m) Met Office sites, using the duration of thaw from a known SWE starting point. The snowmelt runoff estimation in Archer (1981) is based on a network of 25 snow monitoring stations installed in 1979 by the Northumbrian Water Authority. At these, observers recorded daily values of snow depth, density and SWE. Values of SWE and precipitation were compared to direct runoff (i.e. total runoff - base flow) to derive the water released from the snow pack. Snowmelt rates between 12 and 144 mm/day were observed, although it is noted that the separation between rain and snowmelt was difficult. These two approaches are useful, but rely heavily on significant observer time and extrapolation between observation points.

SWE of dry snow can be remotely observed using microwave sensors, but climate and land surface complexities cause large uncertainties (Dong et al., 2005). As discussed in Section 2.4.3, using microwave sensors to observe snow in Scotland is challenging as they find it difficult to quantify wet snow. Foster et al. (2011) produce a blended snow cover product from multiple sources of remotely sensed data, which reduces the weakness associated with individual methods, but it is only available on a 25 km^2 grid.

Another option to quantify snow cover and melt is through modelling; Essery et al. (2013) provide a comprehensive overview. There are two main types of snow modelling: energy balance (e.g. Ferguson and Morris, 1987) and degree-day (also known as temperature index) (DeWalle and Rango, 2008, Chap. 10). Energy balance models are data intensive and hence difficult to use (Bormann et al., 2014) and when Biggs and Whitaker (2012) reviewed the available literature they found temperature index methods more appropriate than energy balance ones over large areas due to the rarity of required data inputs for the latter method. Avanzi et al. (2016) compare a single layer degree-day model (HyS) with a multi-layer energy balance model (Crocus) and find the degree-day model performs comparably well at a daily time step when estimating snow depth, SWE and snow density. Snowmelt models can be calibrated using remotely sensed data (e.g. Clark et al., 2006; Biggs and Whitaker, 2012), but for work in Scotland this has problems previously discussed (Sections 2.4.3 and 3.5). Some early examples of degree-day modelling in the UK include Archer (1983) (Troutbeck, Harwood Beck and Langdon Beck in NE England) and Ferguson (1984) (River Feshie in the Cairngorms, Scotland). These used a lumped model for the whole catchment and included a routing component and compared model output to river flows successfully, but this method neither addresses spatial variations, nor answer questions on snow melt and cover. More recently, Bell and Moore (1999) developed the PACK model, which is essentially a distributed degree-day model with a snow store partitioned between wet and dry. The PACK model was developed for flood forecasting and is now used in G2G (Grid to Grid) by organisations such as the Scottish Environment Protection Agency. In other temperate climates, i.e. Australia, Bormann et al. (2014) have successfully constrained snowmelt results using simulated snow densities in a degree-day model. Martinec and Rango (1986) and Hock (2003) summarise literature on parameters in snowmelt modelling. Martinec and Rango (1986) find degree-day factors (DDF), which govern the rate of melt, between 3.5 and 6 mm/°C/day, with lower values for less dense (newer) snow. Martinec and Rango (1986) also review temperature thresholds between rain and snow and note that these exceed 0°C and are highest in the spring months, e.g. 3°C, but are around 0.75°C at other times of the year. Hock (2003) only reviews DDF and find appropriate values between 2.5 to 5.5 mm/°C/day for non-glaciated sites.

To estimate snowmelt and cover, it is proposed here to use a daily, single-layer degree-day model of snow accumulation and melt. Taking advantage of available SSGB data, this will be calibrated across a range of elevations and will use density estimates to improve performance. The rest of this chapter details the methods used and discusses their appropriateness.

5.2 Methods overview

A single layer degree-day (temperature index) snow model (shown schematically in Figure 5.1), with code shown in Appendix A, was coded in the R language (R Core Team, 2016). The model is based on the methods described in DeWalle and Rango (2008, Chapter 10.3.2). This model takes observations of precipitation and temperature as input and calculates snow water equivalent (SWE) and snowmelt as main outputs. There is a subroutine which estimates snow density and hence depth, which is used to diagnose 50% snow cover in a given area and calibrate the model. The model has been run on a daily time step, but could work at other temporal resolutions (e.g. Tobin et al., 2013).

Model parameters are detailed in Table 5.1. The two primary parameters which control the model are DDF (degree-day factor) and Temp.b. The four other parameters in Table 5.1 fine-tune model output or control the estimation of snow depth.

Table 5.1: *Model parameters.*

Name	Units	Description
DDF	mm/day/ °C	Degree-day factor, which controls the quantity of melt when there is a snow pack.
Temp.b	°C	Temperature threshold between precipitation falling as snow or rain.
den	kg/m^3	Density of snow on the first day it fell.
den.i	$kg/m^3/day$	Daily increase of snow density.
DDF.d	$km/m^3/day$	Daily decrease of degree-day factor.
d.50	mm	Depth at which snow covers 50% of given area.

The model was first run using observations from five Met Office stations: Braemar, Dalwhinnie, Eskdalemuir, Inverailort and Knockanrock (Table 2.3). This initial run was used to establish parameter space, using a wide range of values for all parameters excluding d.50. The d.50 parameter is used to estimate snow cover greater than 50% in a given area from snow depth. The model was then run for a 5 km grid, at cells which overlapped SSGB observations across Scotland. This gridded model run

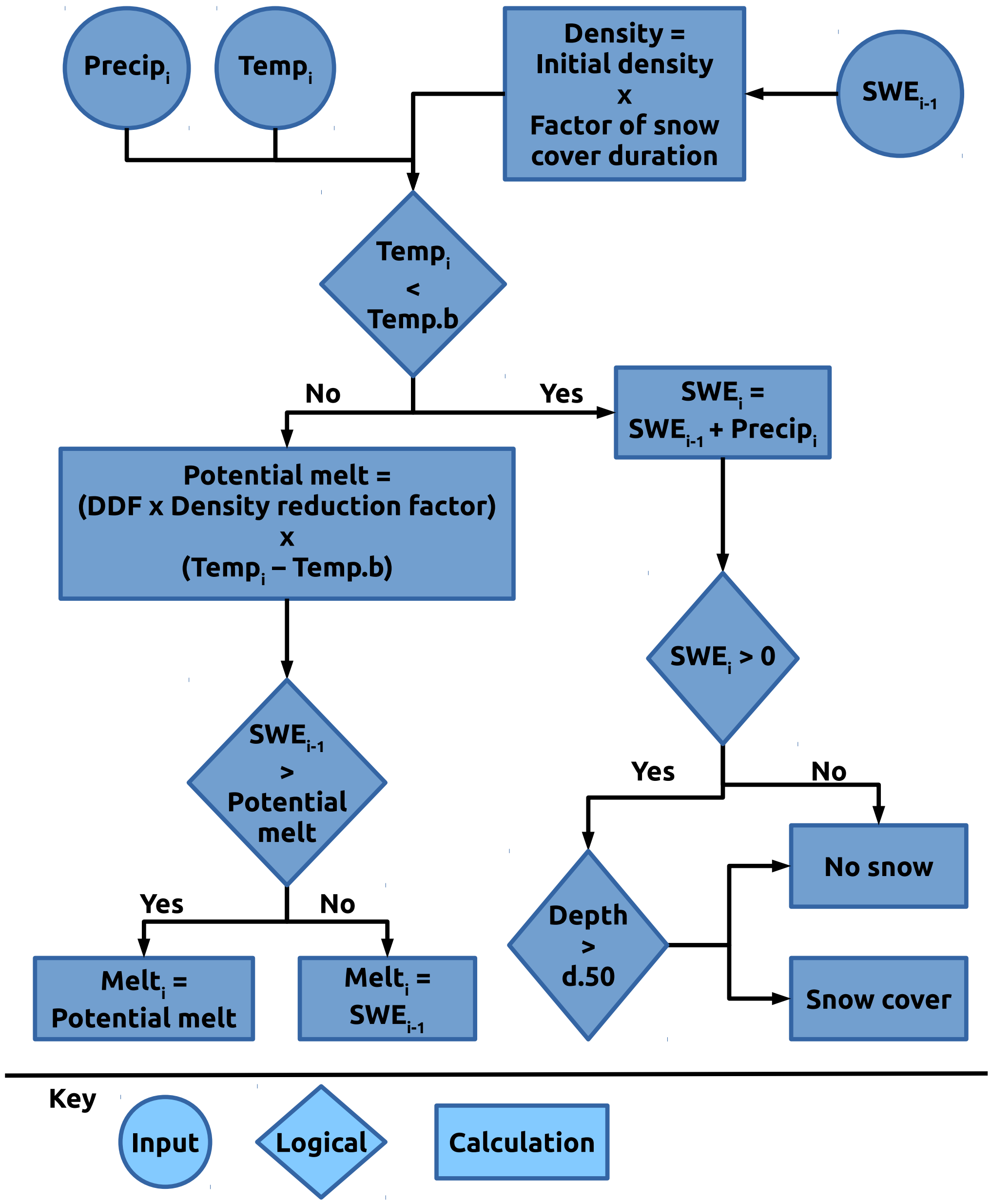


Figure 5.1: *Schematic of the single layer degree-day model used. Precip is daily precipitation; Temp is daily temperature; DDF is degree-day factor; Temp.b is temperature threshold for snow or rain; SWE is snow water equivalent; d.50 is depth at which snow cover for a given area is greater than 50%. See Table 5.1 for more detail.*

used 1960 to 1990 data for calibration and 1991 to 2005 (when the SSGB ended) data for verification. Finally, the model was run on a 5 km grid covering all of Scotland, using those parameters which performed best when compared to the SSGB dataset. This is, essentially, a simplified application of the GLUE (Generalised Likelihood Uncertainty Estimation) method (Beven and Binley, 1992; Beven, 2006), in which parameter sets which perform equally well are all used. However, in this case, only those which perform best are carried through to the next stage of the process. While this does not explicitly address the problem of equifinality or estimate uncertainty, it does allow derivation of an answer within the constraints of computational limitation by severely limiting the number of parameter sets used in the model runs which take the most time (i.e. grid simulations). The following sections detail the individual Met Office station calibration, grid calibration and then model performance.

5.3 Individual station calibration

A series of Met Office stations across Scotland, which covered a range of elevations and reported daily snow depth, precipitation and temperature was identified. These five stations are shown in Figure 2.5 and detailed in Table 2.3. The number of winters (Oct to May) in which at least one of them reported all (244 or 245) days of observations was 19. This count was reduced to 13 winters (Figure 5.2) when subset by those stations that reported at least one day with a snow depth greater than zero; i.e. eliminating stations which reported no snow all winter. Model input was daily temperature and precipitation, with output calibrated against observed snow depth.

Table 5.2: *Model parameter space for Met Office station run. See Table 5.1 for parameter explanations, including units.*

Name	Low	High	Increment
DDF	2	7	0.5
Temp.b	0	1	0.25
den	120	180	10
den.i	0	6	1
DDF.d	0	0.06	0.01

All parameters, except d.50, were varied as shown in Table 5.2, creating 18865 different combinations; d.50 was not included, as its value has no impact on snow depth. These parameter limits (Table 5.2) were set by a coarse increment first run which, aided by literature discussed parameter values (e.g. Martinec and Rango, 1986; Hock, 2003; Essery et al., 2013), were varied over orders of magnitude. The purpose

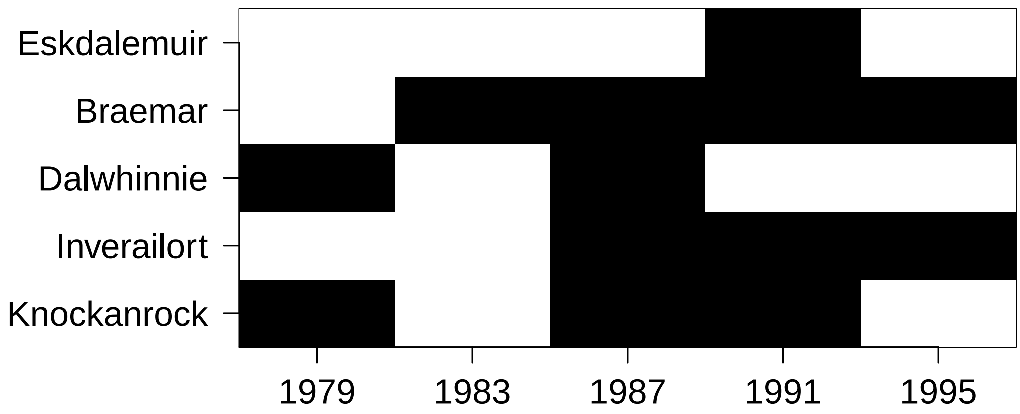


Figure 5.2: *Available winters with complete daily snow depth, precipitation and temperature data for chosen Met Office stations.*

of running the snow model at these Met Office stations was to reduce the set of likely parameter values for the more computationally intensive gridded model run and to calibrate estimates of snow depth.

Model performance was evaluated by calculating the root mean squared error (RMSE) (Zambrano-Bigiarini, 2014) for each parameter set. Eight parameter sets were within 2% of the lowest value of RMSE; these are shown in Table 5.3. All parameters, except Temp.b, have variation. A density of 120 kg/m^3 performed best overall, which is comparable with physically sampled values of 100 to 150 kg/m^3 reported in Archer (1981) during the winters of 1977 and 1978 in Forest, Teesdale, England. DDF.d (the density reduction factor) values of, or close to, zero performed well; this indicates that the d.50 parameter has little effect on the results.

The best performing parameter sets were then identified for each station and each year. The modelled depth from these parameters was then plotted with observed depth (Figure 5.3), which can be compared to best overall parameter depth (Figure 5.4). As can be seen, some observed snow accumulations are missed in all simulations shown, notably for Dalwhinnie in 1979. However, there is not a marked difference between the best parameter sets overall, and those which perform best at a given station for a given winter.

The parameters shown in Table 5.3, which resulted in the snow depths shown in Figure 5.4 are the ones used in the gridded model run.

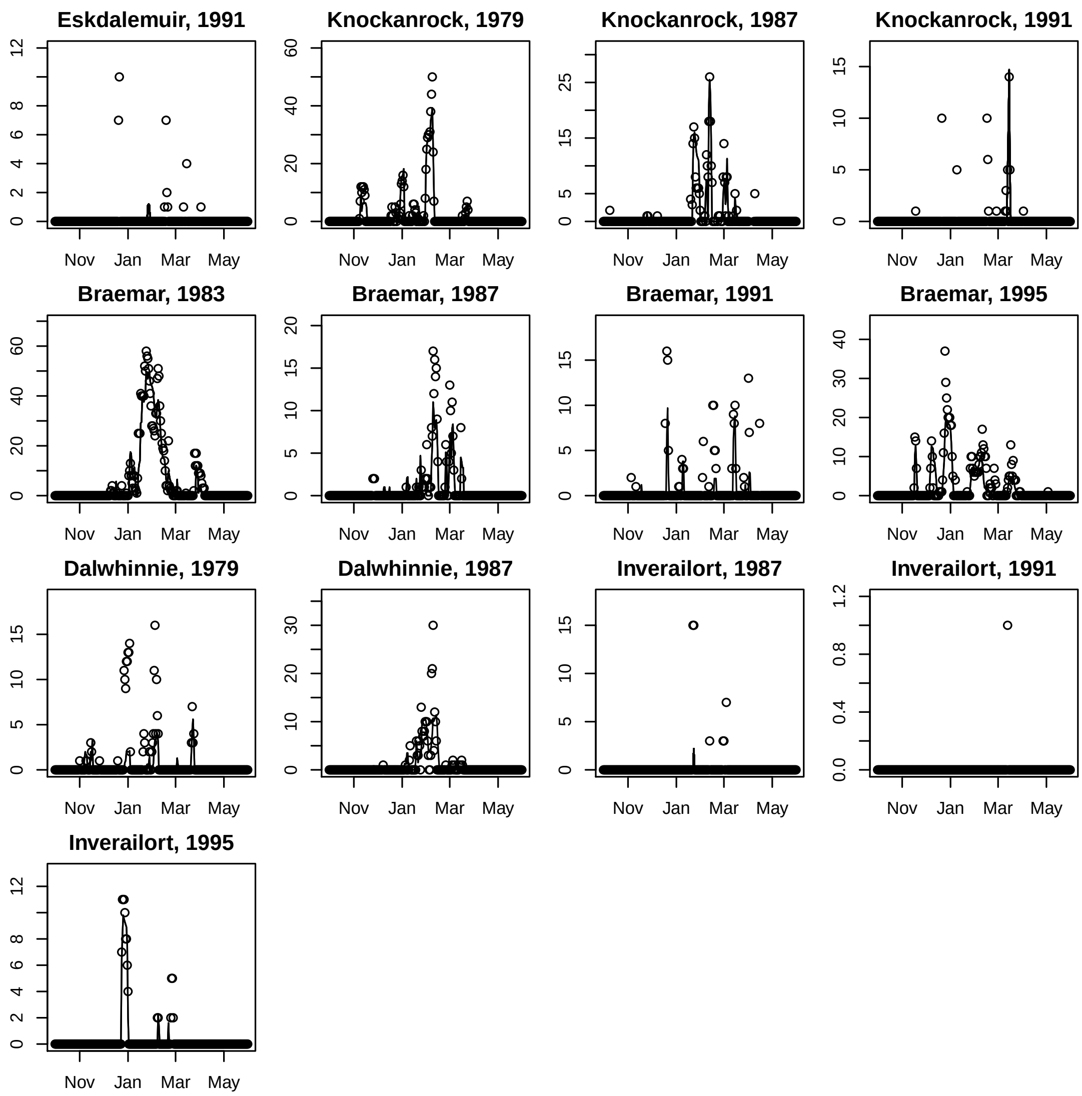


Figure 5.3: *Plots of observed snow depth and modelled snow depth generated by the best performing parameter sets for each station and year. Note that all stations Y-axes show snow depth (mm), circles are observations and lines are model output. Note, the number of model results shown on each plot is 231, 2, 2, 11, 3, 2, 1, 2, 2, 1, 539, 7546 and 2 (starting top left, reading by row).*

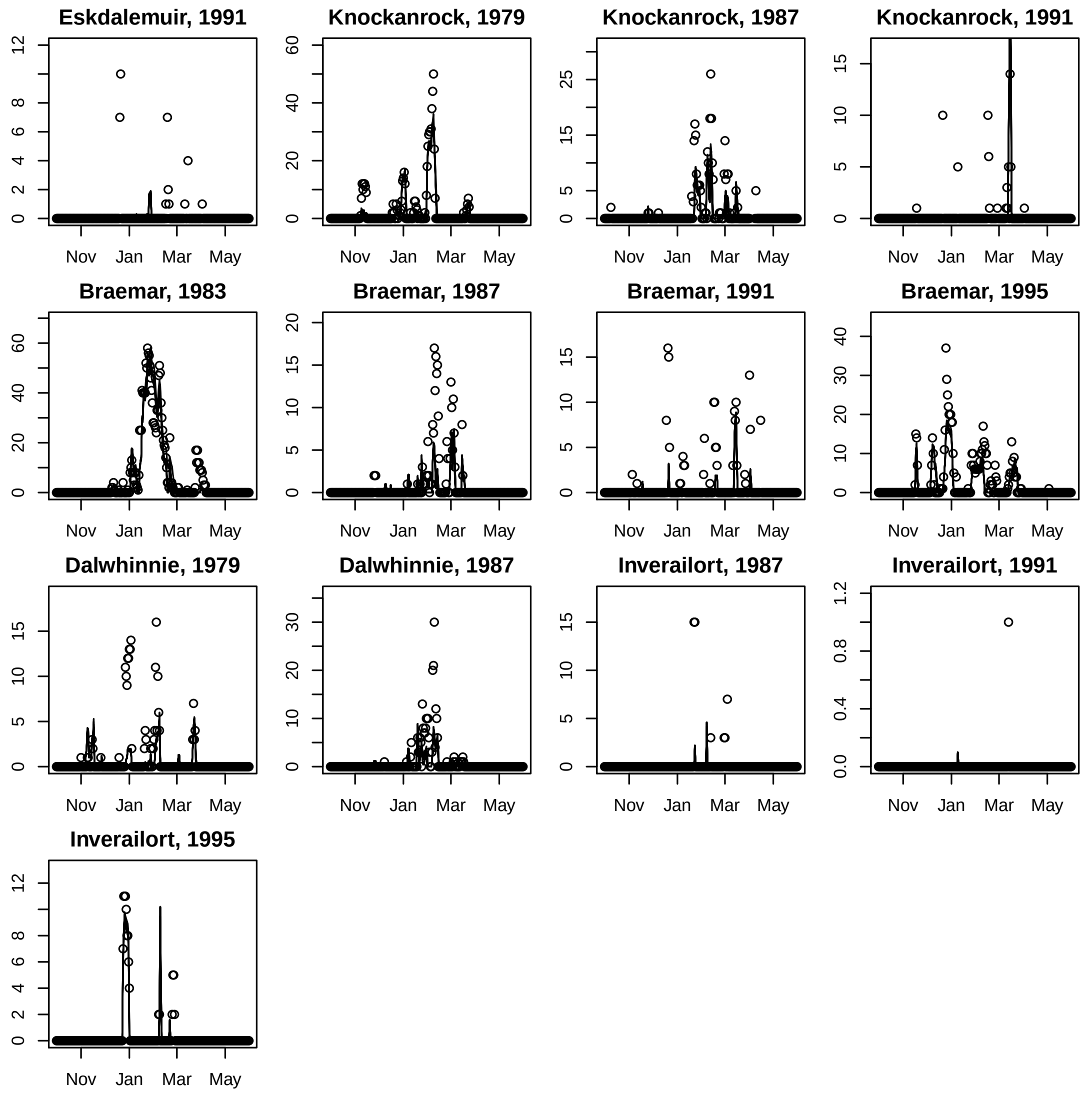


Figure 5.4: *Plots of observed snow depth and modelled snow depth generated by the best performing parameters overall. Y-axes show snow depth (mm), circles are observations and lines are model output.*

Table 5.3: *Model parameters which were within 2% of the lowest RMSE. See Table 5.1 for parameter explanations, including units.*

DDF	Temp.b	den	den.i	DDF.d	RMSE
2.00	0.50	120	1	0.01	23.00
2.00	0.50	120	2	0.01	22.73
2.00	0.50	130	1	0.01	22.98
2.00	0.50	130	2	0.01	23.14
3.00	0.50	120	3	0.00	23.04
3.50	0.50	120	2	0.00	23.03
4.00	0.50	120	2	0.00	23.03
4.50	0.50	120	2	0.00	23.03

5.4 Grid calibration

To calibrate the model on a grid for a range of elevations, the model was resolved on a per cell basis between October and May each winter for a range of cells which overlap areas visible from selected SSGB stations. SSGB stations were selected (Table 5.4) based on a long record, a range of visible elevations and to cover a broad geographical area of Scotland. Viewsheds for each station were overlaid on the UKCP09 5km grid and those cells that intersected the visible envelopes were used for the gridded model calibration (Figure 5.5). There were 76 cells in total.

Table 5.4: *SSGB stations used for model calibration.*

Name	Easting (m)	Northing (m)	Station elevation (m)	Visible hills, as noted by SSGB observer
Ardtalnaig	270200	739400	129	Ben Lawers: 1214 m, 3 km N&NW. Ground to E of station: 685 m. Ben More: 1174 m, 32 km WSW of station.
Cassley PS	239600	923200	100	Ben More Assynt: 998 m. Maovally: 510 m. Ben Hee: 873 m.
Eskdalemuir	323500	602600	231	Ettrick Pen: 692 m, 320°, 6 km. Lochfell: 300°, 688 m, 7 km.
Fersit	235100	778200	240	None noted.
Whitehillocks	344860	779790	261	Up to 914 m

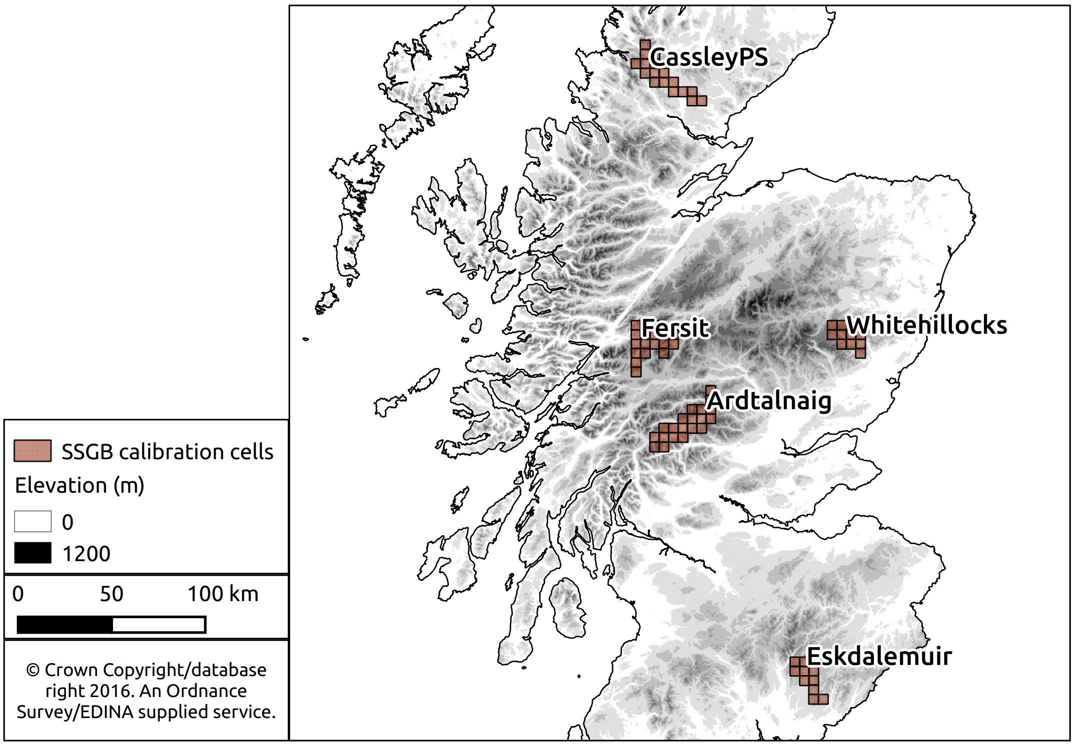


Figure 5.5: *Location of model cells overlapping SSGB station viewsheds used for calibration.*

The model was calibrated on 1960 to 1990 data, with 1991 to 2005 data used for verification. SSGB data which are available for these periods are shown in Figure 5.6a with the range of elevations covered by each station illustrated in Figure 5.6b. Parameters assessed were the six selected in Table 5.3, coupled with a range of values for d.50. d.50 varied between 0 and 300 mm with an increment of 30 mm, making a total of 66 parameter combinations. When depth exceeded the value of d.50, the grid cell was presumed to have snow cover of greater than 50%, the same percentage snow cover SSGB observers used to determine snowline. This binary model output was used for calibration and verification against the SSGB dataset. To match SSGB snowline to model output, the SSGB was converted to a binary presence of snow lying for each cell visible from each SSGB station. Model performance was then evaluated using a penalised approach based on daily correctness, i.e. for each day that the model correctly predicted snow presence or absence it scored one and for each day it was incorrect it scored negative one. Performance of the d.50 parameter was checked by taking the median performance value from each parameter set and plotting against the d.50 value used (Figure 5.7). These show that the best performance is between 150 and 250 mm, broadly similar to Niu and Yang (2007) values of between approximately 10 and 150 mm. Beyond d.50 values of 250 mm there is equifinality.

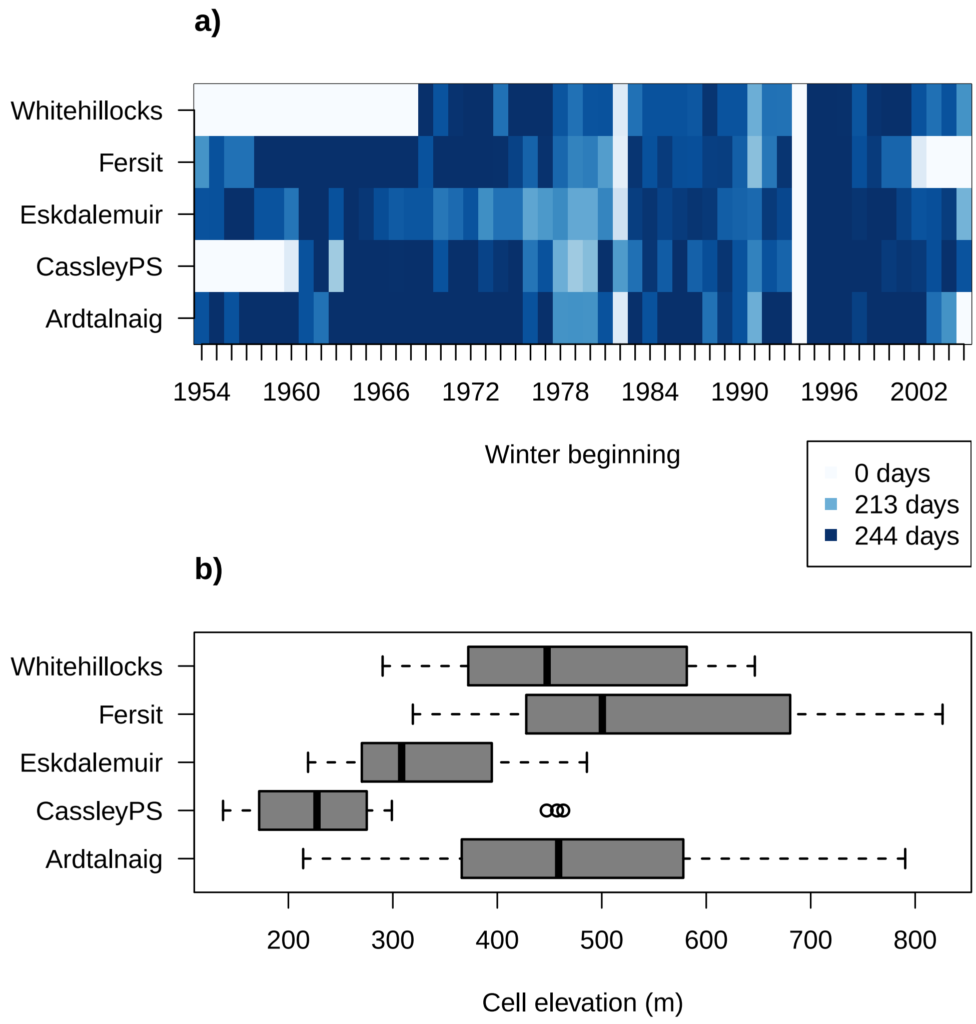


Figure 5.6: *Number of available records (a) and mean cell elevations visible shown with a box and whisker plot (median, quartiles, range and outliers) (b) for the SSGB stations used to calibrate the grid model.*

The model performance was also plotted against model output (Figures 5.8a and b). Both figures show model runs which performed very poorly, these are the result of d.50 being equal to zero. What these figures also show is that with d.50 of zero, there is little impact on the total melt, but that snow cover duration almost doubles that observed by the SSGB. An extreme test for the model would be to see how well these complete melts of snow correspond to long lying snow patch observations (e.g. Watson et al., 2011).

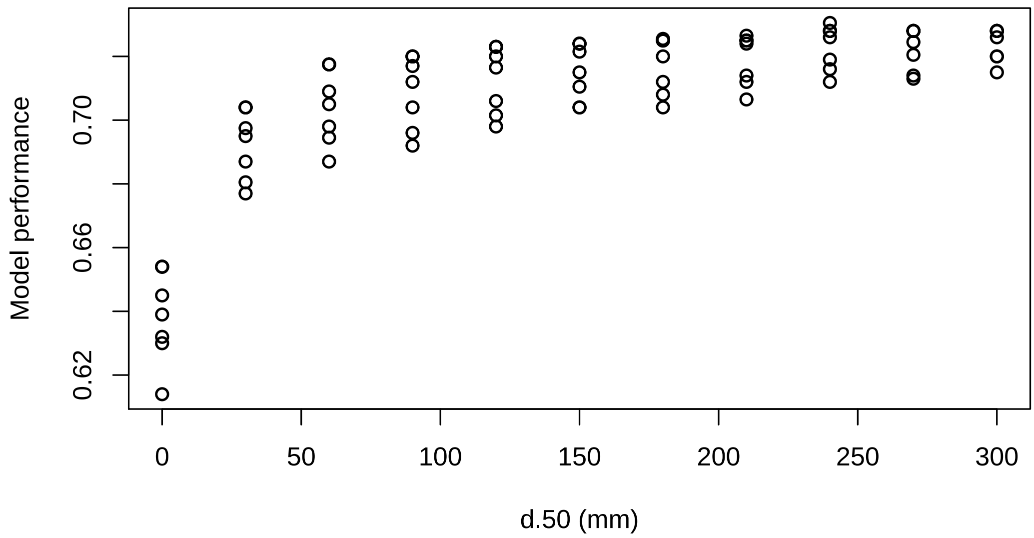


Figure 5.7: *Median model performance over 76 cells between 1960 and 1990 for the d.50 parameter.*

Calibrating the model against SSGB data allows comparison between results from a wide range of elevations. Mean elevations in the 76 calibration cells range from 140 to 830 m. Comparing the parameter performance between these elevation bands shows whether it is appropriate to use different parameter sets at different elevations. Cell elevations were grouped to 150 m elevation bands, matching the SSGB observations, and then a similar plot to Figure 5.7 was made, but points were colour coded by elevation (Figure 5.9). What is apparent is the different response above 300 m, compared to Figure 5.7 where model performance decreases as d.50 increases. The difference between Figures 5.7 and 5.9 is because higher elevation cells are fewer and so their responses to changes in d.50 are overwhelmed by the greater number of lower elevation cells. The reason there is a difference between higher and lower elevations is because presenting the d.50 parameter split by elevation is allowing it to behave as a model residual, i.e. showing unexplained differences in performance at different

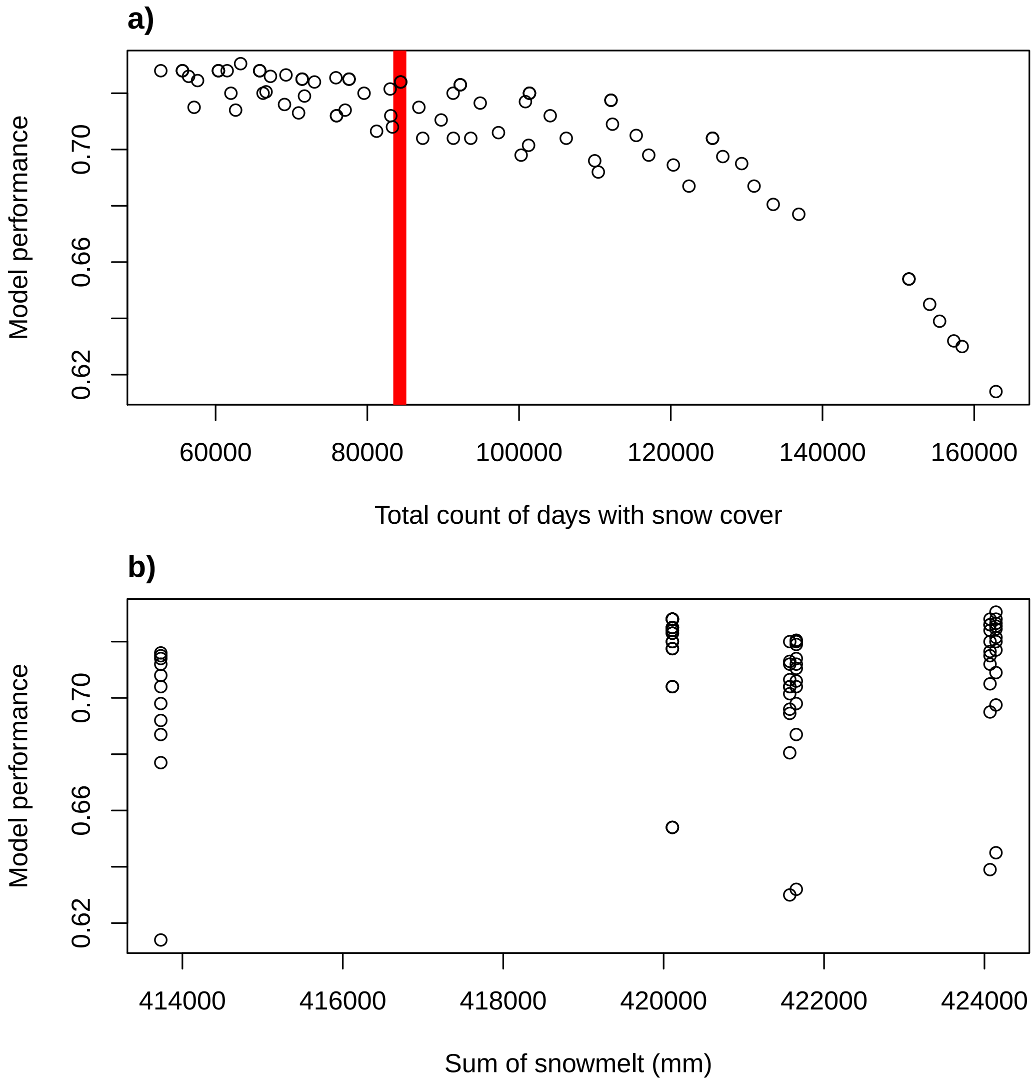


Figure 5.8: *a) Total sum of modelled days with snow cover with a red line indicating the count observed by the SSGB and b) sum of snowmelt plotted against model performance. Both are for d.50 = 0.*

elevations. I believe this is primarily due to CEH GEAR data underestimating higher elevation precipitation (see Section 3.7), causing d.50 to be much smaller than at lower elevations to compensate for a reduced snow accumulation. The other point to note in Figure 5.9 is the saturation of model performance at lower elevations for a higher value of d.50. Lower elevation cells are more likely than high elevation cells to be too warm for snowfall and accumulation, and only in the coldest winters will there be many days with snow cover. If the daily temperature does not fall below 1 to 1.5°C then the model will not accumulate snow, nor is it likely that any would lie in reality. In these conditions it is very easy for the model, almost whatever parameters are chosen, to match all observations. As the median value of model performance has been used in Figure 5.9 then this is reflecting the larger proportion of years when no snow may have fallen at lower elevations.

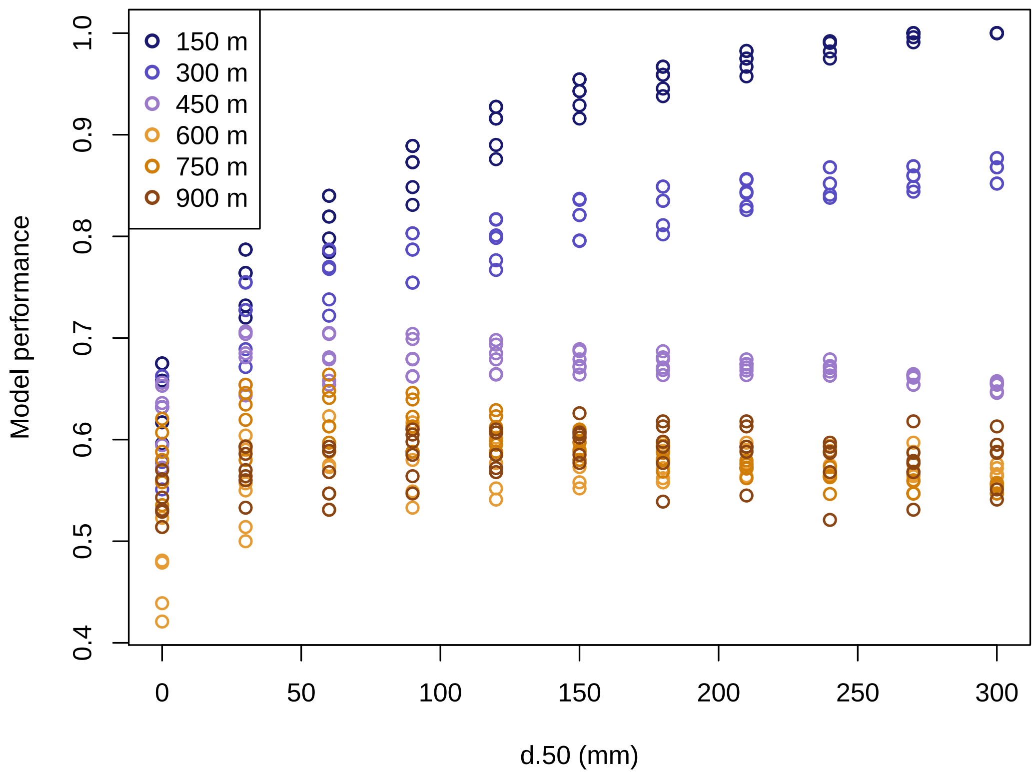


Figure 5.9: *Median model performance over 76 cells between 1960 and 1990 for the d.50 parameter, split by elevation.*

The best performing parameter set scored 0.731 and there were 12 other parameter sets which scored within 0.5% of this. Table 5.5 shows these parameters and their scores. As can be seen, Temp.b and den.i have no variation, although the former was set at the station calibration phase. den and DDF.d have little variation and DDF and d.50 have the largest variation. Given the uncertainty of precipitation at higher elevations, the final model was run with the same parameter set at all elevations as varying parameters did not have enough justification and computing time was prioritised. To do this, the best performing parameters were chosen; these are highlighted with horizontal lines in Table 5.5.

Table 5.5: *Best performing model parameter sets compared to SSGB data, with those used enclosed with lines. Note a d.50 value of 120 mm was used for the final model run.*

DDF	Temp.b	den	den.i	DDF.d	d.50	Performance
2.0	0.5	120	2.0	0.010	270	0.728
2.0	0.5	130	2.0	0.010	240	0.731
2.0	0.5	130	2.0	0.010	300	0.728
3.5	0.5	120	2.0	0.000	240	0.728
3.5	0.5	120	2.0	0.000	270	0.728
3.5	0.5	120	2.0	0.000	300	0.728
4.0	0.5	120	2.0	0.000	240	0.728
4.0	0.5	120	2.0	0.000	270	0.728
4.0	0.5	120	2.0	0.000	300	0.728
4.5	0.5	120	2.0	0.000	240	0.728
4.5	0.5	120	2.0	0.000	270	0.728
4.5	0.5	120	2.0	0.000	300	0.728

5.5 Model performance and complete run

Using the best performing parameters highlighted in Table 5.5, model calibration and validation performance were assessed. The calibration period was 1960 to 1990 and the verification period 1991 to 2005. The verification period finishes three years earlier than the input data (2010) as this is when the SSGB records end. The performance of the calibration and verification periods is shown in Figure 5.10. Some values are less than zero, as a penalty was applied if the model did not agree with SSGB observations. Model performance is better at lower elevations, where there is less snow and it is warmer, hence easier for the model to predict. The model generally performs slightly better in the verification period, compared to the calibration period. Again, this is thought to be because the winters beginning 1991 to 2005 were warmer than 1960 to 1990, meaning fewer days of snow for the model to predict.

To test the theory that the model performs better when there is less snow, model performance was plotted against the number of days with snow cover (Figure 5.11)

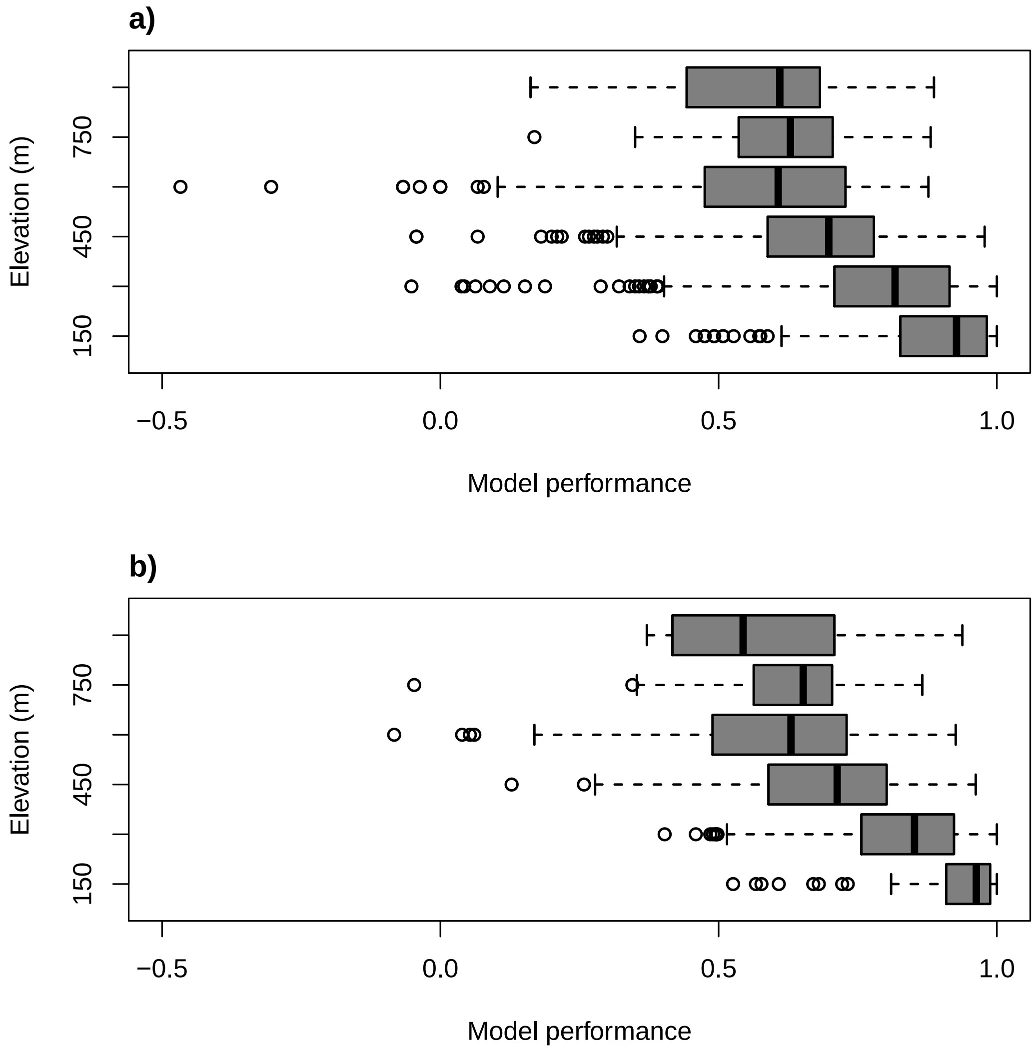


Figure 5.10: *Model performance for the calibration, 1960-1990 (a) and verification, 1991-2005 (b) periods, split by elevation and shown with a box and whisker plot (median, quartiles, range and outliers).*

as recorded by the SSGB. Performance decreases at all elevations as the number of days of snow cover increases. As there are fewer high elevation cells, results for these are less conclusive. The limitation of Figure 5.11 is that there is no differentiation between snowy winters when the temperature fluctuated around 0°C and snowy winters which were much colder. These differences are shown in Figure 5.12, which plots model performance, per cell, per winter, against the average minimum Scottish winter temperature (downloaded from the Met Office[1]). Note the y-axis varies between plots, to better show patterns. Unexpectedly, there is a general peak in model performance around 0°C, although the lowest two elevation bands have a slight decrease in performance very close to 0°C. This wider increase in model performance around 0°C could be due to these temperatures being the most common and so the most training data were available for the model. At elevations including and below 600 m, model performance improves for the coldest and warmest winters, supporting my hypothesis that when precipitation is much more likely to fall as either snow or rain the model does not struggle to differentiate between the two. This trend is not apparent in the 900 m elevation band, perhaps due to a paucity of model results and observations.

The calibrated model was run for the whole of Scotland (approx 3000 5 km cells) for winters beginning in 1960 to 2010. The daily output of SWE, snowmelt and snow cover (based on depth exceeding the d.50 parameter) grids are stored in NetCDF format. These results were used to derive snowmelt and snow cover statistics which are shown in Chapter 6.

5.6 Discussion

A degree-day snowmelt model, validated across a wide elevation range, has yielded daily snowmelt and snow cover data for a 50 year period. This is of particular use in temperate climates where ephemeral snow makes annual snow pack estimation invalid, and where direct wide-scale observation of snow cover is difficult. Absolute snowmelt results, particularly at higher elevations, are uncertain as precipitation input data appear to notably underestimate high elevation precipitation. This means that high elevation snowmelt values are likely to be underestimated. Despite this, I think there is great worth in looking at relative values of melt with the assumption that different locations with the same elevation are likely to be comparable and that differences between high and low elevations are likely to be underestimated. As the model was calibrated on snow cover, results for snow cover are less likely to be

[1]http://www.metoffice.gov.uk/climate/uk/summaries/datasets

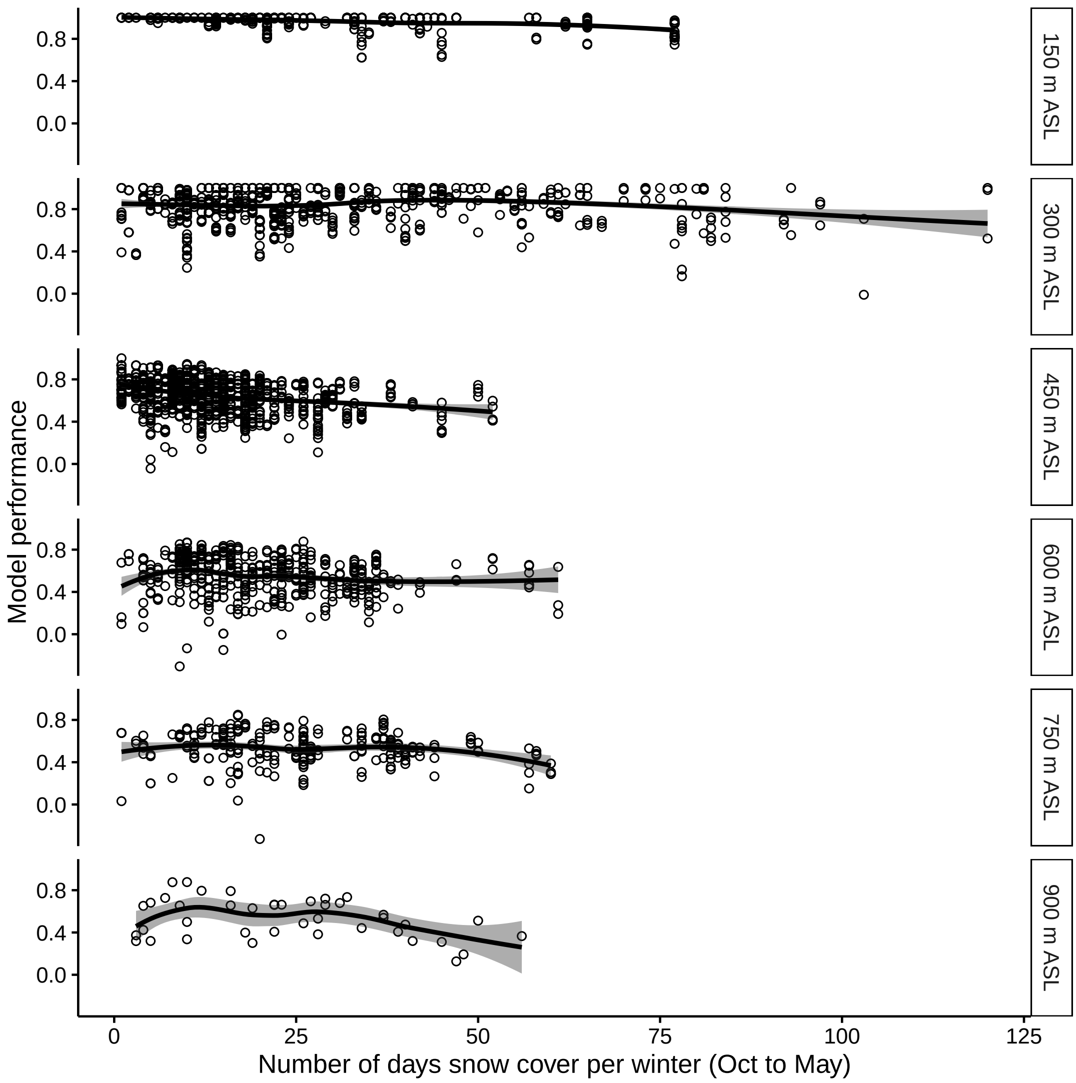


Figure 5.11: *Model performance for the 1960 to 2005 winters, split by elevation and plotted against the number of days with snow cover recorded by the SSGB. The plots are fitted with Loess and 95% confidence limits. Each point represents one cell in one year.*

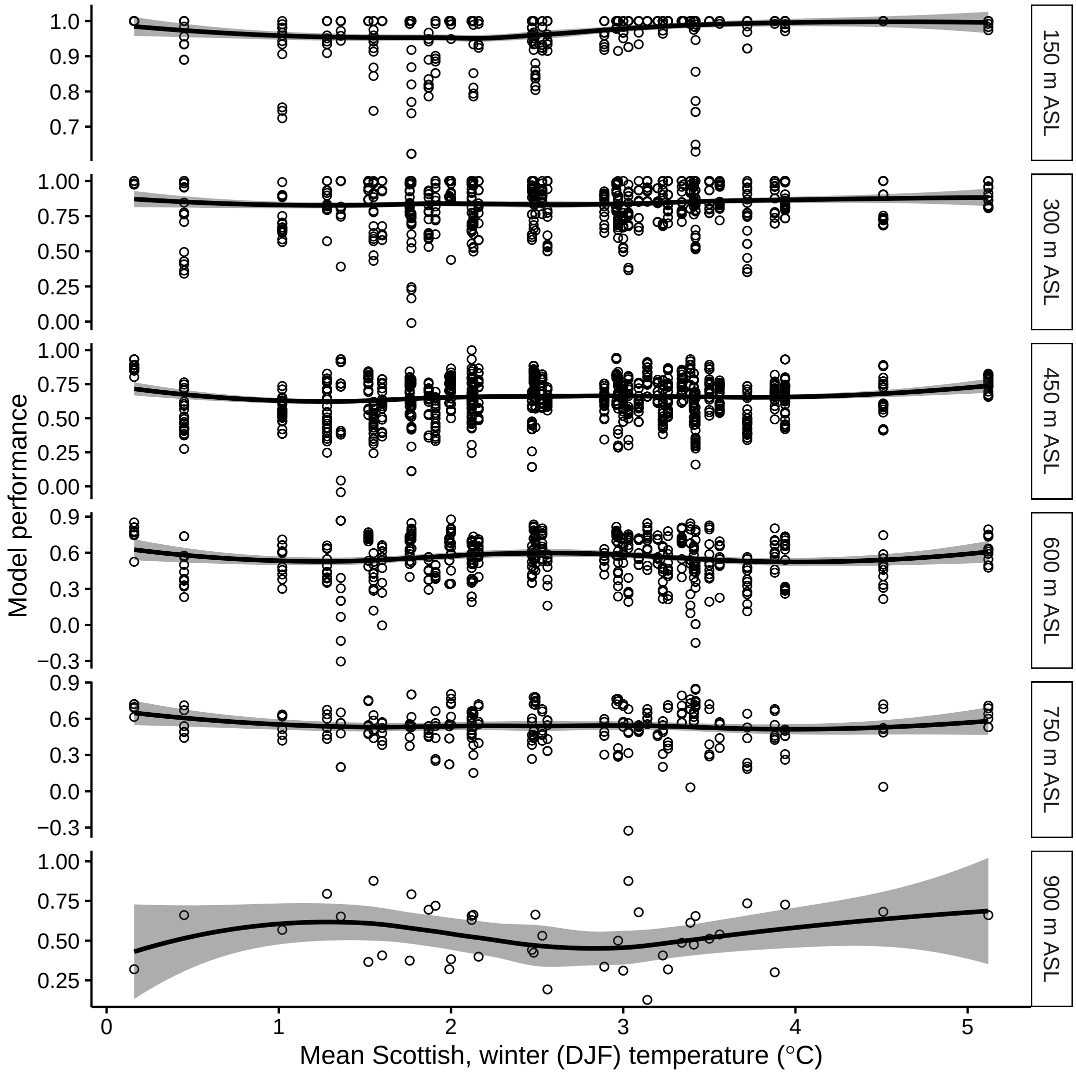


Figure 5.12: *Model performance for the 1960 to 2005 winters, split by elevation and plotted against the UKCP09 average, Scottish winter (DJF) temperature. The plots are fitted with Loess and 95% confidence limits. Each point represents one cell in one year, note that the y axis scales differ between plots.*

affected by an underestimate of high elevation precipitation. It would be of great use to the discipline of flood risk management to derive absolute values of snowmelt, to better inform the estimation of rare floods and protect communities. However, to do this, better estimations of high elevation precipitation are needed, as this is where the greatest uncertainty lies. With these improved input data and more computing resources it would be of interest to run the gridded model stochastically, using a wider range of suitable parameters giving a range of estimates for snowmelt and helping to understand its uncertainty. The following chapter, 6, considers the results from this modelling exercise.

CHAPTER 6

Snow modelling results

6.1 Introduction

This chapter presents the results from the snow accumulation and melt modelling in Chapter 5, which culminated in a 5 km gridded model running across Scotland for winters beginning 1960 to 2010. Outputs from this modelling are daily snowmelt and snow cover. As discussed in Chapter 1 the presence of snow cover has an impact on ecology (e.g. Trivedi et al., 2007) and snowmelt plays an important role in water quality (e.g. Helliwell et al., 1998) and extreme hydrological events (e.g. Black and Anderson, 1994).

The aim of this chapter is to use the modelling results of Chapter 5 to understand the statistical probability of extreme snow cover and melt across Scotland. Pearson correlations are used to show relationships and trends, with the latter being shown as correlations with year. This chapter is split into sections covering snowmelt and snow cover. Each section is then divided by general observations and correlations of the results, and an extreme value analysis.

6.2 Snowmelt

6.2.1 Melt per annum

In order to gauge the importance of snow to Scottish hydrology, the proportion of precipitation as snowmelt was calculated. This describes more than how much solid or liquid phase precipitation fell, as snow can fall and not accumulate, hydrologically behaving as rain. As the model was run at a daily time step, accumulated snow must lie for a minimum of one day, which would delay runoff generation, but this may not reflect reality.

Figure 6.1 shows the median, lower and upper quartiles of winter (Oct to May) modelled snowmelt as a proportion of precipitation for winters beginning 1960 to 2010. Note that there is uncertainty in higher elevation estimates due to the underestimation of precipitation by CEH GEAR (see Chapter 5). This has an uncertain impact on these figures as higher summer precipitation would lower these percentages, but may be balanced by winter precipitation also being underestimated. The underestimation of winter precipitation is likely greater than summer, given the difficulty of snow precipitation measurement (Goodison et al., 1997). For the snowiest areas, melt values vary little between Figures 6.1a to 6.1c, with maximum values of 42, 38 and 47% (median, lower and upper quartiles). There is more variation for median values of snowmelt as a proportion of precipitation, with figures of 3.6, 1.7 and 6% for Figures 6.1a to 6.1c. These results seem spatially coherent too, with high elevation areas in the east of Scotland (e.g. the Cairngorms) getting the highest proportion of snowmelt.

Figure 6.2 shows winter (Oct to May) snowmelt as a proportion of annual precipitation, correlated against a) year and b) mean DJFM NAO index. Both figures use the same colour scale and it is apparent that correlations are generally stronger with the NAO index (-0.69 to 0.47) than with year. Strong negative correlations (-0.54) exist against year (Figure 6.2a), but these are less prevalent than the negative correlations of Figure 6.2b. Decreases in precipitation as snow were reported anecdotally in Black (1995), over an undocumented time period. Figure 6.2a has a single cell of positive correlation (0.34) around Ben Nevis, Scotland's highest peak (1345 m ASL). This suggests that, despite warming temperatures, Ben Nevis is high enough that it remains cold enough for increased precipitation (Macdonald and Phillips, 2006; Zhang et al., 2007) to fall as snow. The strong negative correlations of 6.2b support the findings of Chapter 4 that a negative NAO phase winter brings more snow to Scotland. The strong positive correlations in Figure 6.2b, show that despite a positive phase NAO meaning warmer winter weather is more likely, some western mountain areas are cold enough for the increased precipitation of a positive NAO phase to fall as snow.

6.2.2 Extreme value statistics

Annual (Oct to May) maxima (AMAX) snowmelt values were extracted for each grid cell, resulting in a 51 year series. A generalised extreme value distribution (GEV) was fitted using l-moments for each cell (Gilleland and Katz, 2011). Snowmelt values were derived for 50, 20 and 1% AEP (annual exceedance probability) from the fitted GEV for each grid cell; these are shown in Figure 6.3. Median and maximum snowmelt values from each grid are: a) 10 and 65, b) 15 and 83, and c) 25 and 112 mm/day. As discussed in Chapter 5, these values are subject to uncertainty as the CEH GEAR data underestimates precipitation at higher elevations; it is likely they underestimate the maximum melt. A modelling reason for this is the high value of d.50 used, which enables the model to match observations without needing to melt as much snow. Due to the heterogeneous nature of snow cover, particularly in a mountain environment, the large grid cells used will also underestimate snowmelt as there is no sub-cell parameterisation; i.e. as ground is uncovered by melting snow there is a positive feedback loop due to darker ground absorbing more heat energy and melting snow faster (Essery, 1999). Higher melt values would be in line with Archer (1981), who

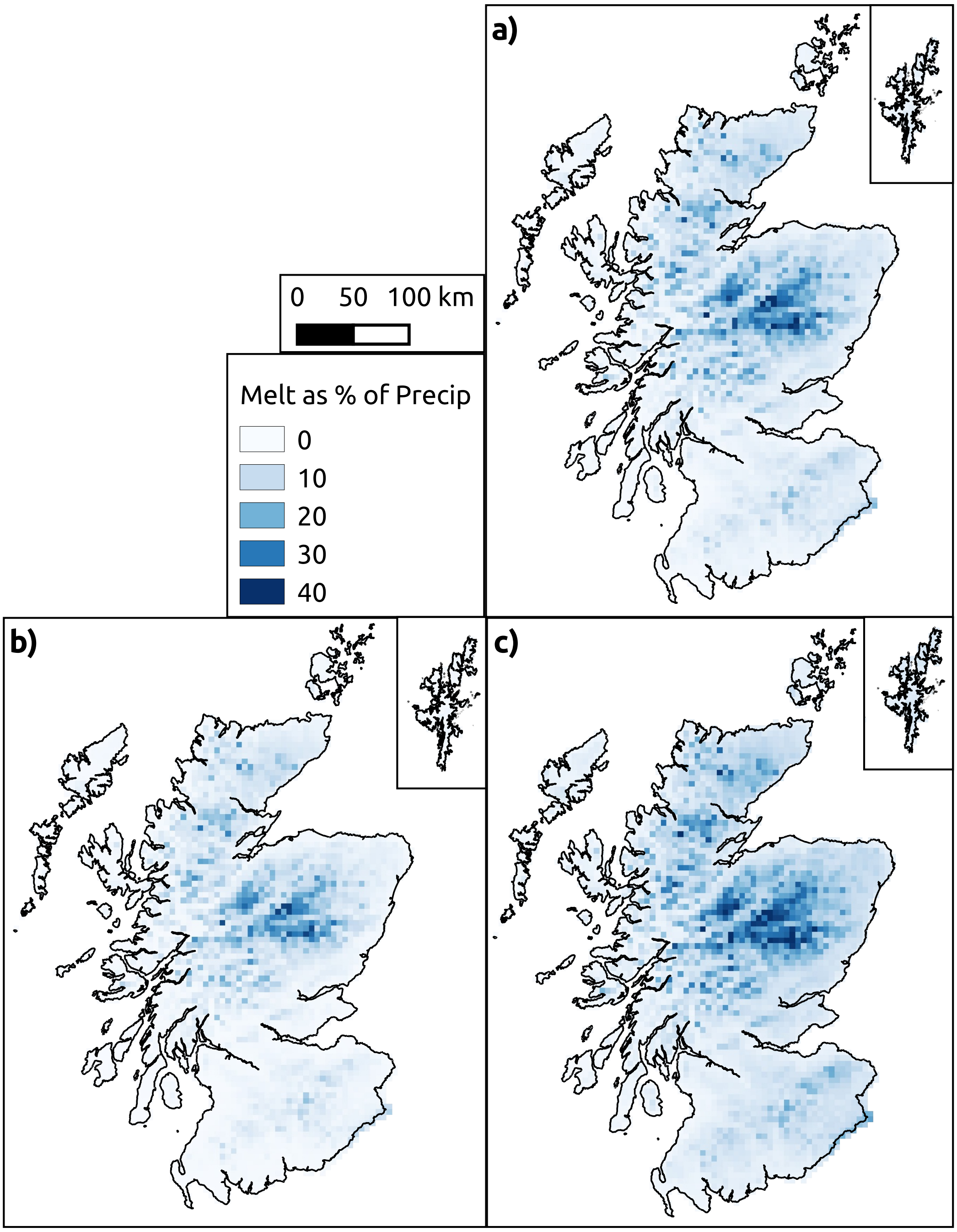


Figure 6.1: *1960-2010 winter (Oct to May) snowmelt as a percentage of annual precipitation: a) median, b) lower quartile, c) upper quartile.*

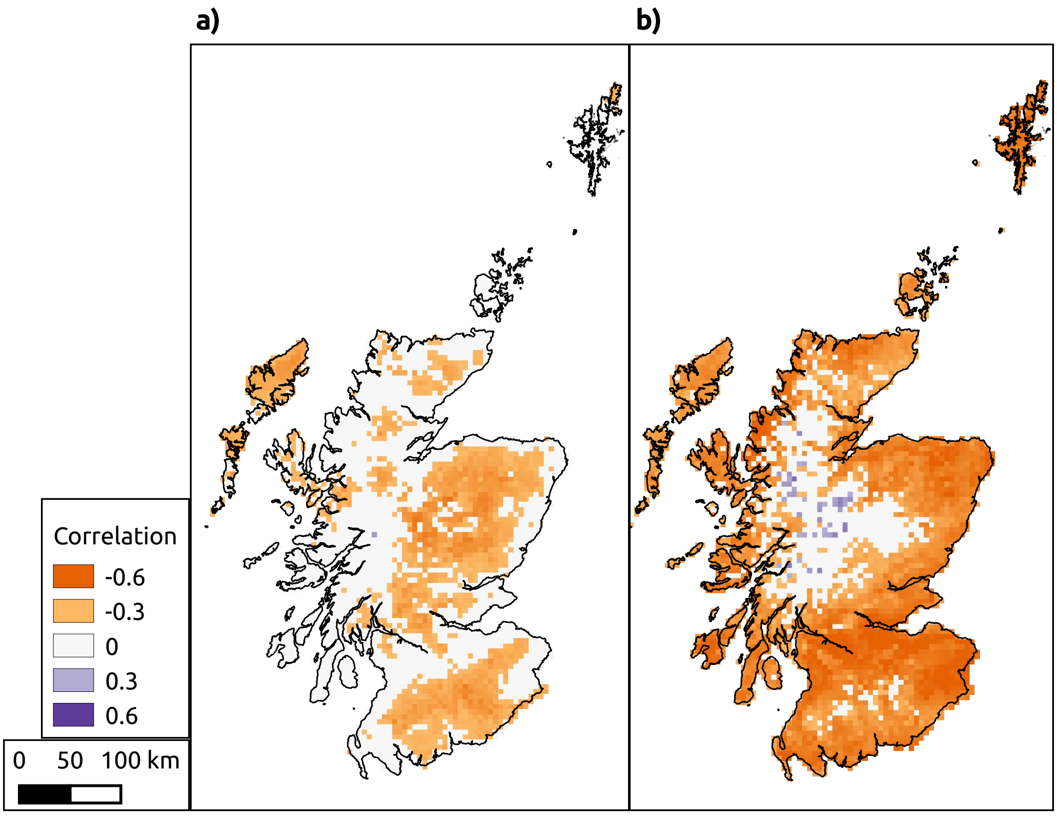


Figure 6.2: *1960-2010 winter (Oct to May) snowmelt as a percentage of annual precipitation correlated against (a) year and (b) DJFM NAO index. Only correlations significant at $p < 0.05$ are shown.*

estimated snowmelt by runoff up to 144 mm/day at Moorhouse in NE England.

Higher rates of snowmelt are not confined to higher elevations. Figure 6.4 shows 50, 20 and 1% AEP plotted against elevation. As can be seen, elevations below 400 m ASL are capable of nearly the highest snowmelt rates. These cells are located in western and northern Scotland and as they do not have particularly large lower return period melt rates (Figure 6.4a and b), the fitted GEV curve must be steeper than at higher elevations. Presumably, then, these areas are more sensitive to winter temperature than predominantly colder areas like eastern Scotland. This means that in some winters these cells are above freezing and snow does not accumulate, but during other winters they are below freezing - but continue to be wet - and large amounts of snow can accumulate. The behaviour of these areas is likely transferred to other locations and elevations in warmer and colder winters.

20% AEP snowmelt was compared to the Hough and Hollis (1997) regression estimate, which used two weather factors: maximum mean daily January air temperature and mean daily January wind speed. A 20% AEP melt rate was used for comparison as these were the only regression equations provided by Hough and Hollis (1997). 1980 to 2010 long term average gridded temperature and wind speed data were downloaded from the Met Office UKCP09 site[1] and the regression was scripted in the R language. The UKCP09 grid dataset used for the Hough and Hollis (1997) regression and model input have the same origin and spacing, meaning a direct comparison of cell values is straightforward. Figure 6.5 shows my 20% AEP snowmelt estimate compared to Hough and Hollis (1997), plotted with a one to one line. As Hough and Hollis (1997) used a large number of low elevation stations, these elevations should have a greater degree of confidence than the lower elevation results presented here. As shown in Figure 6.4, lower elevations generally have lower snowmelt, so the bottom left of Figure 6.5 has the highest confidence. The inflection in Figure 6.5 could relate to the elevation in the model that tends to always be cold enough for snow. However, at this point, Hough and Hollis (1997) snowmelt is approximately double that from my model; as discussed previously, this could be due to an underestimate of higher elevation precipitation.

A brief peaks over threshold (POT) assessment was made (Figure 6.6), where the number of cells that exceeded a melt of 42 mm/day was summed for each year. A value of 42 mm/day was chosen as this is used as a snowmelt design maximum in UK flood estimation (Institute of Hydrology, 1975; Reed et al., 1999). There are no apparent trends, other than a possible reduction in POT cell counts from the 1970s. The indication here is that 42 mm/day is probably an acceptable design maximum for

[1] http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/index.html

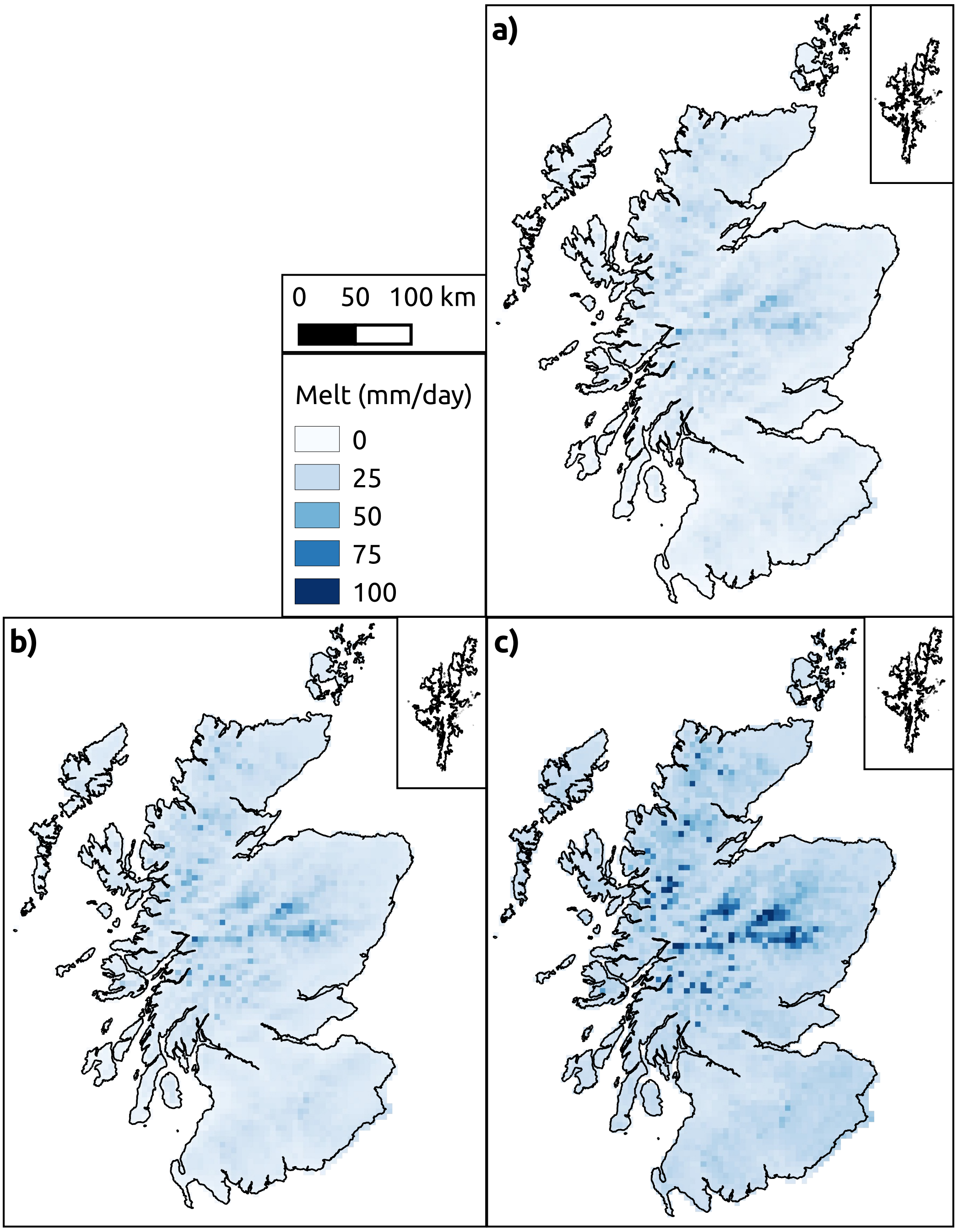


Figure 6.3: *Snowmelt for (a) 50%, (b) 20% and (c) 1% AEP.*

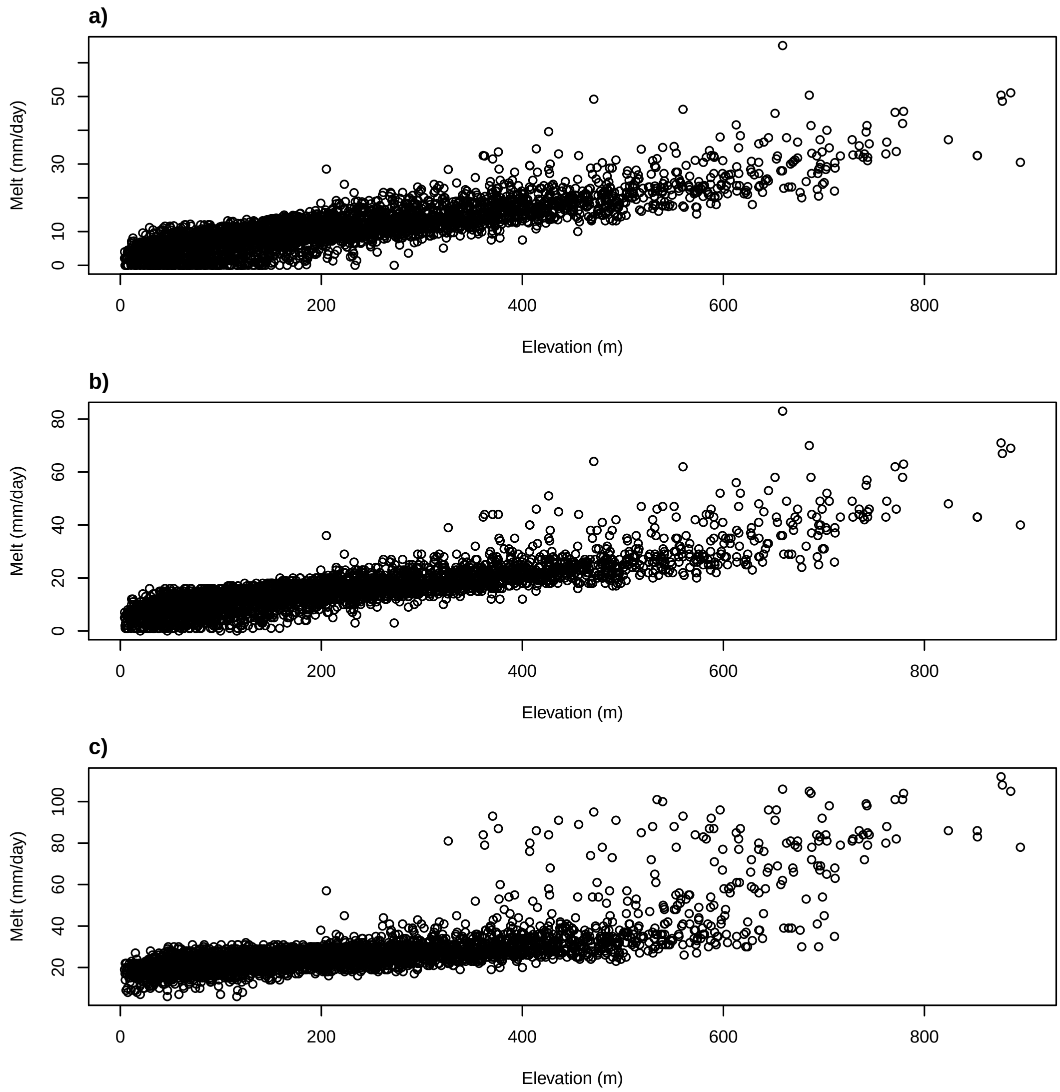


Figure 6.4: *Modelled melt with annual exceedance probabilities of (a) 50%, (b) 20% and (c) 1% plotted against elevation, where each point represents a 5 km grid cell.*

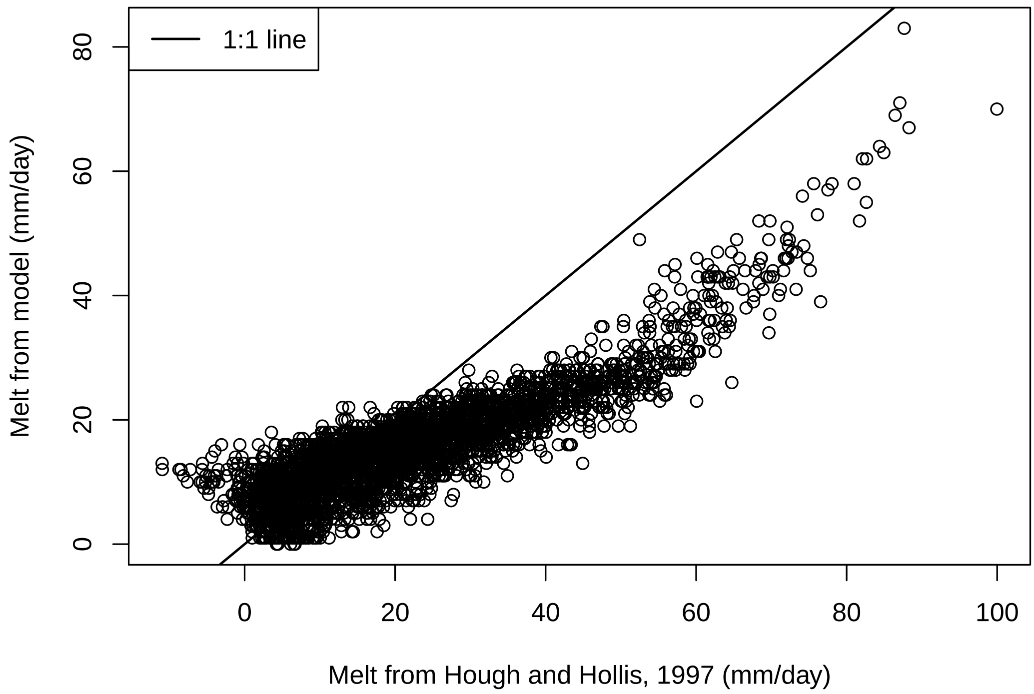


Figure 6.5: *Comparison of 20% AEP melt between Hough and Hollis (1997) and model output, where each point represents a 5 km grid cell in the same location. Hough and Hollis (1997) estimates are derived from a two weather factor (temperature and wind) regression.*

low elevation situations, but not higher elevations. However, it must be noted again that these values of snowmelt are likely underestimates.

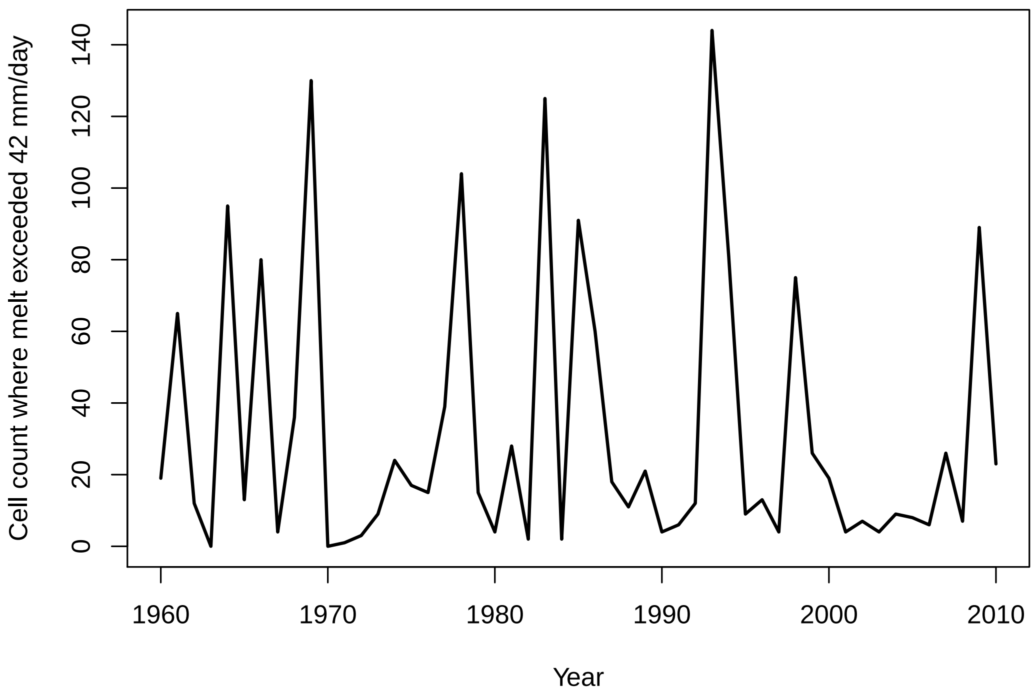


Figure 6.6: *The number of cells each year exceeding a melt rate of 42 mm/day.*

6.3 Snow cover

6.3.1 Snow cover per annum

The number of days with snow cover was extracted for each year and for each grid cell. These were correlated against year and NAO index (Figure 6.7). The correlation range for year (Figure 6.7a) was -0.46 to 0.53 and for NAO (Figure 6.7b) -0.65 to 0.22, but none of the positive correlations with NAO were significant at $p < 0.05$. Supporting the results of Figures 6.1, 6.2 and 6.4, the highest correlation area for snow cover against year is Ben Nevis. Some lowland, coastal areas also show a positive correlation, but these are not significant and are weak (less than 0.25). Strong correlations between snow cover and the NAO phase are prevalent and negative. These negative correlations support the results of Chapter 4. As the modelling results do not have spatial or temporal gaps, the results shown in Figure 6.7b are possibly more important in defining the relationship between NAO and snow cover than the results of Chapter 4. However, the modelling results are subject to the undefined uncertainties of the modelling approach.

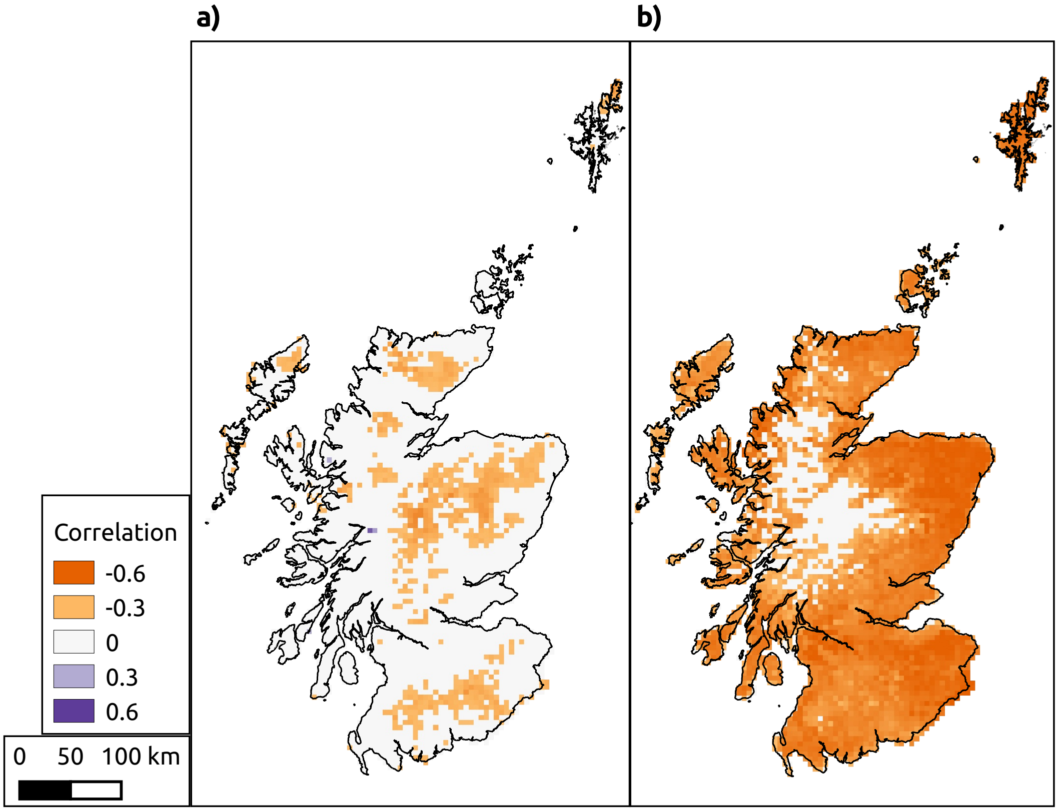


Figure 6.7: *The number of days of snow cover each year correlated against a) year and b) mean DJFM NAO index. Only correlations significant at $p < 0.05$ are shown.*

6.3.2 Extreme value statistics

As outlined in Section 6.2.2, extreme value analysis was repeated for the number of days with snow cover each winter (Oct to May). Figure 6.8 shows the: a) 50% and b) 1% AEP for snow cover each winter. The median and maximum number of days snow cover for 50% AEP are 10 and 207 and for 1% AEP are 74 and 240. As for snowmelt (Section 6.2.2), the GEV fit for snow cover duration in the snowiest areas is flat compared to less snowy areas. This flat GEV fit results in little variation in snow cover duration between frequently occurring and rare return periods in the snowiest areas, particularly the Cairngorms (Figure 6.8). However, the inverse is true for less snowy areas, where the GEV fit is steeper and rarer snow cover events are much greater than frequently occurring ones.

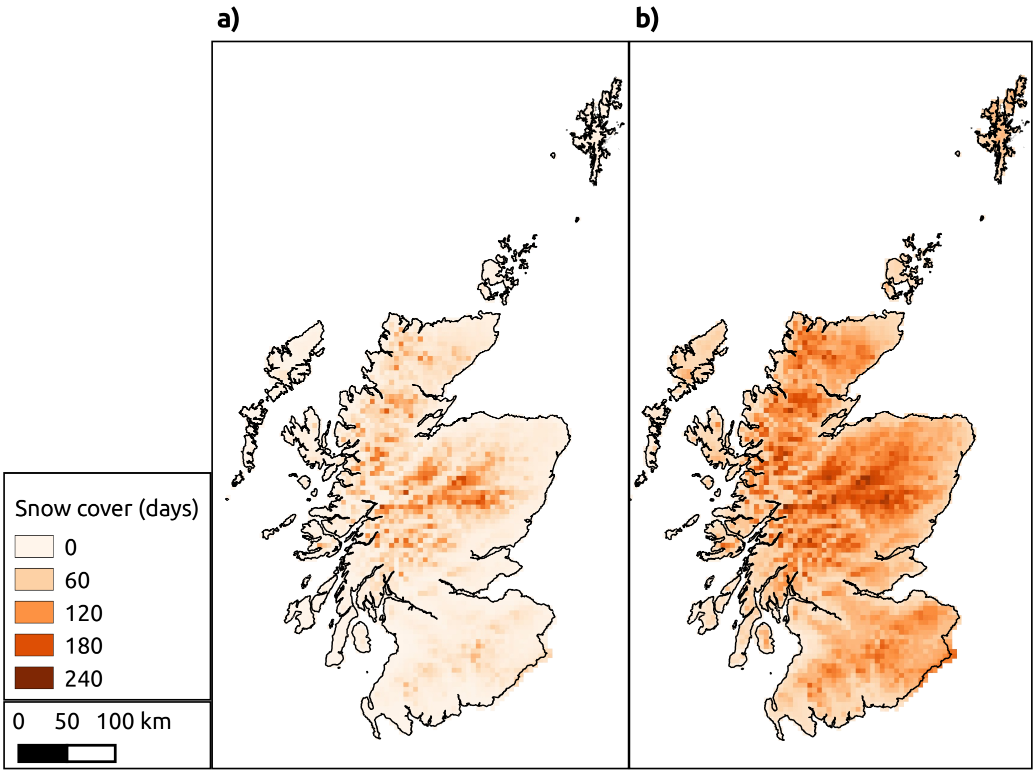


Figure 6.8: *a) 50% and b) 1% AEP for the number of days of snow cover.*

6.4 Discussion

The results of this chapter are novel and warrant publication. The general decrease of snow cover in eastern Scotland and a localised increase in snow cover in western Scotland supports an east-west precipitation trend split, where the west is getting wetter and the east drier (Macdonald and Phillips, 2006). The high proportion of precipitation as snowmelt (up to a median per annum of 42%) emphasises the importance of snow in Scottish hydrology and that more research is justified.

Estimated values of extreme snowmelt are important and those presented in Section 6.2.2 would benefit from refining when better estimates of high elevation precipitation are available. Others have previously considered the veracity of a design snowmelt rate of 42 mm/day for UK engineering hydrology, a digest of this work follows: Archer (1981) summarises the work of the Met Office in deriving extreme snowmelt estimates for use in dam design and other structures affected by floods: A snowmelt rate of 42 mm/day/m^2 was assumed as a realistic design maximum for annual exceedance probabilities (AEP) over 2% in the Flood Studies Report (Institute of Hydrology, 1975), which was then adopted as a design maximum in the Flood Estimation Handbook (Reed et al., 1999). This figure was reached by three methods: 1) by determining the melt rate from the duration of thaw of a measured initial SWE; 2) by converting snow depth to SWE, assuming a snow density and thereby determining daily rates of decline in water equivalent; 3) by determining snowmelt rate as a function of maximum temperature. Hough and Hollis (1997) test the assumption of the guidance that a 42 mm/day maximum melt rate should be applied across the UK. They used hourly reporting Met Office sites to provide melt totals for durations between three and 168 hours (including 24 hours); these were supplemented with high elevation climate stations to make further 24 hour estimates. An extreme value analysis was completed using these annual melt maxima and the AEP of 42 mm/day estimated. AEPs varied between 10% (Pennines and Scotland) and less than 0.1% (low elevation England). Finally they developed four linear models of snowmelt, dependant on altitude, northing, mean January temperature and windspeed. Their model using two weather parameters, temperature and windspeed, achieved the lowest RMSE (6.56 mm). From these studies and the work presented in this chapter, it becomes apparent that a single potential snowmelt rate for all of Great Britain is not appropriate. In some areas the snowmelt risk is underestimated by a large margin, but in most areas structures designed to a 42 mm/day standard are over engineered.

Extending the analysis presented in this chapter to the winter of 2013 to 2014 would be particularly interesting. During the 2013 to 2014 winter there was widespread flooding in southern England, while there were deep accumulations of snow in upland areas of Scotland. These snow accumulations resulted in many snow patches remaining on Scottish hills into the next winter (Cameron et al., 2015). However, an extension of this work will only be possible when the Met Office and CEH release further years of data to use as input for a snowmelt model. A logical next step is to re-run these analyses, beginning with the model runs from Chapter 5, with a range of possible parameter values to give uncertainty bounds for snow cover and snowmelt estimates.

CHAPTER 7
Conclusion

7.1 Summary of findings

In Chapter 1 the aim of this thesis was defined to: **demonstrate the importance of snow in a temperate climate - case study Scotland.** The objectives for achieving this aim were to:

- Show that a volunteer-collected, snowline-observation dataset can be used to quantify snow duration and melt
- Map and quantify the relationship between snow and the NAO index
- Quantify Scottish snow extreme value statistics, i.e. snow cover and snowmelt.

I have demonstrated the importance of snow in Scotland, through a literature review in Chapter 1. This search found Scottish snow impacts flooding, ecology, traffic, recreation and landforms. To support this, analysis in Chapter 6 quantified snowmelt as a proportion of precipitation; this is up to an annual median of 42% for the snowiest areas, although for lowland areas this figure is less than 5%.

Scottish SSGB data between 1945 and 2007 are now available in electronic, transcribed form. They were collected from 140 sites covering mainland Scotland and a number of islands. The longest station record is 52 years in length, which was collected at Couligarten and observed Ben Lomond. This transcribed dataset is stored in the Met Office MIDAS database and is available through the British Atmospheric Data Centre[1]. The SSGB advantages and disadvantages are largely governed by study scale. The main advantages are a long, 60 year, daily record of snow cover observations across Scotland, as recorded by knowledgeable and experienced local weather observers. The disadvantages are that the SSGB covers discrete locations, observed by recorders working in isolation, with missing and lost records caused by observer absence or reduced visibility. These enable the SSGB to be used at a mountain or catchment scale, or to provide spot checks for satellite and Met Office grid data when making national assessments. Hence, using a mixture of datasets to reduce uncertainty is potentially the best way forward. The SSGB offers 60 years of detailed daily records of snow cover from station level up to the highest mountains in Scotland; no other data product contains this resolution of information.

Spatial variability of snow cover is a big challenge, it is difficult to observe and quantify. This is typified by the contrasting results of UKCP09 snow and MODIS data correlations with NAO index (Chapter 4). I have overcome this to correlate snow cover with NAO by using disparate snow cover datasets, encompassing anecdotal

[1] http://badc.nerc.ac.uk

type data (Bonacina snowiness 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. This is in contrast to correlations with precipitation alone. Precipitation, mostly as rain, was found to correlate to a proxy of the NAO index strongest in western Scotland and insignificantly in eastern Scotland (Macdonald and Phillips, 2006). This contrast between spatial correlations of precipitation phases and NAO index is most likely due to the different temperatures experienced during positive and negative phases of the NAO. 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 increases by 6 to 16 days for each unit reduction in 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.

Chapters 5 and 6 presented a simple snow accumulation and melt model. This model was calibrated using Met Office point observations of snow depth and SSGB hillslope-scale snow cover data. The calibration of this model took a simplified approach and did not address equifinality or define uncertainty. The reasons for this were computing time and poor precipitation input data. Precipitation input data used in the snow model were shown (Section 3.7 to underestimate input to a mountainous catchment on the east side of the Cairngorms by a median value of 17%, when compared to river flow. The latter was a bigger restriction; even if it were possible to perfectly fit the model results to observations, underestimated precipitation at higher elevations would lead to erroneous results. Despite an underestimate of high elevation precipitation, meaning there is less potential snowpack to melt, the model simulated some high snowmelt rates. These high melt rates were generally confined to elevations above 400 m ASL, but even at 50% AEP some snowmelt exceeded 42 mm/day, which is the currently recommended maximum used in flood structure design (Reed et al., 1999). Considering snowmelt as an annual proportion of precipitation, allowed me to avoid the uncertainty of higher elevation precipitation. Results from this analysis showed a general Scotland-wide decline between 1960 and 2010 in snowmelt as a proportion of precipitation. However, upland areas around Ben Nevis showed the opposite; indicating that the highest mountains in the west of Scotland remain cold enough to accumulate snow even in a warming climate. The spatial organisation of snowmelt as a proportion of precipitation are, unsurprisingly, similar to a reduction in duration of annual snow cover; there is a widespread reduction, particularly in the east. Duration of snow cover results are less strongly correlated to NAO and show a weaker temporal trend (via correlation with year) than snowmelt and the extent of significant correlations less widespread.

This thesis is early work in the quantification of snowmelt, snow cover in Scotland. The following section contains potential subsequent work that falls into two categories: addressing limitations of this thesis and research derived from this thesis.

7.2 Scope for further work

As new snow datasets 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 better able to understand the link between snow cover and climate variability. Uncertainty also exists in the distribution of snow cover. The SSGB recorded at a hillslope scale, and so has inherent information as to the duration of snow cover on varying slope aspects. South facing slopes face the sun more than north facing slopes and are, hence, warmer; comparisons like this could be used to indicate what may happen in a warming climate to snow cover in Scotland.

Better use should be made of currently collected data. As this thesis has shown, new understanding can be found from re-analysing existing datasets like the SSGB. Hopefully this thesis can be a catalyst for transcription of the remaining SSGB records, held in the Met Office archives (Exeter) and the Manley Archives (Durham). Currently satellite observations of snow cover perform poorly in temperate, cloudy climates. Improving the classification of snow cover from satellite data when temperatures are close to 0 °C and there is cloud would be of obvious use to other temperate regions of the world. Results from this exercise could also be used to improve snow classification in the autumn and spring months of colder regions, where temperatures are closer to 0 °C and observation uncertainty consequently exists. The machine learning approach shown in Chapter 3, which used ground based observations from the SSGB to train a decision tree model to classify MODIS observations into snow cover should be explored further. This could include using other MODIS snow cover data products, for example the dataset which estimates the percentage of snow cover in each cell. To make results from satellite snow cover most usable in a water resources context a spatial reclassification model could be developed which considered river catchments split by elevation band and aspect. Splitting river catchments in this way would group topography into snow cover zones which had similar characteristics. However, care would be needed over scale and topographic generalisation as MODIS snow cover data are available on a 500 m grid and it would be challenging to translate this grid size to represent complex mountain topography.

Another question that remains to be answered includes whether a warmer climate will lead to a higher number of snow accumulation and melt cycles each winter. This could have one of two impacts: that with less time between melt phases less snow accumulates and so maximum melt rates are reduced, or that a warmer climate also brings more precipitation and the rate of snow accumulation increases, bringing more frequent snowmelt episodes which are of an equivalent size to those currently observed. The most prominent potential impact of a change in snowmelt would be on flood risk. As was demonstrated in Chapter 6, potential snowmelt is underestimated in UK flood risk assessments. Related work on snowmelt flood risk could investigate the impact of snowmelt on existing impoundment structures, e.g. dams, considering the potential risk of snowmelt to each structure, based on the results presented in Chapter 6.

Throughout this thesis I have detailed areas which I believe warrant further investigation, these are discussed in the following paragraphs. A priority for British snow modelling is an improvement in available input data. In Section 3.7 I detail the underestimation of precipitation by the CEH GEAR dataset in a high elevation, heavily snow influenced catchment. It would be relatively straightforward to estimate the water balance for a comprehensive number of river gauging stations across Great Britain, to see if the CEH GEAR underestimate is systematic. These results should be checked using observed precipitation lapse rates from a range of elevations.

An improved estimate of precipitation would enable the modelling exercise, detailed in Chapter 5, to be repeated with a more realistic value for water input. A flaw with the modelling presented in Chapter 5 is the limited number of parameter sets used during the grid calibration. This should be addressed and uncertainty estimates made of the model outputs.

With a climate baseline of snowmelt and cover estimates, the presented snow model could be run using future projections of precipitation and temperature to help understand the impact a changing climate could have on Scottish water resources. Another approach to this problem could be the use of SSGB data for calibration of more established and complex land surface models.

Much of the work of this thesis and potential subsequent research, described above, have wide applicability. A key challenge is how can these be incorporated into policy? What options are available for transferring hydro-meteorological, academic research into public and commercial use?

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Appendices

A. Snow model code

```
# ------------------------------------------
# Snow accumulation and melt model
# ------------------------------------------

model = function(st, temp.b=1, DDF=5.5, den=120, den.i=2.5,
            DDF.d=0.01, d.50=100){

   # st = precip and temp data
   # temp.b = temperature threshold for rain/snow
   # DDF = degree day factor
   # den = initial snow density
   # den.i = density increase (as (end-den)/(days-day0))
   # DDF.d = DDF decreaser for slower melt from more dense snow
            (as (DDF-end)/(end-den))
   # d.50 = depth (mm) at which cover is greater than 50%

# Results container
   d = data.frame(Date = character(nrow(st)+1),
                  SWE = numeric(nrow(st)+1),
                  Melt = numeric(nrow(st)+1),
                  PrecipEff = numeric(nrow(st)+1))

# Warmup row
   d$Date = as.character(c(st$Date[1]-1, st$Date))

# Time steps
   for (i in 1:nrow(st)){
      j = i+1

# Density estimate
      # 150 kg/m3 fresh, 250 kg/m3 after 30 days
      y = rep(0, length=nrow(d))
      y[d$SWE > 0] = 1
      # Count days with snow lying, reset at 0
      d$days = y * ave(y, c(0L, cumsum(diff(y) != 0)),
                   FUN=seq_along)
```

```
      # Make density a function of duration
      # den.i(250-den)/(30-1)
      d$density = round(den.i * d$days + (den - den.i))
      d$density[d$density<den] = 0
      if (st$meantemp[i] < temp.b){

# Accumulation model
        d$SWE[j] = d$SWE[j-1] + st$Precip[i]
        d$PrecipEff[j] = 0
        d$Melt[j] = 0
      } else {

# Melt model
        # DDF reduced when density higher
        pot.melt =
          round(DDF.d * d$density[i] + (DDF - DDF.d))
               * (st$meantemp[i] - temp.b)
        # More SWE than melt
        if (pot.melt < d$SWE[j-1]){
          d$SWE[j] = d$SWE[j-1] - pot.melt
          d$Melt[j] = pot.melt
        # No SWE
        } else if (d$SWE[j-1] == 0) {
          d$SWE[j] = 0
          d$Melt[j] = 0
        # Less SWE than melt, but more SWE than 0
        } else {
          d$SWE[j] = 0
          d$Melt[j] = d$SWE[j-1]
        }
        d$PrecipEff[j] = st$Precip[i] + d$Melt[j]
      }
    }

# Snow cover
  d$Date = as.Date(d$Date)
  d = merge(st, d, by="Date", all.x=T)
  # Add model snow/no snow
```

```
    d$Model = 0
    d$Model[d$SWE>0] = 1
    # Add snow depth (mm)
    x = 10 / (d$density / 100)
    d$depth = round(d$SWE * x)
    d$depth[is.nan(d$depth)] = 0
    # Snow cover > 50%
    d$M50 = 0
    d$M50[d$depth>d.50] = 1
    d
}
```

B. Peer reviewed publications

Scottish Geographical Journal, 2014
http://dx.doi.org/10.1080/14702541.2014.900184

The Historical Snow Survey of Great Britain: Digitised Data for Scotland

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ABSTRACT *Mountain snowline is important as it is an easily observable measure of the phase state of water in the landscape. Changes in seasonal snowline elevation can indicate long-term trends in temperature or other climate variables. Snow-cover influences local flora and fauna, and knowledge of snowline can inform management of water and associated risks. Between 1945 and 2007 voluntary observers collected a subjective record of snow cover across Great Britain called the Snow Survey of Great Britain (SSGB). The original paper copy SSGB data is held by the Met Office. This article details the digitisation of the Scottish SSGB data, its spatial and temporal extents, and a brief example comparison of Met Office snow-lying gridded data. The digitised SSGB data are available from the Met Office authors.*

KEY WORDS: snow survey, snowline, Scotland, mountain, hydrology

1. Introduction

Snowline is the visual boundary between snow cover and no snow on a hillside. Records of snowline over time are important as they can provide an indication of climate, ecological and habitat change (Harrison *et al*. 2001; Trivedi *et al*. 2007), help understand large hydrological events (Black & Anderson 1993) and justify winter sports potential (Harrison *et al.* 2001). While undertaking a modelling exercise on snow, Dunn *et al*. (2000) discussed the accumulation, redistribution and ablation of snow in Scotland. The salient points are the high variability and often temporary nature of snow in Scotland. This is caused by colder periods often interspersed with warmer spells, alternating accumulation and melt. It is often windy in Scotland, which can enhance ablation or redistribute snow during cold periods. Therefore, precipitation occurring at higher elevations as snow can melt or be redistributed according to topography and wind direction, resulting in non-uniform snow-cover distribution. From this we can infer that Scottish snow is often ephemeral in time and space, leading to variations between different hill slope aspects, elevations and

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areas. These local conditions create uncertainty when interpolating snow cover from low-lying, discrete observations to mountain environments.

There are already digital snow-lying data sets available for Great Britain. These fall into two categories: point observations and gridded data. The former includes data collated by the Met Office from their network of automated gauges and observers, which record when snow lies on the ground each day. The Met Office also issued a data set as part of the UKCP09 (United Kingdom Climate Projections 2009) assessment that detailed snow lying between 1971 and 2006 on a 5 km grid covering the UK.

The Met Office station observations are discrete and, as discussed later, only available for lower elevations. They were collected at manual Met Office weather sites by observers who noted if snow was lying at the station, and if so with what depth. These observations were interpolated to form the Met Office gridded snow-lying data set by Perry and Hollis (2005). Perry and Hollis (2005) used multiple regressions with geographic factors like elevation and percentage of each grid cell covered with open water as variables to develop the gridded data. The data set provides the number of days with snow lying per month on a grid of 5 km resolution.

Data from satellite instruments are used to derive global snow-cover products, available from 1966 onwards (Matson 1991). Visible satellite remote sensing methods are not ideal for measuring snow cover in Scotland because snow cannot be viewed through the frequent cloud cover. Windows of opportunity for sampling may occur less than once a week (Slater *et al*. 1999). Working in North America, Tang and Lettenmaier (2010) found that MODIS (Moderate-resolution Imaging Spectroradiometer, Hall *et al*. 2002) had the greatest uncertainty measuring snow covered area during the autumn and spring months, when snow was accumulating or ablating. Dong and Peters-Lidard (2010) investigated the relationship between air temperature and MODIS snow covered area error; as expected from the findings of Tang and Lettenmaier (2010), error increased with temperature. This error was quantified to be 80% for temperatures above 15°C reducing to 10% for temperatures below 0°C or −5°C, location dependent. This is of particular note for remote sensing of snow in Scotland where temperatures do not often stay far below freezing. Snow in Scotland is often wet, which also provides a challenge to microwave satellite observation. Rees and Steel (2001) found that for some types of vegetation cover, notably that without trees, they were able to use remote sensing to detect wet snow by considering a reduction in backscatter attributable to the snow.

The subject of this paper, The Snow Survey of Great Britain (SSGB), is a volunteer observer collected data set that offers snow cover data. It was used to produce the annual publication ‘Report on the Snow Survey of Great Britain’ between 1947 and 1992. The title of this varied through time but the content was consistent, an example is Hawke and Champion (1949). The annual SSGB reports from autumn 1953 until spring 1992 are available from the Met Office (Met Office SSGB). Until now, most of the SSGB data have existed only in paper form and little use had been made of them. Jackson (1978) used the SSGB to discuss the frequency and extent of snow cover in Great Britain. Jackson (1977) also used these SSGB data to help complete a snow index of years from 1875/1876 to 1974/1975. Trivedi *et al*. (2007) digitised data for the Ardtalnaig station on Loch Tay for use in vegetation analysis, undertaking data quality assurance by checking other meteorological stations within the station vicinity. Trivedi *et al*. (2007) found that further use of the SSGB would be warranted as it gave a deeper insight into climate change.

This paper covers the history of the SSGB, the area observed in Scotland, the digitisation process and digital data availability, a limited comparison to another snow cover data set to demonstrate the strengths and weaknesses, and a discussion on the application of the SSGB.

2. History

The Snow Survey of the British Isles began in 1937 (Jackson 1978) and was directed by Mr. Gordon Manley (Anon. 1947). After a hiatus during World War II, the snow survey was resumed in autumn 1946 by the British Glaciological Society. The principle aim was to 'secure representative data relating to the occurrence of snow cover at different altitudes in the various upland districts over the period October to June' (Anon. 1947). The reorganisation of the survey was undertaken by Mr. E.L. Hawke, Honorary Secretary of the Royal Meteorological Society and a member of the British Glaciological Society.

In 1953 the collation of data by the British Glaciological Society ceased and was thereafter undertaken by the British Climatology Branch of the Meteorological Office (Met Office 1954). Hawke and Champion (1954) report in their final snow survey summary that the number of participants had increased from 120 to nearly 400, including land stations, lighthouses and light-vessels.

Between 1946/1947 and 1991/1992, an annual report was produced summarising the data returns for the season. Until 1954 this report was issued by the British Glaciological Society. From 1954 onwards, the Met Office produced the annual SSGB report. The survey was administered by the Met Office from the Scottish Weather Observations Centre in Edinburgh, where data were also collated. In 1992, due to the dwindling interest and lack of funding, the annual publication was withdrawn.

Despite the withdrawal of the annual summary publication, data continued to be collected until 2007. In 1994 there was a review of the 77 participating stations and those deemed not to view high ground or those that duplicated other stations were withdrawn from the survey. Thirty-two stations in Great Britain remained after the review. The observer instructions were also updated following the 1994 review; the most important change was that volunteers were no longer required to note when an observation was obscured by cloud or fog or the observer was absent, although some continued to do so.

Scottish data between Autumn 1945 and Summer 2007 are stored in the Met Office archives in Edinburgh. This pre-dates the beginning of the survey as noted by (Anon. 1947). A likely reason for this is that stations continued reporting snow cover during the Second World War. Some earlier records have been located in the Gordon Manley papers archive (Manley, see references), but these have not been viewed or digitised. The Met Office archive in Exeter holds records for English and Welsh stations between 1946 and 1992.

3. Coverage

The SSGB was collected across Great Britain, but digitisation has only been undertaken for Scottish records, as few English and Welsh records are kept in the Edinburgh archives. Records for 145 sites in Scotland were found within the Met Office archive; the most southerly is Kirkbean near Dumfries and the most northerly is Collafirth Hill on the Shetland Isles. The elevation range from which observations were made is from sea level to 724 m ASL (above sea level), at Lowther Hill near Wanlockhead. Figure 1 shows the

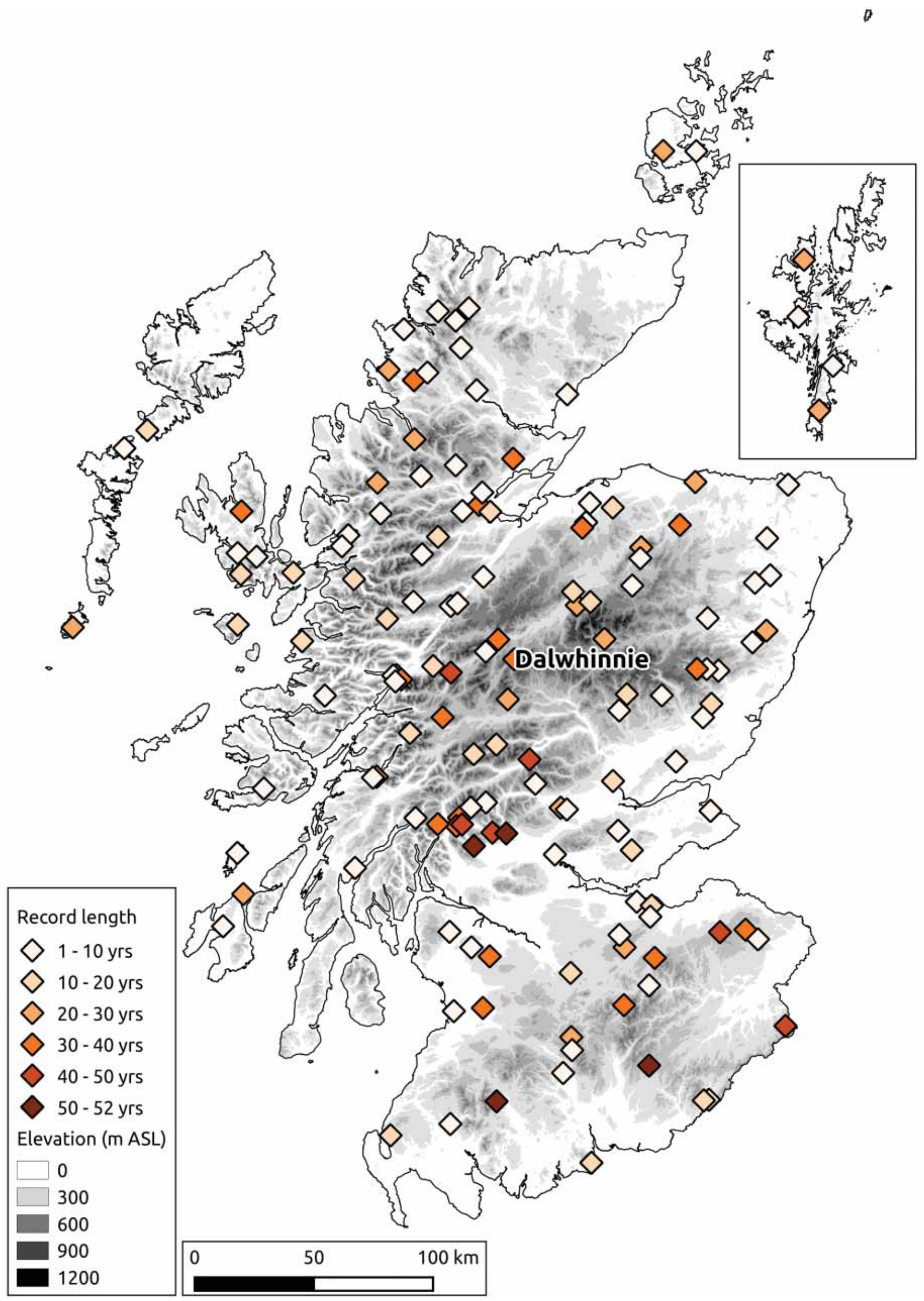


Figure 1 Location of Scottish SSGB stations graded by record length in years. Contains Ordnance Survey and Met Office data © Crown copyright and database right 2014.

distribution of the recording stations, with each station colour graded to indicate its record length. Table 1 details the 10 stations with the longest records.

The observers looked out on the hills that surrounded their location and noted at what level snow was lying. Elevations were grouped into 150 m bands from 0 to 1200 m ASL or 500 feet increments earlier in the record, with most stations supplying metric returns by the early 1980s. The observers were asked (taken from January 1992 instructions) to record at 0900 'or thereabouts' when snow or sleet was falling at station level and if snow was lying at station level, with depth. Lying snow was to be recorded at visible elevations when it covered greater

Table 1 Ten longest operating SSGB stations

name	visible hills	record length (years)	beginning	ending
Couligarten	Ben Lomond	52	1954	2006
Eskdalemuir	Ettrick Pen	51	1954	2005
Forrest Lodge	Corserine, Galloway	51	1954	2005
Loch Venachar	Ben Ledi	50	1954	2004
Ardtalnaig	Ben Lawers	50	1954	2004
Sourhope	Cheviot	49	1954	2003
Fersit	Creag Meagaidh	48	1954	2002
Cassley power station	Ben More (Assynt)	46	1960	2006
Hopes Reservoir	Pentlands	45	1957	2002
Stronachlachar	Stob Choin	43	1954	1997

than half the ground at a given elevation. Finally they were asked to record when fog or cloud obscured observation. The results of this process can be seen in Figure 2, an example return card from Dalwhinnie; note the visible hills listed.

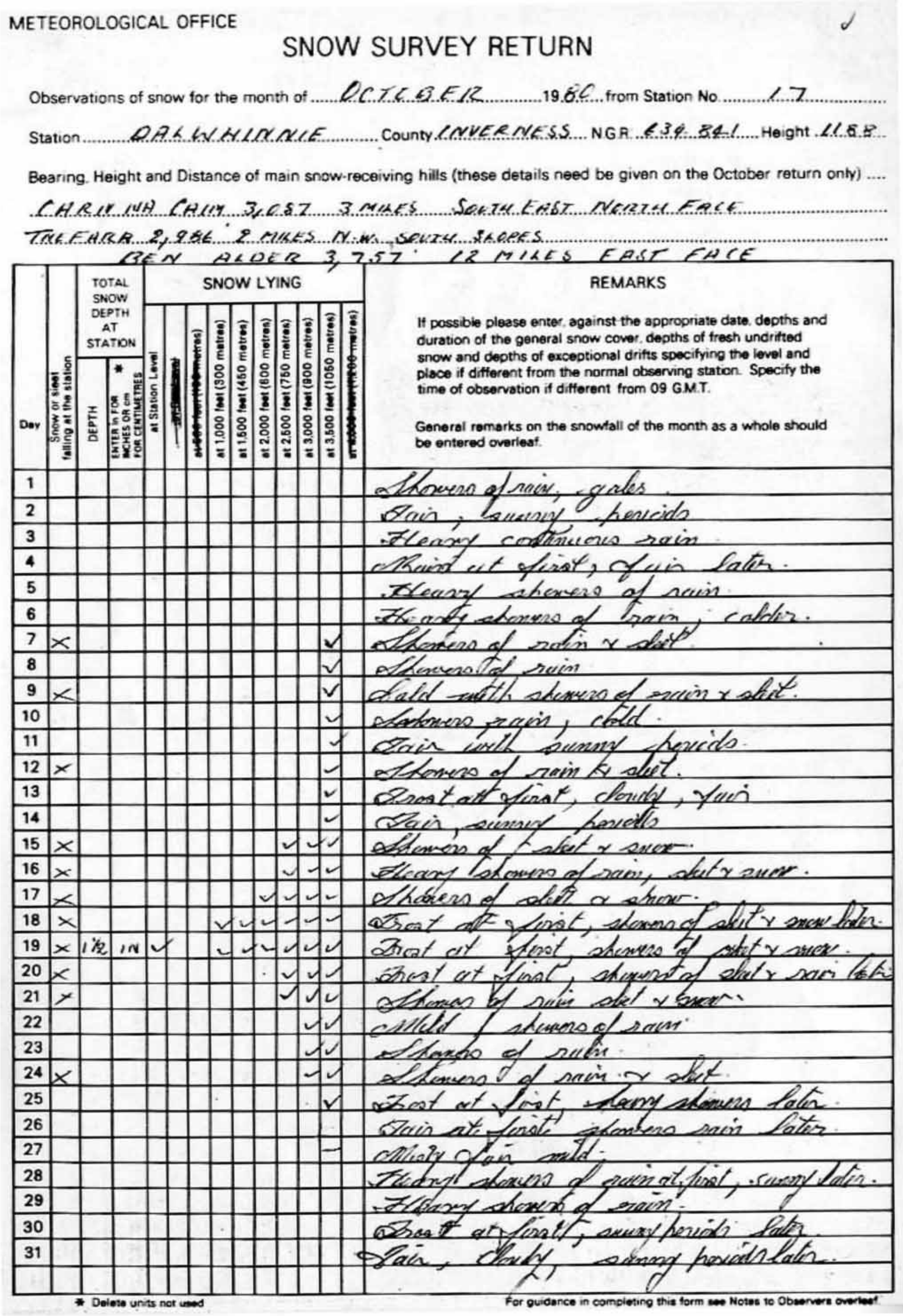
We have assessed the area visible from each SSGB site using line of sight analysis in the GIS software GRASS (GRASS Development Team 2013). Using the Panorama digital terrain model (Ordnance Survey), an area was calculated which shows the land visible from each SSGB station based on grid reference and a viewing elevation of 10 m. The visible areas were combined for the 145 sites and split into SSGB elevation bands. Each SSGB visible area band was then divided by the area of Scotland in that elevation band, giving percentages of each elevation band visible. These are compared in Table 2 to the number of Met Office stations reporting snow lying in each elevation band. The SSGB covers a greater proportion of higher than lower elevations and the Met Office stations are the inverse of this, in-line with the 1946 aims of the survey (Anon. 1947).

From studying the returns and the annual reports, it appears that some hard copy data are missing. While disappointing, it is unsurprising as the paper records have changed hands and locations through the years. Figure 3 shows the number of stations in Scotland for which paper copies exist, by year. Data are missing from 1994 as only three station records were found for that year. This coincided with the station review and perhaps there was confusion over which stations were still to submit reports. Annual SSGB summary reports before 1955 indicate nearly 400 stations across Great Britain, but fewer than 30 were found in the archives. According to Jackson (1978), there are data from 1937 onwards; some of this is in the Manley archives (Manley, see references).

4. Digitisation

For each station encountered, metadata from the SSGB return sheets were noted. This information was: site name; elevation (m ASL); Easting; Northing; hills visible; comments. These data are useful for identifying sites and establishing what was visible from each location. The comments section was used to record notes on data quality. For example, Brig-O-Turk recorded lowest lying isolated snow patch, not level of snow cover greater than 50%. Brig-O-Turk also noted where continuous snow lay in the comments; this value was used in the digitisation.

Where noted, missing values when observation was obscured by poor visibility or the observer was absent were digitised. However, these cannot always be distinguished from


METEOROLOGICAL OFFICE

SNOW SURVEY RETURN

Observations of snow for the month of OCTOBER 1980 from Station No. 17

Station DALWHINNIE County INVERNESS NGR 634 841 Height 1168

Bearing, Height and Distance of main snow-receiving hills (these details need be given on the October return only) ....

CHRIN NA CAIM 3,087 3 MILES SOUTH EAST NORTH FACE

THE FARR 2,986 2 MILES N.W. SOUTH SLOPES

BEN ALDER 3,757 12 MILES EAST FACE

REMARKS: If possible please enter, against the appropriate date, depths and duration of the general snow cover, depths of fresh undrifted snow and depths of exceptional drifts specifying the level and place if different from the normal observing station. Specify the time of observation if different from 09 G.M.T.

General remarks on the snowfall of the month as a whole should be entered overleaf.

Day	Snow or sleet falling at the station	Total snow depth at station: Depth	Remarks
1			Showers of rain, gales
2			Fair, sunny periods
3			Heavy continuous rain
4			Rain at first, fair later
5			Heavy showers of rain
6			Heavy showers of rain, colder
7	×		Showers of rain & sleet
8			Showers of rain
9	×		Cold with showers of rain & sleet
10			Showers rain, cold
11			Fair with sunny periods
12	×		Showers of rain & sleet
13			Frost at first, cloudy, fair
14			Fair, sunny periods
15	×		Showers of sleet & snow
16	×		Heavy showers of rain, sleet & snow
17	×		Showers of sleet & snow
18	×		Frost at first, showers of sleet & snow later
19	×	1½ IN	Frost at first, showers of sleet & snow
20	×		Frost at first, showers of sleet & snow later
21	×		Showers of rain sleet & snow
22			Mild showers of rain
23			Showers of rain
24	×		Showers of rain & sleet
25			Frost at first heavy showers later
26			Fair at first showers rain later
27			Misty fair mild
28			Heavy showers of rain at first, sunny later
29			Heavy showers of rain
30			Frost at first, sunny periods later
31			Fair, cloudy, sunny periods later

* Delete units not used

For guidance in completing this form see Notes to Observers overleaf

Figure 2 Example SSGB return from Dalwhinnie in October 1980. Contains Met Office data ©Crown copyright and database right 2014.

Table 2 Percentage of each elevation band in Scotland, percentage of each elevation band visible from SSGB stations, compared to percentage of Met Office Stations (total 281) sited in each elevation band

elevation (m ASL)	Scotland (%)	SSGB visible (%)	Met Office stations (%)
0–150	41	12	75
150–300	28	10	21
300–450	17	9.9	3.2
450–600	8	11	0.36
600–750	4.1	11	0.36
750–900	1.6	13	0
900–1050	0.36	17	0
1050–1200	0.073	22	0
1200 and above	0.0079	37	0

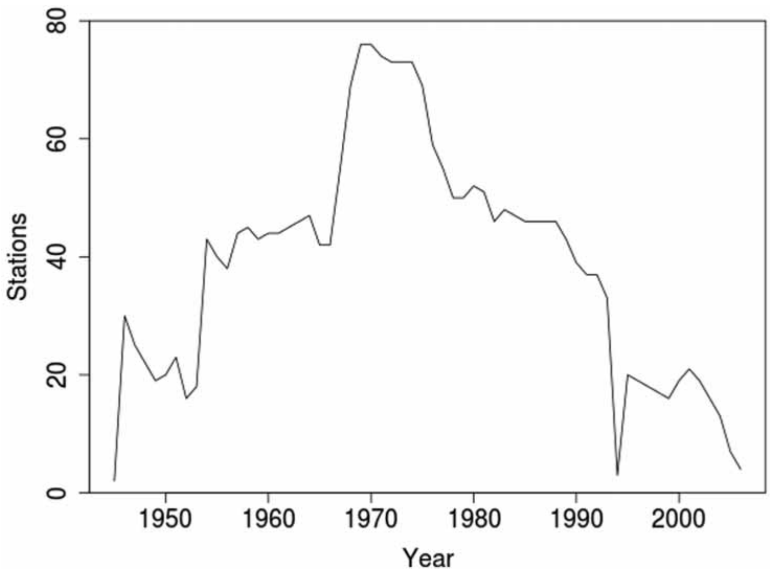


Figure 3 Number of Scottish SSGB stations found within the Scottish Met Office archives with data available by year.

when there was no snow. Quality assurance was undertaken to check for typographical errors, but no further data checks were carried out.

Following digitisation, data were uploaded to the Met Office database MIDAS (Met Office Integrated Data Archive System) and is now managed by the Met Office and is available through the Met Office authors (shona.hogg@metoffice.gov.uk or lynne.chambers@-metoffice.gov.uk). The SSGB data set will eventually be available through the British Atmospheric Data Centre (BADC).

5. Data Comparison

5.1. Method

A data comparison was made between the Met Office snow-lying grid and the SSGB as both cover a large range of elevations, these data were compared for the Dalwhinnie station. Dalwhinnie was chosen as it has a long record (39 years from winters 1967/1968 to 2006/2007, missing 1994) that overlapped the Met Office grid record, and it has a good range of visible elevations from the Spey valley at 350 m ASL to Ben Alder at 1148 m ASL. Visible elevations were established from the SSGB return and verified by a GIS line of sight analysis, using the Ordnance Survey Panorama data (Ordnance Survey), shown in Figure 4.

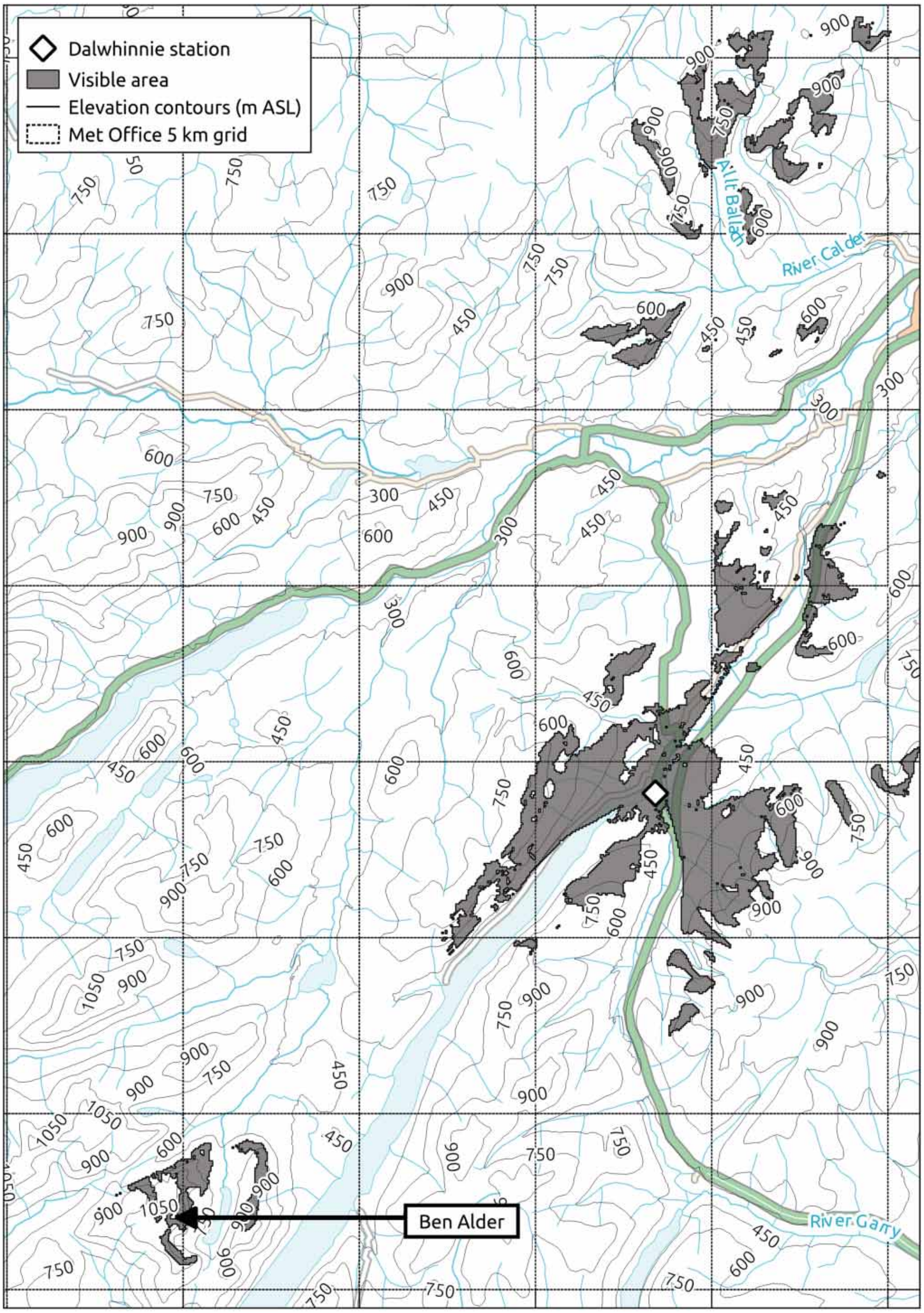


Figure 4 Line of site analysis for Dalwhinnie SSGB station, showing Ben Alder. Contains Ordnance Survey and Met Office data ©Crown copyright and database right 2014.

The Met Office grid data use, amongst others, Dalwhinnie station data. Data collection began on 1 September 1973 and ended on 31 January 2007. There were whole months missing of October and November 1973, January 1978 and also missing data from May 1995 until November 1996. The Met Office grid was interpolated from other reporting stations outside the observed time periods. The closest with snow-lying data for the 95/96 winter is Dall Rannoch School, approximately 30 km to the south.

The monthly Met Office grid data were extracted for the grid cells covering Dalwhinnie and Ben Alder. These were converted to snow years defined, for the purposes of this comparison, as from the beginning of September until the end of August. The mean elevation for these two grid cells were calculated from the Ordnance Survey Panorama as 485 m ASL for the Dalwhinnie cell and 821 m ASL for the Ben Alder cell. The altitude of Dalwhinnie station is 362 m ASL.

The SSGB Dalwhinnie data were then lumped into two groups with snow line of 450 m ASL and below and a snowline of 900 m ASL and below, to correspond with snow lying at the elevations of the Dalwhinnie and Ben Alder grid cells.

A summary of the Met Office grid and SSGB data sets for the Dalwhinnie and Ben Alder grid cells is shown in Table 3. In order to fill gaps in the SSGB due to missing returns the days with snow lying at the Dalwhinnie station were added to the SSGB record for Ben Alder and Dalwhinnie. Days of snow lying per year in the Met Office grid were subtracted from those in the revised SSGB for both Dalwhinnie and Ben Alder. These differences were plotted as time series with box and whisker plots to show data spread (Figure 5). For comparison, the number of missing observations per year was also plotted. Missing values comprise two types: those when no monthly return was submitted or has been lost, and when observation was not possible due to observer absence or reduced visibility. The revised SSGB values were compared to the Met Office grid for Dalwhinnie and Ben Alder (Figure 6) as scatter plots.

5.2. Results

Table 3 compares Ben Alder and Dalwhinnie average grid cell elevations using the SSGB and Met Office grid. Of note is the similarity in days snow lying between Ben Alder and Dalwhinnie according to the Met Office grid, this appears unrealistic as snow often falls more frequently and lies for greater periods at higher elevations. The SSGB values have a greater spread, with the mean value for Ben Alder within 7% of the Met Office grid maximum.

Figure 5 shows the difference between the SSGB and Met Office grid for each cell. It was expected that the Dalwhinnie difference would be above zero for winters in which data from

Table 3 Comparison between days of snow lying per winter at Ben Alder and Dalwhinnie, elevation averaged for 5 km grid cell, using SSGB and Met Office grid

	Met Office grid		SSGB	
	Dalwhinnie	Ben Alder	Dalwhinnie	Ben Alder
Minimum	10	25	23	36
Maximum	114	120	126	172
Mean	47	60	63	112
Standard deviation	23	21	27	40

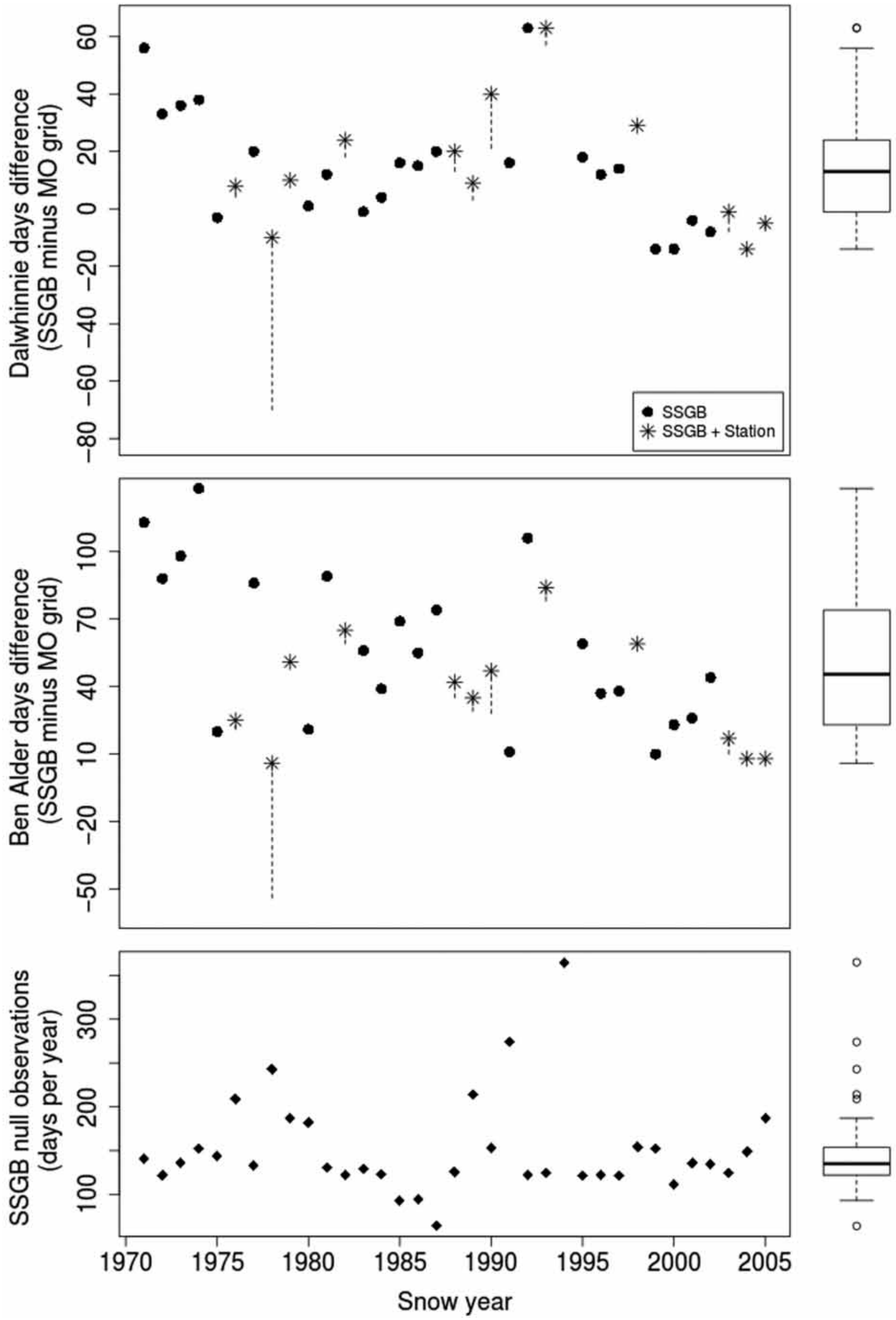


Figure 5 Difference between SSGB and Met Office grid data at Dalwhinnie and Ben Alder, including median and quartiles. The SSGB data was selected to match the average elevation of each Met Office grid square. Where SSGB returns were missing, Met Office station snow-lying data have been added to SSGB records, adjustment is indicated by dashed line from the original SSGB position to the revised value, marked by an asterisk. Numbers of missing values for the SSGB are also shown.

the station were used in deriving the gridded product because the altitude of Dalwhinnie station is 362 m ASL while the grid square average is 485 m ASL. The data distribution for Dalwhinnie is not symmetrical around zero, but have a mean of 14 days and a standard

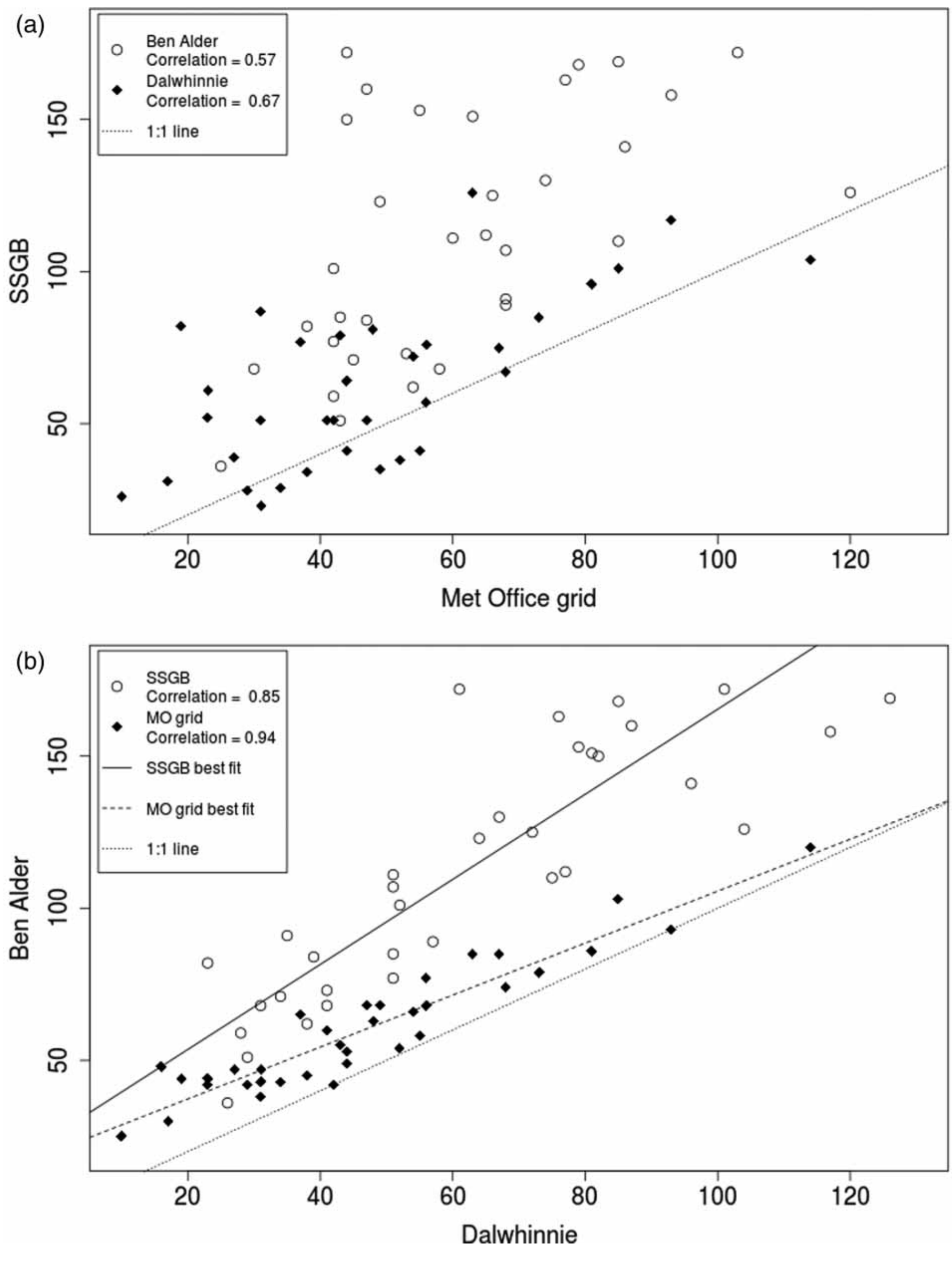


Figure 6 (a) Comparison between Met Office grid and SSGB numbers of days of snow lying per snow year for each site. (b) Comparison between sites for Met Office grid and SSGB numbers of days of snow lying per snow year.

deviation of 21 days. There is a greater variation in data than expected, as it is reasonable to suppose the SSGB was collected by the same observer who recorded the Met Office station lying data used to interpolate the Met Office grid. Some of the higher values coincide with time periods when no snow-lying observation was being made at Dalwhinnie, notably 1971 and 1972. However, some other high values do not match. The greater difference lies with the Ben Alder grid cell data. The mean of these differences is 48 days with a standard deviation of 36 days, indicating that the Met Office grid underestimates the days of snow cover at higher elevations. An outlier was the 1978/1979 winter, during which the SSGB recorded

54 fewer days with snow than the Met Office grid estimated at Ben Alder. This does not coincide with a year of high missing observations, but the SSGB returns for December, February and March were missing. The 1979 snow survey report (Met Office 1979) describes the season as having frequent snow cover with over twice the 1941–1970 average. The anomaly is caused by the three months of missing returns during the peak snow-lying season: the Met Office Dalwhinnie station data recorded snow lying for nearly all of February and March. In total 58 days with snow lying at the Dalwhinnie station were recorded during December, February and March over the 1978/1979 winter. With these added to the SSGB, the outlier is reduced. This process was repeated for other months with missing SSGB returns, shown in Figure 5 using a dashed line and asterisk.

The two scatter plots comparing sites and data sets in Figure 6 show broadly positive correlation. The Met Office grid are most strongly related, correlation 0.94, Figure 6(b), as both sites are compiled from the same data and extrapolated to the higher elevation. The SSGB correlation for Figure 6(b) is 0.85. Figure 6(a) shows a weaker correlation between the data sets at each site than each data set shows with itself in Figure 6(b), correlation of 0.67 for Dalwhinnie and 0.57 for Ben Alder.

6. Discussion

The Met Office gridded snow-lying data set has value for national assessments. However, there are two key limitations for use at a local scale: the spatial resolution of the grid is coarse and the underlying observations used to create the grid have been extrapolated horizontally and vertically. The 5 km cell covering Dalwhinnie, for example, varies in elevation from 350 to 858 m with a mean of 485 m. It is challenging in environmental analysis to work with a single elevation value for a large area, as variation occurs over small vertical and horizontal distances. With nearly all Met Office snow-lying observations recorded at low level and interpolated into mountainous areas, there is uncertainty in a data set when the grid cell covers an area with a large elevation range. This is re-enforced by the small difference in number of days with snow lying between Ben Alder and Dalwhinnie as given by the Met Office grid.

The SSGB is not without its limitations, prominent on this list is the observer error. For example, the observer for Blair Castle Gardens stated an early submission that they did not have access to a ‘local’ map giving exact elevations. While this is unfortunate, there is still great value in these Blair Castle data as they are relative to themselves and the observer would have known the surrounding area well. In contrast, Crathes Castle station was staffed by Adam Watson, who would have had an excellent understanding of the lie of land and the snow conditions on it, as evidenced by his snow patch work (Watson & Cameron 2010; Watson *et al*. 2011).

Known missing data caused by cloud cover, observer absence or a missing return marks time periods of data uncertainty. What is more challenging is the unknown missing data when an observer submitted a return but did not indicate cloud, fog or absence: this would be interpreted as no snow. When working with a small number of sites or a data period, this should be verifiable by correlating general weather observations, particularly cloud cover, visibility and temperature, with gaps in the SSGB record. For the latter part of the record, the observations can be checked against satellite data, although this may not be straightforward: when cloud cover obscured the SSGB observations, it could also have obscured visible satellite observations; this would not be the case with a cloud inversion below the snowline. Known missing values could be infilled using machine learning like self-organising maps (Mwale *et al.* 2012), although this relies on the SSGB observations and their inherent uncertainty.

7. Conclusion

A newly digitised data set of snow cover in Scotland from 1945 until 2006 snow years is presented. It is taken from 145 sites covering mainland Scotland and a number of islands. The longest station record is 52 years in length at Couligarten observing Ben Lomond.

The digitised data are stored in the Met Office MIDAS database and is available from the Met Office authors and eventually through BADC. Before use, it is suggested that some quality assurance should be undertaken to ensure that these data are fit for the purpose. This could include comparing the SSGB snow cover to nearby Met Office station snow lying, temperature and precipitation data, satellite snow-cover observations or avalanche survey records.

The SSGB advantages and disadvantages are largely governed by the study scale. The main advantages are a long, 60 year, daily record of snow-cover observations across Scotland as recorded by knowledgeable and experienced local weather observers. The disadvantages are that the SSGB covers discreet locations, observed by recorders working in isolation, with missing and lost records due to observer absence or reduced visibility. These lend the SSGB to be used at a mountain or catchment scale, or to provide spot checks for satellite and Met Office grid data when making national assessments. Hence, using a mixture of data sets to reduce uncertainty is potentially the best way forward. The SSGB offers a detailed daily record of snow cover from the station level up to the highest mountains in Scotland; no other snow cover data product contains this resolution of information for Scotland.

Acknowledgement

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Scottish snow cover dependence on the North Atlantic Oscillation index

Michael Spencer and Richard Essery

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).

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).

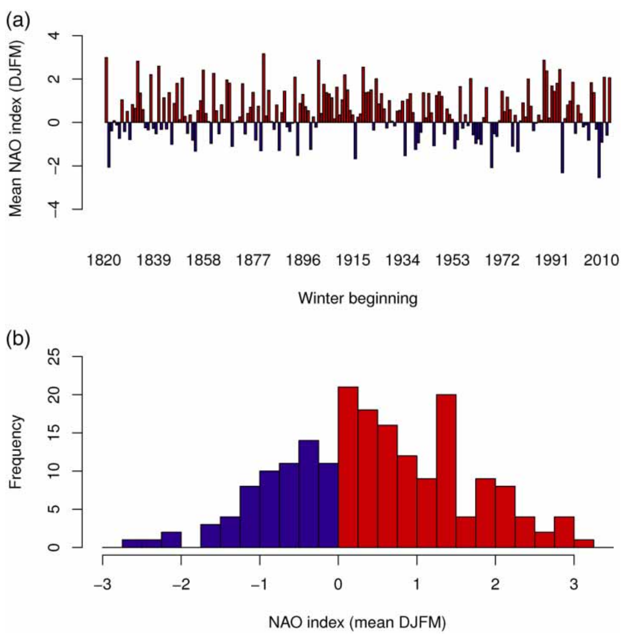

Figure 1 | Mean DJFM NAO index shown: (a) through time and (b) as a histogram.

UKCP09

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

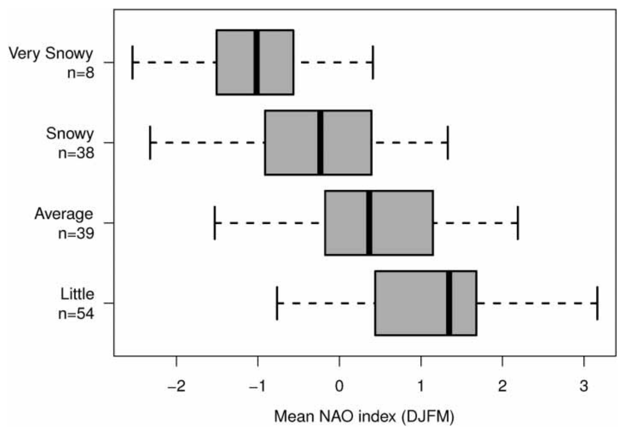

Figure 2 | Boxplots (median, upper and lower quartiles and range) showing winter NAO index grouped by Bonacina snowiness categories.

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

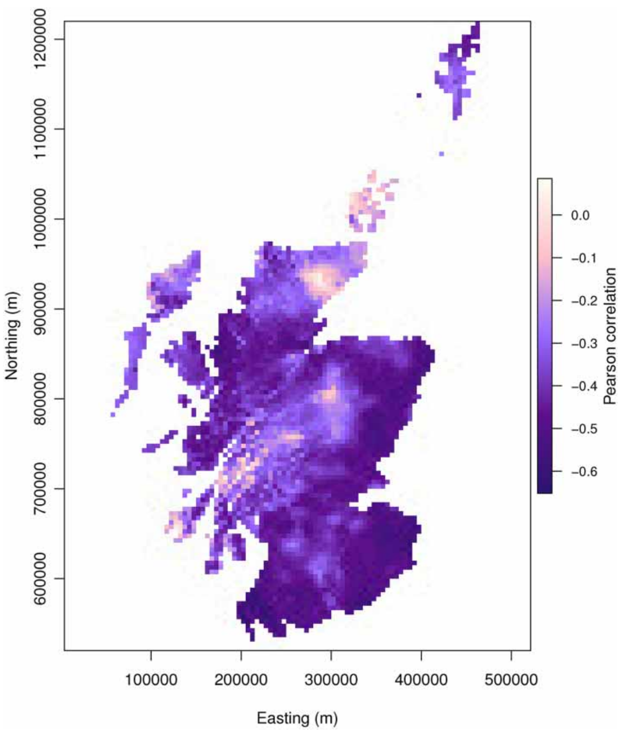

Figure 3 | Map of Pearson correlation values between UKCP09 snow and the NAO index. Contains Met Office data © Crown copyright and database right 2015.

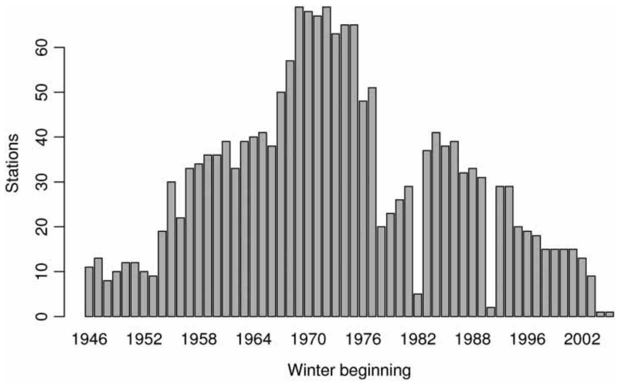

Figure 4 | Number of SSGB stations each year recording all 6 months between November and April.

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.

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

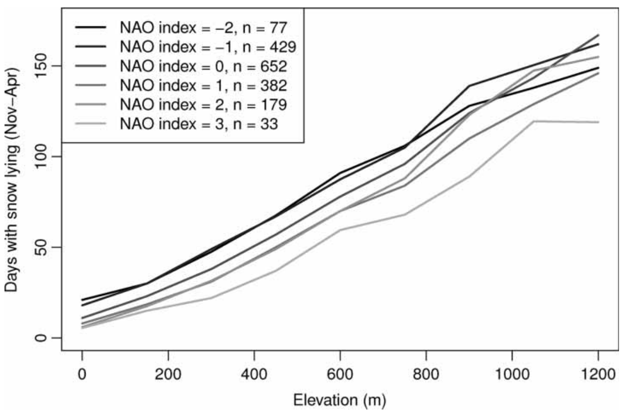

Figure 5 | Snow cover duration curves derived from SSGB data between 1946 and 2006 (November to April), grouped by (rounded) mean DJFM NAO index.

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).

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

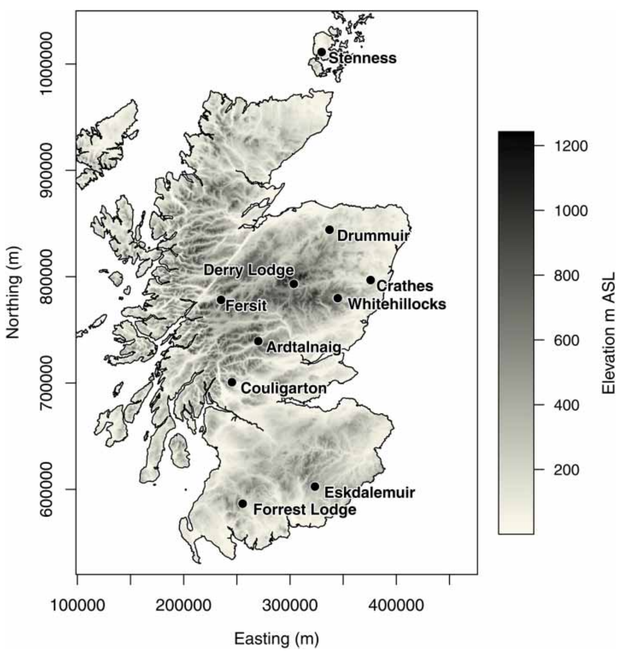

Figure 6 | Selected SSGB station locations. Contains Ordnance Survey data © Crown copyright and database right 2015.

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.

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

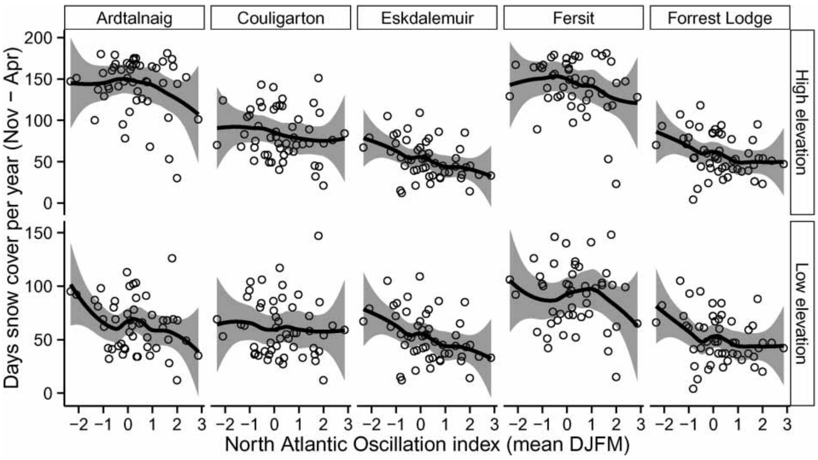

Figure 7 | Long-record SSGB stations snow cover plotted against the NAO index, shown with a LOESS and 95% confidence bounds.

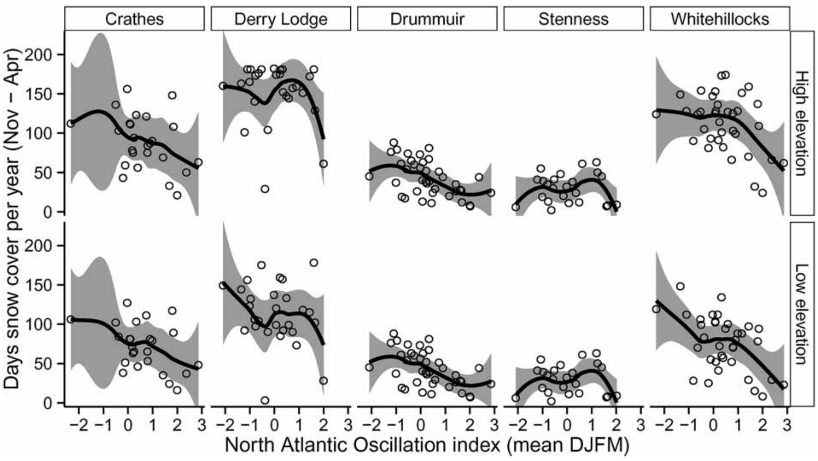

Figure 8 | Eastern and Orkney SSGB stations snow cover plotted against the NAO index, shown with a LOESS and 95% confidence bounds.

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

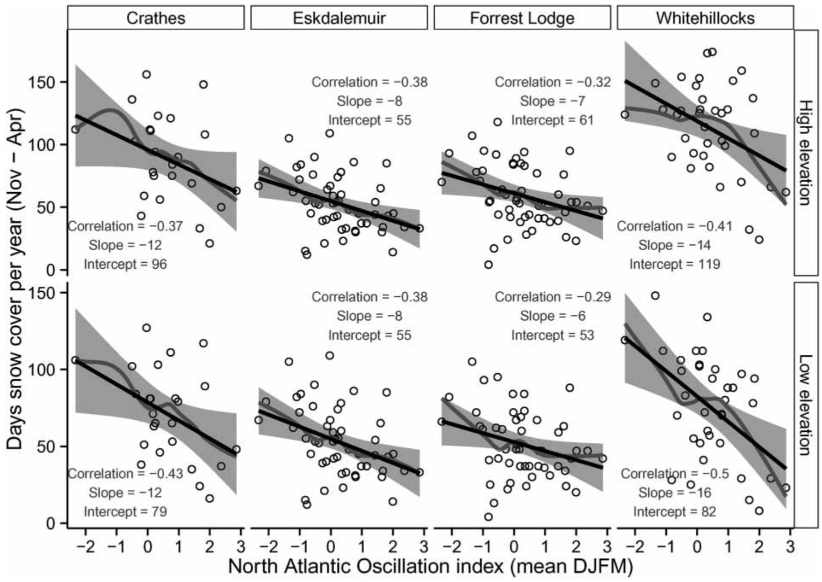

Figure 9 | Comparison between days of snow cover at select SSGB stations in years that reported all months between November and April and the NAO index. Shown with a linear model with 95% confidence bounds and a LOESS smoother (dark grey) for comparison.

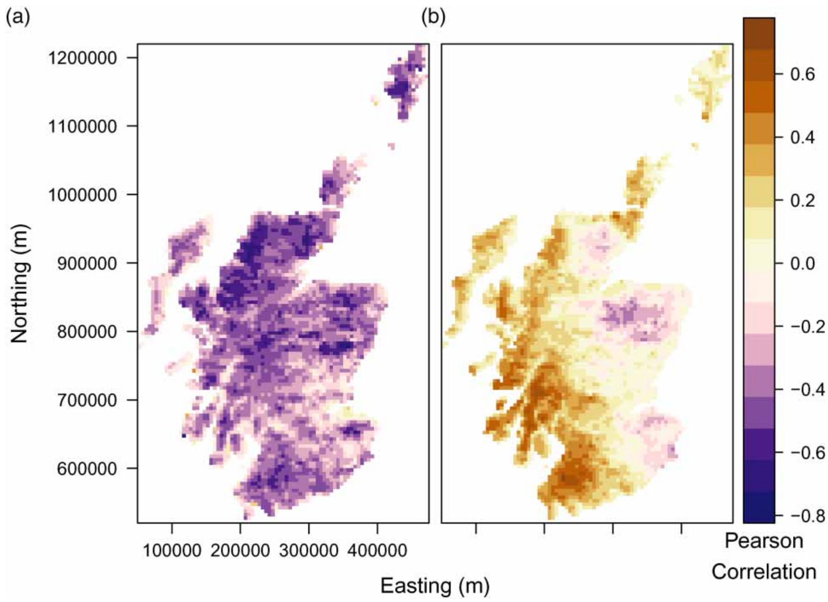

Figure 10 | (a) Correlation between number of days MODIS recorded snow cover each winter (November to April) and the mean DJFM NAO index. (b) Correlation between number of days MODIS recorded cloud cover each winter (November to April) and the mean DJFM NAO index.

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 micro-climates 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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