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Long-term observations of increasing snow cover in the western Cairngorms.

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Abstract
As part of the UK Environmental Change Network (ECN) long-term monitoring, an automatic repeat-photography camera was installed to record changes in landscape phenology in the Allt a'Mharcaidh catchment, Cairngorms National Park, Scotland. For 13 consecutive winters between 2002 and 2015, the date for the onset of continuous winter snow cover, and subsequent melt was recorded on slopes of north and north-easterly aspect at altitudes between 450m and 1111m a.s.l. Results show that the period of time during which snow is continuously present in the catchment has increased significantly by 81 (±21.01) days over the 13 year period, and that this is largely driven by a significantly later melt date, rather than earlier onset of winter snow cover.

Introduction
It is commonly thought with so much publicity around increased global temperatures that there will be less snow cover in the Cairngorms as a result of global warming. This opinion is supported by previous studies (Harrison et al, 2000). However, as data from a long term monitoring site in the Cairngorms reveal there is in fact evidence of increased snow cover over the past 13 years.

Snow fall is one of the most important seasonal meteorological events in mountainous regions as the presence (or absence), thickness and duration of snow cover has wide ranging socio-ecological impacts and benefits, ranging from the local scale ecological (limiting access to food and water resources, or reducing the length of the growing season to plants), to wider down slope flooding risk associated with rapid thaw. As well as this, snow can provide an important ecosystem service and economic activity in the form of water regulation, snow sports and wider winter tourism.

Long-term environmental monitoring in the Cairngorms
Long-term monitoring of physical, chemical and biological processes has taken place in the Allt a'Mharcaidh catchment in the Cairngorms National Park (57° 6' 28"N, 3° 50' 6"W) as part of the UK Environmental Change Network (ECN, www.ecn.ac.uk) since 1998. At the heart of the monitoring is a Campbell Scientific automatic weather station (AWS), located at 700m a.s.l on the edge of the Cairngorm plateau. For this study we extracted seasonal mean air temperature (Nov-May) between 2002 and 2015. Data on snow presence were recorded by means of an automatic repeat photography system, installed to monitor changes in landscape phenology, including snow cover, on a daily basis from 2002 to date.

The repeat photography system was targeted toward the north slopes of Sgoran Dubh Mor (1111m) and north-north-eastern slopes of Meall Bhuidhe (960m) and Geal Charn (920m), located within in the Allt a'Mharcaidh catchment, Invereshie and Inshriach National Nature Reserve, Cairngorms National Park, Scotland. The hillslope visible to the camera covers a range of some 650m altitude, from 450m a.s.l in the valley to 1111m a.s.l at the highest summit (see figure 1 for example catchment images). Despite the northerly aspects of the slopes in question, snow does not generally persist beyond late spring/early summer, in large part to a lack of the shading/sheltering rock formations which would assist with the creation of persistent accumulations.

A Remote monitoring system

Two fixed point repeat photography camera systems have been used at the site between 13 November 2002 and 13 November 2015. Between 2002 and 2009 a single photograph was captured daily at noon using an in-house built system utilizing an Olympus C860 digital camera (high resolution), a timer, and a solenoid to actuate the shutter release within a weatherproof housing. From 05 September 2009 a purpose built time-lapse package built by Habortronics utilizing a Pentax K200D DSLR, Pentax 18-55mm zoom lens set at 35mm, and a DigiSnap 2100 Controller contained within waterproof housing fitted with a 5W solar panel for continuous operation was used. This system recorded three images daily (0900, 1100 and 1300), increasing the probability of capturing an unobscured image of the hillslope.

From photographs to data

Scoring of snow cover followed a similar approach to that described in Andrews et al (2011) for photographic records in Abisko, Sweden. A crude scale of snow cover ranging from 1 (no snow) to 6 (full snow cover) was devised (see Fig 1) so as to be clearly and repeatedly assignable in each photograph. Where data were missed on the remote system due to obscuring weather or a system failure, secondary photographs taken during weekly site visits were used to provide bridging data of snow conditions where possible. During periods of continuous winter snow cover, and post-summer melt, missing photographs could be safely presumed to have snow as 'present' or 'absent'.

Persistent winter snow cover was judged to have commenced each year from the day when snow cover scored 2 or more (Patches/remnant snow) on a consistent basis. The subsequent melt was judged to have occurred at the point where no snow was left visible within an image. The period of snow presence is the number of days between these two points.

Data processing

We used linear regression (R Core Team, 2015) considered significant at the 5% level, to test for changes in period of snow presence, onset and spring melt dates. For examining the relationship between snow presence and temperature, the temperature difference from the long-term mean (2002-2015) was calculated for each winter season, and used in a linear regression model against snow presence. Finally, to examine the wider context of snow presence in the Allt a'Mharcaidh we tested our snow presence data against snow patch survival data (i.e. persisting from one winter to the next) gathered across the wider Cairngorm region by Iain Cameron (see Cameron *et al.* (2015) for further details on this data).

Changes in period of snow presence

The significance of the effect between year and snow presence was tested using the F-statistic with 1 and 11 degrees of freedom (*df*) and this showed that the significance level (p) was 0.002. Although variable year by year, the results show the period of laying snow to have significantly increased over the thirteen year period, increasing by 6.8 (±1.6) days per year^{-1} (Fig 2), and ranging between a minimum of 157 days in 2002/03 and a maximum 260 days in 2012/13.

This increase in the period that snow was present in the catchment was found to be largely driven by a later melting of remnant snow patches (F9.07, *df*= 12, p= 0.012), accounting for c70% of the 6.8 days per year increase (Fig 3). Although onset of continuous snow cover during the early winter also appeared to be occurring earlier over the 13 years, this was not found to be a significant change (F= 2.29, *df*= 12, p= 0.159).

The importance of seasonal temperature

Relatively modest changes in seasonal temperature was found to have a significant effect on the period snow was present in the catchment (F9.31, *df*= 7, p= 0.022; Fig 4). For every 1 degC increase

in the December-May mean temperature, above the long-term mean for the site (2003-2015), the period of snow cover decreased by 15.5 (±5.1) days.

However it was found that the model was not a good fit for the two winters with longest snow cover (2012/13 and 2013/14), and thus is probably not a good predictor of the effects of extreme snowfall events. By any measure these two winters were considered exceptional for snow cover compared with the long term mean. Snow during the winter of 2012/13 largely occurred later in the year than usual, with heaviest snowfalls during spring (Cameron *et al.*, 2014) resulting in a colder than usual spring, followed by a later than expected melt date. The winter of 2013/14 differed by the exceptionally large accumulations of snow above 600m throughout the winter period (Cameron *et al.*, 2015). Larger accumulations as witnessed in 2013/14 are likely less sensitive to climatic conditions (Trivedi et al., 2007), and despite a warmer than usual spring, the shear depth of snow required to melt resulted in a much later melt date than was predicted by the model.

In the context of increasing global temperatures, an increase in snow cover might be unexpected for maritime climates as found here in the UK. However, although increased winter precipitation has been shown for the UK (Osborn & Hulme, 2002), temperatures remain cool enough at higher elevations to see this predominantly fall as snow rather than rain. This phenomenon has previously been recorded at higher latitudes such as in Sweden (Kohler, 2006), where winter temperatures are lower than those found in the UK. However, for mountains in central Scotland where winter temperatures are higher, future predictions made using a regional climate model (HadRM3) and snow cover data (where 50% if study area is covered by snow), show that high-elevation snow cover duration is likely to decrease under all climate scenarios, and further that under the high emissions scenario winter snow could become absent below 900m by the 2080s (Trivedi et al., 2007). So despite increases in snow cover duration over the past 13 winters in the Allt a'Mharcaidh, ultimately we are likely to see a reduction in the period of snow cover in the Scottish hills, reversing the trend seen here.

Comparisons with regional Cairngorms snow patch data

To look at our monitoring data in a wider context, we tested for correlations between the period of snow cover in the Allt a'Mharcaidh, and annual snow patch survival rates across the wider Cairngorms region. Although monitoring slightly different aspects of snow cover, it was considered likely that such data might show some correlation, whereby we could predict annual Cairngorms snow patch survival, depending on the melt dates in the Allt a'Mharcaidh. However no such correlation was found to exist ($F= 4.21$, $df= 9$, $p= 0.071$). Differences between the two data may be a result of variations in topography, with the open-slopes of the Allt a'Mharcaidh catchment accumulating considerably less snow during winter months, and providing less shade from solar radiation during the spring. By comparison, long-lived/semi-permanent snow patches which survive between subsequent winters, can generally be found occupying steep north-to-east facing ground either in rock gullies, or beneath rocky corries, which accumulate more snow during the winter, and which provide a degree protection from direct sun light and moisture laden, mild south westerly weather systems.

Regardless, it is interesting to note that despite a series of relatively mild winters at lower altitudes in the latter years of this study, snow cover is generally on the increase in this part of the Cairngorms.

Summary

Between 2002 and 2015 the period of continuous high elevation snow presence in the Allt a'Mharcaidh catchment has significantly increased by around 81 (±21.01) days. Although year-to-year variation exists, for the past 13 winters the trend is toward increasing period of persisting snow

cover at the site. This appears to be largely a result of a delayed spring/summer melt, rather than an earlier onset of winter snow cover, and driven by fairly modest variations in the mean winter/spring temperature. Snow data for the catchment did not closely correlate with a snow patch survival rates for the wider Cairngorm region, highlighting how snow cover regimes vary at the local scale, despite larger scale regional predictions for future change.

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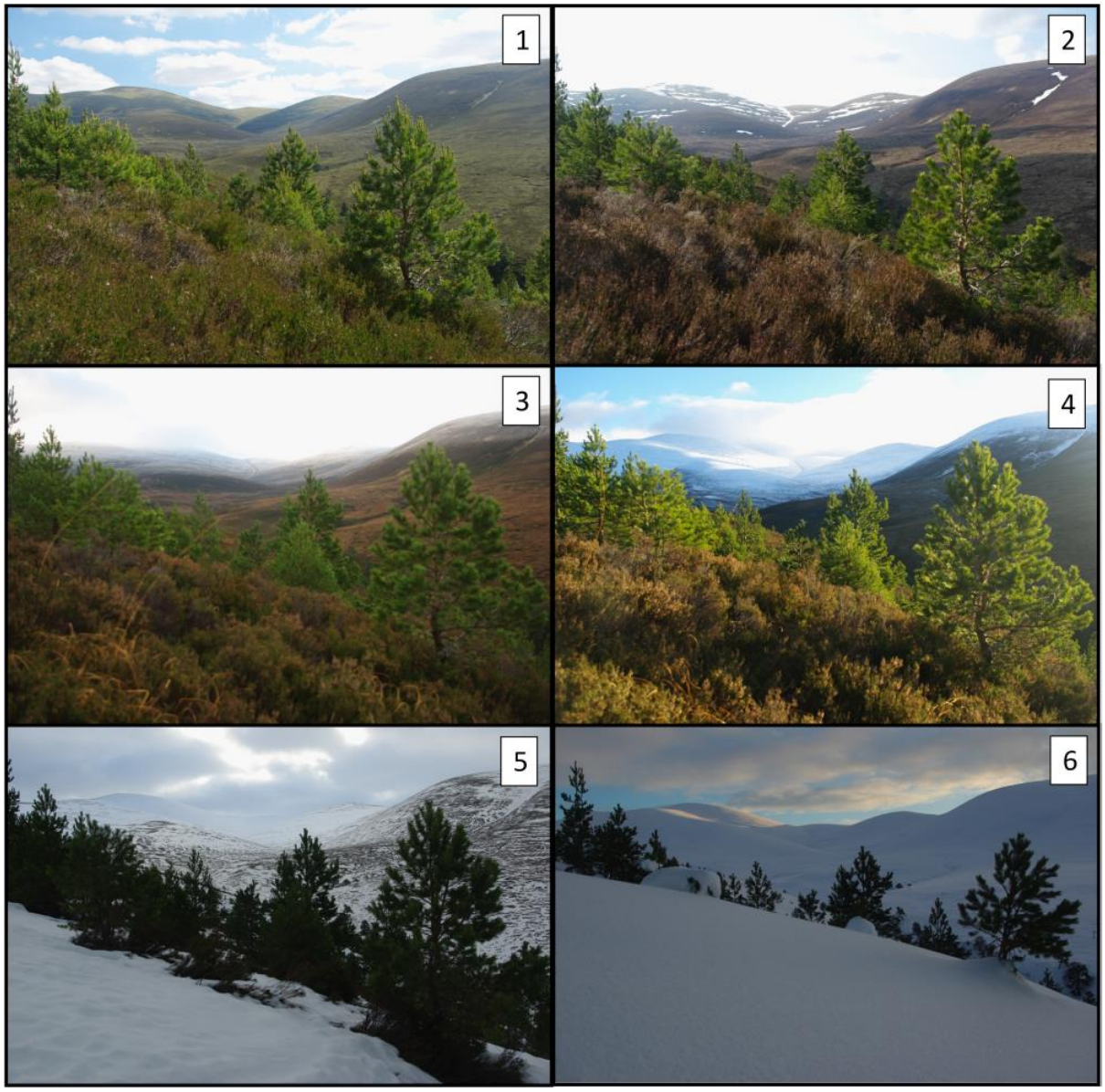

Fig 1 Example images for the scoring of snow cover on a six point scale in the Allt a'Mharcaidh catchment, Cairngorms National Park, Scotland. Scale as follows: No snow (1), Patches/Remnant snow (2), fresh dusting (3), more ground than snow (4), more snow than ground (5), and full snow cover (6).

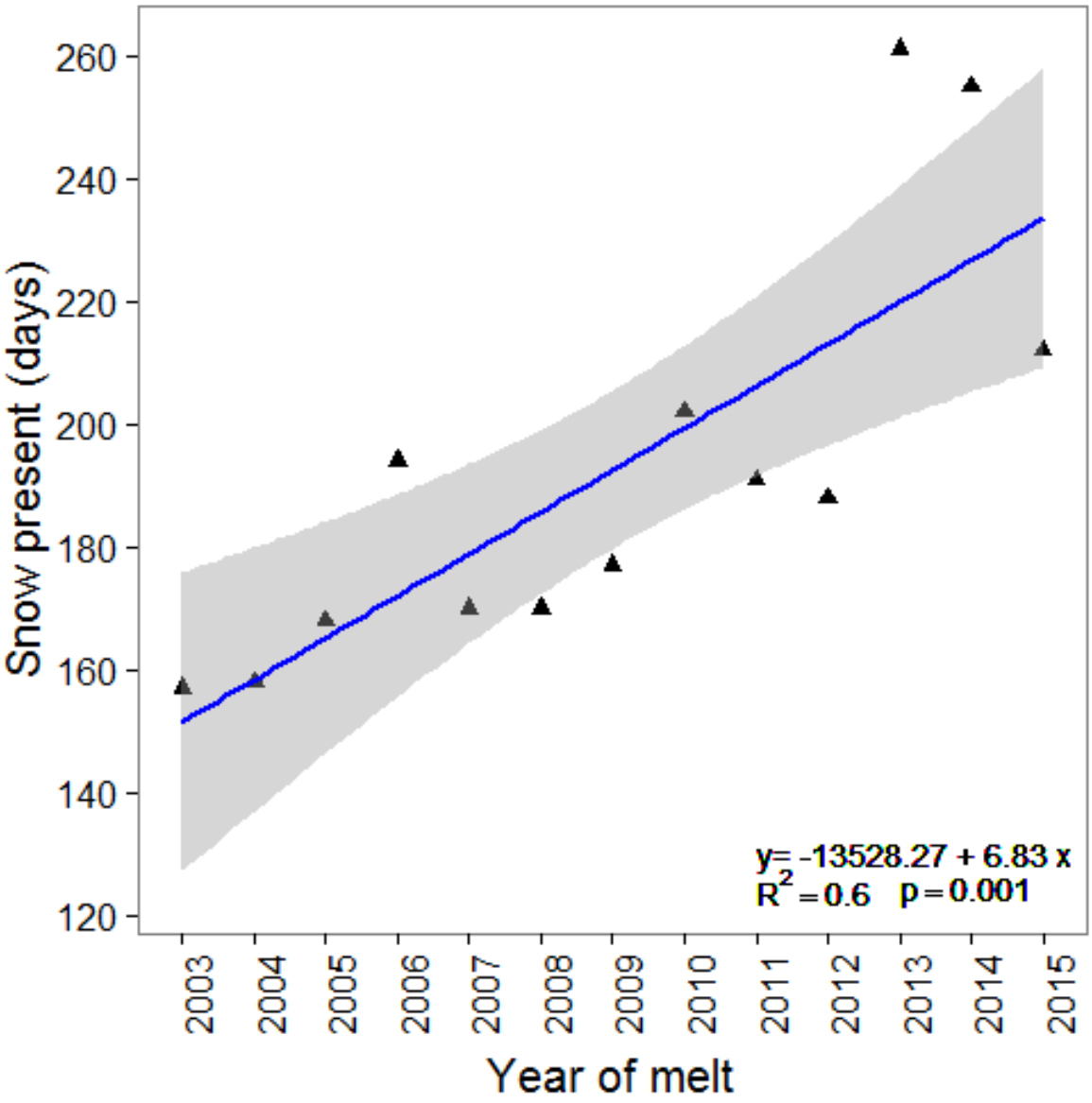

Figure 2 Total number of days winter snow persisted in the Allt a'Mharcaidh catchment (first continuous cover until complete melt of all remnant snow patches) for thirteen winters from 2002 to 2015, Cairngorms National Park, Scotland. Linear regression line and 95% confidence limits are shown.

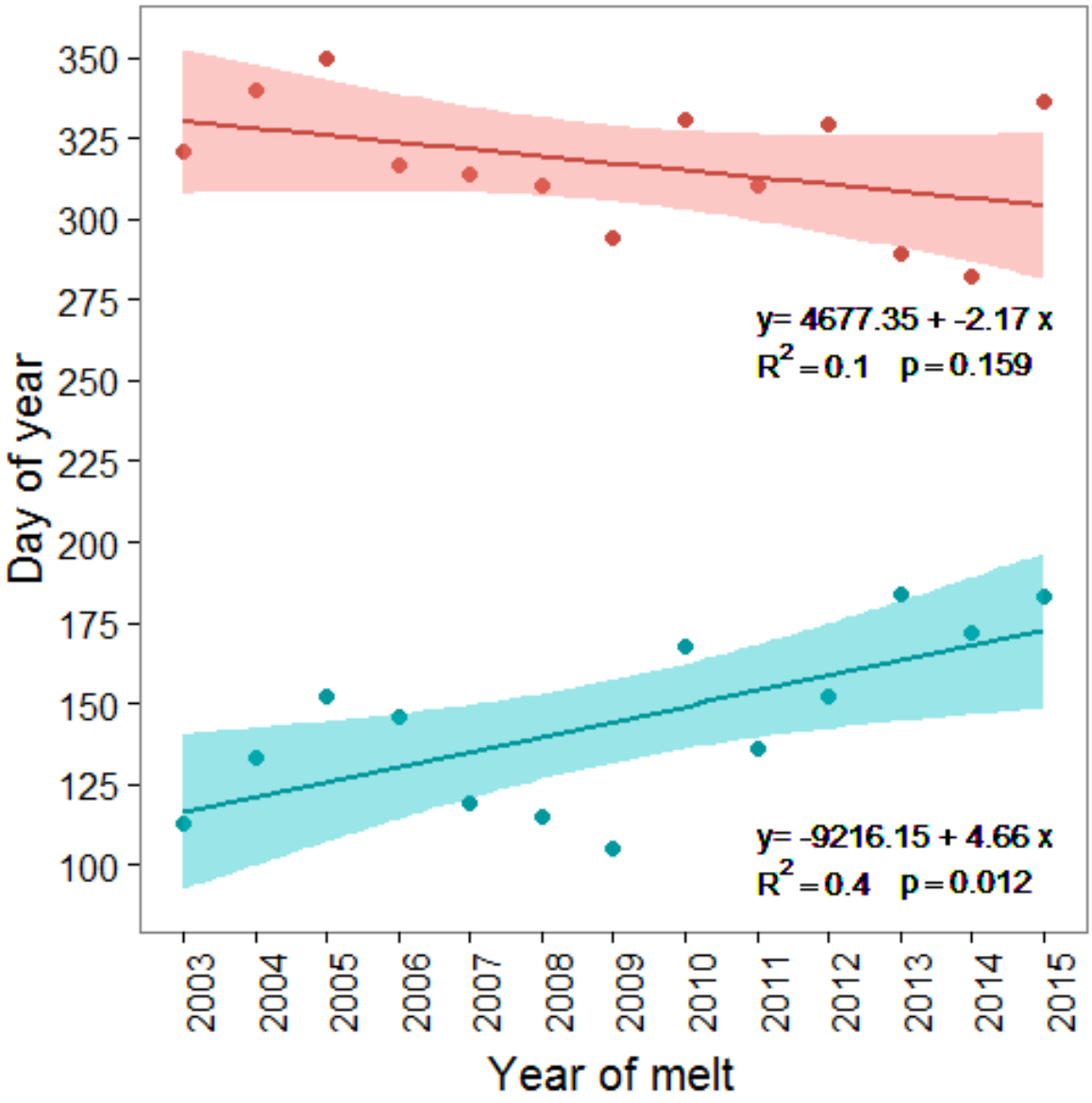

Figure 3 Day of year of first continuous winter snow cover (red), and subsequent melt of remnant snow patches (blue) for thirteen winters from 2002 to 2015 in the Allt a'Mharcaidh catchment, Cairngorms National Park, Scotland. Linear regression line and 95% confidence limits are shown.

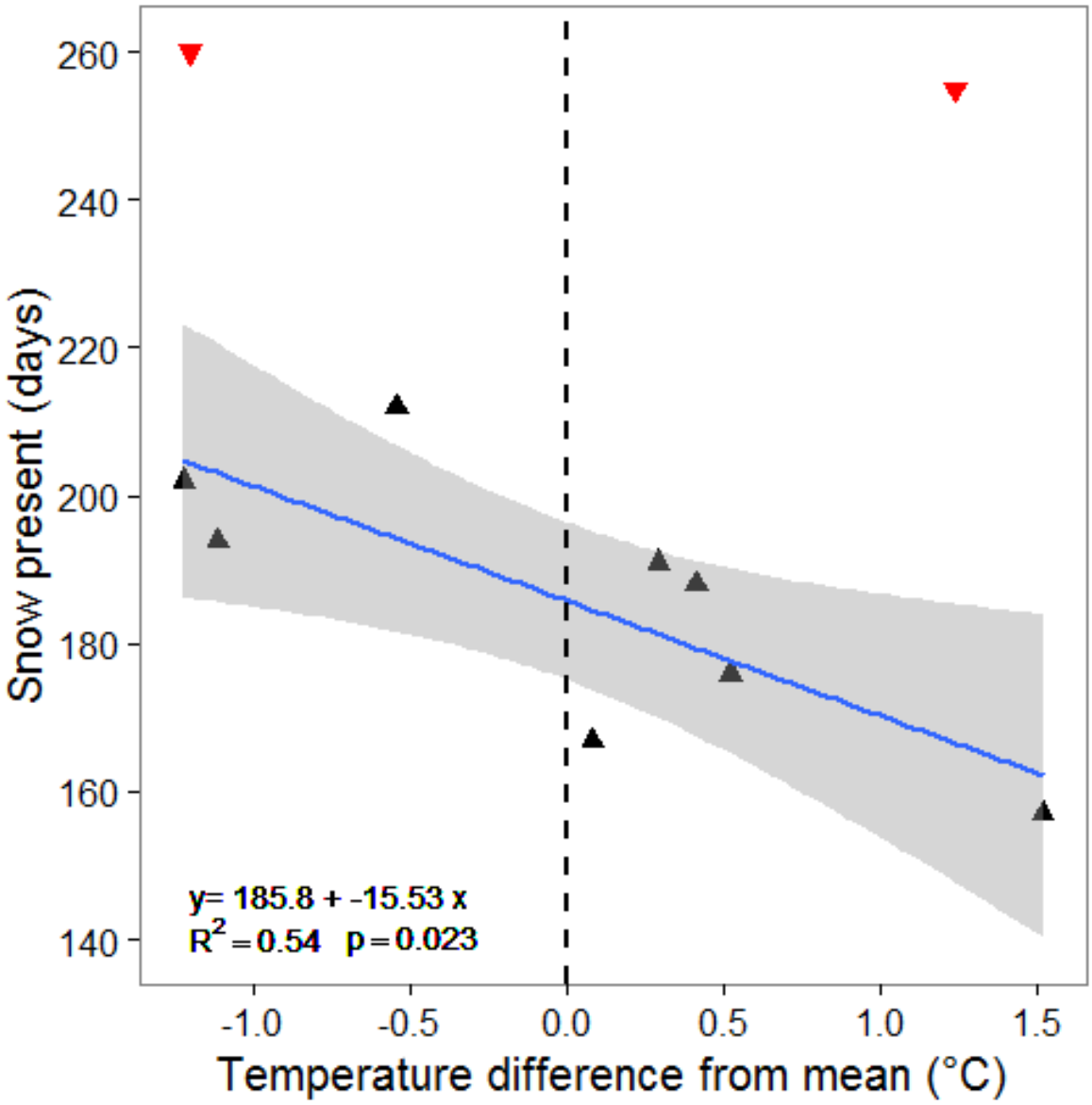

Figure 4 Relationship between number of days winter snow persisted and difference in Dec-May daily mean temperature from 13 year mean (2003-2015). Linear regression line and 95% confidence limits are shown. Two points shown in red inverted triangles have large influence on the regression coefficient and were excluded from the model (see text).