Snow Cover and Climate Change on Cairngorm Mountain

A report for the Cairngorms National Park Authority

Mike Rivington

(The James Hutton Institute)

Mike Spencer

(SRUC)

28th April 2020

Executive Summary

This report details research findings on the historical changes in snow depth and number of days of snow on Cairngorm Mountain and how snow may respond under climate change. It is an extension to the report 'Snow Cover and Climate Change in the Cairngorms National Park: Summary Assessment' produced by ClimateXChange in 2019[1].

Key Findings: Observed changes

- There has been a decrease in the observed maximum and average snow depth since the beginning of records (1983-84 winter). Maximum snow depth has declined by c. 10cm and the average by c. 3cm.
- There has been an observed decrease in the number of days when snow depth exceeds specific amounts. The largest decreases have occurred for shallower depths (>2<5, >5<10 cm) of c. 10 days since 1983.
- The mean snow depth per month has decreased in January and February since 1983. Depth per month has been highly variable but the observed trend has been downwards. Other months have different trends: March has had a slight decrease whilst November has been consistent and December a slight increase.
- For all months there is a clear increasing warming trend in observed maximum and minimum temperature between 1960 and 2019. The largest increases have occurred in April. The main snow fall months of January and February have had a relatively small increase in temperature.
- There has been an increasing trend of mean monthly precipitation amount for November, December and January since 1960, whilst March's amount has decreased.
- There has been an increase in mean monthly solar radiation (MJ m^2 day^{-1}) in February, March and April since 1994, implying greater heat energy input at the ground surface.

Key Findings: Future projections

- Likely to be a decline in snow cover days per year from the 2030s for Aviemore, the Cairngorm Chairlift meteorological station and Ptarmigan Restaurant on Cairngorm Mountain. This trend will continue through to the 2080s.
    - There will be large variation between years and there are likely to still be some years comparable with past amounts of snow cover, but these will be less frequent.
    - These findings are in line with results from the UK Meteorological Office and Inter-governmental Panel on Climate Change.
- Temperatures are projected to continue increasing, with a higher probability of having more days when the temperature is above a threshold of 2°C for snow formation.
- There is an increasing probability of more heat energy input on ground surfaces with an increasing snow melting affect.
- Snow is complex to model and project in the future, especially in temperate regions like Scotland with its strong maritime (Atlantic Ocean) climatic influence. Changes in seasonal variability will depend on how air flow over the UK (e.g. location of the jet stream) is affected by global scale ocean-atmosphere circulation processes. Our findings are a good indicator of future trends, but there remain substantial uncertainties at Cairngorm Mountain that need to be considered in making this a more detailed assessment of future snow cover.

Conclusions:

Warming will continue meaning snow cover and depth is likely to decrease on Cairngorm Mountain from the 2030s. There are likely to be some years with snow comparable to the past but overall there will likely be a decrease.

[1] https://www.climatexchange.org.uk/research/projects/snow-cover-and-climate-change-in-the-cairngorms-national-park/

Contents

Table of Figures

Acknowledgements:

This report has been supported by the Cairngorms National Park Authority.

We would like to acknowledge the UK Meteorological Office for the use of the MIDAS observed data, the gridded observed weather data and the UKCP18 climate projections. The capability to use the climate data and bias correct it to higher spatial resolution has been developed under the Scottish Government's RESAS Strategic Research Programme 2011-2016 and 2016-2021.

This report was prepared by:

Mike Rivington, The James Hutton Institute, Aberdeen.

Mike Spencer, SRUC, Edinburgh.

28th April 2020.

Please Cite as:

Rivington M and Spencer M (2020) Snow Cover and Climate Change on Cairngorm Mountain: A report for the Cairngorms National Park Authority. The James Hutton Institute, Aberdeen, UK.

Introduction

The spatial extent of snow cover, here defined as its duration (number of days per year snow is on the ground) and its quantity (depth) is an essential part of the ecology and hydrology in the Cairngorms National Park (CNP) and is a key factor influence winter sports and tourism activities. It also influences greenhouse gas emissions and sink potential from peatlands. Whilst there has been large inter-annual variation in the past, there are substantial concerns that, as a result of climate change, there may be significant decreases in snow cover, quantity and spatial extent, in the future.

This study explored the likelihood of these decreases in snow cover and depth in the future on Cairngorm Mountain. The aim was to assess the general past trends and plausible possible future snow cover. This study builds upon the work undertaken in 2019 to assess snow cover for the whole Cairngorms National Park. For full details on methods, results, key messages and caveats please refer to Rivington et al 2019.

There are many weather factors that determine the creation of snow. The UK's heaviest snowfalls are associated with temperatures between 0 and 2°C. Above 2°C snowflakes will likely either not form, or if they do, melt and fall as sleet or rain. Some years have experienced large snowfalls, e.g. the winter of 2009/10 when a blocking high pressure system meant cold air from the north mixed with warm moist air from the Atlantic. This gave the coldest December on record since 1910[2]. There are also many factors determining how long it snows for and what happens to it once on the ground (e.g. movement by wind, ground temperature). These are beyond the scope of this study and there are many uncertainties associated with projecting these other factors and the conditions they create in the future.

In this study we use a well-established assumption that snow cover is more correlated to temperature than precipitation, based on good evidence indicating temperature is a primary influencing factor as it influences formation and controls depth and duration (Harrison et al 2001, Beniston et al 2003, Trivedi et al 2007). A study at the Ben Lawers National Nature Reserve found that snow cover duration at mid to upper altitudes (600–900 m) responds most strongly to variation in mean daily temperature: a 1 °C rise in temperature can correspond to a 15-day reduction in snow cover at 130 m and a 33-day reduction at 750 m (Trivedi et al 2007).

Much of the analysis focusses on the drivers of changes in snow amount, primarily temperature but also precipitation and solar radiation, as there is adequate observed data for this, whereas there are issues of data quality and period of coverage for snow depth and areal coverage. Hence the results are best interpreted by combining an understanding of how the key drivers have changed up to now, and what the modelling of future conditions indicate.

Report structure

This report first presents the summary of the findings from the study of snow cover for the whole Cairngorms National Park area (Rivington et al 2019) and an overview of the methods used. Results are presented of analyses of observed weather data to identify historic trends in temperature, precipitation and solar radiation. These are important indicators of factors likely to influence the formation and accumulation of snow. For temperature we show future projections to 2080. The results of snow cover modelling under climate projections and conclusions are then provided. Supporting information is included in an appendix.

[2] https://www.metoffice.gov.uk/weather/learn-about/weather/case-studies/uk-snow-2010

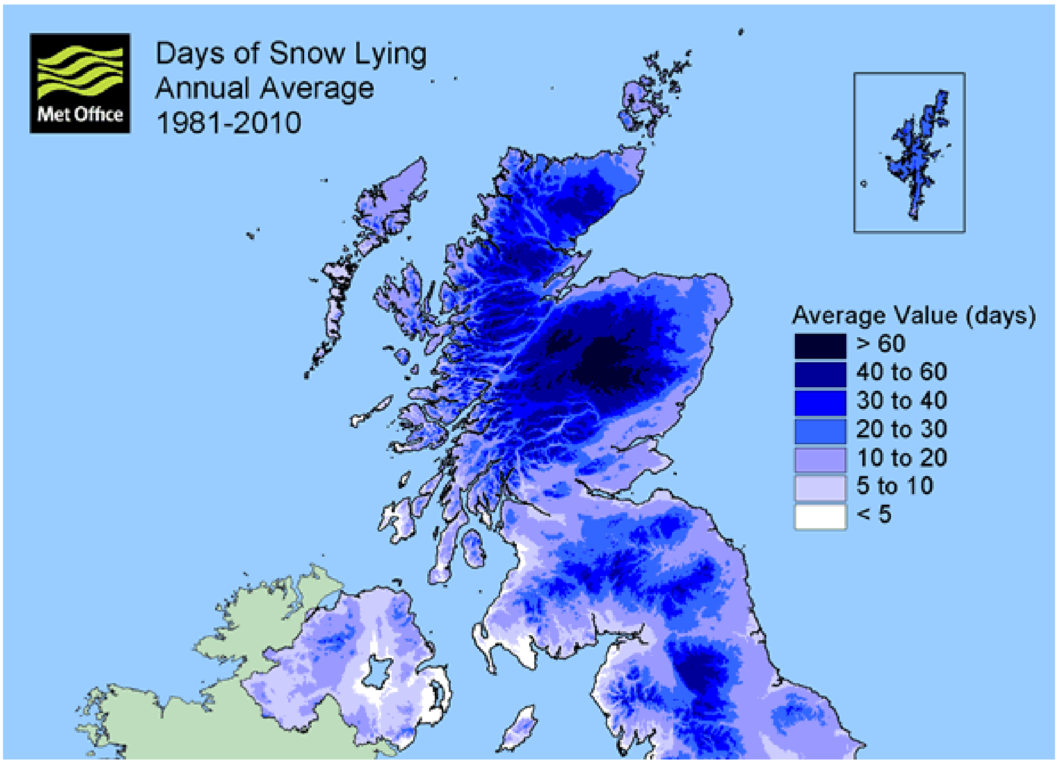

Figure 1. Days of lying annual average snow (1981-2010). Source: UK Met Office.

The weather station at the Cairngorm chairlift has the highest average number of days of snow falling, with snow falling on 76.2 days throughout the year (based on 1981-2010 averages), while the station at Aviemore records 66 days[3].

Summary of Cairngorms Snow Cover Report

To assist in interpreting the results presented here, the following are the key findings from the CXC report on snow cover for the whole of the Cairngorms National Park[1].

1) There has been an overall decline in observed snow cover in the Cairngorms National Park (1969-2005). This trend conforms to those seen across other mountain areas and the Arctic and is in keeping with the observed global warming trend. However, some variability can also be seen with significant snow events and a possible increase in snow cover in the last decade. The overall declining snow cover trend is projected to continue and accelerate in the future.
2) A warming trend has been observed at meteorological stations (Balmoral) in the CNP since 1918 for both maximum and minimum temperature. There is variation between months:
    a) October and November show approximately 1.6°C + maximum temperature and 0.8 °C minimum temperature rises. This may influence the likelihood of when seasonal snow forms and cover becomes established.
    b) March, April and May show a warming trend indicating likelihood of earlier onset of snow melting.
    c) Precipitation (measured as rainfall and snow or ice) per month is variable between years with no strong trend observed.
3) There is a clear observed decrease in the number of days of snow cover at all elevation levels over the 35 winters between 1969/70 and 2004/05, with higher elevations having a larger proportional decrease (Snow Survey of Great Britain, Whitehillocks observing location, south-east CNP).

[3] https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/snow/snowiest-places

4) In the near-term, our estimates indicate the potential for a continuation of snow cover at the current range of variation, but with a substantial decline from the 2040s. These findings are in line with results from the UK Meteorological Office and Inter-governmental Panel on Climate Change (IPCC 2019). There will be some years in the future when the weather conditions create snow and enable lying snow that may be comparable to the past, but such occasions will become fewer. This applies to all elevations, but with larger proportional decreases at higher levels. Results indicate a likelihood of some years with very little or no snow by 2080.

Approach and Methods

We first assessed past trends using observed weather and snow depth records from the UK Meteorological Office to identify possible correlations between observed weather and snow depth trends. We then used climate model projections from the Met Office in a snow model to estimate future snow cover responses. Full details are available in the CXC report, including reviews of uncertainties and caveats.

An initial assessment of the data available from the UK Meteorological Office for the Cairngorm Chairlift site showed that the data for the count of days of snow, sleet or hail were either missing or of insufficient quality to be used in this study. Our analysis was therefore restricted to snow depth.

It is important to note that snow depth and cover are different, but with our current snow modelling projection capabilities we are not able to simulate snow depth. Hence there is need for interpretation on how much changes in snow cover can be correlated with changes in snow depth. The assumption is that more extensive snow cover implies greater depth and vice-versa.

For the future projections we used the UK Climate Projections 2018 (UKCP18) daily data for the RCP8.5 emission pathway (current emissions trajectory). The UKCP18 data is produced by a Regional Climate Model (HadRM3). This is run twelve separate times with variations in the model parameters that result in variations in the model estimates. This is done to capture the range of uncertainty in the parameters and provides a probabilistic range of possible future climate conditions. Each of the 12 model runs is referred to as an *ensemble member*. The ensemble mean is the average across the 12 members and represents the 50% (mid-range) probability level.

These are the only daily data released (the snow model used here needs daily data), hence this is just one possible future scenario. Scenarios with lower greenhouse gas emissions may reduce the likelihood of snow cover loss, but the world is locked into some global warming already in the next 30-40 years due to past emissions.

Temperature, precipitation and solar radiation

We examined daily observed weather data from the Cairngorm Chairlift meteorological station (1980 – 2019), plus daily data from a 1km resolution gridded data set (1960 – 2019) to assess evidence of the past trends for maximum and minimum air temperature and precipitation. This analysis was repeated using the UKCP18 climate model data to assess how past rends may align with future projections. We analysed mean maximum and minimum air temperature to assess the change in range and potential consequences of differences in rates of change and levels of variation between them.

We also analysed solar radiation data estimated from satellite data (1994 – 2018)[4] to assess potential changes in the micro-climate energy inputs. Solar radiation is an indication of the energy input at the surface level and determines the temperatures in micro-climates. Air temperatures (at

[4] See SolarGIS: https://solargis.com/

1.5m above ground, as measured by met stations) are influenced by wider movements of air masses. Increases in ground level receipt of solar radiation can be interpreted as additional drivers of snow melt through direct energy transfer (e.g. through dark surfaces on or near snow).

Future snow modelling

To estimate future snow cover we ran a snow model over all the 5 km grid cells covering the whole National Park (226 cells in total, see Figure 8). The model estimates snow cover based on daily temperature and precipitation. Data from the 3 5km cells covering Aviemore, the Cairngorm Chairlift and Cairn Gorm summit were then extracted. Input future daily weather data (temperature and precipitation) to the model were from the UKCP18 climate projections. When temperature is below a threshold, precipitation accumulates as snow and when temperature rises above the threshold the snow melts. For more information on the model and calibration see Spencer 2016.

Results

Observed Temperature, Precipitation and Solar Radiation trends.

The analysis of temperature and precipitation for the observed and climate model projected future period are shown for January and February in Figures 2 and 3 (see Appendix Figs. 10 – 13 for other winter months). Interpretations can be summarised as:

- For all months there is a clear increasing trend in maximum and minimum temperature observed data between 1960 and 2019 (Figures 2, 3 and 10 - 13).
- There is large inter-annual observed variation.
- Climate model projections indicate a continuation of this warming trend and variation.
- The climate model ensemble mean projected maximum temperature fits well to the extended estimated observed trend line. For minimum temperature the climate model estimates are greater than the extended estimated observed trend line. Previous evaluation of the climate model (Rivington et al 2008) established that the model tends to over-estimate minimum temperature. However, the climate model data used here has been through a bias correction method that aims to correct for such errors. Our interpretation is that minimum temperature may increase by a greater amount than maximum temperature under future climate conditions.
- The number of years in the future when the minimum temperature is above 0°C each month is much greater. December, January and February are key months for snowfall (see Figure 4).
- December: the climate model ensemble mean estimates minimum temperature is likely to be consistently greater than 0°C by mid-2030's. However, the extended observed trend indicates this may not occur until the mid-2060's. Maximum temperatures are projected to be consistently greater than the 2°C temperature recognised as the upper limit for snow creation and when snowflakes melt[5].
- January: future minimum temperatures are likely to be consistently greater than 0°C by mid-2030's. However, the extended observed trend indicates this may not occur until the mid-2060's. Maximum temperatures are likely to be consistently greater than 2°C.
- Precipitation has been highly variable between years, with the level of variability estimated to continue in the future. Since 1960 the trends have been: November, December and January have had an increase in mean monthly precipitation (Appendix Figure 15) of approximately 40mm; February and April show no trend; but March and May have a small decrease.

[5] Air temperatures at 1.5m above the ground are used, whereas snow creation will likely be at higher altitudes where temperatures are lower. The ground level temperatures indicate probability of snowflakes melting.

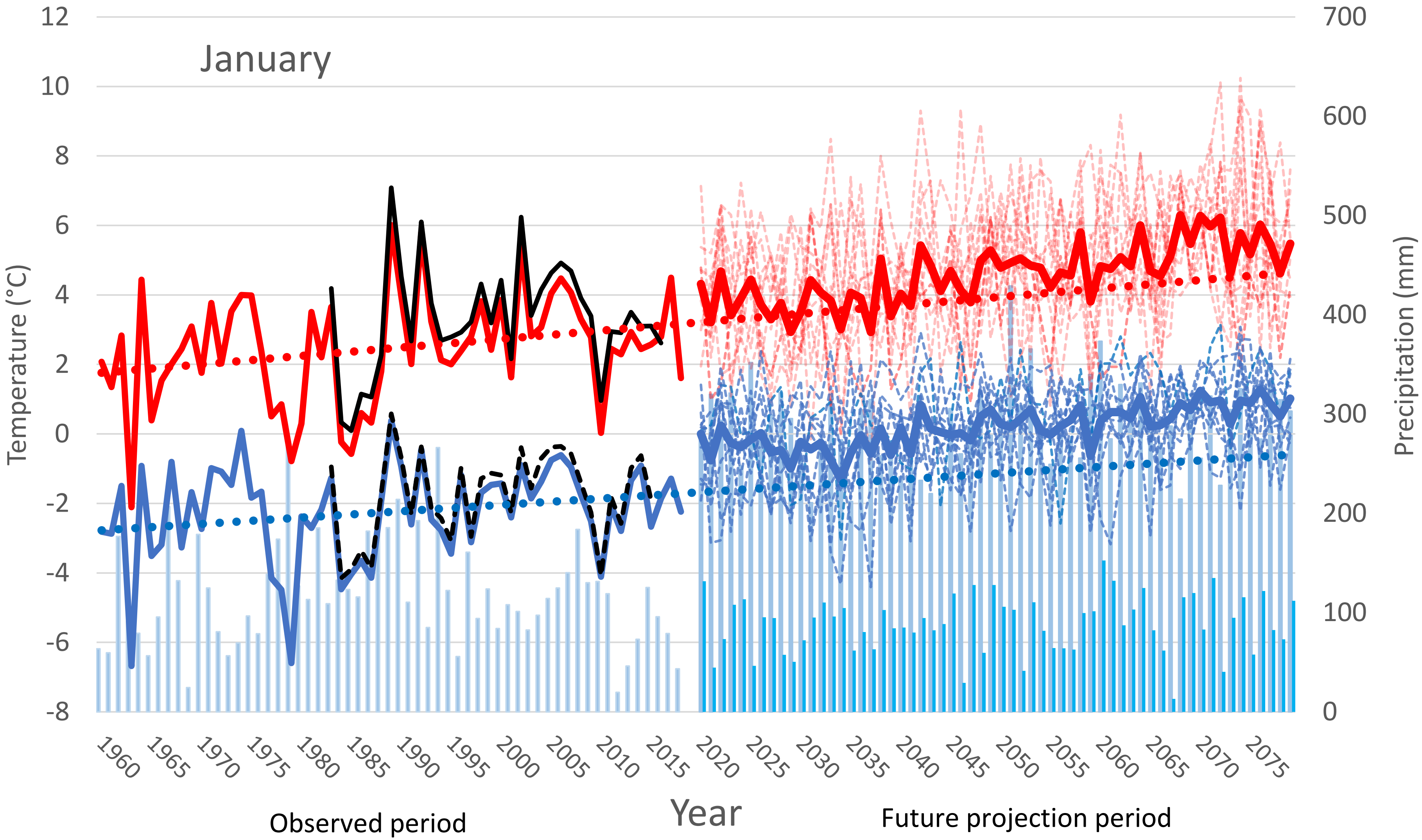

Figure 2. January temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

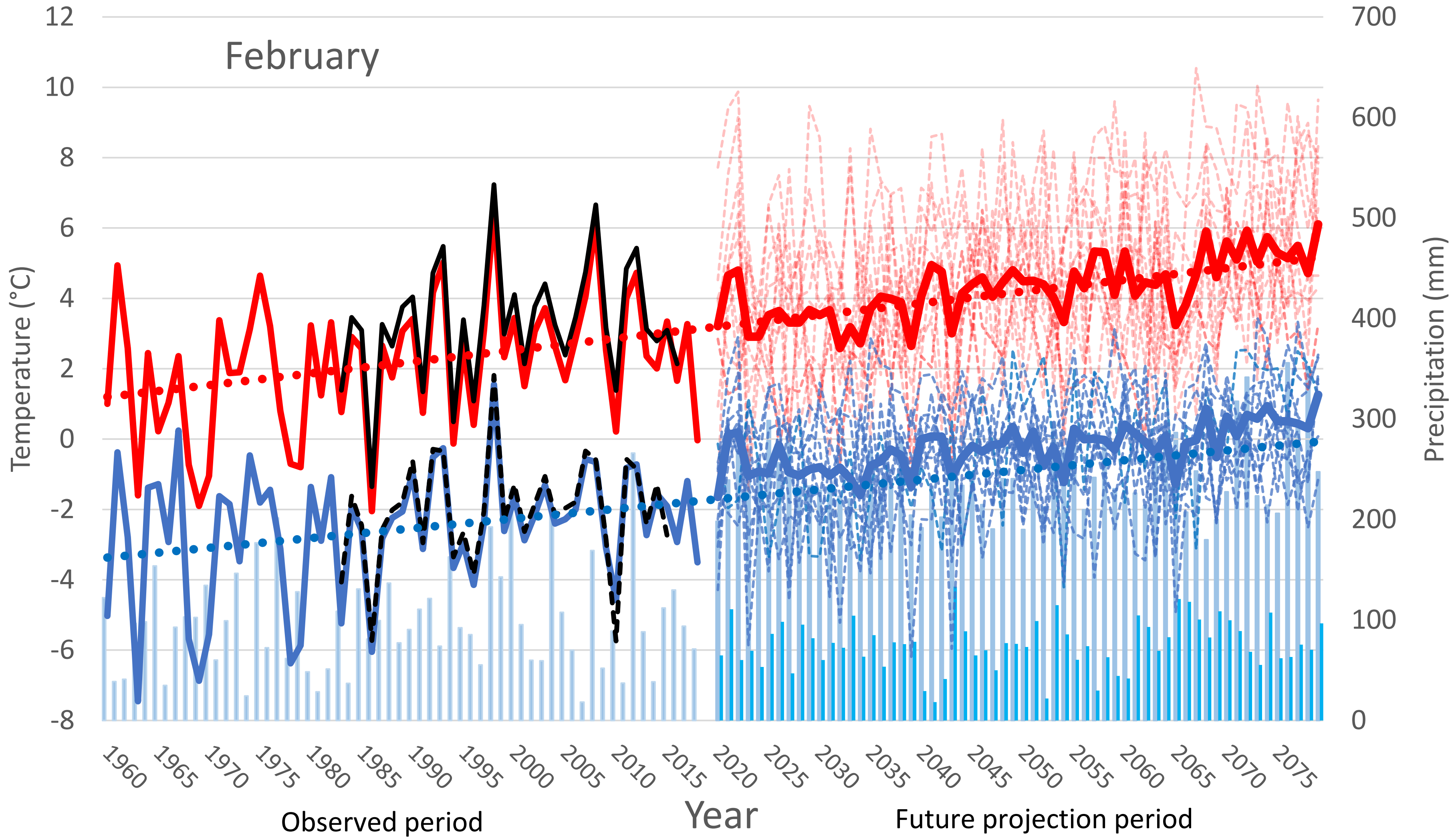

Figure 3. February temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

Temperature

Key Finding: The mean monthly maximum (Tmax) and minimum (Tmin) temperatures have increased for all winter months since 1982 (Figures 2-3, Appendix Figs. 10-13, 14). The largest increases have occurred in April. The main snow fall months of January and February have had a relatively small increase in mean Tmax and Tmin.

Mean maximum and minimum temperature for the Cairngorm Chairlift meteorological station have been highly variable between years but there has been an increased trend in all winter month. November and March have seen an increase of Tmin above 0°C since 1982. The trend lines for Tmin have all remained below the 2°C temperature threshold indicator for snow creation, but recently there are more years when in some months the Tmin has been above 2°C.

The mean Tmin in the main snow fall months of January and February has increased by c. 0.5°C. The mean Tmax in April has increased by c. 1.2°C.

Precipiation

Key Finding: There has been an increasing mean monthly precipitation amount trend for November, December and January since 1960, whilst March's amount has decreased (see Appendix Figure 15).

Precipitation has also been highly variable between years. January's mean monthly total precipitation has increased by c. 50mm and February's by c.35mm. This coupled with increases in mean, Tmax and Tmin temperatures indicates greater probability of melting of accumulated snow.

Solar Radiation

Key Finding: There has been an increase in mean monthly solar radiation (MJ m^2 day^{-1}) in February, March and April since 1994 (see Appendix Figure 16). Mean monthly solar radiation for the other winter months has remained constant.

Snow Depth

Snow depth is highly spatially and temporally variable, hence assessing spatial distribution using data from single meteorological station is problematic.

The siting of a met station (e.g. on a ridge or hollow) can have substantial effects on how well data represents the wider area. The Cairngorm Chairlift station (pictured opposite) is located on a raised ridge area hence may under-represent surrounding snow depth. However, trends can be identified from the time-series data enabling relative interpretations to be made about the wider surrounding areas.

When snow depth accumulates is temporally highly variable (Figure 4 and Appendix Fig. 17). For example, in 2006 the entire snow depth was accumulated in March only. For many years most depth accumulation occurs in January and February.

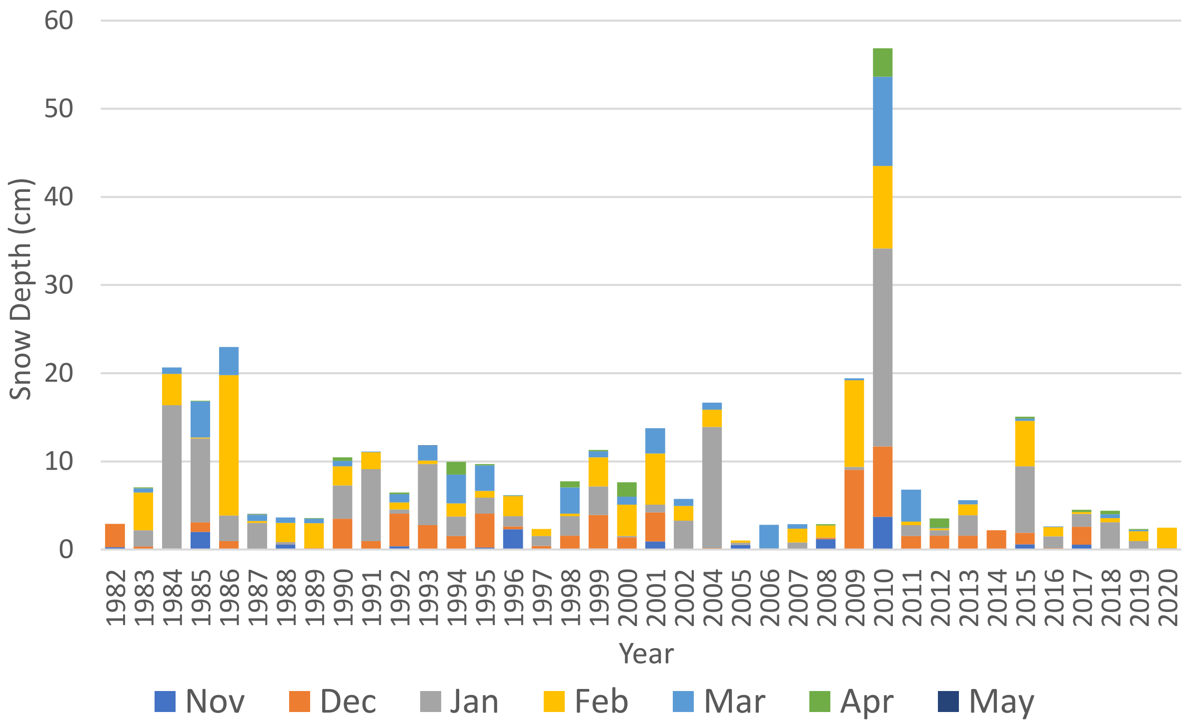

Figure 4. Snow depth (cm) per winter by month, Cairngorm Chairlift meteorological station (Note data for 2003 is missing).

There have been many periods of snow depth accumulation followed by melting and subsequent further snow events leading to accumulation again (e.g. winter of 2009-10 had the largest snow depth recordings but these consisted of four distinction time periods, see Appendix Figure 17). Detecting trends within this mix of variation is problematic.

To address this, the average and maximum snow depths per winter provide some evidence of observed trends. Figure 5 indicates a decreasing trend in maximum snow depth (considering substantial yearly variation) of approximately 10 cm since 1983. Average depth has also decreased.

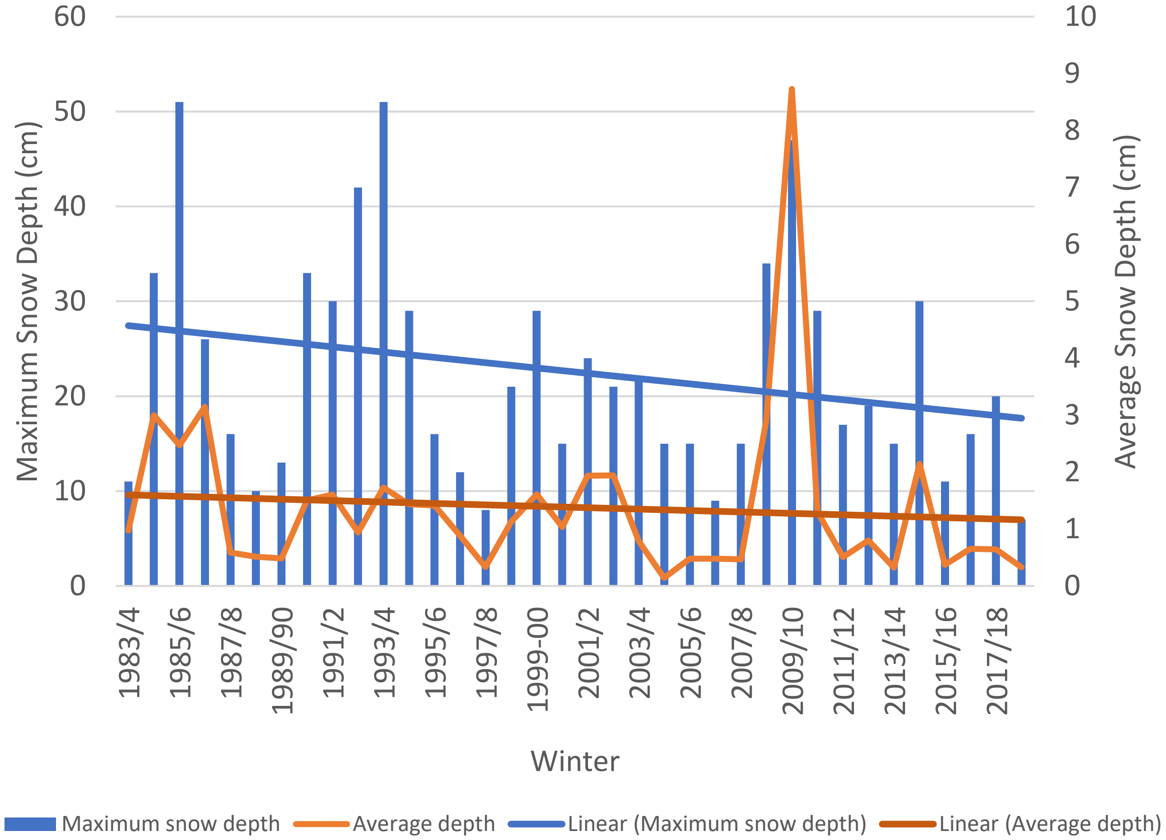

Figure 5. Maximum snow and average snow depth (cm) at Cairngorm Chairlift meteorological station.

Key Finding: There has been a decrease in the observed maximum and average snow depth since the 1983-84 winter (Figure 5). Maximum snow depth has declined by c. 10cm and average by c. 3cm.

These decreases may be correlated with the increases in temperature and changes in precipitation amounts, but it should be noted here that snow depth is also a function of wind speed and direction. This study has not considered these factors, but they are likely to be an important influence on snow depth at the location of the Cairngorms Chairlift meteorological station.

Snow Depth Days

Key Finding: There has been an observed decrease in the number of days when snow depth is at specific amounts (2-5, 5-10, 10-15, 15-20 and +20 cm) (Figure 6). The largest decreases have occurred for shallower depths (2-5, 5-10 cm) of c. 10 days since 1983. This may indicate situations where snow still falls and accumulates but melts more rapidly.

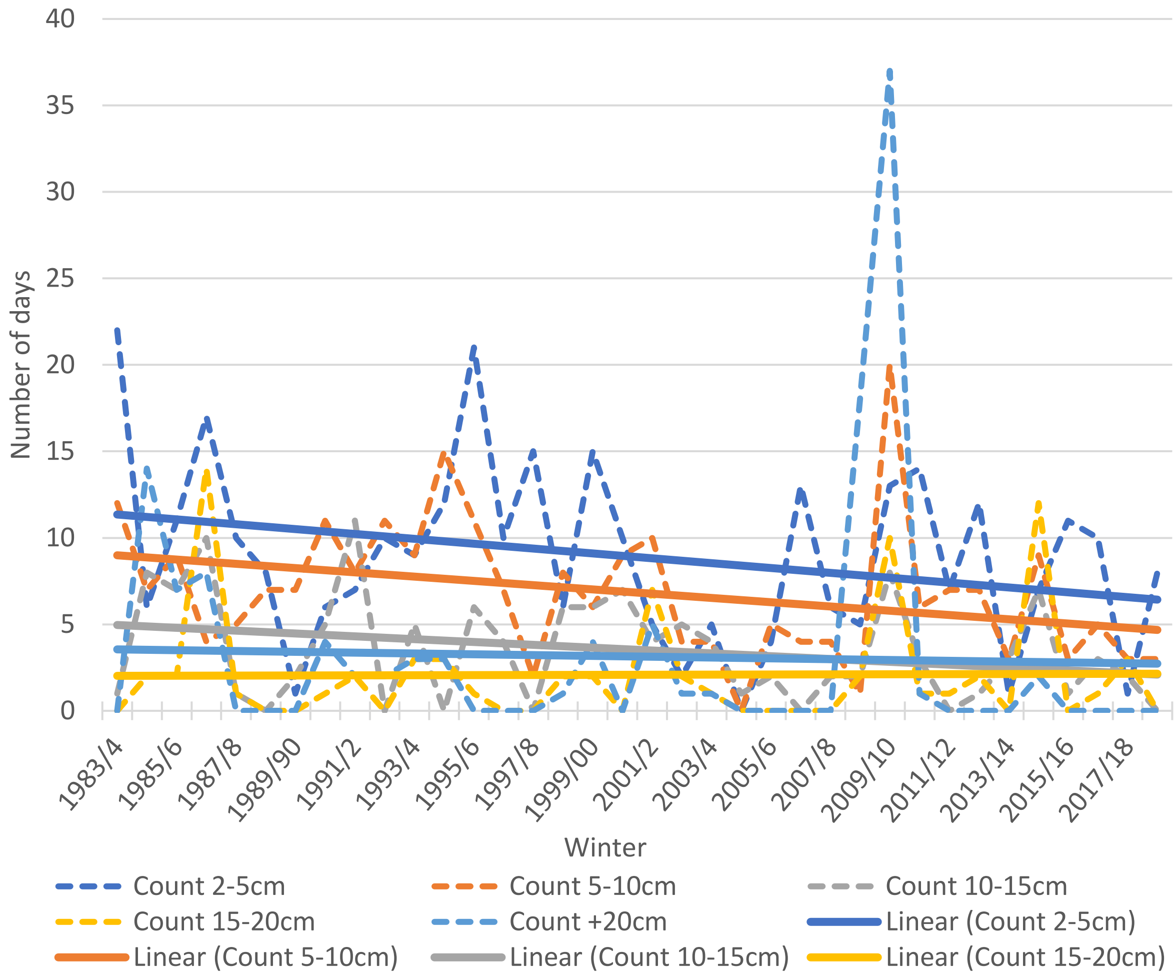

Figure 6. Count of days at different snow depth ranges (2-5, 5-10, 10-15, 15-20 and +20 cm) per year, Cairngorm Chairlift.

This decrease in the number of days at shallower depths may be a function of reduced number of days when it snowed, but also increased melting due to higher temperatures.

Comparing Figures 5 and 6 shows that whilst 1986/86 and 1993/94 winters had maximum snow depths comparable to 2009/20, however the number of days at such depths were less than half. This illustrates how unusual the 2009/10 winter was, but this does not greatly affect the decreasing trend.

Mean monthly snow depth

Key Finding: The mean snow depth per month has decreased in January and February since 1983 (Figure 7). Depth per month has been highly variable but the observed trend has been downwards. Other months have different trends: March has had a slight decrease whilst November has been consistent and December a slight increase.

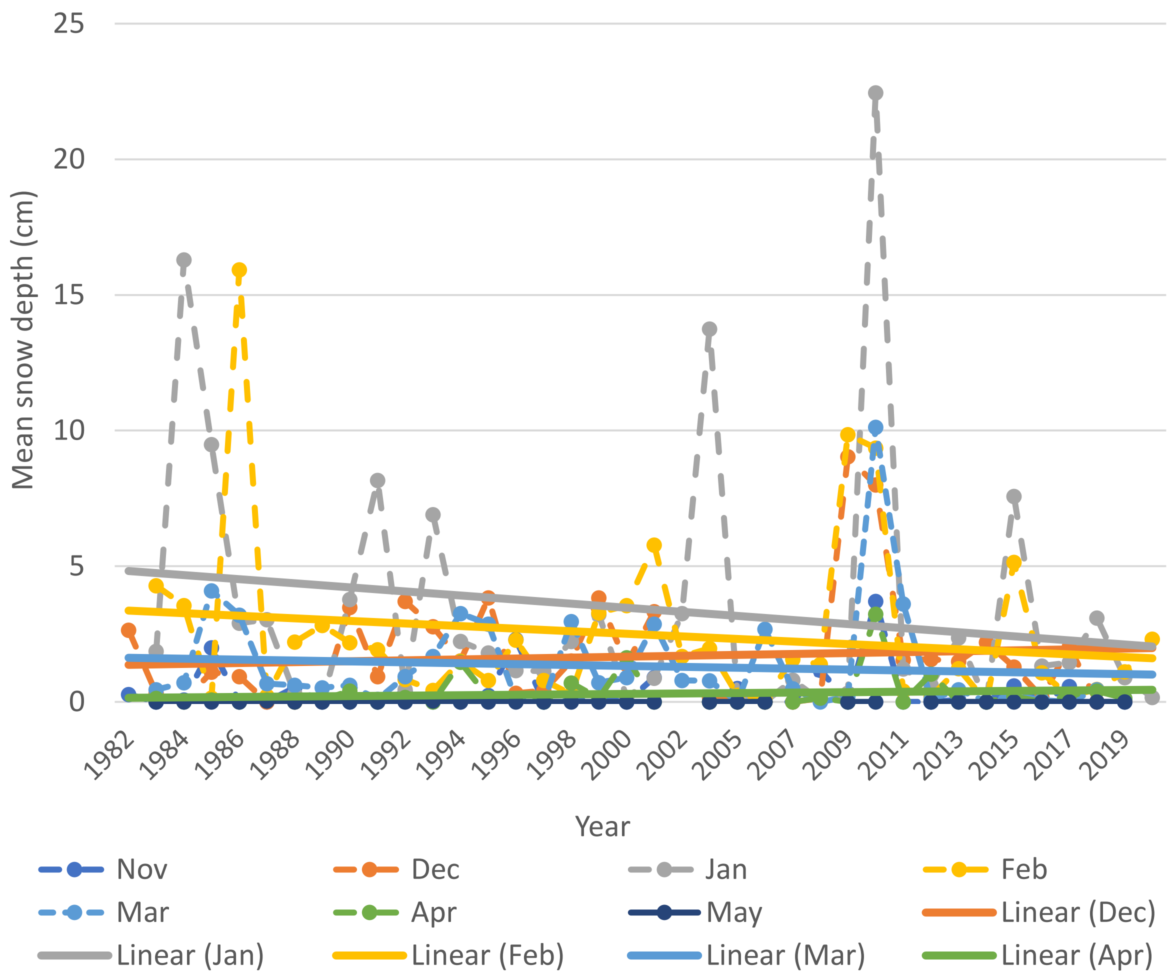

Figure 7. Mean monthly snow depth and trends, Cairngorm Chairlift (1982 – 2020).

Figure 7 illustrates that in January and February, the main months when snow accumulates, there has been a decrease in the mean snow depth. Comparing with Figure 5, winters in the past have had high maximum depths (e.g. 1986/86 and 1993/94), but the means are relatively low.

This illustrate the complexity of snow accumulation events, e.g. where there may be large snowfalls but the snow duration is shorter. Thus it is important to recognise that snow depth does not necessarily reflect snow density, e.g. accumulations may reduce differently in depth due to temperature and possibly precipitation conditions, giving situations where shallower depths may remain for longer periods of time but as dense snow and ice if the right temperature and precipitation conditions are right (e.g. some light rainfall, thawing and then hard freezing). Conversely, if large accumulations experience warm temperatures and high rainfall they may be completely melted. Wind will also redistribute fallen snow and accumulate it in gullies and hollows.

Results: Future Projections

Snow modelling

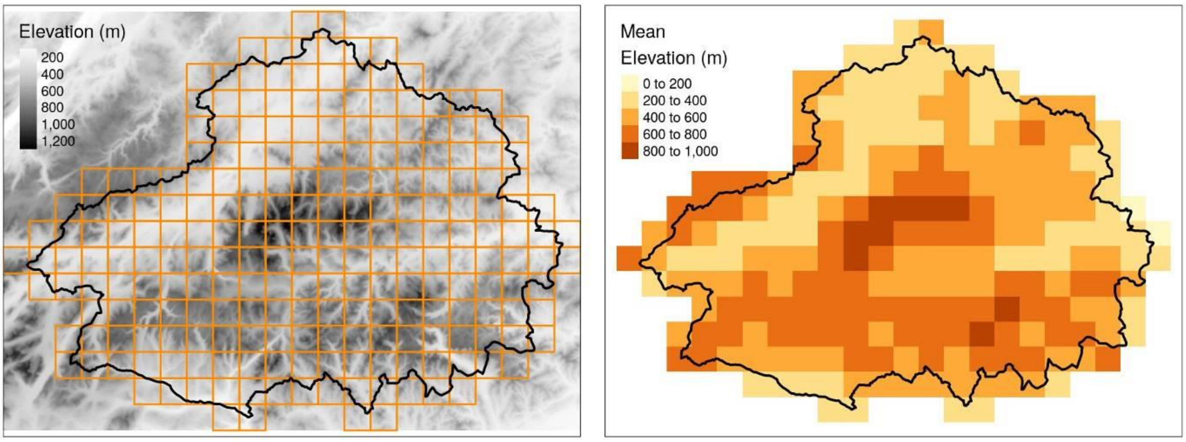

Figure 8. Map of Cairngorm National Park and model grid cells. Elevation is shown on a 50 m (left) and 5 km (right) grid. Contains Ordnance Survey data © Crown copyright and database right 2019. [6]

Snow cover data for the cells containing Aviemore (228m, mean grid cell elevation 402m asl), the Cairngorm Chairlift meteorological station ("Base" in Figure 9, 663 m, mean grid cell 485m) and Ptarmigan Restaurant (1097 m, mean grid cell 902m) on Cairngorm Mountain were extracted from the whole National Park area data set. Results are presented in Figure 9.

Key Finding: The future projections indicate a decline in snow cover days per year from the 2030s for Aviemore, the Cairngorm Chairlift meteorological station (Base) and Ptarmigan Restaurant on Cairngorm Mountain. This trend will continue through to the 2080s. There will be large variation between years and there are likely to still be some years comparable with past amounts of snow cover.

[6] See Footnote 1 for original source.

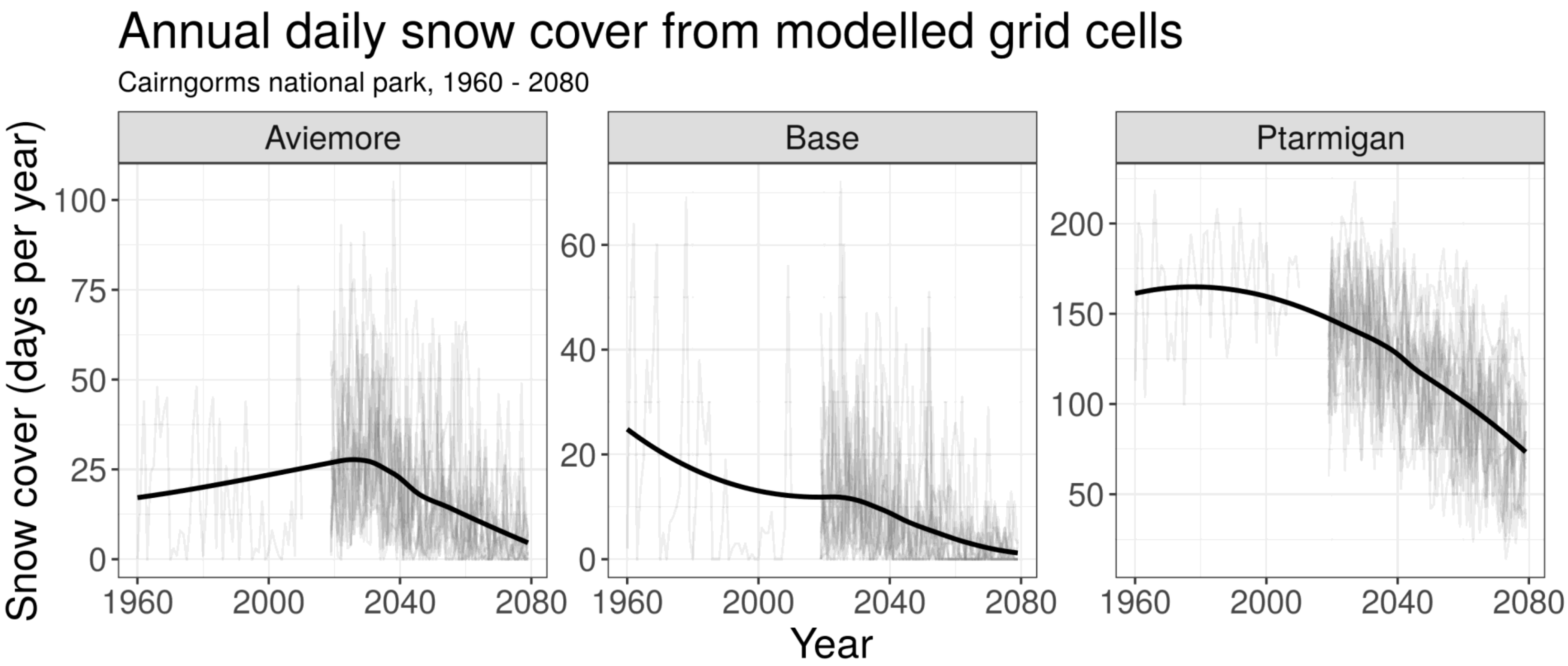

Figure 9. Annual snow cover (days per year) at three elevation ranges for Aviemore, the Cairngorm Chairlift (Base) and Ptarmigan visitor centre (near Cairngorm Mountain summit). Light grey lines show individual model runs with UKCP18 ensemble members and the heavy black line indicating the smoothed average of these. Note different scales on snow cover axes.

The results show that snow cover may continue to be similar to the past for the next 1-2 decades but will decline substantially afterwards. This applies to all elevations, but with larger proportional decreases at higher levels. These declines may be associated with passing a temperature threshold where precipitation no longer falls as snow and any lying snow melts sooner. An overview timeline is approximately:

- 2020-2030: similar amounts and level of annual variation of snow cover to the past at all elevations. Some years likely to be similar or even possibly greater snow cover than in the past.
- 2030-2040: declining snow cover but with similar levels of annual variation to the past at all elevations. Some years likely to be similar to the past but not achieving the larger amounts of snow cover, especially at the low- to mid-range elevations.
- 2040-2050: rate of decline increases at all elevations to approximately half of historic long-term average snow cover. Average amounts of snow cover similar to the lowest levels seen in the past at higher elevations.
- 2050-2080: continued increasing rate of decline particularly at higher elevations, approaching 70-80 days less at the Ptarmigan on average, but with some years where the largest amount of snow cover is similar to the historic low amounts. By 2080 there is potential that the snow cover at the high elevation site is c. 50% less than the historic average.

These results are in line with site-specific studies of observations. e.g. Trivedi et al (2007) found an observed relationship of a 1°C temperature rise at a meteorological station at Ben Lawers corresponding to a 15-day reduction in snow cover at 130m elevation and a 33-day reduction at 750m.

Currently some evidence indicates an increase in snow cover in the last decade (Andrews et al 2016 and anecdotal), with substantial snow events in 2018, 2013, 2010 and 2009 (against a background of an overall drop since 1960) (UKCP18 2019b). Near-term climate projections indicate a potential for snow cover continuation (Figure 9 2020 to c. 2030), with large inter-annual variability and hence potential for some years with long snow cover duration.

These results are consistent with other studies. Using a low emissions scenario, Trevidi et al (2007) modelled projections of a 93% reduction in snow cover at 130m, 43% at 600m and 21% at 1060m. For a higher emissions scenario they projected 100%, 68% and 32% for these elevations, respectively. The UKCP18 report a decrease in both falling and lying snow across the whole UK for the period 2061-2080 (using the same climate model data as our study). This decrease is smaller for the Scottish mountains, but still in the order of 20-60% (snowfall) and 60-100% (lying snow) (UKCP18 2019b).

Our study has used climate projection data derived from global and regional climate models (HadGEM3 and HadRM3) using a high level of radiative forcing[7] (Representative Concentration Pathway 8.5) associated with the current trajectory of greenhouse gas emissions. Thus, if mitigation efforts are successful in reducing emissions, then the longer-term projections of snow cover decline may be less. However, there will be some locked in climate change even if emissions ceased now, that will lead to further warming for the next 3-4 decades.

[7] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism.

Translating estimates of future snow cover to snow depth

This is a problematic research challenge, however the evidence of historical temperature, precipitation and solar radiation trends provide a clear indication of the direction of change (e.g. Figures 2-3 and Appendix Figs. 10-13). The observed deceases in mean and maximum snow depth (Figure 5) and count of days at different depths (Figure 6) imply a reduction in snow cover, which is represented in the snow cover modelling of the historical data (Figure 9). However, in translating future estimates of snow cover to depth, there is an assumption that a reduction in cover also means shallower depths.

In terms of site-specific assessment and use of a single meteorological stations' data, there is a risk of under- or over recording observed snow depth. The location of the meteorological station at the Cairngorm Chairlift may under record depth due to its location. Conversely, if it was sited in a gully or hollow, it would over record depth.

Interpreting this and the future snow cover projections, it seems reasonable to conclude that whilst there may be a reduction in snow cover and mean depth, there will still likely be specific locations where snow accumulates and remains even under greater thermal energy inputs.

Conclusions

Using observed weather and snow depth data to assess past trends and modelled future estimates of snow cover, we found an observed increase in temperature for all winter months and precipitation in January and February, whilst solar radiation has increased in February, March and April. There has been a decrease in observed snow depth at the Cairngorm Chairlift base station. This is projected to remain similar for the next 1-2 decades but then continue to decrease in the future. There appears to be a correlation between decreasing snow depth and increasing temperature.

The observed warming trend seen for Cairngorm Mountain, which fits within the observed increases across the UK, is projected to continue in keeping with the wider UK (UKCP18) and global climate projections (CMIP5[8]).

Our modelled future estimates indicate a potential for snow cover in the next decade to continue at a similar duration to the recent past, with large inter-annual variability. However, from c. 2030-2040 there is likely to be a substantial decline in the number of days of snow cover. By c. 2050 the trend seen in the past may have continued to the extent that the number of days of snow cover is about half of the long-term observed average. However, variations from year to year, both observed and modelled, suggests the potential that snow cover in some future years may be comparable with past records. The long-term trend is towards greatly reduced snow cover with the possibility of some years of very little snow by 2080 at the highest elevations.

Changes in snow cover will also influence the albedo (surface reflectance) and localised thermodynamics; changes from white snow (reflecting solar radiation) to darker vegetation, soil and rock will absorb more heat energy leading to warmer surface temperatures. The current global rate of emissions still puts the world on a trajectory towards the higher temperature rise range (c. 3 to 4°C). This, combined with UKCP18 projections for high resolution spatial modelling only being available for the high emissions RCP8.5 scenario, means that our results are based on an assumption of a continued future of high fossil fuel use in the absence of globally effective climate policies.

[8] https://esgf-node.llnl.gov/projects/cmip5/

References

Andrews C. Ives S. Dick J (2016) Long-term observations of increasing snow cover in the western Cairngorms. Weather 71, No. 7. https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/wea.2731

Beniston M. Keller F. Koffi, B.and Goyette S. (2003). Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions. Theoretical and Applied Climatology 76:125–140.

Harrison J. Winterbottom S. and Johnson R. (2001) Climate change and changing snowfall patterns in Scotland Edinburgh Scottish Executive Central Research Unit.

Rivington M, Spencer M, Gimona A, Artz R, Wardell-Johnson D, Ball J (2019) Snow Cover and Climate Change in the Cairngorms National Park: Summary Assessment. James Hutton Institute, November 2019. https://www.climatexchange.org.uk/media/3900/cxc-snow-cover-and-climate-change-in-the-cairngorms-national-park_1.pdf

Rivington M, Miller D, Matthews KB, Russell G, Bellocchi G, Buchan K (2008) Downscaling regional climate model estimates of daily precipitation, temperature and solar radiation data. Climate Research 35(3): 181-202

Spencer, M. (2016). Reanalysis of Scottish mountain snow conditions. PhD Thesis, Edinburgh University. http://hdl.handle.net/1842/25527

Trivedi MR, Browne MK, Berry PM, Dawson TP and Morecroft MD (2007) Projecting Climate Change Impacts on Mountain Snow Cover in Central Scotland from Historical Patterns. Arctic, Antarctic and Alpine Research 39, 488-499.

Appendix

The following figures are for additional information and used to support details presented in the report.

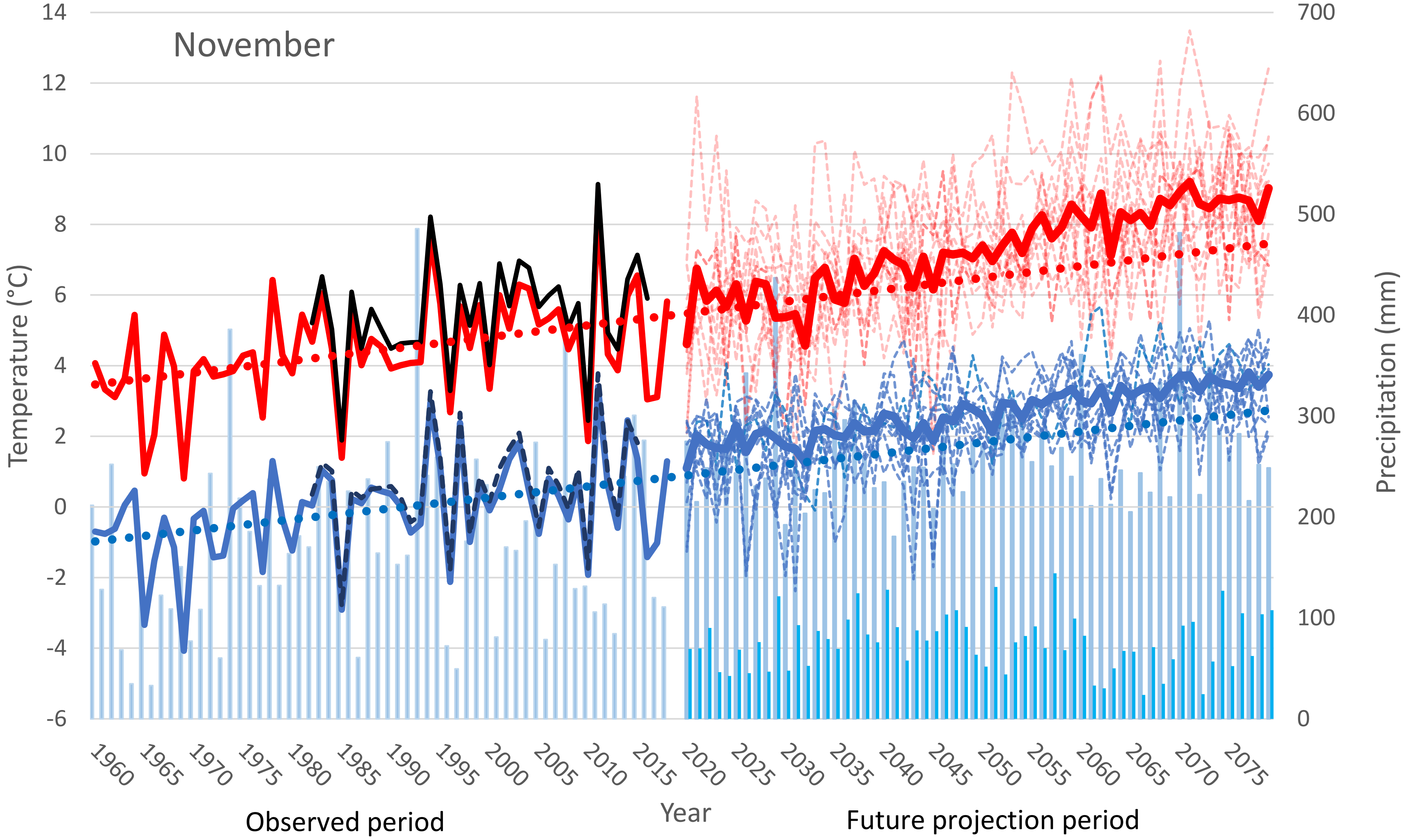

Figure 10. November temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

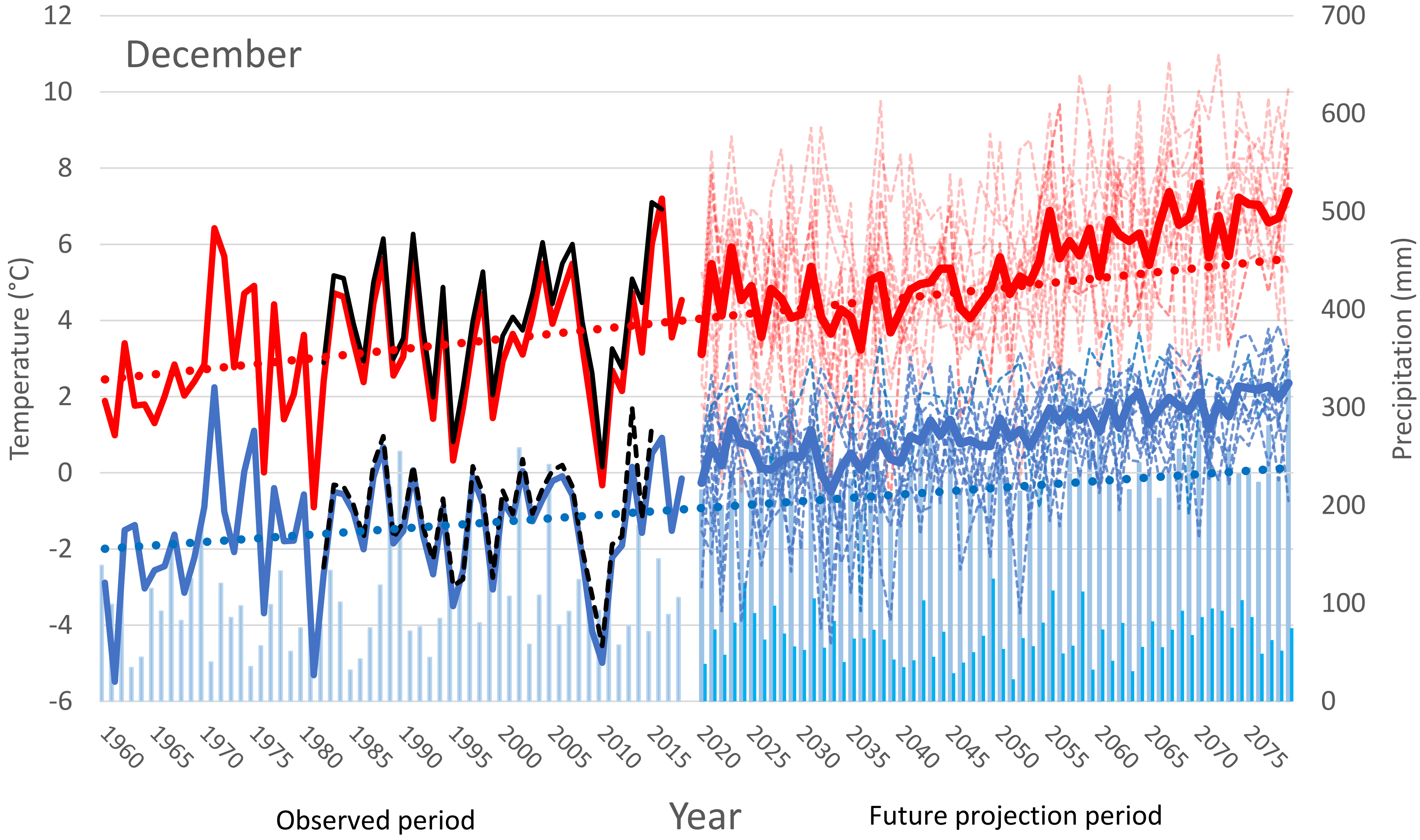

Figure 11. December temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

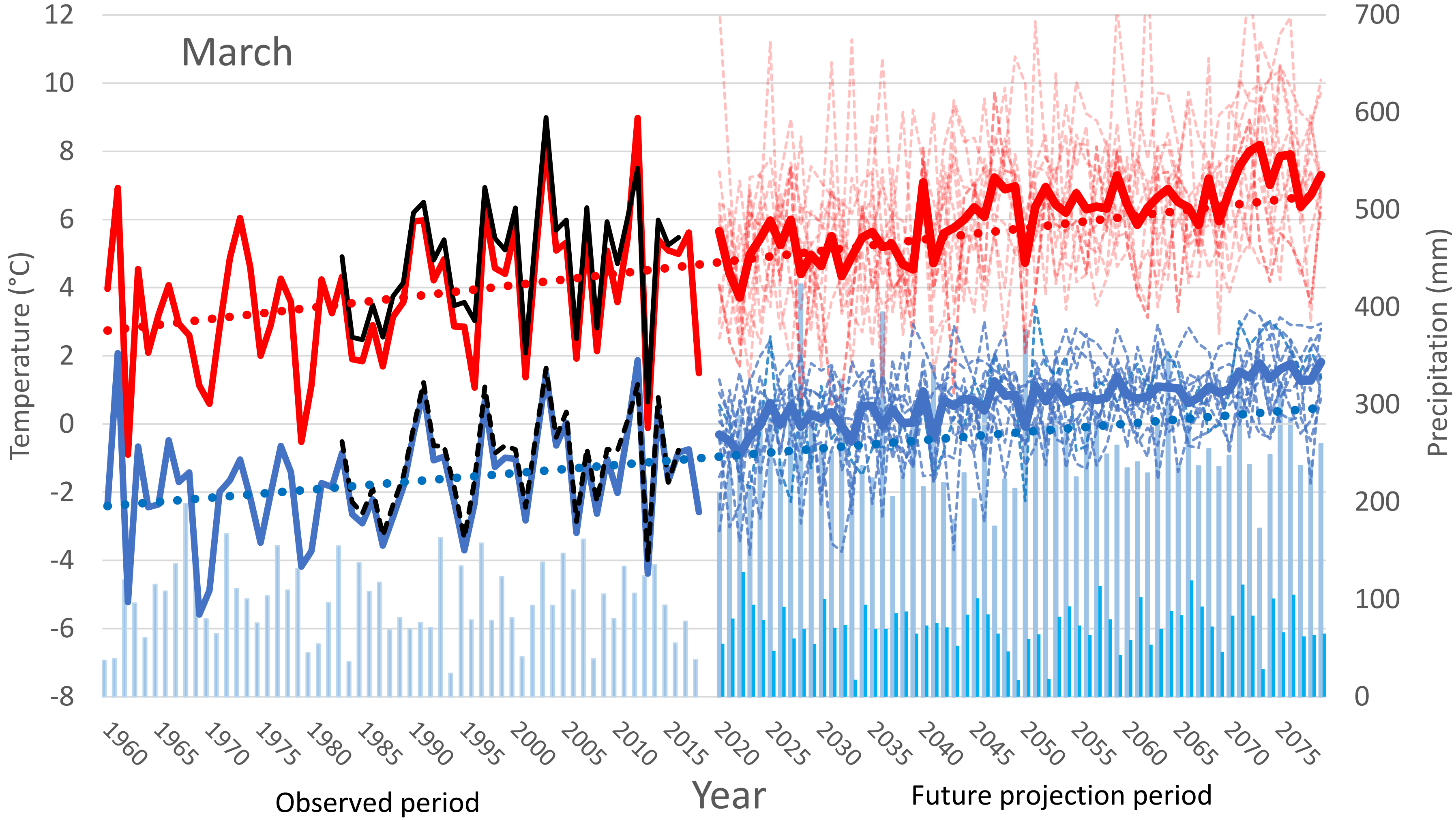

Figure 12. March temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

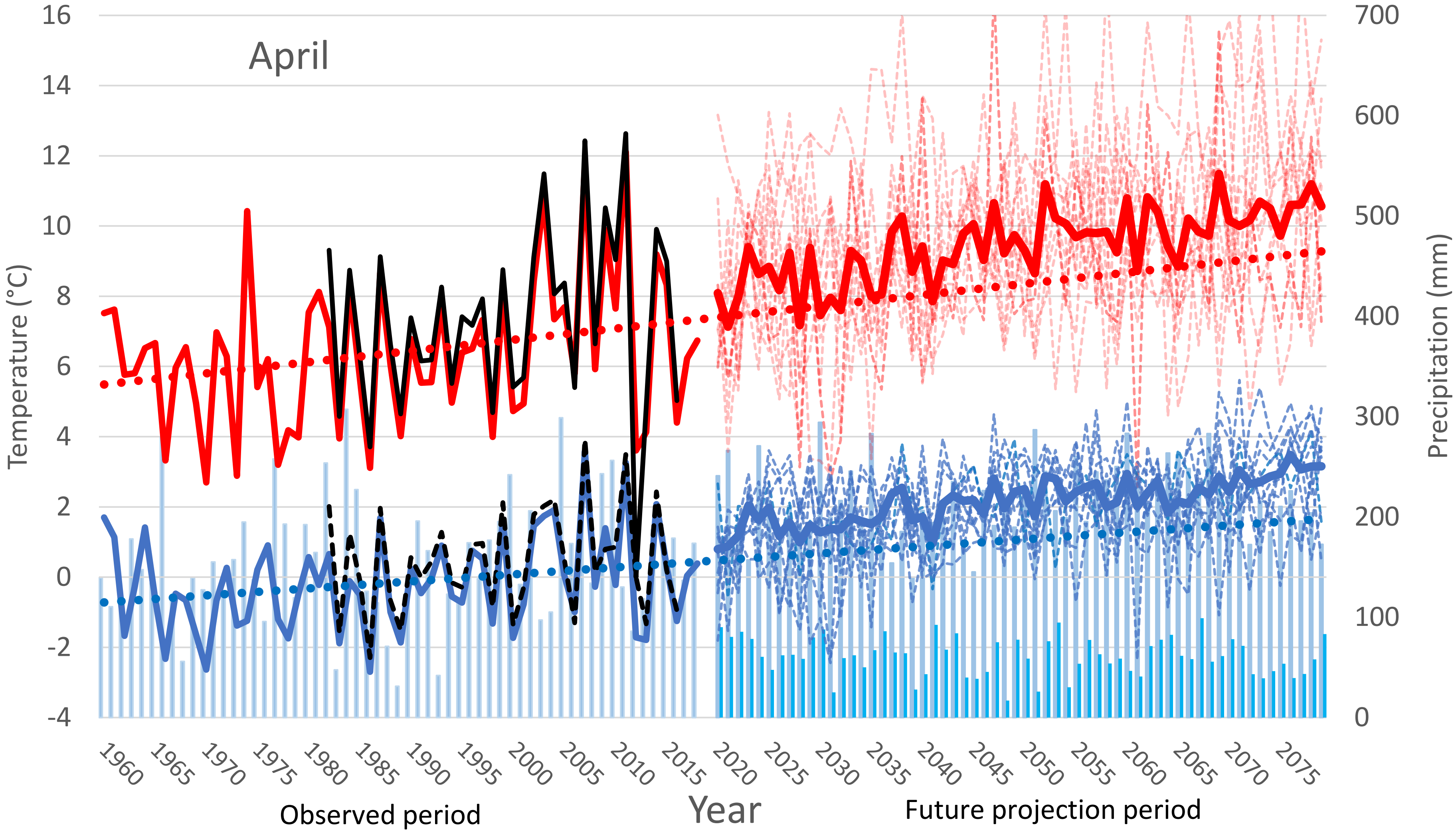

Figure 13. April temperature: 1km interpolated gridded observed mean maximum (red line) and minimum (blue line) temperature (°C) where dotted lines are the observed trends extended by 60 years to 2080, and precipitation (blue bars). The future projection period data are: climate model ensemble mean (large solid line) and individual ensemble members (thin dashed line), lowest (dark blue bars) and largest (light blue bars) precipitation estimates for an ensemble member model. Black lines are the observed temperatures measured at the Cairngorm Chairlift meteorological station.

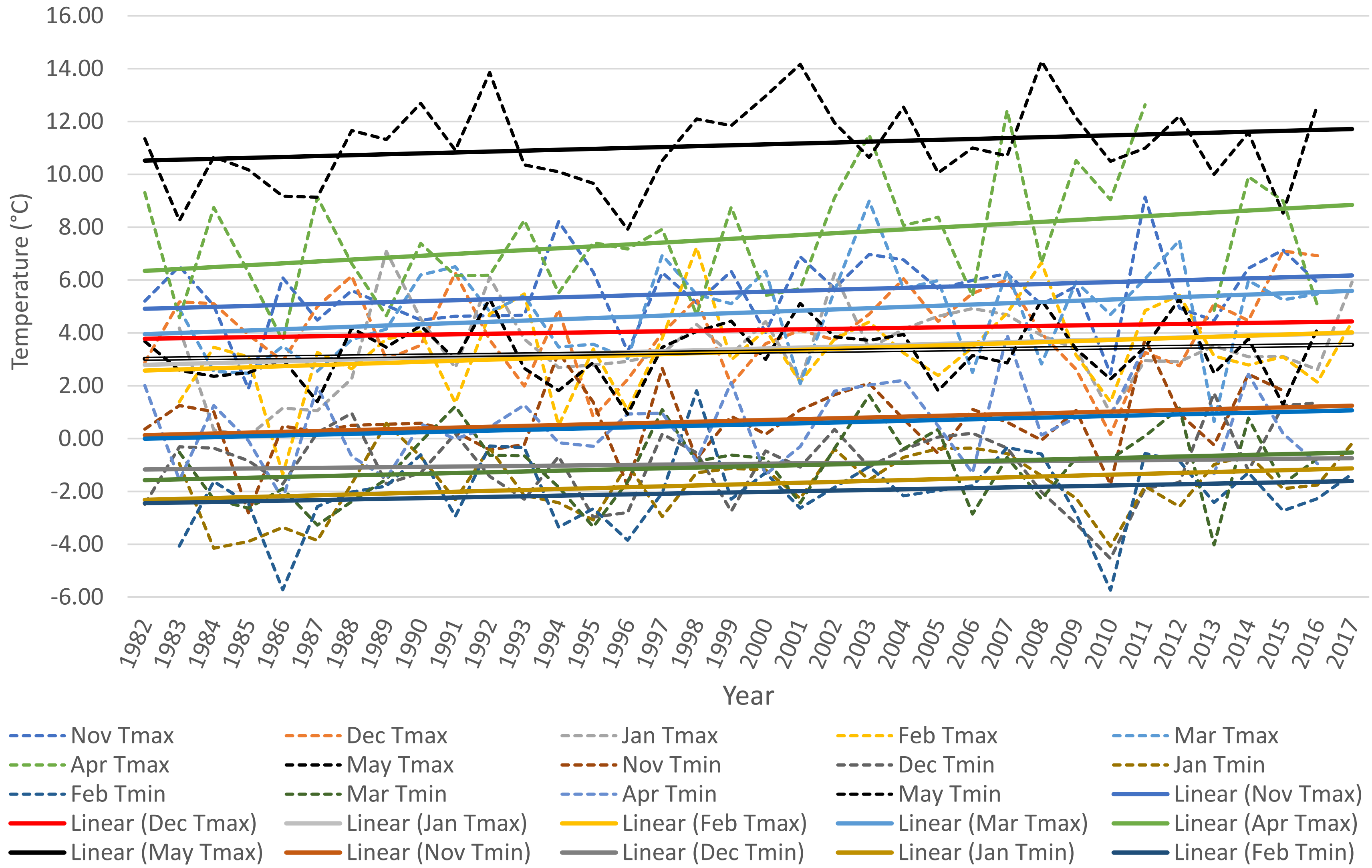

Figure 14. Monthly mean maximum (Tmax) and minimum (Tmin) temperatures per year and trends (1982 – 2018) for Cairngorm Chairlift meteorological station

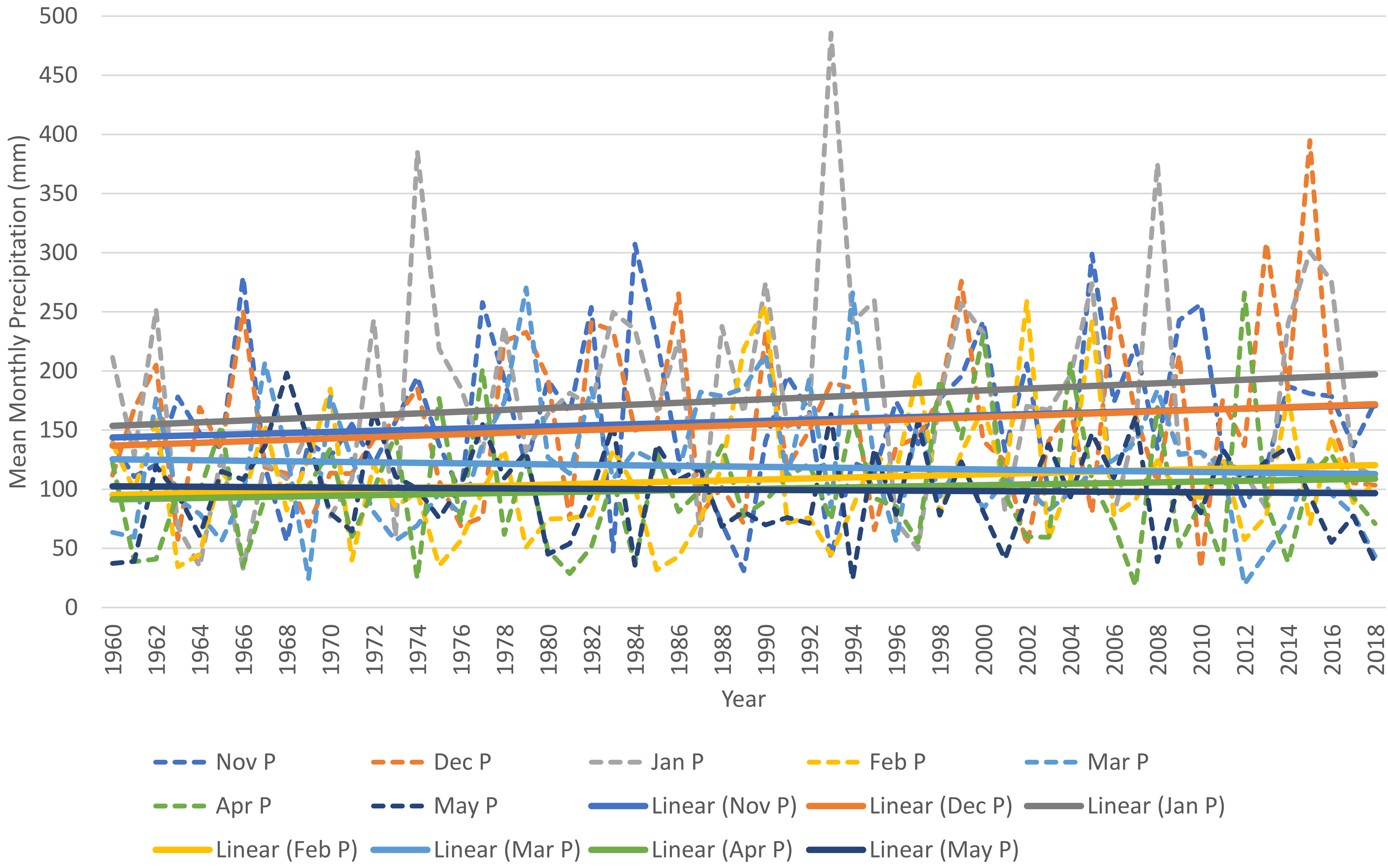

Figure 15. Cairngorm Chairlift location (1km resolution interpolated data) mean monthly precipitation (1960 -2018).

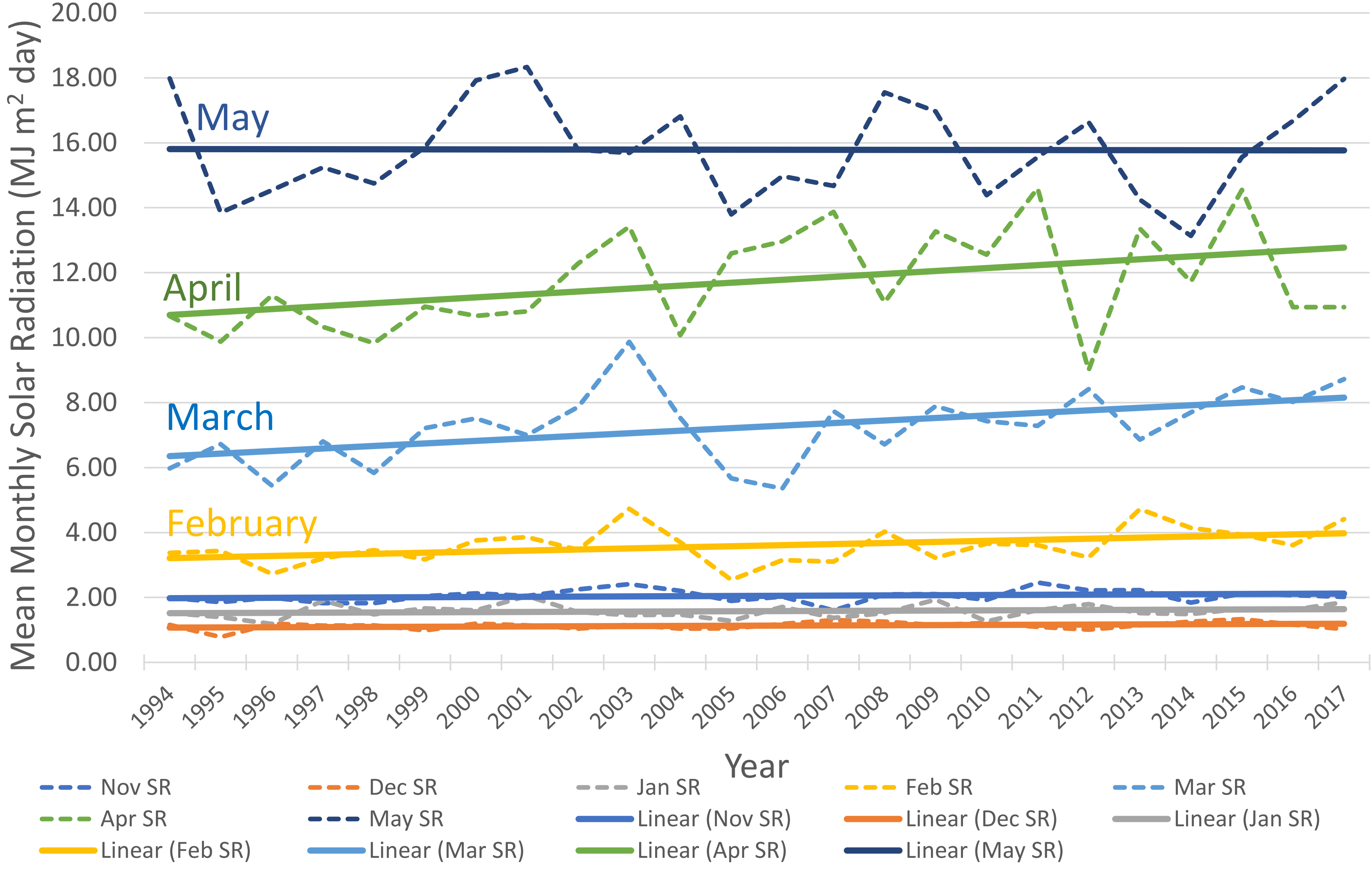

Figure 16. Mean monthly solar radiation (MJ m2 day-1) and trends over time (1994 – 2017). Data estimated from satellite observations (SolarGIS)

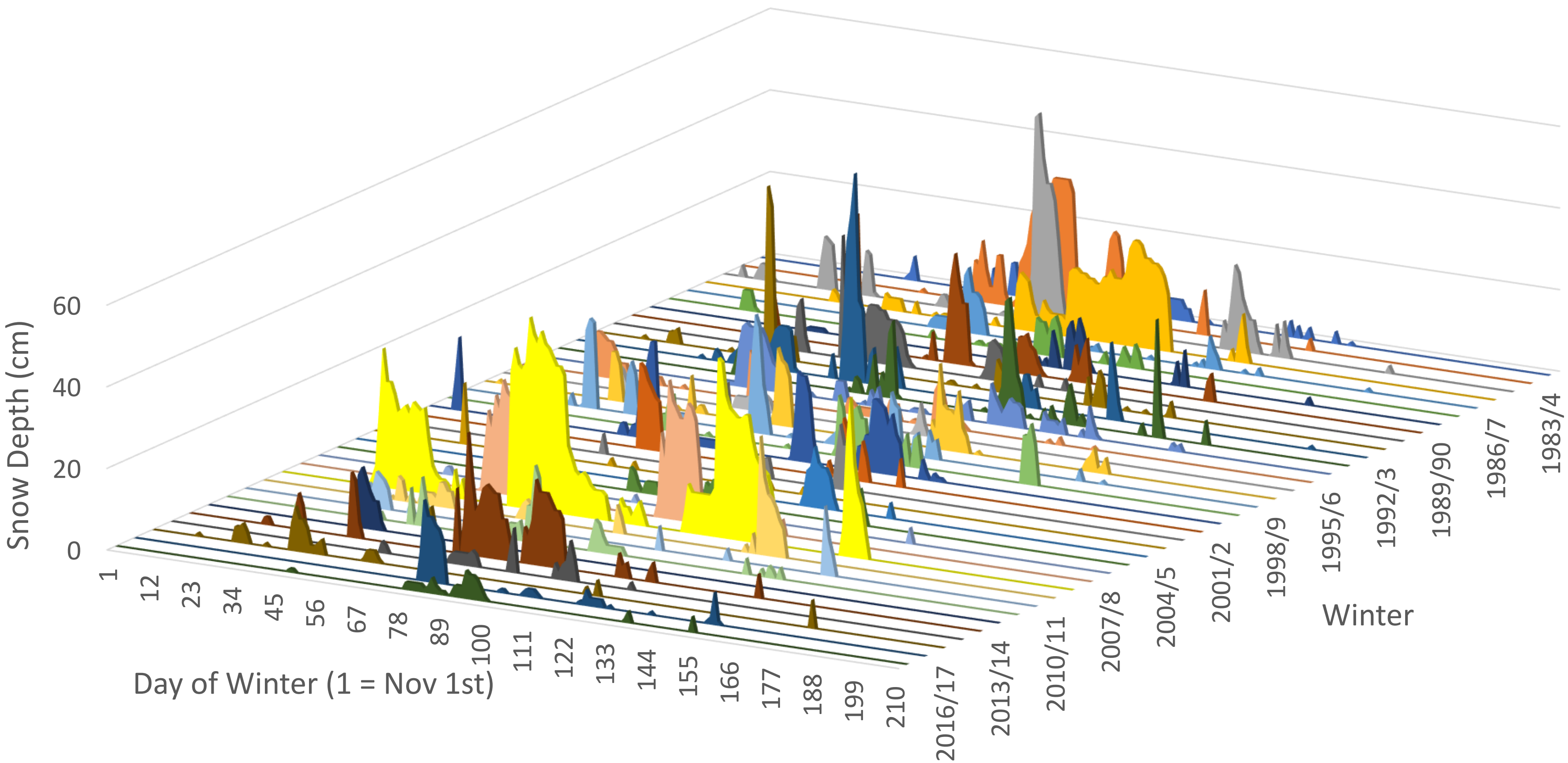

Figure 17. Daily snow depth (cm) per winter.

Thermal Time Accumulation

Thermal time accumulation (TTA, units are degree days) is a useful indicator of accumulated thermal energy and may be seen as an indicator of snow cover probabilities. It is derived by taking difference between maximum and minimum temperatures on one day and adding it to the value gained from the previous day.

For example: Day 1 Tmax = 4°C, Tmin = 2°C, difference = 2°C. Day 2 Tmax = 5°C, Tmin = 1°C, difference = 4°C. Day 3 Tmax = 2°C, Tmin = -1°C, difference = 2°C (where below zero temperatures are not used as they do not add to the positive accumulation). So, the thermal time accumulation is 2+4+2 = 8°C. If temperatures are below 0°C then there is no accumulation until above 0°C again.

A winter with consistently cold temperatures will have a low thermal time accumulation rate and total value, whereas as a winter with higher temperatures will have a more rapid accumulation rate and total value. A general assumption may be that higher rates of TTA imply lower amounts of snow depth and cover. However, there are cases when years with higher amounts of snow have also occurred when the TTA is close to the average (e.g. the first, second and third large accumulations of snow in the winter of 2009-10, Figure 18).

Future projections of thermal time accumulation (based on climate model projections of Tmax and Tmin) indicate that the ensemble mean rate and end of winter total will increase (Figure 18) and that the highest rates for individual years will be considerably larger than the observed mean (c. 200 degree days by the end of January). However, the lower rate of TTA in some years and ensemble members is similar to the observed low TTA rates. Overall, the means per individual climate model run and the ensemble mean indicate an increase in the TTA rate and total accumulate in the winter and thus additional thermal energy that may decrease the probability of snow formation and increase the probability of snow melt.

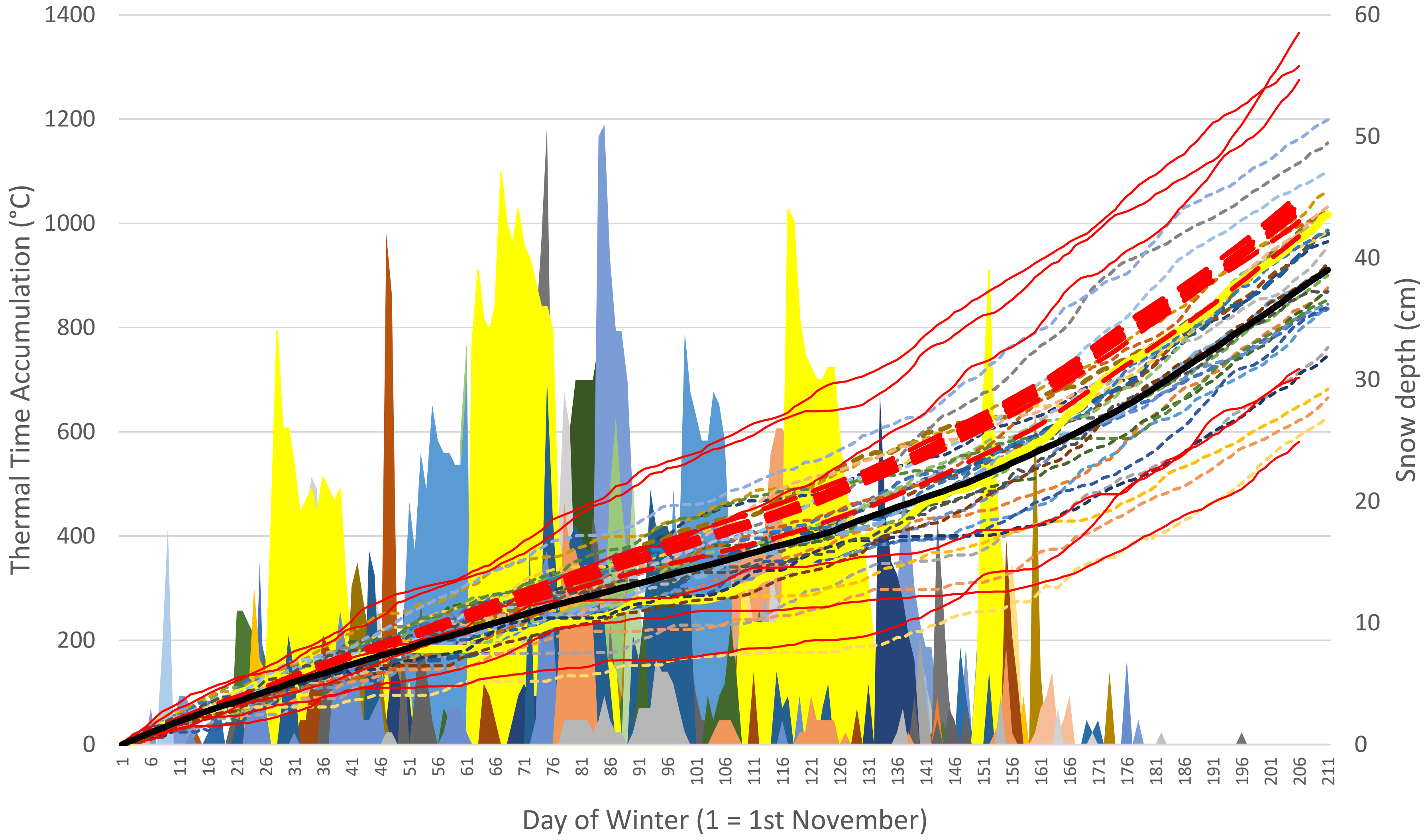

Figure 18. Snow depth and observed thermal time accumulation per winter (small dashed lines) and future climate projections. Large dashed red lines are the 2020-2080 means for each climate model ensembles member, thin solid red lines are the highest (upper lines) and lowest (lower lines) individual years from three example ensemble members. Solid yellow line is the thermal time accumulation and yellow bars are the snow depths for winter 2009-10.

The James Hutton Institute

SRUC