METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **19**: 454–463 (2012)
Published online 30 June 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.276

How can meteorological observations and microclimate simulations improve understanding of 1913–2010 climate change around Abisko, Swedish Lapland?

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ABSTRACT: A detailed analysis of 2 years' hourly microclimatic (mainly surface air temperature) data recently acquired from locations widely dispersed over 700 km^2 in the Abisko catchment encompassing Lake Torneträsk in Swedish Lapland is presented in this study. This project is designed to explore the effects of microclimatic variability, past and future climate change (1913–2100) on regional vegetation and land-use changes, at an unique Arctic ecological and climate monitoring site, to aid adaptation of stakeholders to future climate change. Dominant altitudinal lapse rate and radiation effects during summer are revealed in detailed analysis of spatial variations in temperature between the different sites, which become largely negated during winter when cold-air ponding is much more significant. Moreover, near-shore temperatures are moderated significantly by Lake Torneträsk during the spring lake-ice melt season. The extent to which synoptic meteorological conditions affect these factors is explored. Examples of gridded temperature maps for the Abisko region are also presented, produced using a downscaling model based on the temperature data, which have numerous ecological and other applications. The long-term Abisko Scientific Research Station meteorological record, which spans almost a century from 1913 to present is also explored, for evidence of climate change, to set the temperature logger data in a long-term climate context. Exploratory analysis of the possible influence of future regional climate change on ecological/vegetation zones is also briefly discussed. Copyright © 2011 Royal Meteorological Society

KEY WORDS climate change; Sweden; temperature; Arctic; adaptation

Received 23 September 2010; Revised 22 March 2011; Accepted 23 May 2011

1. Introduction

Much attention has been focussed on climate change and its resulting impacts on ecosystems and people at high latitudes (Callaghan, 2005; IPCC, 2007; Callaghan *et al*., 2010). In the sub-Arctic region around Abisko, Swedish Lapland, unusually comprehensive and wide-ranging climate and ecological records were measured for the past century (Callaghan *et al*., 2004, 2010; Kohler *et al*., 2006). In the Abisko Scientific Research Station (ANS), the climate has been continuously monitored since 1913 at one site. In addition, short-term, sparse and discontinuous climate records were also measured for sites in various, environmentally diverse locations surrounding the main ANS climate station. Records from these sites were used to identify microclimate variability and explore climate-vegetation relationships at various spatial scales. However, while the vegetation (e.g. the treeline) and soil/permafrost distributions are related to the microclimate patterns, these various aspects are not necessarily in equilibrium, so discussion of the microclimate patterns therefore needs to be put within the context of long-term (particularly the last 10–100 years') climate change.

In this study, the results from an investigation of short-term (2008–2010) microclimate characteristics of the landscape around Abisko are presented within the context of long term (1913–2009) climate change, to provide an understanding of the impacts of climate change at the local level. To shed light on such climate change impacts, the spatial distributions of two important temperature thresholds have been modelled over the long term to quantify and locate areas of potential changes in the abundance of permafrost (Åkerman and Johansson, 2008) and treeline position (MacDonald *et al*., 2008; Van Bogaert *et al*., 2011).

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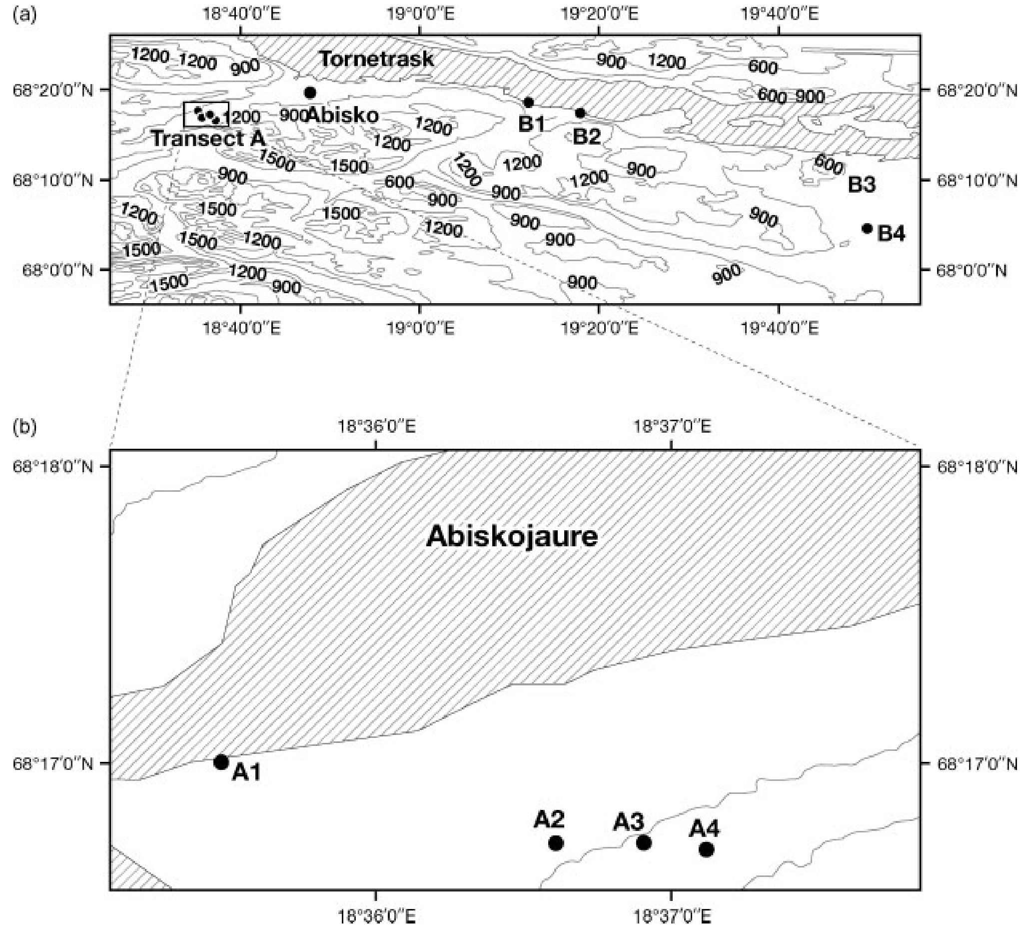

Figure 1. Locations of the Abisko Station and meteorological-station network in the contour maps: panel (a) shows meteorological stations in Transects A (sites A1 to A4, Abiskojaure profile) and Transect B (sites B1 to B4, Torneträsk profile) as circles, while (b) is a close-up of Transect A (Abiskojaure profile).

2. Site and methods

The study site includes the Lake Torneträsk catchment and surrounding areas, 68°0′–68°30′N, 18°40′–19°50′E, and covers a region of 700 km^2 in the extreme north of Sweden, classed as sub-Arctic (Figure 1). Vegetation is dominated mainly by birch forest with a few localized pine stands, wetland and tundra. The area includes Lake Torneträsk, a large (330 km^2) and deep (up to 168 m) lake within a drainage area of 3300 km^2, that meets many needs of local communities, e.g. ice fishing, winter transport and conservation. The catchment is relatively close to the Atlantic Ocean (<100 km), Narvik in Norway being the nearest port, but lies in the rain shadow of the Norwegian mountains. As a result, the climate of this region is among the most continental to be found in the Nordic countries (Tveito *et al*., 2000), being considerably milder and drier than other areas at similar latitudes. Based on the long-term climate record at ANS, the mean annual temperature (MAT) is −0.6 °C for the period 1 January 1913 to 28 January 2010 and mean monthly temperature ranges from −10.8 °C in January to +11.7 °C in July (Callaghan *et al*., 2010). Mean annual precipitation is 305 mm, which is relatively low compared to nearby locations such as Narvik in Norway (about 800 mm), due to Abisko's location in a rain shadow: the wettest month is July (50.7 mm) and the driest month is April (11.5 mm), and the winters and springs are much drier compared to the summers and autumns (Callaghan *et al*., 2010).

A network of eight temperature loggers was deployed at a range of sites denoted as A1–A4 (Abiskojaure profile) and B1–B4 (Torneträsk profile) (Figure 1). The Abiskojaure profile was set up to explore the influence of the mountains on surface air temperature (SAT) by monitoring over an altitudinal range of 300 m, while the Torneträsk profile was set up to understand the lake effect by measuring SAT at different distances up to 13 km from Lake Torneträsk. The loggers were set up during a period of fieldwork spanning 23–28 July 2008. Half-hourly wind speed data were recorded by an anemometer logger (Madgetech model 110) ~3 m above the ground at the A1 logger locations, from July 2008 through June 2009. These wind-speed values were extrapolated to 10 m elevation using a logarithmic equation for the wind profile at different heights (Linacre, 1992).

Prior to deployment in the field, all the Tinytag temperature loggers (obtained from Gemini Data Loggers UK Inc.) were calibrated through comparison with control data from an officially calibrated UK Met. Office sea thermometer at the Sheffield Norwood Climatological Observers Link automatic weather station, UK. The loggers were set up in the same thermometer screen as the standard temperature sensor and readings were taken at 5 min intervals during a 2 month calibration period. The offsets of the loggers from the standard thermometer ranged from 0.1 to 0.3 °C. Taking into account the uncertainties due to the performance of the loggers in extremely cold conditions, the maximum SAT uncertainty of 0.5 °C is assumed. In the field, screen-level SAT at each station was recorded at 1 h intervals. During their placement in the field, each logger was deployed in a small plastic radiation shield and mounted on aluminium poles set at a height of 1.5 m above ground level. Logger locations were representative of the local topography/vegetation conditions within a radius of tens to hundreds of metres. All the temperature and wind-speed logger data were downloaded during August 2010, yielding a 320 day dataset from 28 July 2008 to 12 June 2009, and a 336 day dataset from 20 September 2009 to 24 August 2010. The temperature data during the summer of 2009 were lost due to logger malfunctions. The wind-speed loggers' data were downloaded during June 2009 yielding a 320 day dataset from 28 July 2008 to 12 June 2009. Using the length of daylight algorithm (Holtslag and Van Ulden, 1983), the SAT data were divided into daytime and night time sections according to seasonally varying length of daylight (Holtslag and Van Ulden, 1983). Daytime is defined as the time after sunrise and before sunset, i.e. 24 h during the polar day and nil during the polar night, and all times referred to here are UTC.

3. Results and discussion

3.1. The seasonal and daily cycles from the microclimate measurement

The seasonal cycle of SAT for Transect A (Abiskojaure profile) is shown in Figure 2. The lowest hourly SAT of around −20 °C (depending on site) was recorded around mid-February, and the highest SAT of around 10 °C was recorded around mid-July.

The daily cycle of SAT is represented by the hourly breakdown of the SAT record in Abiskojaure and strongly correlates to the diurnal cycle in solar radiation (Figure 3). Firstly, the daily SAT amplitude in summer was clearly greater than that in winter. Secondly, the SAT amplitude during the daytime was larger than that during the night time, particularly in the 'transitional' season months April and October (Figure 3). During summer, SAT reached its peak around 1300 and its amplitude reached up to 12 °C within 1 day or as much as 5 °C within 1 h (Figure 3). In contrast, during winter, SAT was relatively stable and its daily amplitude generally kept within 2–3 °C.

3.2. Microclimatic fluctuations – a combination of both lake and mountain effects

According to the records from the meteorological station network, the SAT microclimate at Abisko was mainly dominated by two interactive systems: (1) Lake Torneträsk through the lake-land breeze system, and, (2) the surrounding mountains through the surface-atmosphere energy exchange. In addition, there is a distinct maritime-continental gradient running west-east across the Abisko region, as evidenced, for example, by more extreme seasonal temperatures at the northernmost Swedish city of Kiruna (well to the east of the region explored here) than Abisko. However, because the study domain is quite small – only a few tens of kilometres across – this ocean-land contrast is secondary to the lake (Tornetrask) effect in the study region.

3.2.1. Lake effects

As the seventh largest lake in Sweden, a locally maritime climate is created by Lake Torneträsk, and the surrounding SAT during the summer is lowered, while during late autumn/early winter the energy exchange

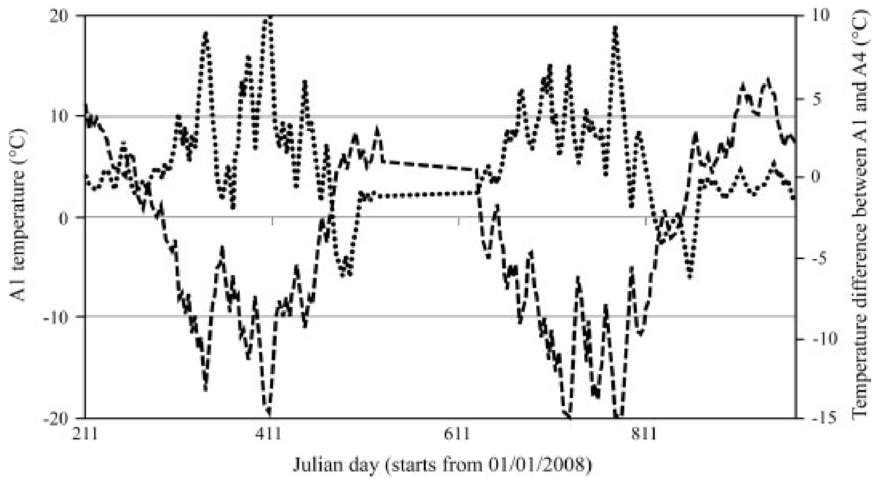

Figure 2. Temperature records in transect A (Abiskojaure profile) (10 day means). A1 values are shown on the left-hand vertical axis (long dash lines), while the difference between A1 and A4 is indicated by the right-hand vertical axis (dotted lines), Julian day 1 = 1 January 2008.

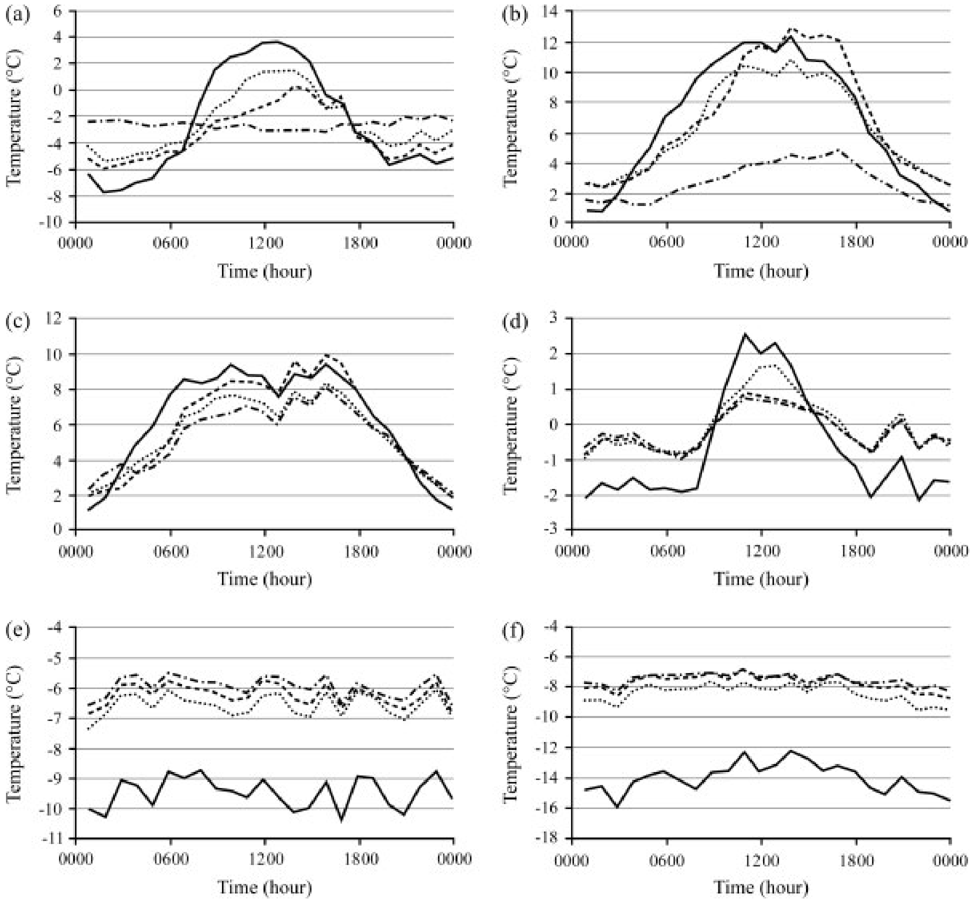

Figure 3. A comparison of the hourly temperature records in the Abiskojaure profile: the numbers after the site are the altitudes (m.a.s.l) for each site, A1-490 (solid lines), A2-585 (dotted lines), A3-627 (dash lines), A4-655 (dash-dotted lines). (a) April; (b) May; (c) June; (d) October; (e) November; (f) December.

between the (still incompletely frozen) lake and surrounding terrain results in a warming influence on areas immediately surrounding the lake. Moreover, snow is likely to be accumulated around Lake Torneträsk due to the wind from surrounding valleys. The moderating influence of Lapland lakes was previously thought to be only about 1.5–2 °C at the 1 km scale (Vajda and Venalnen, 2003) but in this study the SAT difference between B1 (near the lake) and B4 (13 km distant from the lake and with an altitude difference of only 128 m) went up to 8 °C during winter and down to 0.5 °C during summer (Figure 4). In Figure 4, the mean diurnal SAT variation is shown for selected months, again emphasizing relatively colder conditions at B4 (and to a lesser extent B3) during winter, particularly in December when a 4 °C low offset at B4 was observed. This pattern is also apparent for night time during other seasons, but is least noticeable in August – late summer (Figure 4). Also noteworthy is that the daily SAT amplitude at B4 generally exceeded that at B1 (Figure 4).

3.2.2. Mountain effects

The influence of the mountains on SAT at a particular location in the Abiskojaure profile was characterized by SAT fluctuations resulting from altitude, slope, aspect, and topographic position that affect solar radiation, wind and cold-air ponding.

To understand the influence of altitude on SAT variation, simple linear regression was used to define the relationship between mean monthly SAT and altitude, and a seasonal record of the lapse rates during the day- and night-time was derived based on all stations (Table I). Over the year, the annual lapse rates ($-3.9\,^{\circ}C\ km^{-1}$) are similar to those for Sweden as a whole ($\sim-4\,^{\circ}C\ km^{-1}$) and Fennoscandia ($\sim-5.7\,^{\circ}C\ km^{-1}$) found in previous studies (Laaksonen, 1976; Sjörs, 1999; Konay *et al.*, 2007). The lapse rate during the night time is lower than that of the daytime, and the lapse rates show considerable seasonal variation: highest during summer ($-9.2\,^{\circ}C\ km^{-1}$), and lowest or even inverse during winter (generally -2 to $-3\,^{\circ}C\ km^{-1}$ but notably $+8.7\,^{\circ}C\ km^{-1}$ in the coldest month, February). This abnormal lapse rate may be attributed to the malfunction of the SAT loggers under extreme cold environments (about $-30\,^{\circ}C$), which needs to be further explored.

Besides the influence of altitude, SAT was also dependent on microclimate characteristics (Scherrer and Körner, 2010), i.e. the moderating effect of the large lake (see above) and temperature inversions due to the ponding of cold air in steep-sided valleys, especially during

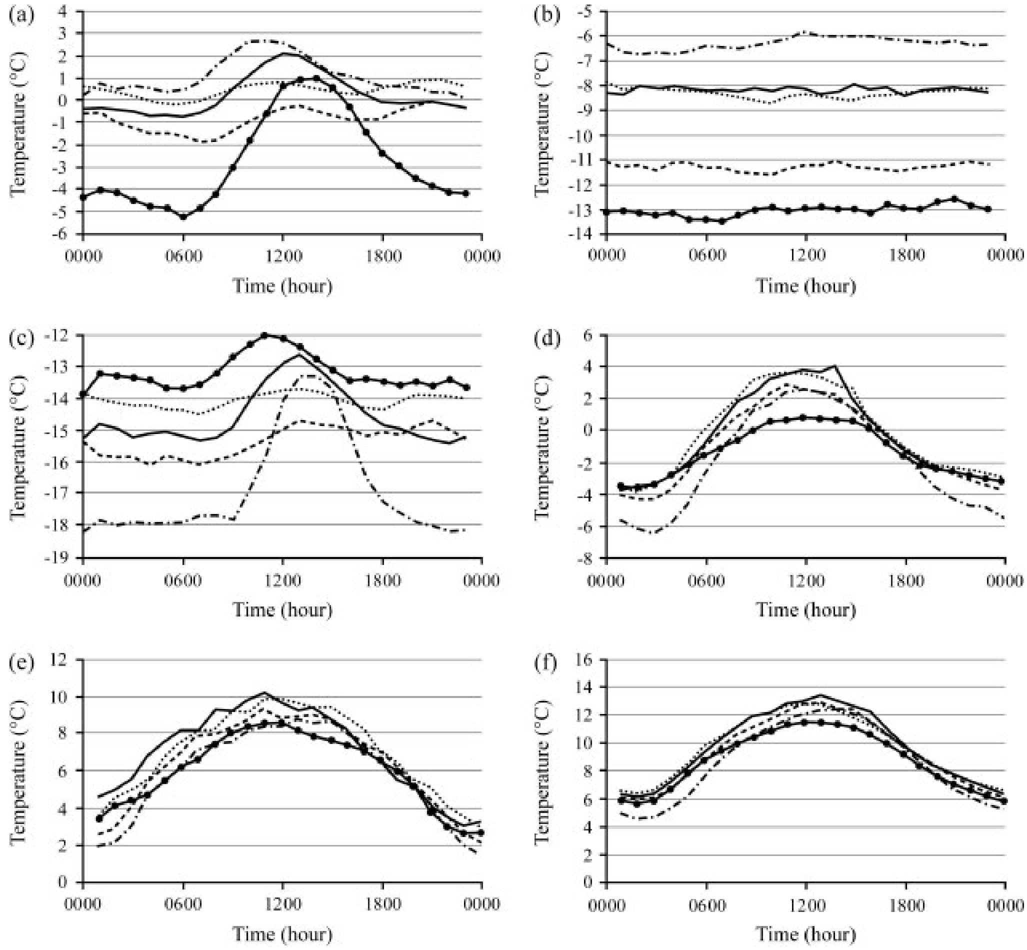

Figure 4. A comparison of the hourly temperature records among transect B (Torneträsk profile) locations and the Abisko Station [B1 (solid lines), B2 (dotted lines), B3 (dash lines), B4 (dash-dotted lines), Abisko (solid dotted lines)]: (a) October; (b) December; (c) February; (d) April; (e) June; (f) August.

the winter. For the Abiskojaure profile, the lowest site A1 (490 m.a.s.l) showed the strongest inversions (i.e. increase of SAT with height) during January and February, when the SAT difference reached 10 °C within an altitudinal range of less than 200 m (Figure 3). Moreover, it was found that there were: (1) fewer SAT inversions during the daytime because other factors, especially solar radiation, dominate the SAT pattern, (2) stronger SAT inversions (up to 18 °C) during winter, and, (3) stronger SAT inversions during calm nights when the average wind speed was less than 0.5 m s^{-1} (Figure 5). Up to more than 90% of the calm nights were accompanied by SAT inversions during winter. During calm nights/winter, cold-air ponding tends to occur in the Abiskojaure Valley. However, during windy nights when the average wind speed is more than 3 m s^{-1}, the accelerated air-mixture (due to stronger winds in mountainous terrain) dramatically reduces the lapse rate, especially in winter.

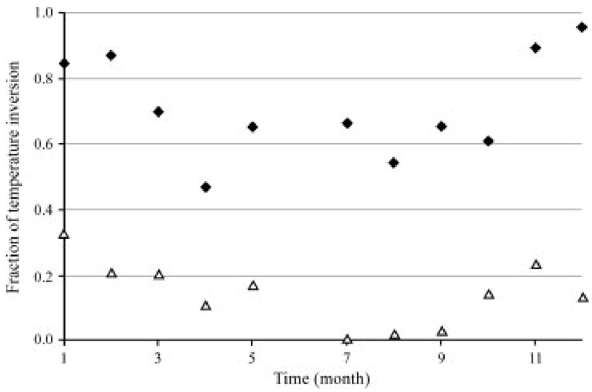

Figure 5. The fraction of temperature inversion at site A3 under relatively calm (<0.5 m s^{-1}) (diamonds) and windy nights (>3 m s^{-1}) (triangles) for different months. The temperature inversion is defined when the temperature of the upper site (A3) is higher than the temperature at the valley bottom (site A1).

3.3. Long-term climate change recorded at ANS

The main and longest-running meteorological record from ANS dates back to 1913 and is one of the most complete of its kind in the Arctic. Several published works have discussed the warming trend at Abisko over the last century (Kohler *et al*., 2006; Johansson *et al*., 2008) and analysed climate change and its multiple environmental implications in detail (Kohler *et al*., 2006; Johansson *et al*., 2008; Callaghan *et al*., 2010). This long-term record is characterized by two warming periods, with the

Table I. Monthly lapse rate at Abisko (based on the 1 year dataset from July 2008–June 2009).

	lapse rate (day)	lapse rate (night)	Nuolja (day)	Nuolja (night)
Annual rate	−3.8	−1.3	–	–
January	−1.1	−3.1	–	–
February	10.4	8.3	–	–
March	−5.8	−1.0	–	–
April	−8.7	−4.3	−3.6	−4.6
May	−9.2	−3.4	−5.1	−6.4
June	−6	–	−7.5	–
July	–	–	–	–
August	−6.3	−2.4	–	–
September	−5.4	−0.6	–	–
October	−3.4	−1.7	–	–
November	−2.6	−2.0	–	–
December	–	−2.4	–	–

Lapse rates are derived from our meteorological-station fieldwork network. The daytime (night time) local lapse rate during June (December) is not available due to polar day (night), and the July value is missing due to insufficient data during July 2008. Njuolja is a mountain close to the lake Torneträsk.

earlier one during the late 1930s to early 1940s, and the later one spanning from 1975 until present (Figure 6(a)). The analyses show a MAT increase of 2.5 °C since 1913, and an accelerated increase of some 1.5 °C since 1974 (Callaghan *et al*., 2010). These warming rates are statistically significant at the 99% confidence level. While the variability in the extremes of daily precipitation has increased (Callaghan *et al*., 2010) the variability in seasonal SAT has decreased, although this is statistically significant only for summer (Figure 6(b)).

3.4. How can microclimate temperature modelling tell us about long-term variability of surface-air temperature throughout a catchment?

To explore the evolution of microclimate within the context of long-term climate change, the fine-scale (50 m resolution), long-term (1913–2010) SAT for the Abisko region were modelled (Figure 7) assuming a 'static' nature of microclimate patterns (Zhenlin *et al*., 2011). In this modelling exercise, (1) synoptic-scale SAT data from the European Centre for Medium-Range Weather Forecasts ERA40 reanalysis dataset, (2) existing weather stations, and, (3) microscale SAT data from the fieldwork measurements, were combined and analysed. A comparison of the mean June and December SAT for different interannual periods shows the landscape-level pattern of warming driven by the point measurements at ANS (Figure 7). Superimposed on this long-term but recently accelerating (Callaghan *et al*., 2010) climate warming is interannual variability in SAT, which is exemplified by the two most recent winter (December–February) seasons 2008–2009 and 2009–2010 (mean SAT of −9.2 and −12.1 °C, respectively, according to the SAT record at ANS) (Figure 8). The large difference of ∼3 °C in mean winter SAT between these years reflects the unusually cold winter of 2009–2010 in Lapland, similar to that in the UK and elsewhere in northern Europe (National Climate Information Centre, 2010). While SAT at ANS was about −11 °C in winter 2009–2010, the modelling results show that SAT was even lower in the surrounding landscape and down to about −15 °C (Figure 7(b)), which can be confirmed from the measurements (Figures 3 and 4). In contrast, during summer, modelled SAT in the surrounding landscape was not much higher than that of ANS because ANS lies in one of the warmest areas (Figure 7).

The difference in these two winter conditions can be explained by the NCEP/NCAR Reanalysis 500 hPa upper-air charts (Figure 9), which show a weaker, northwesterly circulation over Abisko in 2009–2010 and a much milder, stronger, west-southwesterly circulation over the region during winter 2008–2009.

3.5. Applications of integrating short-term measurements of microclimate variability with long-term climate change

Many climate impacts on ecology and geomorphological processes at the landscape scale operate when SAT threshold values have been exceeded. Permafrost dynamics, for example, are potentially related to the 0 °C MAT threshold (Christensen *et al*., 2004; Johansson *et al*., 2006). SAT increases above 0 °C potentially result in thawing and loss of existing sporadic and discontinuous lowland permafrost, although peat soils, snow cover and vegetation in this area can modify the effects of SAT (Johansson *et al*., 2006). Therefore, the spatial changes of the 0 °C isotherm over the past 100 years were modelled by calculating the area covered by MAT above 0 °C (Figure 10): this area increased from only 10% of the whole area during 1913–1920 to around 35–40% after the year 2000. While there were some fluctuations during the 1940–1960s, the extent of the area in which permafrost, if present, could be at risk from thawing after 2000 exceeded that of the earlier warming period during 1930–1940s by more than 10%. Although the actual

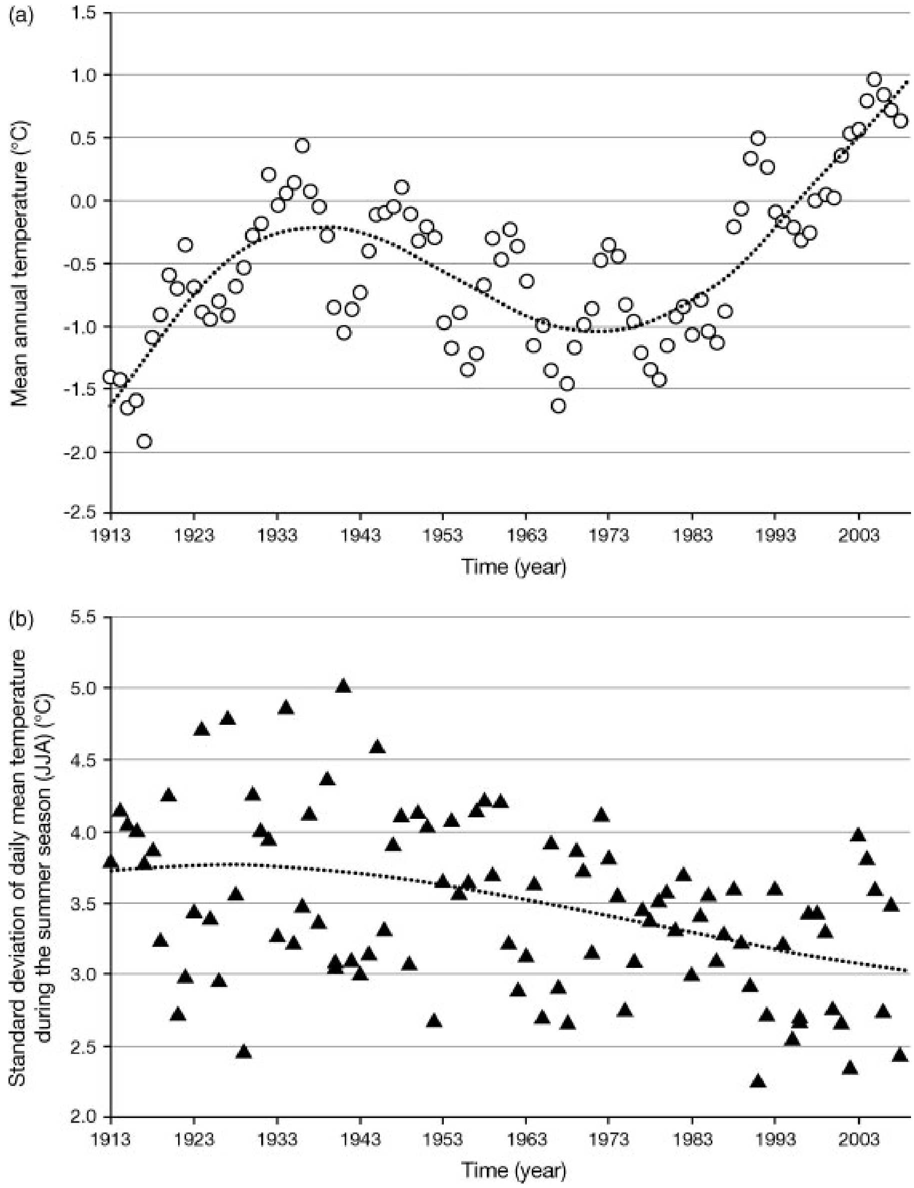

Figure 6. (a) Abisko long-term temperature record (1913–2009) (based on 5 year mean value), the dotted line denotes the polynomial curve trough mean annual air temperature, using the Legendre polynomial regression as Callaghan *et al*. (2010), and (b) the temperature variation during the summer (June/July/August) represented by the standard deviation of the daily mean temperature from the mean temperature during the summer, the dotted line denotes the polynomial curve trough standard deviation of daily mean temperature during the summer, using the Legendre polynomial regression as Callaghan *et al*. (2010).

distribution of permafrost depends on longer-term climate history as well as on the other factors mentioned above (Johansson *et al*., 2006; Ridefelt *et al*., 2008), and cannot therefore be assumed to be 90% of the area in 1913–1920 and 60–65% of the area after 2000, the changes in the location of the 0 °C MAT isotherm over time pinpoint particular areas to survey in addition to those currently monitored by Åkerman and Johansson (2008). Their study showed recent, unprecedented, melting of lowland permafrost in peatlands: of a total of nine mires investigated permafrost had disappeared from three of them while accelerated loss was occurring in all the remaining mires.

The location of the treeline can be also partly explained by a SAT threshold, i.e. the mean July SAT isotherm of 11 °C (Körner, 1998; MacDonald *et al*., 2008) and climate warming would be expected to displace the location of this isotherm and hence potential treeline. From the modelling results, the area covered by mean July SAT above 11 °C decreased since the mid-1930s before increasing again after the 1960s (Figure 11). The warming period during the 1930–1940s resulted in increasing coverage of favourable areas for tree establishment at treeline, while the declining trend after the 1940s would inhibit tree establishment but probably would not kill trees established earlier. While the long-term warming trend is indicated by comparing conditions favourable for tree establishment between 1913 and 2008 (Figure 11), shorter-term summer SAT fluctuations are also obvious: more than 60% of the area exceeded 11 °C

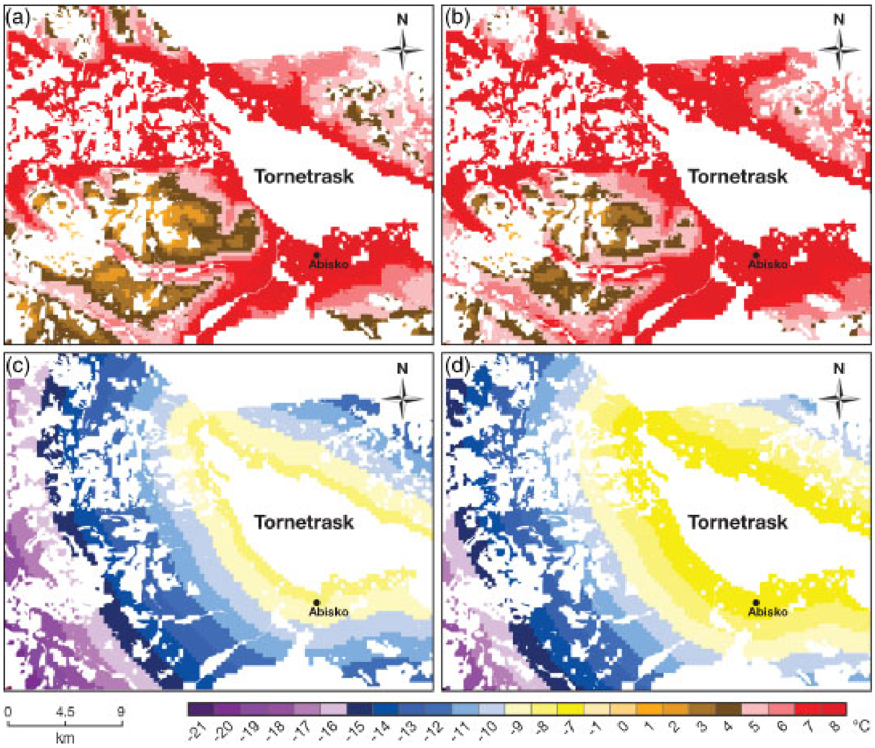

Figure 7. Modelled monthly surface-air-temperature pattern for different periods: (a) June 1913–2009, (b) June 2000–2009 (c) December 1913–2009, (d) December 2000–2009. White denotes missing data for water bodies and high-elevation barren ground.

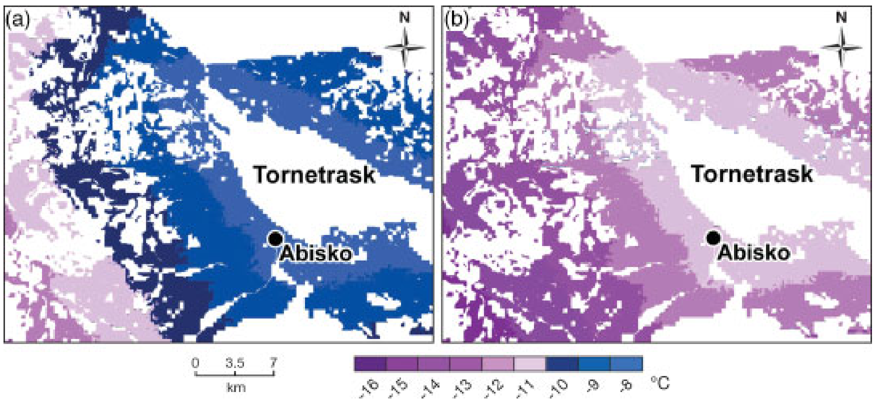

Figure 8. Modelled surface-air temperature variability for the two recent winters (December–February) seasons (a) 2008–2009 and (b) 2009–2010. White denotes missing data for water bodies and high-elevation barren ground.

in the warmest July in 1937, compared with none in the coldest July in 1917 (unpublished data). Such extreme individual years can have profound effects on the failure or success of tree seed production and establishment (Körner, 2003; Van Bogaert *et al*., 2011). Besides this, while the potential thawing of permafrost has been validated by actual accelerated thawing during the last decade (Åkerman and Johansson, 2008; Callaghan *et al*., 2010) the potential recent upward movement of the treeline described here does not exceed that of the last warming period during the 1930–1940s. Van Bogaert *et al*. (2011) seem to support this by claiming that recent actual changes in treeline are not primarily caused by warming but are influenced by recovery from human disturbance, and herbivore activity. Furthermore, the recent high MAT that potentially affects permafrost results from increases in spring, autumn and winter SAT rather than increases in summer SAT. In contrast, summer SAT affects treeline position but has not significantly increased since 1913 (Callaghan *et al*., 2010).

A particular strength of the model is its predictive power at high spatial resolution. Some small areas (50×50 m) within expansive existing birch forest have experienced SAT favourable for tree establishment only since 2008 (Figure 11). This is counter-intuitive but closer observation of the model shows that these small patches are colder than the surrounding area due to shading from neighbouring mountains. Such predictions can be validated in future measurements of microclimate and vegetation surveys.

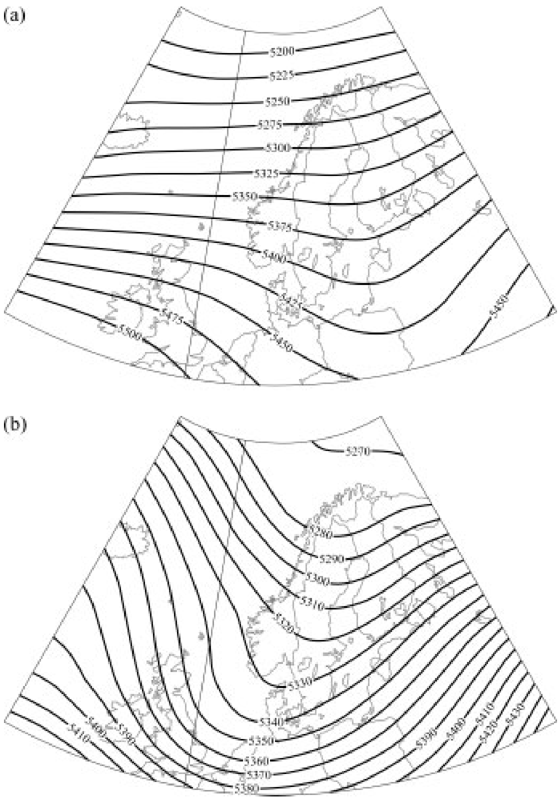

Figure 9. NCEP/NCAR reanalysis 500 hPa geopotential height upper-air charts for the two recent winter (December–February) seasons 2008–2009 (a) and 2009–2010 (b). Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.esrl.noaa.gov/psd/

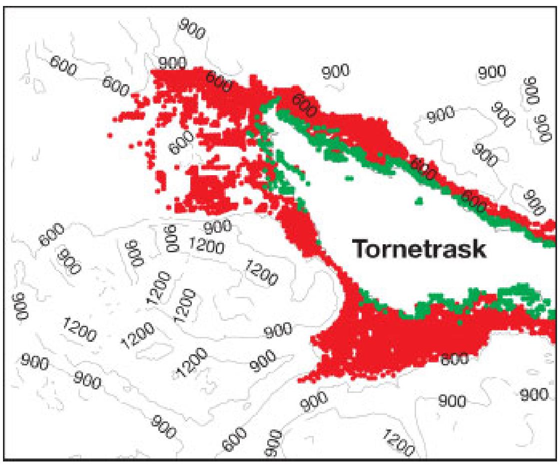

Figure 10. Comparison of the area around Abisko above 0 °C mean annual temperature between 1913 and 2008. Green dots represent this area for 1913, while red dots show the new areas covered in 2008 (2009 was not used as it was an unusually cold year).

4. Conclusions

The climate record from the long-standing Abisko Scientific Research Station (ANS) meteorological station reveals a long-term warming trend over the last century with two peaks, one in the late 1930s and the other one in the past two decades (Callaghan *et al*., 2010). However, information from one location cannot be applied easily to infer changes in surface air temperature (SAT) variability throughout the whole landscape. As microclimate variability drives ecological and geomorphologic processes during a period of climate change, a better understanding of microclimate characteristics is required. In the present study, based on data from a dense/small-scale meteorological-station network set among the mountains, and a model of downscaled SAT, the influence of the mountain environment on microclimate variability throughout a landscape was identified. This variability is driven mainly by the surface-atmosphere energy exchange and the influence of Lake Torneträsk through the lake-land breeze system.

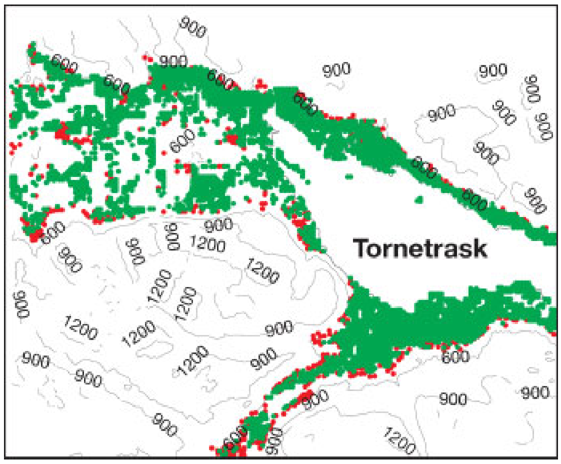

Figure 11. Comparison of the area around Abisko above 11 °C in July between 1913 and 2008. Green dots represent this area for 1913, while red dots show the new areas covered in 2008 (2009 was not used as it was an unusually cold year).

Quantification of the short-term microclimate pattern, together with climate downscaling, has revealed pronounced changes in the SAT pattern at the 50 m scale across the Abisko region over the last century, and substantial potential impacts on ecology and permafrost in this region. The SAT maps at 50 m scale can be used in conjunction with the long-term Abisko Station SAT record to study the impacts of climate change and variability (as well as mean conditions) on other factors such as ecosystem structure and function and human land-use changes, particularly those relating to changes in reindeer herding, infrastructure development and tourism. This landscape level assessment provides a powerful analysis and visualization tool to improve our understanding of climate impacts at the local level, which are most relevant to local stakeholders. The results of the study therefore help enable adaptation in this remote but important sub-Arctic region, while the methodology and concepts can be applied to mountain areas in general.

Acknowledgements

This work was conducted as part of the Marie Curie Early Stage Training network – Multiarc-supported by European Union FP7. This work was also partially supported by FORMAS projects 'Climate change, impacts and adaptation in the sub Arctic: a case study from the northern Swedish mountains' (214-2008-188) and 'Advanced Simulation of Arctic climate change and impact on Northern regions' (214-2009-389). We would like to thank Abisko Scientific Research Station staff for help and data collection. Fieldwork was partly carried out using helicopter support from the Abisko IPY project 'ENVISNAR' to which this project contributes.

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