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Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic

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Abstract

One predicted consequence of global warming is an increased frequency of extreme weather events, such as heat waves, droughts, or heavy rainfalls. In parts of the Arctic, extreme warm spells and heavy rain-on-snow (ROS) events in winter are already more frequent. How these weather events impact snow-pack and permafrost characteristics is rarely documented empirically, and the implications for wildlife and society are hence far from understood. Here we characterize and document the effects of an extreme warm spell and ROS event that occurred in High Arctic Svalbard in January–February 2012, during the polar night. In this normally cold semi-desert environment, we recorded above-zero temperatures (up to 7 °C) across the entire archipelago and record-breaking precipitation, with up to 98 mm rainfall in one day (return period of >500 years prior to this event) and 272 mm over the two-week long warm spell. These precipitation amounts are equivalent to 25 and 70% respectively of the mean annual total precipitation. The extreme event caused significant increase in permafrost temperatures down to at least 5 m depth, induced slush avalanches with resultant damage to infrastructure, and left a significant ground-ice cover (~5–20 cm thick basal ice). The ground-ice not only affected inhabitants by closing roads and airports as well as reducing mobility and thereby tourism income, but it also led to high starvation-induced mortality in all monitored populations of the wild reindeer by blocking access to the winter food source. Based on empirical-statistical downscaling of global climate models run under the moderate RCP4.5 emission scenario, we predict strong future warming with average mid-winter temperatures even approaching 0 °C, suggesting increased frequency of ROS. This will have far-reaching implications for Arctic ecosystems and societies through the changes in snow-pack and permafrost properties.

S Online supplementary data available from stacks.iop.org/ERL/9/114021/mmedia

Keywords: climate change impact, wildlife, permafrost, icing, warm spell, rain on snow, avalanche risk

1. Introduction

Understanding and predicting the effects of extreme weather events, such as heat waves, drought or heavy rainfall represent one of the major challenges in current climate research (Stocker *et al* 2013, Field *et al* 2014). The frequency of warm spells and heavy rain-on-snow (ROS) events in the Arctic is increasing and is expected to increase further during the 21st century (Rennert *et al* 2009). An emerging body of evidence indicates that such extreme winter weather may have far-reaching geophysical implications (Putkonen *et al* 2009). First, changes in snow-pack properties following heavy ROS events can lead to severe avalanches (Conway and Raymond 1993, Stimberis and Rubin 2011) and formation of thick ice layers within the snow-pack or at the ground surface (Putkonen and Roe 2003, Hansen *et al* 2011). Second, heat transfer to the ground during ROS and warm spells (Putkonen and Roe 2003) can alter deep-layer permafrost characteristics (Isaksen *et al* 2007a, Westermann *et al* 2011). These sudden changes in the tundra winter environment can in turn be expected to influence human infrastructure, e.g. through snow and slush avalanches and debris flow (Stimberis and Rubin 2011), and vegetation and wildlife through the formation of ice-layers in the snow-pack or basal ice on the ground (hereafter 'ground-ice'; Forchhammer and Boertmann 1993, Coulson *et al* 2000, Kohler and Aanes 2004, Bjerke 2011, Hansen *et al* 2011, 2013, Stien *et al* 2012). In particular, high-latitude tundra ecosystems seem vulnerable to heavy ROS events because the food resources of the overwintering herbivores can be completely covered by ice ('locked pastures'), causing starvation and population crashes across species, which in turn cascade to other trophic levels in the ecosystem (Hansen *et al* 2013). Here we (1) characterize a record-breaking warm spell and associated heavy ROS events occurring in High Arctic Svalbard during the polar night; (2) examine its effects on permafrost temperatures and snow-pack (through ground-ice formation); and (3) document the impact on wildlife and society of a weather phenomenon currently considered as 'extreme' but likely to become increasingly common across the Arctic.

2. An extreme rain-on-snow event in High Arctic Svalbard

The archipelago of Svalbard (74–81°N, 10–35°E; figure 1(a)) is characterized by continuous permafrost (Liestøl 1976) and large inter-annual variability in air temperatures. At the Svalbard Airport meteorological station (78°13′N and 15°38′ E) close to Longyearbyen, the largest settlement in Svalbard (population ~2000), mean annual total precipitation and mean annual temperature are 190 mm and −6.7 °C respectively (for standard normal period 1961–1990). For winter (here defined as November–April), mean total precipitation and mean temperature are 113 mm and −12.7 °C, but warm spells with above-zero temperatures occur relatively frequently given the high latitude (Benestad *et al* 2002). Due to the archipelago's location in the Arctic Ocean, temperatures and precipitation patterns are sensitive to the coupled sea-ice-ocean atmosphere system (Benestad *et al* 2002). For instance, Isaksen *et al* (2007a) documented the significance of likely episodic warming as opposed to gradual change by describing the observed response of permafrost temperatures to an extreme temperature anomaly during winter-spring 2005–06. The anomaly coincided with open water in most of the fjords and in the surrounding waters through the whole winter and highlighted the effects that atmosphere-ocean-sea ice coupling has had in amplifying recent warming in this region.

Mid-winter 2011–12 was associated with a strong positive temperature anomaly across most of the Barents Sea and surrounding waters (figure 1(b)). In late January-early February, a long-lasting high pressure over northern Scandinavia directed low pressure systems with mild and humid air northward to Svalbard. These lows, with their associated frontal passages, had large-scale horizontal convergence, resulting in two weeks (i.e. approximately 26 January–9 February) of extreme warm periods with prolonged rainfall across most of the archipelago. Above-zero temperatures were recorded at all weather stations on the archipelago during this period (figure 1(a)), yet the warm spell was most profound in western parts of Svalbard. At Svalbard Airport, the average temperature on 30 January was 4.0 °C (figure 1(c); Norwegian Meteorological Institute, data available at http://eklima.no), almost 20 °C higher than the daily normal, and in fact, higher than at any weather station in mainland Norway on that day. On 8 February, the maximum temperature T_{max} at Akseløya (figure 1(a)) reached 7.8 °C, i.e. the highest temperature ever recorded in Svalbard in February. Across Svalbard, the warm spell was immediately followed by a cold period, with T_{max} typically ~−10 °C or lower.

Daily amount of precipitation (measured once or twice daily (at 0600/1800 h) and covering the previous 12/24 h period) has been recorded continuously for multiple decades at three manned weather stations in Spitsbergen (the largest island on Svalbard, Stations 1–3, figure 1(a)): the small research settlement Ny-Ålesund (population ~30 year-round; Norwegian Meteorological Institute, data available at http://eklima.no), the Russian settlement of Barentsburg (population ~435; data available at www.tutiempo.net/en/Climate/BARENCBURG/07-1973/201070.htm), and Svalbard Airport. At all three weather stations, several heavy rainfalls were associated with the two-week warm spell (figure 1(c), table 1). The most striking event was recorded in Ny-Ålesund on January 30th when 98 mm rain fell (T_{max} = 4.3 °C), which had (prior to this event) a return period of >500 years following the Norwegian manual for calculation of probable extreme daily precipitation values (Førland 1992), and which

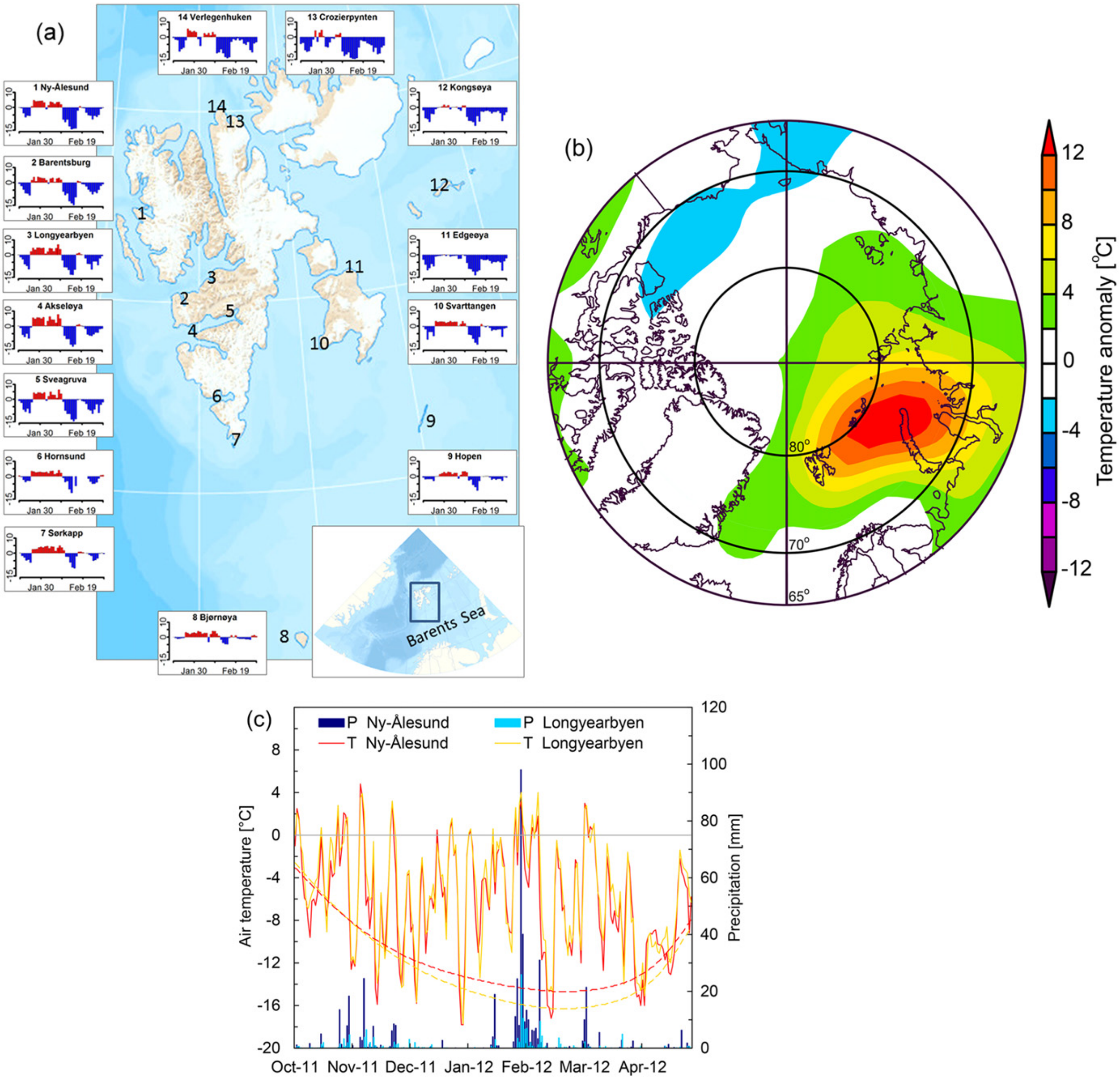

Figure 1. (a) Map of the study area Svalbard, situated at 74–81°N and 10–35°E in the Arctic Ocean between northern Norway and Greenland (insert). Bar plots show records of daily maximum temperatures (daily mean temperature for Station 13 Crozierpynten) in °C at available weather stations between 20 January and 29 February 2012, i.e. before, during and after the extreme warm spell and ROS event. Red and blue bars represent positive and negative temperatures, respectively. Most of the weather stations (1–7 and 13–14) are located at the largest island Spitsbergen. All weather stations are close to the coast and at elevations <30 m a.s.l., except Station 2 Barentsburg, which is at 75 m asl. (b) Average temperature anomalies across the Arctic during mid-winter (December–February) 2011–12 with respect to the 1981–2000 mean, based on NCEP reanalysis data (Kalnay *et al* 1996) provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado (www.esrl.noaa.gov/psd/). (c) Daily precipitation and temperature during winter 2011–12 in Longyearbyen (Svalbard Airport; light blue bars, yellow line) and Ny-Ålesund (dark blue bars, red line), Svalbard. Stippled lines represent the daily average temperatures for the standard normal period 1961–90.

corresponds to 25% of the mean annual total precipitation (table 1).

Winter (November–April) 2011–2012 was overall extreme, with the highest average temperature ever (figure 2(a)) in the Svalbard Airport (Longyearbyen) composite series, which starts in 1898 and represents one of very few long-term (>100 yr) instrumental temperature series from the High Arctic (Nordli *et al* 2014). Both in Longyearbyen and Ny-Ålesund, average winter temperature has increased by ~4–5 °C since the mid 1990's (figure 2(a)), with an associated increased probability for above-zero temperatures and winter precipitation falling as rain. Winter rain is hereafter referred to as ROS, since with very few exceptions (such as immediately after heavy rainfalls), there is continuous snow cover during November–

Table 1. Weather characteristics during the extreme warm spell (26 January–9 February 2012) at the three manned weather stations in Spitsbergen, Svalbard, where precipitation data have been collected continuously for multiple decades (see figure 1(c) for locations). At Svalbard Airport (Longyearbyen) and Ny-Ålesund, comparison to annual amount of precipitation is based on the standard normal period 1961–1990, while for Barentsburg the comparison is to the period 1973–1987 (data not available for the whole standard normal period). T_{max} = daily maximum temperature.

Weather station	Mean T_{max} °C	Max. T_{max} °C	No. days $T_{max} > 3$ °C	Precipitation	Max. daily precipitation
Svalbard Airport	3.9	7.0	11	70.3 mm (37% of 190 mm annual normal)	25.9 mm (14%)
Ny-Ålesund	3.0	4.8	10	272.0 mm (71% of 385 mm annual normal)	98.0 mm (25%)
Barentsburg	2.3	3.9	6	136.0 mm (22% of 606 mm annual normal)	27.2 mm (4%)

April. We calculated annual amounts of ROS (i.e. winter rain) based on precipitation records from Ny-Ålesund (1969–2012) and the Svalbard Airport composite series (1957–2012), which is based on station measurements made in Longyearbyen (1957–1975) and at Svalbard Airport (1975–2012). The composite series is considered to be homogeneous. We calculated ROS according to the World Meteorological Organisation (WMO) protocol codes 4677 (WW) and 4561 (W1). Only events with measured 12 h precipitation more than 0.0 mm, visually classified as drizzle (WW = 50–59) or rain (WW = 60–67) by the observers, were used. Annual ROS amounts were positively correlated with winter temperatures, both in Ny-Ålesund ($r = 0.37$, $P < 0.05$) and Longyearbyen ($r = 0.32$, $P < 0.05$). Because of the extreme event in January—February 2012, the winter of 2011–2012 had the largest (Ny-Ålesund) and third largest ROS amount (Longyearbyen) ever recorded (figure 2(b)).

3. Impact on ground temperatures and permafrost

In 1998, two permafrost boreholes (15 and 102 m deep) were drilled on Janssonhaugen (Sollid *et al* 2000), approximately 20 km from Longyearbyen. The boreholes were established for long-term permafrost temperature monitoring and represent the northernmost stations of a latitudinal transect of deep boreholes established by the PACE project (Harris *et al* 2001b). The boreholes were drilled into sandstone bedrock with low ice content overlain by a thin weathering layer. The ground surface has no vegetation, and during winter snow cover is thin or completely absent due to deflation. The site is representative for the mountains and mountain slopes around Longyearbyen and central parts of Spitsbergen. The near-surface thermal response on Janssonhaugen to the anomalously warm winter and especially the extreme weather event in January–February 2012 was clearly evident from observed mean ground temperatures for the 30-days period centred at the end of January (figure 3(a)). Mean ground surface (0.2 m) and permafrost table (2.0 m) temperatures were 7.0 °C and 3.6 °C above the 2000–2011 average and 1.3 °C and 1.9 °C higher than the previously recorded maximum values.

The response of the near ground surface temperatures (GST; see supplementary material 1, figure S1, available at stacks.iop.org/ERL/9/114021/mmedia) to such extreme weather events in permafrost areas is strongly modulated by snow cover, vegetation, soil type (mainly water content and porosity) and the amount of rain (see Westermann *et al* 2011). Thus, the GST temperature response at the dry and strongly wind-exposed Janssonhaugen site (ground surface dominated by *in situ* weathered bedrock) was of shorter duration (supplementary material 1, figure S1) and weaker (figure S2) than in many other study sites with different soil types and more developed vegetation cover, snow cover and ground-icing (see below: 4. *Ground-ice formation*). At several of the study sites GST stayed at or near 0 °C for two weeks or more after the main event on 30 January, despite air temperatures below −10 °C. This was caused by water from melting snow and rain that percolated through the snow to the cold ground surface and forming basal ice layers at the ground surface (Woo and Heron 1981).

The permafrost on Janssonhaugen has warmed considerably during the last decades (Isaksen *et al* 2000, 2007b). Significant warming of the permafrost is detectable down to at least 60 m depth, and the present decadal warming rate at the permafrost surface (ca. 2 m depth) is in the order of 0.07 °C a^{-1}, with indications of accelerated warming during the last decade (Isaksen *et al* 2007b). Thus the 2012 extreme event presented here was superimposed on a significant warming trend. Isaksen *et al* (2007a) suggested that the process of near-surface permafrost warming on Svalbard in the future may be irregular rather than gradual and punctuated by a higher frequency of warm spells, such as the one described here. In addition, multi-annual simulations by Westermann *et al* (2011) indicated that ROS events can significantly accelerate the warming of soil temperatures in permafrost areas, and that initially stable permafrost system may in certain areas start to thaw if environmental conditions such as those observed in January–February 2012 return for several consecutive winters. Increases in active-layer thickness (cf. Etzelmüller *et al* 2011) may be associated with unprecedented thaw settlement as ice-rich soils near the permafrost table melt (Nelson *et al* 2001), leading to a marked increase in slope instability (Harris *et al* 2001a).

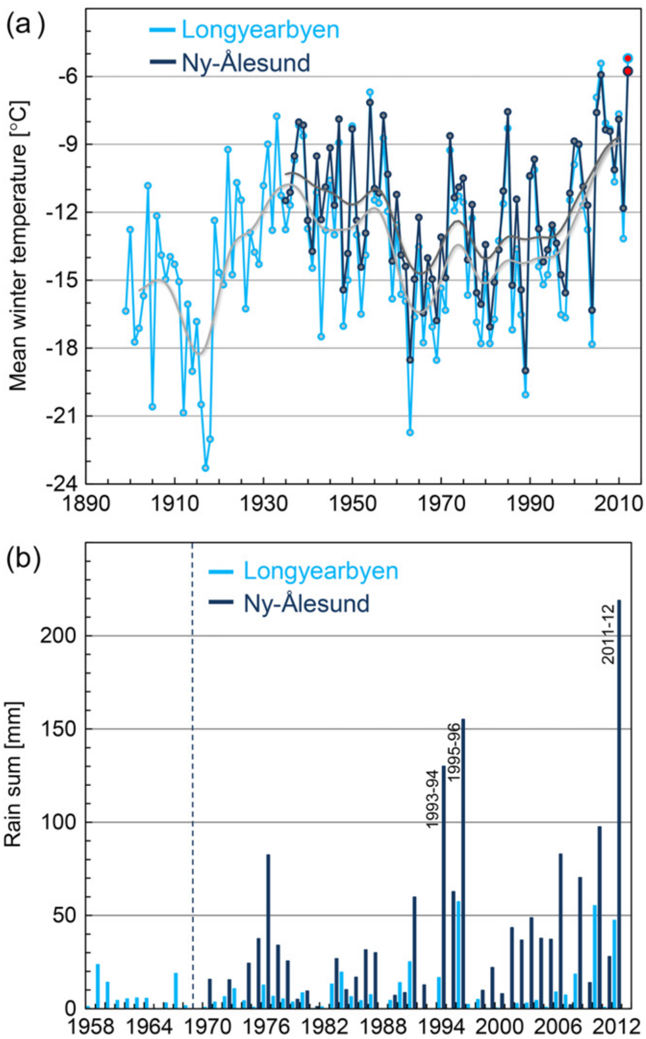

Figure 2. (a) Long-term homogenized mid-winter (December–February) mean air temperature series from Longyearbyen (Svalbard Airport composite series, 1898–2012 light blue) and Ny-Ålesund (1934–2012, dark blue). 2011–12 is highlighted in red. To identify variations on decadal timescales, a low-pass Gaussian filter (light grey and dark grey curves) with a standard deviation of 3 years in the Gaussian distribution was applied. (b) Total amount of rain for winters (November–April) 1957–2012 in Longyearbyen (light blue) and 1969–2012 in Ny-Ålesund (dark blue; dotted line indicates the first year of measurements). Rain amount was calculated based on both present and past weather according to the World Meteorological Organisation (WMO) protocol codes 4677 (WW) and 4561 (W1), respectively. Only events with measured 12 h precipitation amounts more than 0.0 mm, visually classified as drizzle (WW = 50–59) or rain (WW = 60–67) by the observers, were used.

4. Ground-ice formation

Ice can form in the snow-pack or on the ground following thaw-freezing, rain on frozen ground (i.e. 'black icing') or ROS (Putkonen and Roe 2003, Grenfell and Putkonen 2008, Putkonen *et al* 2009). In particular, ROS can strongly influence the heat budget of the snow-pack as well as the soil by percolating through the snow (Putkonen and Roe 2003). The water freezes and releases latent heat to the snow and the frozen soil, and a coat of solid ground-ice can build up and cover the underlying vegetation (Woo and Heron 1981, Hansen *et al* 2010), which in Svalbard consists mainly of mosses, lichens, dwarf shrubs, forbs and graminoids (Jónsdottir 2005) and rarely exceeds ~10 cm height. We measured thickness of the ground-ice resulting from the warm spell and heavy ROS event(s) in late January-early February 2012. Data were collected across a range of environmental gradients (supplementary material 1) as soon as the conditions had stabilized with air temperatures well below zero. In Ny-Ålesund, where the heaviest rainfall was recorded, a thick ice-coat more or less completely covered the tundra from sea level up to elevations of 3–400 m a.s.l. (figure 3(b); supplementary material 2 (video)) (see also Maturilli *et al* 2014: changes in surface albedo). Solid ground-ice ~10–20 cm thick (minimum thickness = 6 cm) was found at virtually all sampling sites ($n = 195$ out of 200 sites distributed in varied topography and vegetation types) and was still covering approximately 50% of the ground as late as in mid-June. Although generally less thick, a ground-ice layer (⩾1 cm thick) was also present in the majority of the sampling sites (i.e. $n = 114$ out of 128) located in ridge and sub-ridge vegetation communities in the Reindalen–Semmeldalen–Colesdalen valley system. Likewise, ground-ice (⩾1 cm thick) was present in most sampling sites ($n = 19$ out of 31) in ridge and sub-ridge vegetation in the neighbouring valley Adventdalen, close to Longyearbyen.

Ground-icing appears to be relatively common in western Svalbard with its coastal climate. Heavy icing has been documented (or anecdotally reported) in and around Ny-Ålesund in the winters 1993–94, 1995–96, 2005–06, and 2009–10 (Putkonen and Roe 2003, Kohler and Aanes 2004, Hansen *et al* 2010, 2011, Hansen and Aanes 2012). These observations corroborate this study's estimates of annual ROS amounts (figure 2(b)), which are record-high or close to record-high during the extremely icy winter of 2011–2012. This study thus adds strong empirical support to the overall consensus that on the High Arctic tundra with its deeply frozen ground, melting of the snow-pack due to warm spells and associated heavy ROS events is likely to cause extensive ground-icing (Putkonen and Roe 2003, Kohler and Aanes 2004, Grenfell and Putkonen 2008, Rennert *et al* 2009, Hansen *et al* 2011).

5. Effects on infrastructure, society and wildlife

5.1. Infrastructure and society

The heavy rainfall during the early phase of the warm spell triggered several slush avalanches in and close to the major settlement, Longyearbyen, which is located in a U-shaped valley with steep mountain sides. In the city centre, a major avalanche hit and destroyed a pedestrian bridge (figure 4(a)) following ~20 mm of rain during a 12 h period on 30 January, and all roads in and around Longyearbyen were closed for up to several days due to other avalanches (Fjellestad 2012b). Historically, slush avalanches of similar dimensions in Longyearbyen have mainly occurred during the spring melting period rather than mid-winter (but see Eckerstorfer 2013), such as in June 1953 when a major avalanche destroyed the hospital and other buildings, causing three fatalities and 30

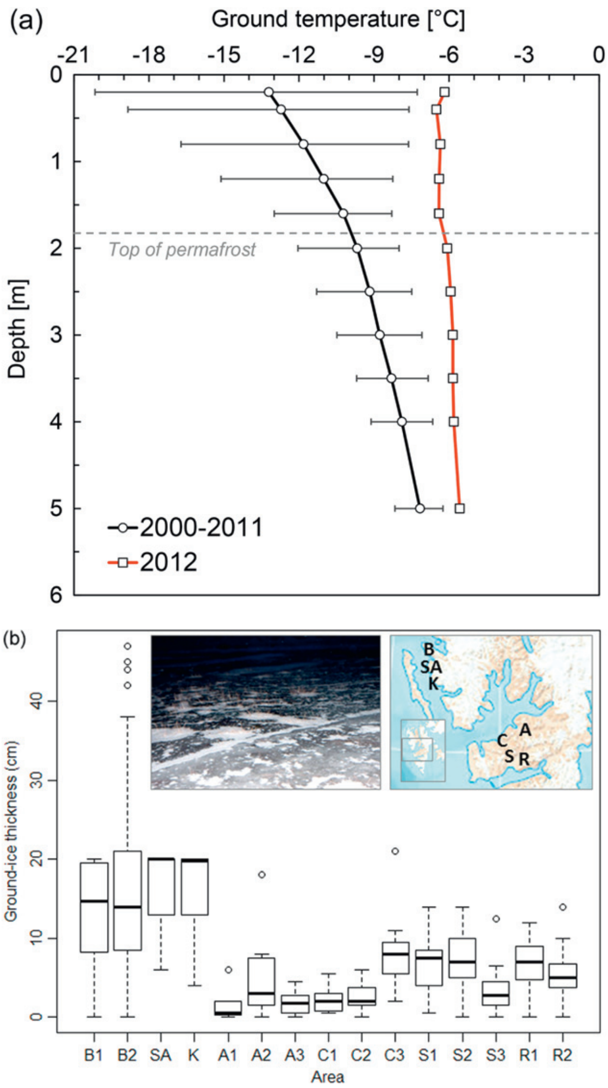

Figure 3. The extreme warm spell and ROS events in January–February 2012 caused dramatic changes in the properties of the permafrost and the snow-pack. (a) 30-Day mean ground temperature centred at 30 January down to 5 m depth at Janssonhaugen (in Adventdalen, close to Longyearbyen) for 2011–12 (red line) compared to the mean for 2000–11 (black line). Horizontal bars show the absolute variations of the previous years, grey dotted line indicates the top of permafrost. To be representative and detect the full effect of the extreme warm spell that penetrated into the permafrost, the period for the 30-day mean ground temperature values in the series is adjusted successively with depth for the phase lag following calculations made for the study site by Isaksen *et al* (2000). (b) Ground-ice thickness measured across a range of topography and climatic zones in Spitsbergen following the extreme ROS events and subsequent freeze-up (see supplementary material 1 for detailed description of sampling regime). Boxes enclosing the median represent the first and third quartiles, while whiskers extend to the smallest or largest values or (when there are outliers) to the smallest (or largest) value within 1.5 times the interquartile range from the first (or third) quartile. Open circles are outliers. The sampling sites were located in varied topography in areas close to Ny-Ålesund (B1-B2/SA/K; see inserted map for sampling locations), and in ridge/sub-ridge vegetation in areas close to Longyearbyen (A1-A3/C1-C3/S1-S3/R1-R2). Note that ice thickness was not measured deeper than 20 cm in B1, SA, and K because the drill was too short.

injured (Per Ruud, pers.comm.). As many buildings and other installations in Svalbard were built without evaluation of natural disaster potentials, much infrastructure is located in areas exposed to slush or debris flows. Thus, with a warming winter climate including more frequent and longer episodes of above-zero temperatures and ROS (see below; 6. *Future prospects*), we can expect an increasing risk for natural disasters with damage to infrastructure.

The heavy rain in January–February 2012 caused severe icing on the town's central radio-antenna and impeded radio broadcasting (Fjellestad 2012b), and ground-ice built up around the settlements and on the tundra (figures 3(b) and 4(b), (c)), with wide societal implications. Because of a slippery runway there were no flights to or from Svalbard Airport on 29 and 31 January, and several other flights were delayed for up to two days (Morten Ulsnes, pers.comm.). Flights were also cancelled on 27 January and 6 February owing to icing on the airport runway in Ny-Ålesund (Elisabeth Melø, pers.comm.). Because there are so few flights to and from these airports (only twice a week in Ny-Ålesund), these cancellations and delays caused travel disruptions extending far beyond the actual closing days.

Furthermore, snow-mobile driving, dog-sledding and hiking were nearly impossible during the weather event, and the resultant ground-ice strongly restricted travel in the terrain for the remaining winter season. This reduced mobility led to trip cancellations and changes in the activities of the local tourism industry (Fjellestad 2012a), for which guided snow-mobile tours are one of the main sources of income. The annual number of snow-mobile days on guided tours operated through the tourist companies was reduced by 28% ($n = 2659$ field days) compared with the previous winter, i.e. the lowest ever since continuous annual statistics started in 2001 (Ronny Brunvoll, Visit Svalbard AS, pers.comm.). Ice-caving activities were reduced by 62% ($n = 300$ field days), and glacier hiking was reduced by 57% ($n = 19$) from the previous winter. Total monthly hotel overnight stays in Longyearbyen were consistently reduced the remainder of the winter season, when compared with the same calendar month the previous year, by 2% ($n = 4800$ overnight stays), 12% ($n = 8300$), 5% ($n = 11\,300$), and 13% ($n = 7600$) for the months February–May (Statistics Norway: www.ssb.no). This was in sharp contrast to the preceding winter months; monthly number of overnights prior to the extreme event (November–January) had increased by 8% ($n = 1900$ accommodations), 2% ($n = 2100$), and 76% ($n = 2100$) compared with the previous year, strongly indicating that the extreme weather event was responsible for the subsequent decline.

5.2. Wildlife

Several studies have suggested that icing following warm spells and heavy ROS events can seriously reduce the availability of food for herbivores (Ims *et al* 2008, Kausrud *et al* 2008, Gilg *et al* 2009, Hansen *et al* 2011, 2013, Stien *et al* 2012). In the High Arctic, vegetation is low-growing, and thus may be completely covered by ground-ice resulting from ROS. High-latitude island populations of reindeer and caribou are especially vulnerable to heavy ROS events because natural barriers restricts migration to ice-free ranges, potentially resulting in mass starvation in late winter (Parker *et al* 1975, Forchhammer and Boertmann 1993, Kohler and Aanes 2004). For instance, a population of wild Svalbard reindeer (*Rangifer tarandus platyrhynchus*) in Ny-Ålesund crashed from 360 to ~80 individuals during the winter of 1993–94 (Kohler and Aanes 2004), when the amount of ROS and the ground-icing almost reached the extreme levels observed in 2011–12 (figure 2(b)).

We calculated an annual mortality index for all monitored populations of Svalbard reindeer based on the number of carcasses recorded during population counts in summer (Hansen *et al* 2013), divided by the number of live reindeer the previous summer. It is assumed that the number of carcasses found on the tundra in summer reflects the starvation rates the preceding winter (Tyler and Øritsland 1998). In spite of very favourable winter feeding conditions until the extreme warm spell and ROS events, the number of carcasses found during the summer 2012 censuses was among the highest ever recorded, and the estimated mortality indices for winter 2012 were hence generally very high (figure 5). Thus, even though the 2012 extreme ROS events occurred relatively late in the winter, the resulting ice layer and 'locked pastures' (figures 3(b) and 4(c)) caused extensive starvation among the reindeer.

Besides its direct effects on herbivores through locked pastures, ground-ice may negatively affect soil arthropods (reduced survival; Coulson *et al* 2000) and vegetation (damaging vascular plants and lichens; Robinson *et al* 1998, Bjerke 2011). Furthermore, because top predators such as the Arctic fox (*Vulpes lagopus*) are influenced through changes in prey or reindeer carcass availability (Eide *et al* 2012, Hansen *et al* 2013), it is likely that the effects of such rare weather events indirectly impact migratory prey (i.e. ground-breeding birds) in summer (Fuglei *et al* 2003) and thereby cause trophic cascades through the entire tundra food-web. Consequently, changes in the frequency of warm spells, extreme ROS, and icing events, as reported here, may have severe socioeconomic implications for indigenous Arctic people, which partly depend on tundra ecosystems and their wildlife species (AMAP 2011, CAFF 2013).

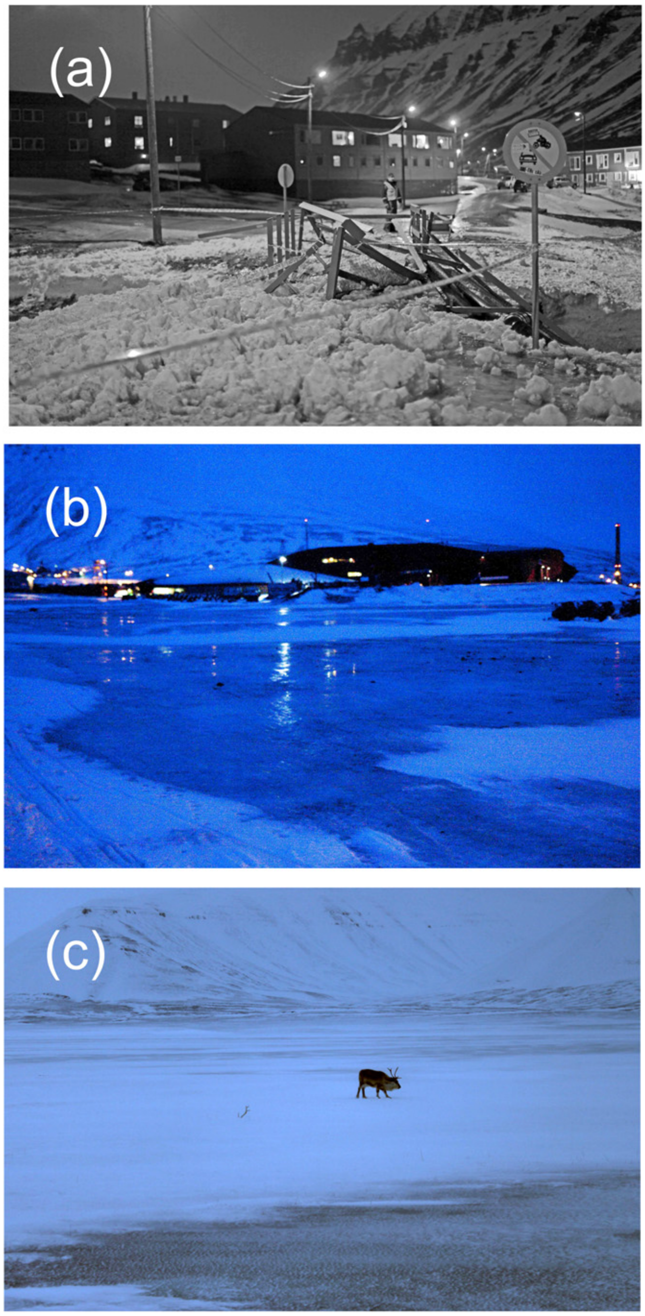

Figure 4. The extreme warm spell and ROS events in January–February 2012 had major implications for the society and wildlife in Svalbard. (a) Slush avalanches caused closed roads and schools and destroyed a bridge in the major settlement Longyearbyen (photo: Kjersti Strømmen). (b) A thick layer of ground-ice built up on roads and airport runways in Longyearbyen (photo: Øystein Varpe) and Ny-Ålesund. (c) A wild female reindeer struggles to find food on the ice-encapsulated tundra in Reindalen (R1 in figure 3(b)) one week subsequent to the warm spell and ROS (photo: Brage B Hansen).

6. Future prospects

The Arctic climate is likely to warm at a faster rate than the global mean (Stocker *et al* 2013). The effect of greenhouse gases on global climate is estimated through Global Climate Models (GCMs), but the expected response to a doubling in the CO_2 levels varies across the different models. GCMs are poorly resolved models. Therefore, in order to obtain details on the local climate downscaling is required (Benestad *et al* 2008). To account for the differences between the output of different GCMs and the range of natural variations, empirical-statistical downscaling (ESD) can be applied to multi-model ensembles (Benestad 2011). Here we estimated mid-winter (December–February) mean temperature for Svalbard Airport (figure 6) using state-of-the-art GCMs from the CMIP5 experiment (Flato *et al* 2013), the RCP4.5 scenario for prescribing future levels of greenhouse gases and

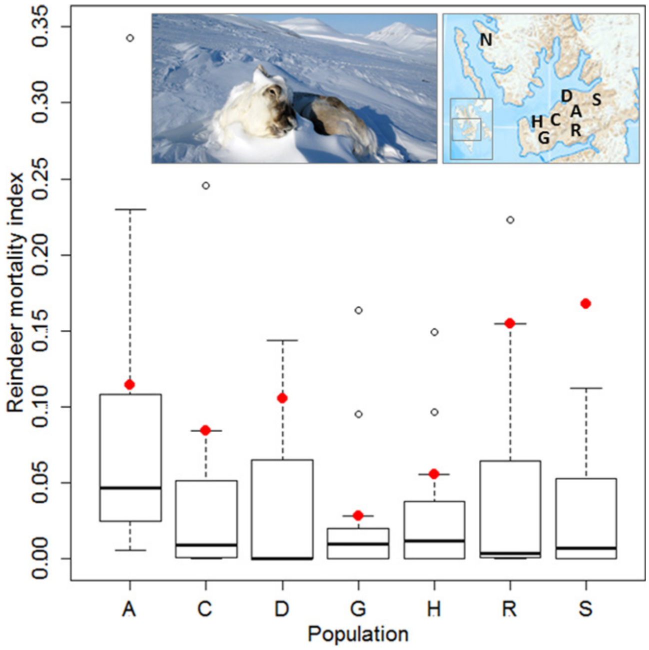

Figure 5. Ground-icing following the extreme warm spell and ROS events in January–February 2012 caused locked pastures and extensive starvation in wild Svalbard reindeer. Reindeer mortality indices for winter 2012 (red circles) were far higher than the average year in all monitored populations. Boxes, whiskers and open circles show same statistics as in figure 3(b). The mortality index was calculated as the number of carcasses found in summer divided by the number of live animals in the previous summer during population monitoring in 1979–2012 (Adventdalen; see Hansen *et al* 2013) and 1997–2005, 2007, and 2009–2012 (Colesdalen, Diabas, Grøndalen, Hollenderdalen, Reindalen, Sassendalen; data from the Governor of Svalbard). Populations are named by their first letter. The inserted map shows locations of the study populations (N = the Ny-Ålesund population, which also was subject to higher-than average mortality; R Aanes and Å Ø Pedersen, unpubl. data). Photo: Eva Fuglei.

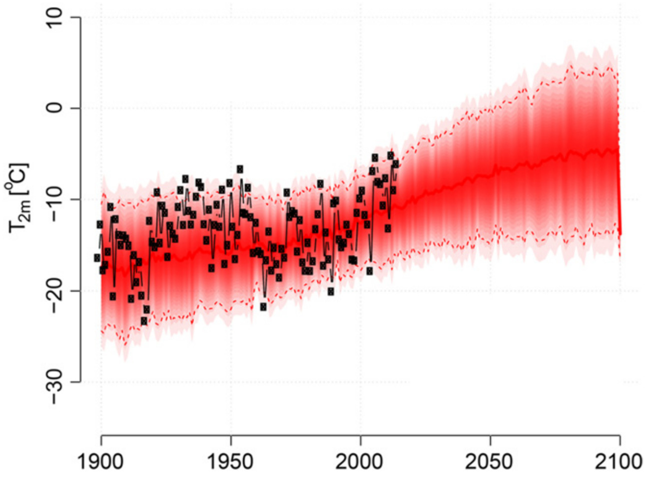

Figure 6. Downscaled (red shading) and observed (black symbols; Nordli *et al* 2014) mid-winter (December–February) mean temperature at Svalbard Airport (Longyearbyen). Red shaded area shows the spread between the 108 GCM simulations, and grey dashed lines indicate 90% confidence interval based on this spread. The simulated past trend is consistent with the observed trend for the period 1900–2013.

forcings, and ESD based on regression and common empirical orthogonal functions (Benestad 2001). The predicted warming implies more frequent episodes with above-zero winter temperatures, and if the projections hold, we can even expect to see some winters with mid-winter mean temperatures above 0 °C after about 2050 (figure 6). Accordingly, the frequency of ROS events and annual ROS amount will likely increase dramatically as the probability of crossing the near-zero °C threshold for precipitation falling as rain rather than snow increases (see figures S3 and S4 for relationship between annual ROS and temperature; Rennert *et al* 2009, Hansen *et al* 2011). Clearly, this may have far-reaching implications for Arctic societies (figure 4) and ecosystems (figure 5) through changes in snow-pack and permafrost properties (figure 3).

Note that, besides effects of overall warming, the conditions favourable for ROS events are also strongly dependent on atmospheric circulation patterns, including variation in the barometric pressure, frontal systems, location of the atmospheric jet, and wind direction (e.g. Cohen *et al* 2014). Indeed, the low-pressure system at lower latitudes in January–February 2012 brought mild and moist air to Svalbard. However, we are not addressing the question regarding high-pressure blocking patterns and storm tracks here, since there are still unknown aspects as to which degree a GCM is able to reproduce the observed phenomena.

7. Conclusions

In this case study from High Arctic Svalbard we have demonstrated that a long-lasting extreme warm spell with several heavy rainfalls during the polar night (figure 1) caused a substantial rise in permafrost temperatures and changes in snow-pack properties (figure 3) that had strong negative effects on both wild herbivore performance, human infrastructure and tourism activity (figures 4, 5). Because the rapid winter warming observed in Svalbard and many other Arctic areas can be projected to accelerate throughout the century (figure 6), the frequency of extreme warm spells and ROS events will likely increase as well. Due to the currently low frequency of such weather events, the sparse spatial distribution of weather stations, and the overall low human presence at high latitudes, empirical documentation of the characteristics and implications of such events associated with climate change is very rare and generally anecdotal (Rennert *et al* 2009). Thus, while a common assumption is that changes in the environment will be gradual, and modelling outputs tend to reinforce this perception, our results highlight that warming is likely to be punctuated by a shift in winter climate associated with the near-zero °C tipping point between snow and rain, and that Arctic permafrost, wildlife and society are particularly sensitive to these regime shifts in climate. Accordingly, this study from an Arctic 'hotspot' of climate change represents a bellwether of how winter climate change, and extreme events in particular, may cause radical changes in the geophysical environment, with a multitude of severe effects on society and wildlife.

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