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ORIGINAL PAPER

The importance of understanding annual and shorter-term temperature patterns and variation in the surface levels of polar soils for terrestrial biota

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Abstract
Ground temperatures in the top few centimetres of the soil profile are key in many biological processes yet remain very poorly documented, especially in the polar regions or over longer timescales. They can vary greatly seasonally and at various spatial scales across the often highly complex and heterogeneous polar landscapes. It is challenging and often impossible to extrapolate soil profile temperatures from meteorological air temperature records. Furthermore, despite the justifiably considerable profile given to contemporary large-scale climate change trends, with the exception of some sites on Greenland, few biological microclimate datasets exist that are of sufficient duration to allow robust linkage and comparison with these large-scale trends. However, it is also clear that the responses of the soil-associated biota of the polar regions to projected climate change cannot be adequately understood without improved knowledge of how landscape heterogeneity affects ground and sub-surface biological microclimates, and of descriptions of these microclimates and their patterns and trends at biologically relevant physical and temporal scales. To stimulate research and discussion in this field, we provide an overview of multi-annual temperature records from 20 High Arctic (Svalbard) and maritime Antarctic (Antarctic Peninsula and Scotia Arc) sites. We highlight important features in the datasets that are likely to have influence on biology in polar terrestrial ecosystems, including (a) summer ground and sub-surface temperatures vary much more than air temperatures; (b) winter ground temperatures are generally uncoupled from air temperatures; (c) the ground thawing period may be considerably shorter than that of positive air temperatures; (d) ground and air freeze–thaw patterns differ seasonally between Arctic and Antarctic; (e) rates of ground temperature change are generally low; (f) accumulated thermal sum in the ground usually greatly exceeds air cumulative degree days. The primary purpose of this article is to highlight the utility and biological relevance of such data, and to this end the full datasets are provided here to enable further analyses by the research community, and incorporation in future wider comparative studies.

Keywords Terrestrial invertebrates · Plants · Microbiota · Arctic · Antarctic · Energy exchange

Introduction

Perhaps the most striking feature of the polar regions is their chronically low temperature, resulting in extensive snow and ice cover, short growing seasons, often restricted vegetation cover, and a stably stratified atmospheric boundary layer for most of the year. Annual mean air temperature may

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be under 0 °C, and positive daily values are only achieved for the few brief summer months or weeks, and even not at all at the most extreme locations. Standard air temperatures are often employed to designate the polar regions, for example, a frequently cited definition of the Arctic is "land north of the 10 °C July isotherm", although other latitudinal or political borders may also be employed (Meltofte et al. 2013). However, temperature at the ground surface and in the top few centimetres of sub-surface soil layers may differ greatly from air temperature (Geiger et al. 2003; Peck et al. 2006). These temperatures, and the timescales on which they vary, play a central role in influencing polar (and similarly alpine) soil activity, its characteristic floral and faunal communities, and microbially mediated processes (Blaire et al. 2006; Nowinski et al. 2010), such as the efflux of CO_2 and methane (Davey et al. 1992; Oberbauer et al. 2007; Morgner et al. 2010; Cahoon et al. 2012; Everatt et al. 2013; Nielsen and Wall 2013) and plant above-ground/below-ground respiration ratios (Cooper 2004). Furthermore, being able to document and model small-scale variations in microclimatic temperatures can also make an important contribution to understanding and predicting species and ecosystem resilience to environmental changes (see Lenoir et al. 2017). Ground and sub-surface temperatures also influence the surface energy budget through the ground heat flux, determining whether heat will be stored in the ground or released to the atmosphere (Westermann et al. 2009; Sjöblom 2014; Lund et al. 2017).

Temperatures at the surface and in the upper centimetres of the soil profile are influenced by a suite of local factors which may vary over short temporal and spatial scales including, for example, vegetation type, degree and thickness of plant cover, depth of soil, soil type, form and clast size, moisture content, the source of moisture, geomorphological features including substratum, slope and aspect, and macroclimatic features such as solar angle, cloudiness and atmospheric stratification. Exposed ground surfaces absorb and reflect short-wave solar radiation and absorb or emit longwave radiation during the summer period. Consequently, the short-term temperature of the ground may rise well above that of the air (Migała et al. 2014) or, conversely, drop below. There is an increasing appreciation of the importance of winter climate as a driver of polar species and community performance (Cooper 2015; Williams et al. 2015). During the long winter periods the ground becomes uncoupled from solar forcing by ice and snow cover, as well as the extended period of the polar night. Sub-nivean ground and sub-surface temperatures may consistently be well above the generally low air temperatures as well as experiencing greatly reduced fluctuations (Convey et al. 2014a; Cooper 2015).

Pools and ponds may either have a seasonal input of melt water, and hence remain cold owing to constant flushing, or may be shallow and undisturbed with absorption of solar radiation by dark bottom sediments, permitting elevated temperatures to be attained (Peck 2004; Toro et al. 2007; Rautio et al. 2011). The chilling effect of cold water flushing from melting snow patches may also apply to moist soils adjacent to such melt water sources (Migała et al. 2014).

The extremely heterogeneous mosaics that shape polar landscapes preclude broad generalizations and, accordingly, necessitate detailed temperature records at appropriate physical and biological scales (Peck et al. 2006; Convey et al. 2014b). For ecologists, this is yet further complicated by the ability of invertebrates and even some microbiota to move within this thermal mosaic (Woods et al. 2015). Consequently, there is no simple approach to estimate ground and shallow sub-surface temperatures, a fundamental requirement for actual biological microhabitat description, from standard air temperature observations.

In spite of the importance of surface and sub-surface temperatures to the biosphere, lithosphere and hydrosphere of polar environments, robust data are often lacking, especially datasets of a year or greater, or even for only a complete summer season. While long-term temperature data series from the greater depths typical of permafrost studies (e.g. Guglielmin et al. 2008; Christiansen et al. 2010; Guglielmin et al. 2012) or those focused on carbon and nitrogen storage (e.g. Migała et al. 2014) exist, such installations rarely provide suitable data to describe conditions at the ground or in sub-surface soil/vegetation layers of relevance to the terrestrial invertebrate and microbial biota. As a result, few datasets describing biological microhabitat temperatures at diverse sites and habitat types within one geographical area and one time frame exist. Those that do are often restricted to at most one annual cycle, and more usually (part of) one summer field season (e.g. Davey et al. 1992; Coulson et al. 1995, 2013a, b; Migała et al. 2014), although long-term environmental manipulation studies usually include data from control sites (e.g. Bokhorst et al. 2013), providing another source of relevant information. The importance of establishment of long-term research programmes capable of generating such data is starting to be recognized, for example in the Scientific Committee on Antarctic Research's 'Antarctic Terrestrial Observing System' (ANTOS; www.scar.org/science/antos/home/). Routine observations carried out from the Zackenberg research station (two decades; Jensen et al. 2016), Kobbefjord (one decade) and Disko Island (6 years) (www.g-e-m.dk) are now becoming sufficiently extended to allow the addressing of longer-term questions. Relating to the Antarctic, several independent high resolution environmental databases including the continent have very recently been published (Fick and Hijmans 2017; Karger et al. 2017; Vega et al. 2017; Wagner et al. 2017). However, while these studies represent a considerable advance in terms of scales of resolution available in support of environmental and climatic modelling, with scales of resolution > 1 km, they still do not approach the metre to centimetre (and less) scale within which the majority of Antarctic and Arctic terrestrial diversity operates.

One approach to circumvent the lack of ground and sub-surface temperature records in polar regions is to model these temperatures, for instance using sophisticated neural network approaches (Wu et al. 2013; Tabari et al. 2014). Such studies on temperature processes (Kurylyk et al. 2014) are becoming increasingly important due to changes in ground hydrology and soil stability as a consequence of rapid climate changes in the polar regions (IPCC 2014). However, in regions with snow cover soil temperatures are decoupled from the air temperatures that are often used as a predictor variable in these models for extended periods. These studies also often focus on soil types, or depths, that are unrepresentative of tundra conditions, in particular modelling soil temperatures at depths below those at which the large majority of the polar soil fauna and microbiota occur (Kim and Singh 2014). Remote sensing methodologies are also developing rapidly (Wang et al. 2011; Jagdhuber et al. 2014; Bateni et al. 2015), but currently remain relatively coarse and operate at temporal or physical scales that do not provide appropriate resolution of the often extremely patchy polar landscapes.

Given this background, it is clear that a better developed appreciation of ground surface and sub-surface temperatures is required to more fully comprehend biological processes at species, community and ecosystem levels. Moreover, improved surface temperature datasets would strengthen the parameterization of the ground flux in the surface energy balance, making it possible to calculate directly rather than determining it as a residual as is often the case today (Sjöblom 2014). As elsewhere, air temperatures measured by standard meteorological stations provide a poor description, or predictor, of ground temperatures in the polar regions (Smith 1988; Davey et al. 1992; Hodkinson 2003). Similarly, satellite measurements of ground surface temperatures (Westermann et al. 2011) do not adequately describe summer microhabitat temperatures, lacking resolution at the required microhabitat or temporal scales, and being unable to measure conditions experienced under snow or ice cover in winter, spring or autumn. Thus, despite the justifiably great emphasis placed on rapid contemporary warming trends identified in global and regional meteorological datasets, including those in the polar regions (ACIA 2004; Convey et al. 2009; IPCC 2014; Turner et al. 2014), at present it is not possible to link these unequivocally with ground surface or microhabitat temperature trends, or confirm the extent to which they are decoupled. This represents a major lacuna in knowledge, especially in the context of the emphasis given in the polar literature, and elsewhere, to understanding the perceived biological responses to these global/regional climatic changes (Convey 2011). It is essential to include topoclimate—small-scale modelling of climate driven by fine-scale variation in topography, vegetation and soil (Slavich et al. 2014) – in species distribution models to avoid misleading conclusions, for instance concerning alterations in species ranges (Lenoir et al. 2017). Moreover, numerical weather and climate models have a larger uncertainty in polar regions than elsewhere (e.g. Overland et al. 2011). A major reason for this relates to how small-scale features on a sub-grid scale are parameterised, both because the local characteristics in polar regions are not taken into account, and of a general lack of knowledge of these processes.

To provide impetus to advance this field, we here describe 20 datasets documenting ground, sub-surface and microhabitat temperatures at a range of High Arctic (Svalbard) and maritime Antarctic (Antarctic Peninsula and Scotia Arc) locations (Fig. 1). We present data collected over periods of one or more years during various sampling campaigns between 2006 and 2014 and recorded in a variety of ground and vegetation habitats, in order to illustrate the potential value of these datasets. We do not attempt to describe the full extent of inter-annual variation at a particular location or habitat, rather providing (i) representative datasets of a year or greater for ground surface temperatures so as to give a background within which studies may be set, and (ii) descriptors for the thermal environments at each location (iii) considering the relationships between ground temperatures, habitat type and air temperature recorded at standard meteorological stations (iv) enabling extrapolation by the research community in future to other regions within the Arctic and Antarctica, and also other comparable environments such as alpine and desert regions, and the 'third pole' of the Tibetan Plateau, (v) showing the local character of the ground heat flux in the surface energy budget, and finally, (vi) making available the cleaned temperature data in the online supplementary electronic material.

Materials and methods

Site descriptions

Arctic

All Arctic sites included in this study were in the Svalbard archipelago, which is centred on the principle islands of Spitsbergen, Nordaustlandet, Edgeøya and Barentsøya at approximately 78°N, 12°E (Fig. 1b) in the European High Arctic. The islands have a land areal extent of c. 62,000 km^2, 60% of which is permanently covered by ice or snow (Hisdal 1985). The West Spitsbergen Current, a branch of the North Atlantic Drift, transports considerable heat to Svalbard from lower latitudes. The result is that the climate of

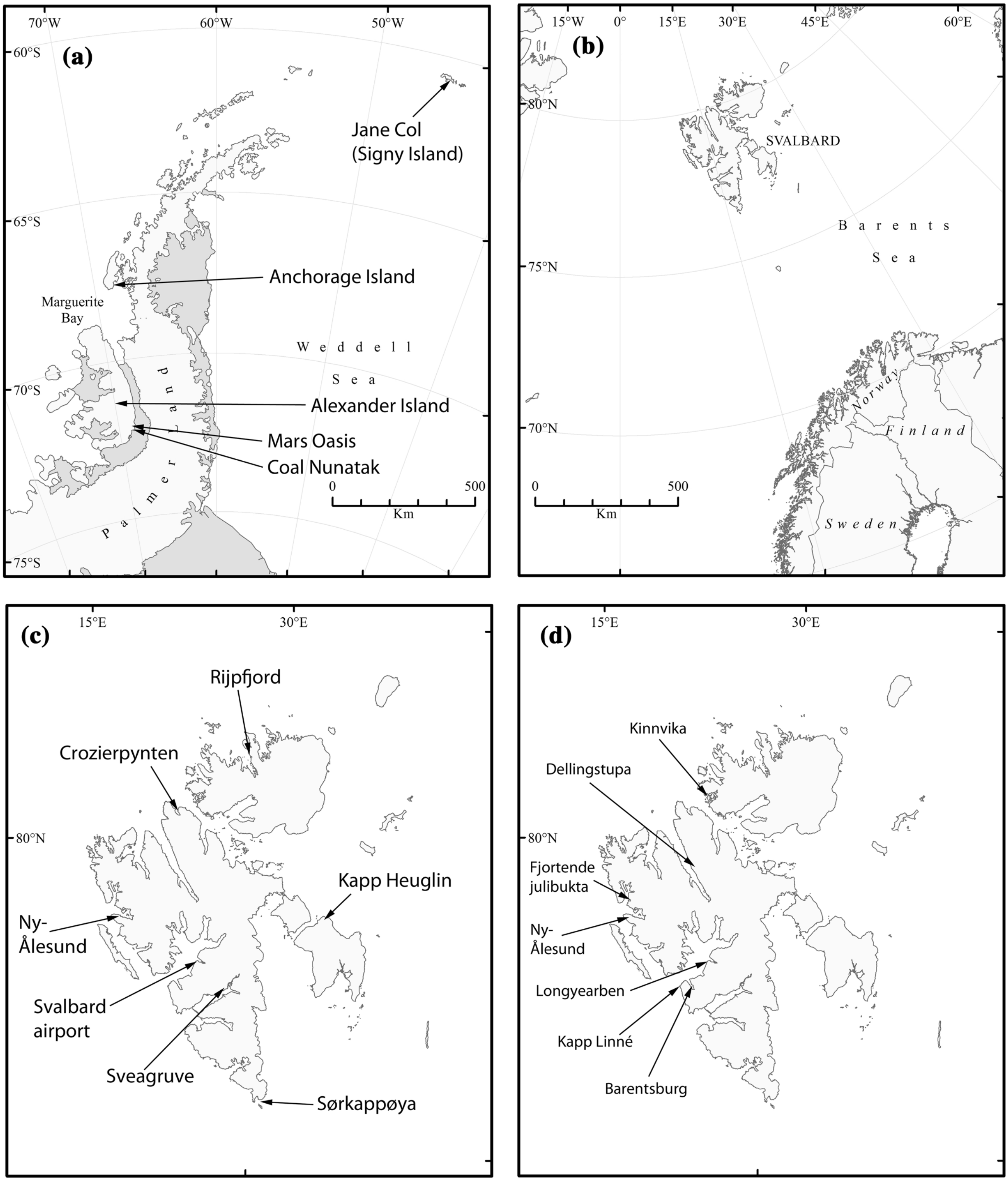

Fig. 1 Locations of **a** sampling sites in the Antarctic; Jane Col (Exposed hill summit) Mars Oasis (Antarctic polar desert), Coal Nunatak (Cryodisturbed terrain), Anchorage (Lichen fellfield); **b** the High Arctic archipelago of Svalbard; **c** meteorological stations in Svalbard referred to in the text; **d** sampling locations in Svalbard; Kinnvika (polar desert); Dellingstupa (High Arctic shrub; steppe vegetation); Fjortendejulibukta (Rich ornithogenic tundra); Ny-Ålesund (Low ridge crest; Moraines, Cliff fissure); Kapp Linné (*Salix* coastal tundra, Large permanent pond); Barentsburg (Poor ornithogenic tundra, Anthropogenic soils); Longyearbyen (*Dryas* tundra; Snow bed hollow, Saline meadow—dry; Saline meadow—wet; Small temporary pond)

the islands is mild for their latitude—the annual mean air temperature at Svalbard airport is − 6.7 °C, but 4 months have positive mean air temperatures, ranging from + 0.3 °C in September to + 5.9 °C in July (Norwegian Meteorological Institute, www.eKlima.no). The west coast has the greatest precipitation (525 mm per year) but the interior regions are substantially dryer; for example Longyearbyen, 50 km from the west coast, receives an annual amount of 210 mm. Most precipitation falls during the winter as snow. Floral communities include sub-zones A (polar desert), B (northern Arctic tundra) and C (middle Arctic tundra) of the Arctic vegetation classification (Jónsdóttir 2005). For this study, 16 sites on Svalbard were selected to describe a wide range of ground, vegetation and freshwater types (Fig. 1d). Site descriptions are provided in Online Resource 1, and illustrative photographs in Online Resource 2 (parts a and b).

Antarctic

The four Antarctic sites represent a range of habitats within the full latitudinal range of the maritime Antarctic (Fig. 1a; Online Resource 2, part c): Exposed hill summit (Jane Col, Signy Island, 60°S), Lichen fellfield (Anchorage Island, 68°S), Antarctic polar desert (Mars Oasis, Alexander Island, 72°S) and Cryodisturbed land (Coal Nunatak, Alexander Island, 72°S) (Online Resource 1). The ameliorating effects of the ocean to the west maintain a relatively mild climate in the maritime Antarctic with a comparatively narrow range of seasonal temperatures and mild, wet summers. Mean monthly air temperatures in coastal areas are slightly positive (0–2 °C) for 1–4 months in summer, dropping to − 10 to − 15 °C in winter (Walton 1982; Convey 2013). On Signy Island, the prevailing winds are from the south-west to north-west, with occasional warm Föhn effects created by the 1200 m high mountain barrier of central Coronation Island to the north (King et al. 2017). Thick low clouds and lack of sunshine are typical features of the climate, with high frequency of precipitation. Anchorage Island similarly experiences a climate for much of the year that is stabilized by the adjacent ocean, although a more continental and colder climate characterizes winter after the formation of sea ice to the west in the Bellingshausen Sea, and cloud cover is generally less. The southernmost exposures of snow- or ice-free ground in the maritime Antarctic occur in south and east Alexander Island. The two sites considered here, Cryodisturbed terrain, and Antarctic polar desert (Fig. 1a), provide an environment intermediate between the typical maritime Antarctic and the drier, cold desert ecosystems of the continental Antarctic. Being sheltered from maritime weather systems approaching from the west and often under the influence of stationary continental high pressure systems to the east/south, these experience low precipitation, and provide the closest comparison with continental "Dry Valley" systems that is present in the Antarctic Peninsula region (Smith 1988; Convey and Smith 1997).

Data collection

Loggers were positioned in 20 diverse habitats representative of a range of terrestrial and freshwater surfaces and habitats occurring in the High Arctic and the maritime Antarctic (Online Resource 1, 2). Because, as is often the case with currently available biological microclimatic datasets, the loggers were deployed within different studies over time, the data obtained represent several, and in some cases non-overlapping, years. Loggers were typically visited/retrieved at best on an annual basis after deployment. Logistic and technical difficulties are a particular problem in servicing stations at remote and unmanned sites such as these, with the result that there are occasional data missing from various intervals during the campaign periods. The full microclimate temperature data considered in this article are provided in spreadsheet form in Online Resource 3.

Arctic

Temperatures were recorded at a depth of approximately 1 cm using Tinytag dataloggers, TGP-4020 (Gemini, Chichester, West Sussex, U.K.) fitted with PB-5001, PB-5009, or PB-5006 external thermistor probes, except for the Small temporary and Large permanent ponds (sites O and P) where TG-4100 submersible loggers were deployed at approximately 10 cm water depth. For logger and probe locations see Online Resource 1. Care was taken to avoid exposing the sensors to direct insolation. Sampling interval was 30, 60 or 120 min, depending on logger memory and expected campaign period.

As air temperatures were not recorded at the 16 locations, due to logistic and permitting limitations on deploying non-maintained structures at these remote sites, standard meteorological air temperatures were taken from six standard Norwegian Meteorological Institute stations (www.eKlima.no). This means that direct comparisons between air and ground temperatures are not possible at individual study locations on Svalbard. Air temperatures at Rijpfjord were collected by the meteorological station established by the CLEOPATRA project (http://www.mare-incognitum.no/) at a height of 4.5 m using solar shielded, naturally ventilated PT1000 sensors connected to a Campbell CR1000 logger (Campbell Scientific, U.K.). Temperatures were logged every hour, and the data presented are the mean of recordings taken every minute. Locations of the meteorological stations are detailed in Online Resource 1 and Fig. 1c.

Antarctic

Ground and air temperatures were recorded using various temperature probes over time (copper/constantan thermocouple wires; type-T thermocouples; Fenwal Unicurve thermistors UUT51J1 (100 KΩ at 25 °C) in type FF catheter probes; HMP45C, Vaisala; Campbell Scientific 107 thermistor probes, Campbell Scientific, UK). For ground temperatures the probe was inserted into the ground surface so as to record surface conditions. Air temperatures were recorded at a height of 2 m within a naturally ventilated solar insolation shield. Data were recorded every hour for the duration of the study using Campbell Scientific CR10X loggers (Campbell Scientific, U.K.).

Results

To demonstrate the potential utility of these datasets, we here describe six aspects of overview observations which are pertinent in particular to the biology at the studied locations. We do not attempt to analyse each location dataset in detail, in particular as is typical of such independent studies and data sources there are a range of confounding factors that may invalidate detailed and explicit analyses between sites. Rather we provide summary descriptive statistics (Tables 1, 2). The full datasets are provided in Online Resource 3, to enable research community access and permit further individual detailed analyses and comparisons to be performed as required.

Observation 1: air temperature patterns and ranges

Annual air temperature at Svalbard airport (2011) (Longyearbyen, Table 1, Fig. 2a) was − 3.3 °C, with maximum

Table 1 Summary air temperature figures for a representative year at seven sites on Svalbard and four in the maritime Antarctic

Site	Winter DJF F-T cycles	Spring MAM F-T cycles	Summer JJA F-T cycles	Autumn SON F-T cycles	Total F-T cycles	Annual mean/max/min air temperature (°C)	Days > 0 °C	Entire dataset max/min air temperature (°C)
Arctic								
Svalbard airport *2011	5	8	0	8	21	− 3.3/16.8/− 29.9	151	16.8/− 30.5
NY-Ålesund *2011	4	9	3	9	25	− 3.6/12.5/− 26.1	144	13.2/− 26.4
Kapp Heuglin *2011	3	9	13	8	33	− 6.2/9.5/− 35.1	113	12.7/− 43.9
Sveagruva *2011	5	11	1	11	28	− 4.6/10.8/− 32.0	143	14.1/− 36.5
Sørkappøya *2011	4	11	6	7	28	− 3.3/6.4/− 27.1	154	8.6/− 27.1
Crozierpynten *2011	4	8	6	9	27	− 5.2/12.6/− 33.6	125	12.6/− 33.6
Rijpfjord *2011	3	10	11	7	31	− 7.2/8.0/− 38.8	106	9.0/− 38.8
	Winter JJA	Spring SON	Summer DJF	Autumn MAM				
Antarctic								
Jane Col, Signy Island *2009	3	38	54	35	130	− 3.9/8.6/− 30.1	95	8.6/− 30.1
Anchorage Island *2007	3	17	62	16	98	− 4.4/6.2/− 21.6	98	6.2/− 21.6
Mars Oasis, Alexander Island *2009	2	15	66	17	100	− 10.6/8.6/− 47.5	65	8.6/− 47.5
Coal Nunatak, Alexander Island *2009	0	10	60	6	76	− 6.3/11.2/− 28.0	52	11.2/− 28.0

Days > 0 °C is number of days mean daily air temperature above 0 °C

Asterisk(*) represents year summarized

F-T: number of freeze–thaw events

DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November

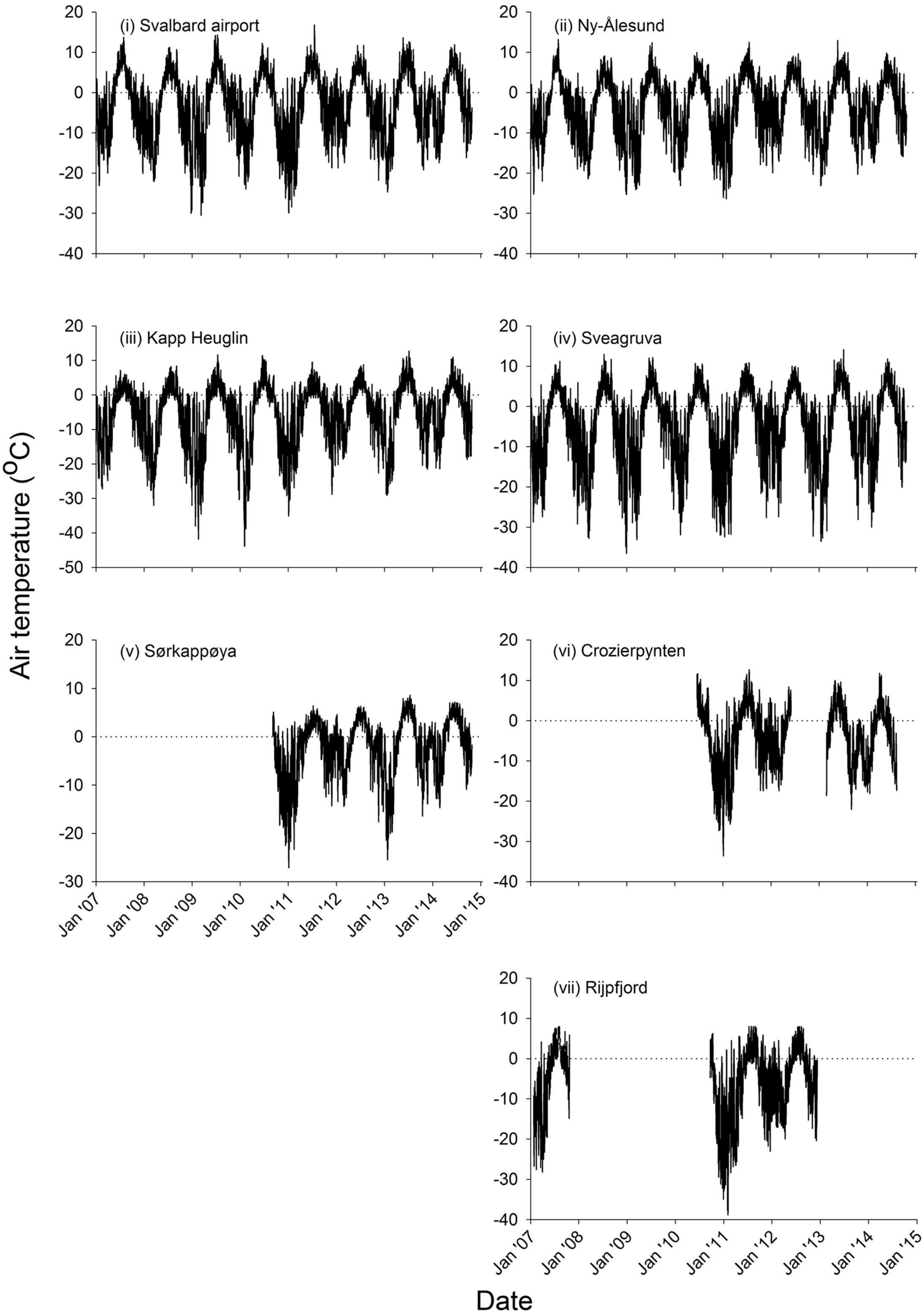

Fig. 2 **a** Air temperatures at meteorological stations in Svalbard; (*i*) Svalbard airport (*ii*) Ny-Ålesund (*iii*) Kapp Heuglin (*iv*) Sveagruva (*v*) Sørkapp (*vi*) Crozierpynten and (*vii*) Rijpfjord. Dotted line indicates 0 °C reference. **b** Air temperatures at meteorological stations in the Antarctic. (*Q*) Exposed hill summit (Jane Col) (*R*) Antarctic polar desert (Mars Oasis) (*S*) Cryodisturbed terrain (Coal Nunatak) (*T*) Lichen fellfield (Anchorage). Dotted line indicates 0 °C reference

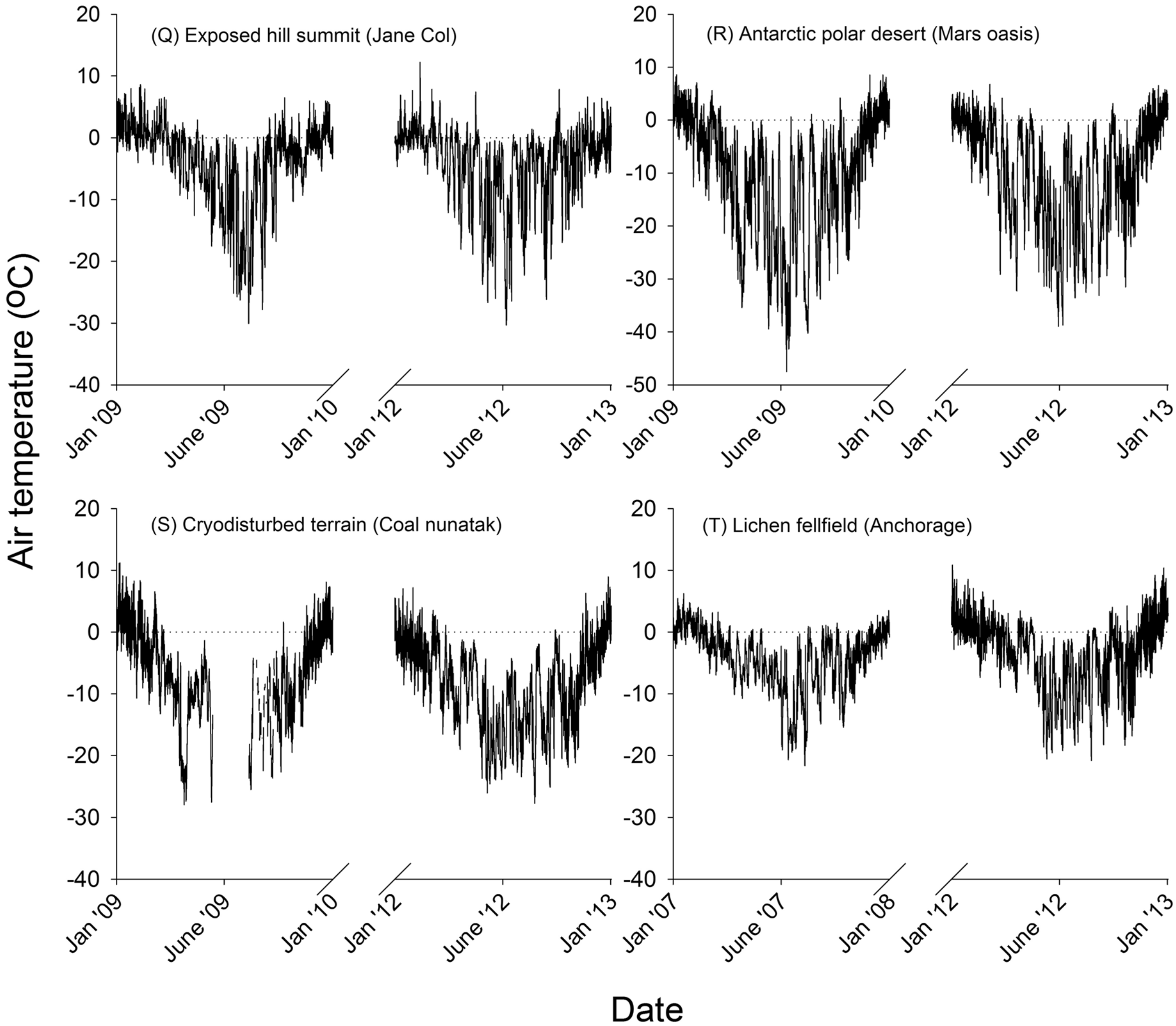

Fig. 2 (continued)

and minimum air temperatures ranging between − 31.5 and + 17.1 °C (Table 1). The summer period showed the minimum range in temperature extremes, as well as not declining below 0 °C. Mean annual air temperatures were lower in the north and east of Svalbard (Crozierpynten, Rijpford and Kapp Heuglin) at around − 5 °C, than at locations further west (Sørkappøya, Svalbard airport, Ny-Ålesund) (Table 1; Online Resource 4), illustrating the effects of the different ocean currents and air masses influencing regions of the archipelago (Coulson et al. 2014; Przybylak et al. 2014). Although air temperatures on the far north coast of Svalbard at Crozierpynten and Rijpfjord were often lower than those at western locations, they followed a similar profile. Minimum temperatures recorded were − 38.8 and − 33.6 °C, respectively, compared with − 26.4 and − 30.5 °C at Ny-Ålesund and Svalbard airport, respectively (Table 1). The total number of days with positive mean temperatures ranged between 106 and 151, generally considerably more than the 52–98 recorded at the Antarctic locations. Freeze–thaw transitions in air temperature were common at all locations and also, at most locations, in all seasons including the winter months. Freeze–thaw events were less frequent at west coast locations but still numbered over 20 per year at all sites.

Air temperatures at the four Antarctic sites (Table 1, Fig. 2b) varied between locations. Lichen fellfield and Exposed hill summit were generally similar despite being separated by eight degrees of latitude. Mean annual temperatures were greatest at Exposed hill summit at − 3.9 °C. This was due largely to the warmer winters (mean monthly winter temperatures − 12.5 to − 8.2 °C) raising the mean temperature, rather than to warmer summers (0 to + 1.7 °C). This site also experienced the largest number of freeze–thaw events in air temperature (130 annually), with all four sites having more than double the number of events of any Svalbard site. All four Antarctic locations experienced the highest frequency of air freeze–thaw cycles during the austral summer, similar numbers of cycles in the spring and autumn months, and fewest in the winter months. The most southern location, Cryodisturbed terrain, at a similar altitude to Exposed hill summit but 12 degrees of latitude further south, was somewhat colder than either Exposed hill summit or Lichen fellfield, with the exception of very similar temperatures in January and December (mid-summer). Antarctic polar desert, located on the ice-shelf-bound east coast of Alexander Island, less than 50 km from Cryodisturbed terrain and part of the same geological formation, had the most extreme climate of the Antarctic sites studied. However, summer temperatures were similar to the other Antarctic locations, and this trend was driven by colder minimum winter mean monthly temperatures. Even at this site there were a high number of freeze–thaw events annually, peaking in December.

Observation 2: ground temperature patterns and ranges

During the summer period, upper ground temperatures followed largely similar profiles to air temperatures (Table 2, Online Resource 5) but often attained seasonal mean, maximum and minimum temperatures several degrees warmer than those of the air. However, while the daily pattern of air temperature fluctuations was mirrored to an extent in the ground temperatures during the summer, in winter uncoupling was evident. Temperature fluctuations reflected those of the air until the late autumn. After this point ground temperature was often significantly greater than corresponding air temperature and displayed reduced daily fluctuation, across all sites.

The coldest Svalbard location in summer was Arctic polar desert on Nordaustlandet (Kinnvika). Here, sub-zero ground temperatures were encountered throughout the year and mean summer temperature (June through August) was only + 2.5 °C. Despite being the most northern site, and with air temperatures in the region regularly falling below − 20 °C, winter ground temperatures at Rijpfjord rarely declined below − 10 °C (Tables 1, 2). Anthropogenic soils were unique, with extremely mild winter temperatures and cool summer conditions. Here, ground temperature remained close to 0 °C throughout the winter despite the low air temperatures. Warming was slow in spring and ground temperature often remained below that of the air.

Both freshwater sites showed similar temperatures, but with variations in late summer when the water level in Small temporary pond fell and the logger was in reality recording temperatures in waterlogged moss and mud. Water temperatures showed damped fluctuations compared to air temperatures (Table 2, Online Resource 5).

Of the four Antarctic sites, ground temperatures at the Exposed hill summit showed the most constant profile, with an annual mean of − 1.7 °C and annual maximum and minimum of + 18.4 and − 8.7 °C respectively. The temperature rose rapidly to 0 °C in austral late winter (early October), and thereafter remained relatively constant close to − 2 °C. In contrast to the other three Antarctic sites, but similar to many of the terrestrial Arctic sites, this site experienced a long period close to 0 °C during the spring thaw, in this case 32 days (Online Resource 5). As with air temperature, the Antarctic polar desert experienced the most extreme ground temperature regime. Ground temperature declined to a minimum of − 38.2 °C during winter (Table 2, Online Resource 5). The annual ground temperature profile at Lichen fellfield resembled that of the Dryas tundra habitat in Svalbard, with three months experiencing positive mean temperatures, and a similar warming pause in spring where, during the melt, the ground took 8.6 days to warm from − 1.0 °C to above 0 °C. However, in contrast to the Arctic, there was a similar pause in the autumn when the ground required 6.2 days to cool from 0 to below − 1 °C. Exposed hill summit also had an extended spring warming pause (15.5 days to warm from − 1 °C to become positive), but with no equivalent pause during cooling in the autumn.

Observation 3: length of summer thawed season in the ground

The timing of the transition from largely negative to positive temperatures was very different between ground and air, as illustrated by temperature accumulation curves (degree days above 0 °C) (Fig. 3), and the duration of positive temperatures (Table 3). Given the level of daily fluctuations, the latter value was calculated by defining the onset of 'spring thaw' as the date on which point temperature exceeded 1 °C, and 'autumn freeze' as that at which it declined to − 1 °C. The number of days with a mean positive temperature was generally greater in the air than for the soil surface (cf. Tables 1, 3). While air temperatures at the Svalbard sites became positive in late April/early May, ground and subsurface temperatures only started to accrue degree days later in spring towards the end of May or early June (Fig. 3). During the spring period ground temperatures showed an initial tendency to warm to close to 0 °C, remain stable for a period of up to several weeks (as noted above) and then climb rapidly to track air temperature fluctuations (Online Resource 5). For most Arctic sites the winter period (ground permanently frozen) typically commenced in early October (Fig. 3, Online Resource 5).

In the Antarctic, the study sites attained positive ground temperatures in a generally reverse latitudinal sequence, with the first being the southern Antarctic polar desert, followed by Lichen fellfield, Cryodisturbed terrain and Exposed hill summit, around five weeks later (Table 3). Antarctic soils began to freeze in February (Table 3) and were constantly

Table 2 Mean, maximum and minimum monthly ground temperatures, freeze–thaw (F-T) events and days with mean (μ) T > 0 °C for each season and annually for a representative year (indicated by * associated with Site) at each study location. See Online Resource 3 for raw data file

Site		Spring MAM mean/max/min	Summer JJA mean/max/min	Autumn SON mean/max/min	Winter DJF mean/max/min	Annual mean/max/min	Annual F-T events	Annual days μ T > 0 °C
Arctic								
Site A—Arctic polar desert *2007–8	Mean	− 11.8/− 6.2/− 16.6	1.2/11.7/− 6.0	− 2.9/6.3/− 10.8	− 8.6/− 5.6/− 11.5	− 5.4/11.7/− 16.6		
	F-T events	0	0	9	0		9	
	Days μ T > 0 °C	0	55	19	0			74
Site B—High Arctic shrub tundra *2012	Mean	− 7.0/12.2/− 17.5	8.1/34.5/− 2.2	− 5.1/10.4/− 20.7	− 10.6/5.0/− 20.3	− 3.6/34.5/− 20.7		
	F-T events	7	3	5	1		16	
	Days μ T > 0 °C	10	89	21	1			122
Site C—steppe vegetation *2012	Mean	− 6.4/0.8/− 12.0	5.4/13.0/− 0.1	− 2.2/6.4/− 9.8	− 6.7/0.2/− 10.9	− 2.5/13.0/− 12.0		
	F-T events	1	1	1	2		5	
	Days μ T > 0 °C	9	91	23	1			124
Site D—Low ridge crest *2012	Mean	− 6.1/5.0/− 16.1	6.7/11.7/2.2	− 4.1/5.1/− 17.1	− 8.1/− 0.9/− 18.9	− 2.9/11.7/− 18.9		
	F-T events	0	0	3	0		3	
	Days μ T > 0 °C	0	92	24	0			121
Site E—*Salix* coastal tundra *2013–14	Mean	− 2.7/− 0.3/− 4.6	6.0/10.7/− 0.3	− 0.1/6.3/− 3.6	− 0.8/0.7/− 2.6	− 4.6/10.7/− 4.6		
	F-T events	1	0	1	0		2	
	Days μ T > 0 °C	0	85	29	20			135
Site F—*Dryas* tundra *2011	Mean	− 5.6/− 0.2/− 12.0	7.6/20.1/0.0	− 1.1/7.4/− 10.0	− 8.6/− 3.0/− 17.7	− 1.9/20.1/− 17.7		
	F-T events	0	0	2	0		2	
	Days μ T > 0 °C	0	92	28	0			120
Site G—snow bed hollow *2011	Mean	− 5.9/0.1/− 12.0	7.1/16.2/− 0.2	− 2.2/8.5/− 15.8	− 11.4/− 2.2/− 21.5	− 3.4/16.2/− 21.5		
	F-T events	0	0	9	0		9	
	Days μ T > 0 °C	1	88	28	0			117
Site H—Saline meadow—wet *2011	Mean	− 3.4/− 0.1/− 7.6	7.8/18.7/− 0.1	− 0.1/10.7/− 8.3	− 6.1/− 1.0/− 8.5	− 0.5/18.7/− 8.5		
	F-T events	0	0	14	0		14	
	Days μ T > 0 °C	3	92	38	0			133
Site I— Saline meadow— dry *2011	Mean	− 4.9/− 0.4/− 9.7	7.2/15.5/− 0.4	− 1.4/9.2/− 12.5	− 8.4/− 3.6/− 12.7	− 1.8/15.5/− 12.7		
	F-T events	0	0	4	0		4	
	Days μ T > 0 °C	0	84	40	0			124
Site J—rich ornithogenic tundra *2010	Mean	− 5.7/11/7/− 17.4	7.8/20.7/0.2	− 3.9/10.7/− 18.3	− 10.9/− 0.3/− 20.0	− 3.1/20.7/− 20.0		
	F-T events	0	0	2	0		2	
	Days μ T > 0 °C	21	92	39	0			152
Site K—poor ornithogenic vegetation *2012	Mean	− 4.0/4.4/− 14.3	8.1/22.8/− 0.7	− 0.8/11.6/− 11.4	− 5.5/0.5/− 14.6	− 0.5/22.8/− 14.6		
	F-T events	7	1	7	2		17	
	Days μ T > 0 °C	14	92	54	10			170
Site L—anthropogenic soils *2012	Mean	0.3/0.6/0.0	6.2/13.8/0.6	− 0.8/8.2/− 2.1	− 0.3/0.6/− 1.7	1.8/13.8/− 2.1		
	F-T events	0	0	6	0		6	
	Days μ T > 0 °C	90	92	52	33			267
Site M—moraines *2012	Mean	− 5.8/1.4/− 11.1	7.8/11.8/4.2	− 3.5/2.8/− 10.2	− 7.1/− 5.3/− 8.7	− 2.2/11.8/− 11.1		
	F-T events	1	0	4	0		5	
	Days μ T > 0 °C	15	92	19	0			126
Site N—cliff fissure	Mean	− 4.6/21.1/− 16.8	8.2/31.8/1.1	− 4.0/21.9/− 16.3	− 10.5/− 0.5/− 24.7	− 3.0/31.8/− 24.7		
	F-T events	1	0	4	0		5	
	Days μ T > 0 °C	32	82	23	0			137
Site O—small temporary pond *2011	Mean	− 5.4/− 0.3/− 13.7	4.8/10.2/− 0.3	− 0.1/5.3/− 4.9	− 8.2/− 2.1/− 14.6	− 2.2/10.2/− 14.6		
	F-T events	0	1	0	0		1	
	Days μ T > 0 °C	0	84	34	0			118
Site P—large permanent pond *2008–9	Mean	− 6.9/− 0.1/− 11.7	5.2/11.3/− 0.1	0.2/6.3/− 4.5	− 6.3/− 0.6/− 13.3	− 1.9/11.3/− 13.3		
	F-T events	0	1	2	3		6	
	Days μ T > 0 °C	0	78	40	0			118

Table 2 (continued)

		Spring SON	Summer DJF	Autumn MAM	Winter JJA			
Antarctic								
Site Q—exposed hill summit (Jane Col) *2009	Mean	− 2.9/0.0/− 6.9	1.4/18.4/− 3.9	− 0.4/11.6/− 8.6	− 5.0/− 1.0/− 8.7	− 1.7/18.4/− 8.7		
	F-T events	0	32	19	0		51	
	Days μ $T > 0$ °C	0	63	26	0			89
Site R—Antarctic polar desert *2009	Mean	− 8.8/15.8/− 27.9	3.2/24.3/− 7.7	− 10.2/5.7/− 24.7	− 19.7/− 4.5/− 38.2	− 9.0/24.3/− 38.2		
	F-T events	15	64	12	0		91	
	Days µ T > 0 °C	13	70	4	0			87
Site S—Cryodisturbed terrain *2009	Mean	− 11.6/− 0.1/− 27.9	2.5/21.8/− 11.9	− 10.7/9.6/− 30.6	Nd	− 6.5/21.8/− 30.6		
	F-T events	0	78	9	Nd		87 (min)	
	Days μ $T > 0$ °C	0	62	4	Nd			66 (min)
Site T—Lichen fellfield *2007–8	Mean	− 3.5/7.3/− 9.9	4.2/21.9/− 4.9	− 3.2/15.5/− 12.4	− 8.5/− 3.9/− 16.4	− 2.8/21.9/− 16.4		
	F-T events	3	42	29	0		74	
	Days μ $T > 0$ °C	4	88	9	0			101

DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November

frozen from March or early April (Fig. 3). Although these Antarctic sites span twelve degrees of latitude, there was no obvious latitudinal relationship in either their spring thaw or autumn freeze dates. Furthermore, despite the lower latitude locations of the Antarctic sites (60–72°S), and unlike the contrast in positive air temperature durations noted above, their unfrozen ground summer periods were only slightly less in duration to those of the High Arctic Svalbard locations at 78–80°N.

Observation 4: timing of ground freeze–thaw events

In contrast to the occurrence of freeze–thaw transitions in air temperature in both spring and autumn at the Svalbard sites, soils only experienced such cycling in the autumn (Tables 1, 2, Online Resource 5). In the autumn, the number of ground freeze–thaw events was also considerably less than those in the air. The single exception to the pattern of freeze–thaw events in the ground being absent in the spring was at Cliff fissure, which experienced events in both the spring and autumn and had the greatest event frequency (21 events in 2008–09). The freshwater bodies exhibited no (Large permanent pond) or one (Small temporary pond) freeze–thaw cycles either in autumn or spring. The latter was probably associated with the drying of the pond later in summer.

In contrast, all four Antarctic sites showed extensive freeze–thaw cycling in the ground surface during both spring and autumn periods, with between 51 and 91 such events being recorded (Table 2, Online Resource 5). The maximum frequency was seen at the Antarctic polar desert, with 15 cycles in the spring, 64 in summer and 12 in autumn. None of the Antarctic locations experienced freeze–thaw events in the winter months.

Observation 5: rates of ground temperature change

Ground and sub-surface temperatures generally displayed slow rates of change during the summer. For example, the Dryas tundra showed a peak warming rate of 1.8 °C h^{-1} on 23 June 2011 when the temperature rose from + 8.9 °C at 1200 to a maximum of + 14.2 °C at 1500. Cooling rates were similarly slow, typically varying between 0.3 and 1.5 °C h^{-1}. The Cliff fissure displayed amongst the greatest rates of change where, on 23 July 2008, the 'daytime' surface temperature reached a maximum of + 31.8 °C. At 2230 the temperature was still above + 30 °C while, 3 h later, it had decreased to + 19.7 °C, a rate of 3.5 °C h^{-1}, and then continued to decline to a minimum of + 12.3 °C over the next 11 h. Warming rates at this location were similarly rapid, increasing from + 10.4 to + 28.7° C over 5 h (3.7 °C h^{-1}), on 23 July 2008.

Ground temperatures were often constant during winter and spring periods, or showed only limited fluctuation, with rates of change rarely greater than 0.1 °C h^{-1}. Nonetheless, on 17 March 2011 ground temperatures at Dryas tundra rose rapidly from − 7.8 °C at 1700 to − 1.3 °C at 1800 and then − 0.2 °C, where they remained until 1800 on 18 March, after which they declined steadily, returning to − 7.8 °C at 0300 on 23 March, some 4.8 days later. This involved warming and cooling rates of 3.8° (and 6.5° over the first hour) and 0.07 °C h^{-1}, respectively. The two freshwater ponds showed

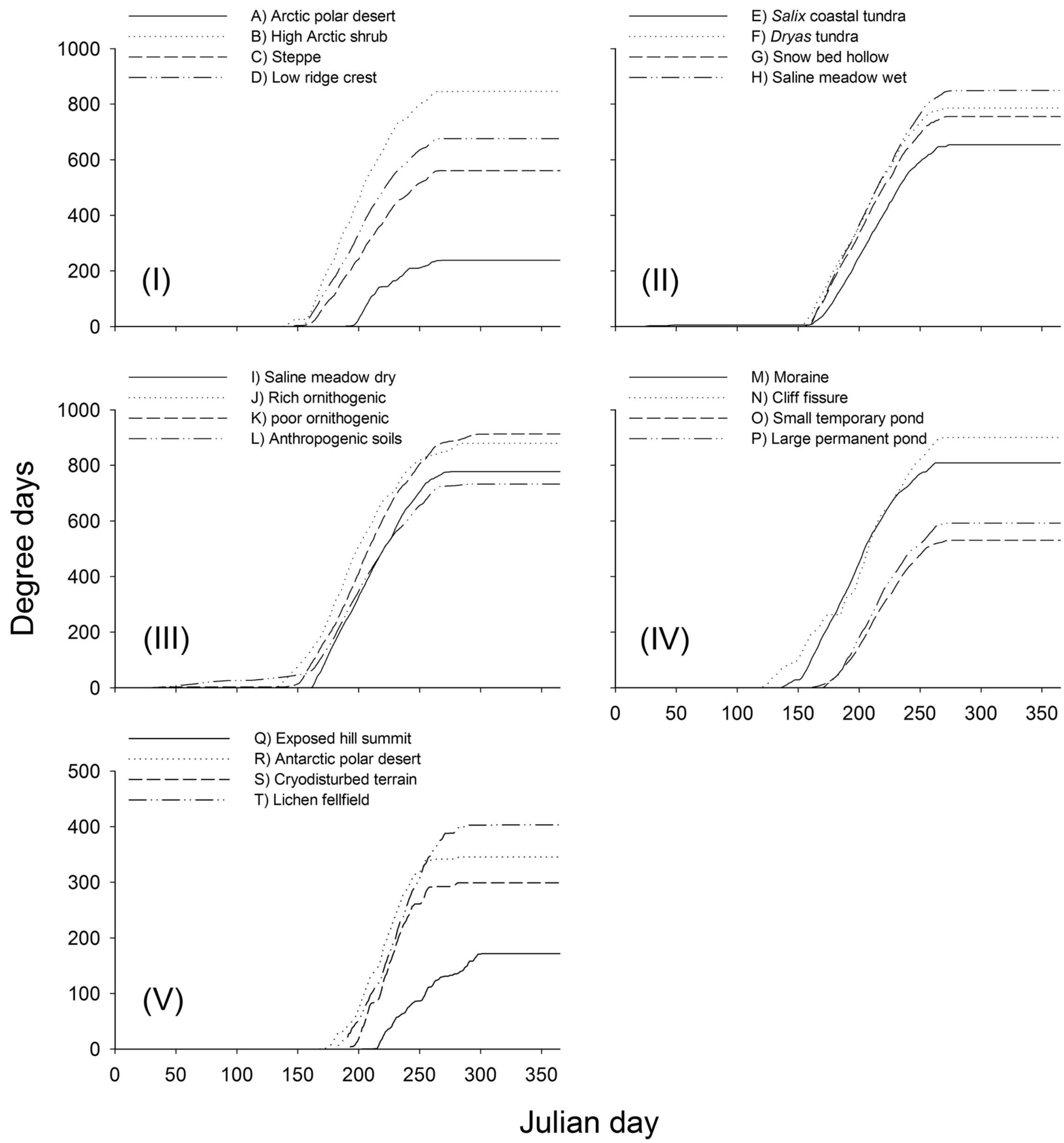

Fig. 3 Cumulative degree days (using 0 °C as a baseline, the sum of mean daily temperature above zero multiplied by the number of days with that mean temperature). **I** (*A*) Arctic polar desert (*B*) High Arctic shrub tundra (*C*) Steppe vegetation (*D*) Low ridge crest. **II** (*E*) *Salix* coastal tundra (*F*) *Dryas* tundra (*G*) Snow bed hollow (*H*) Saline meadow—wet. **III** (*I*) Saline meadow—dry (*J*) Rich ornithogenic tundra (*K*) Poor ornithogenic vegetation (*L*) Anthropogenic soils. **IV** (*M*) Moraines (*N*) Cliff fissure (*O*) Small temporary pond (*P*) Large permanent pond. **V** (*Q*) Exposed hill summit (Jane Col) (*R*) Antarctic polar desert (Mars Oasis) (*S*) Cryodisturbed terrain (Coal Nunatak) (*T*) Lichen fellfield (Anchorage)

only slow rates of temperature change due to their greater specific heat capacity (cf. data from Antarctic ponds presented by Peck 2004).

The Antarctic polar desert ground and sub-surface temperature fluctuations were also large and rapid, in this case particularly in winter. For instance, on 7 July 2012 (mid-winter) the ground temperature began to rise steadily from a minimum of − 37.5 °C. Some 29 h later it had become slightly positive (+ 0.17 °C), an average warming rate of 1.3 °C h^{-1}. The temperature subsequently cooled to − 14.8 °C over 10 h, a cooling rate of 1.5 °C h^{-1}. Similar magnitude temperature swings were evident at the other maritime Antarctic sites but at slower rates.

Table 3 Conservative estimate of duration of soil 'thawing' at each study site, estimated between the dates that soil point temperatures first attained (or exceeded) +1 °C in the spring, and declined to (or below) − 1 °C in the autumn

	>+ 1 °C (A)	<− 1 °C (B)	Number of days between columns A and B
Arctic			
A Arctic polar desert	08/07/08	02/09/07	54
B High Arctic shrub tundra	12/05/17	19/09/17	127
C Steppe vegetation	07/06/12	26/09/12	109
D Low ridge crest	02/06/12	03/10/12	121
E *Salix* coastal tundra	10/06/14	25/09/13	105
F *Dryas* tundra	01/06/11	04/10/11	123
G Snow bed hollow	05/06/11	04/10/11	119
H Saline meadow—wet	08/06/11	04/10/11	116
I Saline meadow—dry	11/06/11	05/10/11	114
J Rich ornithogenic tundra	13/05/10	14/10/10	151
K Poor ornithogenic vegetation	25/05/12	24/10/12	149
L Anthropogenic soils	06/06/12	24/10/12	138
M Moraines	15/05/12	27/09/12	132
N Cliff fissure	28/09/08	30/04/09	212
O Small temporary pond	17/06/11	10/10/11	113
P Large permanent pond	18/06/09	23/10/08	125
Antarctic			
Q Exposed hill summit (Jane Col)	01/01/09	03/04/09	92
R Antarctic polar desert (Mars Oasis)	10/11/09	03/03/09	113
S Cryodisturbed terrain (Coal Nunatak)*	–	–	
T Lichen fellfield (Anchorage Island)	22/11/07	19/03/07	117

*Temperatures at site S (Cryodisturbed terrain) fluctuated greatly throughout the year and it was not possible to identify dates clearly

Observation 6: accumulated thermal sum in the ground

Cumulative temperature sums (degree days above 0 °C) in the air and ground were substantially different at all sites (Fig. 3). Once ground warming had commenced, the ground temperature often rose quickly above that of the air. This pattern typified many of the study locations (Fig. 3, Table 4). Exceptions included the Arctic polar desert, where the ground remained significantly colder than the air, accruing a thermal sum 68% lower than that of the air, and the freshwater habitats, where water temperatures remained below air temperature for much of the summer.

At the maritime Antarctic sites, the thermal sum accrued was less than at the Arctic locations, generally between 300 to 450 degree days compared to the 700 and above that were typical on High Arctic Svalbard. However, the differences between the thermal sums of the air and the ground were more pronounced, with ground temperatures rising rapidly and remaining constantly above air temperature (Table 4, Fig. 3, Online Resource 5). Lichen fellfield accumulated 403 degree days compared to an air sum of 67, a ground gain of almost 500% relative to the air.

Discussion

General patterns of air and soil temperature variation

Ground temperatures in both Arctic and Antarctic are clearly influenced by seasonal variation in air temperatures. During the summer periods, all ground and water temperatures presented here mirrored air temperatures to some extent. The solar forcing and the low albedo of the ground surface results in an unstably stratified atmospheric boundary layer, elevated ground temperatures and cumulative degree days (Fig. 3, Tables 1, 2), often above corresponding air temperatures. However, the number of days with mean daily temperatures above a 0 °C baseline was often greater in the air than in the ground due to the extended period in the spring when the ground was insulated from rising air temperatures by snow and ice cover, which caused a clear uncoupling of ground and air temperatures. Ground and sub-surface temperature fluctuations were clearly decreased during this period and temperatures remained almost constant with slow rates of change. The sometimes extended period spent near 0 °C in either or both of spring or autumn, sometimes known as the 'zero curtain period', is of interest in the studies of

Table 4 Cumulative day degrees difference between soil and air. Svalbard airport used as baseline air temperature for Arctic sites except Arctic polar desert site (Rijpford air temperatures)

Location	Site	Code	% difference
Arctic	Arctic polar desert	A	– 68.4
	High Arctic shrub tundra	B	30.8
	Steppe vegetation	C	– 13.3
	Low ridge crest	D	4.5
	Salix coastal tundra	E	– 10.4
	Dryas tundra	F	4.4
	Snow bed	G	0.3
	Saline meadow—wet	H	12.8
	Saline meadow—dry	I	3.3
	Rich ornithogenic tundra	J	48
	Poor ornithogenic tundra	K	41.3
	Anthropogenic soils	L	13.3
	Moraines	M	25.1
	Cliff fissure	N	45.1
	Small temporary pond	O	– 18.1
	Large permanent pond	P	– 4.5
Antarctic	Exposed hill summit	Q	13.6
	Antarctic polar desert	R	199.8
	Cryodisturbed terrain	S	162.9
	Lichen fellfield	T	495.3

biogeochemistry. The insulating effect of winter snow cover is well appreciated (Leinaas 1981; Cooper 2015), insulation efficiency varying with snow depth and density (crystal form and, hence, water equivalent). Recently, Convey et al. (2014a) reported that soil temperatures under 1 m of snow at the Saline meadow— wet (site H in this study) remained close to – 2 °C throughout the winter and until March despite air temperatures declining to – 26.8 °C. Snow accumulation was less at the adjacent Saline meadow—dry, with a maximum snow depth of only 30 cm. At the latter site, soil temperatures declined gradually through the winter, reaching a minimum of – 12.3 °C during the campaign period.

There were exceptions to this general pattern, such as the spike in ground temperature noted at Dryas tundra on March 17 2011 (Online Resource 5), which coincided with air temperatures becoming positive on 16 March and rising to + 3.5 °C, along with 18.2 mm of precipitation, likely as rain, on 17 March (www.eKlima.no). Such rain-on-snow (ROS) events result in rainwater percolating through the snow pack to the frozen ground surface and elevate the ground surface temperature (Hansen et al. 2014) due to both the temperature of the water on deposition and also the release of latent heat as this water freezes on contact with the impermeable frozen ground. Although the ground temperature rose rapidly in this event to – 0.2 °C, it remained below 0 °C and there was no freeze–thaw event. A greater ROS event occurred in January–February 2012. On this occasion above zero air temperatures (up to + 7 °C) occurred across the entire Svalbard archipelago along with record precipitation, with up to 98 mm rainfall in one day at Ny-Ålesund. This exceptionally rare event (return period of > 500 years prior to this event), combined with a 2-week-long warm spell during which 272 mm of precipitation was received, caused increases in permafrost temperatures to a depth of at least 5 m, induced infrastructure-damaging slush avalanches and created ground-ice cover of up to 20 cm thickness (Hansen et al. 2014). During this ROS event ground sub-surface soil temperatures warmed to just under 0 °C but, as above, did not continue increasing to the point of a freeze–thaw event.

The uniquely mild winter climate of the Anthropogenic soil is likely a consequence of the deep snow accumulation in the gully that forms this location and, possibly, thermogenic decomposition processes in the rich organic soils. These soils are discarded chernozym soils originally imported from the Ukraine or southern European Russia for use in the settlement's greenhouse (Coulson et al. 2013a, b). The slow warming recorded in spring, and soil temperatures often remaining below that of the air, may be due to the presence of an insulating cover of tall alien plant species, for example *Anthriscus sylvestris* (Governor of Svalbard 2014), providing a moist and shaded environment. Such anthropogenic sites also may act as colonization nuclei for invasive species, as well as being colonized themselves by native species. Understanding conditions in such sites is a further important part of characterizing the available terrestrial habitats in polar regions, even though this specific site, to our knowledge, is the only such site with any environmental data currently available, and also helps understanding of potential environmental threats.

Freshwater pond temperatures remained below air temperature and displayed less diurnal variation, as would generally be expected due to the heat capacity of the contained water (Peck 2004; Peck et al. 2006). At the Large permanent pond this was likely due to the large thermal mass of the water body. Small ponds in the Antarctic have been shown to achieve summer temperatures greater than that of the air through absorption of solar energy by dark benthic substrata or microbial mats (Peck 2004). However, the Small temporary pond is fed for a large part of the early summer by melt water from a receding snow patch. This constant input of cold water likely holds this pond's temperature low despite the extended insolation experienced during the period of the midnight sun.

In the Antarctic, similar to the Arctic sites, winter temperatures were decoupled from air at three of the locations, indicating the presence of a significant snow cover. The exception to this generalization was at the Antarctic polar desert, where ground temperature fluctuations remained strong throughout the winter, indicating that snow cover was limited in extent. This site is depicted in Online Resource 2 at mid-winter (1 June 2007) when it exhibited only a thin and patchy snow cover. The temperature profile for the Exposed hill summit presented in this analysis (year 2009) matches very closely the data of Davey et al. (1992) from the same site recorded 22 years previously (1987).

It is consequently clear that, while summer ground conditions can be imprecisely estimated from air temperatures - with an understanding of the ground surface and prevailing insolation/cloudiness - there is very great heterogeneity between sites and local site characteristics play a large role. Linking patterns of temperature variation with biological consequences, however, introduces further complexity. For instance, maximum and particularly minimum temperatures, for example lower and upper thermal death points, may have more biological significance than the daily or monthly means often used to present weather and climate temperature data. Neither has the ability of fauna to move and find the most favourable thermal regime within particular microhabitats been fully taken into account (Woods et al. 2015). Moreover, once snow cover has begun to accumulate, and despite the presence of permafrost and the polar night, the uncoupling of the ground from the air results in rather mild sub-nivean conditions where temperatures typically are between – 5 and − 15 °C, and sometimes closer to 0 °C (see review of Convey (1996) relating to all Antarctic regions, and compare with Heilbronn and Walton (1984) for sub-Antarctic South Georgia, Davey et al. (1992) for maritime Antarctic Signy Island, or Convey et al. (2014a) for Svalbard). At such temperatures, microbial and even invertebrate activity remains possible (West 1982; Schmidt 1999; Larsen et al. 2002; Cooper 2015), stored resource depletion through measurable respiration certainly occurs and, where even low levels of light penetrate the snow layer, photosynthesis can occur (Schroeter et al. 2011). In contrast, in areas such as the Antarctic polar desert with no, or thin, winter snow accumulation, the ground may be substantially colder. Here ground temperature declined to a winter minimum of − 38.2 °C during the study period.

Length of summer thawed season in the ground

The duration of the summer period that the ground surface experiences is largely dependent on the snow-free period, though it should again be noted that some processes, such as significant soil microbial and invertebrate activity, may occur under snowpack at high sub-zero temperatures, as may photosynthesis. Thawing at the soil surface may effectively lead to a small 'greenhouse' space under snow cover, allowing physiological and ecological activity in soil microbial, invertebrate and plant communities (Aitchison 1979; Cockell and Cordoba-Jabonero 2004; Pauli et al. 2013; Cooper 2015). The duration of the summer thawed period is controlled by many factors including precipitation quantity, wind redistribution of fallen snow, and rate of melt during the spring thaw. For the Svalbard sites, the date of ground release from snow was consistently after the beginning of the period of midnight sun (around 19 April in Svalbard) and varied by 35 days across the study sites, resulting in a "summer" some 1.6 times longer in duration at Dryas tundra than at the northernmost Arctic polar desert.

Great inter-annual variation in the length of the summer period, as defined by the snow-free season, occurs at very small spatial scales, for example in the pattern and rate of melting around the edges of permanent snow patches. Such variations in duration of the summer active period clearly have direct biological relevance and impact both to native communities (Ávila-Jiménez and Coulson 2011) and, of particular relevance today, to non-native species that are increasingly being introduced to parts of the polar regions (e.g. Hughes et al. 2013).

Changes in precipitation, especially during the winter season, are projected by many climate models but are hard to estimate with accuracy (ACIA 2004; SWIPA 2011) and will be site-specific. However, it is clear that environmental changes that result in either more rapid, or delayed, spring snow clearance will have a potentially dramatic influence on ground/sub-surface ecosystems through modulating the duration of the snow-free season and the warming or cooling of the ground (Ávila-Jiménez and Coulson 2011; Cooper 2015). An exception to the general observation that mean daily air temperatures were above 0 °C for a greater proportion of the year than those of the ground is that of the Anthropogenic soils in Barentsburg. These soils had a temperature mean > 0 °C for 271 days. This unusual situation results from the deep organic soils probably generating some heat through decomposition processes, combined with insulation from dense plant cover and the deep accumulation of snow in the gully that forms this site (Coulson et al. 2013a, b).

Timing of ground freeze–thaw events

Snow cover had a clear effect on the frequency of freeze–thaw events experienced by the ground surface. Air temperatures in Svalbard displayed numerous freeze–thaw events in both spring and autumn, but freeze–thaw events only occurred in the ground during the autumn, and then only before snow cover accumulated. Spring ground temperatures at the Svalbard locations revealed a very characteristic profile as the snow pack and underlying soils warmed to become isothermal at close to 0 °C, but then remained stably frozen for up to 36 days. The snow pack finally melted in late May or early June, exposing the ground to 24 h insolation which commences, at the latitude of Longyearbyen (78° 13′ 14″N, 15° 37′ 59″E), on 20 April and lasts until 23 August.

Solar forcing then raised the ground temperature rapidly by c. 6 °C, with only small diurnal temperature variation, and no freeze–thaw events being recorded either in the air or the ground. The situation was different at the lower latitude maritime Antarctic sites where, at all locations, freeze–thaw events were common in spring, summer and autumn. The lower latitude location of the maritime Antarctic sites also results in a shorter (Alexander Island, Anchorage Island), or non-existent (Signy Island), period of midnight sun. These sites therefore experience a greater diurnal variation in the degree of solar forcing of ground temperatures and exhibited a greater frequency of ground freeze–thaw events than in High Arctic Svalbard.

Under current climate modelling scenarios and projected warming, the frequency of freeze–thaw events is expected to increase at polar latitudes (ACIA 2004; Turner et al. 2009; SWIPA 2011; Turner et al. 2014). At the Antarctic sites considered here, given the evidence for relatively limited winter snow cover/depth, this may result in increased frequency of freeze–thaw events. But, while an increase in freeze–thaw events in the air may be anticipated in the Arctic, this might not translate to an increased frequency of such events in the ground and sub-surface layers, due to the presence of considerable snow cover in spring with ground release well after the period of the midnight sun has commenced. Most laboratory studies of the consequences of freeze–thaw events on organisms focus on the impact of a single event. However a few studies (e.g. Bale and Hayward 2010) have emphasized that the cumulative effect of multiple events may have greater biological relevance and cost.

Rates of ground temperature change

The rates of temperature change in soils were generally slow, often as little as 0.03 °C h^{-1}, and even with solar forcing only realizing a peak value of 1.8 °C h^{-1}. While more rapid rates do occasionally occur these are often exceptions associated with the arrival of warm moist air masses from lower latitudes (Førland et al. 2011) or Föhn winds. Such warming was particularly rapid when associated with the warm southerly air masses bringing rain-on-snow events at the Arctic sites. In such circumstances, rain percolates through the snow pack to freeze on the ground surface, which both warms the ground surface rapidly, as seen at the Dryas tundra in 2011, but also creates a surface ice lens (Putkonen and Roe 2003). Such surface icing can have significant detrimental biological effects, often leading to high overwintering mortality in reindeer (Kohler and Aanes 2004; Hansen et al. 2014) and soil invertebrates (Coulson et al. 2000), as well as anoxia at the soil surface. These observed cooling rates bring into question the suitability and biological relevance of faster rates, typically between 0.1 and 1 °C min^{-1}, widely employed in experimental studies of invertebrate cold tolerance (Convey and Worland 2000; Worland and Convey 2001). Site-specific and small-scale characteristics may also clearly have an important influence on ground temperatures across the study locations (*cf.* Lenoir et al. 2017).

Accumulated thermal sum in the ground

Cumulative degree days above 0 °C (CDD) represent the total thermal sum accumulated. When measured in an appropriate biologically relevant context they provide a measure of 'physiological time' that has utility in, for instance, modelling invertebrate life cycles and their responses to changes in local micro-environmental conditions (e.g. Arnold and Convey 1998; Hughes et al. 2013). The accumulation of CDD in the air commenced earlier than at the ground surface at all sites but, at most sites, the ground surface CDD rapidly overtook that of the air, clearly demonstrating the importance of solar forcing on the heat sum of the ground and sub-surface. The Arctic polar desert, Small temporary pond and Large permanent pond provided exceptions to this generalization, again likely due to site-specific features reducing the opportunity to accrue CDD. The Antarctic sites showed a dramatic increase in ground CDD compared to air, up to almost 500% greater, likely due to early release of the ground from snow cover, low air temperatures, and greater solar forcing due to their lower latitude locations and consequent higher elevation of the sun. Reduced cloud cover may also have a role at some sites enabling greater solar forcing of the ground.

Conclusions

It is apparent that polar ground surfaces are highly heterogeneous, and that the thermal environment is site-specific and can differ greatly over a landscape scale. Air temperature is often a poor predictor for ground and sub-surface thermal conditions. This also highlights the local character of the surface exchange processes between the atmosphere and land. For the flora and fauna living in these regions it is the ground and sub-surface temperatures and the patterns of their variation—the microhabitat—that is of greater significance than air temperatures per se. This emphasizes the importance of determining the thermal regimes of these layers and evaluating the ability of air temperatures to adequately describe ground conditions.

The data presented are representative of the thermal microclimates in a range of surface types in polar regions where such data are often difficult to obtain, and provide a context into which polar studies can be placed. Access to such data is currently very limited in the available literature. It is clear that the ecology and the responses of the flora and fauna of polar regions to projected climate change cannot be adequately understood without a better knowledge of landscape habitat temperature heterogeneity at a range of spatial scales, or be effectively predicted from projected gross regional shifts in atmospheric temperature norms. Moreover, features such as maximum and minimum environmental temperatures, or rates of change, may have a greater biological significance than the means frequently applied to describe the climate of a region.

There is an urgent requirement for biologically relevant long-term ground and sub-surface datasets by which to better understand how climate variability and change affects different ground surface types in order to comprehend the resilience, or vulnerability, of their associated biological communities to change. Initiatives such as ANTOS are setting out to establish a continental-scale network of observing stations across Antarctica and the sub-Antarctic islands to provide robust, long-term and biologically relevant descriptions of both microclimates and key biological processes. Similarly, at Zackenberg in north-east Greenland, long-term monitoring of aspects of terrestrial environmental variables is recognized as being key to unravelling biological responses to environment and change (Jensen et al. 2016).

It remains a reality that many studies that require or take advantage of environmental data will be designed based on the specific needs of each particular short-term study and the constraints of the supporting funding agency and process. However, to address the continuing and fundamental gap in ability to link biological processes and environmental conditions at relevant temporal scales in polar (and alpine) regions, we urge the development of long-term monitoring programmes using standard stations recording a suite of biological and physical environmental variables across a representative range of habitats and geographical areas, such as proposed by ANTOS.

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