Implications of annual and shorter term temperature patterns and variation in the surface levels of polar soils for terrestrial biota.

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Abstract

Ground surface and sub-surface temperatures in the top few centimetres of the soil profile are key in many environmental processes. They can vary greatly seasonally and at various spatial scales across the often highly complex and heterogeneous landscapes of the polar regions. Hence it is challenging to extrapolate these temperatures from meteorological air temperature records. Ground surface and sub-surface thermal conditions are vital to the flora, fauna, microbial activity, geochemistry, and physical characteristics such as the surface energy budget. It is clear that the responses of the soil-associated biota of these regions to projected climate change cannot be adequately understood without improved knowledge of how landscape heterogeneity affects ground and sub-surface biological microclimates. Such data are also important for determination of the surface energy budget and turbulent exchange processes between the air and the land. Yet, few temperature data sets exist from these soil surface layers of soils in the polar regions, especially over longer timescales.

Multi-annual temperature records from 20 sites representing a range of High Arctic and maritime Antarctic ground surface and sub-surface soil habitats are described. We highlight that (a) summer ground and sub-surface temperatures vary much more than air; (b) winter ground temperatures were uncoupled from atmospheric temperatures; (c) the ground thawing

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period may be considerably shorter than that of positive air temperatures; (d) ground freeze-thaw patterns differed between Arctic and Antarctic; (e) rates of ground temperature change were generally low; (f) accumulated thermal sum in the ground usually greatly exceeded air cumulative degree days.

Key words

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 be under 0°C and only achieve positive daily values 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 on occasion (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). These temperatures play a central role in polar 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). 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).

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

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atmospheric stratification. Exposed ground surfaces absorb solar radiation during the summer period and, consequently, short-term temperatures may rise well above that of the air (Migała et al. 2014). 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 subsurface temperatures may consistently be well above the generally low air temperatures as well as experiencing greatly reduced fluctuations (Convey et al. 2014; 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; Rautio et al. 2011; Toro et al. 2007). 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. 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 subsurface 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. Christiansen et al. 2010; Guglielmin et al. 2008, 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 location 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, 2013; Migała et al. 2014),

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although long-term environmental manipulation studies usually include data from control sites (e.g. Bokhorst et al. 2013), providing another source of relevant information.

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 modeling 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 2015), but currently remain relatively coarse and operate at 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 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, 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 with probable ground surface or microhabitat temperature trends. 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

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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. 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 (South Orkney Islands, Marguerite Bay and Alexander Island) 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 to other regions within the Arctic and Antarctica, 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

<u>Arctic</u>

The Svalbard archipelago 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 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 the islands is mild for their latitude - the annual mean air temperature at

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Svalbard airport is –6.7°C, but four 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 (Jonsdóttir 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 Supplementary Table 1, and illustrative photographs in Supplementary Fig. 1a,b.

Antarctic

The four Antarctic sites were selected to represent a range of habitats within the full latitudinal range of the maritime Antarctic (Fig. 1a; Supplementary Fig. 1c): *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) (Supplementary Table 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 1,200 m high mountain barrier of central Coronation Island to the north. Frequent 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* (Coal Nunatak, site Q), and *Antarctic polar desert* (Mars Oasis, site R) (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

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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 habitat forms selected to be representative of the range of the terrestrial and freshwater surfaces and habitats occurring in the High Arctic and the maritime Antarctic (Supplementary Table 1, Supplementary Fig. 2a,b,c,). Because, as is often the case with currently available biological microclimatic datasets, the loggers were deployed within different studies and monitoring programs over time, they represent several, and in some cases non-overlapping, years. Logistic and technical difficulties are a particular problem in servicing stations at remote and un-manned sites such as these, with the result that there are occasional data missing from various intervals during the campaign periods. The microclimate temperature data considered in this article are provided in spreadsheet form in Supplementary Table 2.

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 thermister 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 Supplementary Table 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.

Standard meteorological air temperatures were taken from Norwegian Meteorological Institute stations (www.eKlima.no). 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 presented in Supplementary Table 1 and Fig. 1c.

Antarctic

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Ground and air temperatures were recorded using temperature probes (copper/constantan thermocouple wires) (HMP45C; 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 and Discussion

To demonstrate the potential utility of these datasets, we here describe them and present six aspects of overview observations and interpretations arising which are pertinent to the biology, meteorology and geomorphology at the studied locations. We do not attempt to analyse each location dataset in detail but provide summary descriptive statistics (Table 1a, b). The full datasets are provided in Supplementary Table 2, to enable access and permit individual detailed analyses to be performed as required.

Observation 1: air temperatures show the greatest range during the winter months.
Annual air temperature at Svalbard airport (2011) (Longyearbyen, Fig. 2a) was -3.3°C. Maximum and minimum air temperatures at this location ranged between -31.5 and +17.1°C (Table 1a, Fig 2a). The summer period showed the minimum range in temperature extremes. At Svalbard airport summer temperatures did not decline below 0°C. During other seasons air temperatures regularly fluctuated between positive and negative values (freeze-thaw events) especially in spring and autumn. Mean monthly temperatures varied between a winter minimum of -15.2°C in January and a summer maximum of +6.9°C in July and August.

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 1a, Fig. 2a), illustrating the effects of the different ocean currents and air masses influencing regions of the archipelago (Coulson et al. 2014; Przybylak et al. 2014). The more continental Sveagruva, located at the head of van Mijenfjord, recorded intermediate values. Although air temperatures on the far north coast of Svalbard at Crozierpynten and Rijpfjord were often lower than those at Svalbard airport, 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. Freeze-

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thaw transitions in air temperature were common at all locations but particularly frequent at Rijpfjord, where 31 cycles were recorded in 2011. Crozierpynten, located approximately 110 km south-west of the Rijpfjord station, experienced 27 freeze-thaw events. On the west coast, freeze-thaw events were less frequent but still numbered over 20 per year at all sites. These events occurred most frequently in the spring period, particularly in May and June. However, they could occur at all times of the year, for example as observed at Rijpfjord.

Air temperatures at the four Antarctic sites (Table 1a, Fig. 2b) varied between locations. *Lichen fellfield* (2007) and *Exposed hill summit* (2009) were generally similar despite being separated by eight degrees of latitude. Mean annual temperatures were greatest at *Exposed hill summit* with an annual mean of -3.9°C (2009). 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 a large number of freeze-thaw events (130 annually). The *Lichen fellfield*, with a slightly lower mean annual air temperature of -4.4°C, experienced fewer freeze-thaw events (98). Both sites had fewest freeze-thaw events in the austral summer and the greatest frequency in the winter period, in clear contrast to the Arctic sites. 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*, although temperature data for mid-winter are missing. For months with comparable data, *Cryodisturbed terrain* was consistently colder than *Exposed hill summit*, 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, with a mean annual air temperature of -10.6°C. Summer temperatures were similar to the other Antarctic locations, but the minimum winter mean monthly temperature was -24.7°C (July). Despite the low annual temperatures there were a high number of freeze-thaw events (100), peaking in December.

Observation 2: summer ground temperatures mirror air temperature fluctuation but with greater range and higher peaks due to solar forcing. Winter ground temperatures are uncoupled from air temperatures due to insulation by snow and ice cover and display milder, and more constant, temperatures.

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During the summer period, upper ground temperatures followed largely similar profiles to air temperatures (Table 1, Figs. 3, 4) but often attained greater monthly mean, maximum and minimum temperatures than those of the air. For example, while the Svalbard airport July 2011 mean air temperature was +6.9°C with maximum and minimum temperatures of +13.3° and +2.4°C respectively, at the *Dryas tundra* the mean ground temperature was +8.3°C with a maximum of +18.6°C and a minimum of +4.7°C (Figs. 3a, 4a, Table 1a, b). This was typical for all of the Arctic locations. However, while the daily pattern of air temperature fluctuations was mirrored in the ground temperatures during the summer, in winter uncoupling was evident. Temperature fluctuations reflected those of the air closely until the late autumn. After this point ground temperature was often significantly greater than corresponding air temperature and displayed reduced daily fluctuation. The *Dryas tundra*, for instance, had a mean monthly ground temperature in February of -11.1°C with a maximum of -7.1°C and a minimum of -13.9°C, compared to respective air temperatures of -12.7, +4.5 and -29.9°C (Table 1a, b). Winter ground temperatures remaining above mean air temperatures and with lessened variability was a common observation across the sites.

Several Arctic locations showed site-specific ground temperature features. Maximum summer temperatures were experienced in *Cliff fissure*, where +31.8°C was recorded in July but, throughout the summer, minimum monthly temperatures were close to 1°C (Table 1b). The coldest 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 (Table 1a), winter ground temperatures at Rijpfjord rarely declined below -10°C (Table 1b, Fig. 4). *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 remained often 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 were mild and more constant, with damped fluctuations compared to air temperatures (Fig. 4b, Table 1a, b).

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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, the *Exposed hill summit* experienced a long period close to 0°C during the spring thaw, in this case 32 days (Fig. 4c). As with air temperature, the *Antarctic polar desert* experienced the most extreme ground temperature regime. Ground temperature declined to a minimum of -47.5°C at mid-winter (July) and reached a summer maximum of only +8.6°C (Table 2b, Fig. 4c). Mean annual air temperature at this site was -10.6°C and only 1-2 months had positive mean temperatures. *Cryodisturbed terrain* had a similar temperature profile to the *Antarctic polar desert* but data were missing for mid-winter. At the *Lichen fellfield*, the annual mean ground temperature was -2.8°C. The annual ground temperature profile resembled that of the *Dryas tundra* habitat in the Arctic, with three months experiencing positive mean temperatures and maximum and minimum daily temperatures of +21.9 and -16.4°C. Additionally, the ground temperature profile displayed a similar warming pause where, during the spring melt, the ground took 8.6 days to warm from -1.0°C to above 0°C. 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. While the *Exposed hill summit* had an extended warming pause (15.5 days to warm from -1°C to become positive) there was no equivalent pause during cooling in the autumn.

<u>Interpretation</u>

Ground temperatures in the Arctic are clearly influenced by seasonal variation in air temperatures. During the summer periods, all ground and water temperatures presented here mirrored air temperatures to a greater or lesser extent. The solar forcing and the low albedo of the ground surface results in an unstable stratified atmospheric boundary layer, elevated ground temperatures and cumulative degree days (0°C baseline) (Fig. 5, Table 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 (Table 1a, b) 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 insulating effect of winter snow cover is well appreciated (Leinaas 1981; Cooper 2015), insulation efficiency

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varying with snow depth and form. More recently Convey et al. (2014) observed 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 this site, soil temperatures declined gradually through the winter, reaching a minimum of -12.3°C during the campaign period. However, there were exceptions to this pattern, such as the spike in ground temperature noted at *Dryas tundra* on March 17 2011 (Fig. 4a), 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 two-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.

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Freshwater pond temperatures remained below air temperature and displayed less diurnal variation. 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 (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 the pond temperature low despite the extended insolation experienced during the period of the midnight sun.

In the Antarctic, ground temperatures also reflected those of the air. 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 generalisation 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 Supplementary Fig. 1c 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). Here the summer temperatures peaked at approximately +17°C, with winter minima of -8°C. Furthermore, Davey et al. (1992) present snow depth data indicating a peak depth of 80 cm in July (austral winter).

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 site heterogeneity. Maximum and particularly minimum temperatures, for example lower and upper thermal death points, may have more biological significance than the 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 to -15°C, and sometimes closer to 0°C (compare with Convey et al. 2014). 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.

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Observation 3: the thawed summer season in the ground may be considerably shorter than the period of positive air temperatures due to the timing of release from snow-ice cover. 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. 4, Table 1a, b). The number of days with a mean temperature above 0°C was generally greater in the air than for the soil surface. For example, while Svalbard airport recorded 151 days with a mean daily air temperature above 0°C, at the *Dryas tundra*, only 8 km distant and in the same valley system, only 120 such days occurred in the ground and sub-surface (Table 1a, b). Similarly, while air temperature in Svalbard became positive in late April/early May, ground and sub-surface temperatures only started to accrue degree days later in spring towards the end of May or early June. The *Cliff fissure* was the first location to thaw, with temperatures rising above 0°C from 30 May, and the latest was *Arctic polar desert*, where ground and sub-surface temperatures only became positive after 6 July (julian day 187) (Fig. 4). During the spring period ground temperatures showed an initial tendency to warm to close to 0°C, remain stable for a period and then climb rapidly to track air temperature fluctuations (Fig. 3a, b). For example, ground temperature at the *Dryas tundra* warmed from a mid-winter minimum of -17.7°C to reach -1.5°C on 25 April, then remained between -0.2 and -3.3°C until 31 May when it first became positive (Fig. 3a). Daily mean ground temperatures at the *Dryas tundra* then remained above 0°C for 120 days (Table 1a). At the most northern site, *Arctic polar desert*, ground surface temperatures first became positive around 5 July in 2008 (julian day 186), some 35 days later than at the more southern *Dryas tundra* (Table 1a, Fig. 4). Moreover, the *Arctic polar desert* ground also began to freeze earlier in autumn, providing a thawed period of only 74 days. Ground freezing at the *Dryas tundra* commenced on 19 September, although the site continued to experience periods of positive temperatures until 29 November, after which point there was no further accrual of degree days (Figs. 3a, 4). At the *Arctic polar desert*, ground temperatures dipped below 0°C for the first occasion in the autumn on 29 August. Again, some temperature cycling followed, but temperatures were constantly below 0°C after 24 September. For most Arctic sites the winter period (ground permanently frozen) typically commenced in early October (Figs. 3a, b, 4).

In the Antarctic the first site to attain positive ground temperatures was the southern *Antarctic polar desert*, on 14 November 2012, followed by *Lichen fellfield*, *Cryodisturbed terrain* and *Exposed hill summit*, the latter finally thawing on 20 December (Fig. 3c). Due to the large number of freeze-thaw events at the Antarctic sites throughout the year (Table 1b) the precise

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date of the end of the winter freeze is more difficult to define precisely. However, an estimate can be obtained by taking the first date that temperatures remained constantly above normal summer freeze-thaw fluctuations (-3°C). Likewise, it is difficult to identify a clear-cut date for the onset of the winter freeze due to frequent freeze-thaw events. However, the Antarctic soils began to freeze in February, with *Exposed hill summit* on 2 February, and finally *Lichen fellfield* on 27 February. Soils were constantly frozen from March, this point being reached at the *Cryodisturbed terrain* site on 8 March followed by *Antarctic polar desert* (10 March), *Exposed hill summit* (29 March) and finally *Lichen fellfield* on 6 April (Fig. 3c). Despite the lower latitude locations of these Antarctic sites (60-72°S), their unfrozen summer periods were similar in duration to those at the High Arctic locations at 78-80°N, with periods ranging from close to 100 days (Jane Col, Coal Nunatak and Mars Oasis) to a maximum of 120 days (Anchorage Island). These observations, again, highlight the general lack of any clear influence of the wide (c. 12 degrees of latitude) latitudinal range of these sites across the maritime Antarctic. However, while in the Arctic the unfrozen period had very precise boundaries, this was not the always the case in the maritime Antarctic, particularly at the most southern *Cryodisturbed terrain* at Coal Nunatak and *Antarctic polar desert* at Mars Oasis, where multiple freeze-thaw events blurred the seasonal end points due to a lack of, or at most thin, snow cover (Fig. 3c). The pattern of thawing at the other two maritime Antarctic locations featured long pauses in ground warming, taking between 15.5 (*Exposed hill summit*) and 8.6 days (*Lichen fellfield*) to warm from -1°C to above 0°C, suggesting the presence of a thicker snow cover and similar thawing process to that observed at many of the Arctic sites.

Interpretation

The duration of the summer period that the ground surface experiences is largely dependent on the snow free-period, though it should be noted that some processes, such as significant soil microbial activity may occur under snowpack at high sub-zero temperatures (Schmidt 1999; Larsen et al. 2002; Cooper 2015), as may photosynthesis in some polar lichens (Schroeter et al. 2011). 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 et al. 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 High Arctic sites, the date of ground release from snow was consistently after the beginning of the period of midnight sun (around 19 April in Svalbard)

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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. An example is provided by the timing of the break of the stem of a distinctive champagne-glass-shaped snow patch on Operafjellet close to Longyearbyen (Svalbard) (Fig. 5a). Voting to predict the date the stem ‘breaks’ has been a popular competition in the local community, and the date the snow patch clears has been carefully noted from at least 2004. During this 11 year period the date the ground under the “stem” has been released from snow and ice has varied between 28 June (2005) and 31 August (2012) (Fig. 5b), with a median date of 19 July (julian day 201). Clearly the date this particular patch of ground clears will be dependent on multiple micro- and macro-scale environmental variables such as snow accumulation (itself dependent on multiple variables), icing, sunshine or cloudiness, and air temperature. Nevertheless, this example integrates these variables to demonstrate at a specific location the potential extent of inter-annual variation in date of snow clearance and the resulting duration of the summer period. Such variations in duration of the thawed summer period have consequences for the flora and fauna (Ávila-Jiménez and Coulson 2011).

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 the environmental changes that result in either more rapid, or delayed, spring snow clearance will have a potentially dramatic influence on ground/sub-surface ecosystems via modulating the duration of the snow-free season and the energy budget 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. Here the soils had a temperature mean of greater than 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).

Observation 4: in the High Arctic ground freeze-thaw events only occur in the autumn. At the lower latitude sites in the Antarctic freeze-thaw events also occurred in the spring.

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In contrast to the occurrence of freeze-thaw transitions in air temperature in both spring and autumn at the Arctic sites, soils only experienced such cycling in the autumn (Table 1a, b, Figs. 2a, b, 3a-c). At the *Dryas tundra*, for instance, although the ground surface temperature was between -3.3 and -0.2°C for 36 days in spring 2011, no freeze-thaw events occurred (Table 1b, Fig. 3a). In the autumn, the same site had its only two such events in September 2011 (compared to a September ground count of five and an annual sum of 60 in the air) (Tables 1a, b, Fig. 2a). The *Arctic polar desert* also did not experience freeze-thaw events during the spring melt period (Table 1a, Fig, 3a) while nine such events occurred during the autumn freeze and there were 47 freeze-thaw transitions in the air during the nine months the meteorological station on Nordaustlandet (Rjipfjord) was functioning. The single exception to the pattern of freeze-thaw events in the ground being absent in the spring was at the *Cliff fissure*, which experienced events in both the spring and autumn and had the greatest event frequency (21 events in 2008-09) of all the ground sites.

The *Large permanent pond* exhibited no freeze-thaw cycles either in autumn or spring. Water temperature decreased during the autumn and freezing commenced on 3 October and then took a further 20 days to decline to -1°C. Temperatures rose gradually in spring reaching -1°C on 17 May, but took an additional four weeks to attain +1°C (18 June). The *Small temporary pond* (O) displayed one freeze-thaw event in 2011. This was probably associated with the drying of the pond later in summer.

In contrast, the Antarctic sites all showed extensive freeze-thaw cycling in the ground surface during both spring and autumn periods, with between 51 and 91 such events being recorded. Freeze-thaw events also occurred in the ground during the winter period (Fig. 3c, Table 1b). The maximum frequency was seen at the *Antarctic polar desert*, with 15 cycles in the autumn, 64 in winter and 12 in spring. None of the Antarctic locations experienced freeze-thaw events in the summer months.

<u>Interpretation</u>

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 before a snow cover had accumulated. The only exception to this pattern was the *Cliff fissure*, a site where snow cover was absent throughout the year due to the vertical nature of

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the cliff (Supplementary Fig. 1b). At the other locations in the Arctic, spring ground temperatures 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 the 24 h insolation of the midnight sun 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 both spring and autumn, and even in winter at sites where there was lower overall snow accumulation and thermal protection (Fig. 3c, Supplementary Fig 1c). 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 the High Arctic.

Under current climate modeling scenarios and projected warming, the frequency of freeze-thaw events is expected to increase at low polar latitudes (ACIA 2004; SWIPA 2011; Turner et al. 2009, 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.

3.5 Observation 5: rates of ground temperature change were generally low; amongst the fastest rates of change occurred during the winter associated with rain-on-snow events.

Ground and sub-surface temperature generally displayed slow rates of change during the summer. For example the *Dryas tundra* showed a peak warming rate of 1.8°C hr^{-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 hr^{-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 (Fig. 3b, Table 1b). At 2230 the

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temperature was still above +30°C while, three hours later, it had decreased to +19.7°C, a rate of 3.5°C hr^{-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 hr^{-1}), on 23 July 2008.

Ground temperatures were often constant during winter and spring periods, or showed only limited temperature fluctuation, with rates of change rarely greater than 0.1°C hr^{-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 (Fig. 3a), where they remained until 1800 on 18 March, after which they started to decline 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 hr^{-1}, respectively. By contrast the *Large permanent* and *Small temporary* ponds showed only slow rates of temperature rise due to the greater specific heat capacity of the water masses. Similar patterns were reported in freshwater pools on Anchorage Island in the Antarctic by Peck (2004).

The *Antarctic polar desert* ground and sub-surface temperature fluctuations were also large and rapid, particularly in winter (Fig. 3c). 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 hr^{-1}. The temperature subsequently cooled to -14.8°C over 10 h, a cooling rate of 1.5°C hr^{-1}. Similar magnitude temperature swings were evident at the other maritime Antarctic sites but at slower rates.

Interpretation

The rates of temperature change in soils were generally slow, often as little as 0.03°C hr^{-1}, and even with solar forcing during the period of the midnight sun only realizing 1.8°C hr^{-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 (*Exposed hill summit*). Such warming was particularly rapid when associated with these warm air masses bringing rain-on-snow events. 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

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invertebrates (Coulson et al. 2000), as well as anoxia at the soil surface. These observed cooling rates bring into question the suitability of faster rates, typically between 0.1 and 1°C min^{-1}, widely employed in invertebrate overwintering and cold tolerance studies.

Site-specific characteristics may also have an important influence on ground temperatures. The *Cliff fissure* was situated on a south-westerly facing cliff and was free of snow cover throughout the winter. During the period of the polar night, temperatures in the fissure closely followed variation in air temperature. However, after the return of the sun, and direct solar insolation onto the cliff face, the cliff temperatures began to display pronounced diurnal variations with the face warming up considerably during the afternoon and early evening. Similarly, the thermal mass of the freshwater sites largely eliminated diurnal, or rapid, temperature fluctuations (*cf.* Peck 2004; Peck et al. 2006).

Observation 6: accumulated thermal sum in the ground usually greatly exceeded the equivalent air cumulative degree days (CDD); however, this was site-specific and, on occasion, air CDD could surpass ground surface

Cumulative temperature sums (degree days above 0°C) in the air and ground were substantially different at all sites (Fig. 4). As noted above, the ground warmed above 0°C later in the year than the air due to late release from snow and ice cover. However, once ground warming had commenced, the ground temperature often rose quickly above that of the air. For example, the thermal sum of the *Dryas tundra* ground lagged behind that of the air until 13 June but then reached a maximum value on 27 September at 786 degree days, some 4.4% greater than the comparable air temperature sum (Table 2). A similar overall pattern, but greater response, was observed at the *Cliff fissure*, which started to accumulate degree days on 30 May and accrued a greater thermal sum more rapidly than air temperature during the period the loggers were operating in 2008 (Fig. 4). This pattern was repeated at many of the other locations (Fig. 4, Table 2). 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 acquired was less than at the Arctic locations, often only between 300 to 450 degree days compared to the 700 and above that were common High Arctic Svalbard. The differences between the thermal sums of the air and

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the ground were more pronounced, with ground temperatures warming rapidly and remaining constantly above air temperature (Table 1b, Figs. 2b, 4). *Lichen fellfield* accumulated 403 degree days compared to an air sum of 67, a ground gain of almost 500% relative to the air (Fig. 4, Table 2).

<u>Interpretation</u>

Cumulative degree days above 0°C (CDD) represent the total thermal sum accumulated. The CDD in the air commenced earlier than at the ground surface at all sites but, with the exception of the *Arctic polar desert*, 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 generalisation. At the former, snow clearance was late in the summer with a consequential delay in the accumulation of ground CDD. By late summer, and despite the period of the midnight sun extending until the end of August in Svalbard, the elevation of the sun is constantly low and the extent of solar forcing declines, resulting in a reduced accumulation of CDD and the surface at this site failing to accrue a similar, or greater, CDD sum as that of the air. The ice cover of the *Small temporary pond* melted in early to mid-June but the pond continued to be fed by snow melt. Consequently the water temperature remained low, only occasionally exceeding +8°C, and the thermal sum lagged behind that of the air. 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 the low lower latitude location 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 – the microhabitat – that is of greater significance than air temperatures *per se*. This emphasises the

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importance of determining the thermal regimes of these layers and evaluating the ability of air temperatures to adequately describe ground conditions.

The data presented here provide representative descriptions of the thermal microclimate 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. It is patently 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 or be effectively predicted from projected gross regional shifts in atmospheric temperature norms. Moreover, maximum and minimum environmental temperatures may have a greater biological significance than the means frequently applied to describe the climate of a region. Therefore, there is a requirement for biologically-relevant long-term ground and sub-surface datasets by which to better understand how climate variability and change affects the assortment of ground surface types in order to comprehend the resilience, or vulnerability, of their associated biological communities to change.

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Table 1a. Summary air temperature figures for a representative year at sites on Svalbard and the maritime Antarctic (see Fig. 1 for locations). F-T=number of freeze-thaw events per month; Days μ T > 0°C=number of days mean daily ground temperature above 0°C; *=year summarised.

Site		**Winter**		**Spring**			**Summer**			**Autumn**			**Winter**		**Days > 0°C**	**Entire dataset**
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		
ARCTIC																
Svalbard Airport	Mean	-15.2	-12.9	-12.8	-6.0	-1.6	4.8	6.9	7-0	4.4	-2.6	-6.0	-6.5	-3.3	151	-
*2011	Maximum	3.6	3.7	3.5	2.7	5.0	11.4	11.8	16.8	9.7	3.9	5.4	2.6	16.8	-	16.8
	Minimum	-29.9	.28.4	-25.7	-22.6	-7.7	1.2	3.1	2.1	-1.1	-12.3	-15.7	-18.7	-29.9	-	-30.5
	F-T events	1	1	2	3	3	0	0	0	2	4	2	3	21	-	-
Ny-Ålesund	Mean	-13.8	.10.8	-12.8	-5.4	-2.1	3.7	6.3	5.8	3.0	-3.4	-6.8	-6.9	-3.6	139	-
	Maximum	1.6	3.2	3.9	4.6	4.8	7.7	9.8	12.5	8.1	5.0	6.5	1.9	12.5	-	13.2
*2011	Minimum	-26.1	-26.4	-23.9	-20.4	-8.4	-0.4	2.0	1.1	-4.6	-12.7	-17.9	-18.1	-26.1	-	-26.4
	F-T events	1	1	3	3	3	3	0	0	3	3	3	2	25	-	-
Kapp Heuglin	Mean	-19.0	-15.7	-14.3	-8.9	-4.3	0.0	2.1	2.4	2.2	-2.7	-6.3	-11.3	-6.2	113	-
	Maximum	0.7	2.7	3.7	3.0	3.8	4.4	9.5	7.3	6.8	3.3	3.2	-1.0	9.5	-	12.7
*2011	Minimum	-35.1	-30.8	-26.9	-21.0	-12.0	-3.8	-0.9	-0.9	-1.7	-12.3	-16.3	-28.8	-35.1	-	-43.9
	F-T events	1	2	2	3	4	10	1	2	1	4	3	0	33	-	-
Sveagruva	Mean	-17.3	-14.1	-14.9	-7.2	-2.8	3.7	6.0	5.5	3.7	-2.8	-7.1	-9.4	-4.6	141	-
	Maximum	3.0	3.4	2.3	3.0	3.7	8.9	10.7	10.8	8.0	3.2	4.5	0.3	10.8	-	14.1
*2011	Minimum	-32.0	-32.4	-31.8	-28.7	-11.6	-0.8	2.3	1.2	-1.2	-13.0	-21.6	-27.6	-32.0	-	-36.5
	F-T events	1	2	2	3	6	1	0	0	1	5	5	2	28	-	-

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Sørkappøya	Mean	-14.0	-11.8	-9.1	-4.8	-2.2	1.0	2.0	3.2	3.3	-0.6	-3.0	-4.7	-3.3	154	-
	Maximum	1.7	2.3	3.1	2.3	1.7	4.6	5.4	6.4	5.8	4.0	3.4	0.5	6.4	-	8.6
*2011	Minimum	-27.1	-23.5	-23.5	-15.6	-8.6	-3.3	-0.4	0.9	-0.2	-10.6	-12.5	-14.3	-27.1	-	-27.1
	F-T events	0	3	2	3	6	5	1	0	0	3	4	1	28	-	-
Crozierpynten	Mean	-17.4	-11.9	-15.8	-8.1	-3.6	1.0	5.0	5.1	2.5	-3.6	-7.0	-8.0	-5.2	125	-
	Maximum	0.3	4.8	3.5	5.7	5.0	4.9	11.4	12.6	9.7	4.5	7.7	0.5	12.6	-	12.6
*2011	Minimum	-33.6	-31.3	-25.7	-24.4	-12.1	-2.3	0.6	0.7	-3.9	-13.5	-17.3	-17.4	-33.6	-	-33.6
	F-T events	1	1	1	3	4	6	0	0	2	4	3	2	27	-	-
Rijpfjord	Mean	-21.9	-12.6	-16.6	-10.1	-5.2	-0.5	2.3	2.8	2.5	-4.1	-8.0	-10.0	-7.2	95	-
	Maximum	2.2	4.5	2.4	5.5	5.4	3.7	8.0	7.9	8.0	4.3	5.8	0.9	8.0	-	9.0
*2011	Minimum	-38.8	-35.6	-26.9	-26.5	-14.9	-4.9	-0-9	-1.2	-4.4	-14.2	-20.2	-23.0	-38.8	-	-38.8
	F-T events	1	1	2	2	6	6	2	3	1	4	2	1	31	-	-
ANTARCTIC																
Lichen fellfield (Anchorage)	Mean	1.3	0.1	-2.3	-4.8	-4.1	-6.8	-12.6	-7.8	-5.2	-6.5	-3.1	-0.5	-4.4	54	-
	Maximum	6.2	4.0	3.2	1.0	0.5	-2.6	-0.7	0.9	1.1	1.4	1.7	3.5	6.2	-	-
*2007	Minimum	-2.7	-3.5	-6.9	-10.8	-9.1	-11.1	-20.7	-21.6	-14.9	-15.4	-11.5	-4.4	-21.6	-	-
	F-T events	19	23	7	5	4	0	0	3	6	4	7	20	98	-	-
Cryodisturbed terrain (Coal nunatak)	Mean	1.9	-2.5	-4.5	-14.6	-9.4	-	-	-	-12.7	-11.1	-4.4	0.3	-6.3	54	-
	Maximum	11.2	8.3	6.5	-3.2	-1.4	-	-	-	-3.1	1.6	6.2	8.1	11.2	-	-
*2009	Minimum	-6.1	-11.7	-13.2	-28.0	-15.5	-	-	-	-23.6	-22.7	-15.3	-8.3	-28.0	-	-
	F-T events	18	15	6	0	0	-	-	-	0	1	9	27	76	-	-

Antarctic polar desert (Mars Oasis)	Mean	1.4	-3.3	-4.2	-17.1	-12.7	-20.1	-24.7	-17.3	-14.1	-11.6	-4.3	1.2	-10.6	65	-
	Maximum	8.6	7.1	5.6	-1.1	0.0	-2.2	0.6	1.1	-0.2	4.4	8.5	8.6	8.6	-	-
*2009	Minimum	-5.6	14.3	-21.4	-35.4	-28.4	-39.4	-47.5	-40.2	-33.8	-29.0	-20.4	-8.7	-47.5	-	-
	F-T events	25	12	17	0	0	0	1	1	0	5	10	29	100	-	-
Exposed hill summit (Jane Col)	Mean	1.7	0.8	0.7	-2.7	-4.0	-8.2	-11.9	-12.5	-6.1	-2.1	-2.1	0.0	-3.9	100	-
	Maximum	8.0	8.6	6.6	2.5	2.9	-0.2	0.5	0.1	3.9	6.5	6.0	6.0	8.6	-	-
*2009	Minimum	-2.8	-4.0	-4.4	-9.3	-12.6	-17.5	-26.3	-30.1	-27.8	-10.3	-9.3	-5.4	-30.1	-	-
	F-T events	15	15	16	15	4	1	1	1	10	15	13	24	130	-	-

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Table 1b. Mean, maximum and minimum monthly ground temperatures and freeze-thaw events for a representative year at each location. F-T=number of freeze-thaw events per month; Days µ T > 0°C=number of days mean daily ground temperature above 0°C; *=year summarised; **=total data range. See Supplementary Table 2 for raw data.

Site		Winter			Spring			Summer			Autumn		Winter		Days > 0°C	
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		**Data set**
ARCTIC																
Arctic polar desert	Mean	-7.5	-9.6	-13.5	-13.5	-8.5	-3.0	3.6	3.1	0.9	-2.5	-7.2	-8.6	-5.4	74	-
A	Maximum	-5.6	-7.8	-11.0	-10.9	-6.2	-0.1	13.3	11.7	6.3	-0.3	-3.6	-6.0	13.3	-	16.3
*2007-2008	Minimum	-10.3	-11.5	-16.6	-16.2	-10.9	-6.0	-0.1	-0.4	-1.1	-6.8	-10.8	-11.3	-16.6	-	-20.1
** 29/07/07-	F-T events	0	0	0	0	0	0	0	0	7	2	0	0	9	-	-
13/08/09	Days µ T > 0°C	0	0	0	0	0	0	26	29	19	0	0	0	74	-	-
High Arctic shrub tundra	Mean	-10.0	-8.6	-9.0	-11.2	-0.8	8.1	10.0	6.2	2.0	-5.4	-11.9	-13.2	-3.6	122	-
B	Maximum	0.9	-0.2	-1.7	-3.3	12.2	31.7	34.5	20.2	10.4	0.8	-1.9	5.0	34.5	-	35.2
*2012	Minimum	-16.9	-16.3	-16.9	-17.5	-5.5	-0.3	1.9	-2.2	5.1	-14.3	-20.7	-20.3	-20.7	-	-27.7
** 11/08/11-	F-T events	1	0	0	0	7	0	0	3	4	1	0	0	16	-	-
06/07/13	Days µ T > 0°C	1	0	0	0	10	27	31	31	20	1	0	0	121	-	-
Steppe vegetation	Mean	-6.2	-5.9	-7.3	-9.5	-2.4	4.3	6.6	5.2	1.9	-2.4	-6.0	-7.9	-2.5	128	-
C	Maximum	-9.2	-9.7	-10.2	-12.0	-7.0	-0.1	2.8	-0.1	-2.7	-7.2	-9.8	-10.9	10.9	-	14.5
*2012	Minimum	0.2	0.1	-4.3	-6.1	0.8	12.3	13.0	12.5	6.4	0.7	-0.3	-4.0	-6.1	-	-17.4
**11/08/11-	F-T events	1	1	0	0	1	1	0	0	0	1	0	0	5	-	-

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Site		Winter		Spring			Summer			Autumn			Winter		Days > 0°C	
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		Data set
06/07/13	Days µ T > 0°C	1	0	0	0	9	29	31	31	22	1	0	0	124	-	-
Low ridge crest	Mean	-6.7	-7.2	-7.1	-9-9	-1.2	6.8	8.1	5.3	1.9	-4.1	-10-0	-10.4	-2.9	121	-
D	Maximum	-0.9	-1.1	-1.8	-3.6	5.0	10.4	11.7	8.1	5.1	-0.2	-4.7	-5.2	11.7	-	11.2
* 2012	Minimum	-14.3	-17.1	-12.6	-16.1	-5.4	2-7	4.5	2.2	-0.5	-11.7	-17.1	-18.9	-18.9	-	-19.5
**13/08/11-	F-T events	0	0	0	0	0	0	0	0	1	2	0	0	3	-	-
20/06/13	Days µ T > 0°C	0	0	0	0	0	30	31	31	24	0	0	0	116	-	-
Salix coastal tundra	Mean	-0.9	-0.2	-2.3	-3.9	-1.9	3.4	7.6	6.9	2.9	-1.7	-1.5	-1.3	-4.6	135	-
E	Maximum	0.7	0.5	-0.9	-3.2	-0.3	8.2	10.7	8.8	6.3	3.0	-0.8	0.3	0.6	-	14.3
*2013-14	Minimum	-1.9	-1.4	-3.6	-4.6	-4.0	-0.3	5.4	3.6	-1.2	-3.6	-2.7	-2.6	10.7	-	-5.3
**13/08/13-	F-T events	0	0	0	0	1	0	0	0	0	1	0	0	2	-	-
17/08/14	Days µ T > 0°C	8	10	0	0	0	23	31	31	27	2	0	2	134	-	-
Dryas tundra	Mean	-10.0	-11.1	-8.3	-7.5	-1.0	7.2	8.3	7.2	3.0	-2.5	-3.9	-4.7	-1.9	120	-
F	Maximum	-7.2	-7.1	-0.2	-1.3	-0.3	20.1	18.6	15.3	7.4	-0.2	-0.4	-3.0	20.1	-	21.2
*2011	Minimum	-17.7	-13.9	-11.8	-12.0	-3.3	0.0	4.7	3.1	-0.6	-7.6	-10.0	-11.1	-13.9	-	-13.9
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
11/07/14	Days µ T > 0°C	0	0	0	0	0	30	31	31	28	0	0	0	120	-	-
Snow bed hollow	Mean	-13.4	-12.3	-7.8	-7.7	-2.2	6.1	8.2	7.0	3.3	-3.2	-6.7	-8.6	-3.4	121	-
G	Maximum	-5.2	-4.6	0.1	-3.3	-0.2	16.0	16.2	14.4	8.5	0.1	0.1	-2.2	16.2	-	16.2
*2011	Minimum	-19.0	-17.1	-12.0	-11.6	-4.2	-0.2	4.3	2.2	-1.8	-13.5	-15.8	-21.5	-21.5	-	-21.5
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	7	1	1	0	9	-	-
05/07/12	Days µ T > 0°C	0	0	1	0	0	26	31	31	28	0	0	0	117	-	-
Saline meadow – wet	Mean	-6.8	-7.2	-4.4	-5.1	-0.8	6.5	9.0	7.8	4.3	-1.2	-3.4	-4.2	-0.5	129	-
H	Maximum	-5.2	-1.0	-0.3	-3.2	-0.1	18.5	17.0	18.7	10.7	0.7	0.4	-2.5	18.7	-	18.7
*2011	Minimum	-8.0	-8.5	-7.6	-6.8	-3.2	-0.1	4.4	3.6	-0.1	-4.9	-8.3	-8.5	-8.5	-	-13.4

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Site		Winter		Spring			Summer			Autumn		Winter			Days > 0°C	
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		**Data set**
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	9	5	0	0	5	-	-
25/09/12	Days μ T > 0°C	0	0	0	0	3	30	31	31	30	6	2	0	133	-	-
Saline meadow – dry	Mean	-9.3	-10.4	-5.4	-7.3	-2.0	5.6	8.4	7.5	3.7	-2.4	-5.5	-5.5	-1.8	123	-
I	Maximum	-7.1	-3.9	-0.4	-4.8	-0.4	15.5	14.7	14.3	9.2	0.4	0.3	-3.6	15.5	-	15.5
*2011	Minimum	-11.3	-12.7	-9.7	-9.6	-4.8	-0.4	4.6	3.2	0.3	-8.4	-12.5	-10.0	-12.7	-	-13.1
**04/09/10-	F-T events	0	0	0	0	0	0	0	0	0	3	1	0	4	-	-
05/07/12	Days μ T > 0°C	0	0	0	0	0	22	31	31	31	7	2	0	124	-	-
Rich ornithogenic tundra	Mean	-8.7	-12.5	-13.5	-5.9	2.4	7.7	9.4	6.2	1.9	-2.2	-11.3	-11.4	-3.1	156	-
J	Maximum	-0.3	-6.1	-6.7	-0.1	11.7	20.5	20.7	18.9	10.7	5.2	-5.4	-3.5	20.7	-	20.7
*2010	Minimum	-18.6	-20-0	-17.4	-13.7	-4.4	0.9	3.3	0.2	-0.9	-10.8	-18.3	-18.9	-20.0	-	-20.4
**08/08/09-	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
29/06/11	Days μ T > 0°C	0	0	0	0	21	30	31	31	29	10	0	0	152	-	-
Poor ornithogenic vegetation	Mean	-5.3	-4.2	-5.2	-6.6	-0.2	7.3	9.9	7.2	3.9	0.3	-6.6	-6.9	-0.5	171	-
K	Maximum	0.4	0.5	0.1	-0.2	4.4	22.1	22.8	20.9	11.6	2.1	1.5	-4.2	22.8	-	23.6
*2012	Minimum	-13.4	-14.6	-12.6	-14.3	-3.8	-0.1	3.1	-0.7	0.0	-3.9	-11.4	-11.0	-14.6	-	-14.9
**19/07/11-	F-T events	0	2	1	0	6	0	0	1	0	5	2	0	17	-	-
01/07/13	Days μ T > 0°C	4	6	0	0	14	30	31	31	30	21	3	0	170	-	-
Anthropogenic soils	Mean	-0.3	0.4	0.4	0.1	0.5	4.7	8.0	5.9	3.6	-0.3	-1.0	-1.0	1.8	271	-
L	Maximum	0.1	0.6	0.6	0.5	0.6	12.7	13.8	10.0	8.2	0.6	0.4	-0.3	13.8	-	16.2
*2012	Minimum	-0.9	0.1	0.3	0.0	0.4	0.6	4.9	2.6	0.0	-2.5	-2.1	-1.7	-2.5	-	-2.6
**19/07/11-	F-T events	0	0	0	0	0	0	0	0	0	5	1	0	6	-	-
02/07/13	Days μ T > 0°C	4	29	31	28	31	30	31	31	30	20	2	0	267	-	-

.

Site		Winter		Spring			Summer			Autumn		Winter			Days > 0°C	
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		**Data set**
Moraines	Mean	-6.7	-6.6	-7.5	-9.8	0.0	8.3	9.3	5.7	2.0	-3.6	-9.0	-8.1	-2.2	128	-
M	Maximum	-5.3	-5.6	-6.4	-8.3	1.4	11.2	11.8	7.5	2.8	-2.9	-7.9	-7.5	11.8	-	16.3
*2012	Minimum	-8.0	-7.6	-8.7	-11.1	-1.1	5.7	7.5	4.2	1.3	-4.3	-10.2	-8.7	-11.1	-	-19.9
**13/08/11-	F-T events	0	0	0	0	1	0	0	0	2	2	0	0	5	-	-
20/06/13	Days µ T > 0°C	0	0	0	0	15	30	31	31	19	0	0	0	126	-	-
Cliff fissure	Mean	-12.9	-10.0	-9.9	-7.3	3.4	6.6	11.0	7.1	3.4	-6.2	-9.1	-8.5	-3.0	148	-
N	Maximum	-0.5	-0.9	-1.4	14.8	21.1	20.7	31.8	29.6	21.9	0.7	-1.8	-2.0	31.8	-	31.7
*2008-09	Minimum	-24.7	-18.0	-16.7	-16.8	-4.9	1.1	1.1	1.3	-3.6	-13.9	-16.3	-18-0	-24.7	-	-24.7
**06/07/08-	F-T events	0	0	0	12	5	0	0	0	4	0	0	0	21	-	-
23/06/09	Days µ T > 0°C	0	0	0	3	29	23	28	31	23	0	0	0	137	-	-
Small temporary pond	Mean	-8.8	-11.4	-8.1	-7.1	-1.1	1.3	6.6	6.5	2.8	-0.9	-2.3	-4.4	-2.2	119	-
O	Maximum	-5.6	-5.1	-2.1	-1.6	-0.3	4.7	10.2	8.9	5.3	0.4	-0.3	-2.1	10.2	-	12.9
*2011	Minimum	-13.0	-14.4	-13.7	-11.3	-3.8	-0.3	3.5	4.3	0.4	-3.3	-4.9	-14.6	-14.6	-	-14.6
**05/06/10-	F-T events	0	0	0	0	0	1	0	0	0	0	0	0	1	-	-
02/08/12	Days µ T > 0°C	0	0	0	0	0	22	31	31	30	4	0	0	118	-	-
Large permanent pond	Mean	-8.7	-7.2	-8.2	-9.3	-3.2	1.5	8.0	6.2	3.5	-0.6	-2.2	-3.0	-1.9	123	-
P	Maximum	-4.1	-2.2	-5.7	-7.7	-0.1	4.4	11.3	7.6	6.3	0.9	-0.4	-0.6	11.3	-	13.8
*2008-09	Minimum	-13.2	-13.3	-11.7	-10.8	-8.2	-0.1	4.2	4.9	0.7	-4.0	-4.5	-6.4	-13.3	-	-13.5
**12/08/08-	F-T events	1	1	0	0	0	1	0	0	2	0	0	1	6	-	-
09/08/09	Days µ T > 0°C	0	0	0	0	0	16	31	31	30	10	0	0	118	-	-
ANTARCTIC																
Exposed hill summit (Jane Col)	Mean	2.7	1.6	1.0	-1.4	-0.8	-2.3	-5.1	-7.5	-5.2	-1.8	-1.8	-0.1	-1.7	89	-

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Site		Winter		Spring			Summer			Autumn		Winter			Days > 0°C	
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		Data set
Q	Maximum	14.6	18.4	11.6	1.9	0.2	-1.0	-3.1	-5.8	0	-0.1	-0.1	1.4	18.4	-	-
*2009	Minimum	-2.6	-3.9	-4.9	-8.6	-1.7	-4.6	-7.5	-8.7	-6.9	-2.6	-2.8	-0.9	-8.7	-	-
**01/01/09-	F-T events	13	16	13	6	0	0	0	0	0	0	0	3	51	-	-
31/12/09	Days µ T > 0°C	30	23	23	1	2	0	0	0	0	0	0	10	89	-	-
Antarctic polar desert (Mars Oasis)	Mean	5.3	0.5	-2.9	-13.5	-14.3	-17.6	-23.7	-17.7	-14.7	-10.1	-1.6	3.8	-9.0	87	-
R	Maximum	24.3	18.7	5.7	-3.9	-4.3	-6.6	-8.4	-4.5	-6.0	0.6	15.8	15.6	24.3	-	-
*2009	Minimum	-3.7	-7.7	-13.7	-24.1	-24.7	-30.9	-38.2	-35.1	-27.9	-23.1	-14.6	-6.8	-38.2	-	-
**01/01/09-	F-T events	19	23	10	2	0	0	0	0	0	0	15	22	91	-	-
31/12/09	Days µ T > 0°C	31	11	4	0	0	0	0	0	0	0	13	28	87	-	-
Cryodisturbed terrain (Coal nunatak)	Mean	5.5	-0.3	-4.9	-15.5	-11.8	-	-	-	-14.3	-12.7	-7.7	2.4	-6.5	66	-
S	Maximum	21.8	16.0	9.6	-3.3	-5.7	-	-	-	-11.1	-9.0	-0.1	19.4	21.8	-	-
*2009	Minimum	-5.8	-11.9	-15.5	-30.6	-19.7	-	-	-	-27.9	-17.1	-16.1	-7.3	-30.6	-	-
**01/01/09-	F-T events	22	30	9	0	0	-	-	-	0	0	0	26	-	-	-
31/12/09	Days µ T > 0°C	30	12	4	0	0	-	-	-	0	0	0	20	-	-	-
Lichen fellfield (Anchorage)	Mean	5.7	3.5	-0.6	-4.6	-4.3	-6.9	-11.2	-7.5	-4.6	-4.7	-1.1	3.5	-2.8	101	-
T	Maximum	21.9	20.9	15.5	2.0	-0.4	-3.9	-4.0	-4.2	-1.1	-0.9	7.3	18.1	21.9	-	-
*2007-08	Minimum	-1.9	-4.6	-7.0	-12.4	-11.0	-11.8	-16.4	-12.7	-9.0	-9.0	-4.9	-4.9	-16.4	-	-
**01/01/07	F-T events	5	16	20	9	0	0	0	0	0	0	3	21	74	-	-
31/12/07	Days µ T > 0°C	31	27	8	1	0	0	0	0	0	0	4	30	101	-	-

.

Table 2. Cumulative day degrees (CDD) 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

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Figure Legends

Figure 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 localitions 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).

Figure 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.

Figure 3. (a) Hourly temperature data for A) Arctic polar desert, B) High Arctic shrub tundra, C) Steppe vegetation, D) Low ridge crest, E) *Salix* coastal tundra, F) *Dryas tundra*, G) Snow bed hollow, H) Saline meadow – wet. (b) Hourly temperature data for I) Saline meadow – dry, J) Rich ornithogenic tundra, K) Poor ornithogenic vegetation, L) Anthropogenic soils, M) Moraines, N) Cliff fissure, O) Small temporary pond, P) Large permanent pond. (c) Hourly temperature data for Q) Exposed hill summit (Jane Col), R) Antarctic polar desert (Mars Oasis), S) Cryodisturbed terrain (Coal Nunatak), T) (Lichen fellfield (Anchorage). Dotted lines indicate 0°C reference.

Figure 4. Cumulative degree-days (0°C baseline). **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).

Figure 5. Date of the breaking of the 'champagne glass' snow patch. (a) the snow patch on Operafjellet with broken stem (24 July 2006) as seen from Longyearbyen; (b) variation in the date of the breaking of the stem; period 2004-2015. Reference lines indicate 1 July and 1 September. Source Svalbardposten.

Supplementary material

Figure 1 Images of the Arctic sites. All represent the summer period, July-August; (a) A) Arctic polar desert, B) High Arctic shrub tundra, C) Steppe vegetation, D) Low ridge crest, E) *Salix* coastal tundra, F) *Dryas* tundra, G) Snow bed hollow, H) Saline meadow – wet; (b) I) Saline meadow – dry, J) Rich ornithogenic tundra, K) Poor ornithogenic vegetation, L) Anthropogenic soils, M) Moraines, N) Cliff fissure, O) Small temporary pond, P) Large permanent pond; **(c)** Images of the Antarctic sites. All represent the summer period, except Mars Oasis which depicts the situation on mid-winters day (1 June 2007); Q) Exposed hill summit (Jane Col), R) Antarctic polar desert (Mars Oasis), S) Cryodisturbed terrain (Coal Nunatak), T) (Lichen fellfield (Anchorage).

Table 1. Site descriptions

Table 2. Cleaned temperature data (example for submission purposes)

Figure 1 Click here to download Figure Figure 1.jpg

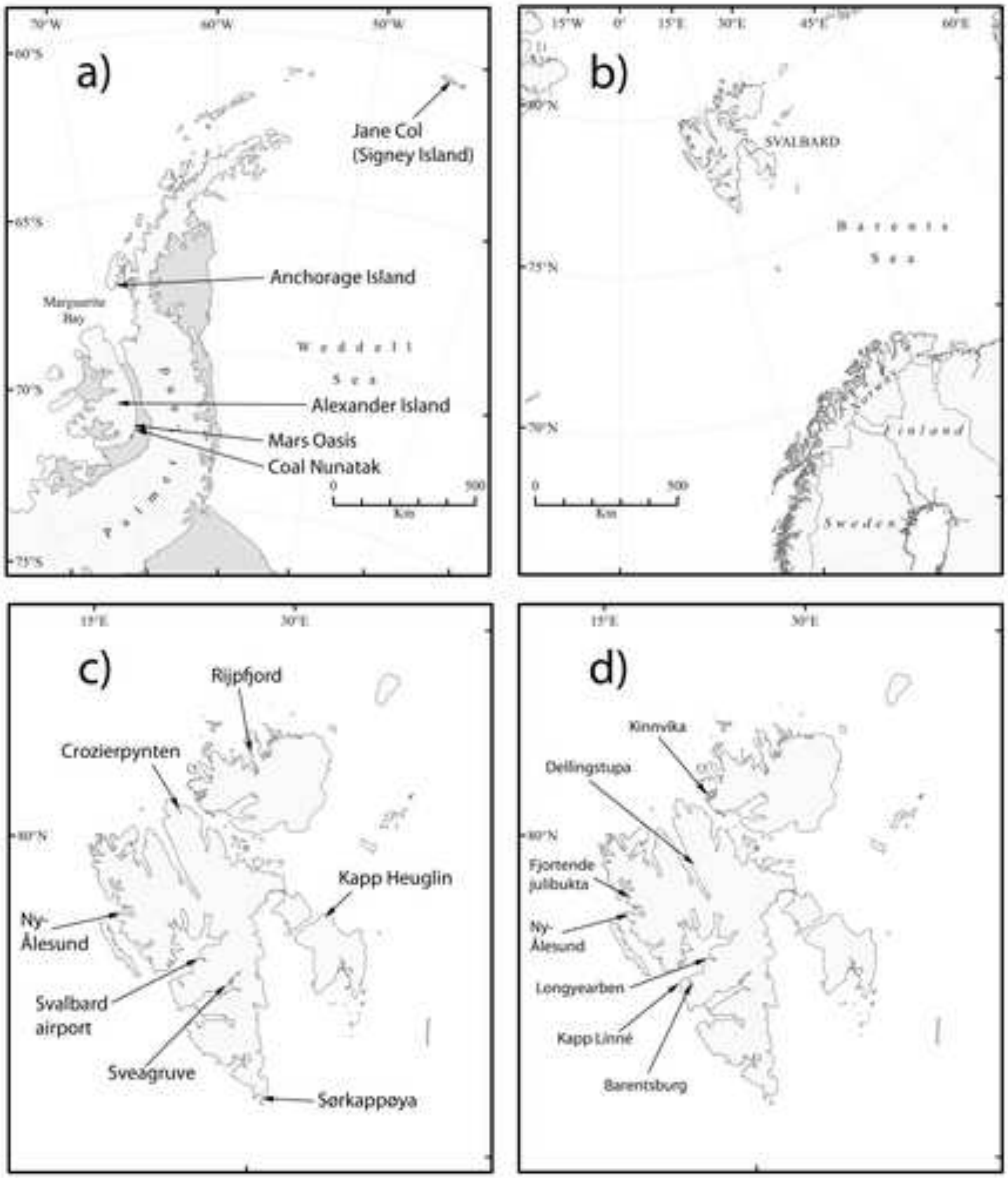

Figure 2a

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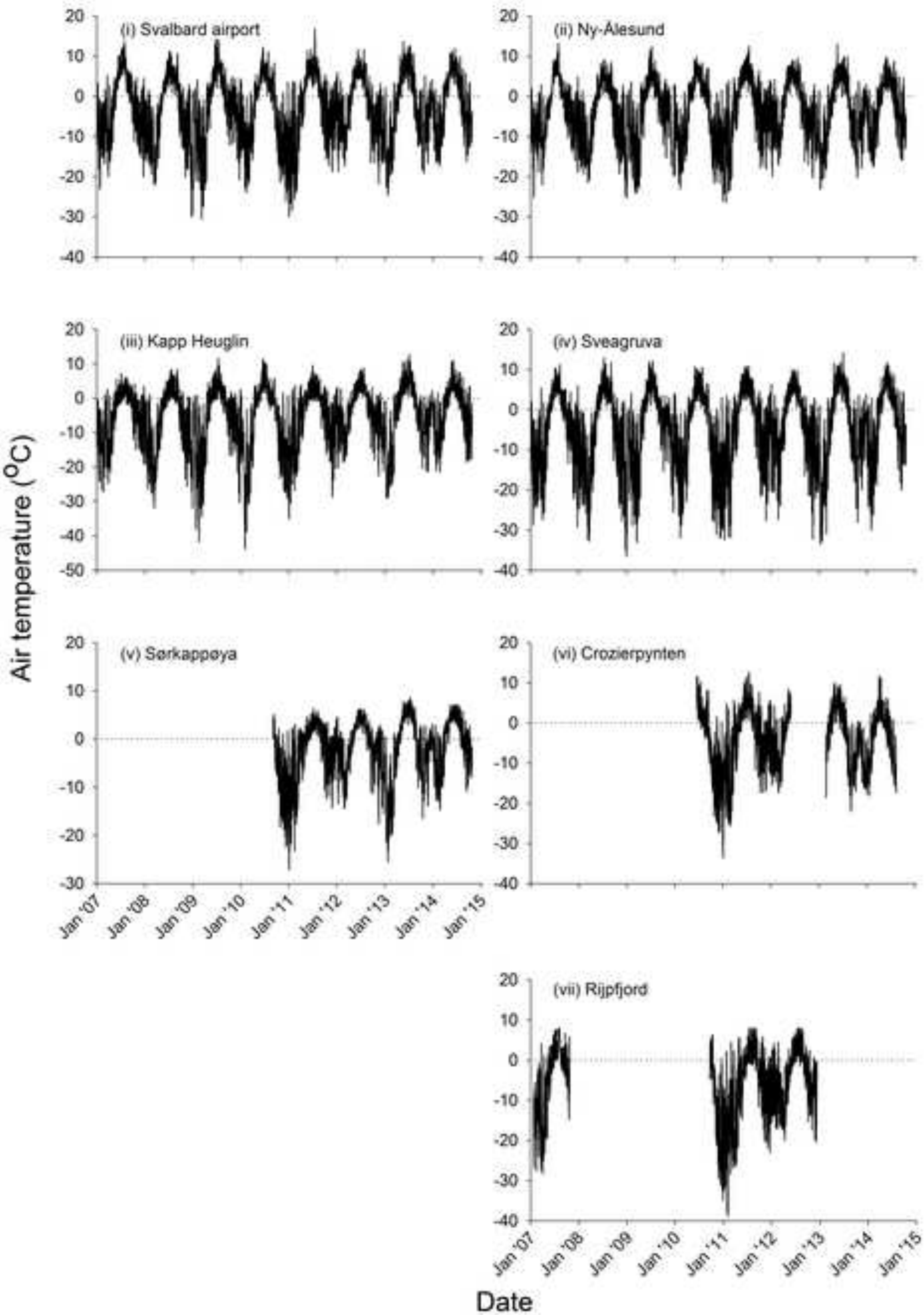

Figuree 2b

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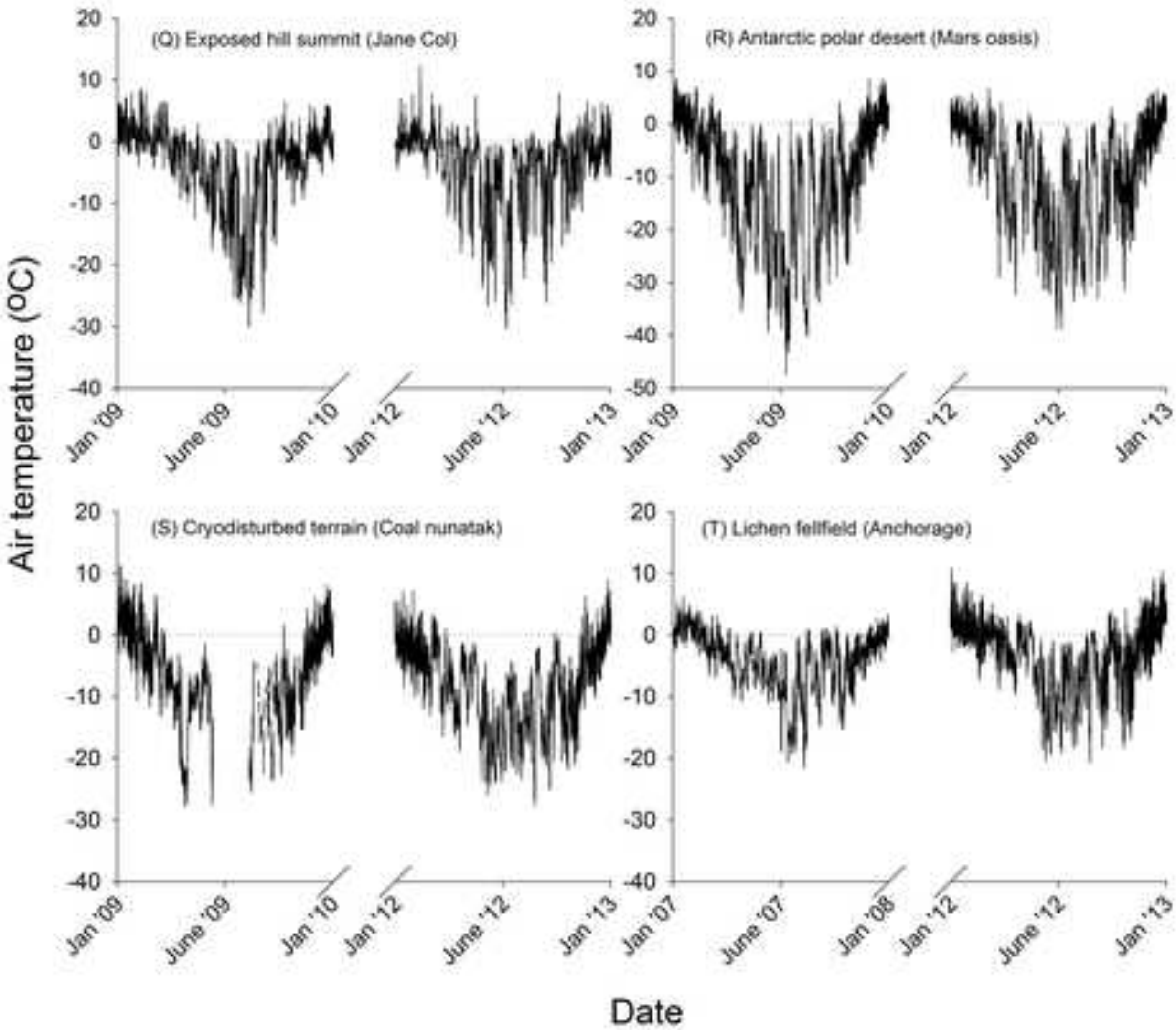

Figure 3a

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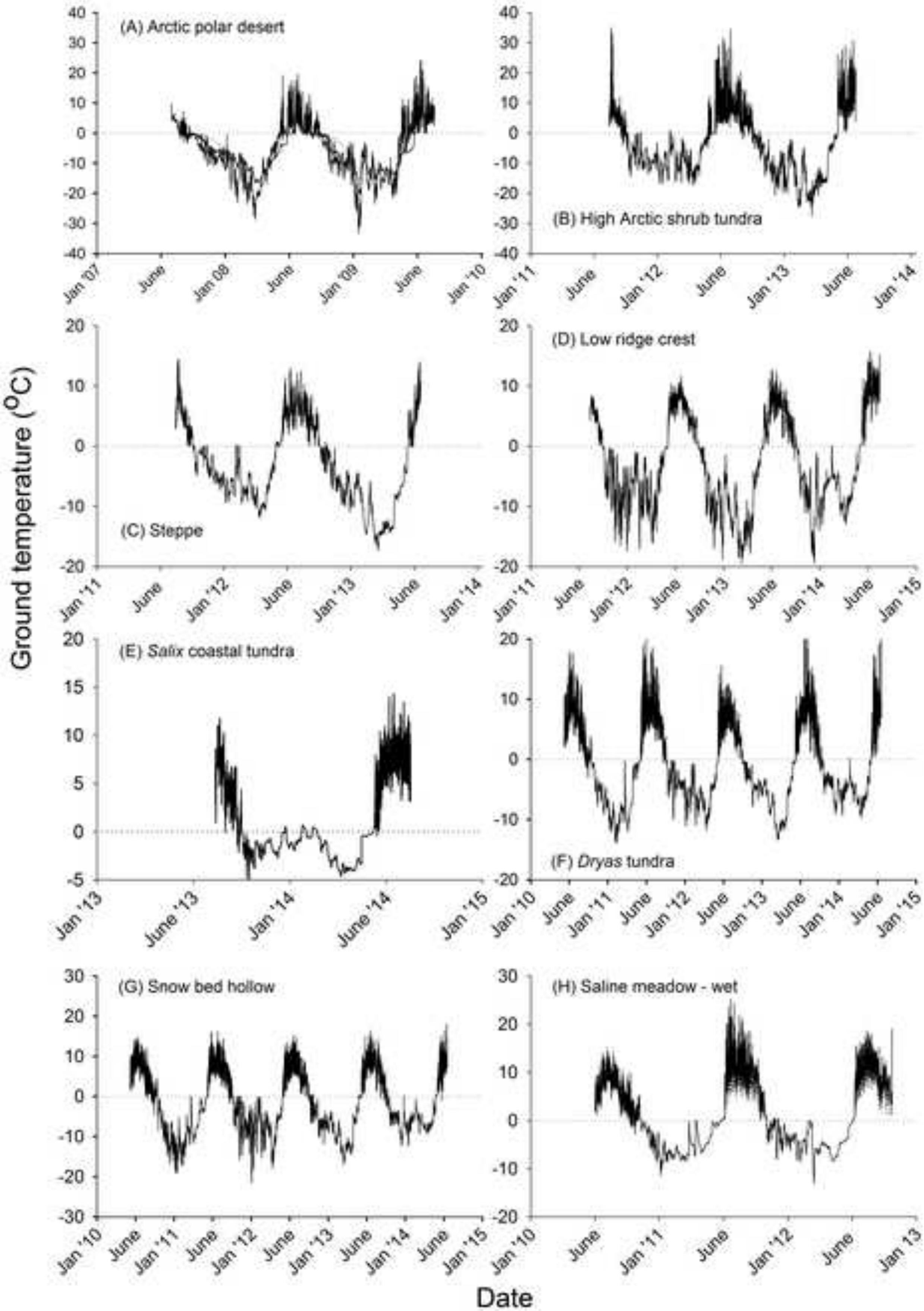

Figure 3b

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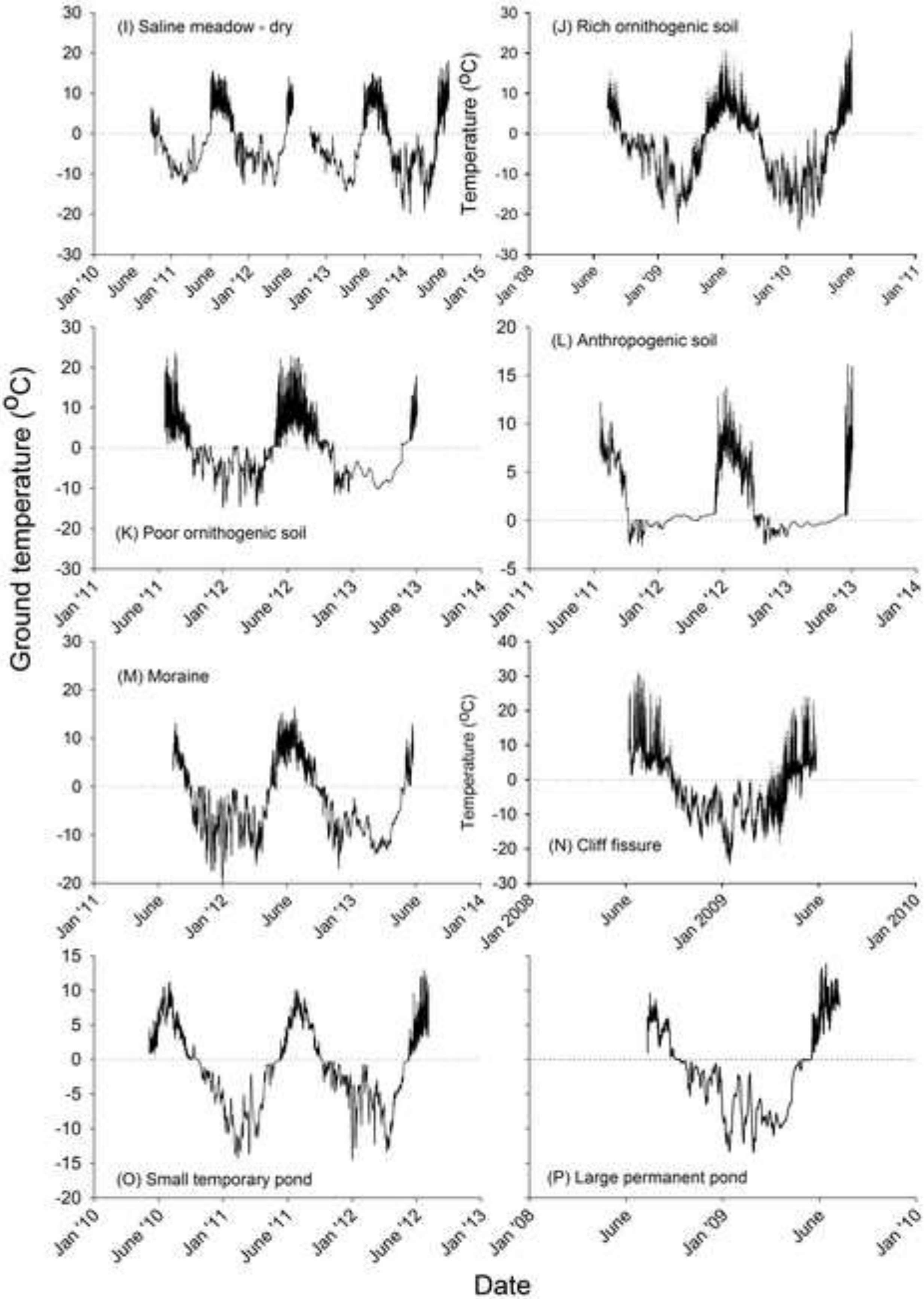

Figure 3c

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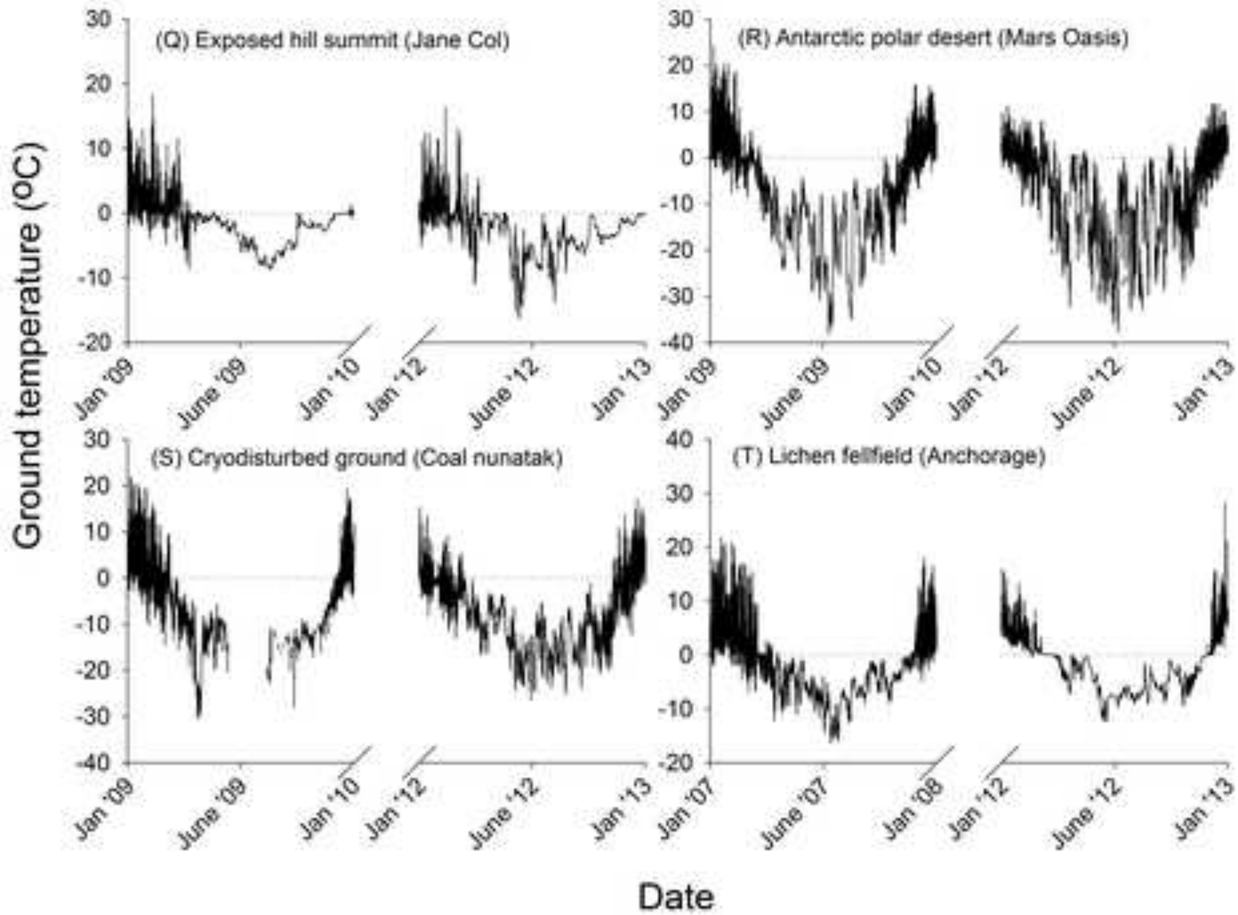

Fgure 4

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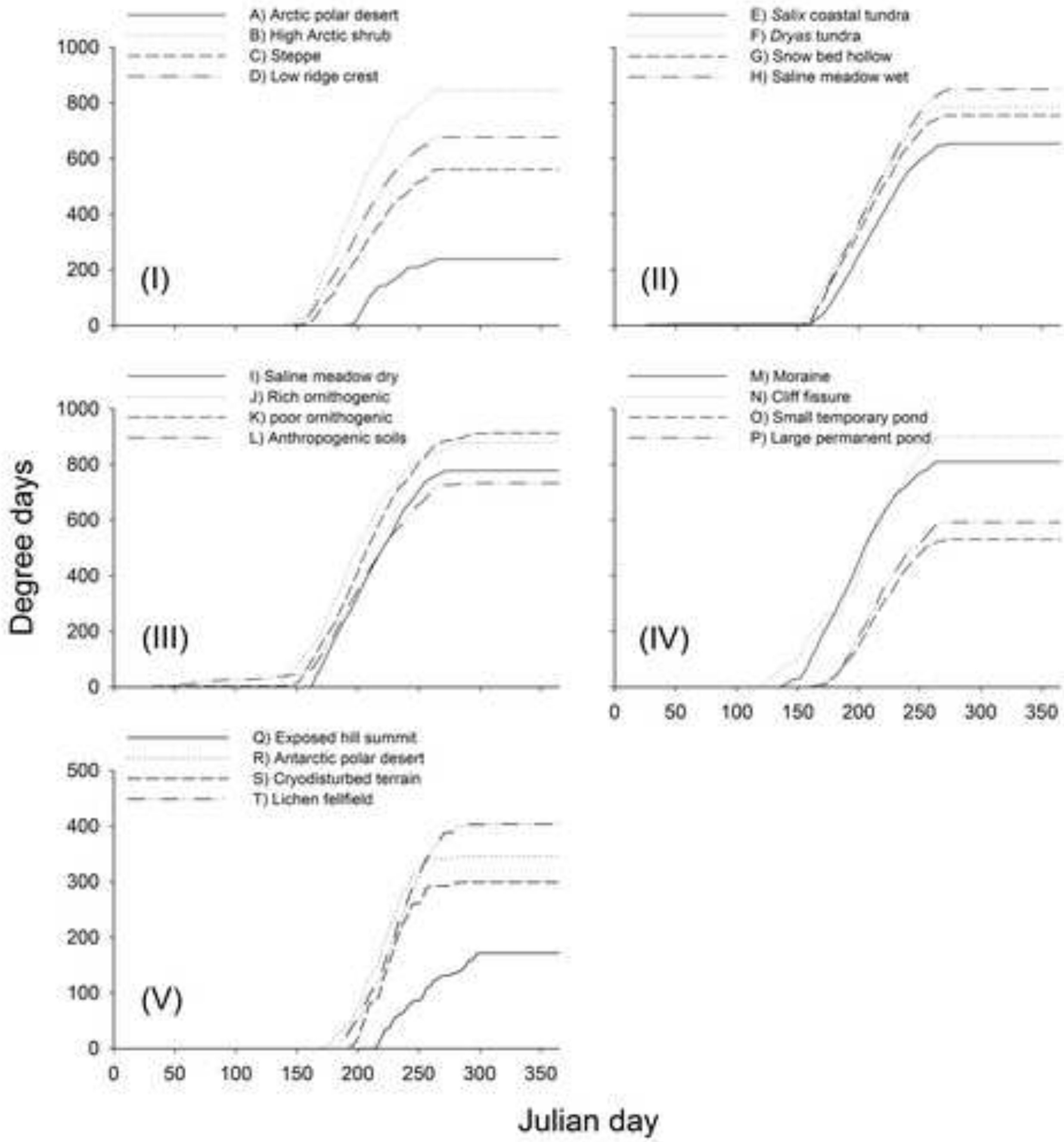

Figure 5

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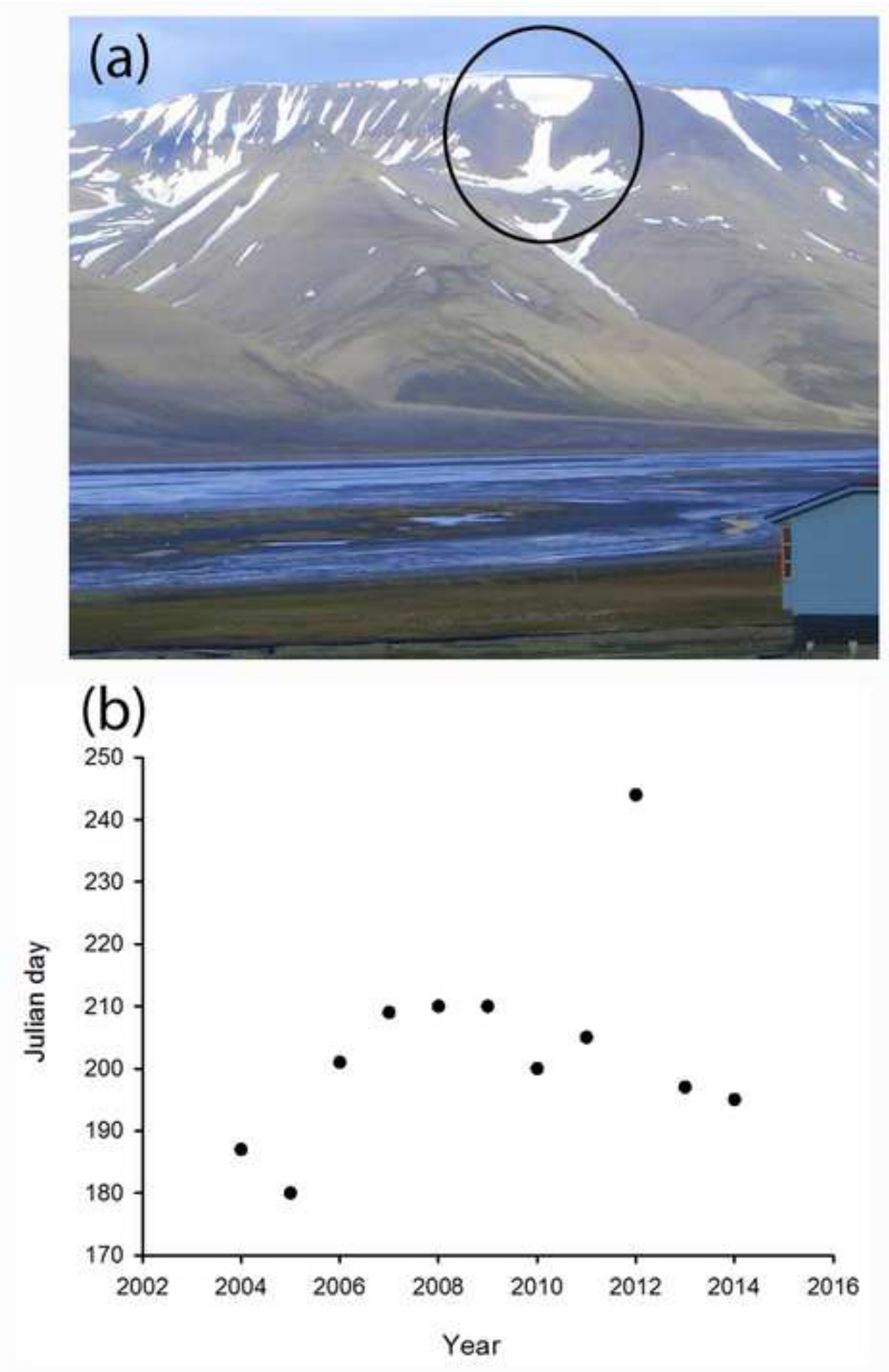

Table 1a Click here to download Table Table 1a.docx

Table 2a. Summary air temperature figures for a representative year at Svalbard and the martime Antarctic. F-T=number of freeze-thaw events per month; Days µ T > 0°C=number of days mean daily ground temperature above 0°C; *=year summarised. Ann.=Annual.

Site		**Winter**		**Spring**			**Summer**			**Autumn**			**Winter**		**Days > 0°C**	**Entire dataset**
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Ann.**		
ARCTIC																
Svalbard Airport	Mean	-15.2	-12.9	-12.8	-6.0	-1.6	4.8	6.9	7-0	4.4	-2.6	-6.0	-6.5	-3.3	151	-
*2011	Maximum	3.6	3.7	3.5	2.7	5.0	11.4	11.8	16.8	9.7	3.9	5.4	2.6	16.8	-	16.8
	Minimum	-29.9	.28.4	-25.7	-22.6	-7.7	1.2	3.1	2.1	-1.1	-12.3	-15.7	-18.7	-29.9	-	-30.5
	F-T events	1	1	2	3	3	0	0	0	2	4	2	3	21	-	-
Ny-Ålesund	Mean	-13.8	.10.8	-12.8	-5.4	-2.1	3.7	6.3	5.8	3.0	-3.4	-6.8	-6.9	-3.6	139	-
	Maximum	1.6	3.2	3.9	4.6	4.8	7.7	9.8	12.5	8.1	5.0	6.5	1.9	12.5	-	13.2
*2011	Minimum	-26.1	-26.4	-23.9	-20.4	-8.4	-0.4	2.0	1.1	-4.6	-12.7	-17.9	-18.1	-26.1	-	-26.4
	F-T events	1	1	3	3	3	3	0	0	3	3	3	2	25	-	-
Kapp Heuglin	Mean	-19.0	-15.7	-14.3	-8.9	-4.3	0.0	2.1	2.4	2.2	-2.7	-6.3	-11.3	-6.2	113	-
	Maximum	0.7	2.7	3.7	3.0	3.8	4.4	9.5	7.3	6.8	3.3	3.2	-1.0	9.5	-	12.7
*2011	Minimum	-35.1	-30.8	-26.9	-21.0	-12.0	-3.8	-0.9	-0.9	-1.7	-12.3	-16.3	-28.8	-35.1	-	-43.9
	F-T events	1	2	2	3	4	10	1	2	1	4	3	0	33	-	-
Sveagruva	Mean	-17.3	-14.1	-14.9	-7.2	-2.8	3.7	6.0	5.5	3.7	-2.8	-7.1	-9.4	-4.6	141	-
	Maximum	3.0	3.4	2.3	3.0	3.7	8.9	10.7	10.8	8.0	3.2	4.5	0.3	10.8	-	14.1
*2011	Minimum	-32.0	-32.4	-31.8	-28.7	-11.6	-0.8	2.3	1.2	-1.2	-13.0	-21.6	-27.6	-32.0	-	-36.5
	F-T events	1	2	2	3	6	1	0	0	1	5	5	2	28	-	-
Sørkappøya	Mean	-14.0	-11.8	-9.1	-4.8	-2.2	1.0	2.0	3.2	3.3	-0.6	-3.0	-4.7	-3.3	154	-
	Maximum	1.7	2.3	3.1	2.3	1.7	4.6	5.4	6.4	5.8	4.0	3.4	0.5	6.4	-	8.6
*2011	Minimum	-27.1	-23.5	-23.5	-15.6	-8.6	-3.3	-0.4	0.9	-0.2	-10.6	-12.5	-14.3	-27.1	-	-27.1
	F-T events	0	3	2	3	6	5	1	0	0	3	4	1	28	-	-

Site		Winter		Spring			Summer			Autumn			Winter		Days > 0°C	Entire dataset
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Ann.		
Crozierpynten	Mean	-17.4	-11.9	-15.8	-8.1	-3.6	1.0	5.0	5.1	2.5	-3.6	-7.0	-8.0	-5.2	125	-
	Maximum	0.3	4.8	3.5	5.7	5.0	4.9	11.4	12.6	9.7	4.5	7.7	0.5	12.6	-	12.6
*2011	Minimum	-33.6	-31.3	-25.7	-24.4	-12.1	-2.3	0.6	0.7	-3.9	-13.5	-17.3	-17.4	-33.6	-	-33.6
	F-T events	1	1	1	3	4	6	0	0	2	4	3	2	27	-	-
Rijpfjord	Mean	-21.9	-12.6	-16.6	-10.1	-5.2	-0.5	2.3	2.8	2.5	-4.1	-8.0	-10.0	-7.2	95	-
	Maximum	2.2	4.5	2.4	5.5	5.4	3.7	8.0	7.9	8.0	4.3	5.8	0.9	8.0	-	9.0
*2011	Minimum	-38.8	-35.6	-26.9	-26.5	-14.9	-4.9	-0-9	-1.2	-4.4	-14.2	-20.2	-23.0	-38.8	-	-38.8
	F-T events	1	1	2	2	6	6	2	3	1	4	2	1	31	-	-
ANTARCTIC																
		Summer		**Autumn**			**Winter**			**Spring**			**Summ er**			
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Ann.**		
Lichen fellfield (Anchorage)	Mean	1.3	0.1	-2.3	-4.8	-4.1	-6.8	-12.6	-7.8	-5.2	-6.5	-3.1	-0.5	-4.4	54	-
	Maximum	6.2	4.0	3.2	1.0	0.5	-2.6	-0.7	0.9	1.1	1.4	1.7	3.5	6.2	-	6.2
*2007	Minimum	-2.7	-3.5	-6.9	-10.8	-9.1	-11.1	-20.7	-21.6	-14.9	-15.4	-11.5	-4.4	-21.6	-	-21.6
	F-T events	19	23	7	5	4	0	0	3	6	4	7	20	98	-	-
Cryodisturbed terrain (Coal nunatak)	Mean	1.9	-2.5	-4.5	-14.6	-9.4	-	-	-	-12.7	-11.1	-4.4	0.3	-6.3	54	-
	Maximum	11.2	8.3	6.5	-3.2	-1.4	-	-	-	-3.1	1.6	6.2	8.1	11.2	-	11.2
*2009	Minimum	-6.1	-11.7	-13.2	-28.0	-15.5	-	-	-	-23.6	-22.7	-15.3	-8.3	-28.0	-	.28.0
	F-T events	18	15	6	0	0	-	-	-	0	1	9	27	76	-	-
Antarctic polar desert (Mars Oasis)	Mean	1.4	-3.3	-4.2	-17.1	-12.7	-20.1	-24.7	-17.3	-14.1	-11.6	-4.3	1.2	-10.6	65	-
	Maximum	8.6	7.1	5.6	-1.1	0.0	-2.2	0.6	1.1	-0.2	4.4	8.5	8.6	8.6	-	8.6
*2009	Minimum	-5.6	14.3	-21.4	-35.4	-28.4	-39.4	-47.5	-40.2	-33.8	-29.0	-20.4	-8.7	-47.5	-	-47.5
	F-T events	25	12	17	0	0	0	1	1	0	5	10	29	100	-	-

Site		Winter		Spring			Summer			Autumn			Winter		Days > 0°C	Entire dataset
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Ann.**		
Exposed hill summit (Jane Col)	Mean	1.7	0.8	0.7	-2.7	-4.0	-8.2	-11.9	-12.5	-6.1	-2.1	-2.1	0.0	-3.9	100	-
	Maximum	8.0	8.6	6.6	2.5	2.9	-0.2	0.5	0.1	3.9	6.5	6.0	6.0	8.6	-	8.6
*2009	Minimum	-2.8	-4.0	-4.4	-9.3	-12.6	-17.5	-26.3	-30.1	-27.8	-10.3	-9.3	-5.4	-30.1	-	-30.1
	F-T events	15	15	16	15	4	1	1	1	10	15	13	24	130	-	-

Table 1b

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Table 2b. Mean, maximum and minimum monthly ground temperatures and freeze-thaw events for a representative year at each location. F-T=number of freeze-thaw events per month; Days µ T > 0°C=number of days mean daily ground temperature above 0°C; *=year summarised; **=total data range. See supplementary electronic material for raw data file.

Site		**Winter**			**Spring**			**Summer**			**Autumn**		**Winter**		**Days > 0°C**	
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		**Data set**
ARCTIC																
Arctic polar desert	Mean	-7.5	-9.6	-13.5	-13.5	-8.5	-3.0	3.6	3.1	0.9	-2.5	-7.2	-8.6	-5.4	74	-
A	Maximum	-5.6	-7.8	-11.0	-10.9	-6.2	-0.1	13.3	11.7	6.3	-0.3	-3.6	-6.0	13.3	-	16.3
*2007-2008	Minimum	-10.3	-11.5	-16.6	-16.2	-10.9	-6.0	-0.1	-0.4	-1.1	-6.8	-10.8	-11.3	-16.6	-	-20.1
** 29/07/07-	F-T events	0	0	0	0	0	0	0	0	7	2	0	0	9	-	-
13/08/09	Days µ T > 0°C	0	0	0	0	0	0	26	29	19	0	0	0	74	-	-
High Arctic shrub tundra	Mean	-10.0	-8.6	-9.0	-11.2	-0.8	8.1	10.0	6.2	2.0	-5.4	-11.9	-13.2	-3.6	122	-
B	Maximum	0.9	-0.2	-1.7	-3.3	12.2	31.7	34.5	20.2	10.4	0.8	-1.9	5.0	34.5	-	35.2
*2012	Minimum	-16.9	-16.3	-16.9	-17.5	-5.5	-0.3	1.9	-2.2	5.1	-14.3	-20.7	-20.3	-20.7	-	-27.7
** 11/08/11-	F-T events	1	0	0	0	7	0	0	3	4	1	0	0	16	-	-
06/07/13	Days µ T > 0°C	1	0	0	0	10	27	31	31	20	1	0	0	121	-	-
Steppe vegetation	Mean	-6.2	-5.9	-7.3	-9.5	-2.4	4.3	6.6	5.2	1.9	-2.4	-6.0	-7.9	-2.5	128	-
C	Maximum	-9.2	-9.7	-10.2	-12.0	-7.0	-0.1	2.8	-0.1	-2.7	-7.2	-9.8	-10.9	10.9	-	14.5
*2012	Minimum	0.2	0.1	-4.3	-6.1	0.8	12.3	13.0	12.5	6.4	0.7	-0.3	-4.0	-6.1	-	-17.4
**11/08/11-	F-T events	1	1	0	0	1	1	0	0	0	1	0	0	5	-	-
06/07/13	Days µ T > 0°C	1	0	0	0	9	29	31	31	22	1	0	0	124	-	-
Low ridge crest	Mean	-6.7	-7.2	-7.1	-9-9	-1.2	6.8	8.1	5.3	1.9	-4.1	-10-0	-10.4	-2.9	121	-
D	Maximum	-0.9	-1.1	-1.8	-3.6	5.0	10.4	11.7	8.1	5.1	-0.2	-4.7	-5.2	11.7	-	11.2
* 2012	Minimum	-14.3	-17.1	-12.6	-16.1	-5.4	2-7	4.5	2.2	-0.5	-11.7	-17.1	-18.9	-18.9	-	-19.5
**13/08/11-	F-T events	0	0	0	0	0	0	0	0	1	2	0	0	3	-	-

Site		Winter			Spring			Summer			Autumn		Winter		Days > 0°C	
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**		**Data set**
20/06/13	Days μ T > 0°C	0	0	0	0	0	30	31	31	24	0	0	0	116	-	-
Salix coastal tundra	Mean	-0.9	-0.2	-2.3	-3.9	-1.9	3.4	7.6	6.9	2.9	-1.7	-1.5	-1.3	-4.6	135	-
E	Maximum	0.7	0.5	-0.9	-3.2	-0.3	8.2	10.7	8.8	6.3	3.0	-0.8	0.3	0.6	-	14.3
*2013-14	Minimum	-1.9	-1.4	-3.6	-4.6	-4.0	-0.3	5.4	3.6	-1.2	-3.6	-2.7	-2.6	10.7	-	-5.3
**13/08/13-	F-T events	0	0	0	0	1	0	0	0	0	1	0	0	2	-	-
17/08/14	Days μ T > 0°C	8	10	0	0	0	23	31	31	27	2	0	2	134	-	-
Dryas tundra	Mean	-10.0	-11.1	-8.3	-7.5	-1.0	7.2	8.3	7.2	3.0	-2.5	-3.9	-4.7	-1.9	120	-
F	Maximum	-7.2	-7.1	-0.2	-1.3	-0.3	20.1	18.6	15.3	7.4	-0.2	-0.4	-3.0	20.1	-	21.2
*2011	Minimum	-17.7	-13.9	-11.8	-12.0	-3.3	0.0	4.7	3.1	-0.6	-7.6	-10.0	-11.1	-13.9	-	-13.9
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
11/07/14	Days μ T > 0°C	0	0	0	0	0	30	31	31	28	0	0	0	120	-	-
Snow bed hollow	Mean	-13.4	-12.3	-7.8	-7.7	-2.2	6.1	8.2	7.0	3.3	-3.2	-6.7	-8.6	-3.4	121	-
G	Maximum	-5.2	-4.6	0.1	-3.3	-0.2	16.0	16.2	14.4	8.5	0.1	0.1	-2.2	16.2	-	16.2
*2011	Minimum	-19.0	-17.1	-12.0	-11.6	-4.2	-0.2	4.3	2.2	-1.8	-13.5	-15.8	-21.5	-21.5	-	-21.5
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	7	1	1	0	9	-	-
05/07/12	Days μ T > 0°C	0	0	1	0	0	26	31	31	28	0	0	0	117	-	-
Saline meadow – wet	Mean	-6.8	-7.2	-4.4	-5.1	-0.8	6.5	9.0	7.8	4.3	-1.2	-3.4	-4.2	-0.5	129	-
H	Maximum	-5.2	-1.0	-0.3	-3.2	-0.1	18.5	17.0	18.7	10.7	0.7	0.4	-2.5	18.7	-	18.7
*2011	Minimum	-8.0	-8.5	-7.6	-6.8	-3.2	-0.1	4.4	3.6	-0.1	-4.9	-8.3	-8.5	-8.5	-	-13.4
**05/06/10-	F-T events	0	0	0	0	0	0	0	0	9	5	0	0	5	-	-
25/09/12	Days μ T > 0°C	0	0	0	0	3	30	31	31	30	6	2	0	133	-	-
Saline meadow – dry	Mean	-9.3	-10.4	-5.4	-7.3	-2.0	5.6	8.4	7.5	3.7	-2.4	-5.5	-5.5	-1.8	123	-
I	Maximum	-7.1	-3.9	-0.4	-4.8	-0.4	15.5	14.7	14.3	9.2	0.4	0.3	-3.6	15.5	-	15.5
*2011	Minimum	-11.3	-12.7	-9.7	-9.6	-4.8	-0.4	4.6	3.2	0.3	-8.4	-12.5	-10.0	-12.7	-	-13.1
**04/09/10-	F-T events	0	0	0	0	0	0	0	0	0	3	1	0	4	-	-
05/07/12	Days μ T > 0°C	0	0	0	0	0	22	31	31	31	7	2	0	124	-	-

Site		Winter		Spring			Summer			Autumn		Winter			Days > 0°C	
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		Data set
Rich ornithogenic tundra	Mean	-8.7	-12.5	-13.5	-5.9	2.4	7.7	9.4	6.2	1.9	-2.2	-11.3	-11.4	-3.1	156	-
J	Maximum	-0.3	-6.1	-6.7	-0.1	11.7	20.5	20.7	18.9	10.7	5.2	-5.4	-3.5	20.7	-	20.7
*2010	Minimum	-18.6	-20-0	-17.4	-13.7	-4.4	0.9	3.3	0.2	-0.9	-10.8	-18.3	-18.9	-20.0	-	-20.4
**08/08/09-	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
29/06/11	Days µ T > 0°C	0	0	0	0	21	30	31	31	29	10	0	0	152	-	-
Poor ornithogenic vegetation	Mean	-5.3	-4.2	-5.2	-6.6	-0.2	7.3	9.9	7.2	3.9	0.3	-6.6	-6.9	-0.5	171	-
K	Maximum	0.4	0.5	0.1	-0.2	4.4	22.1	22.8	20.9	11.6	2.1	1.5	-4.2	22.8	-	23.6
*2012	Minimum	-13.4	-14.6	-12.6	-14.3	-3.8	-0.1	3.1	-0.7	0.0	-3.9	-11.4	-11.0	-14.6	-	-14.9
**19/07/11-	F-T events	0	2	1	0	6	0	0	1	0	5	2	0	17	-	-
01/07/13	Days µ T > 0°C	4	6	0	0	14	30	31	31	30	21	3	0	170	-	-
Anthropogenic soils	Mean	-0.3	0.4	0.4	0.1	0.5	4.7	8.0	5.9	3.6	-0.3	-1.0	-1.0	1.8	271	-
L	Maximum	0.1	0.6	0.6	0.5	0.6	12.7	13.8	10.0	8.2	0.6	0.4	-0.3	13.8	-	16.2
*2012	Minimum	-0.9	0.1	0.3	0.0	0.4	0.6	4.9	2.6	0.0	-2.5	-2.1	-1.7	-2.5	-	-2.6
**19/07/11-	F-T events	0	0	0	0	0	0	0	0	0	5	1	0	6	-	-
02/07/13	Days µ T > 0°C	4	29	31	28	31	30	31	31	30	20	2	0	267	-	-
Moraines	Mean	-6.7	-6.6	-7.5	-9.8	0.0	8.3	9.3	5.7	2.0	-3.6	-9.0	-8.1	-2.2	128	-
M	Maximum	-5.3	-5.6	-6.4	-8.3	1.4	11.2	11.8	7.5	2.8	-2.9	-7.9	-7.5	11.8	-	16.3
*2012	Minimum	-8.0	-7.6	-8.7	-11.1	-1.1	5.7	7.5	4.2	1.3	-4.3	-10.2	-8.7	-11.1	-	-19.9
**13/08/11-	F-T events	0	0	0	0	1	0	0	0	2	2	0	0	5	-	-
20/06/13	Days µ T > 0°C	0	0	0	0	15	30	31	31	19	0	0	0	126	-	-
Cliff fissure	Mean	-12.9	-10.0	-9.9	-7.3	3.4	6.6	11.0	7.1	3.4	-6.2	-9.1	-8.5	-3.0	148	-
N	Maximum	-0.5	-0.9	-1.4	14.8	21.1	20.7	31.8	29.6	21.9	0.7	-1.8	-2.0	31.8	-	31.7
*2008-09	Minimum	-24.7	-18.0	-16.7	-16.8	-4.9	1.1	1.1	1.3	-3.6	-13.9	-16.3	-18-0	-24.7	-	-24.7
**06/07/08-	F-T events	0	0	0	12	5	0	0	0	4	0	0	0	21	-	-
23/06/09	Days µ T > 0°C	0	0	0	3	29	23	28	31	23	0	0	0	137	-	-
Small temporary pond	Mean	-8.8	-11.4	-8.1	-7.1	-1.1	1.3	6.6	6.5	2.8	-0.9	-2.3	-4.4	-2.2	119	-
O	Maximum	-5.6	-5.1	-2.1	-1.6	-0.3	4.7	10.2	8.9	5.3	0.4	-0.3	-2.1	10.2	-	12.9
*2011	Minimum	-13.0	-14.4	-13.7	-11.3	-3.8	-0.3	3.5	4.3	0.4	-3.3	-4.9	-14.6	-14.6	-	-14.6
**05/06/10-	F-T events	0	0	0	0	0	1	0	0	0	0	0	0	1	-	-

Site		Winter		Spring			Summer			Autumn		Winter			Days > 0°C	
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		Data set
02/08/12	Days µ T > 0°C	0	0	0	0	0	22	31	31	30	4	0	0	118	-	-
Large permanent pond	Mean	-8.7	-7.2	-8.2	-9.3	-3.2	1.5	8.0	6.2	3.5	-0.6	-2.2	-3.0	-1.9	123	-
P	Maximum	-4.1	-2.2	-5.7	-7.7	-0.1	4.4	11.3	7.6	6.3	0.9	-0.4	-0.6	11.3	-	13.8
*2008-09	Minimum	-13.2	-13.3	-11.7	-10.8	-8.2	-0.1	4.2	4.9	0.7	-4.0	-4.5	-6.4	-13.3	-	-13.5
**12/08/08-	F-T events	1	1	0	0	0	1	0	0	2	0	0	1	6	-	-
09/08/09	Days µ T > 0°C	0	0	0	0	0	16	31	31	30	10	0	0	118	-	-

ANTARCTIC

		Summer		Autumn			Winter			Spring		Summer				
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		
Exposed hill summit (Jane Col)	Mean	2.7	1.6	1.0	-1.4	-0.8	-2.3	-5.1	-7.5	-5.2	-1.8	-1.8	-0.1	-1.7	89	-
Q	Maximum	14.6	18.4	11.6	1.9	0.2	-1.0	-3.1	-5.8	0	-0.1	-0.1	1.4	18.4	-	-
*2009	Minimum	-2.6	-3.9	-4.9	-8.6	-1.7	-4.6	-7.5	-8.7	-6.9	-2.6	-2.8	-0.9	-8.7	-	-
**01/01/09-	F-T events	13	16	13	6	0	0	0	0	0	0	0	3	51	-	-
31/12/09	Days µ T > 0°C	30	23	23	1	2	0	0	0	0	0	0	10	89	-	-
Antarctic polar desert (Mars Oasis)	Mean	5.3	0.5	-2.9	-13.5	-14.3	-17.6	-23.7	-17.7	-14.7	-10.1	-1.6	3.8	-9.0	87	-
R	Maximum	24.3	18.7	5.7	-3.9	-4.3	-6.6	-8.4	-4.5	-6.0	0.6	15.8	15.6	24.3	-	-
*2009	Minimum	-3.7	-7.7	-13.7	-24.1	-24.7	-30.9	-38.2	-35.1	-27.9	-23.1	-14.6	-6.8	-38.2	-	-
**01/01/09-	F-T events	19	23	10	2	0	0	0	0	0	0	15	22	91	-	-
31/12/09	Days µ T > 0°C	31	11	4	0	0	0	0	0	0	0	13	28	87	-	-
Cryodisturbed terrain (Coal nunatak)	Mean	5.5	-0.3	-4.9	-15.5	-11.8	-	-	-	-14.3	-12.7	-7.7	2.4	-6.5	66	-
S	Maximum	21.8	16.0	9.6	-3.3	-5.7	-	-	-	-11.1	-9.0	-0.1	19.4	21.8	-	-
*2009	Minimum	-5.8	-11.9	-15.5	-30.6	-19.7	-	-	-	-27.9	-17.1	-16.1	-7.3	-30.6	-	-
**01/01/09-	F-T events	22	30	9	0	0	-	-	-	0	0	0	26	-	-	-
31/12/09	Days µ T > 0°C	30	12	4	0	0	-	-	-	0	0	0	20	-	-	-

Site		Winter		Spring			Summer			Autumn		Winter		Days > 0°C	
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		Data set
Lichen fellfield (Anchorage)	Mean	5.7	3.5	-0.6	-4.6	-4.3	-6.9	-11.2	-7.5	-4.6	-4.7	-1.1	3.5	-2.8	101	-
T	Maximum	21.9	20.9	15.5	2.0	-0.4	-3.9	-4.0	-4.2	-1.1	-0.9	7.3	18.1	21.9	-	-
*2007-08	Minimum	-1.9	-4.6	-7.0	-12.4	-11.0	-11.8	-16.4	-12.7	-9.0	-9.0	-4.9	-4.9	-16.4	-	-
**01/01/07	F-T events	5	16	20	9	0	0	0	0	0	0	3	21	74	-	-
31/12/07	Days μ T > 0°C	31	27	8	1	0	0	0	0	0	0	4	30	101	-	-

Table 3. 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