

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

3
4 P. Convey¹, S. J. Coulson^{2,3}, M. R. Worland¹ and A. Sjöblom⁴

5
6 ¹British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, U.K.

7 ²Department of Arctic Biology, University Centre in Svalbard, Post Box 156, 9171
8 Longyearbyen, Svalbard, Norway

9 ³ArtDatabanken, The Swedish Species Information Centre, Swedish University of
10 Agricultural Sciences, Box 7007, SE-75007 Uppsala, Sweden

11 ⁴Department of Earth Sciences, Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden

12
13 Correspondence to: P. Convey (pcon@bas.ac.uk)

14
15
16 **Abstract**

17 Ground surface and sub-surface temperatures in the top few centimetres of the soil profile are
18 key in many environmental processes. They can vary greatly seasonally and at various spatial
19 scales across the often highly complex and heterogeneous landscapes of the polar regions.

20 Hence it is challenging to extrapolate these temperatures from meteorological air temperature
21 records. Ground surface and sub-surface thermal conditions are vital to the flora, fauna,
22 microbial activity, geochemistry, and physical characteristics such as the surface energy
23 budget. It is clear that the responses of the soil-associated biota of these regions to projected
24 climate change cannot be adequately understood without improved knowledge of how
25 landscape heterogeneity affects ground and sub-surface biological microclimates. Such data
26 are also important for determination of the surface energy budget and turbulent exchange
27 processes between the air and the land. Yet, few temperature data sets exist from these soil
28 surface layers of soils in the polar regions, especially over longer timescales.

29
30 Multi-annual temperature records from 20 sites representing a range of High Arctic and
31 maritime Antarctic ground surface and sub-surface soil habitats are described. We highlight
32 that (a) summer ground and sub-surface temperatures vary much more than air; (b) winter
33 ground temperatures were uncoupled from atmospheric temperatures; (c) the ground thawing

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

5 6 7 **Key words**

8 Terrestrial invertebrates, plants, microbiota, Arctic, Antarctic, energy exchange
9
10

11 **Introduction.**

12 Perhaps the most striking feature of the polar regions is their chronically low temperature,
13 resulting in extensive snow and ice cover, short growing seasons, often restricted vegetation
14 cover, and a stably stratified atmospheric boundary layer for most of the year. Annual mean
15 air temperature may be under 0°C and only achieve positive daily values for the few brief
16 summer months or weeks, and even not at all at the most extreme locations. Standard air
17 temperatures are often employed to designate the polar regions, for example, a frequently
18 cited definition of the Arctic is “land north of the 10°C July isotherm”, although other
19 latitudinal or political borders may also be employed on occasion (Meltøfte et al. 2013).

20 However, temperature at the ground surface and in the top few centimetres of sub-surface soil
21 layers may differ greatly from air temperature (Geiger et al., 2003). These temperatures play a
22 central role in polar soil activity, its characteristic floral and faunal communities and
23 microbially-mediated processes (Blair et al. 2006; Nowinski et al. 2010), such as the efflux
24 of CO₂ and methane (Davey et al. 1992; Oberbauer et al. 2007; Morgner et al. 2010; Cahoon
25 et al. 2012, Everatt et al. 2013; Nielsen and Wall 2013) and plant above ground/below ground
26 respiration ratios (Cooper 2004). Ground and sub-surface temperatures also influence the
27 surface energy budget through the ground heat flux, determining whether heat will be stored
28 in the ground or released to the atmosphere (Westermann et al. 2009; Sjöblom 2014).

29
30 Temperatures at the surface and in the upper centimetres of the soil profile are influenced by a
31 suite of local factors which may vary over short temporal and spatial scales including, for
32 example, vegetation type, degree and thickness of plant cover, depth of soil, soil type, form
33 and clast size, moisture content, the source of moisture, geomorphological features including
34 substratum, slope and aspect, and macroclimatic features such as solar angle, cloudiness and

1 atmospheric stratification. Exposed ground surfaces absorb solar radiation during the summer
2 period and, consequently, short-term temperatures may rise well above that of the air (Migala
3 et al. 2014). There is an increasing appreciation of the importance of winter climate as a
4 driver of polar species and community performance (Cooper 2015; Williams et al. 2015),
5 During the long winter periods the ground becomes uncoupled from solar forcing by ice and
6 snow cover, as well as the extended period of the polar night. Sub-nivean ground and
7 subsurface temperatures may consistently be well above the generally low air temperatures as
8 well as experiencing greatly reduced fluctuations (Convey et al. 2014; Cooper 2015).

9
10 Pools and ponds may either have a seasonal input of melt water, and hence remain cold owing
11 to constant flushing, or may be shallow and undisturbed with absorption of solar radiation by
12 dark bottom sediments, permitting elevated temperatures to be attained (Peck 2004; Rautio et
13 al. 2011; Toro et al. 2007). The chilling effect of cold water flushing from melting snow
14 patches may also apply to moist soils adjacent to such melt water sources (Migala et al. 2014).
15 The extremely heterogeneous mosaics that shape polar landscapes preclude broad
16 generalizations and, accordingly, necessitate detailed temperature records at appropriate
17 physical and biological scales. For ecologists, this is yet further complicated by the ability of
18 invertebrates and even some microbiota to move within this thermal mosaic (Woods et al.
19 2015). Consequently, there is no simple approach to estimate ground and shallow sub-surface
20 temperatures, a fundamental requirement for actual biological microhabitat description, from
21 standard air temperature observations.

22
23 In spite of the importance of surface and subsurface temperatures to the biosphere, lithosphere
24 and hydrosphere of polar environments, robust data are often lacking, especially datasets of a
25 year or greater, or even for only a complete summer season. While long-term temperature
26 data series from the greater depths typical of permafrost studies (e.g. Christiansen et al. 2010;
27 Guglielmin et al. 2008, 2012) or those focused on carbon and nitrogen storage (e.g. Migala et
28 al. 2014) exist, such installations rarely provide suitable data to describe conditions at the
29 ground or in sub-surface soil/vegetation layers of relevance to the terrestrial invertebrate and
30 microbial biota. As a result, few datasets describing biological microhabitat temperatures at
31 diverse sites and habitat types within one geographical location and one time frame exist.
32 Those that do are often restricted to at most one annual cycle, and more usually (part of) one
33 summer field season (e.g. Davey et al. 1992; Coulson et al. 1995, 2013; Migala et al. 2014),

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

3
4 One approach to circumvent the lack of ground and sub-surface temperature records in polar
5 regions is to model these temperatures, for instance using sophisticated neural network
6 approaches (Wu et al. 2013; Tabari et al. 2014). Such studies on temperature processes
7 (Kurylyk et al. 2014) are becoming increasingly important due to changes in ground
8 hydrology and soil stability as a consequence of rapid climate changes in the polar regions
9 (IPCC 2014). However, in regions with snow cover soil temperatures are decoupled from the
10 air temperatures that are often used as a predictor variable in these models for extended
11 periods. These studies also often focus on soil types, or depths, that are unrepresentative of
12 tundra conditions, in particular modeling soil temperatures at depths below those at which the
13 large majority of the polar soil fauna and microbiota occur (Kim and Singh 2014). Remote
14 sensing methodologies are also developing rapidly (Wang et al. 2011; Jagdhuber et al. 2014;
15 Bateni 2015), but currently remain relatively coarse and operate at scales that do not provide
16 appropriate resolution of the often extremely patchy polar landscapes.

17
18 Given this background, it is clear that a better developed appreciation of ground surface
19 temperatures is required to more fully comprehend biological processes at species,
20 community and ecosystem levels. Moreover, improved surface temperature datasets would
21 strengthen the parameterization of the ground flux, making it possible to calculate directly
22 rather than determining it as a residual as is often the case today (Sjöblom 2014). As
23 elsewhere, air temperatures measured by standard meteorological stations provide a poor
24 description, or predictor, of ground temperatures in the polar regions (Smith 1988; Davey et
25 al. 1992; Hodkinson 2003). Similarly, satellite measurements of ground surface temperatures
26 (Westermann et al. 2011) do not adequately describe summer microhabitat temperatures,
27 lacking resolution at the required microhabitat or temporal scales, and being unable to
28 measure conditions experienced under snow or ice cover in winter, spring or autumn. Thus,
29 despite the justifiably great emphasis placed on rapid contemporary warming trends identified
30 in global and regional meteorological datasets, including those in the polar regions (ACIA
31 2004; Convey et al. 2009; IPCC 2014; Turner et al. 2014), at present it is not possible to link
32 these with probable ground surface or microhabitat temperature trends. This represents a
33 major lacuna in knowledge, especially in the context of the emphasis given in the polar
34 literature, and elsewhere, to understanding the perceived biological responses to these

1 climatic changes (Convey 2011). It is essential to include topoclimate – small-scale modelling
2 of climate driven by fine-scale variation in topography, vegetation and soil (Slavich et al.
3 2014) – in species distribution models to avoid misleading conclusions, for instance
4 concerning alterations in species ranges. Moreover, numerical weather and climate models
5 have a larger uncertainty in polar regions than elsewhere (e.g. Overland et al. 2011). A major
6 reason for this relates to how small-scale features on a sub-grid scale are parameterised, both
7 because the local characteristics in polar regions are not taken into account, and of a general
8 lack of knowledge of these processes.

9
10 To provide impetus to advance this field, we here describe 20 datasets documenting ground,
11 sub-surface and microhabitat temperatures at a range of High Arctic (Svalbard) and maritime
12 Antarctic (South Orkney Islands, Marguerite Bay and Alexander Island) locations (Fig. 1).
13 We present data collected over periods of one or more years during various sampling
14 campaigns between 2006 and 2014 and recorded in a variety of ground and vegetation
15 habitats, in order to illustrate the potential value of these datasets. We do not attempt to
16 describe the full extent of inter-annual variation at a particular location or habitat, rather
17 providing (i) representative datasets of a year or greater for ground surface temperatures so as
18 to give a background within which studies may be set, and (ii) descriptors for the thermal
19 environments at each location, (iii) considering the relationships between ground
20 temperatures, habitat type and air temperature recorded at standard meteorological stations,
21 (iv) enabling extrapolation to other regions within the Arctic and Antarctica, v) showing the
22 local character of the ground heat flux in the surface energy budget, and finally, vi) making
23 available the cleaned temperature data in the online supplementary electronic material.

24 25 26 **Materials and Methods**

27 *Site descriptions*

28 Arctic

29 The Svalbard archipelago is centred on the principle islands of Spitsbergen, Nordaustlandet,
30 Edgeøya and Barentsøya at approximately 78° N, 12° E (Fig. 1b) in the European High
31 Arctic. The islands have a land areal extent of 62,000 km², 60% of which is permanently
32 covered by ice or snow (Hisdal 1985). The West Spitsbergen Current, a branch of the North
33 Atlantic Drift, transports considerable heat to Svalbard from lower latitudes. The result is that
34 the climate of the islands is mild for their latitude - the annual mean air temperature at

1 Svalbard airport is -6.7°C , but four months have positive mean air temperatures, ranging from
2 $+0.3^{\circ}\text{C}$ in September to $+5.9^{\circ}\text{C}$ in July (Norwegian Meteorological Institute,
3 www.eKlima.no). The west coast has the greatest precipitation (525 mm per year) but the
4 interior regions are substantially dryer; for example Longyearbyen, 50 km from the west
5 coast, receives an annual amount of 210 mm. Most precipitation falls during the winter as
6 snow. Floral communities include sub-zones A (polar desert), B (northern Arctic tundra) and
7 C (middle Arctic tundra) of the Arctic vegetation classification (Jonsdóttir 2005). For this
8 study, 16 sites on Svalbard were selected to describe a wide range of ground, vegetation and
9 freshwater types (Fig. 1d). Site descriptions are provided in Supplementary Table 1, and
10 illustrative photographs in Supplementary Fig. 1a,b.

11 Antarctic

12 The four Antarctic sites were selected to represent a range of habitats within the full
13 latitudinal range of the maritime Antarctic (Fig. 1a; Supplementary Fig. 1c): *Exposed hill*
14 *summit* (Jane Col, Signy Island, 60°S), *Lichen fellfield* (Anchorage Island, 68°S), *Antarctic*
15 *polar desert* (Mars Oasis, Alexander Island, 72°S) and *Cryodisturbed land* (Coal Nunatak,
16 Alexander Island, 72°S) (Supplementary Table 1). The ameliorating effects of the ocean to
17 the west maintain a relatively mild climate in the maritime Antarctic with a comparatively
18 narrow range of seasonal temperatures and mild, wet summers. Mean monthly air
19 temperatures in coastal areas are slightly positive ($0\text{-}2^{\circ}\text{C}$) for 1-4 months in summer, dropping
20 to -10 to -15°C in winter (Walton 1982; Convey 2013). On Signy Island, the prevailing winds
21 are from the south-west to north-west with occasional warm Föhn effects created by the 1,200
22 m high mountain barrier of central Coronation Island to the north. Frequent thick low clouds
23 and lack of sunshine are typical features of the climate, with high frequency of precipitation.
24 Anchorage Island similarly experiences a climate for much of the year that is stabilized by the
25 adjacent ocean, although a more continental and colder climate characterizes winter after the
26 formation of sea ice to the west in the Bellingshausen Sea, and cloud cover is generally less.
27 The southernmost exposures of snow- or ice- free ground in the maritime Antarctic occur in
28 south and east Alexander Island. The two sites considered here, *Cryodisturbed terrain* (Coal
29 Nunatak, site Q), and *Antarctic polar desert* (Mars Oasis, site R) (Fig. 1a), provide an
30 environment intermediate between the typical maritime Antarctic and the drier, cold desert
31 ecosystems of the continental Antarctic. Being sheltered from maritime weather systems
32 approaching from the west and often under the influence of stationary continental high
33 pressure systems to the east/south, these experience low precipitation, and provide the closest
34

1 comparison with continental "Dry Valley" systems that is present in the Antarctic Peninsula
2 region (Smith 1988; Convey and Smith 1997).

4 *Data collection*

5 Loggers were positioned in 20 diverse habitat forms selected to be representative of the range
6 of the terrestrial and freshwater surfaces and habitats occurring in the High Arctic and the
7 maritime Antarctic (Supplementary Table 1, Supplementary Fig. 2a,b,c.). Because, as is often
8 the case with currently available biological microclimatic datasets, the loggers were deployed
9 within different studies and monitoring programs over time, they represent several, and in
10 some cases non-overlapping, years. Logistic and technical difficulties are a particular problem
11 in servicing stations at remote and un-manned sites such as these, with the result that there are
12 occasional data missing from various intervals during the campaign periods. The
13 microclimate temperature data considered in this article are provided in spreadsheet form in
14 Supplementary Table 2.

16 Arctic

17 Temperatures were recorded at a depth of approximately 1 cm using Tinytag dataloggers,
18 TGP-4020 (Gemini, Chichester, West Sussex, U.K.) fitted with PB-5001, PB-5009, or PB-
19 5006 external thermister probes, except for the *Small temporary* and *Large permanent ponds*
20 (sites O and P) where TG-4100 submersible loggers were deployed at approximately 10 cm
21 water depth. For logger and probe locations see Supplementary Table 1. Care was taken to
22 avoid exposing the sensors to direct insolation. Sampling interval was 30, 60 or 120 min,
23 depending on logger memory and expected campaign period.

25 Standard meteorological air temperatures were taken from Norwegian Meteorological
26 Institute stations (www.eKlima.no). Air temperatures at Rjipfjord were collected by the
27 meteorological station established by the CLEOPATRA project ([http://www.mare-
29 incognitum.no/](http://www.mare-
28 incognitum.no/)) at a height of 4.5 m using solar shielded, naturally ventilated PT1000 sensors
30 connected to a Campbell CR1000 logger (Campbell Scientific, U.K.). Temperatures were
31 logged every hour, and the data presented are the mean of recordings taken every minute.
32 Locations of the meteorological stations are presented in Supplementary Table 1 and Fig. 1c.

33 Antarctic

1 Ground and air temperatures were recorded using temperature probes (copper/constantan
2 thermocouple wires) (HMP45C; Campbell Scientific, UK). For ground temperatures the
3 probe was inserted into the ground surface so as to record surface conditions. Air
4 temperatures were recorded at a height of 2 m within a naturally ventilated solar insolation
5 shield. Data were recorded every hour for the duration of the study using Campbell Scientific
6 CR10X loggers (Campbell Scientific, U.K.).

9 **Results and Discussion**

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

17 *Observation 1: air temperatures show the greatest range during the winter months.*

18 Annual air temperature at Svalbard airport (2011) (Longyearbyen, Fig. 2a) was -3.3°C .
19 Maximum and minimum air temperatures at this location ranged between -31.5 and $+17.1^{\circ}\text{C}$
20 (Table 1a, Fig 2a). The summer period showed the minimum range in temperature extremes.
21 At Svalbard airport summer temperatures did not decline below 0°C . During other seasons air
22 temperatures regularly fluctuated between positive and negative values (freeze-thaw events)
23 especially in spring and autumn. Mean monthly temperatures varied between a winter
24 minimum of -15.2°C in January and a summer maximum of $+6.9^{\circ}\text{C}$ in July and August.

26 Mean annual air temperatures were lower in the north and east of Svalbard (Crozierpynten,
27 Rijpfjord and Kapp Heuglin) at around -5°C , than at locations further west (Sørkappøya,
28 Svalbard airport, Ny-Ålesund) (Table 1a, Fig. 2a), illustrating the effects of the different
29 ocean currents and air masses influencing regions of the archipelago (Coulson et al. 2014;
30 Przybylak et al. 2014). The more continental Sveagruva, located at the head of van
31 Mijenfjord, recorded intermediate values. Although air temperatures on the far north coast of
32 Svalbard at Crozierpynten and Rijpfjord were often lower than those at Svalbard airport, they
33 followed a similar profile. Minimum temperatures recorded were -38.8 and -33.6°C
34 respectively compared with -26.4 and -30.5°C at Ny-Ålesund and Svalbard airport. Freeze-

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

7
8 Air temperatures at the four Antarctic sites (Table 1a, Fig. 2b) varied between locations.
9 *Lichen fellfield* (2007) and *Exposed hill summit* (2009) were generally similar despite being
10 separated by eight degrees of latitude. Mean annual temperatures were greatest at *Exposed hill*
11 *summit* with an annual mean of -3.9°C (2009). This was due largely to the warmer winters
12 (mean monthly winter temperatures -12.5 to -8.2°C) raising the mean temperature, rather than
13 to warmer summers (0 to $+1.7^{\circ}\text{C}$). This site also experienced a large number of freeze-thaw
14 events (130 annually). The *Lichen fellfield*, with a slightly lower mean annual air temperature
15 of -4.4°C , experienced fewer freeze-thaw events (98). Both sites had fewest freeze-thaw
16 events in the austral summer and the greatest frequency in the winter period, in clear contrast
17 to the Arctic sites. The most southern location, *Cryodisturbed terrain*, at a similar altitude to
18 *Exposed hill summit* but 12 degrees of latitude further south, was somewhat colder than either
19 *Exposed hill summit* or *Lichen fellfield*, although temperature data for mid-winter are missing.
20 For months with comparable data, *Cryodisturbed terrain* was consistently colder than
21 *Exposed hill summit*, with the exception of very similar temperatures in January and
22 December (mid-summer). *Antarctic polar desert*, located on the ice-shelf-bound east coast of
23 Alexander Island, less than 50 km from *Cryodisturbed terrain* and part of the same geological
24 formation, had the most extreme climate of the Antarctic sites studied, with a mean annual air
25 temperature of -10.6°C . Summer temperatures were similar to the other Antarctic locations,
26 but the minimum winter mean monthly temperature was -24.7°C (July). Despite the low
27 annual temperatures there were a high number of freeze-thaw events (100), peaking in
28 December.

29
30 *Observation 2: summer ground temperatures mirror air temperature fluctuation but with*
31 *greater range and higher peaks due to solar forcing. Winter ground temperatures are*
32 *uncoupled from air temperatures due to insulation by snow and ice cover and display milder,*
33 *and more constant, temperatures.*

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

16

17 Several Arctic locations showed site-specific ground temperature features. Maximum summer
18 temperatures were experienced in *Cliff fissure*, where +31.8°C was recorded in July but,
19 throughout the summer, minimum monthly temperatures were close to 1°C (Table 1b). The
20 coldest location in summer was *Arctic polar desert* on Nordaustlandet (Kinnvika). Here, sub-
21 zero ground temperatures were encountered throughout the year and mean summer
22 temperature (June through August) was only +2.5°C. Despite being the most northern site,
23 and with air temperatures in the region regularly falling below -20°C (Table 1a), winter
24 ground temperatures at Rippfjord rarely declined below -10°C (Table 1b, Fig. 4).

25 *Anthropogenic soils* were unique, with extremely mild winter temperatures and cool summer
26 conditions. Here, ground temperature remained close to 0°C throughout the winter despite the
27 low air temperatures. Warming was slow in spring and ground temperature remained often
28 below that of the air.

29

30 Both freshwater sites showed similar temperatures, but with variations in late summer when
31 the water level in *Small temporary pond* fell and the logger was in reality recording
32 temperatures in waterlogged moss and mud. Water temperatures were mild and more
33 constant, with damped fluctuations compared to air temperatures (Fig. 4b, Table 1a, b).

34

1 Of the four Antarctic sites, ground temperatures at the *Exposed hill summit* showed the most
2 constant profile, with an annual mean of -1.7°C and annual maximum and minimum of $+18.4$
3 and -8.7°C respectively. The temperature rose rapidly to 0°C in austral late winter (early
4 October), and thereafter remained relatively constant close to -2°C . In contrast to the other
5 three Antarctic sites, but similar to many of the terrestrial Arctic sites, the *Exposed hill*
6 *summit* experienced a long period close to 0°C during the spring thaw, in this case 32 days
7 (Fig. 4c). As with air temperature, the *Antarctic polar desert* experienced the most extreme
8 ground temperature regime. Ground temperature declined to a minimum of -47.5°C at mid-
9 winter (July) and reached a summer maximum of only $+8.6^{\circ}\text{C}$ (Table 2b, Fig. 4c). Mean
10 annual air temperature at this site was -10.6°C and only 1-2 months had positive mean
11 temperatures. *Cryodisturbed terrain* had a similar temperature profile to the *Antarctic polar*
12 *desert* but data were missing for mid-winter. At the *Lichen fellfield*, the annual mean ground
13 temperature was -2.8°C . The annual ground temperature profile resembled that of the *Dryas*
14 *tundra* habitat in the Arctic, with three months experiencing positive mean temperatures and
15 maximum and minimum daily temperatures of $+21.9$ and -16.4°C . Additionally, the ground
16 temperature profile displayed a similar warming pause where, during the spring melt, the
17 ground took 8.6 days to warm from -1.0°C to above 0°C . In contrast to the Arctic, there was a
18 similar pause in the autumn when the ground required 6.2 days to cool from 0 to below -1°C .
19 While the *Exposed hill summit* had an extended warming pause (15.5 days to warm from -1°C
20 to become positive) there was no equivalent pause during cooling in the autumn.

21

22 Interpretation

23 Ground temperatures in the Arctic are clearly influenced by seasonal variation in air
24 temperatures. During the summer periods, all ground and water temperatures presented here
25 mirrored air temperatures to a greater or lesser extent. The solar forcing and the low albedo of
26 the ground surface results in an unstable stratified atmospheric boundary layer, elevated
27 ground temperatures and cumulative degree days (0°C baseline) (Fig. 5, Table 2), often above
28 corresponding air temperatures. However, the number of days with mean daily temperatures
29 above a 0°C baseline was often greater in the air than in the ground (Table 1a, b) due to the
30 extended period in the spring when the ground was insulated from rising air temperatures by
31 snow and ice cover, which caused a clear uncoupling of ground and air temperatures. Ground
32 and sub-surface temperature fluctuations were clearly decreased during this period and
33 temperatures remained almost constant with slow rates of change. The insulating effect of
34 winter snow cover is well appreciated (Leinaas 1981; Cooper 2015), insulation efficiency

1 varying with snow depth and form. More recently Convey et al. (2014) observed that soil
2 temperatures under 1 m of snow at the *Saline meadow – wet* (site H in this study) remained
3 close to -2°C throughout the winter and until March despite air temperatures declining to -
4 26.8°C. Snow accumulation was less at the adjacent *Saline meadow – dry*, with a maximum
5 snow depth of only 30 cm. At this site, soil temperatures declined gradually through the
6 winter, reaching a minimum of -12.3°C during the campaign period. However, there were
7 exceptions to this pattern, such as the spike in ground temperature noted at *Dryas tundra* on
8 March 17 2011 (Fig. 4a), which coincided with air temperatures becoming positive on 16
9 March and rising to +3.5°C, along with 18.2 mm of precipitation, likely as rain, on 17 March
10 (www.eKlima.no). Such rain-on-snow (ROS) events result in rainwater percolating through
11 the snow pack to the frozen ground surface and elevate the ground surface temperature
12 (Hansen et al. 2014) due to both the temperature of the water on deposition and also the
13 release of latent heat as this water freezes on contact with the impermeable frozen ground.
14 Although the ground temperature rose rapidly in this event to -0.2°C, it remained below 0°C
15 and there was no freeze-thaw event. A greater ROS event occurred in January–February 2012.
16 On this occasion above-zero air temperatures (up to +7°C) occurred across the entire Svalbard
17 archipelago along with record precipitation, with up to 98 mm rainfall in one day at Ny-
18 Ålesund. This exceptionally rare event (return period of >500 years prior to this event),
19 combined with a two-week-long warm spell during which 272 mm of precipitation was
20 received, caused increases in permafrost temperatures to a depth of at least 5 m, induced
21 infrastructure-damaging slush avalanches and created ground-ice cover of up to 20 cm
22 thickness (Hansen et al. 2014). During this ROS event ground sub-surface soil temperatures
23 warmed to just under 0°C but, as above, did not continue increasing to the point of a freeze-
24 thaw event.

25

26 The uniquely mild winter climate of the *Anthropogenic soil* is likely a consequence of the
27 deep snow accumulation in the gully that forms this location and possibly thermogenic
28 decomposition processes in the rich organic soils. These soils are discarded chernozym soils
29 originally imported from the Ukraine or southern European Russia for use in the settlement's
30 greenhouse (Coulson et al. 2013a,b). The slow warming recorded in spring, and soil
31 temperatures often remaining below that of the air, may be due to the presence of an
32 insulating cover of tall, alien plant species, for example *Anthriscus sylvestris* (Governor of
33 Svalbard 2014), providing a moist and shaded environment.

34

1 Freshwater pond temperatures remained below air temperature and displayed less diurnal
2 variation. At the *Large permanent pond* this was likely due to the large thermal mass of the
3 water body. Small ponds in the Antarctic have been shown to achieve summer temperatures
4 greater than that of the air (Peck 2004). However, the *Small temporary pond* is fed for a large
5 part of the early summer by melt water from a receding snow patch. This constant input of
6 cold water likely holds the pond temperature low despite the extended insolation experienced
7 during the period of the midnight sun.

8
9 In the Antarctic, ground temperatures also reflected those of the air. Similar to the Arctic
10 sites, winter temperatures were decoupled from air at three of the locations, indicating the
11 presence of a significant snow cover. The exception to this generalisation was at the *Antarctic*
12 *polar desert*, where ground temperature fluctuations remained strong throughout the winter,
13 indicating that snow cover was limited in extent. This site is depicted in Supplementary Fig.
14 1c at mid-winter (1 June 2007) when it exhibited only a thin and patchy snow cover. The
15 temperature profile for the *Exposed hill summit* presented in this analysis (year 2009) matches
16 very closely the data of Davey et al. (1992) from the same site recorded 22 years previously
17 (1987). Here the summer temperatures peaked at approximately +17°C, with winter minima
18 of -8°C. Furthermore, Davey et al. (1992) present snow depth data indicating a peak depth of
19 80 cm in July (austral winter).

20
21 It is consequently clear that, while summer ground conditions can be imprecisely estimated
22 from air temperatures - with an understanding of the ground surface and prevailing
23 insolation/cloudiness - there is very great site heterogeneity. Maximum and particularly
24 minimum temperatures, for example lower and upper thermal death points, may have more
25 biological significance than the means often used to present weather and climate temperature
26 data. Neither has the ability of fauna to move and find the most favourable thermal regime
27 within particular microhabitats been fully taken into account (Woods et al. 2015). Moreover,
28 once snow cover has begun to accumulate, and despite the presence of permafrost and the
29 polar night, the uncoupling of the ground from the air results in rather mild sub-nivean
30 conditions where temperatures typically are between -5 to -15°C, and sometimes closer to 0°C
31 (compare with Convey et al. 2014). In contrast, in areas such as the *Antarctic polar desert*
32 with no, or thin, winter snow accumulation, the ground may be substantially colder. Here
33 ground temperature declined to a winter minimum of -38.2°C during the study period.

34

1 *Observation 3: the thawed summer season in the ground may be considerably shorter than*
2 *the period of positive air temperatures due to the timing of release from snow-ice cover.*
3 The timing of the transition from largely negative to positive temperatures was very different
4 between ground and air, as illustrated by temperature accumulation curves (degree days above
5 0°C) (Fig. 4, Table 1a, b). The number of days with a mean temperature above 0°C was
6 generally greater in the air than for the soil surface. For example, while Svalbard airport
7 recorded 151 days with a mean daily air temperature above 0°C, at the *Dryas tundra*, only 8
8 km distant and in the same valley system, only 120 such days occurred in the ground and sub-
9 surface (Table 1a, b). Similarly, while air temperature in Svalbard became positive in late
10 April/early May, ground and sub-surface temperatures only started to accrue degree days later
11 in spring towards the end of May or early June. The *Cliff fissure* was the first location to thaw,
12 with temperatures rising above 0°C from 30 May, and the latest was *Arctic polar desert*,
13 where ground and sub-surface temperatures only became positive after 6 July (julian day 187)
14 (Fig. 4). During the spring period ground temperatures showed an initial tendency to warm to
15 close to 0°C, remain stable for a period and then climb rapidly to track air temperature
16 fluctuations (Fig. 3a, b). For example, ground temperature at the *Dryas tundra* warmed from a
17 mid-winter minimum of -17.7°C to reach -1.5°C on 25 April, then remained between -0.2 and
18 -3.3°C until 31 May when it first became positive (Fig. 3a). Daily mean ground temperatures
19 at the *Dryas tundra* then remained above 0°C for 120 days (Table 1a). At the most northern
20 site, *Arctic polar desert*, ground surface temperatures first became positive around 5 July in
21 2008 (julian day 186), some 35 days later than at the more southern *Dryas tundra* (Table 1a,
22 Fig. 4). Moreover, the *Arctic polar desert* ground also began to freeze earlier in autumn,
23 providing a thawed period of only 74 days. Ground freezing at the *Dryas tundra* commenced
24 on 19 September, although the site continued to experience periods of positive temperatures
25 until 29 November, after which point there was no further accrual of degree days (Figs. 3a, 4).
26 At the *Arctic polar desert*, ground temperatures dipped below 0°C for the first occasion in the
27 autumn on 29 August. Again, some temperature cycling followed, but temperatures were
28 constantly below 0°C after 24 September. For most Arctic sites the winter period (ground
29 permanently frozen) typically commenced in early October (Figs. 3a, b, 4).
30
31 In the Antarctic the first site to attain positive ground temperatures was the southern *Antarctic*
32 *polar desert*, on 14 November 2012, followed by *Lichen fellfield*, *Cryodisturbed terrain* and
33 *Exposed hill summit*, the latter finally thawing on 20 December (Fig. 3c). Due to the large
34 number of freeze-thaw events at the Antarctic sites throughout the year (Table 1b) the precise

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

22 23 Interpretation

24 The duration of the summer period that the ground surface experiences is largely dependent
25 on the snow free-period, though it should be noted that some processes, such as significant
26 soil microbial activity may occur under snowpack at high sub-zero temperatures (Schmidt
27 1999; Larsen et al. 2002; Cooper 2015), as may photosynthesis in some polar lichens
28 (Schroeter et al. 2011). Thawing at the soil surface may effectively lead to a small
29 ‘greenhouse’ space under snow cover, allowing physiological and ecological activity in soil
30 microbial, invertebrate and plant communities (Aitchison 1979; Cockell et al. 2004; Pauli et
31 al. 2013; Cooper 2015). The duration of the summer thawed period is controlled by many
32 factors including precipitation quantity, wind redistribution of fallen snow, and rate of melt
33 during the spring thaw. For the High Arctic sites, the date of ground release from snow was
34 consistently after the beginning of the period of midnight sun (around 19 April in Svalbard)

1 and varied by 35 days across the study sites, resulting in a “summer” some 1.6 times longer in
2 duration at *Dryas tundra* than at the northernmost *Arctic polar desert*.

3
4 Great inter-annual variation in the length of the summer period, as defined by the snow-free
5 season, occurs. An example is provided by the timing of the break of the stem of a distinctive
6 champagne-glass-shaped snow patch on Operafjellet close to Longyearbyen (Svalbard) (Fig.
7 5a). Voting to predict the date the stem ‘breaks’ has been a popular competition in the local
8 community, and the date the snow patch clears has been carefully noted from at least 2004.
9 During this 11 year period the date the ground under the “stem” has been released from snow
10 and ice has varied between 28 June (2005) and 31 August (2012) (Fig. 5b), with a median date
11 of 19 July (julian day 201). Clearly the date this particular patch of ground clears will be
12 dependent on multiple micro- and macro-scale environmental variables such as snow
13 accumulation (itself dependent on multiple variables), icing, sunshine or cloudiness, and air
14 temperature. Nevertheless, this example integrates these variables to demonstrate at a specific
15 location the potential extent of inter-annual variation in date of snow clearance and the
16 resulting duration of the summer period. Such variations in duration of the thawed summer
17 period have consequences for the flora and fauna (Ávila-Jiménez and Coulson 2011).

18
19 Changes in precipitation, especially during the winter season, are projected by many climate
20 models but are hard to estimate with accuracy (ACIA, 2004; SWIPA, 2011) and will be site
21 specific. However, it is clear that the environmental changes that result in either more rapid,
22 or delayed, spring snow clearance will have a potentially dramatic influence on ground/sub-
23 surface ecosystems via modulating the duration of the snow-free season and the energy
24 budget of the ground (Ávila-Jiménez and Coulson 2011; Cooper 2015). An exception to the
25 general observation that mean daily air temperatures were above 0°C for a greater proportion
26 of the year than those of the ground is that of the *Anthropogenic soils* in Barentsburg. Here
27 the soils had a temperature mean of greater than 0°C for 271 days. This unusual situation
28 results from the deep organic soils probably generating some heat through decomposition
29 processes, combined with insulation from dense plant cover and the deep accumulation of
30 snow in the gully that forms this site (Coulson et al. 2013a, b).

31
32 *Observation 4: in the High Arctic ground freeze-thaw events only occur in the autumn. At the*
33 *lower latitude sites in the Antarctic freeze-thaw events also occurred in the spring.*

1 In contrast to the occurrence of freeze-thaw transitions in air temperature in both spring and
2 autumn at the Arctic sites, soils only experienced such cycling in the autumn (Table 1a, b,
3 Figs. 2a, b, 3a-c). At the *Dryas tundra*, for instance, although the ground surface temperature
4 was between -3.3 and -0.2°C for 36 days in spring 2011, no freeze-thaw events occurred
5 (Table 1b, Fig. 3a). In the autumn, the same site had its only two such events in September
6 2011 (compared to a September ground count of five and an annual sum of 60 in the air)
7 (Tables 1a, b, Fig. 2a). The *Arctic polar desert* also did not experience freeze-thaw events
8 during the spring melt period (Table 1a, Fig. 3a) while nine such events occurred during the
9 autumn freeze and there were 47 freeze-thaw transitions in the air during the nine months the
10 meteorological station on Nordaustlandet (Rjipfjord) was functioning. The single exception to
11 the pattern of freeze-thaw events in the ground being absent in the spring was at the *Cliff*
12 *fissure*, which experienced events in both the spring and autumn and had the greatest event
13 frequency (21 events in 2008-09) of all the ground sites.

14

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

21

22 In contrast, the Antarctic sites all showed extensive freeze-thaw cycling in the ground surface
23 during both spring and autumn periods, with between 51 and 91 such events being recorded.
24 Freeze-thaw events also occurred in the ground during the winter period (Fig. 3c, Table 1b).
25 The maximum frequency was seen at the *Antarctic polar desert*, with 15 cycles in the autumn,
26 64 in winter and 12 in spring. None of the Antarctic locations experienced freeze-thaw events
27 in the summer months.

28

29 Interpretation

30 Snow cover had a clear effect on the frequency of freeze-thaw events experienced by the
31 ground surface. Air temperatures in Svalbard displayed numerous freeze-thaw events in both
32 spring and autumn, but freeze-thaw events only occurred in the ground during the autumn and
33 then before a snow cover had accumulated. The only exception to this pattern was the *Cliff*
34 *fissure*, a site where snow cover was absent throughout the year due to the vertical nature of

1 the cliff (Supplementary Fig. 1b). At the other locations in the Arctic, spring ground
2 temperatures revealed a very characteristic profile as the snow pack and underlying soils
3 warmed to become isothermal at close to 0°C, but then remained stably frozen for up to 36
4 days. The snow pack finally melted in late May or early June, exposing the ground to the 24 h
5 insolation of the midnight sun which commences, at the latitude of Longyearbyen (78° 13'
6 14''N, 15° 37' 59''E), on 20 April and lasts until 23 August. Solar forcing then raised the
7 ground temperature rapidly by c. 6°C, with only small diurnal temperature variation, and no
8 freeze-thaw events being recorded either in the air or the ground. The situation was different
9 at the lower latitude maritime Antarctic sites where at all locations freeze-thaw events were
10 common in both spring and autumn, and even in winter at sites where there was lower overall
11 snow accumulation and thermal protection (Fig. 3c, Supplementary Fig 1c). The lower
12 latitude location of the maritime Antarctic sites also results in a shorter (Alexander Island,
13 Anchorage Island), or non-existent (Signy Island), period of midnight sun. These sites
14 therefore experience a greater diurnal variation in the degree of solar forcing of ground
15 temperatures and exhibited a greater frequency of ground freeze-thaw events than in the High
16 Arctic.

17
18 Under current climate modeling scenarios and projected warming, the frequency of freeze-
19 thaw events is expected to increase at low polar latitudes (ACIA 2004; SWIPA 2011; Turner
20 et al. 2009, 2014). At the Antarctic sites considered here, given the evidence for relatively
21 limited winter snow cover/depth, this may result in increased frequency of freeze-thaw events.
22 But, while an increase in freeze-thaw events in the air may be anticipated in the Arctic, this
23 might not translate to an increased frequency of such events in the ground and sub-surface
24 layers, due to the presence of considerable snow cover in spring with ground release well after
25 the period of the midnight sun has commenced.

26
27 *3.5 Observation 5: rates of ground temperature change were generally low; amongst the*
28 *fastest rates of change occurred during the winter associated with rain-on-snow events.*

29 Ground and sub-surface temperature generally displayed slow rates of change during the
30 summer. For example the *Dryas tundra* showed a peak warming rate of 1.8°C hr⁻¹ on 23 June
31 2011 when the temperature rose from +8.9°C at 1200 to a maximum of +14.2°C at 1500.
32 Cooling rates were similarly slow, typically varying between 0.3 and 1.5°C hr⁻¹. The *Cliff*
33 *fissure* displayed amongst the greatest rates of change where, on 23 July 2008, the 'daytime'
34 surface temperature reached a maximum of +31.8°C (Fig. 3b, Table 1b). At 2230 the

1 temperature was still above +30°C while, three hours later, it had decreased to +19.7°C, a rate
2 of 3.5°C hr⁻¹, and then continued to decline to a minimum of +12.3°C over the next 11 h.
3 Warming rates at this location were similarly rapid, increasing from +10.4 to +28.7°C over 5
4 h (3.7°C hr⁻¹), on 23 July 2008.

5
6 Ground temperatures were often constant during winter and spring periods, or showed only
7 limited temperature fluctuation, with rates of change rarely greater than 0.1°C hr⁻¹.
8 Nonetheless, on 17 March 2011 ground temperatures at *Dryas tundra* rose rapidly from -
9 7.8°C at 1700 to -1.3°C at 1800 and then -0.2°C (Fig. 3a), where they remained until 1800 on
10 18 March, after which they started to decline steadily, returning to -7.8°C at 0300 on 23
11 March, some 4.8 days later. This involved warming and cooling rates of 3.8° (and 6.5° over
12 the first hour) and 0.07°C hr⁻¹, respectively. By contrast the *Large permanent* and *Small*
13 *temporary* ponds showed only slow rates of temperature rise due to the greater specific heat
14 capacity of the water masses. Similar patterns were reported in freshwater pools on
15 Anchorage Island in the Antarctic by Peck (2004).

16
17 The *Antarctic polar desert* ground and sub-surface temperature fluctuations were also large
18 and rapid, particularly in winter (Fig. 3c). For instance, on 7 July 2012 (mid-winter) the
19 ground temperature began to rise steadily from a minimum of -37.5°C. Some 29 h later it had
20 become slightly positive (+0.17°C), an average warming rate of 1.3°C hr⁻¹. The temperature
21 subsequently cooled to -14.8°C over 10 h, a cooling rate of 1.5°C hr⁻¹. Similar magnitude
22 temperature swings were evident at the other maritime Antarctic sites but at slower rates.

23 24 Interpretation

25 The rates of temperature change in soils were generally slow, often as little as 0.03°C hr⁻¹, and
26 even with solar forcing during the period of the midnight sun only realizing 1.8°C hr⁻¹. While
27 more rapid rates do occasionally occur these are often exceptions associated with the arrival
28 of warm moist air masses from lower latitudes (Førland et al. 2011) or Föhn winds (*Exposed*
29 *hill summit*). Such warming was particularly rapid when associated with these warm air
30 masses bringing rain-on-snow events. In such circumstances, rain percolates through the snow
31 pack to freeze on the ground surface, which both warms the ground surface rapidly, as seen at
32 the *Dryas tundra* in 2011, but also creates a surface ice lens (Putkonen and Roe 2003). Such
33 surface icing can have significant detrimental biological effects, often leading to high
34 overwintering mortality in reindeer (Kohler and Aanes 2004; Hansen et al. 2014) and soil

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

4
5 Site-specific characteristics may also have an important influence on ground temperatures.
6 The *Cliff fissure* was situated on a south-westerly facing cliff and was free of snow cover
7 throughout the winter. During the period of the polar night, temperatures in the fissure closely
8 followed variation in air temperature. However, after the return of the sun, and direct solar
9 insolation onto the cliff face, the cliff temperatures began to display pronounced diurnal
10 variations with the face warming up considerably during the afternoon and early evening.
11 Similarly, the thermal mass of the freshwater sites largely eliminated diurnal, or rapid,
12 temperature fluctuations (*cf.* Peck 2004; Peck et al. 2006).

13
14 *Observation 6: accumulated thermal sum in the ground usually greatly exceeded the*
15 *equivalent air cumulative degree days (CDD); however, this was site-specific and, on*
16 *occasion, air CDD could surpass ground surface*

17 Cumulative temperature sums (degree days above 0°C) in the air and ground were
18 substantially different at all sites (Fig. 4). As noted above, the ground warmed above 0°C later
19 in the year than the air due to late release from snow and ice cover. However, once ground
20 warming had commenced, the ground temperature often rose quickly above that of the air. For
21 example, the thermal sum of the *Dryas tundra* ground lagged behind that of the air until 13
22 June but then reached a maximum value on 27 September at 786 degree days, some 4.4%
23 greater than the comparable air temperature sum (Table 2). A similar overall pattern, but
24 greater response, was observed at the *Cliff fissure*, which started to accumulate degree days on
25 30 May and accrued a greater thermal sum more rapidly than air temperature during the
26 period the loggers were operating in 2008 (Fig. 4). This pattern was repeated at many of the
27 other locations (Fig. 4, Table 2). Exceptions included the *Arctic polar desert*, where the
28 ground remained significantly colder than the air, accruing a thermal sum 68% lower than that
29 of the air, and the freshwater habitats, where water temperatures remained below air
30 temperature for much of the summer.

31
32 At the maritime Antarctic sites, the thermal sum acquired was less than at the Arctic
33 locations, often only between 300 to 450 degree days compared to the 700 and above that
34 were common High Arctic Svalbard. The differences between the thermal sums of the air and

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

6 Interpretation

7 Cumulative degree days above 0°C (CDD) represent the total thermal sum accumulated. The
8 CDD in the air commenced earlier than at the ground surface at all sites but, with the
9 exception of the *Arctic polar desert*, the ground surface CDD rapidly overtook that of the air,
10 clearly demonstrating the importance of solar forcing on the heat sum of the ground and sub-
11 surface. The *Arctic polar desert*, *Small temporary pond* and *Large permanent pond* provided
12 exceptions to this generalisation. At the former, snow clearance was late in the summer with a
13 consequential delay in the accumulation of ground CDD. By late summer, and despite the
14 period of the midnight sun extending until the end of August in Svalbard, the elevation of the
15 sun is constantly low and the extent of solar forcing declines, resulting in a reduced
16 accumulation of CDD and the surface at this site failing to accrue a similar, or greater, CDD
17 sum as that of the air. The ice cover of the *Small temporary pond* melted in early to mid-June
18 but the pond continued to be fed by snow melt. Consequently the water temperature remained
19 low, only occasionally exceeding +8°C, and the thermal sum lagged behind that of the air.
20 The Antarctic sites showed a dramatic increase in ground CDD compared to air, up to almost
21 500% greater, likely due to early release of the ground from snow cover, low air temperatures,
22 and greater solar forcing due to the low lower latitude location and consequent higher
23 elevation of the sun. Reduced cloud cover may also have a role at some sites enabling greater
24 solar forcing of the ground.

27 **Conclusions**

28 It is apparent that polar ground surfaces are highly heterogeneous, and that the thermal
29 environment is site-specific and can differ greatly over a landscape scale. Air temperature is
30 often a poor predictor for ground and sub-surface thermal conditions. This also highlights the
31 local character of the surface exchange processes between the atmosphere and land. For the
32 flora and fauna living in these regions it is the ground and sub-surface temperatures – the
33 microhabitat – that is of greater significance than air temperatures *per se*. This emphasises the

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

3
4 The data presented here provide representative descriptions of the thermal microclimate in a
5 range of surface types in polar regions where such data are often difficult to obtain, and
6 provide a context into which polar studies can be placed. It is patently clear that the ecology
7 and the responses of the flora and fauna of polar regions to projected climate change cannot
8 be adequately understood without a better knowledge of landscape habitat temperature
9 heterogeneity or be effectively predicted from projected gross regional shifts in atmospheric
10 temperature norms. Moreover, maximum and minimum environmental temperatures may
11 have a greater biological significance than the means frequently applied to describe the
12 climate of a region. Therefore, there is a requirement for biologically-relevant long-term
13 ground and sub-surface datasets by which to better understand how climate variability and
14 change affects the assortment of ground surface types in order to comprehend the resilience,
15 or vulnerability, of their associated biological communities to change.

16 17 18 **Acknowledgements**

19 We thank students taking UNIS course AB:201 Arctic Terrestrial Biology and Erlend
20 Lorentzen (Norwegian Polar Institute) for assistance in setting out and/or recovering loggers,
21 and the Kinnvika International Polar Year project for access and logistics to Nordaustlandet.
22 Image of Mars Oasis (Supplementary Fig. 1c) kindly provided by Kevin Newsham (British
23 Antarctic Survey). Fig 1. kindly drawn by Oliva Martin-Sanchez (Mapping and Geographic
24 Information Centre, British Antarctic Survey). Project work in Barentsburg was funded as
25 part of the AVIFauna project (Norwegian Research Council 6172/S30). PC and MRW were
26 supported by core funding from NERC to the BAS 'Ecosystems' and 'Biodiversity, Evolution
27 and Adaptation' Programmes. This paper also contributes to the SCAR AnT-ERA
28 programme. We thank the Norwegian Meteorological Institute (www.eKlima.no) and the
29 CLEOPATRA project for access to air temperature data.

30 31 32 **References**

33 ACIA (2004) Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge
34 University Press, Cambridge, UK

- 1 Aitchison C (1979) Winter-active subnivean invertebrates in southern Canada .1. Collembola.
2 Pedobiologia 19:113-120
- 3 Ávila-Jiménez ML, Coulson SJ (2011) Can snow depth predict the distribution of the high
4 Arctic aphid *Acyrtosiphon svalbardicum* (Hemiptera: Aphididae) on Spitsbergen?
5 BMC Ecol 11:25
- 6 Bateni SM, Margulis SA, Podest E, McDonald KC (2015) Characterizing snowpack and the
7 freeze-thaw state of underlying soil via assimilation of multifrequency passive/active
8 microwave data: a case study (NASA CLPX 2003) IEEE. T Geosci Remote 53:173-
9 189
- 10 Blaire S, Leveille R, Pollard WH, Whyte LG (2006) Microbial ecology and biodiversity in
11 permafrost. Extremophiles 10:259-267
- 12 Bokhorst S, Huiskes A, Aerts R, Convey P, Cooper EJ, Dalen L, Erschbamer B,
13 Gudmundsson J, Hofgaard A, Hollister RD, Johnstone J, Jónsdóttir IS, Lebouvier M,
14 Van De Vijver B, Wahren CH, Dorrepaal E (2013) Variable temperature effects of
15 Open Top Chambers at polar and alpine sites explained by irradiance and snow depth.
16 Glob Change Biol 19:64–74
- 17 Cahoon SMP, Sullivan PF, Shaver GR, Welker JM, Post E (2012) Interactions among shrub
18 cover and the soil microclimate may determine future Arctic carbon budgets. Ecol Lett
19 15:1415–1422
- 20 Christiansen HH, Etzelmuller B, Isaksen K, Juliussen H, Farbrot H, Humlum O, Johansson
21 M, Ingeman-Nielsen T, Kristensen L, Hjort J, Holmlund P, Sannel ABK, Sigsgaard C,
22 Akerman HJ, Foged N, Blikra LH, Pernosky MA, Odegard RS (2010) The thermal
23 state of permafrost in the Nordic area during the International Polar Year 2007-2009.
24 Permafrost Periglac 21:156-181
- 25 Cockell CS, Cordoba-Jabonero C (2004) Coupling of climate change and biotic UV exposure
26 through changing snow-ice covers in terrestrial habitats. Photochem Photobiol 79:26-
27 31
- 28 Convey P (2011) Antarctic terrestrial biodiversity in a changing world. Polar Biol 34:1629-
29 1641
- 30 Convey P (2013) Antarctic Ecosystems. In: Levin S. (ed) Encyclopedia of Biodiversity.
31 Elsevier, San Diego, pp 179-188
- 32 Convey P, Smith, RIL (1997) The terrestrial arthropod fauna and its habitats in northern
33 Marguerite Bay and Alexander Island, maritime Antarctic. Antarct Sci 9:12-26

1 Convey P, Abbandonato HDA, Bergan F, Beumer LT, Biersma EM, Bråthen VS, D'Imperio
2 L, Jensen CK, Nilsen S, Paquin K, Stenkewitz U, Svoen ME, Winkler J, Müller E,
3 Coulson SJ (2014) Survival of rapidly fluctuating natural low winter temperatures by
4 Arctic soil invertebrates. *J Thermal Biol* DOI: 10.1016/j.jtherbio.2014.07.009
5 Cooper EJ (2004) Out of sight, out of mind: Thermal acclimation of root respiration in Arctic
6 *Ranunculus*. *Arct Antarct Alp Res* 36:308-313
7 Cooper EJ (2015) Warmer shorter winters disrupt Arctic terrestrial ecosystems. *Annu Rev*
8 *Ecol Evol Syst* 45:71–95
9 Coulson SJ, Convey P, Aakra K, Aarvik L, Ávila-Jiménez ML, Babenko A, Biersma E,
10 Boström S, Brittain J, Carlsson AM, Christoffersen KS, De Smet WH, Ekrem T,
11 Fjellberg A, Füreder L, Gustafsson D, Gwiazdowicz DJ, Holmstrup M, Hansen LO,
12 Holmstrup M Kaczmarek L, Kolicka M, Kuklin V, Lakka H-K, Lebedeva N,
13 Makarova O, Maraldo K, Melekhina E, Ødegaard F, Pilskog HE, Simon JC, Sohlenius
14 B, Solhøy T, Søli G, Stur E, Tanaevitch A, Taskaeva A, Velle G, Zawierucha K,
15 Zmudczyńska-Skarbek K (2014) The terrestrial and freshwater invertebrate
16 biodiversity of the archipelagoes of the Barents Sea; Svalbard, Franz Josef Land and
17 Novaya Zemlya. *Soil Biol Biochem* 68:440-470
18 Coulson SJ, Fjellberg A, Gwiazdowicz DJ, Lebedeva NV, Melekhina EN, Solhøy T, Erséus
19 C, Maraldo K, Miko L, Schatz H, Schmelz RM, Søli G, Stur E (2013a) Introduction of
20 invertebrates into the High Arctic via imported soils: the case of Barentsburg in
21 Svalbard. *Biol Invasions* 15:1-5
22 Coulson SJ, Fjellberg A, Gwiazdowicz DJ, Lebedeva NV, Melekhina EN, Solhøy T, Erséus
23 C, Maraldo K, Miko L, Schatz H, Schmelz RM, Søli G, Stur E (2013b) The
24 invertebrate fauna of anthropogenic soils in the High Arctic settlement of Barentsburg;
25 Svalbard. *Polar Res* 32:19273
26 Coulson SJ, Hodkinson ID, Strathdee AT, Block W, Webb NR, Bale JS, Worland MR (1995)
27 Thermal environments of Arctic ground organisms during winter. *Arct Alp Res*
28 27:365-371
29 Coulson SJ, Leinaas HP, Ims RA, Søvik G (2000) Experimental manipulation of the winter
30 surface ice layer: the effects on a High Arctic ground microarthropod community.
31 *Ecography* 23:299-314
32 Davey MC, Pickup J, Block W (1992) Temperature variation and its biological significance in
33 fellfield habitats on a maritime Antarctic island *Antarct Sci* 4:383-388

- 1 Everatt MJ, Bale JS, Convey P, Worland MR, Hayward SAL (2013) The effect of acclimation
2 temperature on thermal activity thresholds in polar terrestrial invertebrates. *J Insect*
3 *Physiol* 59:1057-1064
- 4 Fjørland EJ, Benestad R, Hanssen-Bauer I, Haugen JE, Skaugen TE (2011) Temperature and
5 precipitation development at Svalbard 1900–2100. *Adv Meteorol* 2011:893790
- 6 Geiger R, Aron RH, Todhunter P (2003) *The climate near the ground*. Rowman and
7 Littlefield, Lanham
- 8 Governor of Svalbard (2014) *Handlingsplan mot skadelige fremmede arter på Svalbard*, (in
9 Norwegian). Sysselmannen på Svalbard, Longyearbyen, Norway
- 10 Guglielmin M, Ellis-Evans CJ, Cannone N (2008) Active layer thermal regime under different
11 vegetation conditions in permafrost areas. A case study at Signy Island (Maritime
12 Antarctica). *Geoderma* 144:73–85
- 13 Guglielmin M, Worland MR, Cannone N (2012) Spatial and temporal variability of ground
14 surface temperature and active layer thickness at the margin of maritime Antarctica,
15 Signy Island. *Geomorphology* 155:20–33
- 16 Hansen BB, Isaksen K, Benestad RE, Kohler J, Pedersen ÅØ, Loe LE, Coulson SJ, Larsen JO,
17 Varpe Ø (2014) Warmer, wetter, wilder winters: Characteristics and implications of an
18 extreme weather event in the High Arctic. *Environ Res Lett* 9:114021
- 19 Hisdal V (1985) *Geography of Svalbard*. Norwegian Polar Institute, Oslo, Norway
- 20 Hodkinson ID (2003) Metabolic cold adaptation in arthropods: a smaller-scale perspective.
21 *Funct Ecol* 17:562-567
- 22 IPCC (2014) *Climate Change 2014: Synthesis Report*. International Panel on Climate Change.
23 http://ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf.
24 Accessed 3/11/14, 2014.
- 25 Jagdhuber T, Stockamp J, Hajsek I, Ludwig R (2014) Identification of soil freezing and
26 thawing states using SAR polarimetry at C-band. *Remote Sens* 6:2008-2023
- 27 Jónsdóttir IS (2005) Terrestrial ecosystems on Svalbard: heterogeneity, complexity and
28 fragility from an Arctic island perspective. *P Roy Irish Acad B* 105:155-165
- 29 Kim S, Singh VP (2014) Modeling daily soil temperature using data-
30 driven models and spatial distribution. *Theor Appl Climatol* 118:465-479
- 31 Kohler J, Aanes R (2004) Effect of winter snow and ground-icing on a Svalbard reindeer
32 population: results of a simple snowpack model. *Arct Antarct Alp Res* 36:333–41

- 1 Kurylyk BL, MacQuarrie KTB, McKenzie JM (2014) Climate change impacts on
2 groundwater and soil temperatures in cold and temperate regions: Implications,
3 mathematical theory, and emerging simulation tools. *Earth-Science Rev* 138:313–334
- 4 Larsen KS, Jonasson S, Michelsen A (2002) Repeated freeze–thaw cycles and their effects on
5 biological processes in two arctic ecosystem types. *Appl Soil Ecol* 21:187–95
- 6 Migala K, Wojtuń B, Szymański W, Muskała P (2014) Soil moisture and temperature
7 variation under different types of tundra vegetation during the growing season: A case
8 study from the Fuglebekken catchment, SW Spitsbergen. *Catena* 116:10-18
- 9 Meltofte H, Huntington HP, Barry T (2013) Introduction. In: Meltofte H. (ed), *Arctic
10 Biodiversity Assessment. Status and trends in Arctic biodiversity: Synthesis.
11 Conservation of Arctic Flora and Fauna (CAFF)*, Arctic Council, Akureyri, Iceland, pp
12 9-17
- 13 Morgner E, Elberling B, Strebel D, Cooper EJ (2010) The importance of winter in annual
14 ecosystem respiration in the High Arctic: effects of snow depth in two vegetation
15 types. *Polar Res* 29:58-74
- 16 Nielsen UN, Wall D (2013) The future of soil invertebrate communities in polar regions:
17 different climate change responses in the Arctic and Antarctic? *Ecol Lett* 16:409-419
- 18 Nowinski NS, Taneva L, Trumbore SE, Welker JM (2010) Decomposition of old organic
19 matter as a result of deeper active layers in a snow depth manipulation experiment.
20 *Oecologia* 163:785-792
- 21 Oberbauer SF, Tweedie CE, Welker JM, Fahnestock JT, Henry GRH, Webber PJ, Hollister
22 RD, Walker MD, Kuchy A, Elmore E, Starr G (2007) Tundra CO₂ fluxes in response
23 to experimental warming across latitudinal and moisture gradients. *Ecol Monogr*
24 77:221-238
- 25 Overland JE, Wang M, Bond NA, Walsh JE, Kattsov VM, Chapman WL (2011)
26 Considerations in the selection of global climate models for regional climate
27 projections: the Arctic as a case study. *J Climate* 24:1583-1597
- 28 Pauli JN, Zuckerberg B, Whiteman JP, Porter W (2013) The subnivium: a deteriorating
29 seasonal refugium. *Front Ecol Environ* 11:260-267
- 30 Peck LS (2004) Physiological flexibility: the key to success and survival for Antarctic fairy
31 shrimps in highly fluctuating extreme environments. *Freshwater Biol* 49:1195-1205
- 32 Peck LS, Convey P, Barnes DKA (2006) Environmental constraints on life histories in
33 Antarctic ecosystems: tempos, timings and predictability. *Biol Rev* 81:75-109

1 Przybylak R, Arażny A, Nordli Ø, Finkelnburg R, Kejna M, Budzik T, Migala S, Sikora S,
2 Puczko D, Rymerg K, Rachlewiczg G (2014) Spatial distribution of air temperature on
3 Svalbard during 1 year with campaign measurements. *Int J Climatol* 34:3702–3719
4 Putkonen J, Roe G (2003) Rain-on-snow events impact soil temperatures and affect ungulate
5 survival. *Geophys Res Lett* 30:4
6 Rautio M, Dufresne F, Laurion I, Bonilla S, Warwick SV, Christoffersen KS (2011) Shallow
7 freshwater ecosystems of the circumpolar Arctic. *EcoScience* 18:204-222
8 Schmidt IK (1999) Mineralization and microbial immobilization of N and P in arctic soils in
9 relation to season, temperature and nutrient amendment. *Appl Soil Ecol* 11:147–60
10 Schroeter B, Green TGA, Pannewitz S, Schlenso M, Sancho LG (2011) Summer variability,
11 winter dormancy: lichen activity over 3 years at Botany Bay, 77°S latitude, continental
12 Antarctica. *Polar Biol* 34:13-22
13 Sjöblom A (2014) Turbulent fluxes of momentum and heat over land in the High-Arctic
14 summer: the influence of observation techniques. *Polar Res* 33:21567
15 Slavich E, Warton DI, Ashcroft MB, Gollan JR, Ramp D (2014) Topoclimate versus
16 macroclimate: how does climate mapping methodology affect species distribution
17 models and climate change projections? *Divers Distrib* 20:952-963
18 Smith RIL (1988) Recording bryophyte microclimate in remote and severe environments In:
19 Glime J.M. (ed) *Methods in Bryology. Proceedings of the Bryological Methods*
20 *Workshop, Mainz. Hattori Botanical Laboratory, Nichinan, pp 275-284.*
21 SWIPA (2011) *Snow, water, ice and permafrost in the Arctic (SWIPA). Arctic Monitoring*
22 *and Assessment Programme (AMAP), Oslo, Norway*
23 Tabari H, Talaee PH, Willems P (2014) Short-term forecasting of soil temperature using
24 artificial neural network. *Meteorol Appl* 22; 576-585
25 Toro M, Camacho A, Rochera C, Rico E, Banon M, Fernandez-Valiente E, Marco E, Justel
26 A, Avendano MC, Ariosa Y, Vincent WF, Quesada A (2007) Limnological
27 characteristics of the freshwater ecosystems of Byers Peninsula, Livingston Island, in
28 maritime Antarctica. *Polar Biol* 30:635-649
29 Turner J, Barrand NE, Bracegirdle TJ, Convey P, Hodgson DA, Jarvis M, Jenkins A,
30 Marshall G, Meredith MP, Roscoe H, Shanklin J, French J, Goosse H, Guglielmin M,
31 Gutt J, Jacobs S, Kennicutt II MC, Masson-Delmotte V, Mayewski P, Navarro F,
32 Robinson S, Scambos T, Sparrow M, Summerhayes C, Speer K, Klepikov, A (2014)
33 Antarctic climate change and the environment: an update. *Polar Record* 50:237-259

- 1 Walton DWH (1982) The Signy Island terrestrial reference sites. XV. Microclimate
2 monitoring, 1972-74. *Brit Antarct Surv Bull* 55:111-126
- 3 Wang L, Wolken GJ, Sharp MJ, Howell SEL, Derksen C, Brown RD, Markus T, Cole J
4 (2011) Integrated pan-Arctic melt onset detection from satellite active and passive
5 microwave measurements, 2000–2009. *J Geophys Res* 116:D22103
- 6 Westermann S, Lüers J, Langer M., Boike J (2009) The annual surface energy budget of a
7 High-Arctic permafrost site on Svalbard. *The Cryosphere* 3:345-263
- 8 Westermann S, Langer M, Boike J (2011) Spatial and temporal variations of summer surface
9 temperatures of high-arctic tundra on Svalbard — Implications for MODIS LST based
10 permafrost monitoring. *Remote Sens Environ* 115:908-922
- 11 Williams CM, Henry HAL, Sinclair, B.J. (2015) Cold truths: how winter drives responses of
12 terrestrial organisms to climate change. *Biol Rev* 90:214–235
- 13 Woods HA, Dillon ME, Pincebourde S (2015) The roles of microclimatic diversity and of
14 behavior in mediating the responses of ectotherms to climate change. *J Thermal Biol*
15 54:86-97
- 16 Wu W, Tang XP, Guo NJ, Yang C, Liu HB, Shang YF (2013) Spatiotemporal modeling of
17 monthly soil temperature using artificial neural networks. *Theor Appl Climatol*
18 113:481-494
- 19
20

- 1 **Table 1a.** Summary air temperature figures for a representative year at sites on Svalbard and the maritime Antarctic (see Fig. 1 for locations). F-
 2 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 *2011	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	-
	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 *2011	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
	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 *2011	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
	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	-	-
Sveagruba *2011	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
	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	-	-
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	-	-

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

1
2
3
4
5
6
7
8

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		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
ARCTIC																
Arctic polar desert A *2007-2008 ** 29/07/07- 13/08/09	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	7	2	0	0	9	-	-
	Days μ T > 0°C	0	0	0	0	0	0	26	29	19	0	0	0	74	-	-
High Arctic shrub tundra B *2012 ** 11/08/11- 06/07/13	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	-
	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
	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
	F-T events	1	0	0	0	7	0	0	3	4	1	0	0	16	-	-
	Days μ T > 0°C	1	0	0	0	10	27	31	31	20	1	0	0	121	-	-
Steppe vegetation C *2012 **11/08/11-	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	-
	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
	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
	F-T events	1	1	0	0	1	1	0	0	0	1	0	0	5	-	-

Site		Winter		Spring			Summer			Autumn		Winter		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
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	-	-
<i>Salix</i> 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	-	-
<i>Dryas</i> 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

Site		Winter		Spring			Summer			Autumn		Winter		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
**05/06/10- 25/09/12	F-T events	0	0	0	0	0	0	0	0	9	5	0	0	5	-	-
	Days μ T > 0°C	0	0	0	0	3	30	31	31	30	6	2	0	133	-	-
Saline meadow – dry I	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	-
	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- 05/07/12	F-T events	0	0	0	0	0	0	0	0	0	3	1	0	4	-	-
	Days μ T > 0°C	0	0	0	0	0	22	31	31	31	7	2	0	124	-	-
Rich ornithogenic tundra J	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	-
	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- 29/06/11	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
	Days μ T > 0°C	0	0	0	0	21	30	31	31	29	10	0	0	152	-	-
Poor ornithogenic vegetation K	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	-
	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- 01/07/13	F-T events	0	2	1	0	6	0	0	1	0	5	2	0	17	-	-
	Days μ T > 0°C	4	6	0	0	14	30	31	31	30	21	3	0	170	-	-
Anthropogenic soils L	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	-
	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- 02/07/13	F-T events	0	0	0	0	0	0	0	0	0	5	1	0	6	-	-
	Days μ T > 0°C	4	29	31	28	31	30	31	31	30	20	2	0	267	-	-

Site		Winter		Spring			Summer			Autumn		Winter		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
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	-

Site		Winter		Spring			Summer			Autumn		Winter		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
Q *2009 **01/01/09- 31/12/09	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	-	-
	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	-	-
	F-T events	13	16	13	6	0	0	0	0	0	0	0	3	51	-	-
	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 *2009 **01/01/09- 31/12/09	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	-	-
	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	-	-
	F-T events	19	23	10	2	0	0	0	0	0	0	15	22	91	-	-
	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 *2009 **01/01/09- 31/12/09	Maximum	21.8	16.0	9.6	-3.3	-5.7	-	-	-	-11.1	-9.0	-0.1	19.4	21.8	-	-
	Minimum	-5.8	-11.9	-15.5	-30.6	-19.7	-	-	-	-27.9	-17.1	-16.1	-7.3	-30.6	-	-
	F-T events	22	30	9	0	0	-	-	-	0	0	0	26	-	-	-
	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 *2007-08 **01/01/07 31/12/07	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	-	-
	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	-	-
	F-T events	5	16	20	9	0	0	0	0	0	0	3	21	74	-	-
	Days μ T > 0°C	31	27	8	1	0	0	0	0	0	0	4	30	101	-	-

1
2
3
4

1 **Table 2.** Cumulative day degrees (CDD) difference between soil and air. Svalbard airport
 2 used as baseline air temperature for Arctic sites except *Arctic polar desert* site (Rijpfjord air
 3 temperatures)
 4

Location	Site	Code	% difference
<i>Arctic</i>			
	Arctic polar desert	A	-68,4
	High Arctic shrub tundra	B	30,8
	Steppe vegetation	C	-13,3
	Low ridge crest	D	4,5
	<i>Salix</i> coastal tundra	E	-10,4
	<i>Dryas</i> 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
<i>Antarctic</i>			
	Exposed hill summit	Q	13,6
	Antarctic polar desert	R	199,8
	Cryodisturbed terrain	S	162,9
	Lichen fellfield	T	495,3

5
 6
 7
 8

1 **Figure Legends**

2

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

12

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

19

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

28

29 **Figure 4.** Cumulative degree-days (0°C baseline). **I)** A) Arctic polar desert, B) High Arctic
30 shrub tundra, C) Steppe vegetation, D) Low ridge crest. **II)** E) *Salix* coastal tundra, F) *Dryas*
31 tundra, G) Snow bed hollow, H) Saline meadow – wet. **III)** I) Saline meadow – dry, J) Rich
32 ornithogenic tundra, K) Poor ornithogenic vegetation, L) Anthropogenic soils, **IV)** M)
33 Moraines, N) Cliff fissure, O) Small temporary pond, P) Large permanent pond, **V)** Q)

1 Exposed hill summit (Jane Col), R) Antarctic polar desert (Mars Oasis), S) Cryodisturbed
2 terrain (Coal Nunatak), T) Lichen fellfield (Anchorage).

3

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

8

9

10 **Supplementary material**

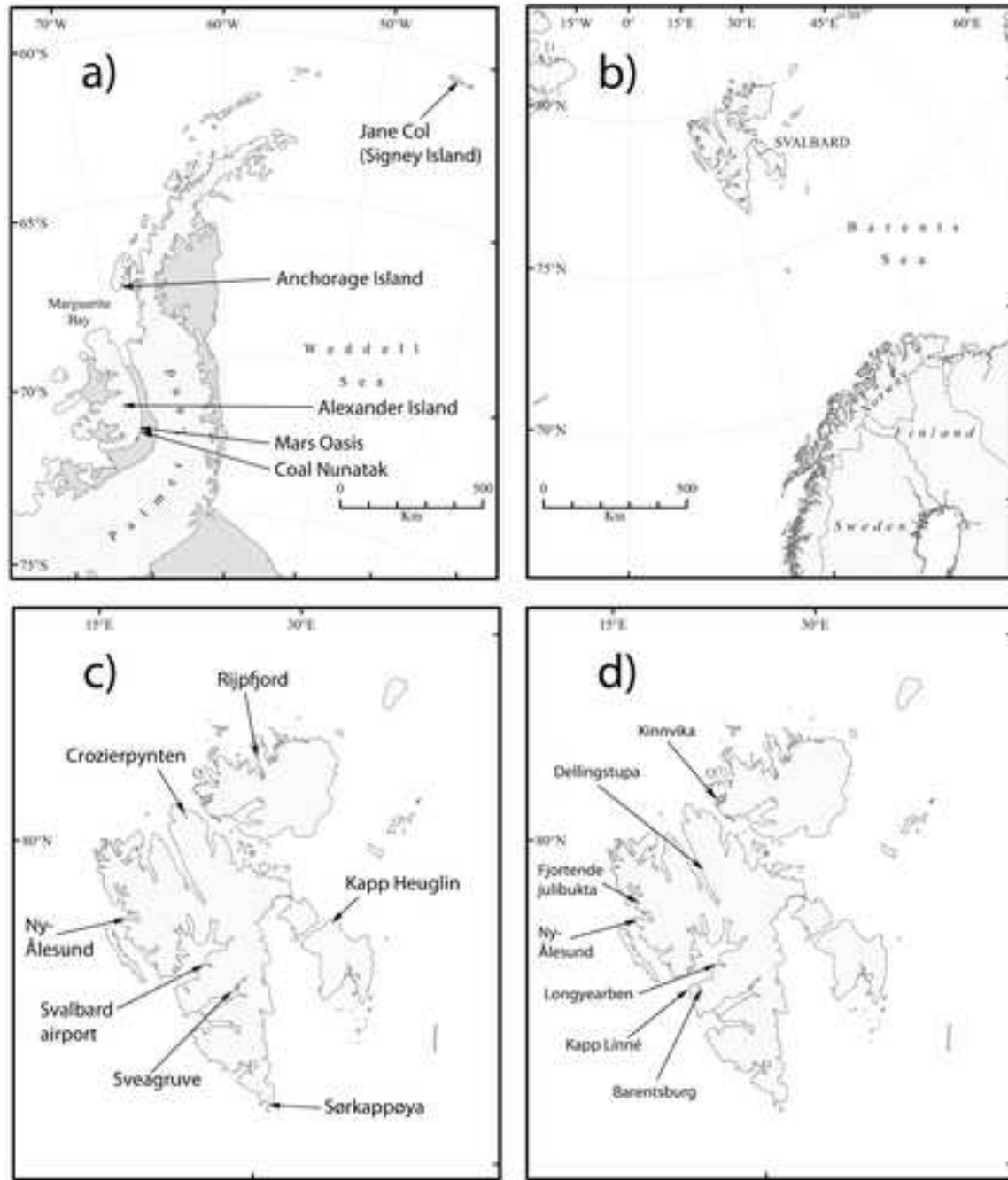
11

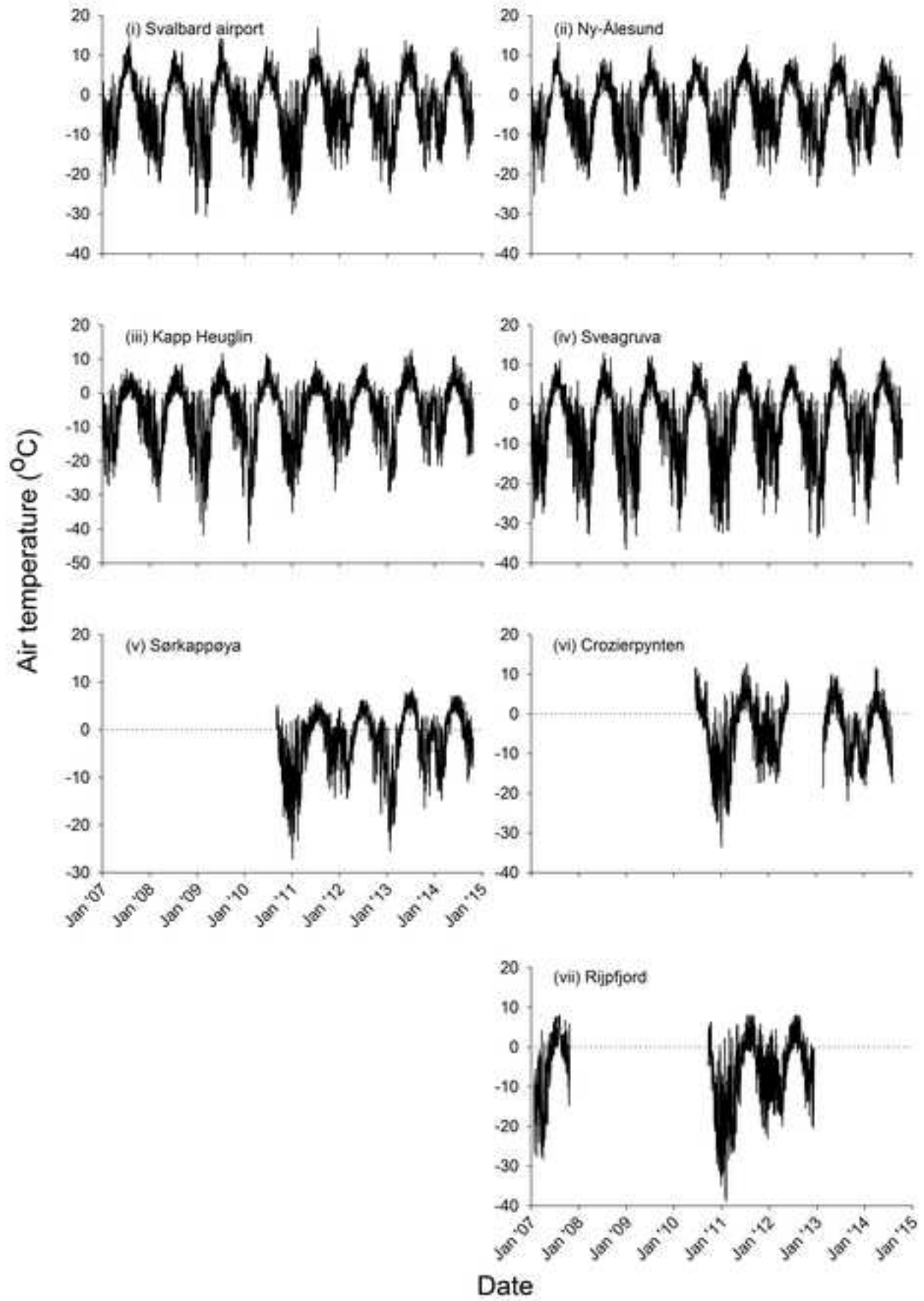
12 **Figure 1** Images of the Arctic sites. All represent the summer period, July-August; (a) A)
13 Arctic polar desert, B) High Arctic shrub tundra, C) Steppe vegetation, D) Low ridge crest, E)
14 *Salix* coastal tundra, F) *Dryas* tundra, G) Snow bed hollow, H) Saline meadow – wet; (b) I)
15 Saline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

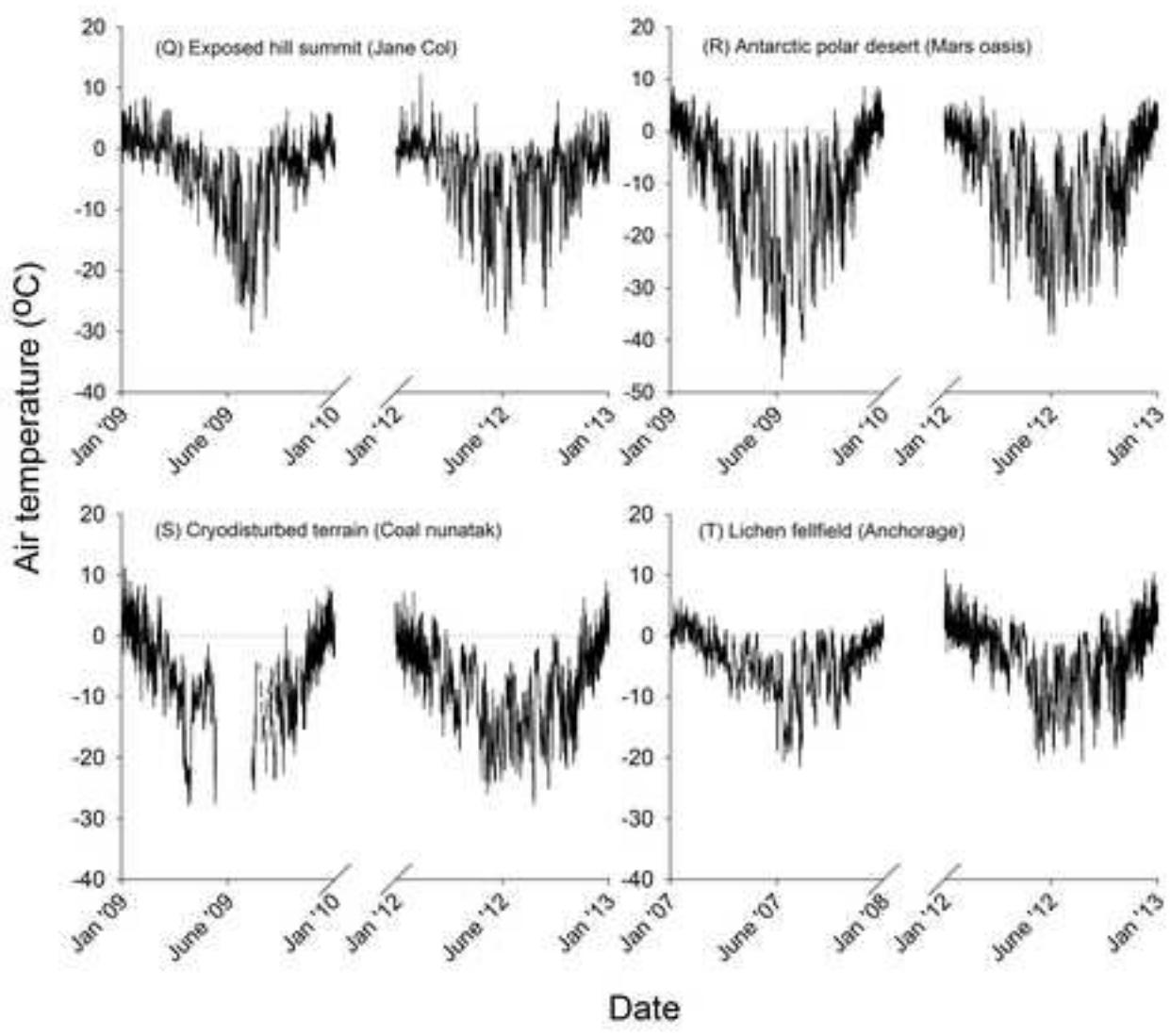
21

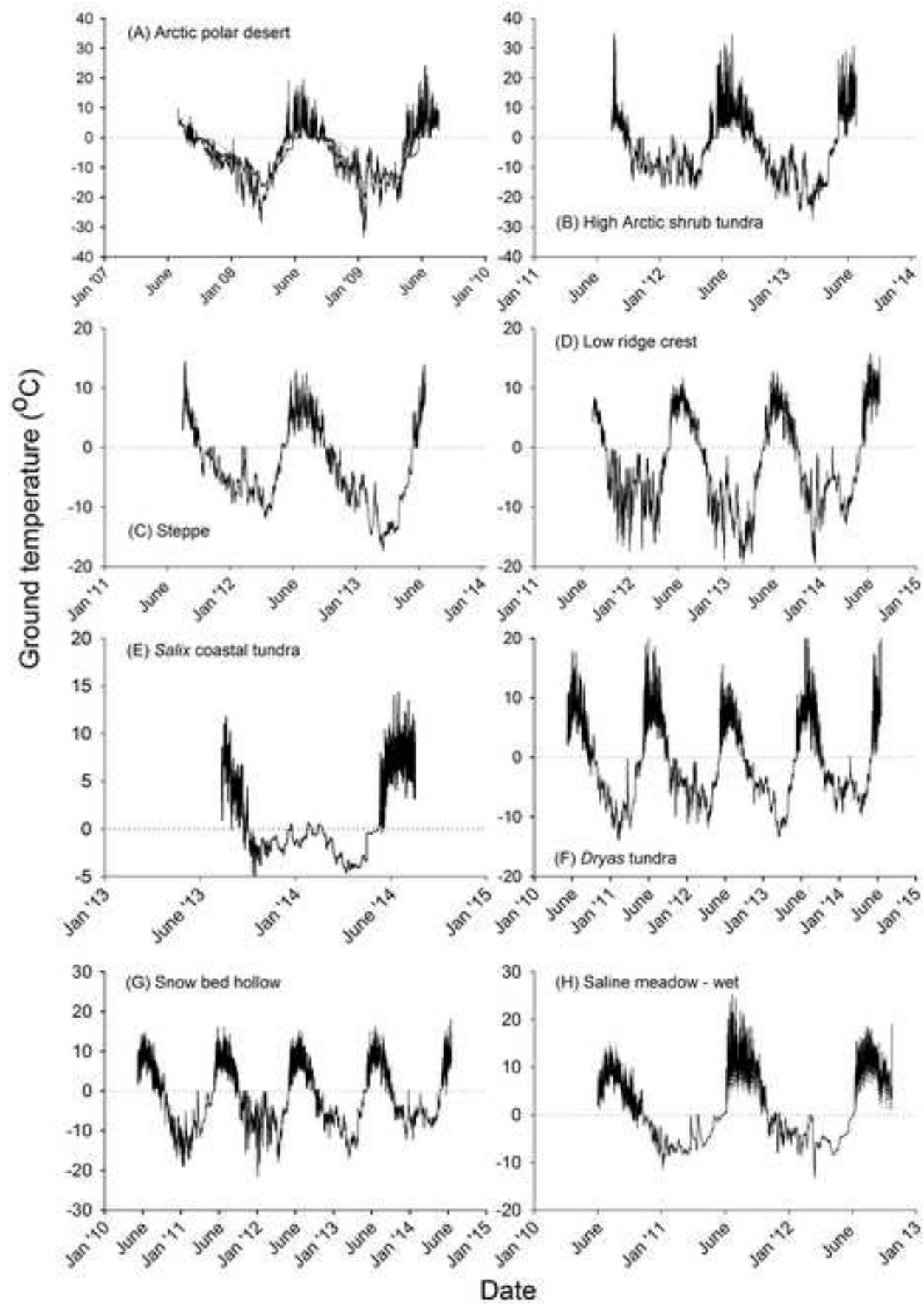
22 **Table 1.** Site descriptions

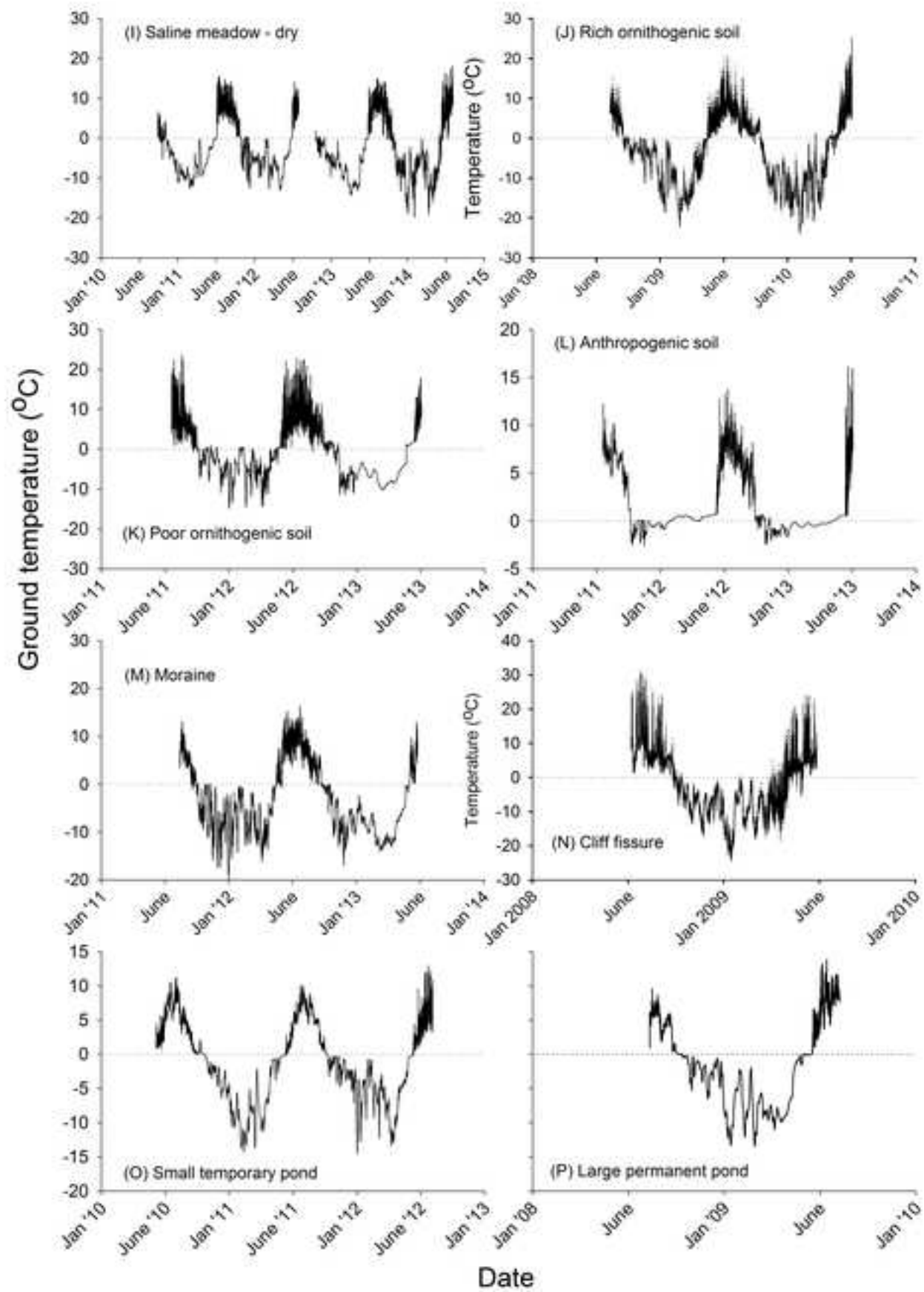
23 **Table 2.** Cleaned temperature data (example for submission purposes)

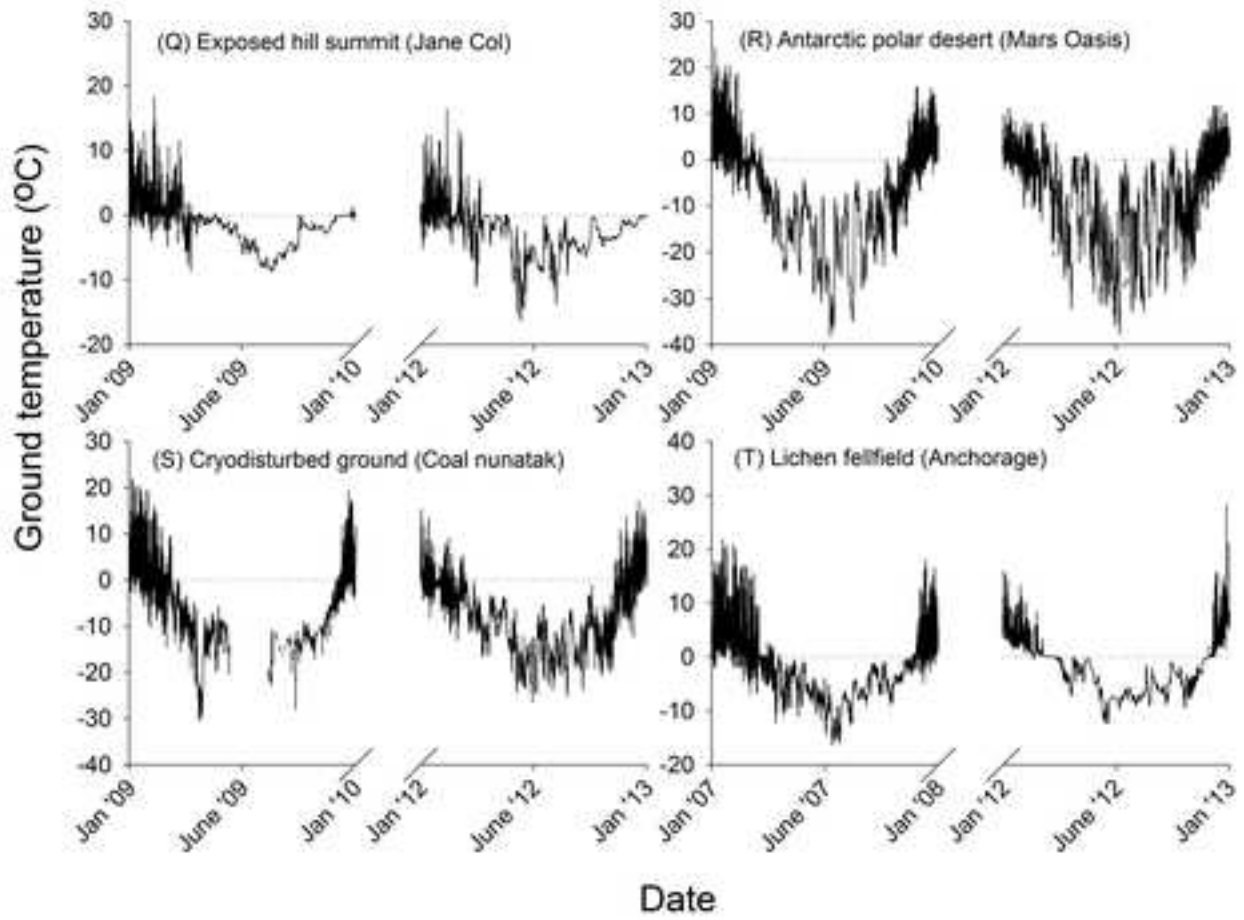


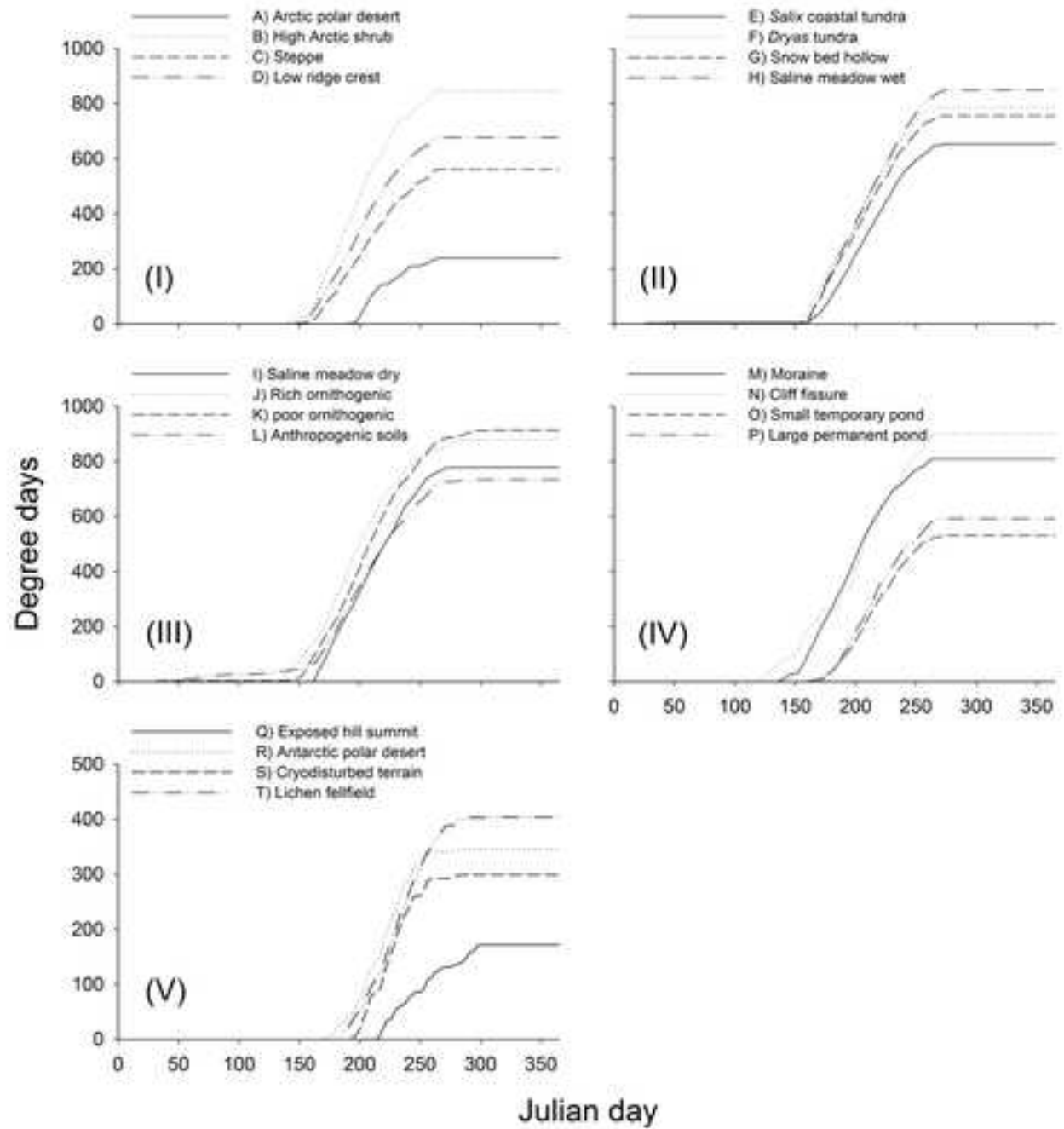












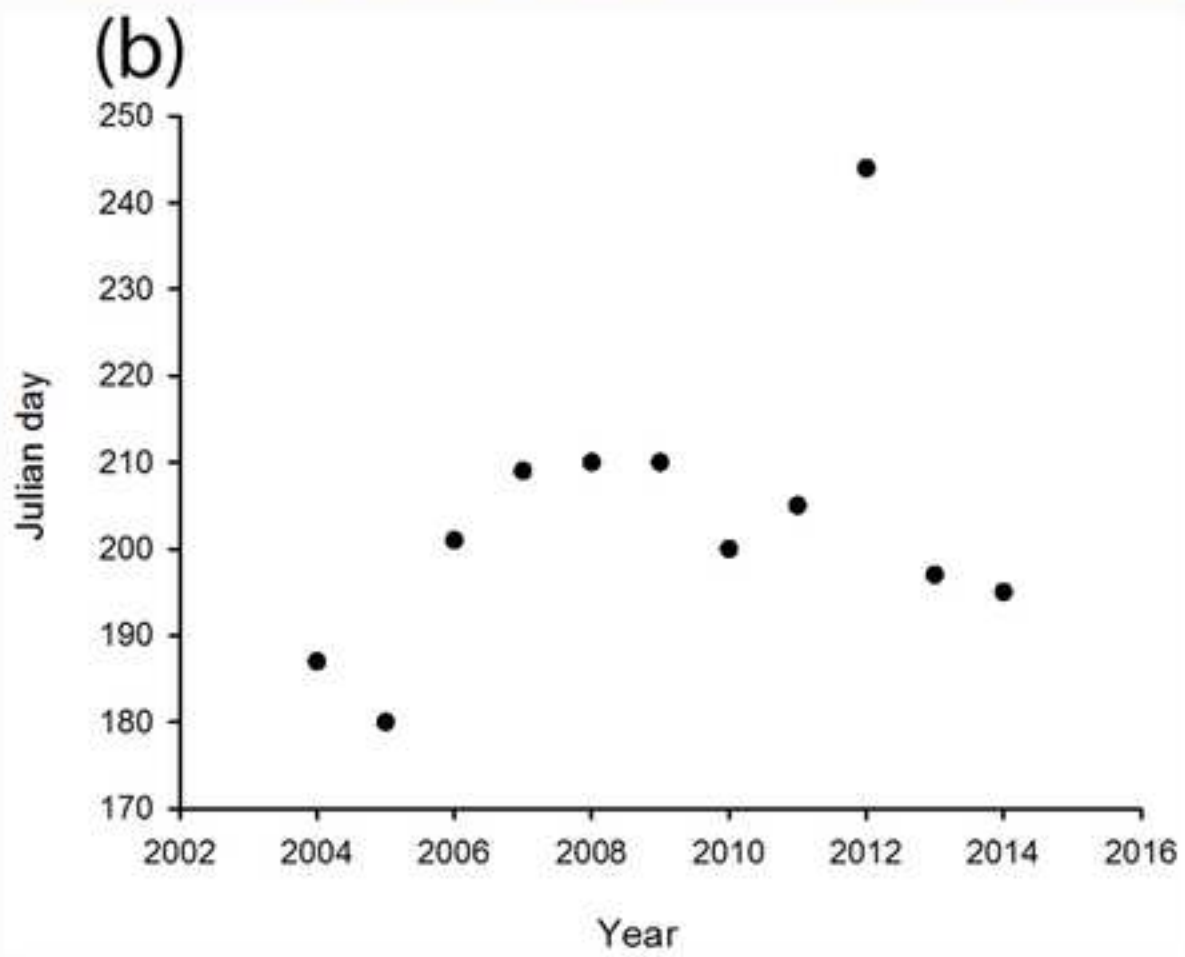


Table 2a. Summary air temperature figures for a representative year at Svalbard and the maritime Antarctic. F-T=number of freeze-thaw events per month; Days μ T > 0°C=number of days mean daily ground temperature above 0°C; *=year summarised. Ann.=Annual.

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 *2011	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	-
	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 *2011	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
	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 *2011	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
	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 *2011	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
	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 *2011	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
	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 *2011	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	
	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 *2011	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	
	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			Summer			
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Ann.			
Lichen fellfield (Anchorage) *2007	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	
	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) *2009	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	
	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) *2009	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	
	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) *2009	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
	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	-	-

Site		Winter		Spring			Summer			Autumn			Winter		Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		
20/06/13	Days μ T > 0°C	0	0	0	0	0	30	31	31	24	0	0	0	116	-	-
<i>Salix</i> coastal tundra E	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	-
	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
	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
	F-T events	0	0	0	0	1	0	0	0	0	1	0	0	2	-	-
**13/08/13-17/08/14	Days μ T > 0°C	8	10	0	0	0	23	31	31	27	2	0	2	134	-	-
<i>Dryas</i> tundra F	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
**05/06/10-11/07/14	Days μ T > 0°C	0	0	0	0	0	30	31	31	28	0	0	0	120	-	-
Snow bed hollow G	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	7	1	1	0	9	-	-
**05/06/10-05/07/12	Days μ T > 0°C	0	0	1	0	0	26	31	31	28	0	0	0	117	-	-
Saline meadow – wet H	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	9	5	0	0	5	-	-
**05/06/10-25/09/12	Days μ T > 0°C	0	0	0	0	3	30	31	31	30	6	2	0	133	-	-
Saline meadow – dry I	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	0	3	1	0	4	-	-
**04/09/10-05/07/12	Days μ T > 0°C	0	0	0	0	0	22	31	31	31	7	2	0	124	-	-

Site		Winter		Spring			Summer			Autumn		Winter		Annual	Days > 0°C	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec			
Rich ornithogenic tundra J *2010 **08/08/09- 29/06/11	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	2	0	0	0	2	-	-
	Days μ T > 0°C	0	0	0	0	21	30	31	31	29	10	0	0	152	-	-
Poor ornithogenic vegetation K *2012 **19/07/11- 01/07/13	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	-
	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
	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
	F-T events	0	2	1	0	6	0	0	1	0	5	2	0	17	-	-
	Days μ T > 0°C	4	6	0	0	14	30	31	31	30	21	3	0	170	-	-
Anthropogenic soils L *2012 **19/07/11- 02/07/13	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	-
	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
	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
	F-T events	0	0	0	0	0	0	0	0	0	5	1	0	6	-	-
	Days μ T > 0°C	4	29	31	28	31	30	31	31	30	20	2	0	267	-	-
Moraines M *2012 **13/08/11- 20/06/13	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	-
	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
	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
	F-T events	0	0	0	0	1	0	0	0	2	2	0	0	5	-	-
	Days μ T > 0°C	0	0	0	0	15	30	31	31	19	0	0	0	126	-	-
Cliff fissure N *2008-09 **06/07/08- 23/06/09	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	-
	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
	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
	F-T events	0	0	0	12	5	0	0	0	4	0	0	0	21	-	-
	Days μ T > 0°C	0	0	0	3	29	23	28	31	23	0	0	0	137	-	-
Small temporary pond O *2011 **05/06/10-	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	-
	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
	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
	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	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		
02/08/12	Days μ T > 0°C	0	0	0	0	0	22	31	31	30	4	0	0	118	-	-
Large permanent pond P *2008-09 **12/08/08-	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	-
	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
	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
	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) Q *2009 **01/01/09-	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	-
	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	-	-
	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	-	-
	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) R *2009 **01/01/09-	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	-
	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	-	-
	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	-	-
	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	13	28	87	-	-	
Cryodisturbed terrain (Coal nunatak) S *2009 **01/01/09-	Mean	5.5	-0.3	-4.9	-15.5	-11.8	-	-	-	-14.3	-12.7	-7.7	2.4	-6.5	66	-
	Maximum	21.8	16.0	9.6	-3.3	-5.7	-	-	-	-11.1	-9.0	-0.1	19.4	21.8	-	-
	Minimum	-5.8	-11.9	-15.5	-30.6	-19.7	-	-	-	-27.9	-17.1	-16.1	-7.3	-30.6	-	-
	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	Data set
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual		
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 (Rijpfjord air temperatures)

Location	Site	Code	% difference
<i>Arctic</i>	Arctic polar desert	A	-68,4
	High Arctic shrub tundra	B	30,8
	Steppe vegetation	C	-13,3
	Low ridge crest	D	4,5
	<i>Salix</i> coastal tundra	E	-10,4
	<i>Dryas</i> 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
<i>Antarctic</i>	Exposed hill summit	Q	13,6
	Antarctic polar desert	R	199,8
	Cryodisturbed terrain	S	162,9
	Lichen fellfield	T	495,3