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A comparison of annual and seasonal carbon dioxide effluxes between sub-Arctic Sweden and High-Arctic Svalbard

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Abstract

Recent climate change predictions suggest altered patterns of winter precipitation across the Arctic. It has been suggested that the presence, timing and quantity of snow all affect microbial activity, thus influencing CO_2 production in soil. In this study annual and seasonal emissions of CO_2 were estimated in High-Arctic Adventdalen, Svalbard, and sub-Arctic Latnjajaure, Sweden, using a new trace gas-based method to track real-time diffusion rates through the snow. Summer measurements from snow-free soils were made using a chamber-based method. Measurements were obtained from different snow regimes in order to evaluate the effect of snow depth on winter CO_2 effluxes. Total annual emissions of CO_2 from the sub-Arctic site (0.662–1.487 kg CO_2 m^{-2} yr^{-1}) were found to be more than double the emissions from the High-Arctic site (0.369–0.591 kg CO_2 m^{-2} yr^{-1}). There were no significant differences in winter effluxes between snow regimes or vegetation types, indicating that spatial variability in winter soil CO_2 effluxes are not directly linked to snow cover thickness or soil temperatures. Total winter emissions (0.004–0.248 kg CO_2 m^{-2}) were found to be in the lower range of those previously described in the literature. Winter emissions varied in their contribution to total annual production between 1 and 18%. Artificial snow drifts shortened the snow-free period by 2 weeks and decreased the annual CO_2 emission by up to 20%. This study suggests that future shifts in vegetation zones may increase soil respiration from Arctic tundra regions.

During the last decade, the role of winter snow in Northern Hemisphere ecology has been highlighted as part of the current climate debate. Climate predictions include severe changes in Arctic environments, with increased temperature and altered precipitation patterns (Symon et al. 2005; Anisimov et al. 2007). Although it has been reported that the annual mean snow cover of the Northern Hemisphere has declined (Lemke et al. 2007), changes in precipitation patterns may increase winter precipitation over some areas, such as northern Scandinavia (Busuioc et al. 2001) and North Atlantic regions (Symon et al. 2005), resulting in changes in snow abundance. Positive trends in mean winter snow depth (Kohler et al. 2006) and annual mean air temperature (Björk, Majdi et al. 2007) have already been observed in the sub-Arctic part of Sweden. Within Arctic regions, large areas experience a snow-covered period that exceeds the duration of the growing season. The insulating effect of snow often decouples the underlying soil from ambient air temperatures, particularly when the snow cover reaches a thickness of 30 cm (Barry 1992) or over 100 cm in very cold environments (Grogan & Jonasson 2006). This can keep the soil from freezing, or can allow geothermal energy to thaw frozen soil (Schürmann et al. 2002; Björk & Molau 2007). The timing and quantity of snow that accumulates is also crucial for determining the soil winter temperature (Björk & Molau 2007), and, hence, soil respiration in the winter (Brooks et al. 1997). Winter soil temperatures have been found to increase as a result of deeper snow (Welker et al. 2000), leading to enhanced microbial activity in the soil (Schimel et al. 2004). Enhanced microbial activity will result in higher CO_2 emissions from the soil, i.e., higher soil respiration (e.g., Brooks et al. 1995; Welker et al. 2000; Nobrega & Grogan 2007). However, soil respiration at temperatures as low as –12°C has been reported in field studies (Elberling 2007), and there is *in vitro* evidence of measurable CO_2 production at temperatures as low as –39°C (Panikov et al. 2006). Brooks et al. (1997) concluded that there was no direct relationship between CO_2 production and soil temperatures in the range from 0 to –5°C under natural snow cover.

The highly complex nature of snow affects the diffusivity of the gases through it (Schindlbacher et al. 2007). In addition, the well-described (e.g., Albert & Hardy 1995; Massman et al. 1995; Jones et al. 1999) and modelled (Massman et al. 1997; Massman 2006) pressure pumping, caused by wind and changes in atmospheric pressure, may alter diffusion rates, making winter CO_2 emissions hard to quantify. The objectives of this study were, therefore: (1) to investigate and compare annual and seasonal patterns of CO_2 efflux from High- and sub-Arctic soils; and (2) to study the impact of different plant communities and snow depths on these CO_2 effluxes. The third objective was to quantify winter CO_2 effluxes using a new diffusion technique in which the trace gas SF_6 was used to account for the problems arising with snow complexity and possible pressure pumping effects.

Materials and methods

Study sites

The studies were conducted in the High Arctic at Adventdalen, Svalbard (78°10′N, 16°04′E, 40 m a.s.l.), and in the sub-Arctic at Latnjajaure field station, Sweden (68°20′N, 18°30′E, 980 m a.s.l.). The annual mean temperature and precipitation at Adventdalen are –4.9°C and 181 mm (1993–2005, Svalbard Airport, data available at http://www.eklima.no), and –1.9°C and 855 mm at Latnjajaure (1993–2007). The coldest month, February, has a mean temperature of –14.0°C at Adventdalen and –9.6°C at Latnjajaure. The warmest month, July, has a mean temperature of +6.7°C at Adventdalen and +8.6°C at Latnjajaure.

At each site, measurements where obtained from two different vegetation types: heath and meadow. Within each vegetation type two sorts of snow accumulation were chosen: high and low. The experimental set-up included three replicates in each vegetation type/snow regime combination (n_{total} = 24). At Adventdalen, measurements were taken in artificial snowdrifts (deep snow), behind 1.5 m high and 6.2 m long wooden snow fences (installed perpendicular to the prevailing wind direction in autumn 2006; the snow accumulation area was at least 70 m^2) and in natural snow cover (shallow snow). In the Latnjajaure area, measurements were taken in naturally occurring snowbeds (deep snow), covering a minimum of 500 m^2, and where exposure to wind was greater (shallow snow).

The natural snow-covered heath at Adventdalen is dominated by *Cassiope tetragona* in the hollows and *Dryas octopetala* on the ridges, whereas the natural snow-covered mesic meadow is characterized by *Dryas octopetala*, *Luzula arcuata* subsp. *confusa*, *Salix polaris* and *Bistorta vivipara*; both areas have an average snow cover of 25 (± 15) cm. The Adventdalen heath and meadow snow fences are both situated within the corresponding plant communities, but have an average winter snow cover of 120 (± 30) cm.

At Latnjajaure the two vegetation types with shallow snow cover, heath and meadow, accumulate 30 (± 20) cm of snow. The vegetation of the shallow snow-covered heath is dominated by dwarf shrubs, and this community is found on moist soils. The dominant species are *Juncus trifidus*, *Salix herbacea*, *Betula nana*, *Empetrum hermaphroditum*, *Carex bigelowii*, the mosses *Hylocomium splendens* and *Aulacomnium turgidum*, and the lichens *Cetraria nivalis* and *Cetraria delisei*. The shallow snow-covered meadow is dominated by *Dryas octopetala*, *Vaccinium uliginosum*, *Carex bigelowii*, *Carex digyna* and *Bistorta vivipara*. The Latnjajaure heath snowbed develops a snow depth of 245 (± 75) cm, with a characteristic snowbed plant community comprising a discontinuous vascular plant canopy characterized by only a few species, including *Salix herbacea*, *Gnaphalium supinum*, *Carex lachenalii*, *Carex bigelowii* and *Cassiope hypnoides*. Few lichens are adapted to conditions in the heath snowbeds, but *Solorina crocea*, *Cetraria delisei* and *Stereocaulon alpinum* perform optimally in this habitat. The bryophyte cover is extensive, including *Kiaeria starkei* and *Polytrichastrum sexangulare*. The snow depth at the meadow snowbed reaches 145 (± 35) cm, and this plant community is dominated by *Salix polaris*, *Ranunculus pygmaeus*, *Ranunculus nivalis*, *Carex lachenalii*, *Taraxacum croceum*, *Phleum alpinum*, *Viola biflora* and *Oxyria digyna*. Bryophytes are not as noticeable as in the heath snowbed, but are an important component of the plant community structure: the most common bryophyte in the meadow snowbed is *Sanionia uncinata*. All four Latnjajaure plant communities are described in detail by Björk, Klemedtsson et al. (2007).

Both the Adventdalen natural snow cover plots and the Latnjajaure shallow snow plots experience snow cover

Table 1 Sampling schedule for the period 2007–08 at Latnjajaure, northern Sweden, and Adventdalen, Svalbard; summer measurements were collected using an infrared gas analyser, and winter measurements were taken through the snow using the trace gas technique described in this paper.

	Latnjajaure		Adventdalen	
	Summer	Winter	Summer	Winter
2007				
August	19 Aug		22 Aug	
September	2 Sep		4 Sep	
November/December		—		28 Nov–3 Dec
2008				
January/February		24–27 Jan		2–5 Feb
March		4–7 Mar		6–7 Mar
April		19–21 Apr		1–2 Apr
Early May		—		6 May
Mid-May		16–19 May		—
Late May	28 May[a]	27–29 May		22 May
Early June	6 Jun[a]	9 Jun[b]	4–5 Jun	
Mid-June	11 Jun		11 Jun	
June/July	28 Jun–1 Jul		28 Jun	
Mid-July	16–17 Jul		16 Jul	
Late July	—		29 Jul	
August	26 Aug		—	

[a] The heath and meadow with shallow snow cover were free from snow.
[b] Measurements only obtained in the meadow snowbed because of waterlogged snow within the heath snowbed.

for 7–8 months of the year; snow cover at the snow-fence and snowbed plots lasts 2–4 weeks longer.

Summer measurements on snow-free soil

Measurements of CO_2 emissions from the soil during the snow-free period (see Table 1) were conducted using closed dark-chamber techniques and portable infrared gas analysers (Li-Cor 6400-09/6262 Soil CO_2 Flux Chamber; LI-COR Biosciences, Lincoln, NE, USA) in Adventdalen, and with an SBA-4 OEM CO_2 Analyzer (PP Systems International, Amesbury, MA, USA) at Latnjajaure. The chambers were placed on top of permanent soil collars (10 cm in diameter) to minimize soil disturbance during the measurements. Data from Adventdalen snow-free soils are also presented in Morgner et al. (2010 [this issue]).

Measurements from snow-covered soil

The winter measurements (Table 1) of CO_2 emissions were achieved by air sampling, for both CO_2 and the trace gas, within and above the snowpack. To quantify diffusion through the snow accurately an external trace gas, SF_6, was released through air-permeable membranes at the bottom of the snowpack, with an exposed membrane area of 75 cm^2 (Accurel PP V8/2; Membrana, Wupertal, Germany; Fig. 1). SF_6 is an artificial trace gas that can be detected down to a few ppb in natural environments.

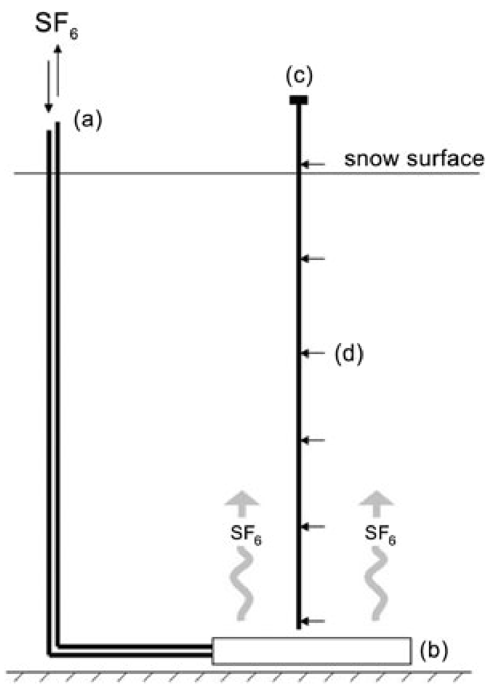

Fig. 1 Schematic overview of the gas diffusion technique. The trace gas, SF_6, is circulated by a pump (a) down to the air-permeable membrane (b), which allows the trace gas to diffuse out into the surrounding snow. Air samples were withdrawn with a syringe through 1.6-mm diameter tubing attached to an avalanche probe (c), thereby allowing the sampling of air (d) at distinct levels.

Membranes were installed at each of the 24 plots in early September 2007, and were connected to stainless steel tubes reaching above the snow to allow access during the winter without disturbing the snowpack. Air samples were withdrawn using a gas-proof syringe through stainless steel tubes (1.6 mm in diameter) attached to an avalanche probe. The probe was inserted into the snowpack above the membranes during sampling, and the gas samples were transferred from the syringe to headspace bottles and stored for later analysis by gas chromatography (Varian 3800; Varian Inc., Palo Alto, CA, USA; Klemedtsson et al. 1997) to quantify concentrations of CO_2 (ppm) and SF_6 (ppb–ppm). This technique allowed sampling every 25 cm (deep snow), or every 7.5 cm (shallow snow). Samples were collected in a time series following the release of the trace gas, with a minimum interval of 10 min over a period of 50 min (shallow snow), and with a maximum interval of 45 min over a period of 225 min (deep snow), to follow the diffusion of SF_6 through the snowpack. SF_6 was released during 30–60 s of circulation of trace gas down to the membrane at a flow rate of 400 ml min^{-1}. Concentrations of circulated SF_6 ranged between 10 ppm (shallow snow) and 1% (deep snow). The SF_6 concentration used for calculations was the actual measured concentration from probe sampling. After each sequence of gas sampling, measurements of snow density, snow temperature and snow profile (ICSI/IAHS 1981) were taken and used in flux calculations. These measurements were obtained approximately 2–4 m from the membranes to avoid any disturbance of the natural snow cover.

Winter flux calculation

Winter fluxes of CO_2 were calculated using Fick's First Law (e.g., Sommerfeld et al. 1993):

$$F = -sD\left(\frac{d_c}{d_z}\right),$$

where the diffusion coefficients (D) were set to D_{CO2} = 0.1381 $cm^2\,s^{-1}$ (Massman 1998) and D_{SF6} = 0.12 $cm^2\,s^{-1}$ (Thibodeaux 1996), and are corrected for snow temperature and air pressure according to Massman (1998). The concentration gradient (d_c/d_z) is the result of a difference in concentration (d_c) between sample heights, divided by the difference in distance (d_z). The value s describes the combined porosity (Φ) and tortuosity (t), $s = \Phi t$, and was calculated for each membrane using Fick's First Law with s as the unknown factor, and where F was set as the increase of SF_6 at a certain height within the snowpack. The concentration gradient (d_c/d_z) then denotes the trace gas sampled. The porosity (Φ_{cal}) and tortuosity (t_{cal}) were calculated from the snow density according to Albert & Shultz (2002) and Prieur Du Plessis & Masliyah (1991), respectively, giving a calculated s value (s_{cal}) that was compared with the measured s value.

Total annual and seasonal production was determined by interpolating emission data to cover the intervening periods using the data available from each site and snow regime. Winter was defined as the period between the development of continuous snow cover and the melt-out of each plot.

Soil temperature

Soil temperatures were measured constantly at –5 cm in Adventdalen and at –10 cm in Latnajaure, using Tinytag Plus loggers (Gemini Data Loggers, Chichester, West Sussex, UK).

Statistical analysis

Annual and seasonal CO_2 emissions were analysed using a nested ANOVA, with site (two), season (two), treatment combinations (four vegetation type and snow regimes) and replications (three) as fixed factors within a hierarchical design. In addition, one-way ANOVAs, combined with Turkey's honestly significant difference (HSD) post hoc tests, were used to make pairwise comparisons between treatment combinations at each site, and for each season. Prior to the analyses, data was log-transformed to achieve normal distributions, and additionally a constant was added to eliminate skewness and ensure variance homogeneity (for further details, see Økland et al. 2001). Statistical analyses were conducted using SPSS 14.0 (SPSS Inc., Chicago, IL, USA).

Results

Soil temperature and snow depths

Soil temperature measurements (Fig. 2) showed that only the two snowbeds in Latnjajaure exhibited stable winter soil temperatures. These had the deepest snow cover (maximum 320 and 190 cm, respectively). Generally, Adventdalen soils experienced a lower overall temperature than those at Latnjajaure; hence, the temperature probes at Latnjajaure were installed 5 cm deeper than those at Adventdalen. Field observations indicated great stocasticity in snow abundance at all sites with shallow snow accumulation, and snow depth could vary by up to 40 cm (400%) between sampling occasions (data not shown).

CO_2 effluxes

CO_2 effluxes (in mg $CO_2\,m^{-2}\,h^{-1}$) were significantly higher at sub-Arctic Latnjajaure than at Adventdalen in

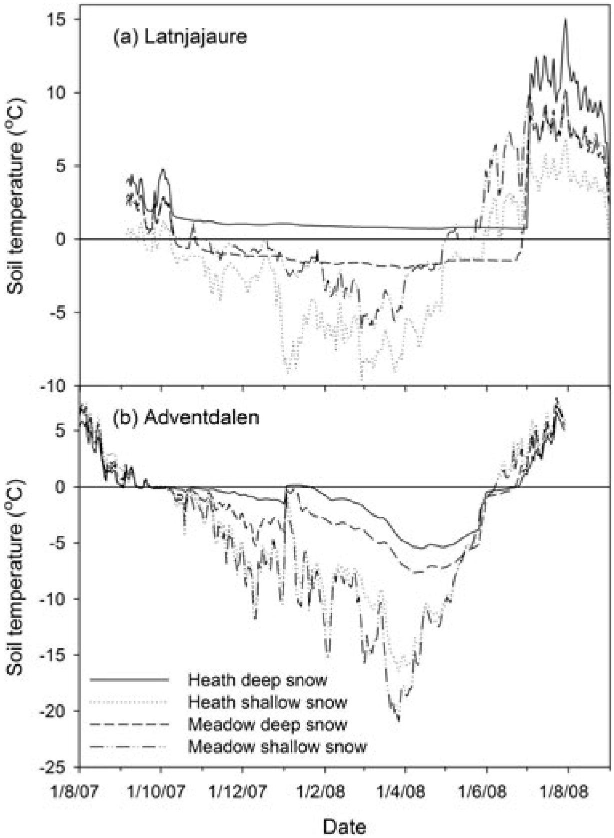

Fig. 2 Daily soil temperature averages measured at (a) 10-cm soil depth at Latnajajaure, northern Sweden, and (b) 5-cm soil depth at Adventdalen, Svalbard, in two different vegetation types (heath and meadow) and in two different snow regimes (deep and shallow).

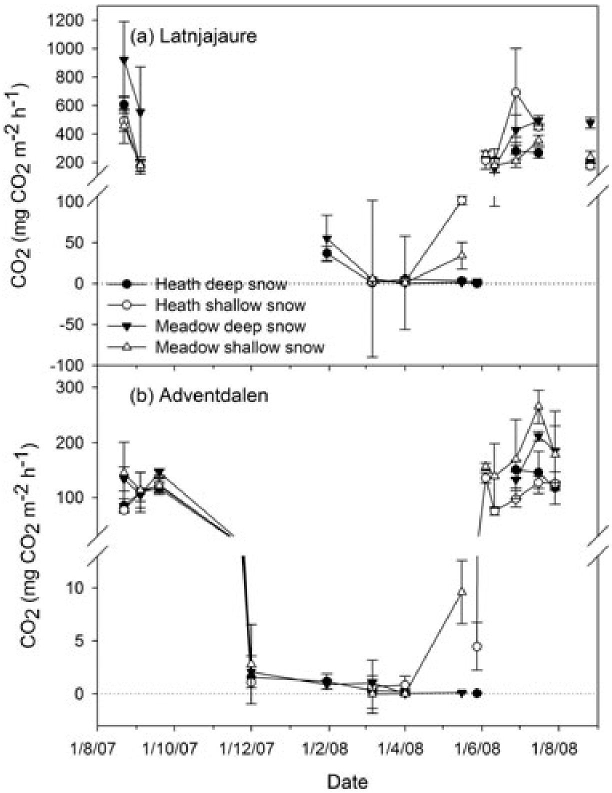

Fig. 3 Mean CO_2 effluxes (± SE) at (a) Latnajajaure, northern Sweden, and (b) Adventdalen, Svalbard, in two vegetation types (heath and meadow) and in two snow regimes (deep and shallow).

the High Arctic ($P < 0.001$; Fig. 3), so that the total annual CO_2 emission (in kg CO_2 m^{-2} yr^{-1}) at Latnjajaure was more than double that at Adventdalen (Table 2). Furthermore, at both sites there was also a significant difference ($P < 0.001$) between summer and winter CO_2 effluxes, with 10–100 times higher CO_2 emission rates during the summer (Fig. 3). However, no significant difference was found when comparing the winter CO_2 effluxes from these two sites, although the total winter CO_2 emission from Latnjajaure was double that from Adventdalen. The differences between the CO_2 effluxes of the two sites were the result of significantly higher CO_2 effluxes ($P < 0.001$) in Latnjajaure during the summer.

No significant differences in CO_2 effluxes were found between plant communities, or sites, during the winter (Fig. 3). In Adventdalen, summer CO_2 effluxes were significantly different ($P = 0.014$) between vegetation types. This was because of a higher CO_2 efflux ($P = 0.017$) from the meadow with shallow snow cover (166.8 mg CO_2 m^2 h^{-1}) than from the heath with shallow snow cover (107.0 mg CO_2 m^2 h^{-1}) (Fig. 3b). The CO_2 effluxes from the deep snow meadow (153.9 mg CO_2 m^2 h^{-1}) tended to be higher than the CO_2 effluxes from the shallow snow heath ($P = 0.096$), whereas no differences were found between the deep snow heath (121.8 mg CO_2 m^2 h^{-1}) and the other vegetation types (Fig. 3b). However, because of the prolonged winter period at both the snow-fence sites, the annual CO_2 emissions were reduced by 10–20% (Table 2). At the sub-Arctic site of Latnjajaure, summer CO_2 effluxes also differed significantly ($P < 0.001$) between vegetation types, with the meadow snowbed having a significantly higher ($P < 0.02$) summer CO_2 efflux (575.9 mg CO_2 m^2 h^{-1}) than the other treatment combinations, which had mean CO_2 effluxes ranging from 239.1 to 313.7 mg CO_2 m^2 h^{-1} (Fig. 3a). No other differences between the vegetation types at Latnjajaure were found.

Snowpack properties

The mean snow density of the sites with deep snow cover increased over the period measured (Table 3), but no difference between Adventdalen and Latnjajaure could be found. However, shallow snow had slightly lower

Table 2 Annual and seasonal emissions of CO_2 from Latnjajaure, northern Sweden, and Adventdalen, Svalbard. Winter was defined as the period between the development of continuous snow cover and the melt-out of the membrane. The mean values (±range) are derived from integrated values between the samples across the sampling intervals.

		Annual emissions (kg CO_2 m^{-2} yr^{-1})	Summer emissions (kg CO_2 m^{-2} yr^{-1})	Winter emissions (kg CO_2 m^{-2} yr^{-1})	Winter emissions as a % of annual emissions
Latnjajaure					
Heath	Deep	0.662 ± 0.115	0.541 ± 0.087	0.121 ± 0.028	18
	Shallow	1.148 ± 0.268	1.137 ± 0.266	0.011± 0.002	1
Meadow	Deep	1.487 ± 0.697	1.252 ± 0.583	0.235 ± 0.114	16
	Shallow	0.881 ± 0.590	0.858 ± 0.169	0.023 ± 0.421	3
Adventdalen					
Heath	Deep	0.369 ± 0.059	0.365 ± 0.056	0.004 ± 0.003	1
	Shallow	0.410 ± 0.048	0.404 ± 0.043	0.006 ± 0.004	2
Meadow	Deep	0.475 ± 0.078	0.470 ±0.074	0.005 ± 0.004	1
	Shallow	0.591 ± 0.143	0.579 ± 0.131	0.012 ± 0.012	2

Table 3 Calculated porosity (Φ_{cal}), tortuosity (t_{cal}) and s_{cal}, based on the mean snow density (±SE), and the measured mean *s* values (±SE) using the trace gas technique from deep snow measurements at Latnjajaure, northern Sweden, and Adventdalen, Svalbard.

	Snow density	Calculated			Measured *s*	
	(kg dm^{-3})	Φ_{cal}	t_{cal}	s_{cal}	Adventdalen	Latnjajaure
November/December	0.290 ± 0.004	0.683	0.784	0.535	0.072 ± 0.032	—
January/February	0.324 ± 0.016	0.647	0.780	0.505	0.080 ± 0.025	1.336 ± 0.391
March	0.408 ± 0.006	0.552	0.752	0.415	0.153 ± 0.029	0.120 ± 0.060
April	0.415 ± 0.005	0.547	0.750	0.410	0.035 ± 0.012	0.179 ± 0.161
Early May	0.443 ± 0.022	0.517	0.744	0.385	0.006[a]	—
Mid-May	0.442 ± 0.007	0.518	0.744	0.385	—	0.070 ± 0.028
Late May	0.455 ± 0.006	0.504	0.741	0.374	0.005[a]	0.023 ± 0.016
June	0.486 ± 0.009	0.470	0.734	0.345	—	0.035 ± 0.009

[a] Based on one measurement.

density (0.300–0.380 kg dm^{-3}), with less pronounced temporal trends in snow density. In the deep snow cover the measured *s* values generally decreased during late winter, whereas the calculated values of Φ_{cal}, t_{cal} and s_{cal} decreased as a function of the increase in snow density (Table 3). The measured values of *s* ranged between 0.001 and 2.74 within the deep snowpacks, with the highest values found during the January measurements in Latnjajaure. (The non-physical values of *s* [$s > 1$] are discussed in more detail below.) No specific temporal pattern could be found in shallow snow, where the measured *s* values ranged between <0.001 and 2.42. Ice lenses were present at both sites and snow regimes, and varied widely in thickness and quantity. Snow density, snow temperature and CO_2 concentration through a representative Latnjajaure snow profile are shown in Fig. 4.

Discussion

Unlike most other winter respiration studies (e.g., Brooks et al. 1995; Welker et al. 2000; Nobrega & Grogan 2007), our study suggests that winter snow depth has little influence on soil CO_2 effluxes through the snow. The total winter emissions in this study, from both shallow and deep snow, were all in the lower part of the range previously described in the literature from the same types of ecosystems: i.e., from 0.005–0.040 kg CO_2 m^{-2} yr^{-1} (Fahnestock et al. 1998) to 0.407–0.693 kg CO_2 m^{-2} yr^{-1} (Grogan & Chapin 1999). Furthermore, it should be noted that our calculations of total winter emission, based upon interpolation of a restricted number of winter measurements, may not give an accurate estimate of the winter CO_2 emission. This is because our sample intensity was biased towards the late winter season. Measurements during the early winter season were lacking, in particular for Latnjajaure, as it was not possible to reach Latnjajaure from October to December 2007, as shallow snow cover prevented the transport of personnel and equipment by snowmobile or ski. This lower frequency sampling may have led to an underestimation of the total winter emissions, and a further detailed study would be required to fill in these missing winter measurements. The high variation in winter CO_2 effluxes found in the literature could be a result of the different techniques used. For example, Fahnestock et al. (1998) used a concentration gradient to calculate the flux, whereas Grogan & Chapin

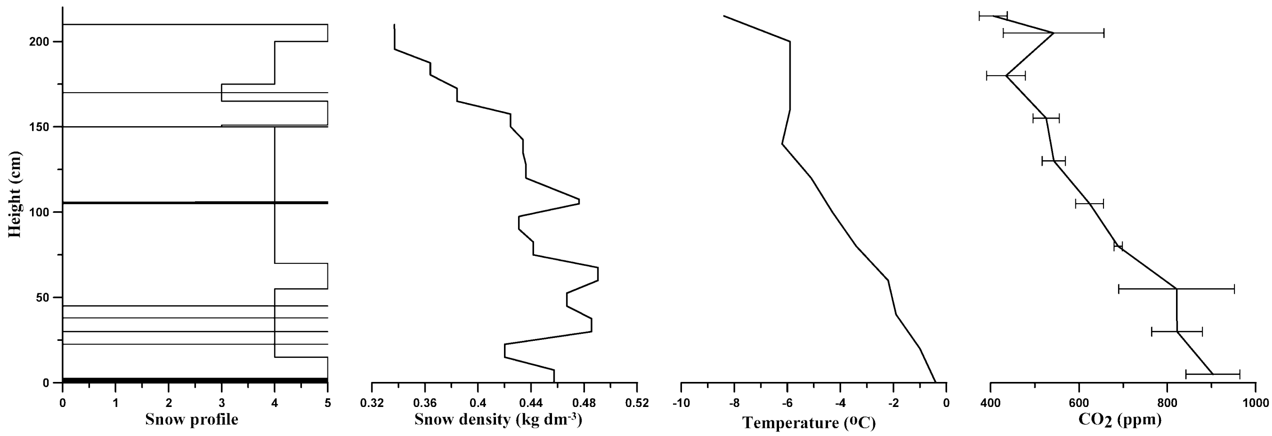

Fig. 4 Snow profile, density, temperature and CO_2 concentration at different depths through a heath snow pack in Latnjajaure on 4 March 2008. In the snow profile, the numbers 1–5 denote the hardness of the snow corresponding to when a object (a fist [1], four fingers [2], a finger [3], a pencil [4] and a knife [5]) can be pushed into the snow with moderate force of ca. 30 N (ICSI/IAHS 1981), whereas a continuous line between 0 and 5 indicates an ice layer.

(1999) used soda-lime traps. Other approaches have also been used, e.g., closed chambers connected to an infrared gas analyser in snow pits (Grogan & Jonasson 2006; Elberling 2007; Morgner et al. 2010) or on top of the snow cover (McDowell et al. 2000). Different estimates have also been obtained by the use of diffusion approaches (e.g., Sommerfeld et al. 1993; Schindlbacher et al. 2007). However, our trace gas technique measures the real-time diffusion rate through the snow, accounting for the complexity of snowpacks with their layered structure and frequent ice lenses, a complexity that is hard to take into account when using other techniques. There is also a high risk that pressure pumping, caused by wind and changes in atmospheric pressure, may occur during sampling (Albert & Hardy 1995; Massman et al. 1995; Jones et al. 1999). The trace gas technique takes account of these errors because the diffusion of SF_6 is affected in the same way as CO_2. The same is true if CO_2 emissions are affected by natural convection (Sturm & Johnson 1991). By using the method suggested in this study, real-time diffusion rates of CO_2 can be obtained, providing new insights into soil winter respiration.

Furthermore, our results indicate that annual CO_2 production is considerably higher in the sub-Arctic than in High-Arctic areas. Our results are within the same range as a previous study (Elberling 2007) in the same High-Arctic region (0.377–0.645 kg CO_2 m^{-2} yr^{-1}). However, we found a much higher annual production at Latnjajaure, the sub-Arctic site, than has been presented in earlier studies (e.g., Welker et al. 2000) at the same latitude (0.257–0.432 kg CO_2 m^{-2} yr^{-1}).

At Adventdalen, the increased snow depth decreased the total annual CO_2 emission by 10–20%; at Latnjajaure, where the snowbed communities are all natural, this pattern was only found in the heath communities, where 43% less CO_2 was produced than from the more exposed areas. In contrast, the meadows had 70% higher annual CO_2 emission from the natural snowbeds than from the shallow snow sites. Contrary to our snow-fence results, it has recently been suggested that increased snow depth increases the annual respiration rate because of the addition of soil moisture in deeper soil layers (Chimner & Welker 2005). However, increased snow depth may also alter the net ecosystem exchange (NEE; not measured in this study) of CO_2, through a decrease in the photosynthetic period; this could translate our decrease in annual respiration to an annual increase in NEE (Nobrega & Grogan 2007). In the long term it is also likely that increased snow depth will change the plant community (Wahren et al. 2005), but not necessarily the soil microbial community (Björk et al. 2008). Our results from naturally occurring snowbeds indicate that a clear trend associated with future climate scenarios cannot be drawn, as responses are highly dependent on parameters other than snow accumulation: for example, the type of vegetation and length of the growing season.

Soil temperature differences between High- and sub-Arctic areas show a clear pattern of lower temperatures with increased latitude. This can partly be explained with the deeper installation of temperature probes in Latnjajaure. Furthermore, Adventdalen has a permafrost, whereas Latnjajaure does not (Beylich et al. 2003), indicating a physical difference between the two locations. An increase in snow depth promotes stability with respect to soil temperatures (Welker et al. 2000), as observed in both snow-fence and snowbed communities, although the total decoupling of soil temperature from ambient air temperature did not occur at the fenced sites. The gradual decrease in soil temperature observed at all sites throughout the winter was probably caused by a decrease in air temperature, in combination with cooling from the permafrost at the High-Arctic site. The positive temperatures recorded for New Year 2007/08 at Adventdalen were associated with rain, which permeated through the snowpack and raised the soil temperatures considerably. Neither of the shallow sites at Adventdalen and Latnjajaure had continuous snow cover of more than 30 cm, the figure considered to represent the minimum snow depth that will thoroughly insulate soil temperature from ambient air temperature (Barry 1992). Sullivan et al. (2008) showed that winter air and soil temperature are controlling factors with respect to soil respiration. However, comparing winter soil temperatures with CO_2 effluxes in this study indicates that soil temperatures have little effect on the CO_2 emissions during the winter season, suggesting that other parameters such as nutrient availability and soil moisture are key controlling factors for winter soil microbial activity and respiration (Clein & Schimel 1995; Brooks et al. 2004).

Evaluation of the trace gas technique

Earlier studies that have used Fick's First Law (e.g., Sommerfeld et al. 1993; Zimov et al. 1996) have used the snow density for the evaluation of snow porosity and tortuosity, or have used a fixed tortuosity value, which results in slightly higher efflux rates than given by our trace gas technique (Björkman et al. unpubl. ms). However, the frequently occurring ice layers in this study (see Fig. 4) are hard to take into account when measuring snow density. The porosity equation provided by Prieur Du Plessis & Masliyah (1991) tells us that a layer of pure ice would decrease the porosity towards zero, blocking the diffusive pathways. However, cracks and holes in ice lenses are present, allowing diffusion of gases through the snowpack. The trace gas technique used in this study accounted for the complexity of the snowpack, but a few drawbacks exist that need to be discussed for future improvements of the technique.

First, we obtained large variation in *s* values that may be a result of the small membranes used in our study. The source of CO_2 is assumed to be the entire soil surface, reducing lateral diffusion along the soil. In contrast, the diffusion of the trace gas is rather a three-dimensional system, whereas we have assumed that the diffusion of the trace gas follows the pattern of CO_2 by being one dimensional. This may reduce the diffusion rates, and also results in problems with tracking the diffusion gradient through the snowpack. However, we have partly overcome this problem by optimizing the SF_6 concentrations to be sure that SF_6 reaches the top of the snowpack. Consequently, lateral diffusion should have had a minor affect on the vertical diffusion. Another problem was the small membrane size. Even though the exact membrane position at ground level was known, it was hard to reach the membrane position with the sampling probe in deep snow cover. In our study, this is most likely to be the reason for the slightly higher *s* values given in Latnjajure during the April measurements. Therefore, larger air-permeable membranes are recommended in future studies. This would improve the similarity between trace gas diffusion and the expected CO_2 diffusion, giving a true one-dimensional diffusion, and would also improve the accuracy in sampling.

Second, there was a problem detecting an SF_6 diffusion gradient through shallow snowpacks that also may have contributed to the large variation in *s* values. As shown in Fig. 3, negative fluxes of CO_2 were sometimes measured during this study. However, soil is most unlikely to assimilate CO_2 during a dark Arctic winter, and these negative fluxes are most likely to be caused by sampling inaccuracies, when the ambient air has been contaminated by respired air or snow grains partly block the inlets of the avalanche probe. This is especially sensitive in shallow snowpacks where the short diffusion pathway has a large impact on the concentration gradient (d_c/d_z). Shallow snowpacks are also sensitive to ventilation (Albert & Hardy 1995), and make gas transport and within-snow concentrations highly variable in moderate wind conditions. Shallow snow cover sensitivity to ventilation is also reflected in our *s* values, between <0.001 and 2.42, with the highest values found in Latnjajaure during April measurements (hourly average wind speed 8 m s^{-1}). By constantly circulating the trace gas during the measurements a steady supply of the trace gas would improve the accuracy of the technique in both deep and shallow snow cover, but would also simplify the calculations of *s* values. Furthermore, the wind-driven ventilation of snow can exceed several metres (Albert & Shultz 2002), and in this study one such occasion was found, in January at Latnjajaure when the meadow snowbed sites were sampled. On that occasion the measurements were obtained at the end of a windy (hourly average 12 m s^{-1}) period, with *s* values of up to 2.74. Hence, both porosity and tortuosity are described by values between 0 and 1; therefore, a calculated *s* value can never exceed 1. However, it is our supposition that the high *s* values found in this study are driven from other transport mechanisms than diffusion, such as pressure pumping and other types of ventilation.

Conclusion

The trace gas diffusion technique presented in this study shows some apparent advantages, as to a large extent it managed to account for the complexity of the snowpack, and can track ventilation events. However, larger air-permeable membranes combined with the continuous circulation of the trace gas could further improve the method, and reduce the uncertainties in the method presented by Sommerfeld et al. 1993. Furthermore, in this study we showed that the actual release of CO_2 to the atmosphere from snow-covered soil had no direct link to the thickness of the snow cover. However, increased snow depth over areas currently covered with a shallow snowpack can decrease annual CO_2 emissions by up to 20%, by changing the length of the growing season, indicating that if climate change leads to increased winter precipitation this may decrease the annual CO_2 emissions. A comparison between the High Arctic and the sub-Arctic indicates that annual CO_2 emissions are significantly higher in the sub-Arctic, suggesting that future shifts in vegetation zones may increase soil respiration from Arctic tundra regions.

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References

Albert M.R. & Hardy J.P. 1995. Ventilation experiments in a seasonal snow cover. *Biogeochemistry of Seasonally Snow-Covered Catchments 228*, 41–49.

Albert M.R & Shultz E.F. 2002. Snow and firn properties and air–snow transport processes at Summit, Greenland. *Atmospheric Environment 36*, 2789–2797.

Anisimov O.A., Vaughan D.G., Callaghan T.V., Furgal C., Marchant H., Prowse T.D., Vilhjálmsson H. & Walsh J.E. 2007. Polar regions (Arctic and Antarctic). In M.L. Parry et al. (eds.): *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Pp. 653–685. Cambridge: Cambridge University Press.

Barry R. 1992. Climate–ice interactions. In W.A. Nierenberg (ed.): *Encyclopedia of Earth system science*. *Vol. 1.* Pp. 517–524. Orlando: Academic Press.

Beylich A.A., Kolstrup E., Linde N., Pedersen L.B., Thyrsted T., Gintz D. & Dynesius L. 2003. Assessment of chemical denudation rates using hydrological measurements, water chemistry analysis and electromagnetic geophysical data. *Permafrost and Periglacial Processes 14*, 387–397.

Björk R.G., Björkman M.P., Andersson M.X. & Klemedtsson L. 2008. Temporal variation in soil microbial communities in alpine tundra. *Soil Biology & Biochemistry 40*, 266–268.

Björk R.G., Klemedtsson L., Molau U., Harndorf J., Ödman A. & Giesler R. 2007. Linkages between N turnover and plant community structure in a tundra landscape. *Plant and Soil 294*, 247–261.

Björk R.G., Majdi H., Klemedtsson L., Lewis-Jonsson L. & Molau U. 2007. Long-term warming effects on root morphology, root mass distribution, and microbial activity in two dry tundra plant communities in northern Sweden. *New Phytologist 176*, 862–873.

Björk R.G. & Molau U. 2007. Ecology of alpine snowbeds and the impact of global change. *Arctic, Antarctic and Alpine Research 39*, 34–43.

Björkman M.P., Morgner E., Cooper E.J., Elberling B., Klemedtsson L. & Björk R.G. Unpubl. ms. Winter carbon dioxide effluxes from Arctic ecosystems—an overview and comparison of methodologies.

Brooks P.D., McKnight D. & Elder K. 2004. Carbon limitation of soil respiration under winter snowpacks: potential feedback between growing season and winter carbon fluxes. *Global Change Biology 11*, 213–238.

Brooks P.D., Schmidt S.K. & Williams M.W. 1997. Winter production of CO_2 and N_2O from alpine tundra: environmental controls and relationship to inter-system C and N fluxes. *Oecologia 110*, 403–413.

Brooks P.D., Williams M.W., Walker D.A. & Schmidt S.K. 1995. The Niwot Ridge snow fence experiment: biogeochemical responses to changes in the seasonal snowpack. *Biogeochemistry of Seasonally Snow-Covered Catchments 228*, 293–301.

Busuioc A., Chen D. & Hellström C. 2001. Performance of statistical downscaling models in GCM validation and regional climate change estimates: application for Swedish precipitation. *International Journal of Climatology 21*, 557–578.

Chimner R.A. & Welker J.M. 2005. Ecosystem respiration responses to experimental manipulations of winter and summer precipitation in a mixedgrass prairie, WY, USA *Biogeochemistry 73*, 257–270.

Clein J.S. & Schimel J.P. 1995. Microbial activity of tundra and taiga soils at sub-zero temperatures. *Soil Biology & Biochemistry 27*, 1231–1234.

Elberling B. 2007. Annual soil CO_2 effluxes in the High Arctic: the role of snow thickness and vegetation type. *Soil Biology & Biochemistry 39*, 646–654.

Fahnestock J.T., Jones M.H., Brooks P.D., Walker D.A. & Welker J.M. 1998. Winter and early spring CO_2 efflux from tundra communities of northern Alaska. *Journal of Geophysical Research—Atmospheres 103*, 29 023–29 027.

Grogan P. & Chapin F.S. 1999. Arctic soil respiration: effects of climate and vegetation depend on season. *Ecosystems 2*, 451–459.

Grogan P. & Jonasson S. 2006. Ecosystem CO_2 production during winter in a Swedish subarctic region: the relative importance of climate and vegetation type. *Global Change Biology 12*, 1479–1495.

ICSI/IAHS (International Commission of Snow and Ice/ International Association of Hydrological Sciences) 1981. *Avalanche atlas: illustrated international avalanche classification*. Paris: United Nations Education, Scientific and Cultural Organisation.

Jones H.G., Pomeroy J.W., Davies T.D., Tranter M. & Marsh P. 1999. CO_2 in Arctic snow cover: landscape form, in-pack gas concentration gradient, and the implications for the estimation of gaseous fluxes. *Hydrological Processes 13*, 2977–2989.

Klemedtsson L., Kasimir Klemedtsson Å., Moldan F. & Weslien P. 1997. Nitrous oxide emission in Swedish forest soils in relation to liming and simulated increased N-deposition. *Biology and Fertility of Soils 25*, 290–295.

Kohler J., Brandt O., Johansson M. & Callaghan T. 2006. A long-term Arctic snow depth record from Abisko, northern Sweden, 1913–2004. *Polar Research 25*, 91–113.

Lemke P., Ren J., Alley R.B., Allison I., Carrasco J., Flato G., Fujii Y., Kaser G., Mote P., Thomas R.H. & Zhang T. 2007. Observations: changes in snow, ice and frozen ground. In S. Solomon et al. (eds.): *Climate change 2007. The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Pp. 337–383. Cambridge: Cambridge University Press.

Massman W.J. 1998. A review of the molecular diffusivities of H_2O, CO_2, CH_4, O_3, SO_2, NH_3, N_2O, NO, and NO_2 in air, O_2 and N_2 near STP. *Atmospheric Environment 32*, 1111–1127.

Massman W.J. 2006. Advective transport of CO_2 in permeable media induced by atmospheric pressure fluctuations: 1. An analytical model & 2. Observational evidence under snowpacks. *Journal of Geophysical Research—Biogeosciences 111*, G03004 & G03005.

Massman W.J., Sommerfeld R.A., Mosier A.R., Zeller K.F., Hehn T.J. & Rochelle S.G. 1997. A model investigation of turbulence-driven pressure-pumping effects on the rate of diffusion of CO_2, N_2O and CH_4 through layered snowpacks. *Journal of Geophysical Research—Atmospheres 102*, 18 851–18 863.

Massman W.J., Sommerfeld R.A., Zeller K.F., Hehn T., Hudnell L. & Rochelle S.G. 1995. CO_2 flux through a Wyoming seasonal snowpack: diffusional and pressure pumping effects. *Biogeochemistry of Seasonally Snow-Covered Catchments 228*, 71–79.

McDowell N.G., Marshall J.D., Hooker T.D. & Musselman R. 2000. Estimating CO_2 flux from snowpacks at three sites in the Rocky Mountains. *Tree Physiology 20*, 745–753.

Morgner E., Elberling B., Strebel D. & Cooper E.J. 2010. The importance of winter in annual ecosystem respiration in the High Arctic; effects of snow depth in two vegetation types. *Polar Research 29*, 58–74.

Nobrega S. & Grogan P. 2007. Deeper snow enhances winter respiration from both plant-associated and bulk soil carbon pools in birch hummock tundra. *Ecosystems 10*, 419–431.

Økland R.H., Økland T. & Rydgren K. 2001. *Vegetation–environment relationships of boreal spruce swamp forests in Østmarka Nature Reserve, SE Norway*. *Sommerfeltia 29*. Oslo: Natural History Museum, University of Oslo.

Panikov N.S., Flanagan P.W., Oechel W.C., Mastepanov M.A. & Christensen T.R. 2006. Microbial activity in soils frozen to below −39°C. *Soil Biology & Biochemistry 38*, 785–794.

Prieur Du Plessis J. & Masliyah J.H. 1991. Flow through isotropic granular porous media. *Transport in Porous Media 6*, 207–221.

Schindlbacher A., Zechmeister-Boltenstern S., Glatzel G. & Jandl R. 2007. Winter soil respiration from an Austrian mountain forest. *Agricultural and Forest Meteorology 146*, 205–215.

Schimel J.P., Bilbrough C. & Welker J.M. 2004. Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities. *Soil Biology & Biochemistry 36*, 217–227.

Schürmann A., Mohn J. & Bachofen R. 2002. N_2O emissions from snow-covered soils in the Swiss Alps. *Tellus Series B 54*, 134–142.

Sommerfeld R.A., Moiser A.R. & Musselman R.C. 1993. CO_2, CH_4 and N_2O flux through a Wyoming snowpack and implications for global budgets. *Nature 361*, 140–142.

Sturm M. & Johnson J.B. 1991. Natural-convection in the sub-Arctic snow cover. *Journal of Geophysical Research—Solid Earth and Planets 96*, 11 657–11 671.

Sullivan P.F., Welker J.M., Arens S.T.J. & Sveinbjörnsson B. 2008. Continuous estimates of CO_2 efflux from arctic and boreal soils during the snow-covered season in Alaska. *Journal of Geophysical Research—Biogeosciences 113*, G04009.

Symon C., Arris L. & Heal B. (eds.) 2005. *Arctic climate impact assessment*. Cambridge: Cambridge University Press.

Thibodeaux L.J. 1996. *Environmental chemodynamics. Movements of chemicals in air, water and soil*. New York: John Wiley and Sons.

Wahren C-H.A., Walker M.D. & Bret-Harte M.S. 2005. Vegetation responses in Alaskan Arctic tundra after 8 years of a summer warming and winter snow manipulation experiment. *Global Change Biology 11*, 1–16.

Welker J.M., Fahnestock J.T. & Jones M.H. 2000. Annual CO_2 flux in dry and moist Arctic tundra: field responses to increases in summer temperatures and winter snow depth. *Climatic Change 44*, 139–150.

Zimov S.A., Davidov S.P., Voropaev Y.V., Prosinnikov S.F., Semiletov I.P., Chapin M.C. & Chapin F.S. 1996. Siberian CO_2 efflux in winter as CO_2 source and cause of seasonality in atmospheric CO_2. *Climatic Change 33*, 111–120.