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Annual CO_2 budget and seasonal CO_2 exchange signals at a High Arctic permafrost site on Spitsbergen, Svalbard archipelago

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Annual CO_2 budget and seasonal CO_2 exchange signals

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Abstract

The annual variability of CO_2 exchange in most ecosystems is primarily driven by the activities of plants and soil microorganisms. However, little is known about the carbon balance and its controlling factors outside the growing season in arctic regions dominated by soil freeze/thaw-processes, long-lasting snow cover, and several months of darkness. This study presents a complete annual cycle of the CO_2 net ecosystem exchange (NEE) dynamics for a High Arctic tundra area on the west coast of Svalbard based on eddy-covariance flux measurements. The annual cumulative CO_2 budget is close to zero grams carbon per square meter per year, but shows a very strong seasonal variability. Four major CO_2 exchange seasons have been identified. (1) During summer (ground snow-free), the CO_2 exchange occurs mainly as a result of biological activity, with a predominance of strong CO_2 assimilation by the ecosystem. (2) The autumn (ground snow-free or partly snow-covered) is dominated by CO_2 respiration as a result of biological activity. (3) In winter and spring (ground snow-covered), low but persistent CO_2 release occur, overlain by considerable CO_2 exchange events in both directions associated with changes of air masses and air and atmospheric CO_2 pressure. (4) The snow melt season (pattern of snow-free and snow-covered areas), where both, meteorological and biological forcing, resulting in a visible carbon uptake by the high arctic ecosystem. Data related to this article are archived under: http://doi.pangaea.de/10.1594/PANGAEA.809507

1 Introduction

Northern terrestrial ecosystems have become increasingly important to the earth's system over the last few decades because of their ability to sequester the greenhouse gas carbon dioxide (Graven et al., 2013). Our understanding of the transient carbon dynamics of a thawing Arctic remains rudimentary, however, and there have been very few year-long studies of net CO_2, water, and energy exchanges using micrometeorological

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methods, due to the difficulties involved in collecting the necessary measurements in such cold, remote regions. It is therefore critical that we improve our understanding of the variations in carbon and water fluxes across the different types of permafrost tundra ecosystems, in order to be able to validate and predict future carbon and water budgets in coupled earth system models.

The annual carbon budgets of Arctic ecosystems are not only affected by growing-season exchanges, but also to a substantial extent by losses and gains that occur during the transition seasons of spring (snowmelt/soil-thaw) and autumn (senescence/soil-freeze). However, there is considerable variability in the causal processes across the tundra areas of the European Arctic (Heikkinen et al., 2004), Siberia (Corradi et al., 2005), Alaska (e.g. Kwon et al., 2006; Euskirchen et al., 2012), Greenland (e.g. Soegaard et al., 2000), Svalbard (Lloyd, 2001a, b), Canada (Humphreys and Lafleur, 2011) and northern Scandinavia (e.g. Aurela et al., 2004).

Most ecosystems experience inter-annual and across-site variability in CO_2 exchange that is primarily driven by growing-season dynamics and moisture conditions. However, in climatic regions dominated by snow, ice, and soil freeze/thaw processes, interactions between permafrost and atmosphere during the snow-covered dark winter months and early (pre-melt) spring may also make a significant contribution to the carbon cycle. Estimated winter CO_2 releases have been reported to make up between 20 and 40 % of an ecosystem's annual carbon loss (Zimov et al., 1996; Fahnestock et al., 1999; Elberling and Brandt, 2003).

Several studies have shown summer (growing-season) CO_2 exchange in tundra ecosystems to be closely related to the timing of snowmelt, with earlier snowmelt resulting in a greater uptake of atmospheric CO_2 by the ecosystem. Cumulative growing season net ecosystem exchanges (NEEs) between $-1.4\,\mathrm{g\,C\,m^{-2}}$ and $-23.3\,\mathrm{g\,C\,m^{-2}}$ have been reported by Soegaard and Nordstroem (1999), Nordstroem et al. (2001), and Groendahl et al. (2007) from a High Arctic site at Zackenberg, in northeast Greenland (74° N). Previously published values for winter CO_2 release in Alaska have ranged from $+2\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ for tussock tundra in northern Alaska (Fahnestock et al., 1998), to +111

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to +189 $g\,C\,m^{-2}\,yr^{-1}$ at sites in northern and central Alaska (Grogan and Chapin, 1999). Multi-year ground-based carbon budget analyses from Arctic tundra and boreal forest sites show high levels of spatial and temporal variability (Johansson et al., 2006). Aurela et al. (2004) reported that a fen at a sub-Arctic site in Kaamanen (northern Finland) acted as a sink for atmospheric CO_2, with a mean NEE rate of −22 $g\,C\,m^{-2}\,yr^{-1}$, determined from a six-year dataset. Carbon balances reported for sites on the North Slope of Alaska (68° N to 71° N) range from an accumulation of −109 $g\,C\,m^{-2}\,yr^{-1}$ (Chapin et al., 1980) to a release of more than +200 $g\,C\,m^{-2}\,yr^{-1}$ (Oechel et al., 1993). A very large inter-annual variability in the CO_2 ecosystem exchange was also reported by Schuur et al. (2009) from a sub-arctic site with extensive thawing of permafrost, ranging from acting as a source of CO_2 to the atmosphere (at +80 $g\,C\,m^{-2}\,yr^{-1}$) in one year to acting as a sink (at −40 $g\,C\,m^{-2}\,yr^{-1}$) in the following year. This considerable inter-annual and inter-site variability, together with the shortage of year round micrometeorological studies, makes it very difficult to compile a coherent picture of the factors driving NEE, with investigations having to rely on the multitude of short-term CO_2-flux studies.

The only published year-long carbon exchange study on continuous permafrost Arctic tundra using the eddy covariance method was carried out by Euskirchen et al. (2012), who investigated three tundra ecosystems (heath tundra, tussock tundra, and wet sedge tundra) in Imnavait Creek, Alaska. Their study showed that, despite intra-annual and seasonal variability, the net CO_2 accumulation during the growing season was generally lost through respiration during the snow covered months of September–May, and that these ecosystems were therefore net sources of CO_2.

There is clearly a critical need to improve our understanding of the variations in carbon and water fluxes across the different types of tundra, in order to be able to predict future carbon and water budgets. In this paper we present a full annual cycle of the carbon dynamics at a High Arctic site underlain by permafrost that is currently experiencing warming (Isaksen et al., 2007).

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2 Materials and methods

2.1 Study site

These investigations were carried out in the High Arctic Bayelva River catchment area (Fig. 1), close to Ny-Ålesund on Spitsbergen Island in the Svalbard archipelago (78°55′ N, 11°57′ E), where continuous permafrost underlies the unglaciated coastal areas to a depth of about 100 m (Humlum, 2005). The West Spitsbergen Ocean Current, a branch of the North Atlantic Current, warms this area to an average air temperature of about −13 °C in January and +5 °C in July, and provides about 400 mm of precipitation annually, falling mostly as snow between September and May. Significant warming has been detected since 1960, which is generally attributed to changes in the radiation budget and in atmospheric circulation patterns (Hanssen-Bauer and Førland, 1998). This warming is also reflected in the permafrost temperatures, as recorded from boreholes (Isaksen et al., 2001, 2007).

Over the past decade the Bayelva catchment has been the focus of intensive investigations into soil and permafrost conditions, (Roth and Boike, 2001; Boike et al., 2008; Westermann et al., 2010, 2011), the surface energy balance (Boike et al., 2003; Westermann et al., 2009a, b), and the micrometeorological processes controlling the surface gas and energy exchange (Lüers and Bareiss, 2010, 2011, 2013). The catchment area is bordered by two mountains, Zeppelinfjellet and Scheteligfjellet, between which the glacial Bayelva River originates from the two branches of the Brøggerbreen glacier moraine rubble. The terrain flattens out to the north of the study site and at about 1 km downstream the Bayelva River flows into the Kongs Fjord (Kongsfjorden) and the Arctic Ocean. Within the catchment, areas of sparse vegetation alternate with exposed soil and sand, or rock fields. Typical permafrost features such as mud boils and non-sorted circles are found in many parts of the study area.

The Bayelva soil and climate monitoring station, which is located on top of the Leirhaugen hill (25 m a.s.l.), has been recording climatological parameters and permafrost temperatures since 1998, while an eddy-flux tower was added on the gentle

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(< 5°) southern slope of the hill in 2007 (Westermann et al., 2009a). This flux measurement complex consists of a CSAT3 ultra sonic anemometer (Campbell Scientific Ltd.) for measuring turbulence variations of all three wind vectors and sonic temperature, and an LI-7500 open-path gas-analyzer (LI-COR Biosciences) for measuring CO_2 and H_2O concentrations. Both instruments are calibrated by the manufactures every six months. The measurement height is 2.9 above ground-level during the snow-free season. The snow height around the station is continuously monitored by an SR50 sonic ranging sensor (Campbell Scientific Ltd.).

The dominant ground pattern at the study site consists of non-sorted soil circles. The bare soil circle centers are about 1 m in diameter, surrounded by a vegetated rim consisting of a mixture of low vascular plants including various species of grass and sedge (*Carex* spec., *Deschampsia* spec., *Eriophorum* spec., *Festuca* spec., *Luzula* spec.), catchfly, saxifrage, willow, some other locally common species (*Dryas octopetala*, *Oxyria digyna*, *Polegonum viviparum*), and unclassified species of moss and lichen (Ohtsuka et al., 2006). The vegetation cover at the measurement site was estimated to be approximately 60 %, with the remainder being bare soil with a small proportion of stones (Lloyd et al., 2001). The silty clay soil has a low organic content, with volumetric fractions of less than 10 % (Boike et al., 2008).

2.2 Evaluation of CO_2 fluxes

The eddy covariance data for the twelve months from March 2008 to March 2009 were processed with the internationally standardized TK2 eddy-covariance software package (Mauder et al., 2008; Mauder and Foken, 2004, 2011), which produces quality-classified mean values (in our case 30 min aggregated fluxes of NEE, sensible heat, and latent heat) from the high-frequency data. This flux-calculating strategy has been successfully applied in major field experiments outside the Arctic region, such as EBEX-2000 (Mauder et al., 2007; Oncley et al., 2007), LITFASS-2003 (Mauder et al., 2006), and COPS-2007 (Eigenmann et al., 2011), as well as within the Arctic region (ARCTEX-2006, 2009: Lüers and Bareiss, 2010, 2011; Westermann et al., 2009a;

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Jocher et al., 2012). A quality assessment procedure, comprising a steady-state test (trend conditions) and an integral turbulence characteristics test (to assess the development of turbulent conditions) was employed, following the quality classification procedure proposed by Foken and Wichura (1996) and further developed by Foken et al. (2004) and Lüers and Bareiss (2011). These tests were preferred over a friction velocity threshold criterion for a flux data quality assessment, as these tests lead to an increase in the number of valid NEE data, especially during weak turbulent exchange conditions (Ruppert et al., 2006).

The steady-state test indicated generally high-quality measurement conditions for the Bayelva data set. Most of the momentum fluxes (i.e. 98 %) and 92 % of the sensible heat fluxes were classified as high quality. The stationarity assumption was fulfilled for 90 % of the water vapor flux (latent heat) and 92 % of the CO_2 fluxes. Most of the low-quality classes in the steady state test occurred during periods of very stable atmospheric stratification (during winter, spring and fall), and also during storm, rain, or snowfall events. The integral turbulence characteristics test showed that the turbulence of the vertical wind fluctuation was well developed and suitable for reliable flux calculations for 98 %.

A wind-direction (fetch) dependent error – affecting in particular the vertical wind vector component – can occur in the hilly terrain of the Bayelva site in response to the sensor geometry, its position, and its orientation with respect to the topography-dependent wind flow field (Foken et al., 2012; Finnigan et al., 2003). To minimize this tilt error a three dimensional coordinate system transformation by matrix multiplication was applied to the Bayelva data set, using the planar fit method of Wilczak et al. (2001). This method ideally results in a vertical wind vector of zero, averaged over periods of between one and three weeks. For most of these periods the mean bias offset between the measured and fitted planes of the wind flow at Bayelva during 2008/2009 was acceptable and close to 0.01 $m\,s^{-1}$.

Since the footprint analysis by Westermann et al. (2009a) showed that the flow paths of the main wind directions are unobstructed by any artificial structures, we assumed

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an undisturbed footprint area (Fig. 1). Following the suggestion by Foken et al. (2012), the sensor head was inclined at approximately 45° to one side, making it easier for heat generated by the sensor to rise away from the sensor's infrared pathway. Such artificial heating can potentially generate convection within the sampling volume (the infrared pathway) and thus influence the WPL correction for density fluctuations (Lafleur and Humphreys, 2007), but how efficiently this effect can be avoided or corrected remains uncertain (Grelle and Burba, 2007; Burba et al., 2008; Järvi et al., 2009; Burba and Anderson, 2010).

2.3 Error-filtering and gap-filling

Following Papale et al. (2006), we used an expanded multi-step error filter algorithm to statistically examine the aggregated time series of flux and meteorological data for outliers and inhomogeneities, and to separate 30 min flux values according to a quality classification, or to distinct weather conditions. After discarding flux values with low TK2 quality flags according to the quality classification system of Foken and Wichura (1996), an adjustable Multi-Step-Error-Filter including a Status-or-Threshold-Value check and a quantile and standard deviation filter was applied to detect and remove any major outliers.

In total, 27 % of all possible flux data were discarded and had to be gap-filled. Approximately 1 % of the flux data were discarded due to low TK2 quality and 3 % were discarded by the statistical outlier check, typically distributed over very small gaps of only one or two 30 min values. The most common gap sizes otherwise were between one and two hours, or between one and two days (together comprising 16 % of all flux data), due in most cases to snow and/or rain events. Due to malfunctions in the eddy covariance system the flux measurements were interrupted for five days in July (9–13 July 2008), for sixteen days in October 2008 (2–18 October), and for four days each in February and March 2009 (18–21 February and 5–8 March). These periods add up to about 7 % of the entire flux data set. Finally, during a 5 week period from 1 January to 6 February 2009, the high frequency 20 Hz records were not stored due to a memory

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card error, so that processing in the TK2 software package was not possible. However, the pre-calculated 30 min flux data from the data logger's internal Campbell Scientific eddy covariance software were available and could be fitted into the time series without any major gaps.

The very small gaps of only one or two 30 min values were filled by a linear regression with a window size of four values (2 before the gap, and 2 after). To fill the medium-sized gaps (maximum length of 2 days, 58 % of all missing data) and the four large gaps (July and October 2008, February and March 2009) the valid flux values were fitted to the Michaelis–Menten light response function for plants (in the narrow sense of CO_2 assimilation by plants, Michaelis and Menten, 1913; Falge et al., 2001) in dependency of meteorological parameters recorded at the Bayelva climate station such as incoming radiation, wind speed, and air temperature. A reasonable fit was achieved during the snow-free time (including October 2008) so that it was possible to restore the missing flux data from the available record of meteorological variables. For the rest of the year, when there was full snow coverage and/or no sunlight, no significant correlation was found between meteorological parameters (e. g. wind or net radiation) and the CO_2 exchange between the atmosphere and the snowpack. The 4 day gaps in February and March 2009 were therefore statistically filled using smoothed measured data from two days before and two days after the gap.

3 Results

3.1 The annual CO_2 budget

The quality-controlled and gap-filled annual and daily cumulative CO_2 budget can be seen in Fig. 2a demonstrating the effect of error detection and subsequent gap-filling of the (usually 30 min) integrated flux values. Figure 2b shows the time series of the related, additional meteorological parameters between March 2008 and March 2009.

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An annual budget of close to zero grams carbon per square meter per year was found for the Bayelva catchment over the study period, but with a strong seasonality.

Thus, the annual budget can be broken down into four main seasons, with the study area acting as a net sink during snow ablation between mid-May and end of June of $-1.4\,\mathrm{g\,C\,m^{-2}}$ and during the snow free summer July and August of $-10\,\mathrm{g\,C\,m^{-2}}$, and a net source in fall September and October of $+4.6\,\mathrm{g\,C\,m^{-2}}$, and during winter (November 2008 to March 2009) of $+7.1\,\mathrm{g\,C\,m^{-2}}$ (including April 2008: of $+6.4\,\mathrm{g\,C\,m^{-2}}$). These periods also correspond to the characteristic heat and energy balance periods identified for this site (Westermann et al., 2009a).

In 2008, the snowmelt period started in the last week of May and terminated between 20 June and 6 July. The CO_2 flux during intensive snowmelt was mainly directed upward into the atmosphere (with positive flux rates of up to $+0.25\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$), and had a distinctly diurnal character, with higher positive values for CO_2 release at noon and in the afternoon.

Directly after snowmelt the tundra ecosystem changed into a CO_2 sink (with negative flux rates of up to $-0.4\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$) characterized by CO_2 assimilation by plants, as reflected in the diurnal pattern of photosynthetic activity following insolation. During the month of August the balance between assimilation and respiration shifted increasingly towards respiration, which correlated strongly with declining insolation and the first occurrence of darkness at night (on 23 August). During September the decreasing photosynthetic activity, together with the absence of snow, and air and soil temperatures above freezing led to prevalent ecosystem respiration and positive CO_2 fluxes over a three to four week period (Fig. 2).

These positive CO_2 fluxes continued until the first severe frost (25 September 2008) and/or the first full snow coverage (end of October 2008) limited any further biological activity. Respiration was possible as long as there was no soil freezing or snow cover to prohibit the activity of microorganisms or plant roots, but photosynthetic activity ceased in mid-September. During the snow-covered (winter) period October to May, the processes forcing CO_2 accumulation and CO_2 release counterbalance each other,

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resulting in very low flux rates of $\pm 0.1\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$. However, depending on the synoptic weather situation, considerable CO_2 exchange (accumulation into the snowpack or release into the atmospheric boundary layer) of $\pm 2\,\mathrm{g\,C\,m^{-2}}$ can occur within just a few hours (or a few days) during the winter/spring months as it happened in April 2008 or March 2009 (see the following section for further details).

3.2 Snow-atmosphere exchange of CO_2

As is evident from Fig. 2, a number of significant CO_2-exchange events between the snowpack and the atmosphere, both, positive CO_2 release into the atmosphere and negative CO_2 accumulation into the snow occurred during the winter and spring of the investigated period.

One such exchange episode, which occurred during pressure and air mass changes between 13 March and 21 March 2009, is presented in Fig. 3. Following the arrival of a warm front at about 3 a.m. on 16 March, the air mass changed and the atmospheric CO_2 concentration decreased rapidly (Fig. 3a). This event coincided with a rapid fall in air pressure, a sudden increase of the wind speed (from less than $2\,\mathrm{m\,s^{-1}}$ to up to $8\,\mathrm{m\,s^{-1}}$), a change in wind direction blowing from the south instead from the east (Fig. 3b and c), and an air temperature increase from $-25\,^{\circ}\mathrm{C}$ to $-10\,^{\circ}\mathrm{C}$.

Under such conditions (advection of CO_2-depleted air and high wind speeds), a significant CO_2 release from the snowpack (positive sign, upward flux) can be observed, probably as a result of the steep gradient between the advected CO_2-depleted air mass and the relatively CO_2-enriched air within the snowpack. A next air mass change occurred during the ongoing passage of the warm front on the morning of 17 March. The easterly wind had ceased at around midnight and started to blow from the northwest at about 7 a.m. with the wind speed increasing to more than $8\,\mathrm{m\,s^{-1}}$, a change that lasted for the next day and a half. While the atmospheric CO_2 concentration increased slightly, the CO_2 release from the 1.2 m thick snowpack continued at high rates of +40 to $+50\,\mathrm{mg\,C\,m^{-2}}\ 30\,\mathrm{min^{-1}}$ for approximately one day. The CO_2 release rates subse-

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quently displayed a remarkable decline, even though the wind speeds remained high. This entire period terminated with the passage of the cold front at around 3 a.m. on 19 March. The wind ceased and then switched back to blowing from the south accompanied by a drop in air temperature to −26 °C and the CO_2 flux dropping back to around zero. It is remarkable that the sensible and the latent heat fluxes (Q_H and Q_E) did not show any comparable changes during this CO_2-exchange episode.

A similar event occurred in spring 2008, during the pressure and air mass change between 12 April and 24 April, but now different from the previous case with opposite flux directions. A cold front passed on the evening of 16 April resulting in a sharp drop in air pressure of 38 hPa and a change in wind direction, this time coinciding with a measured peak in CO_2 release from the 1 m thick snowpack, again supported by high wind speeds (10 $m\,s^{-1}$). In this instance the strong winds persisted for longer, lasting for almost seven days (until 23 April). While the air pressure and the atmospheric CO_2 concentrations increased continuously during these days, the CO_2 release from the snow decreased (possibly since the CO_2 stored within the snow layer had become depleted) and was replaced by significant CO_2 accumulation into the snow (CO_2 accumulation rates of up to −20 $mg\,C\,m^{-2}$ 30 min^{-1}). The period of significant CO_2 fluxes terminated abruptly on the afternoon of 23 April, after the wind direction changed from north-westerly to south-easterly, and the wind speed calmed down and the atmospheric CO_2 concentration dropped back down to background levels.

4 Discussion

At the Bayelva catchment in 2008 the daily carbon release or uptake rates by the ecosystem during the intensive snowmelt period (carbon release rates up to +0.25 $g\,C\,m^{-2}\,d^{-1}$) and during the summer (carbon uptake rates of −0.4 $g\,C\,m^{-2}\,d^{-1}$) are in agreement with previous measurements by Lloyd (2001a) from the same site during the summer of 1995. Lloyd (2001a, b) reported a net CO_2 source from this site, with a release rate of +0.3 $g\,C\,m^{-2}\,d^{-1}$ during late snowmelt, changing to a net CO_2

assimilation rate of $-0.39\,gC\,m^{-2}\,d^{-1}$ at midsummer, and then returning to a net CO_2 release rate of $+0.1\,gC\,m^{-2}\,d^{-1}$ in the early autumn of 1995. However, the CO_2 release rates of $+0.5\,gC\,m^{-2}\,d^{-1}$ observed in September 2008 are approximately five times greater than those measured by Lloyd (2001a) in autumn 1995. Chamber measurements by Uchida et al. (2009) recorded a CO_2 release of $+0.3\,gC\,m^{-2}\,d^{-1}$ at a nearby site from the thawing soil following complete snowmelt in 2001, but no such effect occurred during our campaign in 2008/2009.

Both summer and winter data have also been collected with non-eddy-covariance methods from other Svalbard sites (Adventdalen, Longyearbyen) using air sampling (in the snow) and closed chamber methods (Bjoerkmann et al., 2010). The winter emissions were estimated to be about 1 % to 2 % of the total annual emissions, which ranged from -82 to $-163\,gC\,m^{-2}$. The differences between these budgets and the atmospheric eddy-flux results reflect a strong seasonality, inter-annual and site specific variation, and differences between the (non-comparable) experimental techniques and models employed.

The daily carbon uptake at the Svalbard site during the summer of 2008 is a little lower than that observed in the summers of 1997 to 2003 (-0.5 to $-1.4\,gC\,m^{-2}\,d^{-1}$) by Groendahl et al. (2007) at the comparable Zackenberg site, in northeast Greenland (74° N). However, in contrast to the Bayelva site, the Zackenberg site has almost a total vegetation cover, dominated by vascular plants.

Compared to much more productive ecosystems in the Arctic (for example Imnavait Creek, Alaska: Euskirchen et al., 2012; Samoylov island, Siberia: Kutzbach et al., 2007; Runkle et al., 2013), the Bayelva site features relatively low daily fluxes of CO_2, both during summer assimilation and autumn respiration. For instance, much larger carbon exchange between June and August (NEE of $-119\,gC\,m^{-2}$) is reported from the Samoylov island. But this Siberian location is characterized by high organic soil content as well as numerous ponds and lakes (Kutzbach et al., 2007). During fall (September) these water bodies account for between 74 and 81 % of the calculated net landscape-scale CO_2 emissions at the Samoylov island, Siberia (Abnizova et al., 2012). At the

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Alaskan sites a range of NEE between +51 to +95 $\mathrm{g\,C\,m^{-2}}$ from different ecosystem types and years is reported (Euskirchen et al., 2012). Nevertheless, the CO_2 uptake of $-12\,\mathrm{g\,C\,m^{-2}}$ during the summer period of the Bayelva site (June, July, August) is remarkably large for such a sparsely vegetated site within the polar climate zone. The release of $+7\,\mathrm{g\,C\,m^{-2}}$ during the autumn (September, October and November) respiration period is also significant to the high arctic carbon balance. During the fully snow-covered winter and early (pre-melt) spring the carbon budget appears to be either extremely low or in balance (with the exceptions of few, but considerable CO_2 exchange events forced by changing meso-scale weather conditions).

An annual cumulative NEE of close to zero was recorded in this study, which is in agreement with the low soil carbon contents previously reported from the study site (Boike et al., 2008). During the polar night season a small but sustained CO_2 release occurs most of the time, which is in agreement with estimations of CO_2 fluxes from snowpacks in the Rocky Mountains (McDowell et al., 2000) and from Alaska (Euskirchen et al., 2012). It seems likely that the snow acts as a storage layer that buffers the exchange with the atmosphere. However, significant CO_2 fluxes in – both – directions can occur between the snowpack and the atmosphere during strong gas-exchange episodes caused by marked air and CO_2 pressure-change effects. It therefore appears that the actual gas exchange, i.e. the rapid emptying (or occasionally refilling) of the storage in the snowpack, is strongly forced by meteorological factors on timescales of hours to days. The resulting flux signal is a consequence of both the production and the release/transfer of trace gases through snow (and ice) as a result of variations in (a) the synoptic weather pattern, (b) the near surface atmospheric flux exchange conditions, (c) the activity of soil organisms (which may still be possible below the snowpack), and (d) the gas diffusion properties of the ice and snow.

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5 Summary and conclusion

The annual carbon balance at this permafrost study site on Spitsbergen is close to zero, displaying a sensitive balance between the short summer carbon uptake and the long fall and winter carbon release. This study has identified four major carbon (or trace gas) exchange seasons, each of which makes a significant contribution to the High Arctic carbon cycle:

1. Spring (May/June, snow ablation) – gas exchange (a) mainly caused by abiotic, meteorological and physico-chemical processes associated with free convections events or marked and rapid air pressure changes, high wind speeds, and advection of air masses that are either CO_2-enriched or CO_2-depleted relative to the snowpack, and (b) by the beginning of biological activity (first occurrence of snow free patches). The total net flux is a carbon uptake of about $-1.5\,\mathrm{g\,C\,m^{-2}}$.

2. Summer (July/August, snow-free) – gas exchange occurring mainly as a result of biological activity, predominantly CO_2 assimilation by plants. The measured cumulative NEE signal shows an accumulation of carbon of $-10\,\mathrm{g\,C\,m^{-2}}$.

3. Autumn (September/October, snow-free/partial snow coverage) – gas exchange again occurring as a result of biological activity, but predominantly CO_2 respiration by microorganisms (and plant roots). The measured cumulative NEE signal shows a release of carbon of about $+4.5\,\mathrm{g\,C\,m^{-2}}$.

4. Winter (November–April) full snow coverage – gas exchange almost entirely caused by abiotic, meteorological, and physico-chemical processes associated with marked and rapid air pressure changes, high wind speeds, and advection of air masses that are CO_2-enriched or CO_2-depleted relative to the snowpack. The total winter net flux is a release of carbon between $+6\,\mathrm{g\,C\,m^{-2}}$ and $+7\,\mathrm{g\,C\,m^{-2}}$ (range from $0.3/0.5\,\mathrm{g\,C\,m^{-2}}$ for January/February to $2.1/1.8\,\mathrm{g\,C\,m^{-2}}$ for November/December).

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The results of this twelve month study emphasize the fact that although winter carbon fluxes may be small, their contribution to the total annual carbon budget of Arctic ecosystems over a long time period is significant. The snow cover plays an important role in storing and releasing CO_2 through atmospheric forcing (changing meso-scale atmospheric circulation and micro-scale atmospheric boundary layer exchange conditions). Questions concerning the current state (source or sink) of an Arctic ecosystem can therefore only be addressed by continued, year round and multi-year measurements of trace gas fluxes and atmospheric circulation and exchange patterns. Permafrost carbon stores may be built up or depleted as a result of ecosystem responses to changes in climate.

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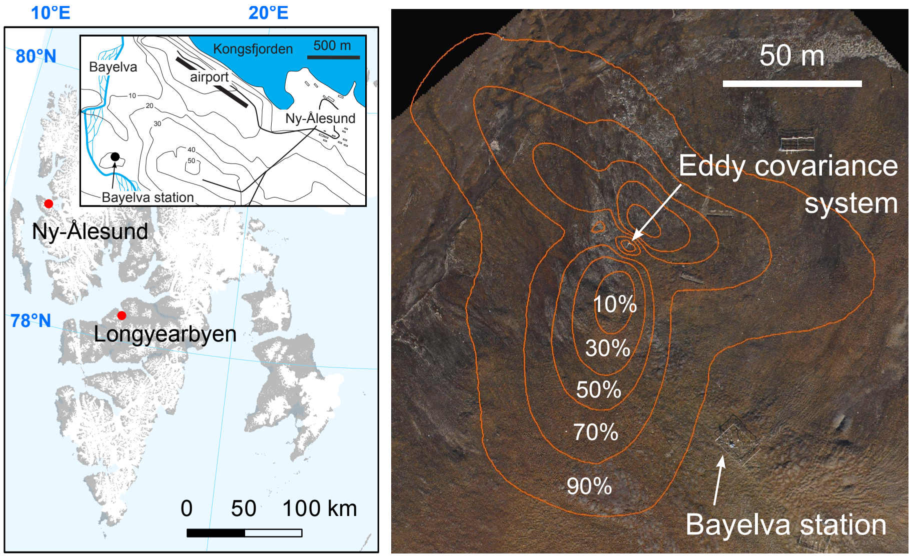

Fig. 1. Left: location of Ny-Ålesund on Svalbard; inset: map of the wider study area with Bayelva station. Right: orthorectified aerial photo with all installations and average footprint of the eddy covariance system from 1 July to 30 September 2008 (based on Westermann et al., 2009a), with fractions of the total flux originating within the respective contours.

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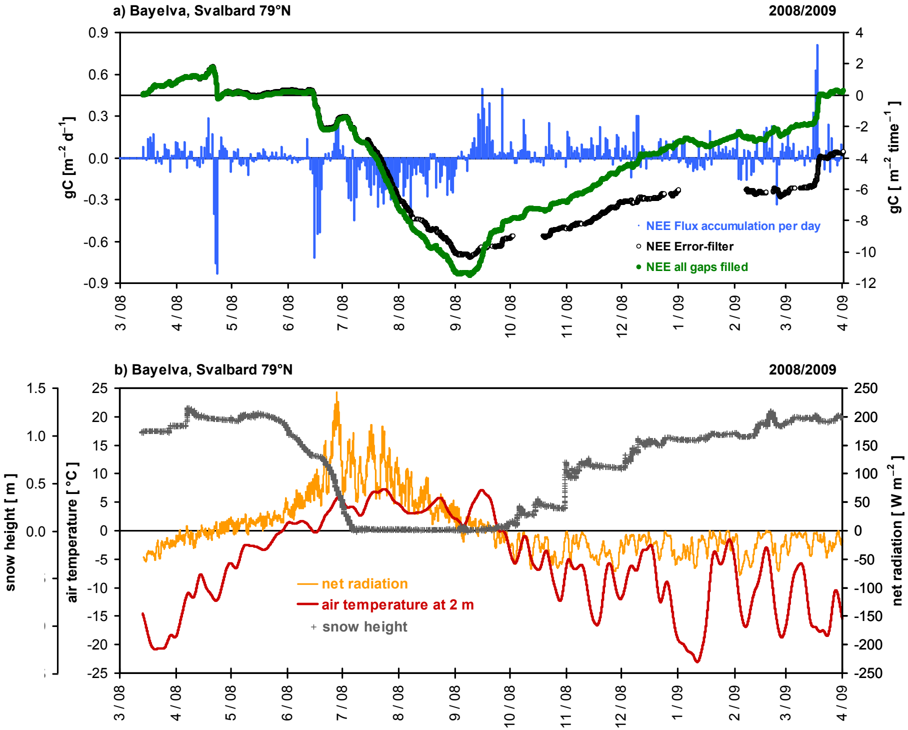

Fig. 2. (a) Cumulative net ecosystem exchange (NEE) of carbon dioxide measured at the Bayelva Eddy-Flux Station, Svalbard, and calculated using the TK2 eddy-covariance software package. Blue bars: daily net CO_2-flux in [$g\,C\,m^{-2}\,d^{-1}$]; black dots (NEE-fluxes verified by the error filter) and green dots (gap-filled final NEE dataset) both annual budget (accumulation between March 2008 and March 2009, [$g\,C\,m^{-2}\,time^{-1}$]). **(b)** Meteorological measurements. Snow height (gray crosses) in meters [m], smoothed air temperatures at 2 m above ground (red line) in [°C], smoothed net radiation (yellow line) in [$W\,m^{-2}$].

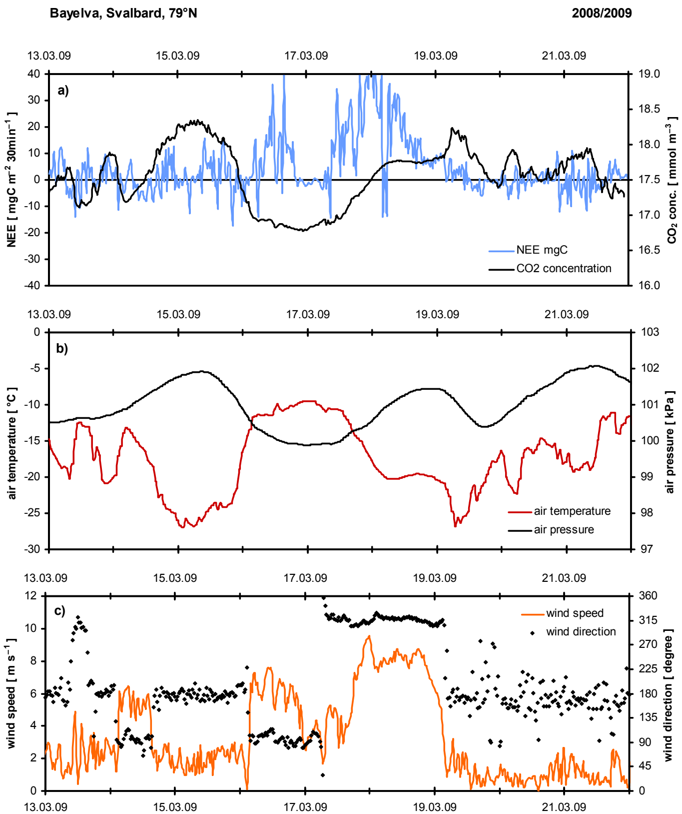

Fig. 3. Gas exchange 13 March to 21 March 2009, full snow cover (1.2 m height); Bayelva Observation Site, Svalbard. **(a)** Blue line: Net Ecosystem Exchange (NEE) of carbon dioxide [$mg\,C\,m^{-2}\,30\,min^{-1}$] and black line: atmospheric CO_2 molar concentration [$mmol\,m^{-3}$], LI-7500 gas-analyzer; **(b)** red line: air temperature at 2 m above ground [°C] and black line: Ny-Ålesund station air pressure [kPa]; **(c)** yellow line: wind speed [$m\,s^{-1}$] and black dots: wind direction [°], ultrasonic anemometer.