Tundra meets atmosphere

Seasonal dynamics of trace gas exchange in the High Arctic

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Abstract
Arctic environments have experienced strong warming in recent decades, which is affecting the carbon cycle of tundra ecosystems. Degrading permafrost, diminishing snow cover, and changing hydrology are examples of ongoing processes that affect the land-atmosphere interactions and seasonal ecosystem dynamics. Since a number of the affected processes involve the exchange of atmospheric greenhouse gases, such as the trace gases methane (CH_4) and carbon dioxide (CO_2), there is a potential for these interactions to lead to climate feedbacks.

The impact this feedback could have on the global climate is currently not well known due to gaps in our knowledge about the involved processes. One reason for this mismatch is the scarcity of direct, continuous and comparable measurements of CH_4 and CO_2 fluxes in the high Arctic tundra. The relatively remote, harsh, and low-flux conditions dominating these environments for most of the year pose challenges for flux measurement techniques that have proven to work well at lower latitudes. The present study is, therefore, not only aiming to advance our understanding of trace gas exchanges in the Arctic tundra, but also trying to improve commonly-used flux measurement techniques to yield new insights.

The two main study sites of this work are located in permafrost-underlain wetlands in Adventdalen, Svalbard and Zackenberg, NE Greenland. These sites show distinctly different processes that govern the trace gas exchange throughout the different seasons: The snow-free season is characterized by high CH_4 emissions, which seem to follow predictable spatial and temporal patterns. Large CO_2 uptake by photosynthesis and release by respiration give rise to a large amplitude of net ecosystem exchange during the growing season. The autumnal freeze-in period can feature the highest gas emissions, most likely due to physical mechanisms connected to the soil freezing that release a part of the soil gas reservoir. During winter and spring a low level of microbial activity is sustained but the gas transport capability of the frozen soil is relatively low. Still, snowpack gas concentrations indicate consistent emissions of CH_4 and CO_2 from the soil. Around the snowmelt period, emissions of stored gases in the snowpack and soil are superimposed on the fast increase of biological activity. The flooded and heterogeneous conditions make the representative flux estimation extremely challenging around this time of year. The diverse range of processes governing the seasonal flux dynamics at these two study sites exemplifies the complexity and possibilities of predicting the resilience and vulnerability of Arctic tundra ecosystems to climate change.

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A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or several other author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

Cover illustration: Adventdalen, Svalbard on 8 October 2015. Thanks to Anders Lindroth for letting me use his drone and Felix Schulze for editing the photo.

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I **Spatial variability of CO_2 uptake in polygonal tundra – large overestimations by the conventional eddy covariance method**

N. Pirk, J. Sievers, J. Mertes, F.-J. W. Parmentier, M. Mastepanov, and T. R. Christensen
2016, Biogeosciences Discussions (in review), doi:10.5194/bg-2016-537

II **Toward a statistical description of methane emissions from Arctic wetlands**

N. Pirk, M. Mastepanov, E. López Blanco, L. H. Christensen, H. H. Christiansen, B. U. Hansen, M. Lund, F.-J. W. Parmentier, K. Skov, and T. R. Christensen
2017, Ambio, 46, S70–S80

III **Snowpack fluxes of methane and carbon dioxide from high Arctic tundra**

N. Pirk, M. P. Tamstorf, M. Lund, M. Mastepanov, S. H. Pedersen, M. R. Mylius, F.-J. W. Parmentier, H. H. Christiansen, and T. R. Christensen
2016, Journal of Geophysical Research: Biogeosciences, 121, 2886–2900

IV **Calculations of automatic chamber flux measurements of methane and carbon dioxide using short time series of concentrations**

N. Pirk, M. Mastepanov, F.-J. W. Parmentier, M. Lund, P. Crill, and T. R. Christensen
2016, Biogeosciences, 13, 903–912

V **Methane emission bursts from permafrost environments during autumn freeze-in: New insights from ground-penetrating radar**

N. Pirk, T. Santos, C. Gustafson, A. J. Johansson, F. Tufvesson, F.-J. W. Parmentier, M. Mastepanov, and T. R. Christensen
2015, Geophysical Research Letters, 42, 6732–6738

The author was involved in the planning of these studies and was responsible for the data analysis, manuscript writing, and a part of the field work. In papers II, III, and IV, field data from various measurement sites was provided by co-authors.

Abstract

Arctic environments have experienced strong warming in recent decades, which is affecting the carbon cycle of tundra ecosystems. Degrading permafrost, diminishing snow cover, and changing hydrology are examples of ongoing processes that affect the land-atmosphere interactions and seasonal ecosystem dynamics. Since a number of the affected processes involve the exchange of atmospheric greenhouse gases, such as the trace gases methane (CH_4) and carbon dioxide (CO_2), there is a potential for these interactions to lead to climate feedbacks.

The impact this feedback could have on the global climate is currently not well known due to gaps in our knowledge about the involved processes. One reason for this mismatch is the scarcity of direct, continuous and comparable measurements of CH_4 and CO_2 fluxes in the high Arctic tundra. The relatively remote, harsh, and low-flux conditions dominating these environments for most of the year pose challenges for flux measurement techniques that have proven to work well at lower latitudes. The present study is, therefore, not only aiming to advance our understanding of trace gas exchanges in the Arctic tundra, but also trying to improve commonly-used flux measurement techniques to yield new insights.

The two main study sites of this work are located in permafrost-underlain wetlands in Adventdalen, Svalbard and Zackenberg, NE Greenland. These sites show distinctly different processes that govern the trace gas exchange throughout the different seasons: The snow-free season is characterized by high CH_4 emissions, which seem to follow predictable spatial and temporal patterns. Large CO_2 uptake by photosynthesis and release by respiration give rise to a large amplitude of net ecosystem exchange during the growing season. The autumnal freeze-in period can feature the highest gas emissions, most likely due to physical mechanisms connected to the soil freezing that release a part of the soil gas reservoir. During winter and spring a low level of microbial activity is sustained but the gas transport capability of the frozen soil is relatively low. Still, snowpack gas concentrations indicate consistent emissions of CH_4 and CO_2 from the soil. Around the snowmelt period, emissions of stored gases in the snowpack and soil are superimposed on the fast increase of biological activity. The flooded and heterogeneous conditions make the representative flux estimation extremely challenging around this time of year. The diverse range of processes governing the seasonal flux dynamics at these two study sites exemplifies the complexity and possibilities of predicting the resilience and vulnerability of Arctic tundra ecosystems to climate change.

Sammanfattning

Arktiska miljöer har de senaste decennierna upplevt en stark temperaturökning, vilket påverkar tundrans kolcykel. Smältande permafrost, minskande snötäcke och förändringar i hydrologiska mönster är exempel på pågående processer som förändrar samspelet mellan mark och atmosfär samt ekosystemens säsongsdynamik. Då ett antal av dessa processer involverar utbyte av växthusgaser, såsom spårgaserna metan (CH_4) och koldioxid (CO_2), finns en möjlighet att dessa samspel har återkopplingar på klimatet.

Påverkan dessa återkopplingar skulle kunna ha på det globala klimatet är för tillfället inte speciellt välkänd på grund av bristande kunskap om de grundläggande processerna. En orsak till detta problem är brist på direkta, kontinuerliga och jämförbara flödesmätningar av CH_4 och CO_2 på den arktiska tundran. De relativt avlägsna och hårda miljöförhållandena samt de låga gasflöden som dominerar dessa miljöer under större delen av året ställer stora tekniska utmaningar på flödesmätningar, som annars har visats fungera väl på lägre breddgrader. Syftet med den här studien är därför både att fördjupa den nuvarande kunskapen om spårgasflöden och förbättra de allmänna teknikerna för att mäta dessa gasflöden.

De två huvudsakliga fältstationerna för den här studien ligger på myrområden med permafrost i Adventdalen, Svalbard och i Zackenberg, Nordöstra Grönland. Det finns tydliga skillnader mellan de processer som styr spårgasutbytet för dessa områden över året: Den snöfria säsongen karaktäriseras av höga utsläpp av CH_4, som tycks följa ett förutsägbart spatialt och temporalt mönster. Under växtsäsongen ger fotosyntes och respiration upphov till stora svängningar i nettoekosystemutbytet av CO_2. På hösten när marken fryser kan de högsta utsläppen från markens gasförråd förekomma, troligtvis genom fysikaliska mekanismer som uppträder i samband med att marken fryser. Under vinter och vår upprätthålls en låg mikrobiell aktivitet i marken, även om gastransporten genom den frusna marken är relativt låg. Trots detta visar snötäckets gaskoncentrationer jämna utsläpp av CH_4 och CO_2 från marken. Vid snösmältningen sker utsläpp av snötäckets och markens gasförråd samtidigt som den biologiska aktiviteten ökar snabbt. De översvämmade och heterogena våtmarkerna gör representativa uppskattningar av flöden mycket svåra under denna tid på året. Den mångfald av processer som styr flödesdynamiken på de två platserna exemplifierar komplexiteten och möjligheterna i att förutsäga sårbarhet och resiliens hos den arktiska tundran i ett förändrat klimat.

Tundra meets atmosphere

1 Introduction

The Arctic is warming. More than any other region on Earth, the Arctic is predicted and observed to experience increases in surface air temperature (AMAP, 2011). The tundra ecosystems of the cold deserts in the High Arctic could respond to the temperature increase in still unknown ways.

A suite of ecosystem interactions coupled to climate warming involve the carbon cycle: All living things contain carbon in different molecular compounds, which are continuously transferred, assimilated, transformed, and decomposed in different parts of our physical environment. The land-atmosphere exchange of carbon occurs predominately in form of the trace gases carbon dioxide (CO_2) and methane (CH_4), which also play a vital role in regulating Earth's surface temperature because they absorb heat radiation in the atmosphere (greenhouse effect). Carbon dioxide is more abundant in the atmosphere than CH_4, but since CH_4 is a stronger greenhouse gas both gases contribute significantly to the greenhouse effect (Stocker et al., 2013). Since the physical, ecological, and biogeochemical processes that control the gas exchange depend on the local climate, changes in temperature can lead to changes in the carbon cycle, and vice versa. In a warming climate, this interaction could create a self-amplifying process (positive feedback).

Since different processes control the gas exchange in the various seasons of the Arctic (e.g. growing season, freeze-in, cold season, thaw), it is important to quantify and study the exchange of CH_4 and CO_2 in all seasons. Traditionally, the small emissions during the cold season (which can be orders of magnitude smaller than growing season fluxes) have received only little attention, even though these consistent fluxes can be critical to close the annual carbon balance (McGuire et al., 2012). Surprisingly, the highest fluxes in high Arctic tundra can sometimes occur during the autumnal freeze-in period, possibly as a result of physical processes that force out soil gases (Mastepanov et al., 2008). The needed process understanding can in some cases be derived from flux comparisons on different spatial scales (from individual plots along transects at one site to inter-site comparisons), where

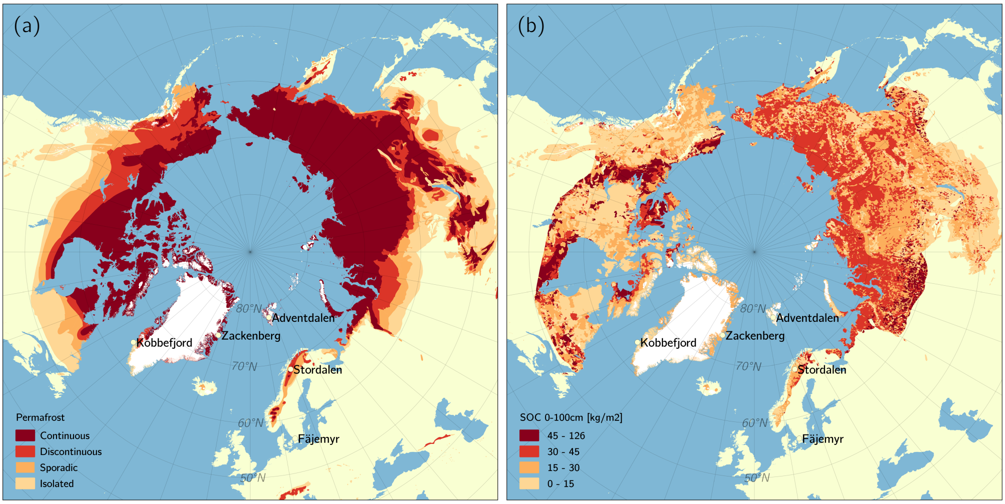

Figure 1: Site locations in the northern circumpolar region. a: Permafrost distribution according to Brown et al. (1997). b: Soil organic carbon (SOC) storage in the top 100 cm of the soil according to Hugelius et al. (2013).

conditions differ significantly. Since different locations can represent different stages in the evolution of the ecosystem, space-for-time substitutions can indicate possible future trends related to climate warming.

The cold climate that Arctic tundra was exposed to during the Holocene limited the decomposition of plant and animal residues by microorganisms. Since the carbon uptake by plants exceeded the slow decomposition, these ecosystems have accumulated relatively large amounts of soil organic carbon (SOC), stored in frozen permafrost and the seasonally unfrozen ground above (Hugelius et al., 2013). Parts of Siberia and Alaska also feature older organic deposits accumulated during the Pleistocene, which are particularly ice and carbon-rich (yedoma). The carbon sink function of the Arctic tundra could be disturbed by climate warming because decomposition rates increase with temperature. In a potentially even stronger feedback, some of the accumulated SOC that is frozen in permafrost could become available for decomposition and increase greenhouse gas emissions into the atmosphere (Shur and Jorgenson, 2007; Schuur et al., 2015).

1.1 Permafrost distribution and landforms

Permafrost is defined as ground that remains at or below 0°C for at least two consecutive years. The present and past climate is the dominant factor for the formation of permafrost, but also the ground exposure given the local geography (e.g. glaciation, vegetation cover, inundation) modulates the permafrost distribution (Shur and Jorgenson, 2007). Figure 1a shows the permafrost distribution in the northern hemisphere according to Brown et al.

(1997), classified into continuous (underlying 90–100% of the landscape), discontinuous (50–90%), and sporadic (0–50%) permafrost. Additionally, there are isolated patches of permafrost, as well as submarine permafrost (not shown). Together, these permafrost regions cover an estimated 23.9% of the exposed land surface of the northern hemisphere (Zhang et al., 2000), and their soils contain about 1300 Pg SOC, distributed as shown in Figure 1b.

Depending on the time of permafrost formation relative to the deposition of the host material, one differentiates between epigenetic permafrost (formed after the host material) and syngenetic permafrost (formed simultaneously with the host material). In reality most areas feature both these types and can therefore be classified as polygenetic (Gilbert et al., 2016). The thickness of permafrost can vary strongly, from a few tens of meters to hundreds of meters (Humlum et al., 2003).

Between permafrost and the ambient atmosphere lies the active layer—the top layer of the ground that is subject to annual thawing and freezing. The active layer is typically fully developed by the end of summer, when its depth can range between a few centimeters to several meters. Spatial and interannual variations of the active layer depth depend on a number of factors, including wintertime snowpack conditions, vegetation cover, soil thermal conductivity and heat capacity, surface albedo, cloud cover, and air temperature (Zhang et al., 1997).

Figure 2: The measurement site in Adventdalen, Svalbard located in a network of ice-wedge polygons.

The periodic freeze-thaw cycles of the active layer and related cryogenic processes shape the landscape. Depending on the soil grain size, water content, slope, and vegetation different landforms are formed over centuries or millennia (French, 2013). These cryogenic ground features can be irregularly spread over the landscape such as ice-cored hills (pingos and palsas), or form regular ground patterns like nets, steps, stripes, circles, and polygons (Åkerman, 1980). Ice-wedge polygons, such as shown in Figure 2, are created by joining subsurface ice wedges (Leffingwell, 1915; Mackay, 1974; Åkerman, 2005; Christiansen et al., 2016): These bodies of massive ground ice are formed as a result of meter-deep, vertical contraction cracks created by thermal contraction of the ground during wintertime. As these cracks are infiltrated by water in the following summer, the refreezing of the water inside the cracks widens the ice wedge and separates the overlying soil into polygonal shapes. Such ground patterns affect the small-scale water availability and vegetation cover, and hence directly influence the greenhouse gas fluxes in Arctic tundra (Vaughn et al., 2016).

Recent decades have seen dramatic changes in permafrost properties (Grosse et al., 2016). Permafrost is disintegrating along the southern margin of the permafrost zone causing ground subsidence and thermokarst (Grosse et al., 2013). However, across the Arctic, colder permafrost experiences the fastest warming rates (Romanovsky et al., 2010). Liljedahl et al. (2016) report the widespread degradation of ice wedges leading to differential ground subsidence with significant changes to the surface hydrology. Such hydrological changes could affect gas production and release, and are therefore important to quantify. To capture the geomorphological development and degradation of ice-wedge polygons, observations need to cover many decades, illustrating the need for analyses of historic aerial photographs of these landscapes.

1.2 Soil gas dynamics

Tundra CH_4 emissions are the net result of the production, transport, and consumption in the soil, i.e. a complex interplay of biogeochemical processes. The highest microbial activity in permafrost-underlain soils takes place in the active layer, as depicted in Figure 3. Inside the active layer, the water table position regulates oxygen availability, which determines the possible metabolic pathways.

In the anaerobic environment of water saturated soils, the decomposition of organic material produces CH_4 as the final product of a series of decomposition processes performed by many microbial communities (Conrad, 1996; Wagner et al., 2003). The methanogenic archaea that produce CH_4 can be classified in three groups based on the methanogenic substrate they use (Garcia et al., 2000): hydrogenotrophs use H_2 and CO_2, methylotrophs use methanol and methylamines, and acetotrophs use acetate and H_2 (Whiticar et al., 1986). These substrates come from either the degradation of old organic material or from fresh organic material such as root exudates from vascular plants (Ström et al., 2005). The different types of methanogenesis respond differently to temperature changes, but all types typically show exponential temperature relationships (Lai, 2009; Blake et al., 2015). The surface CH_4 emission, however, depends not only on the microbial production in the soil, but also on the transport that brings the gas to the surface. The CH_4 diffusing through the aerobic part of the soil can be substrate for methanotrophs, which oxidize CH_4 to CO_2 in their metabolism. These dry soil layers also constitute an important sink for atmospheric CH_4. Methane transported through the aerenchyma of vascular plants or by ebullition, however, largely avoids oxidization since it bypasses the aerobic soil layer. These transport pathways, and their relative contributions, depend very much on the type of ecosystem as well as the seasonally changing soil conditions (Christensen et al., 2003; Whalen, 2005; Goodrich et al., 2011).

Vegetation plays a key role for ecosystem functioning and carbon cycling. During photosynthesis, plants assimilate CO_2 from the atmosphere and produce organic carbohydrates, which the plant needs for maintenance, growth or reproduction. The vertical CO_2 exchange between the ecosystem and the atmosphere (NEE) is the sum of the uptake from the atmosphere through plant photosynthesis (GPP), and the release into the atmosphere due to respiration of the plants themselves (autotrophs) and other organisms in the soil (heterotrophs). Respiration generally depends on temperature, while photosynthesis also depends on incoming sunlight, available water and CO_2, and nutrients such as nitrogen. In wet Arctic tundra with long polar nights and seasonal snow cover (and the contrasting short summers with almost constant sunlight), in particular the sunlight limitation determines the dynamics of GPP.

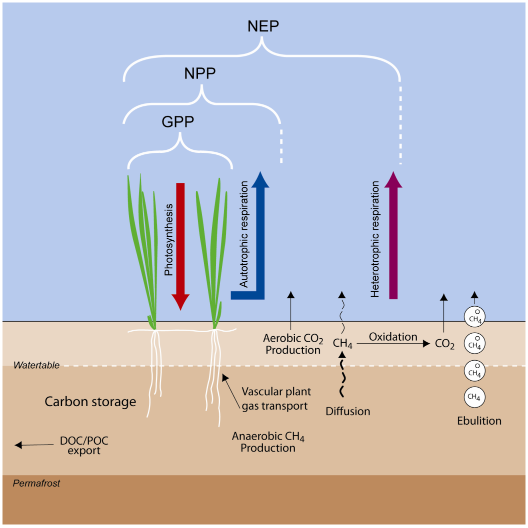

Figure 3: Production and transport of CH_4 and CO_2 in permafrost-underlain tundra, modified from Joabsson (2001).

Some of the CH_4 and CO_2 produced in the soil is not immediately transported to the surface and emitted to the atmosphere (Fechner-Levy and Hemond, 1996). The gas can be stored in free phase, i.e. as bubbles under the water table or in pore spaces of the soil matrix (Lipp et al., 1987; Comas et al., 2007, 2008). Another component of the soil gas reservoir is dissolved gas in liquid water (Melloh and Crill, 1996). Sometimes, parts of this soil reservoir can be suddenly released into the atmosphere, detectable as gas fluxes that cannot be explained by instantaneous CH_4 and CO_2 production alone. Such emission bursts have, for example, been observed during the autumnal freeze-in period in permafrost-underlain tundra (Mastepanov et al., 2008, 2013), suggesting the physical release of soil gases by frost action. The different proposed mechanisms and patterns are, however, still debated (Zona et al., 2016), since measurements of the physical soil composition are difficult to obtain.

1.3 Aims and objectives

The objective of the present work is to better understand the key mechanisms and processes that determine the timing, rate, and magnitude of land-atmosphere CH_4 and CO_2 exchange in high Arctic tundra. As described above, this system involves a number of linked physical, ecological, and biogeochemical elements that vary through space and time. Exploring these relationships requires advances in our conceptualization of the system as well as advances in the measurement of its components. The strategy of this work involves the establishment of a field site in Adventdalen Valley, Svalbard to contribute to the geographical coverage of flux measurements in the Arctic. This site is considered particularly valuable to represent high Arctic conditions with continuous permafrost and is still accessible year-round. Data from Adventdalen is used to study the representativeness of high Arctic ecosystem processes that have been documented in multi-year research efforts on Greenland. Specifically, the present work aims at combining different approaches to answer the following questions:

1. What is the CO_2 exchange between polygonal tundra and the atmosphere, using Adventdalen as a model ecosystem?
2. How do the seasonal CH_4 flux dynamics on Svalbard compare with similar sites on Greenland?
3. What determines the gas flux through the snowpack during wintertime?
4. What are the conceptual uncertainties of flux calculations in commonly used measurement techniques?
5. What is the mechanism behind the large CH_4 emission bursts from permafrost-underlain tundra during the autumnal freeze-in period?

2 Materials and Methods

2.1 Study sites

The main study site of this work is located in Adventdalen Valley (78° 11′N, 15° 55′E) on Svalbard. This tundra lowland is shown in Figure 2. It is located at the bottom of a large, U-shaped, glacial valley, which is carved onto Jurassic and Cretaceous sedimentary bedrock (Steel et al., 1981). The Adventdalen site is about 6 km from the sea in an area that was last deglaciated during the late Weichselian, when this part of the valley was still submerged by the sea (Svendsen and Mangerud, 1997; Lønne and Nemec, 2004). The unconsolidated deposits in the valley bottom therefore contain glacial, marine, alluvial, and eolian deposits from the Holocene (Oliva et al., 2014). The site is located on a river terrace on the flat part of a large alluvial fan, created by the contributory stream of a side-valley (Todalen Valley). These coarse alluvial deposits are covered with a few ten centimeters of fine-grained eolian deposits (loess), which typically stem from wind erosion in the braided riverbed when it dries out in autumn (Bryant, 1982; Oliva et al., 2014). The surrounding mountains feature plateaus of around 450 m a.s.l., formed as a result of the stratification of the sedimentary bedrock. Peaks and ridges of up to 1000 m a.s.l create an alpine topography, which is still partly glaciated (De Haas et al., 2015).

Permafrost in Adventdalen formed during the late Holocene and is today about 100 m thick (Humlum, 2005). The uppermost few meters of permafrost are syngenetic, while the ice-poor permafrost below this layer is epigenetic (Gilbert, 2014). The study site features continuous permafrost and polygonal ground patterns creating fen conditions (Christiansen, 2005; Harris et al., 2009), and its active layer depth typically averages to about 70 cm. The mean annual air temperature at the closest weather station (Svalbard airport, approximately 10 km away) was -6.7°C between 1961 and 1990 (Førland et al., 2012), which has increased to -3.75°C in the period between 2000 and 2011 (Christiansen et al., 2013). The total annual precipitation is about 190 mm, about half of which falls as snow (Førland et al., 2012). The vegetation is dominated by *Salix polaris* in drier areas, *Eriophorum scheuchzeri* and *Carex subspathacea* in wetter locations, and moss species in usually inundated spots.

The second field site of this work is located in Zackenberg Valley (74° 30′N, 21° 00′W) in the Northeast Greenland National Park. It is also a high Arctic tundra ecosystem with continuous permafrost and a longer history of continuous flux measurements than at Adventdalen. The mean annual air temperature of the area was -9.9°C (1958–1987) and the total annual precipitation amounts to 286 mm on average (Hansen et al., 2008). The measurement site is located on the edge of a fen on a larger alluvial fan. No ice wedges are present in the vicinity and maximum snow depths are typically larger than at Adventdalen (Pedersen et al., 2016). The vegetation is dominated by *Eriophorum scheuchzeri*, *Carex* cf. *stans*, *Dupontia psilosantha*, and moss species.

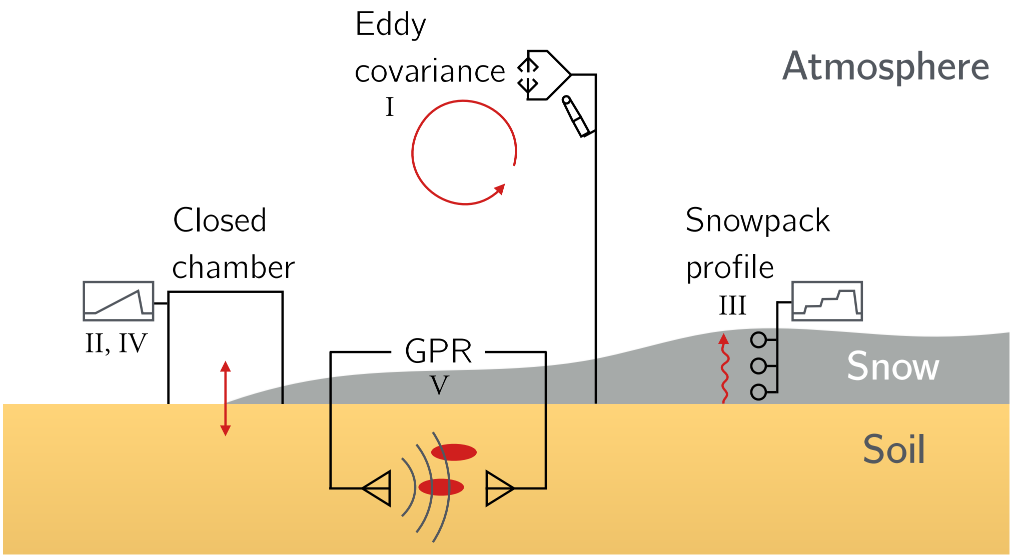

Figure 4: Schematic overview of measurement techniques. Roman numerals indicate the papers mainly using the respective technique. Eddy covariance yields turbulent flux estimates through the covariance of vertical wind speed and gas concentrations. Closed chambers determine gas fluxes from the change of headspace concentrations. Snowpack concentration profiles can estimate gas diffusion through the snow. Ground-penetrating radar (GPR) assesses the soil composition through microwave response functions.

The present study compared these high Arctic sites to sites in the low Arctic (Kobbefjord), sub Arctic (Stordalen), and the temperate region (Fäjemyr). The locations of these sites are shown in Figure 1. All these sites are equipped with flux measurement systems based on one or more complementary measurement techniques depicted in Figure 4. Each of these techniques offers specific advantages that help to achieve this work's aims and objectives.

2.2 Closed chamber technique

Gas exchange measurements have for a long time been done with the closed chamber technique, whereby a chamber is placed on top of the soil for a short period of time and the change in gas concentrations in the chamber headspace is monitored (Lundegårdh, 1927; Svensson, 1980). The resulting time series of gas concentrations can be used to calculate the net gas exchange on the plot on which the chamber was installed (Hutchinson and Mosier, 1981; Hutchinson and Livingston, 1993). Using several chamber locations allows to assess the gas exchange at a spatial resolution appropriate for Arctic tundra. Goulden and Crill (1997) developed an automatic system based on the closed chamber technique, where a set of chambers automatically closed and opened to yield continuous flux time series. While this technique can give accurate flux estimates, details of the flux calculation are still debated (Kutzbach et al., 2007; Forbrich et al., 2010; Pedersen et al., 2010). On the one hand, there can be sudden jumps in gas concentrations indicating ebullition events (e.g., Goodrich et al., 2011), on the other hand, there can be systematically curvilinear concentration changes caused by the presence of the closed chamber (Kutzbach et al., 2007).

Apart from the short-term effect on the measured gas concentration sequence, the installation of automatic flux chambers over several years can alter natural conditions and thereby render the measured fluxes unnatural. The timing of plant phenological events (such as bud break and flowering) of some plant species in the Arctic tundra is known to respond to environmental conditions such as day of snowmelt and air temperature (Khorsand Rosa et al., 2015). These parameters can be altered due to the long-term presence of the flux chamber, changing the plant species composition inside the flux chamber, and thereby affecting the measured gas fluxes (Ström et al., 2005). To be able to detect long-term changes in the gas exchange of an ecosystem, however, a multi-year time series with adequate measurement homogeneity is required.

2.3 Eddy covariance

Less invasive than closed chambers are micro-meteorological measurement techniques, such as eddy covariance (EC), which could therefore provide the needed long-term homogeneity (Arya, 2001; Burba and Anderson, 2010). The EC technique estimates the net gas exchange based on high frequency point measurements of the covariance of vertical wind speed and gas concentration (Aubinet et al., 2012). It therefore yields a turbulent flux estimate that is integrated over a footprint area upwind (in the order of hectares to km^2). Since EC provides a good compromise between the directness of measurement, ecosystem disturbance, and technical reliability, it has become a widely used technique to estimate the gas exchange on an ecosystem scale. The largest systematic uncertainties of the technique result from non-steady atmospheric conditions, heterogeneous surfaces, and complex terrain (Baldocchi, 2003; Billesbach, 2011). The technique also requires specialized gas analyzers and anemometers with sufficient response time, low noise, and little wind flow distortion. Baldocchi (2003) estimated that the systematic error of annual CO_2 balances at sites suited for the EC technique is at most ± 50 g C m^{-2} yr^{-1}.

Depending on the site conditions, a certain amount of the measured fluxes have to be discarded because an assumption of the EC technique is not met. To this end, Foken and Wichura (1996) developed a classification scheme to describe the quality of each measured flux value. The filtering-out of poor-quality measurements gives rise to gaps in the flux time series, and as these gaps can occur systematically on certain times of the day or year, this can introduce a bias to cumulative budgets of trace gases which are known to follow a daily or yearly cycle. Gap-filling techniques are therefore needed to derive unbiased estimates of trace gas budgets (Falge et al., 2001; Reichstein et al., 2005).

The low flux magnitudes characteristic for the long Arctic winter pose difficulties for the accurate flux estimation using EC. Sievers et al. (2015) therefore proposed a flux calculation scheme based on a spectral decomposition of the EC flux estimate. This approach effectively separates the turbulent flux from contributions of larger-scale motions (mesoscale atmospheric movements), which can give non-local flux contributions at low frequencies (Aubinet et al., 2012). If such theoretical problems can be accounted for in the flux calculation, EC can provide reliable year-round flux time series over relatively large surfaces.

2.4 Snowpack gradient

Wintertime emissions of CH_4 and CO_2 are historically understudied, but have been acknowledged to give an important contribution to the annual carbon budget in many Arctic tundra ecosystems (Fahnestock et al., 1999; Panikov and Dedysh, 2000; Lüers et al., 2014; Zona et al., 2016). The closed chamber and EC techniques have difficulties to resolve the typically very small wintertime fluxes, because their precision decreases toward low flux magnitudes. One way to complement these techniques is therefore to quantify the vertical gas concentration gradient in the winter snowpack (Sommerfeld et al., 1993; Smagin and Shnyrev, 2015). Using diffusion theory, this makes it possible to reliably estimate wintertime emissions despite them being orders of magnitude lower than growing season fluxes. Snowpack gas profiles moreover facilitate the studying of processes occurring in the snowpack, such as biological gas production or consumption (Amato et al., 2007), and physical releases of stored gases as sudden burst events during storms or snowmelt (Sullivan et al., 2012). These features render the snowpack gradient technique advantageous to address the present work's aims and objectives.

2.5 Ground-penetrating radar

To explore the possible mechanisms behind the large emission bursts during the freeze-in period, direct measurements of the physical soil composition are desirable. To this end, ground-penetrating radar (GPR) appears to be a promising technique that measures the transmitted and reflected electromagnetic microwave signals carrying information about the dielectric soil properties. As these soil properties depend on those of the constituent materials, GPR can be used to assess the volumetric composition of the soil.

GPR has for a long time been used to map ground features in permafrost regions (Davis et al., 1976), and since it is principally non-invasive, GPR can also be used to quantify the subsurface free phase gas volume without disturbing this fragile regime (Comas et al., 2007, 2008). Different antenna configurations are possible, characterizing different soil volumes for different purposes. Surface reflection type GPR can be used to e.g. image ice and soil wedges in polygonal tundra (Watanabe et al., 2013), whereas transmission GPR may be a suitable tool for the investigation of soil freezing processes.

Many GPR analyses are based on travel time estimations, but signals can similarly be recorded and processed in the frequency domain (Wensink, 1993; Huisman et al., 2004). Santos et al. (2009) developed an ultra-wide band (UWB) GPR which used a vector network analyzer to take frequency domain measurements of a freezing peat soil sample in a laboratory experiment, demonstrating that GPR can detect individual burst events connected to soil thawing. The present work aims at a field application of GPR in combination with the closed chamber technique during the freeze-in period.

3 Results and Discussion

3.1 Carbon dioxide

Paper I uses the EC technique to show that the Adventdalen site was a surprisingly strong annual CO_2 sink in the year 2015. Figure 5a shows the NEE fluxes derived in paper I, which amounted to -82 g C m^{-2} over this year. Due to spatial differences in dark respiration and light use efficiency, drier areas sequestered 32% less CO_2 than wetter areas in the EC footprint (-62 compared to -91 g C m^{-2}). Since polygonal tundra is predicted to dry out due to climate warming (Liljedahl et al., 2016), these results suggest a weakening of the CO_2 sink of these ecosystems. Despite this general prediction, paper I shows that—so far—there is no drying trend observable at the Adventdalen ice-wedge site.

Paper I also uses the EC flux calculation scheme proposed by Sievers et al. (2015) to show that conventional EC calculations give significantly biased annual budgets at Adventdalen. Low frequency flux contributions are the reason for this bias, which likely stem from mesoscale air movements that do not reflect the local turbulent flux. Paper I only investigates this bias at Adventdalen, but similar problems could exist in many high Arctic environments where flux magnitudes are typically small and results therefore prone to this bias.

Figure 5c shows a relatively good agreement between EC and automatic closed chamber fluxes from the footprint at Adventdalen. To study possible biases of the closed chamber fluxes (Hutchinson and Livingston, 1993; Kutzbach et al., 2007), paper IV focuses on different calculation schemes for these fluxes. While paper IV shows that linear and non-linear regression flux calculations have significant episodic differences, the overall flux differences are generally found to be smaller than the local flux variability on the plot scale (both for CO_2 and CH_4). Paper IV furthermore uses the curvature of the recorded concentration sequence to propose a method to partition the net CO_2 flux into photosynthetic uptake and respiratory release. This partitioning can only work when photosynthesis is CO_2-limited, i.e. typically only during high-sunlight conditions. Despite relatively large uncertainties of this curvature partitioning, its results are within the expected range suggested by a commonly used partitioning model. Curvature and other properties of the recorded concentration sequence might therefore open possibilities to advance our understanding of CO_2 flux dynamics based on direct measurements.

Paper III uses the snowpack gradient technique to quantify the CO_2 (and CH_4) flux at Adventdalen and Zackenberg during the cold season. These measurements indicate small but consistent gas emissions from the frozen soil under the snowpack. Similar to findings by one of the first studies of this kind by Sommerfeld et al. (1993), these fluxes suggest continued microbial activity in the frozen soil. At Adventdalen, where the snowpack featured several centimeter-thick ice layers (see Figure 5b), the flux from the soil into the snowpack

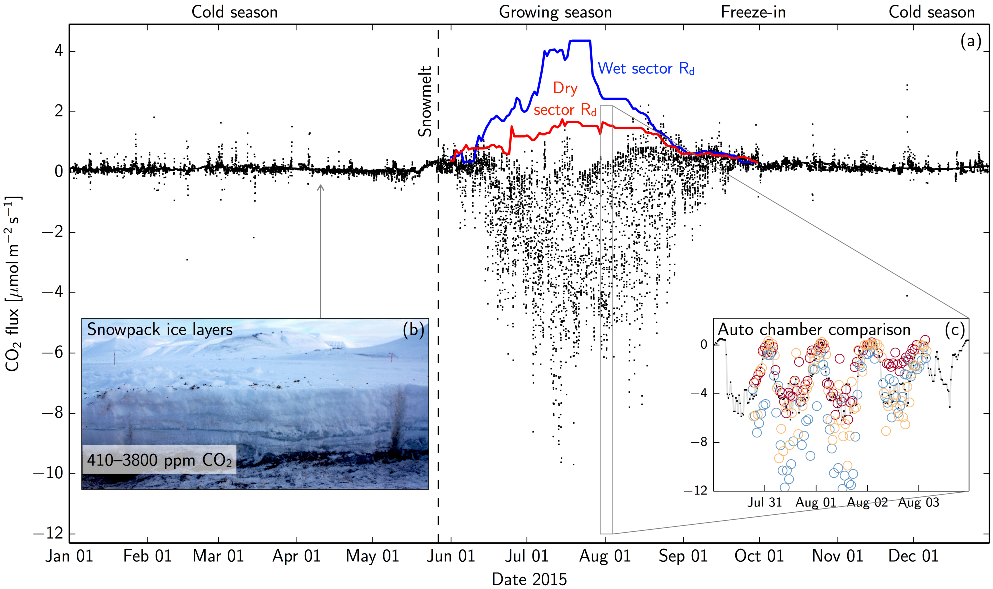

Figure 5: Seasonality of CO_2 exchange at Adventdalen. a: Gap-filled EC time series of NEE for 2015. Growing season dark respiration (R_d), derived from light response curves, differed between wet and dry areas. b: Cross-section of the snowpack containing up to 3800 ppm CO_2 under the ice layers. c: Comparison of EC and automatic chamber flux measurements, where individual chambers are indicated with the same colors as used in paper II.

exceeded the flux from the snowpack into the ambient atmosphere during the weeks before our measurements. This flux difference led to a large accumulation of CO_2 in the snowpack of up to 3800 ppm CO_2 by late winter.

3.2 Methane

Paper II shows that growing season CH_4 fluxes in wetlands on Svalbard and Greenland followed distinctly different seasonal patterns. At Adventdalen, CH_4 fluxes tend to increase gradually between snowmelt and peak growing season, after which they decrease slowly until the freeze-in period, which can feature large emission bursts connected to frost action. At Zackenberg, on the other hand, CH_4 fluxes increase much faster after snowmelt, peak about one month after snowmelt, and then gradually decrease toward the freeze-in period with its large emission bursts. Based on a hypothesis by Mastepanov et al. (2013), paper II formulates a description of these flux patterns based on two distinct CH_4 source components from slow and fast-turnover carbon (see Figure 6a). This description fits the flux time series at Zackenberg, but appears uncertain at Adventdalen and Kobbefjord. For all these sites, the timing of snowmelt seems to be an important reference time for the temporal pattern, even though it appears almost irrelevant for the total seasonal CH_4 emission budget.

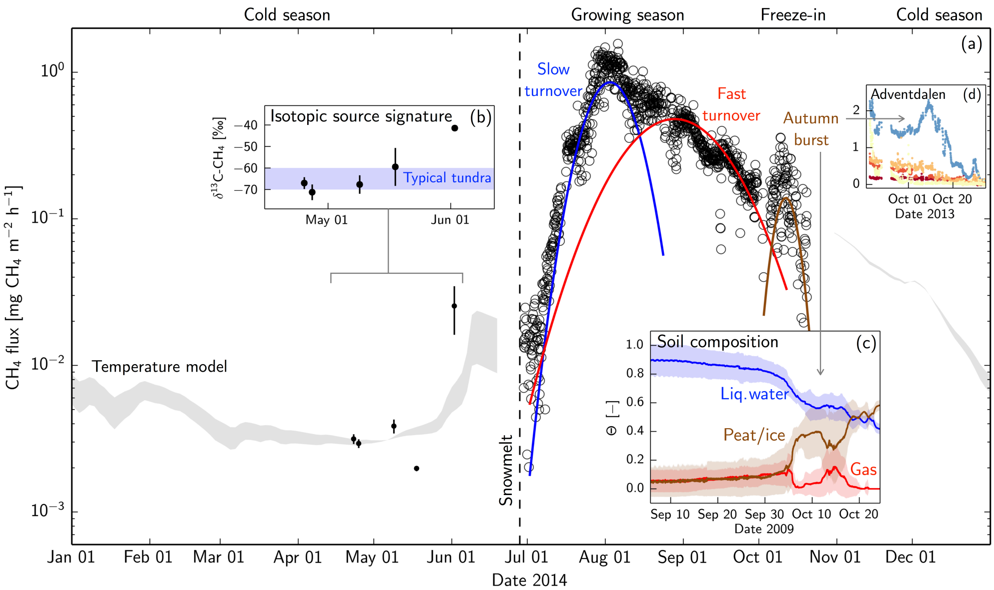

Figure 6: Seasonality of CH_4 exchange. a: Fluxes from chamber 2 at Zackenberg and the corresponding position from snowpack measurements 2014. Growing season fluxes hypothetically stem from two distinct sources related to slow and fast turnover carbon. The autumnal freeze-in period features a separate emission burst. Measured cold season fluxes typically agree with a back-of-the-envelope temperature model. b: Isotopic source signatures agree with the typical tundra signature during the late cold season and deviate during snowmelt. c: Volumetric fractions (Θ), showing the soil composition beneath chamber 2 at Zackenberg during the freeze-in period in 2009, indicate gas compression and expansion in the soil. d: Methane fluxes from individual chambers at Adventdalen during the freeze-in period 2013 (same units as in panel a, but on a linear scale). Chamber colors are the same as used in paper II. Especially the chamber with the largest overall flux featured an autumn peak spread over more than one week.

During the autumnal freeze-in period, the sites at Zackenberg and Adventdalen can show large emission bursts (see Figures 6a and 6d), probably due to physical mechanisms at work in continuous permafrost regions. Paper V describes a new ground-penetrating radar system inspired by Comas et al. (2007) for measurements of the physical conditions in the soil during the freeze-in period. This method was applied at Zackenberg throughout autumn 2009 to derive the volumetric composition of the soil underneath an automatic flux chamber where a series of CH_4 emission bursts occurred (see Figure 6c). These results suggest that the CH_4 autumn burst could be caused by a series of different physical processes: first the compression of the soil reservoir of free phase CH_4, and later the burst itself during the decompression caused by ground cracking and soil heaving.

During the cold season, when the entire active layer is frozen, CH_4 emissions at our sites were orders of magnitude lower than during the growing season. Paper III explores these small fluxes using measurements of snowpack gas concentrations. At Zackenberg, wintertime CH_4 fluxes resembled the same spatial pattern as seen in summertime, which was largely attributed to differences in soil wetness controlling substrate accumulation and microbial activity. The cold season's contribution to the total annual CH_4 budget was about

15% (November–May). This is quite different from EC measurements on the Alaskan Arctic tundra, where more than 50% of the annual CH_4 budget stemmed from the wintertime (September–May) (Zona et al., 2016). Figure 6b shows that the isotopic source signatures derived from the snowpack profiles are typically in agreement with expectations from literature values for tundra wetlands. Only one day during the snowmelt period showed a significantly heavier signature, which fits the hypothesis of a release of a soil gas storage in which methanotrophic microorganisms metabolized a large part of the lighter carbon (^{12}C-CH_4). At Adventdalen, the snowpack featured several ice layers, which suppressed the expected gas emissions to the atmosphere, and conversely led to snowpack gas accumulations of up to 86 ppm CH_4 by late winter. The spatial pattern of snowpack gases resembled the polygonal structure of the soil, with the largest relative CH_4 source located in the rampart of the ice-wedge polygons. This feature suggests that geomorphological soil cracking could have a strong influence on gas exchange processes.

4 Conclusions

The CH_4 and CO_2 exchange between polygonal tundra and the atmosphere is both spatially and seasonally dynamic. This work shows that Adventdalen was a surprisingly large CO_2 sink in the last couple of years, given the relatively shallow organic layer in the soil. The carbon content in the uppermost 100 cm soil is about 30 kg C m^{-2} at the Adventdalen site *(personal communication with Peter Kuhry)*, which would correspond to an accumulation time of only 366 years given 2015's CO_2 uptake from the atmosphere. Since the site has already existed in its current geological setting for a few thousand years, there is a mismatch of the long-term carbon accumulation rate, which poses a number of new questions: Could there be further biases in the eddy covariance measurements, which led to an overestimation of the annual CO_2 uptake in this work? How representative are the last couple of years (2013-2015) for the long-term CO_2 accumulation at Adventdalen? And how large are the unaccounted carbon losses from the soil due to e.g. lateral export of dissolved organic carbon or reindeer grazing?

The seasonal pattern of CH_4 fluxes during the snow-free period at Adventdalen differs from Zackenberg. While both sites feature autumnal bursts, growing season fluxes at Zackenberg follow a more distinct pattern possibly caused by different CH_4 sources related to slow and fast turnover carbon. To further explore these site differences dedicated efforts to measure the isotopic source signature during the growing season are needed at both sites. This work's findings would suggest a more variable signature at Zackenberg than at Adventdalen.

The wintertime gas emissions through the snowpack are a result of soil temperature, wetness (controlling summertime substrate accumulation and microbial activity), snowpack density, wind, and potential soil cracking. Especially the geomorphological soil cracking has received little attention in gas exchange studies, but could be of large-scale importance for polygonal Arctic tundra. Future studies could aim at establishing the direct connection of such soil and ice-wedge cracking with gas emission. Also the outlier of the isotopic source signature observed during snowmelt at Zackenberg should be further investigated, because it might be key to understanding the amount and condition of trapped CH_4 in frozen tundra soils.

Conceptual uncertainties of flux calculations seem to be more problematic in eddy covariance than closed chamber measurements. EC co-spectral ogives indicate frequency mismatches resulting in a significant bias of annual budgets in the low-flux environment of Adventdalen. To what extent other Arctic sites are affected by similar non-local (low frequency) flux contributions remains to be investigated. The present work speculates that the underlying reason for these frequency mismatches is the vertical layering of CO_2 concentrations in the atmosphere above the tower. This hypothesis needs to be tested with suitable measurements, and its effect on EC measurements in general should be assessed.

Ground-penetrating radar measurements suggest that the large CH_4 autumn burst observed at Zackenberg is a result of sequential compression and decompression events of the soil gas reservoir. The proposed mechanism (involving a pressure build-up in the freezing active layer, soil heaving and cracking) could be further explored through measurements of the respective soil parameters. The present work moreover reports the occurrence of the CH_4 autumn burst at Adventdalen, where the continuous permafrost requirement is fulfilled.

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