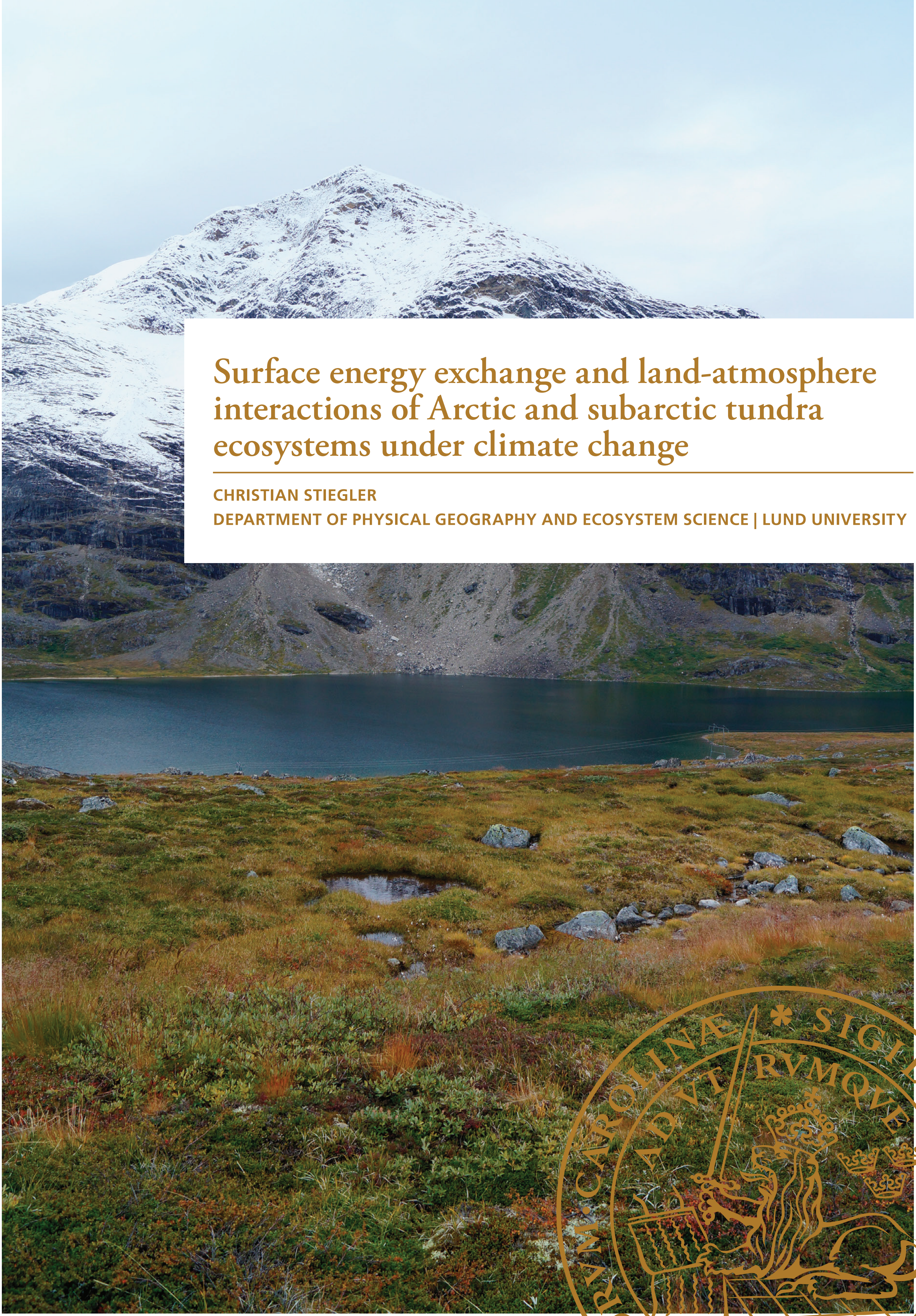

Surface energy exchange and land-atmosphere interactions of Arctic and subarctic tundra ecosystems under climate change

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Contribution

Paper I: The author was involved in the collection of the field data, data analysis and writing of the manuscript.

Paper II: The author is responsible for the design of the study, performed the data analysis, led the writing of the manuscript and carried out the field work.

Paper III: The author is responsible for the design of the study, performed the data analysis and led the writing of the manuscript.

Paper IV: The author is responsible for the design of the study, performed the data analysis and led the writing of the manuscript.

Abstract

The surface energy balance determines the functioning of any ecosystem on the Earth but is still poorly understood in Arctic and subarctic biomes. In a dynamic system, such as the Earth's climate, any change in its characteristics modifies the exchange of energy, water, and greenhouse gases between the surface and the atmosphere. Therefore, this thesis aims to draw a conclusive picture of the surface energy exchange and land-atmosphere interactions of Arctic and subarctic regions under climate change. The aims are achieved by combining *in-situ* field measurements of surface energy balance components, snow manipulation experiments, active layer monitoring, vegetation mapping, and chamber-based carbon dioxide flux measurements from Arctic and subarctic tundra biomes in Greenland, Svalbard and northern Sweden.

Local variability in climate, surface structure, soil moisture and soil thermal regime are the main drivers of variation in the surface energy exchange and ecosystem productivity of Arctic and subarctic tundra ecosystems. At all studied locations, the magnitude of the energy fluxes of sensible heat (H), latent heat (LE) and ground heat (G) were well-correlated with net radiation (R_{net}). However, evapotranspiration (ET) and LE showed a relatively strong coupling to atmospheric vapor pressure deficit (VPD), with more pronounced such control at the dry tundra sites compared to the wet-growing ecosystems. Snow and permafrost determined surface energy balance, energy partitioning and ecosystem productivity. Manipulated increase in snow accumulation at a subarctic tundra peatland complex in northern Sweden resulted in permafrost thaw, soil wetting and increased carbon sequestration. Concurrently, climate-driven increase in both snow accumulation and air temperature triggered dramatic and rapid permafrost degradation in peatland complexes and transition from dry habitats into wet-growing ecosystems, with consequent change in surface energy exchange towards both increased LE and ET at the cost of H. Interannual variability in winter snow accumulation at the high-Arctic tundra environment in Zackenberg (Northeast Greenland) prolonged the growing season during a year with low snow cover and increased the total

accumulated energy balance components of the local heath and fen ecosystems. Further, energy flux partitioning at the heath was strongly determined by the reduction of soil moisture as snow is by far the main supplier of water in this region. The energy exchange of the fen, however, showed attenuated behavior due to groundwater table remaining close to the surface.

The results presented in this thesis suggest that in a future climate, accelerated permafrost thaw and increased interannual variability in snow cover may further modify the energy balance of Arctic and subarctic ecosystems, with profound impact on ecosystem adaptation capacities and the overall climate system.

Sammanfattning

Energibalansen vid jordytan är av avgörande betydelse för Jordens alla ekosystem men när det gäller Arktiska och sub-Arktiska ekosystem är kunskapen bristfällig. I dynamiska system som klimatsystemet, påverkas utbytet av energi, vatten och växthusgaser av små förändringar i ekosystemen. Syftet med denna avhandling är därför att skapa ökad kunskap och en tydligare bild av energiutbytet och interaktioner mellan jordytan och atmosfären i Arktiska och sub-Arktiska ekosystem under ett förändrat klimat. Målen uppnås genom att kombinera fältmätningar av energibalansens olika komponenter, vegetationskartering, kartering av aktiva lagrets mäktighet samtoch kyvettbaserade flödesmätningar av koldioxidutbyte i Arktiska och sub-Arktiska tundra-biom på Grönland, Svalbard och i norra Sverige.

Lokal variation i klimat, ytstruktur, markfuktighet och marktemperatur är de huvudsakliga drivkrafterna bakom variationerna i energiutbyte och produktivitet hos Arktiska och sub-Arktiska tundra-ekosystem. Flödena av sensibelt värme (*H*), latent värme (*LE*) samt markvärmeflöde (*G*) korrelerade starkt med nettostrålningen (R_{net}) för all studerade lokaler. Avdunsting (*ET*) och *LE* var emellertid även under relativt stark kontroll av mättnadsångtrycksdeficitet (*VPD*) med något starkare kontroll för torrare tundraområden än för fuktigare sådana. Snö och permafrost hade stor påverkan på energibalansen samt på hur den tillgängliga energin fördelades mellan komponenterna och på ekosystemens produktivitet. I ett snömanipulationsexperiment i ett sub-Arktiskt tundrakomplex i norra Sverige ledde ökande snömängd till minskande permafrosten, högre markfuktighet och ökande upptag av koldioxid. Sammantaget ledde klimatinducerade ökningar i snödjup och lufttemperatur till snabb och dramatisk degradering av permafrosten i torvmarkskomplexen med omvandling från torra habitat till fuktigare sådana. Detta medförde också förändringar i energibalasen så att *LE* och *ET* ökade på bekostnad av *H*. Mellanårsvariation i snöackumulation i Arktiska Zackenberg på nordöstra Grönland ledde till avsevärt större ackumulerad mängd energi för samtliga energibalanskomponenter både för ett hedmarksekosystem och för ett

kärrmarksekosystem under ett år med liten snöackumulation jämfört med år med stor sådan. Dessutom påverkades fördelningen av den tillgängliga energin mellan de olika energibalanskomponenterna på heden starkt av den minskade markfuktigheten eftersom snön där står för den dominerande delen av vattentillförseln under växtsäsongen. Kärrmarkens energiutbyte påverkades i mycket lägre grad av den låga snötillförseln på grund av att grundvattennivån var fortvarigt hög och nära markytan.

Resultaten som presenteras i denna avhandling indikerar att ett framtida klimat med ökande degradering av permafrosten och ökande mellanårsvariation i snönederbörd kan ha avsevärd modifierande påverkan på energibalansen i Arktiska och sub-Arktiska ekosystem. Detta kan i sin tur få avsevärd påverkan på ekosystemens anpassningsförmåga samt på klimatsystemet i sig självt.

Content

Introduction

The Sun, centering our solar system, and its constant emission of radiation and energy is the unique and inimitable driver of all natural processes on the planet Earth. The Sun's energy sets in motion atmospheric circulation and hydrological cycles but most important, facilitates the development of biological processes on the planet. The redistribution of the Sun's energy takes place in the lowermost layer of the atmosphere, the atmospheric boundary layer (ABL) where biological, hydrological and terrestrial processes exert profound and incessant exchange of energy, water, mass and greenhouse gases with the atmosphere (Monteith and Unsworth, 2008). Because of this close interaction between the atmosphere and the Earth's surface, the surface energy balance of any ecosystem not only governs ecosystem functioning but, ultimately, influences the Earth's climate. One biome attributed to play a major role in the functioning of the Earth's climate system is the circumpolar Arctic and subarctic tundra because it covers large areas of the planet, demonstrates high adaptation to harsh climate conditions, and shows a pronounced sensitivity to climatic and environmental changes (Chapin et al., 2000; Callaghan et al., 2005). However, ongoing and predicted global climate change has started to reshape the circumpolar regions and challenges the adaptation capacity of tundra ecosystems, with direct impact on the surface energy budget and land-atmosphere energy exchange. It is therefore vital to assess the components of Arctic and subarctic energy exchange, its driving parameters and possible feedbacks to the climate system to better understand the firm coupling between the Earth's climate and tundra ecosystems and its future development.

The energy budget at the Earth’s surface

Surface energy balance and radiation balance

The Earth’s climate system is subjected to a continuous flow of energy, matter and mass in multiple directions and forms where the Earth’s surface with its striking heterogeneity is the main transmission area between the atmospheric and terrestrial spheres (Foken, 2008). The Earth’s surface receives energy from the proportion of shortwave solar radiation which has not been reflected by clouds or absorbed in the atmosphere, and by downwelling longwave radiation which originates from radiative emission of clouds, atmospheric gases and particles. Simultaneously, a major fraction of the incoming shortwave radiation is reflected away from the surface and upwelling longwave radiation, emitted by the Earth itself emanates towards the atmosphere. The remaining net radiative forcing (R_{net}) at the surface is the overall driver of surface thermal conditions and the climate system (Oke, 1987).

Following the fundamental principle of the conservation of energy, R_{net} must be balanced by energy leaving the surface via convection or conduction. Therefore, the surface energy balance is written as:

$$R_{net} = RS\downarrow - RS\uparrow + RL\downarrow - RL\uparrow = H + LE + G$$

where R_{net} is the net radiation, $RS\downarrow$ is the downwelling solar shortwave radiation, $RS\uparrow$ is the reflected solar shortwave radiation, $RL\uparrow$ is the upwelling longwave radiation, $RL\downarrow$ is the downwelling longwave radiation, H is the sensible heat flux, LE is the latent heat flux and G is the ground heat flux. The left side of the equation represents the system’s gain of energy and the right-hand side represents the losses of energy. The ratio of

$RS\uparrow$ to $RS\downarrow$ at the surface is defined as solar reflectivity or albedo (Li et al., 2013). Albedo is a dimensionless measure on a scale from 0 to 1 where an albedo of 1 relates to a perfect reflection off a perfectly white surface. Figure 1 shows a conceptual and simplified illustration of the surface energy balance where a positive sign of H, LE and G denotes an energy flux directed away from the surface while a positive value for R_{net} refers to a flux directed towards the surface.

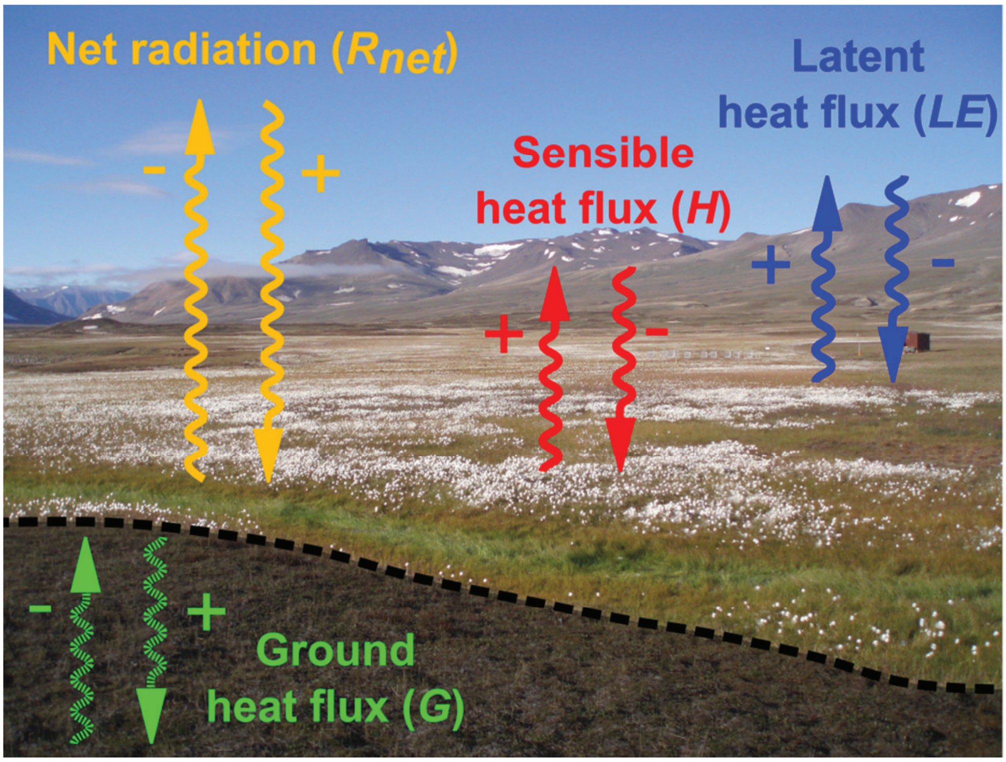

Figure 1: Surface energy balance.
Schematic illustration of the surface energy balance of Arctic and subarctic ecosystems. A positive sign of H, LE and G denotes an energy flux away from the surface, a positive value for R_{net} refers to a flux towards the surface.

Turbulent heat fluxes

Most of the energy converted from R_{net} is transferred into the atmosphere due to a pronounced effectivity of turbulent air motion. Two forms of turbulent energy exchange take place within the land-atmosphere boundary: (a) direct sensible heat transport, and (b) latent heat transport through vertical motion of water vapor and the heat required for evapotranspiration. The fluxes of sensible heat (H) and latent heat (LE) can be described as (Foken, 2008):

$$H = -\rho \, c_p \, K_H \frac{\partial T}{\partial z},$$

$$LE = -\rho \, \lambda \, K_E \, K_H \frac{\partial q}{\partial z}$$

where ρ is the air density, c_p is the specific heat for constant pressure, λ is the evaporative heat of water, $\partial T/\partial z$ and $\partial q/\partial z$ are the vertical gradients of the potential temperature T and specific humidity q, and K_H and K_E are turbulent diffusion coefficients.

Ground heat flux

Through solid media such as soil, heat is transferred mostly through conduction and the ground heat flux is defined as:

$$G = k \frac{\partial T}{\partial z}$$

where k is the thermal conductivity. The thermal conductivity of the soil depends on the soil's composition (mineral type, particle size, and amount of organic matter), bulk density, and water content (Arya, 2001; Sauer and Horton, 2005).

The role of snow and permafrost in the surface energy budget

Snow and permafrost are two key physical components in high-latitude and alpine regions (Walker et al., 1993; Schuur et al., 2015) with profound impact on natural ecosystems, surface energy exchange and human activity. The duration of snow cover and snow cover thickness govern plant phenology, ecosystem functioning and carbon exchange (Grøndahl et al., 2007; Elmendorf et al., 2012) and the snow's high albedo reduces the amount of available energy at the surface which consequently lowers the magnitude of the surface energy balance components (Warren, 1982). The release of water during the spring snowmelt controls soil moisture amount and water table depth over most parts of the subsequent growing season (Buus-Hinkler et al., 2006) and as such, snow meltwater constitutes an important control of the partitioning into sensible and latent heat fluxes over the snow-free period (Langer et al., 2011).

The occurrence of permafrost is dependent on multiple parameters such as climate, topography, substrate, snow and vegetation cover, and soil water content (Cheng, 2004). On top of the permafrost body is the active layer that is exposed to annual freeze and thaw cycles governed by surface cooling or warming. The annual freeze-thaw processes influence soil thermal and hydraulic characteristics with consequent impact on the magnitude and partitioning of the surface energy balance components, moisture exchange, and ecosystem diversity and productivity. However, permafrost thermal state and active layer development is highly sensitive to changes in the physical environment due to its close interaction with physical and biological processes (Callaghan et al., 2011b).

High-latitude ecosystems and climate change

Past and ongoing climate change

Since the end of the Little Ice Age the climate in the Arctic and subarctic has experienced a substantial warming to the highest temperatures in 400 years (Overpeck et al., 1997). During the 20th century, air temperatures increased by 0.09°C per decade in regions north of 60°N (McBean et al., 2005). Since the 1950s warming in the Arctic and subarctic has further accelerated and almost doubled compared to the rest of the globe, with average increase in air temperatures of 0.4°C per decade between the years 1966 and 2003 (Stocker et al., 2013). The observed warming during the period 1989-2008 has been most pronounced during autumn and winter, showing average air temperature increase of 1.6°C while during spring and summer, average temperatures increased by 0.5°C (Screen and Simmonds, 2010). It is suggested that the pronounced warming in the Arctic, known as Arctic temperature amplification, is caused by feedback processes between diminishing sea ice, snow- and ice-albedo properties, and atmospheric energy transport into high-latitude regions (Graversen et al., 2008; Bintanja and van der Linden, 2013).

Precipitation in the Arctic and subarctic is generally low and not uniformly distributed over the region but observations show that during the period 1900-2003 precipitation increased by 1.4% per decade with a distinct increase mostly during winter (McBean et al., 2005; Becker et al., 2013). However, due to increased air temperatures the observed fraction of snow within the annual precipitation has declined over most parts of the northern circumpolar region during the 20th century (Hartman et al., 2013), except for Scandinavia and Eurasia where winter snow depth has increased (Callaghan et al., 2011c). Over most parts of the Arctic and subarctic extreme meteorological events such as successive temperature warming and heavy precipitation have increased over the 20th century while extreme temperature cooling has decreased (Hartman et al., 2013).

Caused by the changes in temperature and precipitation regimes, the closely linked hydrological, geomorphological and biological cycles in the Arctic and subarctic regions have already witnessed substantial shifts. Perennially frozen soils (permafrost) have warmed, permafrost active layer thickness has increased and land areas underlain by permafrost have started to decrease (Åkerman and Johansson, 2008; Romanovsky et al., 2010; Lawrence et al., 2012) with direct impact on surface hydrology and soil moisture availability (Serreze et al., 2000; Hinzman et al., 2005), and ecosystem carbon exchange processes (Schuur et al., 2015). Further, shifts in the seasonal timing of Arctic and subarctic plant phenology, species composition and migration, and ecosystem vitality are considered as direct effects from climate warming (Elmendorf et al., 2012).

Climate change predictions

During the 21st century the ongoing changes in the temperature and precipitation regime are expected to continue. Models based on the Representative Concentration Pathways (RCP) 4.5 scenario predict an average warming of 3.9°C over Arctic land areas (Stocker et al., 2013) and precipitation is expected to increase by more than 50% at the end of the century, mostly during autumn and winter (Stendel et al., 2007; Bintanja and Selten, 2014). The maximum amount of snow accumulation on the ground is projected to increase by 0-30% and total snow cover duration to decrease by 10-20% over most parts of the Arctic and subarctic regions due to increased air temperatures and rain-on-snow events (Callaghan et al., 2011a). Further, winter warming events, interannual fluctuation in snow accumulation, and variability in growing season temperature and precipitation patterns are likely to occur more frequently over the 21st century (Callaghan et al., 2005; Kattsov et al., 2005; Stocker et al., 2013) as hydrological processes and temperature amplification intensify with climate change (Christensen et al., 2007; Serreze et al., 2009). Permafrost is highly sensitive to changes in the physical environment (Callaghan et al., 2011b). Consequently, the mean loss of permafrost area by the year 2100 due to climate change is estimated to be 52 ± 23%, depending on greenhouse gas scenarios (Schaefer et al., 2014).

All of these projected changes in the Arctic and subarctic climate and surface characteristics have a high potential to further challenge the vitality and adaptation capacities of northern circumpolar ecosystems, with strong and pervasive impact on surface energy exchange, plant and ecosystem carbon sequestration, and climate.

Aims and objectives

This thesis uses *in-situ* measurements of surface energy balance components, snow manipulation experiments, active layer monitoring, vegetation mapping, and chamber-based carbon dioxide flux measurements from several northern circumpolar tundra ecosystems to quantify and evaluate the characteristics of Arctic and subarctic surface energy exchange and biosphere-atmosphere interaction. Further, the effects of ongoing and predicted climate change on the magnitude and partitioning of the surface energy balance components and related changes and feedback processes in the land-atmosphere coupling are investigated. More specifically, the main objectives of this PhD thesis were to:

I. Quantify and evaluate the components of the surface energy budget in Arctic and subarctic tundra ecosystems (*Paper II, III, IV*).

II. Identify and assess the controlling factors of the surface energy exchange and energy partitioning regime (*Paper II, III, IV*).

III. Examine the effects of thawing subarctic permafrost on the partitioning of the surface energy balance components and land-atmosphere coupling (*Paper II*).

IV. Demonstrate the response of tundra ecosystem energy exchange and plant carbon sequestration to variability in snow cover and changes in snow accumulation (*Paper I, III*).

Materials and methods

Study sites

Extensive *in-situ* measurements of surface energy exchange components and micrometeorological parameters from several locations within the Arctic and subarctic tundra biome form the basis of this thesis. The investigated study sites stretch from 64°N to 78°N and cover the most common types of Arctic and subarctic tundra ecosystems: Wet fen, dry heath and polygonal tundra. Figure 2 shows the location of the study areas within the northern circumpolar region and Figure 3 shows the study sites in more detail. The sites are embedded in the high-Arctic tundra of Svalbard (Adventdalen) and Northeast Greenland (Zackenberg), low-Arctic tundra of West Greenland (Kobbefjord), and subarctic tundra of the Abisko area in northern Sweden (Stordalen, Storflaket, Torneträsk). A more detailed description of each site is shown below.

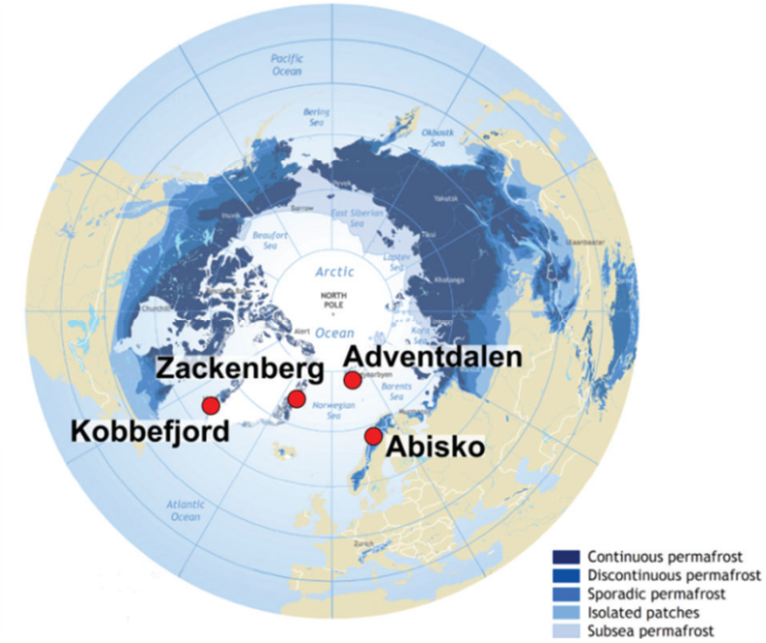

Figure 2: Location of the study sites.
The base map shows the distribution of permafrost within the northern circumpolar and alpine regions. Source: IPA.

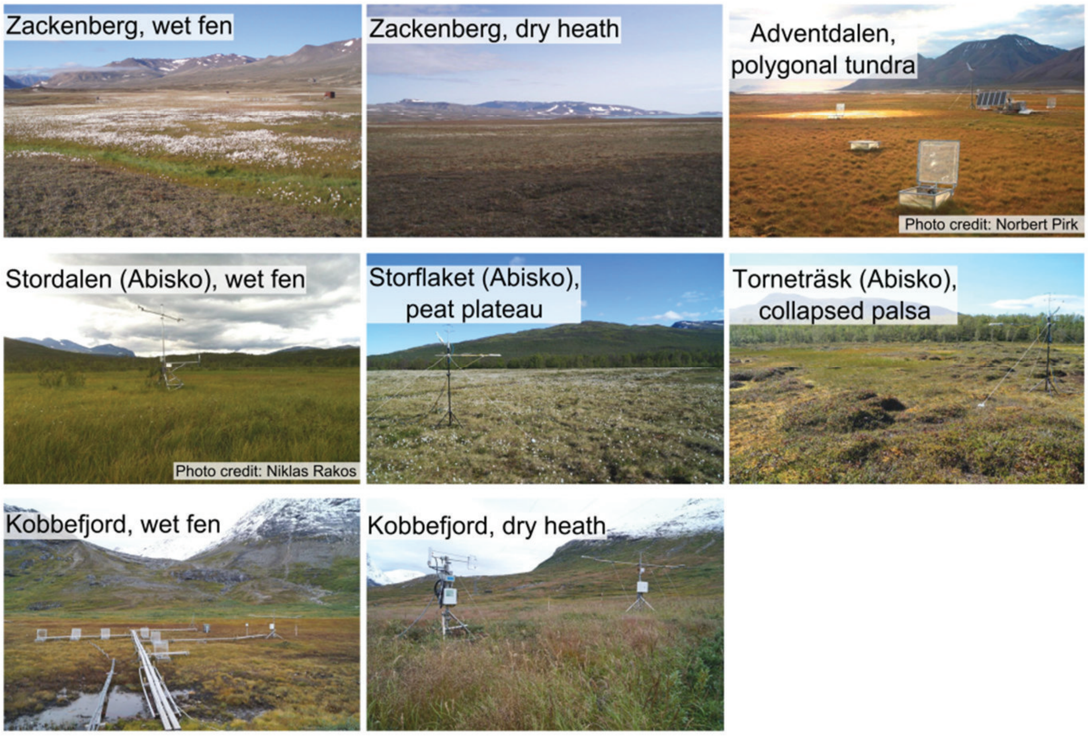

Figure 3: Study sites.

Adventdalen

Adventdalen is an approx. 4 km wide U-shaped valley on the island of Spitsbergen, Svalbard. The valley is oriented north-west to south-east with the surrounding mountains reaching heights between 600 and 900 m. The valley's vegetation spans from productive marsh in the valley floor and swamp and moss tundra on the wet habitats to heath tundra at the hill slopes and open *Dryas-Carex rupestris* communities on ridges (Johansen and Tømmervik, 2014). Measurements for this thesis were conducted at an ice-wedge *Luzula* polygonal tundra site (78°11'N, 15°59'E), approx. 9 km south-east of the main settlement of Longyearbyen.

The mean annual air temperature (MAAT) at the nearest meteorological station (Svalbard Airport) is -4.6°C for the period 1981-2010, mean annual precipitation is low and reaches 191 mm for the same observation period (Førland et al., 2011). Svalbard is located within the zone of continuous permafrost and active layer thicknesses approach approx. 1 m at the end of the summer (Sjöblom, 2014).

Zackenberg

Two study sites are located in the high-Arctic valley of Zackenbergdalen in Northeast Greenland near the Zackenberg Research Station (74°30’N, 20°30’W). The valley is surrounded by mountains to the west, north and east while the Young Sound and Tyrolerfjord form the valley boundary to the south. Sparse vegetation, mainly found in the valley bottom and on the lower parts of the slopes, consists of *Cassiope* heaths, *Salix arctica* snow-beds, grasslands, fens with sedges and grasses, and open *Dryas* sp. heaths (Elberling et al., 2008). Measurements for this thesis were conducted in a wet fen and in a tundra heath, with an aerial distance of approx. 900 m between the sites. The heath is characterized by *Cassiope tetragona*, *Dryas integrifolia*, *Vaccinium uliginosum*, *Eriophorum scheuchzeri*, *Salix arctica* and patches of mosses (Lund et al., 2012). The wet fen consists of a continuous fen dominated by *Eriophorum scheuchzeri*, *Carex stans* and *Duponita psilosantha*, and a hummocky fen dominated by *E. triste*, *S. arctica* and *A. latifolia* (Bay, 1998; Elberling et al., 2008).

Mean annual air temperature for Zackenberg is -9.0°C for the period 1996-2013 (Jensen et al., 2014). Similar to Adventdalen, annual precipitation is low and reaches 261 mm with approx. 85% accumulated as snow (Hansen et al., 2008). Zackenberg is located in the zone of continuous permafrost and active layer thicknesses at the end of the summer reach between 0.4 and 0.8 m (Pedersen et al., 2012).

Abisko

Measurements were performed on three subarctic peatland complexes (Stordalen, Storflaket, and Torneträsk) near Abisko (68°20’N, 18°49’E) in northern subarctic Sweden. Storflaket is located ~6 km, Stordalen ~10 km and Torneträsk ~40 km east of Abisko. The vegetation of the sites can be classified into three major habitats (Johansson et al., 2006; Åkerman and Johansson, 2008): (a) dry ombrotrophic peat plateaus covered with low-growing dwarf shrubs, short sedges, lichen and barren soil, (b) tussock-forming sedges and *Sphagnum* mosses in wet hollows and depressions, and (c) wet *Eriophorum angustifolium* fen with stable water level near the ground surface.

Mean annual air temperature in Abisko for the period 1913-2003 is -0.7°C while for the last decade (2002-2011) MAAT is +0.49°C (Callaghan et al., 2013). Precipitation patterns are dominated by a strong rain shadow effect and mean annual precipitation reaches 304 mm for the period 1913-2003 (Johansson et al., 2006). In the Abisko region lowland permafrost is mainly present in peat plateaus and palsas where active layer thicknesses reach between ~60 cm in dry locations and ~85 cm in wet areas. Within the last decades a significant trend in permafrost degradation has been observed in the Abisko area (Åkerman and Johansson, 2008). Therefore, the study sites in the Abisko area were chosen to capture the most distinct characteristics of subarctic peatlands in northern Fennoscandia in relation to permafrost thermal state: (a) well-developed and extensive peat plateau (Storflaket, Stordalen), (b) rapid and substantial palsa decay and permafrost degradation (Torneträsk, Stordalen), and (c) wet fen with no permafrost left (Stordalen).

Kobbefjord

The two southernmost study sites are located in the low-Arctic Kobbefjord area (64°07'N, 51°22'W) in West Greenland, approx. 18 km west of the Greenlandic capital city of Nuuk. The fjord area is embedded in mountainous terrain with ponds, lakes and rivers. Vegetation in the lowlands of the fjord system is dominated by dwarf shrub heaths, copse and wet fens. The heath areas mainly consist of *Empetrum nigrum*, *Vaccinium uliginosum* and *Betula nana*, while corpse are dominated by *Salix glauca* and fens are covered with *Eriophorum angustifolium* and *Scirpus caespitosus* (Bay et al., 2008). This thesis uses measurements from a dry *Empetrum nigrum* tundra heath and a wet *Eriophorum angustifolium* fen, with an aerial distance of ~1.8 km between the two ecosystems.

Mean annual air temperature for Nuuk is -1.4°C for the period 1961-1990 and annual precipitation reaches 752 mm (Jensen and Rasch, 2008). In Kobbefjord, MAAT is 0.2°C for the period 2008-2013 (Jensen and Rasch, 2014). No permafrost is present in the lowlands of the fjord system.

Measurements and methodology

Micrometeorology and environmental parameters

In general, micrometeorology focusses on the small-scale (time and space) exchange processes of energy, gases and mass between the lowermost layer of the atmosphere, the atmospheric boundary layer (ABL), and the underlying surface (Glickman, 2010). One common tool to capture these exchange processes at the ecosystem-scale is the so-called eddy covariance (EC) technique. This technique allows measurements with high temporal resolution and minimal disturbance to the underlying surface and vegetation. The EC method captures fluxes of energy and mass within a certain area from which the fluxes originate (footprint area) (Schmid, 2002), allowing the study of exchange processes and ecosystem properties of a well-delimited spatial area (Kljun et al., 2004). Despite its general use in studies of ecosystem energy exchange processes, the application of the EC method is limited to horizontally homogeneous surfaces and stationary atmospheric conditions (Baldocchi et al., 2001; Foken, 2008). In addition, the energy balance closure problem is one of the most persistent and pending challenges for EC studies (Foken, 2008; Leuning et al., 2012; Stoy et al., 2013). Nevertheless, the EC technique is considered to provide direct and robust information on the functioning of ecosystems and, especially in combination with cross-site comparisons, vital insights into land-atmosphere interactions and feedback processes (Lee et al., 2005).

In this thesis the turbulent components of the surface energy budget were derived from EC measurements within the different study sites. Permanent eddy flux towers provided data from Adventdalen, Zackenberg, Kobbefjord and Stordalen while a mobile EC tower was used at the sites in Torneträsk and Storflaket. In addition to the EC measurements of the turbulent heat fluxes, ancillary data collection of various meteorological parameters and soil physical properties was performed at each site. Table 1 provides a detailed overview of the used equipment, measured parameters and measurement setup of the EC and micrometeorological towers.

Table 1: List of measurement instruments.

List of measurement instruments at the studied tundra ecosystems in Zackenberg, Adventdalen, Kobbefjord and Abisko.

Study site	Zackenberg dry heath	Zackenberg wet fen	Adventdalen polygonal tundra	Kobbefjord wet fen	Kobbefjord dry heath	Stordalen (Abisko) wet fen	Storflaket (Abisko) peat plateau	Torneträsk (Abisko) collapsed peat plateau
Radiation components [1]	CNR4	CNR4	CNR4	CNR4	CNR4	CNR4	CNR4	CNR4
Sensor height (radiation components)	3 m	3 m	2.8 m	2 m	2 m	4 m	2 m	2 m
Sonic anemometer	Gill R3 [2]	Gill HS [2]	Metek USA-1 [3]	Gill R3 [2]	Gill HS [2]	Metek USA-1 [3]	Metek USA-1 [3]	Metek USA-1 [3]
Sensor height (anemometer)	3 m	3 m	2.8 m	2.2 m	1.8 m	2 m	2.7 m	2.7 m
Gas analyser [4]	LI-7000	LI-7200	LI-7200	LI-7000	LI-7200	-	LI-7500	LI-7500
Tube length (gas analyser)	6.2 m	1 m	1 m	5.4 m	1 m	-	-	-
Flow rate (gas analyser)	5.5 L min^{-1}	15 L min^{-1}	15 L min^{-1}	5.5 L min^{-1}	15 L min^{-1}	-	-	-
Sample rate (gas analyser & sonic anemometer)	20 Hz	20 Hz	10 Hz	20 Hz	20 Hz	10 Hz	10 Hz	10 Hz
Ground heat flux [5]	HFP01	HFP01	HFP01	HFP01	HFP01	HFP01	HFP01	HFP01
Sensor depth (ground heat flux)	4 cm	4 cm	3 cm	4 cm	4 cm	3 cm	5 cm	5 cm
Soil moisture [6]	SM 300	-	SM 300	SM 300	SM 300	-	SM 300	SM 300
Sensor depth (soil moisture)	5, 10, 30, 50 cm	-	5, 10, 30, 50 cm	5, 10, 30, 50 cm	5, 10, 30, 50 cm	-	5, 25, 50 cm	5, 25, 50 cm

Soil temperature [7]	T107	T107	T107	T107	105T	105T	105T	105T
Sensor depth (soil temperature)	2, 10, 20, 40, 60 cm	2, 10, 20, 50 cm	2, 10, 20, 40, 70 cm	2, 10, 20, 50, 70 cm	2, 10, 20, 50, 70 cm	2, 10, 20, 50 cm	2, 20, 50 cm	2, 20, 50 cm
Precipitation	5915x [8]	52203 [9]	52203 [9]	52203 [9]	-	-	-	-
Air pressure [7]	-	CS100	CS100	CS100	-	-	-	-
Air temperature & humidity	HMP 45D [10]	CS2015 [7]	CS2015 [7]	CS2015 [7]	-	-	-	-
Snow depth [7]	SR 50A	SR 50A	SR 50A	SR 50A	SR 50A	SR 50A	-	-

[1]Kipp & Zonen, The Netherlands; [2]Gill Instruments Ltd, UK; [3]Metek GmbH, Germany; [4]LI-COR Inc., USA; [5]Hukseflux, The Netherlands; [6]Delta-T Devices, UK; [7]Campbell Scientific, USA; [8]OTT Hydromet GmbH, Germany; [9]R.M. Young Company, USA; [10]Vaisala, Finland

Permafrost active layer monitoring

To assess the dynamics of active layer development in a subarctic peatland, extensive measurements of permafrost active layer thickness were initiated in 2011. In the central part of the Stordalen peatland complex near Abisko, permafrost active layer thickness was measured every autumn (mid-October) between the years 2011 and 2015 by mechanical probing with a steel rod (1 or 2 m long). The sampling area was arranged in a grid of 300 x 300 m. The grid was subdivided into nine smaller units (100 x 100 m) with active layer measurements performed every 20 m except for the central grid where sampling was conducted every 10 m. At each sampling point the vegetation and surface properties were classified into three distinct categories: (a) dry and elevated peat and palsa plateau, (b) wet hollows and depressions dominated by *Sphagnum* mosses, and (c) wet fen. Wooden sticks marked the position of the sampling points for exact relocation in the subsequent year.

In the data analysis, a value of 200 cm was used for those sampling points where active layer thickness exceeded the length of the steel rod. Contour maps of active layer development were generated by using the inverse distance weighted (IDW) interpolation method in the ArcGIS 10 software package (Esri Inc., USA).

Snow manipulation experiment

To investigate the impact of snow on ecosystem dynamics, 12 random plots of a snow manipulation experiment (Johansson et al., 2013) were established during 2005 in the western part of the Storflaket peat plateau. In six of these plots, snow fences (10 m long, 1 m high) are installed every autumn perpendicular to the main east-west wind direction to accumulate snow. After snowmelt in spring the snow fences are removed from the plots and reinstalled in autumn. The other six plots serve as control plots were no snow manipulation has been performed. In addition, measurements of permafrost active layer thickness are conducted with a metal steel rod at each plot every September.

In the center of each plot and at a height of 50 cm, Minikin QT loggers (EMS Brno, Czech Republic) were installed in July 2010 to measure the reflected photosynthetic photon flux density (*PPFD*) of the vegetated surface. *PPFD* is a quantitative measure of photosynthetic active radiation (*PAR*). Measurements of incident *PPFD* from one upward facing logger at the peat plateau were validated with data of incident *PPFD* from the nearby Abisko Scientific Research Station. Since the surface of the peat plateau is completely covered with vegetation we assume that all of the incoming *PPFD* that is not reflected by the surface is absorbed by vegetation (Frolking et al., 1998; Huemmrich et al., 2010).

Carbon flux measurements

Chamber-based measurements of greenhouse gas fluxes are another important tool to describe land-atmosphere exchange processes since they allow, unlike EC measurements, to capture small-scale spatial variations in soil surface structure, vegetation composition, and gas fluxes (Hutchinson and Livingston, 1993). At the study site in Storflaket, measurements of carbon dioxide (CO_2) fluxes were therefore applied between July and September 2010 within the 12 plots of the snow manipulation experiment. The measurement setup consisted of an EGM-4 gas analyzer (PP Systems, USA) attached to a Plexiglas chamber. Net ecosystem exchange (*NEE*) was measured with a transparent chamber while ecosystem dark respiration (R_{eco}) was obtained by shading the transparent chamber. The difference between *NEE* and R_{eco} was used to estimate the gross primary production (*GPP*) at the measured plots.

Results and discussion

Spatial variability of surface energy exchange in Arctic and subarctic ecosystems

In Paper IV we present 12 site-years of growing season energy flux and meteorological observations from six Arctic and subarctic tundra sites in Greenland, Svalbard and northern Sweden. Overall, our results from Paper I-IV underline that due to the striking small-scale heterogeneity and diversity of northern high-latitude ecosystems (Beschel, 1970) and due to local variability in climate, surface structure, soil moisture and soil thermal regime, the surface energy balance of Arctic and subarctic tundra should not be considered as a single entity.

At all sites, the magnitude of the energy fluxes of sensible heat (H), latent heat (LE) and ground heat (G) were well-correlated with net radiation (R_{net}), with highest values observed shortly after snowmelt. However, our studied waterlogged fen and collapsed peat plateau ecosystems showed a greater fraction of LE/R_{net} and lower Bowen ratio (H/LE) compared to the dry polygonal tundra, heath and peat plateau locations. Due to the strong thermal gradient in permafrost soils, G was a prominent term of the surface energy budget at the sites with permafrost. At the high-Arctic sites in Zackenberg, strong interannual variability in snow accumulation and in the length of the growing season (Paper III) was reflected in the overall energy budget and energy flux partitioning of the heath and the fen.

Mean daily evapotranspiration (ET), with higher ET at the wet locations compared to the dry sites, was generally below its potential rate ($ET_{pot.}$) at all studied ecosystems. The observed low evapotranspiration capacities ($ET/ET_{pot.}$) agree with observations from other circumpolar studies (McFadden et al., 1998; Lloyd et al., 2001; Lund et al., 2014). By analyzing the main drivers of LE we observed that all studied locations (Paper II-IV) had a relatively strong coupling of the tundra surfaces to atmospheric vapor pressure deficit (VPD), with more pronounced such control at the dry tundra sites compared to the wet locations. Further, the latter sites showed lower surface resistances which promoted ET compared to the dry sites. No direct relation between aerodynamic resistances and ET or LE was apparent at any site and during any time of the study period. In Paper III & IV we also demonstrated a clear seasonal trend in decreasing $ET/ET_{pot.}$ and increasing surface resistances over the course of the growing season, presumably governed by the impact of decreasing soil wetness from snowmelt. This seasonal development of both $ET/ET_{pot.}$ and surface resistances was most pronounced at our northernmost locations where growing season precipitation is generally low.

Impact of snow cover on surface energy exchange and ecosystem performance

Understanding of how temporal and spatial variability in snow patterns affect Arctic and subarctic ecosystem productivity and surface energy exchange is crucial to better estimate the effects of climate change on both tundra carbon balance and surface energy budget. For this purpose, we performed (a) snow manipulation experiments in a subarctic peatland complex in northern Sweden to investigate the effect of increased snow cover on plant photosynthesis (Paper I), and (b) examined the impact of strong interannual variability in snow accumulation on the surface energy exchange in a high-Arctic tundra ecosystem in Northeast Greenland (Paper III).

The results of the snow manipulation experiment (Paper I) showed that increased snow accumulation on the treatment plots (Johansson et al., 2013) delayed the onset of the growing season by approx. two weeks compared to the control plots. Since snow accumulation in autumn started at the same time on both control and treatment plots, the growing season was shorter at the treatment plots. However, the carbon flux measurements demonstrated a significant difference in growing season ecosystem productivity, with *GPP* being 57% higher at the treatment plots compared to the control plots. The increase in plant productivity was also reflected in the seasonal amount of accumulated carbon from photosynthesis, showing higher carbon uptake at the treatment plots compared to the control plots. Over the entire study period the fraction of *PAR* absorbed by vegetation (*fAPAR*) was on average 1.3% higher at the treatment plots compared to the control plots, with most pronounced difference during the peak and late growing season.

The additional accumulation of snow on the treatment plots initiates interacting physical, hydrological and biological processes which result in both increased *fAPAR* and plant productivity compared to the control plots. The high insulating potential of the snow cover protects the vegetation from strong atmospheric cooling during the winter (Sturm et al., 1997; Bokhorst et al., 2011). On the other hand, increased snow depth induces thicker active layer, permafrost thawing and ground subsidence (Johansson et al., 2013; Park et al., 2015) with associated impact on soil moisture content, soil temperature regime and nutrient availability

(Schimel et al., 2004; Lawrence et al., 2015). Since tundra ecosystems are adapted to short growing seasons and to limitations in soil moisture (Keuper et al., 2012) any change in the timing of snowmelt, soil temperature or the availability of water has implications on plant productivity and carbon balance (Aurela et al., 2004). A shift in vegetation composition from water-limited hummock vegetation towards wet-growing plant communities and graminoids promotes plant carbon sequestration (Johansson et al., 2006). At our site in Stordalen, a pronounced greening and a dominance of *Eriophorum vaginatum* has been observed (Johansson et al., 2013) resulting from the combined effects of increased soil moisture, soil temperature, and nutrient availability.

A general trend in increasing snow accumulation over Fennoscandia (Callaghan et al., 2013) and its impact on plant productivity is only one aspect of climate change in Arctic and subarctic environments. Of equal importance are the effects of extreme events such as pronounced temperature fluctuation or extreme interannual snow cover variability since they significantly impact ecosystem development and carbon sequestration (Marchand et al., 2005; Bokhorst et al., 2008; Bokhorst et al., 2011). To our knowledge, Paper III is the first study that evaluates the impact of successive and interannual snow cover variability on the land-atmosphere interactions and surface energy balance components in a tundra heath and fen ecosystem.

Record-low snow cover in the Zackenberg region in Northeast Greenland during the winter 2012/13 (Mylius et al., 2014) and above-average snow accumulation in the subsequent winter 2013/14 shortened the snowmelt period in 2013 by four weeks and the surface experienced lower albedo and higher R_{net} compared to the snowmelt period in 2014. The short snowmelt period in 2013 prolonged the subsequent growing season by ~30 days compared to 2014. However, no clear difference in the end of the growing season was observed between the two years. Since snow is by far the main supplier of water in the Zackenberg area (Hansen et al., 2008), the summertime energy partitioning was strongly regulated by the availability of snow meltwater, with most pronounced impact on the surface energy budget of the dry heath compared to the wet fen ecosystem. The intensity and timing of summertime precipitation further promoted the response of the heath's energy budget to soil moisture constraints. The wet fen's energy budget showed to be less affected by changes in snow meltwater availability as it receives its water supply mostly from groundwater.

Overall, the growing season energy flux partitioning at the dry heath performed a pronounced shift from a clear dominance of H over LE and G in 2013 to a more balanced control of both H and LE in 2014 due to an almost doubling of LE and G compared to 2013. Growing season R_{net}, however, experienced a small decrease of ~11% in 2014 compared to 2013. During most of the growing season in 2013 snow meltwater was the lone supplier of soil moisture. The small amount of snow meltwater was evaporated relatively early in the growing season which resulted in low *LE*, low soil thermal conductivity and *G*, and in a clear dominance of *H*. Compared to the wet fen relatively high surface resistance further restrained *LE* at the dry heath. During the growing season in 2014, the soil at the heath showed higher saturation from snow meltwater storage and relatively low surface resistance which resulted in a greater share of *G* and *LE* on R_{net}. The heath's and fen's Bowen ratios (*H/LE*) were almost identical during the growing season in 2014. More important, due to the onset of the snowmelt period and growing season during the time of the year when incoming solar radiation is at its peak, an earlier start of the growing season resulted in a dramatic increase in accumulated R_{net} at both biomes.

In tundra ecosystems *ET* commonly exceeds precipitation during summer (Woo et al., 1992). Any increase in the length of the snow-free season and in R_{net} promotes *ET* and negative water balances if no sufficient precipitation occurs (Euskirchen et al., 2006). In our study (Paper III) we showed that the magnitude of the surface energy balance components and *ET* during the snowmelt and growing season is highly dependent on the winter snow conditions. Both water balances and energy flux partitioning strongly depend on surface and ecosystem characteristics as they amplify (dry heath) or attenuate (wet fen) the effects of interannual variability in snow accumulation.

Permafrost degradation and its impact on the surface energy balance

A general increase in the development of active layer thicknesses in the Abisko area since the 1970s has been reported (Rydén and Kostov, 1980; Johansson et al., 2006; Åkerman and Johansson, 2008; Johansson et al., 2011). Active layer monitoring and vegetation mapping at the Stordalen peatland complex during the second week of October in 2011-2015 confirmed this trend, showing an increase in active layer thickness and an expansion of areas and plant communities dominated by wet soil conditions at the cost of dry and elevated peat and palsa communities. During the observation period the mean thickness of the active layer below hollows and depressions was between 1.24 and 1.57 m (mean 1.37 m). Below palsas and peat plateaus, the interannual variability in active layer thickness was less pronounced and mean active layer ranged between 0.70 and 0.75 m (mean 0.73 m). Active layer thickness below wet fen areas was ~2.0 m for all year.

Perhaps, much more important are the temporal and spatial development of the permafrost thaw depths and the magnitude of the ongoing transformation of the peat plateau into wet habitats during the five years of measurements. The data show that the increase in average thaw depths was most pronounced below hollows and depressions (4.4 cm yr^{-1}) and below wet fen areas (0.9 cm yr^{-1}) while below the peat plateau average thaw depths increased by 0.7 cm yr^{-1}. Within the entire measurement grid the increase in active layer thickness was most pronounced in the south-eastern part of the peatland complex (Figure 4). In total, the percentage of sampling points with active layer thickness <2.0 m decreased from 84% in 2011 to 62% in 2015 (Figure 5). Corresponding to the change in active layer thickness the percentage of sampling points classified as peat and palsa communities decreased from 62% (2011) to 51% (2015) while wet fen areas and hollows and depressions increased from 19% (2011) to 24% (2015) and from 19% (2011) to 25% (2015), respectively (Figure 5).

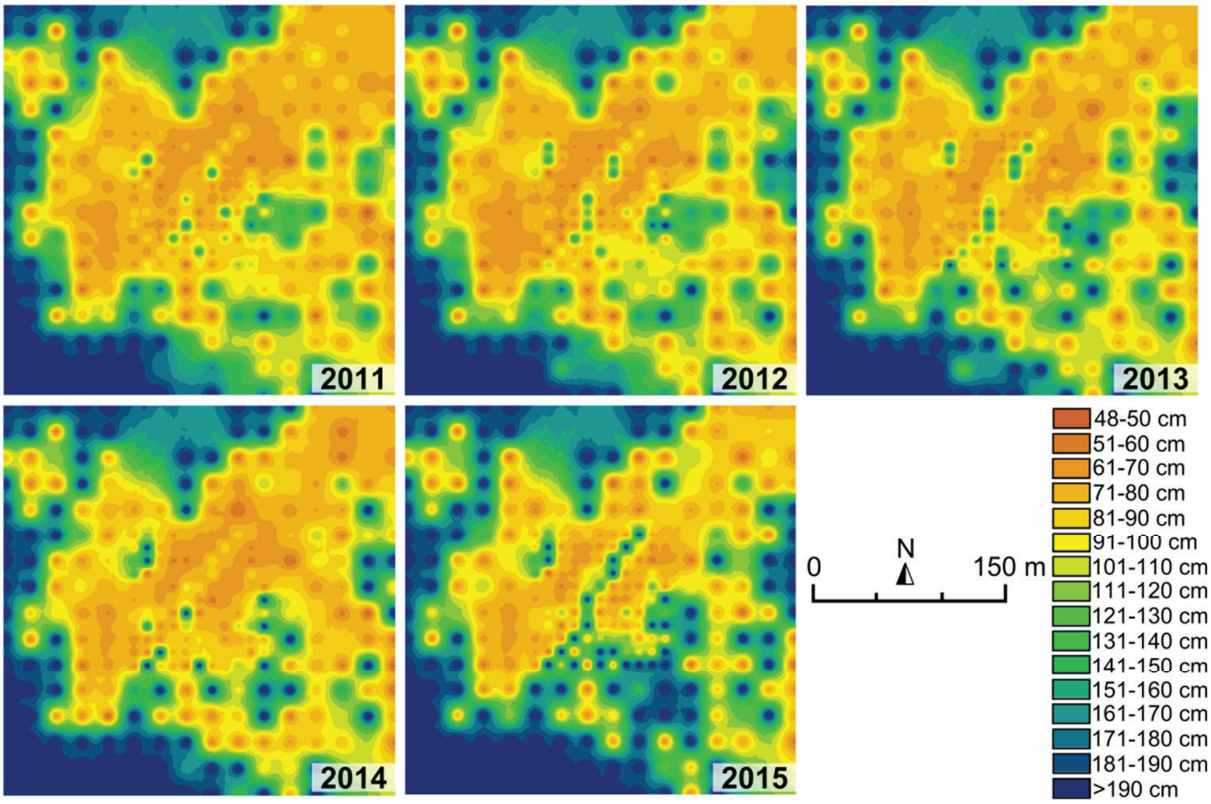

Figure 4: Active layer thickness.
Spatial and temporal variation in active layer thickness at the Stordalen peatland complex from 2011-2015.

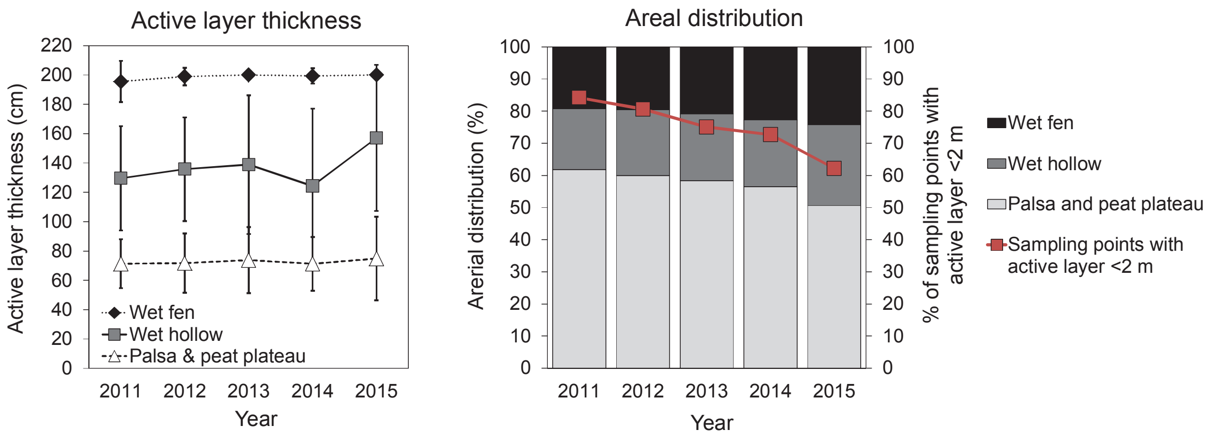

Figure 5: Active layer thickness and vegetation classes.
Development of average active layer thickness within the different vegetation classes (left), and development of vegetation classes and sampling points with active layer <2 m (right) from 2011-2015. The error bars show the standard deviation.

By using micrometeorological measurements we are able to quantify the impact of this ongoing permafrost thaw and degradation of peat plateaus on the surface energy budget of peatland complexes within the Abisko area (Paper II). We observe that the transition of dry peat plateaus into wetland habitats, such as hollows and depressions, collapsed peat plateaus, and wet fen areas, result in enhanced *LE* at the cost of *H*. The difference in the overall flux partitioning between peat plateaus and wet habitats is valid at all radiation levels but more pronounced at higher radiation levels.

Small but significant differences in surface albedo between the three locations suggest that average albedo at the collapsed peat plateau represents a disturbed ecosystem, with relatively high proportion of *Sphagnum* mosses, free water and barren peat with lower albedo. This disturbance is caused by rapid permafrost degradation and the incapacity of the peat plateau's vegetation to adapt to the new moisture conditions. Average albedo at the wet fen and peat plateau, however, result from plant communities which are well-adapted to the moisture regime.

By analyzing the controlling factors of *ET* we observed that the disturbance of the ecosystem at the collapsed palsa due to permafrost degradation resulted in suppressed *ET* below its potential rate. This was mainly attributed to limited ability of free water and mosses to transfer moisture during high atmospheric demands (Rouse et al., 2000; Liljedahl et al., 2011; Pearson et al., 2013). At the peat plateau, however, *ET* was also below its potential rate but *ET* was mainly controlled by soil moisture content (~46%), *VPD* and surface resistance.

Future perspectives of surface energy exchange and land-atmosphere interactions

It is challenging to predict long-term effects of climate warming on Arctic and subarctic ecosystems and surface energy exchange since the coupled hydrological, biological and soil thermal regimes respond nonlinearly to a myriad of controlling factors (Liljedahl et al., 2011) and northern high-latitude ecosystems commonly possess a striking heterogeneity (Paper IV). In general, the ongoing and predicted global increase in air temperature, with pronounced amplification in Arctic and subarctic regions (Serreze and Francis, 2006), is accompanied by higher water vapor saturation pressure and an enhanced ability of the troposphere to hold more water vapor (Raupach, 2001). This atmospheric demand of water vapor needs to be compensated for. The results from Paper II suggest that in Fennoscandia, degraded peat plateaus and wet fens act as a strong source of water vapor since *ET* and *LE* increase in response to higher soil moisture content compared to dry peat plateaus and palsas. However, the results from Paper II indicate that the rapid transition of dry peat plateaus and palsas towards waterlogged surfaces suppresses *ET* below its potential rate. Projected increase in graminoid vegetation at the former peat plateaus (Johansson et al., 2013) might offset the suppressed *ET* and even increase *ET* and *LE* as vascular plants have higher ability of transpiration compared to mosses and open water (Rouse et al., 2000; Liljedahl et al., 2011; Pearson et al., 2013). In Fennoscandia, permafrost and the overlying dry peat plateau vegetation is under severe threat of disappearance (Åkerman and Johansson, 2008) being replaced by waterlogged and wet-growing graminoid vegetation (Bosiö et al., 2012) which may further increase the rate of *ET* to the atmosphere. However, in Paper I we also demonstrated that increased soil moisture, caused by rapid permafrost degradation due to manipulated increase in snow accumulation, stimulates plant photosynthesis and plant carbon sequestration. Nevertheless, the increased plant carbon uptake might be offset by increased methane emissions if the surface of the former peat plateaus remains waterlogged (Bäckstrand et al., 2010; Jackowicz-Korczyñski et al., 2010).

Paper III has shown that in a high-Arctic ecosystem, interannual variability in snow accumulation and a prolonged growing season due to earlier disappearance of the snow cover and limited snow meltwater availability caused a strong response of the ecosystem's surface energy balance. In a future climate the increase in atmospheric moisture, partly supplied by degraded peat plateaus (Paper II), is expected to increase precipitation and its interannual variability over eastern Greenland while temperatures continue to rise (Stendel et al., 2007). Although the fraction of snow on the annual amount of precipitation is expected to decrease (Callaghan et al., 2011a) snow continues to have strong impact on high-Arctic ecosystems by defining the length of the growing season and both surface energy accumulation and energy partitioning (Paper III & IV). However, deeper active layer in the Zackenberg area (Lund et al., 2014) may change growing season surface hydrology by lowering the groundwater table and soil moisture. Combined with increased variability in snow cover and an expected earlier onset of the growing season, this high-Arctic ecosystem may experience strong interannual variability in energy accumulation, reduced surface heat loss from *LE* and increased heat transfer by *H* in years with low snow cover, and changes in the overall strength of carbon sequestration.

Conclusions

The overall focus of this thesis was on the surface energy exchange and land-atmosphere interactions of Arctic and subarctic tundra ecosystems under climate change. The combined implementation of micrometeorological measurements, permafrost active layer monitoring and vegetation mapping, snow manipulation experiments and chamber-based measurements of carbon dioxide fluxes allows us to better understand the close coupling of Arctic and subarctic tundra ecosystems with the overlying atmosphere.

The following conclusions can be drawn from this thesis:

- Energy exchange, energy flux partitioning and ecosystem productivity of Arctic and subarctic tundra ecosystems are closely linked to a myriad of interacting and controlling parameters such as local climate, spatial and temporal variability in surface structure, vegetation cover, soil moisture and soil thermal regimes. It is therefore indispensable to consider Arctic and subarctic regions as a diverse mosaic of ecosystems which show different response to ongoing and predicted climate change.
- Snow is a crucial physical component in the Arctic and subarctic regions. Its interannual and temporal variability at the high-Arctic tundra environment in Zackenberg caused strong response in surface energy partitioning and surface hydrology at the local heath ecosystem while the wet fen showed attenuated behavior. At both locations, a short snow cover period was related to a pronounced increase in both growing season length and total accumulated energy balance components. In northern Fennoscandia, plant carbon sequestration benefited from experimentally increased snow cover due to thicker active layer and increased soil wetness of peat plateaus.
- In northern Fennoscandia, the response of lowland permafrost and peatland ecosystems to climate change is both rapid and dramatic. Increased snow cover and warming temperatures promote permafrost degradation in peatland complexes and transition from dry habitats into wet-growing ecosystems. Concurrently, the surface energy budget experiences an increase in latent heat fluxes and evapotranspiration at the cost of sensible heat fluxes.

- In a warming future wet fen ecosystems and degraded peat plateaus in northern Fennoscandia could act as a strong source to compensate the atmosphere's demand for water vapor while increased plant carbon sequestration could be offset by increased methane emissions.
- Increased interannual variability in snow cover due to climate change may challenge ecosystem adaptation capacities in the Arctic and subarctic regions due to strong variability in energy accumulation and soil moisture regimes.

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