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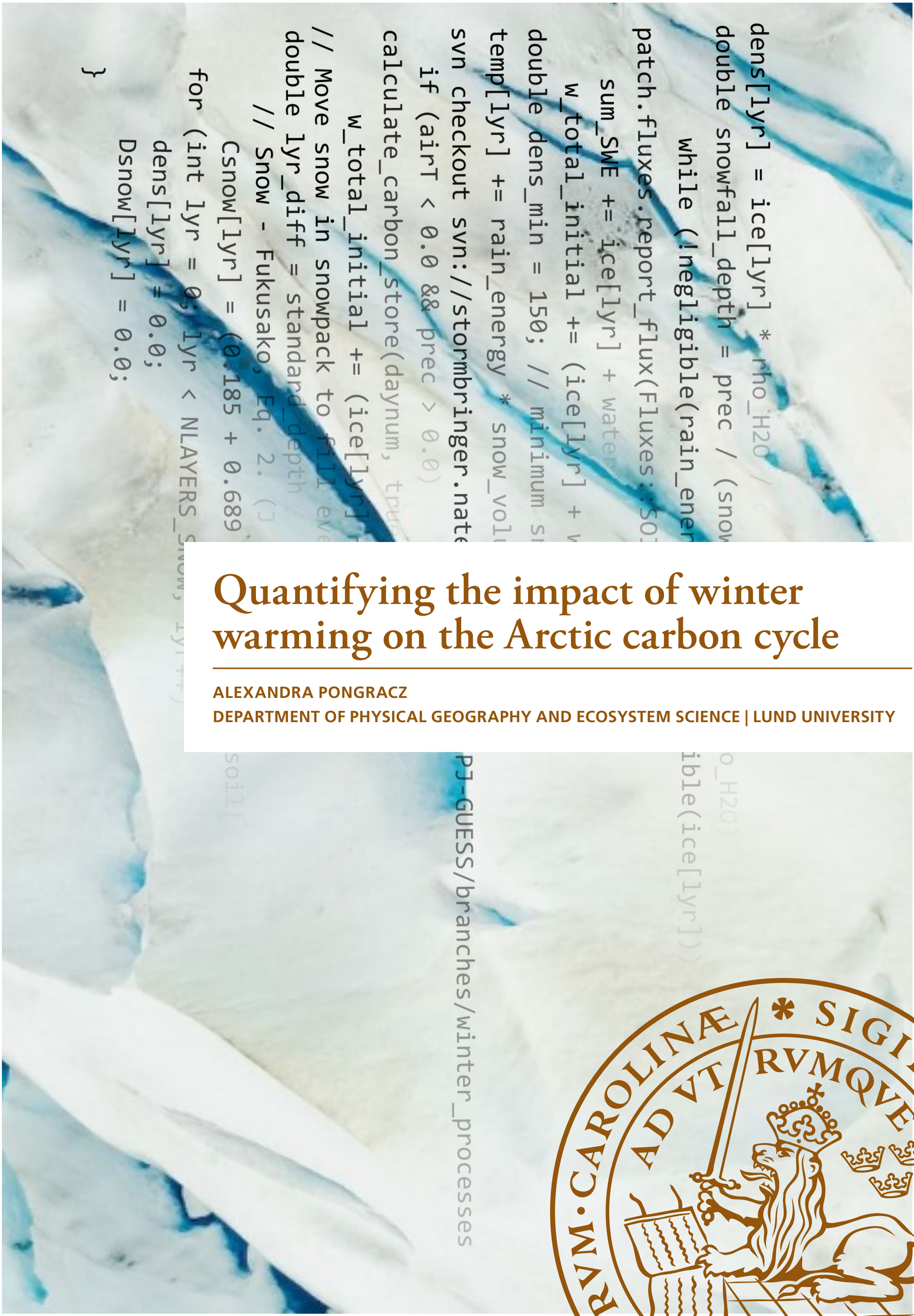

# Quantifying the impact of winter warming on the Arctic carbon cycle

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by Alexandra Pongracz

LUND
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Abstract

The Arctic has undergone extreme changes during the last decades and is warming over twice the global average. There has been increasing interest in understanding how warming and changes in snow and rainfall will affect high-latitude ecosystems. Although observational studies highlight the importance of cold-season carbon fluxes on the annual carbon balance, models, in general, cannot realistically capture these wintertime processes. In this thesis, we developed the LPJ-GUESS ecosystem model to better represent cold season processes. Our aim is to evaluate how changing winter conditions would affect arctic ecosystems and, indirectly, the global carbon and hydrological cycles.

In our first study, we introduced a new snow scheme that improved the pan-Arctic model-data correspondence in observed snow depth, snow season length and snow insulation capacity. We used the updated model to examine the relationships between snow conditions and carbon flux changes under different future scenarios. We found that the coldest regions and coldest season are most vulnerable to environmental changes, which corresponds to the areas where we currently have the largest uncertainties. We explored the impact of extreme winter events on ground conditions and carbon fluxes. This study highlighted the still-existing shortcomings of the model in capturing short-term extreme weather phenomena and their impact. We tested a conceptual model to enable the simulation of autumn-time methane emissions at a high-arctic study site. The updated module could simulate both the growing season and autumn-time methane emission peaks, and we proposed further investigation into the possibilities of including physical controls of methane emissions in the model.

Our studies improved the model's performance in simulating wintertime processes across the Arctic. We highlight the importance of further developing snow dynamics and cold season greenhouse exchange processes in ecosystem models. Further improvements are necessary to create more robust future predictions regarding the impact of climate change on arctic ecosystems and their global consequences.

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LPJ-GUESS, Arctic, permafrost, snow, carbon cycling, non-growing season

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*“I wish it need not have happened in my time,” said Frodo. ”So do I,” said Gandalf, ”and so do all who live to see such times. But that is not for them to decide. All we have to decide is what to do with the time that is given us.”*

- J.R.R. Tolkien, The Fellowship of the Ring

# Contents

# List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **Model simulations of arctic biogeochemistry and permafrost extent are highly sensitive to the implemented snow scheme in LPJ-GUESS**
**A. Pongracz**, D. Wårlind, P. A. Miller, and F.–J. W. Parmentier
Biogeosciences, 2021, 18, 5767–5787, pp. 1–31

II **Contrasting snow conditions drive the future trajectory of Arctic carbon release**

**A. Pongracz**, D. Wårlind, P. A. Miller, S. S. Rabin, A. Gustafson and F.–J. W. Parmentier
Manuscript

III **A conceptual model for methane emissions from permafrost soils**

**A. Pongracz**, D. Wårlind, P. A. Miller, M. Mastepanov, T. R. Christensen, and F.–J. W. Parmentier
Manuscript

IV **High latitude terrestrial ecosystems' contribution to global warming – will the Arctic be a sink or source of greenhouse gases in the 21st century?**
A. Gustafson, S. Olin, A. Ahlström, **A. Pongracz**, L. Niederazik, J. Tang, B. Smith, P. A. Miller
Manuscript

V **Modelling the impacts of future enhanced winter warming events on subarctic ecosystems using LPJ-GUESS**
D. Pascual, M. Johansson, **A. Pongracz**, J. Tang
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I feel privileged that I could study at INES from the very first day of my Bachelor studies; fast forward eight years to completing my PhD project. I wish to thank all I met at INES during this time who encouraged me to be curious, made my day with a small talk or practical advice on surviving academia. Special shout out to the LPJ-GUESS community: from bug-fixing to pep talks and training my Swedish, you always pushed me to keep going and look at the bright side of modelling (the one past your own bugs…). Thanks to all my fellow PhD students for keeping me caffeinated during Wednesday fikas and for the laughs to forget the hard times.

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This thesis wouldn't be the same without you!

# Popular summary

The Arctic has undergone extreme changes during the last decades and is warming three times the global average. There has been increasing interest in understanding how warming and changes in snow and rainfall will affect high-latitude ecosystems. Although observational studies highlight the importance of cold-season carbon fluxes on the annual carbon balance, models, in general, cannot realistically capture these wintertime processes. In this thesis, we developed the LPJ-GUESS ecosystem model to better represent cold-season processes. Our aim is to evaluate how changing winter conditions would affect arctic ecosystems and, indirectly, the global carbon and hydrological cycles.

Our first study introduced a new snow scheme that improved the pan-Arctic model-data correspondence in observed snow depth, snow season length and snow insulation capacity. We used the updated model to examine the relationships between snow conditions and carbon flux changes under different future scenarios. We found that the coldest regions and coldest season are most vulnerable to environmental changes, which corresponds to the areas where we currently have the largest uncertainties. We explored the impact of extreme winter events on ground conditions and carbon fluxes. This study highlighted the still-existing shortcomings of the model in capturing short-term extreme weather phenomena and their impact. We tested a conceptual model to enable the simulation of autumn-time methane emissions at a high-arctic study site. The updated module could simulate both the growing season and autumn-time methane emission peaks, and we proposed further investigation into the possibilities of including physical controls of methane emissions in the model.

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# Populärvetenskaplig sammanfattning

Arktis har genomgått extrema förändringar under de senaste årtiondena och har värmts upp tre gånger så mycket jämfört med det globala genomsnittet vilket har ökat intresset för att förstå hur uppvärmning och förändringar i snö och nederbörd kommer att påverka ekosystemen på höga latituder. Observationsstudier belyser betydelsen av kolflöden under den kalla årstiden för den årliga kolbalansen, men modellerna kan dock inte fånga upp dessa vinterprocesser i allmänhet på ett realistiskt sätt. I den här avhandlingen har vi utvecklat ekosystemmodellen LPJ-GUESS för att bättre representera processer under den kalla årstiden. Vårt mål är att utvärdera hur förändrade vinterförhållanden skulle påverka de arktiska ekosystemen och indirekt de globala kol- och hydrologiska kretsloppen.

I vår första studie uppdaterade vi hur snöprocesser representeras i LPJ-GUESS vilket förbättrade överensstämmelsen mellan modell och data för hela Arktis när det gäller observerat snödjup, snösäsongens längd och snöns isoleringsförmåga. Vi använde den uppdaterade modellen för att undersöka sambanden mellan snöförhållanden och förändringar i kolflödet under olika framtidsscenarier. Vi fann att de kallaste regionerna och den kallaste säsongen visade högst sårbarhet för miljöförändringarna. Dessa områden är även de områden där vi för närvarande kan se de största osäkerheterna i den tillgängliga datan. Vi undersökte även hur extrema vinterhändelser påverkar marktemperatur och kolflöden. Denna studie belyste de brister som modellen fortfarande har gällande att fånga upp kortsiktiga extrema väderfenomen och deras inverkan. Vi testade även en konceptuell modell för att möjliggöra simulering av metanutsläpp under hösten på en högarktisk studieplats. Den uppdaterade modulen kunde simulera både växtsäsongens och höstens metanutsläppstoppar och vi föreslår ytterligare undersökningar om möjligheterna att inkludera fysiska kontroller av metanutsläpp i modellen.

Våra studier förbättrade modellens prestanda när det gäller att simulera processer under vintertid i ekosystem på höga latituder. Vi betonar vikten av att ytterligare utveckla snödynamiken och växthusutbytesprocesser under den kalla årstiden i ekosystemmodeller. Ytterligare förbättringar är nödvändiga för att skapa mer robusta framtida förutsägelser om klimatförändringarnas inverkan på arktiska ekosystem och deras globala konsekvenser.

# Foreword

## 1 Rationale and thesis structure

In this thesis, I use an ecosystem modelling approach to assess how wintertime warming will impact high-latitude ecosystems. We specifically address some of the still-existing knowledge gaps regarding cold season process interactions, focusing on snow- and permafrost dynamics and greenhouse gas exchange.

In Paper I, we present a new scheme in the dynamic vegetation model (DGVM) Lund-Jena-Potsdam General Ecosystem Simulator (LPJ-GUESS) that significantly improved the model's capability to simulate snow dynamics and soil thermodynamics. This development enables further investigation of snow-soil-vegetation interactions in the Arctic-Boreal region. Paper II and IV investigate the future state of the Arctic carbon budget. While Paper II focuses on the relationship between snow conditions and carbon flux changes, Paper IV differentiates between tundra and taiga ecotones' carbon emissions and the global warming potential contribution of greenhouse gases. Paper III presents a novel approach to simulating cold season methane fluxes at a high- latitude site by adapting an empirical soil gas reservoir theory. Paper V applied the new snow scheme in the LPJ-GUESS model to assess how extreme weather events affect carbon fluxes in a sub-arctic catchment.

Taken together, the presented articles highlight the importance of cold season processes in high-latitude ecosystems. While global implications are not explicitly discussed in this thesis, the findings can contribute to our understanding of how arctic warming will affect the global climate system.

# Quantifying the impact of winter warming on the Arctic carbon cycle

## 2 Introduction

Northern high latitudes have undergone unprecedented changes over the past decades. Air temperature has warmed three times the global average, contributing to significant changes to arctic ecosystems. Linkages between the hydrological and carbon cycles resulted in increased tundra biomass along with increased humidity and extreme weather events, and these trends are significantly different from the long-term ecosystem state (AMAP, 2017; IPCC, 2021; Box et al., 2019; Rantanen et al., 2022). The Arctic amplification process has a range of different causes including sea-ice decline, changes in cloud cover and precipitation and changes in atmospheric heat fluxes (Serreze and Barry, 2011). The rapid sea ice decline (up to 30 % area loss per decade) yields a larger ice-free sea surface with lower albedo further increasing the warming process through a positive climate feedback. Sea ice albedo decrease is recognised as one of the key drivers of arctic climate change and it has been linked to rising terrestrial methane emissions (Parmentier et al., 2013).

Arctic precipitation is expected to increase in the future by ca. 1.5-2.0 % per decade, affecting not only the snow-rainfall ratio but also soil moisture controlling plant growth and plant productivity rates (Bintanja and Andry, 2017; Box et al., 2019). Changes in cloud cover may limit incoming solar radiation available for photosynthetic processes and, therefore, decrease ecosystem's carbon sequestration (Serreze and Barry, 2011). Higher atmospheric humidity and increased evapotranspiration in warmer areas may lead to significant changes in global atmospheric circulation (Box et al., 2019). Decrease in ice and snow-cover leads to surface warming, which drives an upward heat-flux affecting regional boundary conditions and atmospheric circulation. Increasing natural particles (sea-spray and biogenic organic compounds) will affect cloud formation and prevalent cloud types due to the aerosol-cloud-climate feedback (Boy et al., 2019). Changes in air temperature and precipitation are linked to pan-arctic surface warming and consequent permafrost thaw, shortening of snow cover duration and carbon sequestration capacity (Meredith et al., 2019; Box et al., 2019). These changes will significantly influence the carbon uptake capacity of the Arctic-Boreal region and consequently the global carbon and hydrological cycles (AMAP, 2017). The already observed environmental changes are very likely to continue in the future, having significant, but differing consequences at both the regional and global scale. It is challenging to project whether climatic changes will turn the current carbon sink to a source, due to multiple interlinked processes occurring at different spatio-temporal scales.

### *Wintertime changes*

Arctic warming is not uniform across the year. As shown in Figure 1, cold season warming is the most pronounced (IPCC, 2021; Bruhwiler et al., 2021). Besides higher air temperature, increased precipitation during the cold season as well as increased frequency and intensity of extreme weather events, such as Rain-On-Snow (ROS) or winter warm spells is expected (IPCC, 2021; AMAP, 2017). These changes will significantly influence arctic ecosystems, but due to the sporadic and short-lived nature of these events there is no scientific consensus on how these changes will affect the regional and global elemental and hydrological cycles. Despite the largest climatic changes to occur during the cold season, historically less focus has been dedicated to this period in climate change impact studies, due to the apparent low biogeochemical process rates.

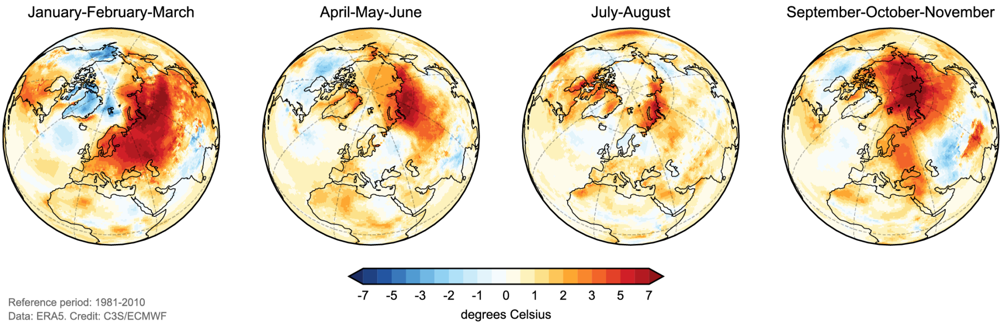

**Figure 1:** Surface temperature anomalies for different periods of 2020: January–March, April–June, July–August and September–November. Anomalies are calculated relative to the 1981 2010 mean. Data source: ERA5. Credit: C3S/ECMWF.

### *Complexity in Arctic ecosystems*

Studying Arctic ecosystems' response to wintertime climatic changes is challenging, not only due to the data-scarcity from the cold season, but also due to the large number of interacting processes to that need be taken into account. To better understand these process interactions, we need an in depth look at some of the key environmental controls on the carbon and hydrological cycles in the region, – such as snow, permafrost and vegetation cover – with an emphasis on snow-soil-vegetation interactions (Box et al., 2019).

## Snow dynamics

Snow is an important component of the Arctic cryosphere, providing an insulating cover over soil and vegetation up to ten months annually during the cold season. The length of the snow season and the timing of snow melt have a significant effect on growing season processes (AMAP, 2017; Krinner et al., 2018). Due to its high albedo, snow efficiently reflects incoming solar radiation, therefore the projected future decreasing snow cover extent and duration (Mudryk et al., 2020; AMAP, 2017) may further increase the regional warming process. Forecasting future snow conditions is challenging due to the dependency on both air temperature and precipitation. Increasing precipitation, with sub-zero temperatures, can lead to more intense snowfall (Bintanja and Selten, 2014).

The Arctic is expected to be less snow-dominated by 2100 (McCrystall et al., 2021). The shift from snow to rain domination could have a significant impact on melt-water discharge and soil temperature. Most studies describe average future snow condition changes across the Arctic, despite the high heterogeneity in future spatio-temporal patterns in forcing variables. Contrasting snowfall trends are often overlooked and disregarded in global, large scale studies (Quante et al., 2021). Projected future changes in snow depth and snow cover length are expected to have a significant impact on soil temperature and should be investigated further to provide more meaningful estimates on how changes in snow conditions will impact the global carbon and hydrological cycles.

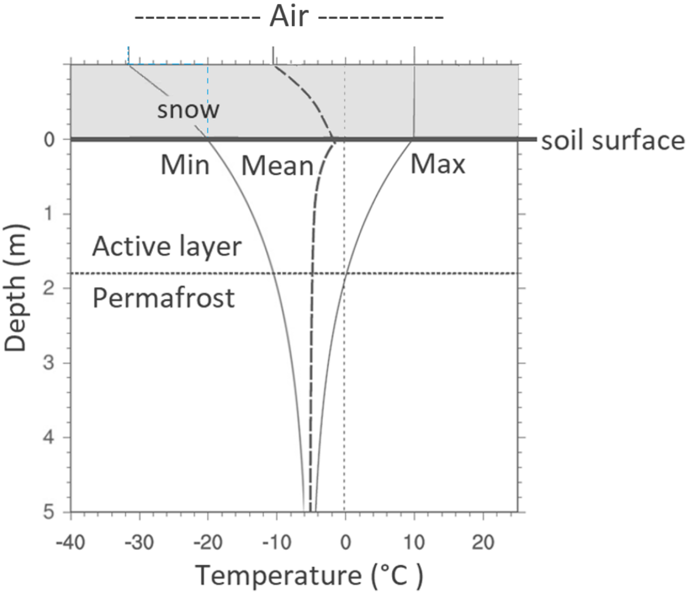

**Figure 2:** Theoretical subsurface temperature profile (adapted after Koven et al. (2013)). Potential snow cover - shown by the shaded grey area - effectively dampens the cooling effect of air during the cold season. The dashed line shows the average temperature profile; solid lines the seasonal maximum and minimum annual curves.

### Permafrost dynamics

By regulating soil temperatures (Fig. 2), snow is the most important control over soil thermodynamics and the thermal state of permafrost. Permafrost soils - ground remaining at or below *0* °C for at least two consecutive years – contain approximately half of the global soil carbon pool (1400-1600 Pg C) (Schuur et al., 2015; Hugelius et al., 2014; Kuhry et al., 2013). The permafrost underlain area is estimated to lie between 2.9 and 17.7 $\times 10^6$ km$^2$, with a central estimate of 13.9 $\times 10^6$ km$^2$, accounting for ca. 15 % of the Northern Hemisphere terrestrial land area (Obu et al., 2019; Obu, 2021). Figure 3 shows the most recent Northern hemisphere permafrost extent estimate, based on mean annual ground temperature (MAGT) > 0 °C (Obu et al., 2019).

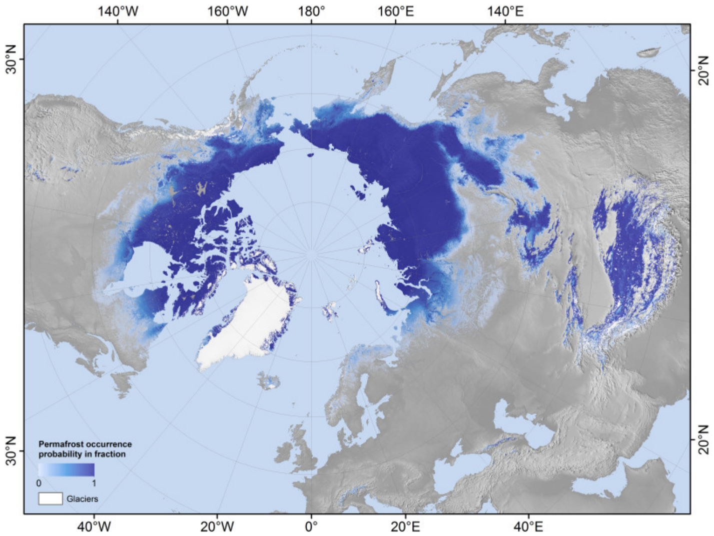

**Figure 3:** Northern hemisphere permafrost extent estimate, defined as mean annual ground temperature > 0 °C. In this thesis, we primarily focus on permafrost underlain areas located > 60 °N. Credit: Obu et al. (2019)

Permafrost soils have warmed by 0.2 - 0.4 °C per decade (Biskaborn et al., 2019), a trend that is likely to continue in the future. Besides air temperature warming, changes in snow depth and snow season length significantly contribute to changes in snow insulation capacity, leading to permafrost degradation. Ground warming leads to increasing active layer depth, which subjects soil carbon to decomposition and ultimately carbon loss. Carbon emissions from permafrost underlain areas can induce a positive carbon cycle feedback, exacerbating the global warming process. Estimated carbon release from permafrost soils varies broadly between 50 and 170 Tg C by 2100, depending on the applied climate scenario and biogeochemical model (Schuur et al., 2015; Hugelius et al., 2020; Schaefer et al., 2014). This permafrost carbon feedback can be a principal control over the future arctic carbon balance. Permafrost degradation can induce contrasting processes: ground warming can lead to drier conditions, enhancing decomposition rates dominated by $CO_2$ emissions, while thawing and subsequent wetter conditions can stimulate $CH_4$ emissions.

### Wetland methane emissions

Permafrost warming is expected to affect soil moisture conditions, wetland extent and consequently greenhouse gas emissions from wetlands. Arctic-Boreal wetlands cover approximately 14-25 % of the Arcitc-Boreal land surface, with the majority located within permafrost underlain regions (Olefeldt et al., 2021; Karesdotter et al., 2021). Wetlands are the largest natural source of methane in the region (Olefeldt et al., 2021; Saunois et al., 2020), therefore it is necessary to evaluate how warming and changes in hydrological conditions may affect wetland carbon emissions. Estimates for current annual wetland emissions vary widely between 9 and 77 Tg C CH4 $yr^{-1}$ depending on the estimated wetland extent and estimation method (Kuhn et al., 2021; Saunois et al., 2020). Top-down estimates (i.e. using inversion models) are generally lower than bottom-up or flux upscaling estimates (Saunois et al., 2020) (see Table 1).

**Table 1:** Annual wetland methane emissions estimates (domain: 45 °N>).

| Annual emission (Tg CH4 $yr^{-1}$) | reference | method |
|---|---|---|
| 22-42 | Saunois et al. (2020) | budget estimate |
| 30-37 | Peltola et al. (2019) | flux upscaling |
| 25 | McGuire et al. (2012) | process-based models |
| 25 | Kirschke et al. (2013) | top-down atmospheric inversions |
| 11-28 | Bruhwiler et al. (2021) | inversion models |

Recent advances in methane budget estimates include the development of more realistic wetland maps for modelling studies (Olefeldt et al., 2021; Karesdotter et al., 2021). There is less effort on quantifying cold season wetland emissions, whose contribution remain often overlooked, due to the lack of comprehensive observational data at a pan-arctic scale. Even though the vulnerability of wetlands to climatic change is under continuous assessment (AMAP, 2017; Karesdotter et al., 2021), wetland carbon emissions remain an uncertain element in carbon budget estimates. Kreplin et al. (2021) discussed that the climate impact on wetlands is challenging to assess due to the many contributing factors and their complex relationships. Sea ice decline and sea surface warming leads to increasing evaporation, affecting cloud formation and precipitation patterns. Surface albedo decrease can induce land cover change by affecting ambient soil conditions affecting vegetation composition and extent. Projected environmental changes can lead to both shrinkage and expansion of wetlands, depending on local climatic and hydrological conditions. Changes in wetland extent can lead to, not only changes in carbon sequestration capacity, but also shifts in land cover and vegetation composition, affecting surface albedo.

### Vegetation dynamics

Remote sensing studies identified that the Arctic has been ”greening” since the 1980s (Xu et al., 2013), meaning a general trend towards increased vegetation cover, a northward shift of vegetation extent and an increase in biomass and height (Myers-Smith et al., 2020). Greening can be mainly attributed to surface temperature warming. However, an in-depth analysis of recent years' processes found that vegetation trends are not uniform, but that they exhibit a complex spatio-temporal pattern with areas of opposing (browning) trends (Myers-Smith et al., 2020). Browning events can be induced by extreme weather events (such as droughts or winter warm spells), and may significantly decrease plant productivity and affect vegetation phenology and growth (Bjerke et al., 2014; Bokhorst et al., 2011).

Due to the sporadic nature of events leading to browning, it is challenging to assess the extent of browning events, mortality or recovery of vegetation. Warming and the lengthening of the growing season can be beneficial to plant growth - given that nutrients and water are not limiting. Increased plant productivity (and/or northward vegetation expansion) may have the ability to offset increased carbon emissions, thereby affecting the future regional carbon balance. Extreme snowfall events and shifts in the snow-precipitation ratio can lead to adverse impacts on vegetation, such as a loss of greenness (browning), and mortality or decrease in productivity. Even single short-term extreme events can have a long-lasting effect on vegetation productivity (Parmentier et al., 2018). Myers-Smith et al. (2020) found contrasting vegetation responses to warming, leading to either greening or browning - affecting carbon sequestration capacity in both cases. This implies that extreme events have the capacity to inflict regionally important processes, for instance, by influencing vegetation productivity and surface albedo. Therefore, understanding and accounting for changes in vegetation dynamics are essential when discussing the future carbon balance.

## 2.1 Regional carbon balance

*Current estimates of the arctic carbon balance*

The Arctic-Boreal region plays an important role in global carbon cycling. Via photosynthesis, tundra and taiga biomes remove carbon from the atmosphere. Ecosystems lose carbon through ecosystem respiration, which may be exacerbated by permafrost degradation. The regional carbon balance depends on the changes in arctic ecosystems' carbon uptake capacity and carbon emissions. Therefore, it is imperative to understand how these processes are affected by warming. The Arctic region currently helps to counteract the increasing atmospheric concentration of greenhouse gases by carbon uptake. Despite the importance for global carbon cycling, large uncertainties exist regarding the current state of the arctic carbon balance. Data syntheses show that the Arctic-Boreal region act as a sink (Virkkala et al., 2021; Lopez-Blanco et al., 2019; McGuire et al., 2012), while others report a source (Belshe et al., 2013; Natali et al., 2019), depending on the estimation methods (see Table 2).

**Table 2:** Annual Arctic carbon balance estimates.

| Annual NEE (Pg C yr$^{-1}$) | reference | method |
|---|---|---|
| −351 to 514 | Natali et al. (2019) | process-based models |
| −67 | Lopez-Blanco et al. (2019) | model-data assimilation |
| −46 to 10 | Virkkala et al. (2021) | flux upscaling |

### The importance of the non-growing season

Cold-season processes were traditionally assumed to be negligible regarding their contribution to the annual carbon budget due to the long snow-covered periods and the prevalent low ground temperatures. Additionally, year-round and non-growing season observational data is scarce; therefore, most studies focus exclusively on growing season processes. However, recent publications highlighted that cold season greenhouse emissions can constitute up to 50% of annual total carbon emissions (Natali et al., 2019; Zona et al., 2016). Non-growing season (NGS) carbon emissions can potentially reach or exceed summertime carbon uptake in high latitude areas, and as climatic changes are expected to be the most significant during winters, cold-season carbon fluxes constitute a vulnerable component of the future arctic carbon balance.

A rapid increase in respiration directly after snow melt was found to offset ca. 40% of summertime carbon uptake at a high arctic site (Arndt et al., 2020), emphasising the link between snow- and carbon dynamics. Earlier snow-melt and subsequent earlier water availability might be beneficial for the early growing season but were found to result in lower August productivity (Zona et al., 2022). Springtime carbon fluxes added up to almost half of the growing season $CO_2$ uptake and contributed significantly to the annual methane budget (Raz-Yaseef et al., 2016). These findings suggest that non-growing season processes will impact carbon cycling via changes in biogeochemical coupling (e.g. snow melt-soil moisture availability relationship). Other studies argue that NGS methane emissions are driven by physical soil processes. Mastepanov et al. (2008, 2013b) and Pirk et al. (2017) showed large $CH_4$ bursts at high latitude sites linked to soil freeze-in (Fig. 4). Accumulated gases are squeezed out during the zero-curtain period – the period when soil temperatures stay at or around zero before freeze-in – due to pore space decrease. This phenomenon may dominate autumn-time carbon emissions in permafrost underlain sites and could lead to lower total carbon emissions in a year after a significant burst. Bao et al. (2021) found autumn-time carbon emissions to exceed spring-time fluxes at a high-arctic tundra site, but it is challenging to compare NGS emission contributions from spring, autumn and winter periods due to the scarcity of year-round measurements. The available site-specific and multi-site observations suggest that NGS carbon emissions can potentially convert the current sink to a source of carbon under the projected warming climate.

A pan-arctic estimate of the contribution to the annual carbon budget is made difficult, as of now, due to the scarcity of year-round carbon flux measurements. The Arctic region has been historically understudied (Euskirchen et al., 2022), with 30 % of observational data derived from just two research sites. Even less research has been conducted with focus on cold-season processes. This is partly due to the remoteness and harsh environmental conditions, and the assumption of lack of a wintertime biogeochemical activity due to the cold air and soil temperatures. As recent years' remote-sensing, observational and modelling efforts have shown, non-growing season processes should be accounted for in the regional carbon balance to obtain robust projections on climate change impacts at northern high latitudes. To overcome the lack of continuous year-round measurements, studies could evaluate the regional importance using ecosystem models. It is challenging to assess the regional cold season contribution to the pan-arctic carbon budget since many ecosystem models do not account for non-growing season processes or limit biogeochemical processes to the growing season (de Vrese et al., 2021). Despite observational evidence of the importance of NGS carbon fluxes on the annual carbon balance, models, in general cannot capture these cold-season processes. Addressing these shortcomings is the main rationale for this thesis.

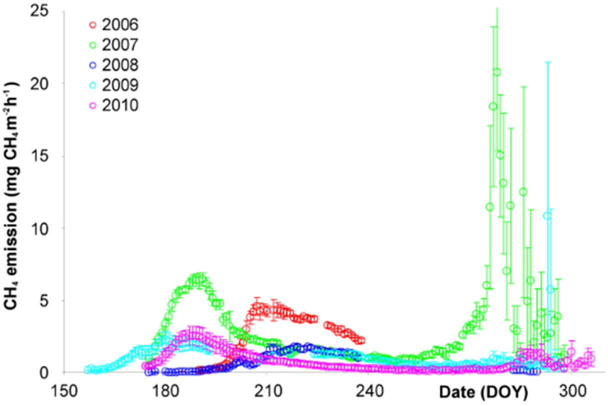

**Figure 4:** *$CH_4$* emission dynamics, normalised to day of year (DOY). Figure adapted after Mastepanov et al. (2013a).

## 2.2 Ecosystem modelling

*"All models are wrong, but some are useful"*
George E. P. Box —

Models are flexible tools to study how ecosystems respond to environmental changes. With the help of models, we can describe the effect of complex factors (i.e. environmental changes) on a range of different variables (i.e. regional carbon balance). We can quantitatively assess future conditions under different climate scenarios and investigate which factors contribute to the results. Global ecosystem models are widely used in climate change and ecological studies, in a stand-alone set-up or as part of an Earth System Model (ESM). Models are especially important tools for Arctic-focused studies, as observational data is scarce and spatially biased (Metcalfe et al., 2018), while remote sensing resources cannot provide continuous, high-resolution data products.

A model is, by nature, a simplification of reality, and one needs to thoroughly assess a model's skill and performance before applying it for scientific purposes. Models need to go through a thorough evaluation and validation process, and their limitations and uncertainties need to be accounted for when discussing model outputs. Over the years, several idealised experimental set-ups have been constructed to enable model comparison studies and derive robust and meaningful estimates of future conditions. One such project is the Coupled Model Intercomparison Project (CMIP6), in which each model's simulations follow a common framework and resulting outputs are publicly made available. Different Shared Socioeconomic Pathways (SSPs) are defined to show the socio-economic and environmental impact depending on climate mitigation measures (O'Neill et al., 2016). Five narratives exist: SSP1 (sustainability, 1.5 °C above pre-industrial target), SSP2 (middle of the road), SSP3 (regional rivalry, high challenges), SSP4 (inequality) and SSP5 (fossil-fueled development) (Tebaldi et al., 2021). Global model evaluation projects (such as CMIP Phase 6) apply these future pathways to visualise the effect of mitigation measures. To represent the climate mitigation levels, each SSP baseline is associated with a Representative Concentration Pathway (RCP) corresponding to positive radiative forcing values in 2100 in $W/m^2$ – for instance 1.9, 2.6, 3.4, 4.5, 7.0 and 8.5. The Paris agreement's target 1.5 - 2°C warming by 2100 is represented by SSP1-1.9, SSP1-2.6 and SSP2-4.5. Figure 5 a) presents several SSPs corresponding mean surface temperature change compared to a historical average.

*Modelling of high latitude ecosystems*

Climatic changes disproportionately affect the Arctic-Boreal region, inducing an exaggerated global warming trend, whereby high latitudes may warm by over 8 °C (Fig 5 b). Due to the complex interactions between arctic and global climate system components, there are several modelling projects directed specifically at studying high-latitude ecosystems' climate change response.

The RECCAP[1] project set out to provide a regional synthesis of sinks and sources of GHG[2] using a unified simulation set up for multiple models (McGuire et al., 2012). Their study showed that there are still significant uncertainties in modelled C balance estimates. They underlined that extensive observational networks are necessary to aid the development of

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[1] REgional Carbon Cycle Assessment and Processes

[2] greenhouse gas

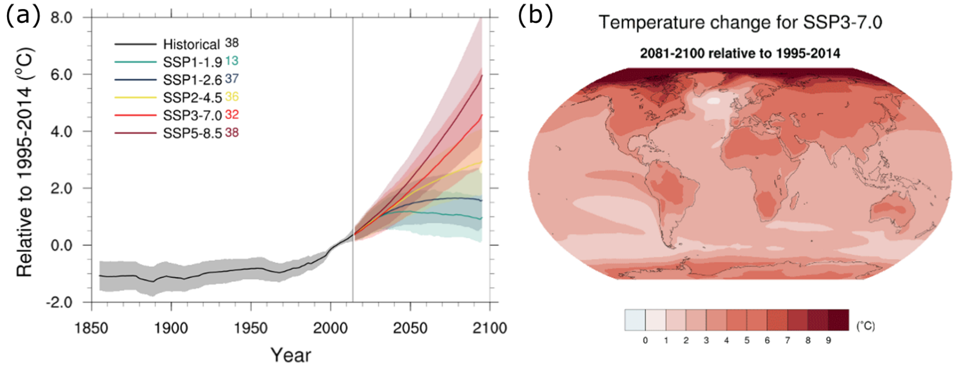

**Figure 5:** (a) Land-only timeseries of mean surface temperature change according to 4 SSPs, relative to the reference period (1995-2014). (b) Changes in surface air temperature (°C) by 2081-2100 relative to 1995-2014. Figures from Tebaldi et al. (2021)

process-based models focusing on Arctic-Boreal processes. Despite their apparent importance in the future climate, certain arctic-related processes (i.e. permafrost dynamics) have only recently been included in ESM that provide the basis for future projections.

*Snow*

Snow representation in models differs depending on the primary target application, i.e. dedicated snow physics models like SNOWPACK (Lehning et al., 2002) or Crocus (Vionnet et al., 2012) can provide robust snow condition estimates. Snow dynamics representation is more simplistic in land surface or dynamic vegetation models, often disregarding small-scale and internal snowpack processes. Snow-focused model intercomparison projects (Krinner et al., 2018; Essery et al., 2020) found that even simple multi-layer snow modules can replicate general snow conditions, while sophisticated snow physics models sometimes lack processes to realistically simulate extreme conditions. Wind compaction, liquid water retention, and snow-vegetation interactions are some processes that are often lacking in ecosystem models. While it is unrealistic to expect all models to implement highly complex snow modules, in general, they should aim at improving therepresentation of snow. Simulating realistic snow conditions is essential to model high-latitude ecosystem process interactions, especially to capture the snow-albedo feedback and the impact on permafrost temperatures.

*Permafrost and soil freeze-thaw cycles*

Modelled permafrost area estimates are typically defined by the simulated annual mean near-surface temperature at 15-25 cm depth. Therefore, snow insulation and soil freeze-thaw process significantly affect permafrost extent estimates. As mentioned, each model handles these processes with different levels of detail and skill, and these uncertainties and limitations result in a wide range of simulated permafrost extents. Uncertainties persist in future projections with a decrease in areal extent by 10-40 % $°C^{-1}$. To better capture permafrost dynamics, carbon pools, and fluxes, Chadburn et al. (2017) propose that model development focuses on dynamic vegetation processes accounting for nutrient limitation and improvement of ice-related soil processes. Advances in soil processes, yielding more realistic SOM, may lead to further improvement in the simulation of permafrost carbon emissions. The underestimation of soil organic matter (SOM) compared to literature estimates is identified as a major limitation of process-based models. These structural and process uncertainties propagate towards the total uncertainty in carbon budget simulations. Quantifying the potential permafrost carbon-climate feedback is essential, as permafrost carbon emissions could significantly affect the future carbon balance (AMAP, 2017; McGuire et al., 2018; Koven et al., 2017).

*Carbon budget*
There are large uncertainties in process-based model estimates on both current and future carbon budgets (Euskirchen et al., 2022). These deviations can be attributed to a climate forcing bias (Ahlström et al., 2017), as well as structural and process uncertainties in models. The high latitude carbon budget depends strongly on processes, such as snow-soil-vegetation dynamics. Changes in vegetation productivity and composition influence the ecosystem's carbon sequestration capacity. Increased carbon uptake can help offset the increased carbon emissions from permafrost soils. Due to the interactions between the carbon and hydrological cycles, it is imperative to look not only at one process at a time but rather at the process interactions and feedback within the climate system.

*Soil moisture*
$CO_2$ emissions are expected to increase quasi-linearly with warming air and ground temperatures, but are dependent on soil moisture conditions. There is a large disagreement between model estimates of wetland carbon emissions and by how much parameter and process uncertainties contribute to the uncertainty in modelled methane fluxes (Melton et al., 2013). Warwick et al. (2016) showed a large spread in modelled $CH_4$ emissions due to uncertainties in methane emission pathways and process parameters (Xu et al., 2013).

*Outlook*
Recent modelling studies highlight model-data match improvements in arctic regions as a result of cold-season process development (Yokohata et al., 2020). Despite the continuous model developments, uncertainties exist, and the fundamental question remains: will the Arctic region act as a carbon sink or source in the future? Cold season process representation needs to be revised and improved to provide robust future projections of the impact of wintertime changes on the carbon uptake capacity of high-latitude ecosystems.

# 3 Aims and objectives

This thesis aims to quantify the changes in Arctic carbon cycling induced by wintertime warming. We set out to decrease uncertainty in model projections by improving cold season process representation in the terrestrial ecosystem model LPJ-GUESS. We focus on assessing how changes in previously understudied winter processes may affect carbon- and hydrological cycling and vegetation dynamics – see Figure ?? fr a graphical overview.

To achieve the above-mentioned aim, the project has the following objectives:

- develop currently missing or overly simplified wintertime processes in the LPJ-GUESS DGVM[3], focusing on snow– and carbon flux dynamics (Paper I, III)
- evaluate the updated model's performance by conducting a pan-arctic scale model-data comparison (Paper I, V)
- quantify the consequences of winter warming on snow-, carbon- and vegetation dynamics under different future scenarios (Paper II and IV)

**Figure 6:** Graphical overview of the key research topics of this thesis.

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[3] Lund-Potsdam-Jena General Ecosystem Simulator Dynamic Global Vegetation Model

# 4 Materials & Methods

## 4.1 Model description

All studies presented in this thesis used the Lund-Potsdam-Jena General Ecosystem Simulator DGVM. LPJ-GUESS is a state-of-the-art process-based model that can capture vegetation establishment, competition for resources (light, water, nutrients), succession and mortality (Smith et al., 2001, 2014). LPJ-GUESS has been widely applied in both global and regional studies. The model has been part of several Arctic-specific modelling projects (Miller Paul and Smith, 2012; McGuire et al., 2012; Gustafson et al., 2021), since it can simulate key governing processes in high latitude ecosystems such as soil freeze-thaw and snow dynamics (McGuire et al., 2012; Stavert et al., 2022). In this thesis, we use a customised Arctic version of LPJ-GUESS, with recent developments in permafrost–, snow–, soil– and vegetation dynamics. We conducted regional and site-specific simulations; Papers I, II and V focus on the Arctic-Boreal region located 60°N. The model is applied at the high arctic site of Zackenberg (74°30’ N, 21°00’ W) in Paper III. Four sites were simulated in Paper IV, each located in close proximity to the Abisko Scientific Research Station (68°20’ N, 18°48’ E) in Northern Sweden. The model used a daily time step and simulates processes at a spatial resolution of 0.5° x 0.5°. For further details on the model structure, see Smith et al. (2001, 2014); Gustafson et al. (2023, in prep.) and references therein. Some of the key model features are detailed below.

*Vegetation dynamics*

Vegetation dynamics in the model are based on the forest gap scheme (Smith et al., 2001), applying a combined individual and patch-based representation driven by competition for light and nutrients (Fig. 7). In each simulated geographical location (grid cell), we simulate multiple patches (0.1 ha) that correspond to the maximum area of influence. Natural vegetation is simulated by a mix of 15 Plant Functional Types (PFTs) (Wolf et al., 2008; Gustafson et al., 2023, in prep.). Each PFT is characterised by their unique bio-climatic limits that govern its potential establishment and competition between individuals. Population dynamics (establishment and mortality) are represented by stochastic processes. Damage is simulated through a decrease in productivity, which occurs once a year, along with mortality and litterfall.

*Carbon and nitrogen cycling*

Gas- and water vapour exchange is simulated at a daily time step. Gross Primary Production (GPP) is computed as a sum of daily carbon sequestered by plants. LPJ-GUESS incorporates explicit carbon-nitrogen interactions (Smith et al., 2014), where nitrogen limitation can restrict plant productivity in high-latitude ecosystems. Net Primary Production (NPP) is dependent on GPP and plants’ maintenance and growth respiration. Heterotrophic respiration is dependent on SOM availability and soil temperature. Heterotrophic respiration

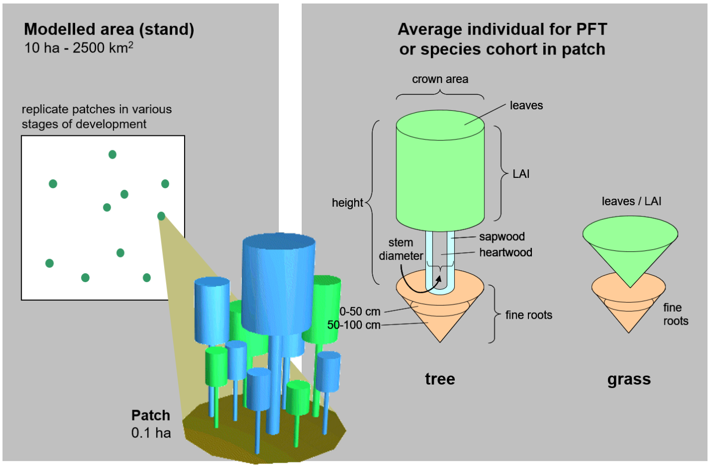

**Figure 7:** Overview of vegetation dynamics and PFT structure in LPJ-GUESS (Fig. B1 in Smith et al. (2014)).

subtracted from NPP yields Net Ecosystem Exchange (NEE), which shows whether the simulated region is a carbon source (positive NEE) or sink (negative NEE).

The model's methane module was adapted from the LPJ-WhyMe[4] implementation (Wania et al., 2009, 2010). The methane module is enabled only on peatland stands, specified by a gridded input product - such as BAWLD (Kuhn et al., 2021) or PEATMAP (Xu et al., 2018). Methane production in each soil layer is defined as a function of the daily heterotrophic respiration and rooting fraction. Methane can be reduced by oxidation, depending on the layer's $O_2$ content. Methane can reach the atmosphere via three transport mechanisms: diffusion, ebullition and plant-mediated transport. Diffusion is a gas transport process driven by the concentration difference between neighbouring soil layers and the atmosphere, calculated by the Crank-Nicholson finite difference equation (Eq. 9 in Pongracz et al. (2021)). Ebullition can occur if methane trapped in water bubbles exceeds the maximum solubility threshold. Plant-mediated transport happens through the aerenchyma of wetland-specific PFTs (spongy tissue creating air channels in the plant). Methane emissions depend strongly on the simulated sites' daily heterotrophic respiration and soil moisture (and water table depth). An up-to-date description of the methane module can be found in Appendix A in Gustafson et al. (2023, in prep.).

*Soil processes*
The soil column consists of 15 layers, 10 cm deep each and five padding layers extending to a total depth of 49.5 m. Heat diffusion is computed by the Crank-Nicholson heat transfer equation (Paper 1, Eq. 9). Thermal properties (thermal conductivity, heat capacity and diffusivity) define the heat transport capacity of soil layers. The presence of ice and liquid water in soil layers regulates these thermal properties. Freeze-thaw processes follow the implementation by Wania et al. (2009) and are further developed by Gustafson et al. (2023,

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[4] Lund-Potsdam-Jena Wetland Hydrology and Methane

in prep.). Water freezing in layers results in latent heat release. The temperature of the soil layer remains at 0 °C until all the water is frozen, and then the remaining energy is used to decrease soil temperature. Thawing of ice occurs in case layer temperature exceeds 0 °C. The addition of liquid water to soil layers occurs directly through rainfall and runoff or indirectly upon snow melt.

*Snow processes*

Originally, LPJ-GUESS used a simplistic static snow scheme. This single-layer implementation had homogeneous snow pack properties - such as temperature, density or thermal conductivity. Snow accumulation was defined by the occurrence of precipitation at or below 0 °C, and snow melt followed a linear function based on air temperature. Wang et al. (2016) highlighted that LPJ-GUESS, with the simplistic snow scheme, could not reproduce the observed snow-soil temperature relationship due to the lack of dynamics in insulation capacity that depend on snow pack properties. It is imperative to improve this model-data mismatch to provide more robust arctic carbon budget estimates, as snow dynamics influence biogeochemical process rates via the control over ground temperatures. Gustafson et al. (2023, in prep.) implemented a simple multi-layer snow scheme with up to 5 snow layers but without individual physical properties. We developed and implemented a more mechanistic snow scheme in LPJ-GUESS, following well-established empirical relationships. The differences between the simple single-layer scheme and the dynamic multi-layer scheme developed in this project are shown in Paper I.

## 4.2 Description of methods in publications

Each paper assessed critical controlling processes in arctic ecosystems. The guiding principle during the development was to maximise the improvement in the model's capacity to simulate biogeochemical variables by adding the least amount of complexity to the model. The focus topic and applied methods in the papers are summarised in Table 3. Paper I and III focus on model development, while Papers II, IV and V are mainly directed at model evaluation and application.

**Table 3:** Summary of presented papers' main topic and applied methods.

| | Topic | Methods |
|---|---|---|
| Paper I | snow | develop and validate dynamic snow scheme |
| Paper II | snow, Arctic carbon balance | evaluate future snow scenarios |
| Paper III | NGS $CH_4$ emissions | implement an experimental soil gas reservoir scheme |
| Paper IV | Arctic C balance | apply recent arctic developments (excl. dynamic snow scheme), calculate C budgets, GWP[a] |
| Paper V | snow, WWE[b] | evaluate WWE impact on a site scale |

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[a] Global Warming Potential

[b] Winter Warming Event

### Paper I

The custom LPJ-GUESS version 4.0 represents snow as a single homogeneous layer, with static snow properties throughout the cold season (Fig. 8 a). Wang et al. (2016) established that this simplistic scheme could not reproduce the observed snow-soil temperature relationship. An improved simple multi-layer scheme was implemented before the start of this project. In that scheme, up to five snow layers could exist, but, the snow layers had identical physical and thermal properties (Fig. 8 b). The updates provided an improvement in the model's capabilities, but, they did not yield a realistic simulation of internal snow pack dynamics. In **Paper I**, we developed and implemented a new, dynamic snow scheme in LPJ-GUESS (Fig. 8 c). This dynamic multi-layer scheme can simulate up to five individual layers, depending on the total snow depth. Each layer can simulate snow pack properties, as well as melt and refreeze of liquid water within snow layers. Further details on the new snow scheme set-up can be found in Paper I. We evaluated the new snow scheme's performance both at the site scale (Zackenberg) and at the regional scale (on a set of Russian sites, n = 256). The pan-arctic scale evaluation focused on how near-surface soil temperature estimates changed using the new, *dynamic* snow scheme and how these changes affected carbon and hydrological fluxes.

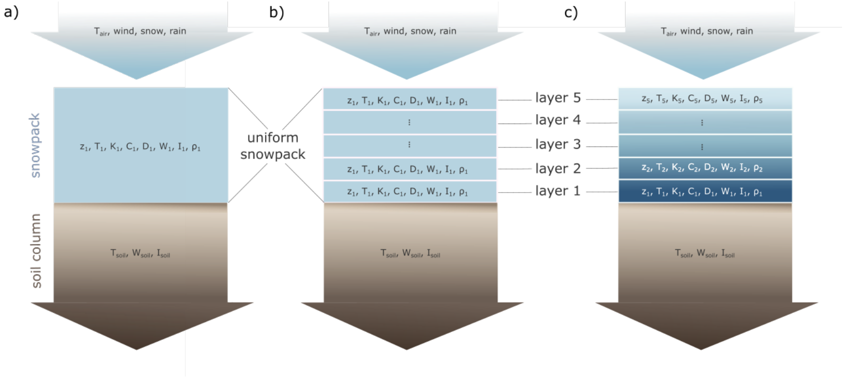

**Figure 8:** Schematic representation of snow pack structure and properties in the a) old, static, b) simple multi-layer and c) dynamic multi-layer snow schemes.

### Paper II

Paper II applied the snow-related developments from Paper I as well as the updated arctic PFT parametrisations and improved soil freeze-thaw processes from in Paper IV. This study aims to assess the relationship between future changes in snow conditions and carbon fluxes. LPJ-GUESS was forced with daily bias-corrected CMIP6 ESM climatic output using three SSPs (SSP1-2.6, SSP3-7.0 and SSP5-8.5). We investigated how the contrasting changes in snow cover conditions (snow depth, snow season length) affect carbon fluxes under different future scenarios. To evaluate spatial patterns, we analysed the changes in four climatic groups defined by mean annual air temperature. We further looked at whether carbon flux changes differ between the warm (Apr-Sep) and cold (Oct-Mar) half of the year.

**Paper III**

We introduced a conceptual model to simulate methane emissions in the non-growing season in permafrost underlain regions in Paper III. The implementation follows the hypothesis proposed by Mastepanov et al. (2008), suggesting that soil freezing controls autumn methane emissions patterns. In the conceptual model, methane emissions are defined as a function of soil pore space availability, defining layer's gas-holding capacity. The dynamics of a layer's gas concentration follow a simple bucket model approach. Gas (methane) can accumulate in soil layers until the maximum gas-holding capacity is exceeded. Then, gases are transported to the neighbouring soil layers, towards the surface, and ultimately emitted to the atmosphere. We disabled the diffusion process when soil gas reservoirs were applied at non-permafrost-underlain sites.

**Paper IV** applied novel high latitude developments related to soil freeze-thaw processes, PFT parametrisations, an updated fire module and nitrogen cycling. In this study, a model version with the simple multi-layer snow scheme was applied (Fig. 8 b). LPJ-GUESS was forced with daily climatic input from 3 ESMs (MRI-ESM2-0, NorESM2-LM, EC-Earth3-Veg) with low to high Equilibrium Climate Sensitivity (ECS). Scenario simulations were conducted following four SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). We assessed the future carbon balance by evaluating the carbon uptake capacity of arctic ecosystems – partitioning forest and tundra ecosystems. The 100-year global warming potential ($GWP_{100}$) was calculated for both $CO_2$ and $CH_4$ to assess the contribution of emissions to the future warming process.

**Paper V** utilised the snow-related developments from Paper I to evaluate the impact of winter warming events on four sub-arctic study sites in the Torneträsk catchment. LPJ-GUESS was forced with monthly climate output from two CMIP6 ESMs (CanESM5 and GFDL-ESM4) under three SSPs (SSP1-1.9, SSP2-7.0 and SSP5-8.5). Through manipulation experiments, the intensity of melt days (S1), rain-on-snow events (S2) and a combination of both (S3) were adjusted to evaluate the magnitude and direction of impacts. Additionally, we evaluated the updated snow scheme's skill to simulate WWE's impact and highlighted potential future development needs in LPJ-GUESS.

# 5 Results & Discussion

## 5.1 Dynamic snow scheme implementation

The site and regional scale evaluation of the new snow module in **Paper I** showed the improvements in simulated snow insulation capacity compared to observations (Fig. 9). Modelled near surface soil temperatures were significantly different than the static snow scheme's estimates. Comparison to the Obu et al. (2019) permafrost extent revealed an improvement in capturing the permafrost areal extent compared to previous model versions. We also assessed the impact of differing ground temperatures on carbon fluxes. We found that changing the snow scheme did not only affect cold season processes, but the summer period too, through persistent changes in soil moisture and temperature. Wintertime heterotrophic respiration increased, leading to an increased carbon release. Also we noted an increased carbon release during the summer using the new snow scheme (Table 4). Besides the seasonal differences, we found divergent patterns in carbon fluxes (NPP, NEE) within permafrost and non-permafrost underlain areas (see Fig. 12 in Paper I for details).

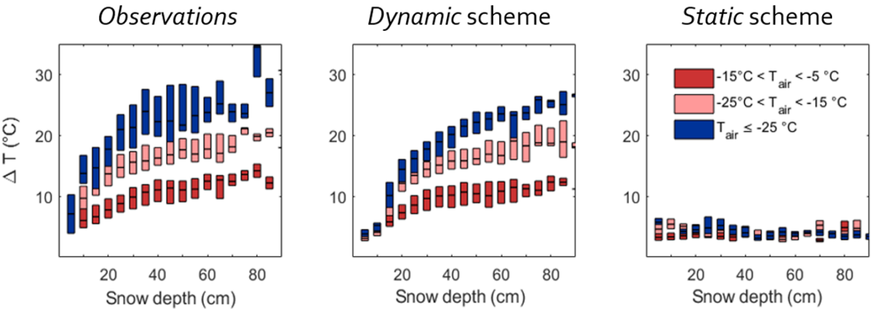

**Figure 9:** Observed and simulated insulation capacity ($\Delta T$ ,°C) (calculated as the air and 25 cm depth soil temperature difference) using the new (Dynamic) and old (Static) snow schemes in LPJ-GUESS at n=256 Russian study sites. Bar colours represent air temperature conditions.

**Table 4:** Differences in carbon fluxes between simulation using the *Dynamic* and *Static* snow schemes for the winter and summer seasons (Dynamic-Static). GPP: gross primary production, NPP: net primary production, Rh: heterotrophic respiration, NEE: net ecosystem exchange

| variable | winter | summer |
|---|---|---|
| GPP | + | - |
| NPP | - | 0 |
| Rh | + | - |
| NEE | increased C emission | increased C uptake |

Our results clearly show that the new snow scheme not only improved soil temperature simulations, but also had an impact on simulated carbon fluxes. Implementing a more realistic snow scheme is a first step towards more robust estimates on the state of the Arctic-

Boreal carbon balance. The improved snow scheme enables further research on snow-soil-vegetation interactions with LPJ-GUESS.

## 5.2 Impact of winter warming events

The skill of the snow scheme in simulating WWEs impact was the focus of **Paper v**. Contrary to previous research, increased frequency and intensity of winter warming and ROS events led to ground cooling. This behaviour can be explained by the model structure and process set-up. The impact on biogeochemical processes was substantial, with an increase in heterotrophic respiration in the birch forest and tundra site, and a decrease at the other two sites. This study highlighted the differences in patterns in four locations close to each other, providing useful information since most studies focus on a regional-global scale.

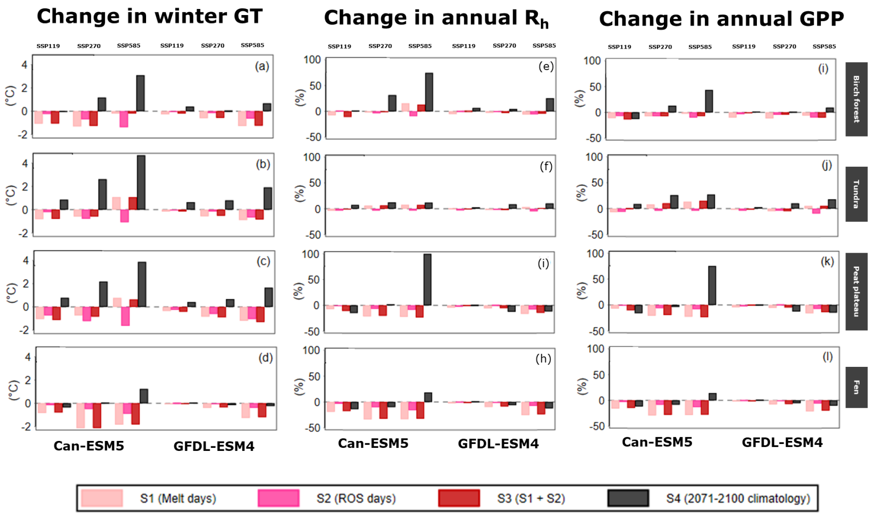

**Figure 10:** Differences between the manipulation (S1-S4) and historical simulations (S0) for winter ground temperature (°C; left; a-d), annual heterotrophic respiration (%; middle; e-h) and annual GPP (%; right; i-l), at the four study sites (columns); (figure edited after Fig. 1 and 2 in Paper v)

In general, changes in ground temperature and carbon fluxes were more pronounced for the higher emission scenarios for both applied models (Fig. 10). To understand model performance and differing results to prior field studies, we mapped out the key process relationships and currently missing processes in the model (see Fig. 11). The findings of this study point out that further cold season process development is required to be able to quantify the impact of increased WWEs on a regional and global scale.

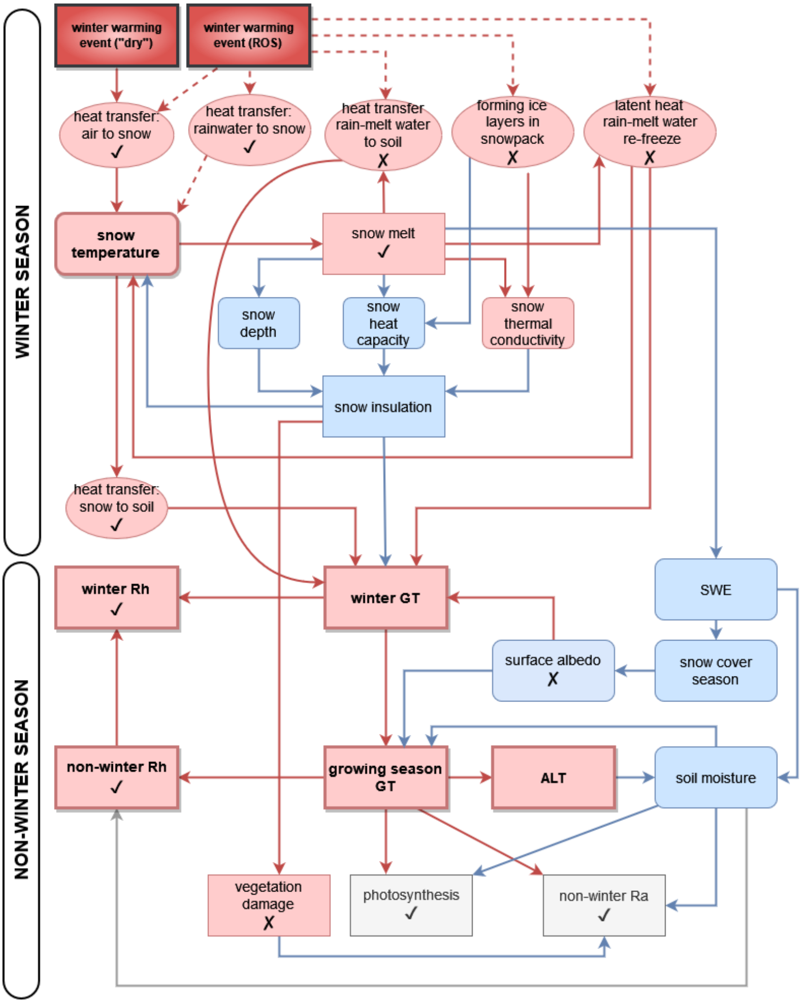

**Figure 11:** Theoretical model of WWE impacts. Box colours indicate the overall direction of changes (red=increase, blue=decrease) in the variables based on the literature. Thick outlines and bold text indicate a disagreement between the literature and our simulations. Arrow colours show the direction of the change exerted by each process. Dashed lines refer to ROS-related processes. Grey boxes and lines refer to uncertain processes and responses. Ticks and crosses indicate WWE-related processes that are, or are not, implicitly implemented in the current model version (figure adjusted after Fig. 3 in Paper v).

## 5.3 Future pan-arctic snow conditions

Our study identified contrasting spatial snow depth changes across the Arctic under different future scenarios, while the mean pan-arctic snow depth decreased. The divergent snow depth trends correspond well spatially with groups classified on mean annual air temperatures. Mean annual snow depth increased in groups 1 and 2, which correspond to the permafrost underlain region (Fig. 12, left). Snow cover duration decreased uniformly across each region and under each scenario, indicating the potential lengthening of the growing season (Fig. 12 b)). GPP and NPP increased during the warm half year in all groups, whereas heterotrophic respiration increased during the cold-half year, indicating an intensification of carbon cycling. As the increase in annual NPP was higher than the increased cold season carbon loss, the Arctic remained a carbon sink under each applied scenario. The largest relative changes in soil temperature and carbon fluxes occurred in the coldest groups and during the cold half year. Carbon residence time decreased by 2-4 times, depending on the climate scenario. Yet again, the largest changes were detected for the coldest group. Faster turnover times point to a higher reactivity to climatic changes, and potential decrease in carbon storage capacity of ecosystems in the future.

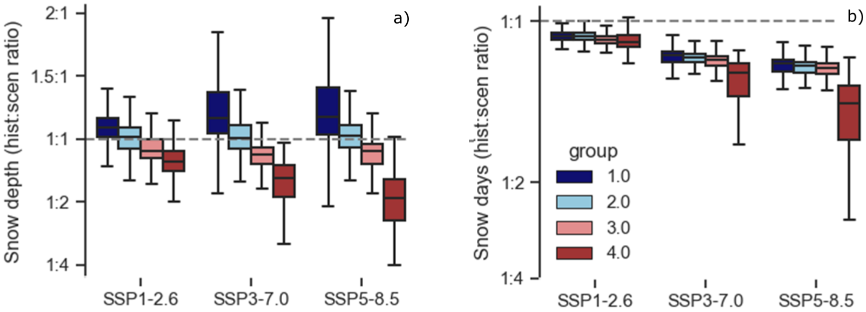

**Figure 12:** Median annual relative differences in the spatial groups for snow depth (left) and snow cover duration (right). Relative differences were computed by subtracting historical from scenario estimates over the historical estimates. The dashed grey line represent no change between the historical and scenario values. Colours represent the four spatial groups.

Detecting the largest influence of snow in the colder, mostly permafrost underlain regions is a valuable finding for further carbon cycling research in high-latitude regions. This finding highlights the further need to assess wintertime climate change impacts and how these changes can contribute to the potential permafrost carbon feedback.

## 5.4 Autumn-time methane emissions

The implementation of a conceptual soil gas reservoir model in **Paper III** improved the model-data match of autumn $CH_4$ burst events. The simple bucket model structure resulted in a direct relationship between soil freeze-in (ice content) and soil layer methane concentrations (see Fig. 13). This experiment showed that mechanistic emission pathways based on the dynamical changes in soil physics can be applied to simulate NGS methane fluxes. Our site-study found that the re-definition of methane efflux did not only affect the seasonality of carbon emissions, but also influenced total annual carbon fluxes. We acknowledge that the soil gas reservoir scheme at its current state is not applicable for a pan-arctic scale application, however with further improvement in parametrisation (Fig. 13) it has the potential to provide an alternative way of describing methane emissions at high latitude regions.

We propose that a further examination of current emission pathways and their suitability in permafrost underlain sites need to be re-examined. Substantial improvements have been made in model simulations of methane dynamics at high-latitudes, with most accounting for production, oxidation and transport of gases via different pathways (Xu et al., 2013; Castro-Morales et al., 2018). The lack of snow, gas transport and peat soil dynamics are some of the identified shortcomings of existing methane modules. Furthermore, NGS methane emissions are underrepresented in most ecosystem models (Warwick et al., 2016), thus future projections do not account for the changes in i.e. wetland methane emissions. Due to model's inability to simulate burst-like autumn emissions of methane (or $CO_2$) observed at multiple sites, it is highly uncertain how significant these events currently are across the Arctic and how their importance might change under future climate scenarios.

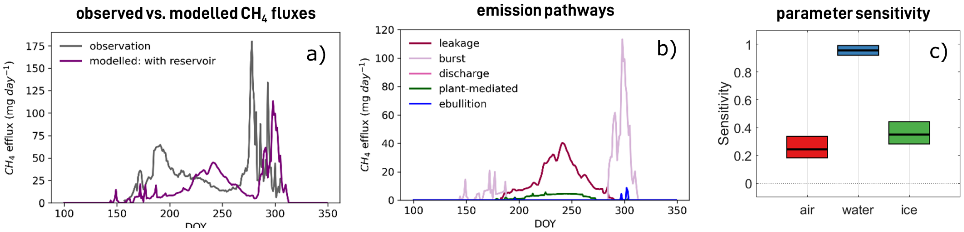

**Figure 13:** a) Observed vs. modelled methane fluxes using the soil gas reservoir at Zackenberg (2007-2010). b) re-defined emissions pathways including soil gas reservoir emissions pathways: leakage, burst and discharge. c) parameter sensitivity of three key variables regulating soil layers' gas holding capacity.

## 5.5 Arctic carbon budget estimates

**Paper IV** shows that simulated NEE is comparable to the regional estimates of Virkkala et al. (2021), although GPP was underestimated compared to literature estimates. These limitations, along with the uncertainties in climate forcing from ESMs, need to be kept in mind when interpreting model outputs. The Arctic-Boreal region was found to remain a carbon sink in the future, with forest ecosystems showing a higher carbon sequestration capacity than tundra ecosystems (Fig. 14). Results indicated that $CO_2$ contributed the most to $GWP_{100}$ (100-year Global Warming Potential). Wetland $CH_4$ emissions were the second largest contributor to $GWP_{100}$. Simulated total annual methane emissions of 11-14 Tg $CH_4$ $yr^{-1}$ are comparable to some inversion and process-based model estimates, however, they are lower than the recent flux upscaling estimate by Peltola et al. (2019). The systematic underestimation is identified as one of the main causes for model-data deviations. Similarly to other process-based models, non-growing season methane fluxes are negligible, contrasting the up to 50% contribution suggested by literature (Treat et al., 2018; Jackowicz-Korczyński et al., 2010). $N_2O$ emissions from boreal forest soils resulted in a ten times higher emission compared to the historical period in two ESMs (NorESM2-LM and EC-Earth3-Veg). Literature results suggest that there is a potential for $N_2O$ emissions from permafrost underlain soils (Voigt et al., 2020).

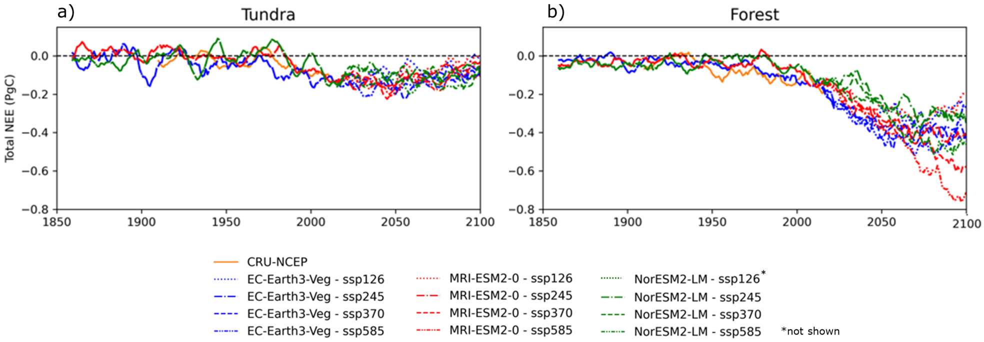

**Figure 14:** Simulated annual net ecosystem exchange (NEE) for tundra (a) and forest (b) ecosystems (figure reproduced from Fig. 3 in Paper IV).

# 6 Key findings

This section briefly summarises the findings of each research paper presented in this thesis.

### Paper I

**Evaluating the performance of the new snow module in LPJ-GUESS**

We introduced a dynamic, multi-layer snow scheme into LPJ-GUESS and tested the model's capability to simulate snow insulation capacity at the local and regional scales. The updates resulted in a more accurate simulation of snow dynamics, permafrost extent and near-surface soil temperatures. The new snow scheme enables us to assess new research questions regarding soil-snow-vegetation interactions.

### Paper II

**Contrasting snow conditions drive future biogeochemical responses across the Arctic**

We used LPJ-GUESS with the updated cold season processes to examine future snow depth and snow season length changes and their impact on carbon cycling. We found that future snow conditions will not change uniformly across the Arctic, a pattern which has mostly been overlooked. Colder regions and the cold season have undergone the largest relative changes in carbon fluxes, indicating high vulnerability under future climate scenarios. Carbon residence time decreased significantly, which is an interesting aspect to further evaluate in relation to permafrost carbon feedback studies.

### Paper III

**Experimental modelling of non-growing season methane fluxes**

We found that the model was able to replicate the secondary autumn peak in methane emissions by defining methane emissions based on soil pore space availability. However, the current scheme has difficulty in capturing the correct timing of emissions and observed inter-annual variability. We propose a further investigation into the physical controls of methane emissions in permafrost-underlain sites and an in-depth evaluation of these processes' representation in ecosystem models.

### Paper IV

**Estimating the future high latitude carbon balance**

Our results suggest that the Arctic will remain a sink of $CO_2$ in the future. High latitude ecosystem carbon sequestration capacity is strongly dependent on vegetation dynamics and also emissions of $N_2O$. The model in general, underestimated tundra carbon fluxes compared to both remotely sensed and flux upscaling estimates. The study confirmed some still existing uncertainties regarding the future carbon balance.

### Paper V

**Enhanced future impact of winter warming events at a sub-arctic site**

Opposed to observations, the model simulated significant ground cooling as a response to increased WWE frequency and magnitude. Results revealed significant changes in biogeochemistry despite the short-lived nature of WWEs. We identified the model's inability to accurately simulate local and fine-scale changes in snow conditions as the underlying reason behind the deviation from previous research.

# 7 Conclusion & Outlook

This thesis assessed how wintertime changes will affect pan-arctic carbon and hydrological cycling. I have presented a series of studies aimed at model development (Paper I and III) and model evaluation and application (Paper II, IV, V). We enhanced the overall performance by LPJ-GUESS in simulating high-latitude ecosystem processes by implementing a new snow scheme and by developing cold-season process parametrisations. We found that snow conditions will significantly influence biogeochemical and hydrological processes in the future, particularly in permafrost-underlain areas. We also identified model limitations regarding the simulation of extreme winter weather events, low soil carbon content with CMIP6 climatic forcing, and difficulties in simulating the seasonality and magnitude of non-growing season carbon fluxes. Ultimately, by improving model-data correspondence of snow depth and soil temperature, we took a step towards decreased model uncertainty and more robust future predictions using LPJ-GUESS. These studies suggest that the Arctic will continue to act as a carbon sink in the future.

In line with observational studies, the results of this thesis highlighted the importance of accounting for cold-season processes in ecosystem models. We acknowledge that due to the addressed limitations (such as low soil carbon content, low arctic plant productivity) more research is needed to determine and decrease the remaining uncertainties in carbon balance estimates. We showed that wintertime warming will have a significant impact on the carbon balance and hydrological cycling, which should be further examined both by field and modelling studies. During the undertaking of this thesis, we identified several areas of interest for further development, such as:

- snow-vegetation interactions: currently, the model does not simulate lateral processes nor snow interception by vegetation. This makes model-data comparisons challenging, where topography and vegetation cover affect snow conditions. Accounting for snow cover over vegetation during the cold season is one of the key defence mechanisms for plants to survive sub-zero conditions, but damage and mortality due to freezing is not accounted for.
- extreme weather events impact on vegetation: the lack of detailed snow-vegetation interactions makes it impossible to account for the impact of frost damage, mortality and recovery event after a winter warm spell. Development in snow-vegetation interactions and building upon the existing hydraulic scheme would enable the simulation of cold hardiness, and the impact of frost drought on ecosystem productivity.
- parametrisation of high-arctic PFTs: current PFT bioclimatic limits are tuned on a handful of well-studied sites, which provide an overall fit when benchmarking model outputs. We identified that the simulated PFT distribution could be further enhanced, as it's the basis for predicting future vegetation shifts due to competition

for resources and adaptation to new climatic conditions. As a first step, it would be beneficial to compare the current vegetation composition and ecoregions to the state-of-the-art literature estimates such as Dinerstein et al. (2017).

- improvement to soil dynamics in LPJ-GUESS is currently ongoing. The emerging multi-layer soil scheme will enable the simulation of SOM vertically in soil layers, depending on environmental conditions. These developments will be valuable in a more detailed analysis on small scale winter warming impacts on soil biogeochemistry.

We emphasise the need for closer collaboration between modelling and experimental scientists to improve process representation in ecosystem models incorporating state-of-the-art understanding of site- and regional-scale processes and their interactions. Pan-Arctic changes can have global consequences via multiple interlinked processes and feedbacks. Therefore, we reiterate the importance of accurately representing key arctic processes in models used for policy and decision-making.

Our study points out the importance of understanding historically understudied phenomena – such as cold-season processes and extreme weather events. By closing the knowledge gap on some of the still-existing questions, we can provide more robust estimates of the role of the Arctic in a changing global climate system.

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# Scientific publications

## Author contributions

Alexandra Pongracz (**AP**), Frans-Jan W. Parmentier (FJWP), Paul A. Miller (PAM), David Wårlind (DW), Didac Pascual (DP)

**Paper i: Model simulations of arctic biogeochemistry and permafrost extent are highly sensitive to the implemented snow scheme in LPJ-GUESS**
**AP** and FJWP designed the research. Model developments were lead by **AP** and implemented by **AP**, DW and PAM. **AP** performed the model simulations and analysed the data. **AP** prepared the paper with contributions from all co-authors.

**Paper ii: Contrasting snow conditions drive the future trajectory of Arctic carbon release**
**AP** and FJWP designed the research. Model developments were lead by **AP** and implemented by **AP**, DW and PAM. **AP** performed the model simulations and analysed the data. **AP** prepared the paper with contributions from all co-authors.

**Paper iii: A conceptual model for methane emissions from permafrost soils**
**AP** and FJWP designed the research. Model developments were lead by **AP** and implemented by **AP**, DW and PAM. **AP** performed the model simulations and analysed the data. **AP** prepared the paper with contributions from all co-authors.

**Paper iv: High latitude terrestrial ecosystems' contribution to global warming – will the Arctic be a sink or source of greenhouse gases in the 21st century?**
AP contributed to the writing of the methane section of the manuscript.

**Paper v: Modelling the impacts of future enhanced winter warming events on subarctic ecosystems using LPJ-GUESS**
AP participated in the discussion and writing of the model evaluation section of the paper.

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